

**Competition, Knowledge Spillover, and Innovation:
Technological Development of Semiconductor Lasers, 1960-
1990**

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Abstract

Knowledge plays an important role in economic growth. The role of technological knowledge significantly increased after the Industrial Revolution. Firms internalised technological knowledge in their R&D laboratories and placed knowledge creation in a central position in their business strategies. Both the stock and flow of technological knowledge and the tight interaction among science and engineering became indispensable to the competitive advantage of industry, as well as modern economic growth.

Directing its attention to knowledge creation and spillover, this thesis scrutinises the development of semiconductor lasers from 1960 to 1990. The semiconductor laser became one of the most important developments in the optoelectronics industry underlying the drastic changes that took place during the last half of the twentieth century in information technology, and it has become the most widely used laser since the 1980s.

Reviewing the optoelectronics industry in the U.S. and Japan, the Japan Technology Evaluation Center (JTEC) found that “Japan clearly led in consumer optoelectronics, that both countries were competitive in communications and networks, and that the United States held a clear lead in custom optoelectronics.” “Japan’s lead in high-volume consumer optoelectronics and related technologies gave it a dominant share of the overall global optoelectronics market.” This thesis explores how the patterns of comparative advantages emerged, which were indicated by the JTEC report. How did Japanese firms gain technological competitiveness in high volume product markets? How did the U.S. firms come to be competitive in niche markets?

Through scrutinizing patent data, it examines the engineers’ network, mobility, and the pattern of technological choice in R&D competition. Introducing the two different types of knowledge--current technological domain specific knowledge and lateral utilization knowledge--it showed how different patterns of knowledge spillover emerged and resulted in the different paths of technological development in the U.S. and Japan. Based on the high star-engineers’ mobility and the well developed research network, the U.S. firms tended to spin off from their parent firms and targeted niche markets. Therefore, knowledge spillover emerged in the areas where semiconductor laser technology was applied and exploited to fill untapped markets. In contrast, the pattern of competition of Japanese firms induced knowledge spillovers to enhance the development of core semiconductor laser technology instead of exploiting niche product markets.

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Abbreviations

Abbreviation	Formal Name
AIST	Agency of Industrial Science and Technology of Japan
CALTECH	California Institute of Technology
ETL	Electrotechnical Laboratory (MITI's Research Laboratory)
GHQ	General Head Quarter
He-Ne	Helium-Neon
HP	Hewlett-Packard Company
IBM	International Business Machines
JAP	Journal of Applied Physics
JAPL	Journal of Applied Physics Letters
JTEC	Japan Technology Evaluation Centre
KDD	Kokusai Denshin Denwa (International Telegram and Telecommunication)
LASER	Light Amplification by Stimulated Emission
LPE	Liquid Phase Epitaxy
MASER	Microwave Amplification by Stimulated Emission
MBE	Molecular Beam Epitaxy
MIT	Massachusetts Institute of Technology
MITI	Ministry of International Trade and Industry
MOCVD	Metal-Organic Chemical Vapour-phase Deposition
NASA	National Aeronautics and Space Administration
NEC	Nippon Electric Company, Ltd
NTT	Nippon Telegraph and Telephone Corporation
RCA	Radio Corporation of America
OITDA	Optoelectronics Industry and Technology Development Association
OMCS	Optoelectronics Measurement Control System
SCAP	Supreme Commander for the Allied Powers
SEMATECH	Semiconductor Manufacturing Technology Consortium
TRW	TRW Incorporated (the former name: Thomson Ramo Wooldridge Inc)
UIUC	University of Illinois at Urbana-Champaign

1. Introduction

Following from Albert Einstein's 1905 theoretical conception of the photoelectric effect, an American physicist, Gordon Gould, invented Laser (Light Amplification by Stimulated Emission of Radiation) in 1958. It was called "the greatest invention of the century."

A laser is an optical source that emits a narrow beam of coherent light. The power in a continuous beam ranges from a fraction of a milliwatt to more than a mega watt. The range of laser application is broad in scope ranging from commercial uses to special military applications.

The semiconductor laser became one of the most important technologies underlying the dramatic changes that took place during the last half of the 20th century in information technology, and it has become the most widely used laser since the 1980s. It is mainly used for information storage such as the compact disc and digital videodisc system, which can store a 30-volume encyclopaedia set of information on a disc and can access an arbitrary element of information in equal time. It is also employed for fibre-optic communication, which permits digital data transmission over long distances and at higher data rates than electronic communication.

Reviewing the optoelectronics industry in the U.S. and Japan in 1996, the Japan Technology Evaluation Center (JTEC) estimated that "Japan now dominates some 90% of the world optoelectronics markets and can be expected to continue its dominance for a number of years."¹ It also indicated, "Japan clearly led in consumer optoelectronics, that both countries were competitive in communications and networks, and that the United States held a clear lead in custom optoelectronics." "Japan's lead in high-volume consumer optoelectronics and related technologies

¹ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, p.xv.

gave it a dominant share of the overall global optoelectronics market.”²

Scrutinizing the development of semiconductor laser technology from 1960 to 1990, this thesis explores how the patterns of comparative advantages indicated by the JTEC report emerged. How did Japanese firms gain technological competitiveness in high volume product markets? How did the U.S. firms come to be competitive in niche markets?

This chapter contains four sections. The first section aims to present key issues of this study and to induce the research questions by overviewing the previous theoretical literature about competition, knowledge spillover, and technological change in technology-intensive industries. The second and third section introduces semiconductor laser and its epitaxy technology, which is the most important semiconductor laser technology. The last section presents this thesis’s approach to these research questions. It introduces the research design, perspectives, and measurement methodology. It also presents the sources and an outline of the argument of the study.

² Ibid., p.xv.

1.1. Knowledge, Knowledge Spillover and Technological Change³

Technology and technological knowledge played an important role in economic growth. The British Industrial Revolution (1760-1830) was the first event of modern times in which technological changes reshaped society and accelerated innovation. Indicating that the growth of the stock of knowledge played a important role in modern economic growth, Kuznets incorporated knowledge in the framework of economic analysis.⁴ He argued, “indeed, one might define modern economic growth as the spread of a system of production, in the widest sense of the term, based upon the increased application of science, that is an organized system of tested knowledge.”⁵ However, Mokyr noted that Kuznets’s theory did not attract much attention.⁶ One of the reasons was that economic historians found that the role of scientific knowledge in the British Industrial Revolution was quite modest.⁷

The role of technological knowledge, however, significantly increased after the Industrial Revolution.⁸ Pharmaceutical and chemical firms (e.g., Du Pont) were probably the first to allocate an enormous amount of resources to R&D.⁹ Examining three dominant technologies--the internal combustion engine, chemicals, and electric power--in the U.S., Mowery and Rosenberg described how funding, institutional

³ The second chapter, *Literature Review: Technological Development in Post-war Japan*, will more broadly review the previous studies of technological change in post-war Japan to show how this study aims to contribute to the broader line of previous arguments. This section focuses on the studies arguing the relationship between knowledge spillover and competition, which is the focus of this study.

⁴ Kuznets, *Economic Growth and Structure*.

⁵ Ibid, p.84.

⁶ Mokyr, "Innovation in an Historical Perspective: Tales of Technology and Evolution", p. 25.

⁷ On recent discussions on the role of scientific revolution in the British Industrial Revolution, see Allen, "The British Industrial Revolution in Global Perspective: How Commerce Created the Industrial Revolution and Modern Economic Growth"; Khan and Sokoloff, "The Evolution of Useful Knowledge: Great Inventors, Science and Technology in British Economic Development, 1750-1930."

⁸ Mokyr, "Innovation in an Historical Perspective: Tales of Technology and Evolution."

⁹ On the business history of DuPont, see Hounshell and Smith, *Science and Corporate Strategy: Du Pont R&D, 1920-1980*.

settings (e.g., patent law), and R&D systems interacted to shape the path of innovation.¹⁰ Examining the consumer electronics and computer industry, Chandler et al. revealed that the firms internalised technological knowledge into their R&D laboratories and placed knowledge creation in a central position in their business strategies.¹¹ It is generally accepted that both the stock and flow of technological knowledge and the tight interaction among science and engineering became indispensable to the competitive advantage of industry and firms, as well as modern economic growth.¹²

Knowledge Spillover

Regarding knowledge, technology, and human capital as exogenous factors, neo-classical economics used to view labour and capital as the only two factors of production important for manufacturing. However, the new growth theory contends that both knowledge and technology play significant roles in long-term economic growth.¹³ New knowledge is a source of innovation and contributes to productivity growth. Knowledge spillovers also play crucial roles in various economic contexts. Much of the current literature in both economics and economic history agrees that knowledge creation and spillover are important factors leading to economic growth. Reviewing the previous literature, this section discusses the two standpoints on competition and technological spillover, which induce the research questions.

Maintaining that technological knowledge is inherently a public good, Kenneth Arrow focused on non-rivalness and non-excludability.¹⁴ First, an unlimited

¹⁰ Mowery and Rosenberg, *Paths of Innovation: Technological Change in 20th-Century America*.

¹¹ Chandler et al., *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries*.

¹² Regarding the relationship between science and industry, see Rosenberg, "How Exogenous Is Science?"

¹³ For example, Grossman and Helpman, *Innovation and Growth in the Global Economy*; Grossman and Helpman, "Endogenous Innovation in the Theory of Growth"; Romer, "Increasing Returns and Long-Run Growth"; Romer, "Endogenous Technological Change."

¹⁴ Arrow also emphasised that knowledge is characterised by a greater degree of uncertainty, indivisibility, and asymmetry than are other types of economic goods. These issues will be introduced in the following discussion. Regarding non-excludability and externality of

number of agents can use the same technological knowledge at the same time. Second, once a firm has publicly released technological knowledge, it is difficult for the firm to keep other firms from using that knowledge. These characteristics of technological knowledge play an important role in knowledge spillovers.

While no formal definition of knowledge spillovers exists, Griliches's definition has been most straightforward. He has defined knowledge spillovers as "ideas borrowed by research teams of industry i from the research results of industry j ."¹⁵ Following Griliches's definition, this thesis defines technological knowledge spillover as learning or knowledge externalities from another firm's R&D.

Spillovers occur because new knowledge created by an organisation cannot be kept perfectly secret in the organisation. Technological knowledge emerges in numerous ways. Technological knowledge leaks out through patents, academic papers, and academic presentations.¹⁶ It is also transferred when knowledge-bearing employees change firms. Additionally, knowledge spillovers arise through informal personal relationships.

Knowledge spillovers play significant roles in various economic and business contexts. Following Schumpeter and Solow, recent economic growth literature maintains the importance of knowledge spillovers in sustainable economic growth. For instance, assuming that knowledge input in production increases marginal productivity, Romer presented a model of long-run economic growth based on the new growth theory.¹⁷ Developing economic growth models, Grossman and Helpman proposed that technology spillovers, which bring about increasing returns, are the engine of endogenous economic growth.¹⁸ In their model, the innovative

technological information, see Arrow, "Economic Welfare and the Allocation of Resources for Invention."

¹⁵ Griliches, "The Search for R&D Spillovers", p.13.

¹⁶ Appleyard has suggested that there are many different ways of knowledge sharing and technological knowledge leaking. Appleyard, "How Does Knowledge Flow? Interfirm Patterns in the Semiconductor Industry", pp.139-140.

¹⁷ Romer, "Increasing Returns and Long-Run Growth"; Romer, "Endogenous Technological Change."

¹⁸ Grossman and Helpman, *Innovation and Growth in the Global Economy*. Grossman and Helpman, "Endogenous Innovation in the Theory of Growth."

activities of firms not only lead to the introduction of new products and the improvement of product quality, but they also contribute to a general stock of knowledge on which subsequent innovators can build. This knowledge base grows over time, allowing innovation without the continual increase of R&D resources. Taking the discussion of technological knowledge spillover one step down from the national economy to corporate R&D, Griliches argued that technological spillover is a source of increasing returns in R&D and enhances technological development.¹⁹ Bernstein and Nadiri calculated social and private rates of return and estimated the effects of R&D spillovers.²⁰ Their estimation found that R&D spillovers brought important positive returns to both society and a firm and that the social return exceeded the private return, even though there is significant variation across industries in the differential between the social and private rate of return.

New knowledge in an R&D project affects the productivity of other R&D projects. Therefore, R&D spillovers have been conceptualised as a positive externality from the body of knowledge that other firms created. The previous literature has attempted to gauge the broad importance of the spillover phenomenon by looking at the average effect that other firms' R&D has on the productivity of a firm's own R&D.²¹

¹⁹ Griliches, "The Search for R&D Spillovers", p.1. Grossman and Helpman also pointed out that technology-entailed spillovers was the engine of economic endogenous economic growth. Grossman and Helpman, "Comparative Advantage and Long-Run Growth"; Grossman and Helpman, "Endogenous Innovation in the Theory of Growth."

²⁰ Bernstein and Nadiri, "Research and Development and Intraindustry Spillovers: An Empirical Application of Dynamic Duality."

²¹ Griliches, "Issues in Assessing the Contribution of Research and Development to Productivity Growth"; Jaffe, "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value."

Entrepreneurial Ventures and Spin off Engineers

One important issue--the effect of spillover--has received considerable attention since the 1970s, when many information technology business ventures spilled over from the 1960s in the area called Silicon Valley, California, in the U.S.²² Inventing the solid-state transistor in 1947 at Bell Telephone Laboratory with John Bardeen and Walter H. Brattain, American physicist William B. Shockley established Shockley Semiconductor Laboratory in Mountain View, California, in 1955 in order to commercialise his new transistor design. Spilling over from Shockley Semiconductor Laboratory, many engineers began to establish new ventures in the Stanford University area. For instance, eight engineers who had worked with Shockley left Shockley Semiconductor Laboratory and established Fairchild Semiconductor in 1956. In the 1960s, engineers spilled over from Fairchild and established new ventures. Robert Noyce and Gordon E. Moore established Intel Corporation in 1968. Shockley Semiconductor Laboratory and Fairchild Semiconductor became the intellectual hubs for many semiconductor-related business ventures. Supplying risk money to entrepreneurs, venture capitalists supported these startups. Due to the ample supply of advanced engineers from universities such as Massachusetts Institute of Technology (MIT) and Harvard University, similar entrepreneurial spillovers emerged in the area of Route 128 in Boston, Massachusetts, in the U.S. in the 1970s.²³

Spilling over from intellectual hub organisations such as Fairchild Semiconductor and MIT, numerous engineers began to establish technology-intensive businesses. As a result of flexible labour mobility and risk money supplied by venture capitalists, technological spillovers arose through knowledge-bearing engineers and spun off from the intellectual hubs; new ventures were established.

²² On technology-intensive firms in Silicon Valley, see Freiburger and Swaine, *Fire in the Valley: The Making of the Personal Computer*; Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970*, *Inside Technology*; Lee, *The Silicon Valley Edge: A Habitat for Innovation and Entrepreneurship*; Zhang, *High-Tech Start-Ups and Industry Dynamics in Silicon Valley*.

²³ On the comparison of Silicon Valley with Route 128, see Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*.

Entrepreneurship in this pattern of startups and knowledge spillovers is considered an engine of economic and technological development. Pointing out the importance of industrial clusters, Alfred Marshall suggested that knowledge spillovers facilitate innovation within an industrial cluster.²⁴ Jaffe also perceived knowledge spillovers as a major cause of spatial industrial clustering.²⁵ These reports have directed attention to the construction of regional industrial clusters such as Silicon Valley and Route 128, in which innovative firms spilled over from intellectual hubs.²⁶

While the previous literature argued that technology-intensive ventures played an important role in knowledge spillovers in technology-intensive industries of the U.S. after the 1970s, many reports on the economic and business history of post-war Japan agreed that this pattern of technological spillover was seldom observed in post-war Japan. Compared to the U.S. and European countries, post-war Japan experienced an under-developed labour market and low labour mobility.²⁷ It has been argued that employees did not have a strong incentive to leave their firms in the middle of their careers under the lifetime employment system and seniority-based wages.²⁸ It has also been pointed out that the entrepreneurial and technology-intensive spillovers were more limited in post-war Japan than in the U.S. These arguments imply an important point to this study: technology-intensive startups spinning off from the intellectual hub played an important role in knowledge spillovers in the U.S., while they were fairly limited in post-war Japan.

²⁴ Marshall, *Principles of Economics*, pp.267-277.

²⁵ Jaffe, "Real Effects of Academic Research"; Jaffe, Trajtenberg, and Henderson, "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations."

²⁶ For instance, Koeppe, *Clusters of Creativity: Enduring Lessons on Innovation and Entrepreneurship from Silicon Valley and Europe's Silicon Fen*; Porter, "Clusters and the New Economics of Competition."

²⁷ Hazama, *The History of Labour Management in Japan*.

²⁸ For instance, see Ariga, Ohkusa, and Brunello, *Internal Labor Markets in Japan*. pp.13-34.

Technological Proximity

A second issue is related to competition, technological proximity, and knowledge spillovers. Examining the conditions in which research consortia work, Katz maintained that technological proximity plays an important role in inducing technological spillover.²⁹ It is necessary to have a certain technological similarity to induce spillover effects. Griliches and Jaffe also contended that more technological spillovers emerged if the firms that adopted similar technology and targeted similar markets conducted R&D in the same technological areas.³⁰ In other words, technological spillovers are enhanced with increased technological proximity among research engineers or organisations.

The Agency of Industrial Science and Technology of Japan (AIST) surveyed key industrial technologies in 1983 and concluded that semiconductor laser technology was one of the most competitive key industrial technologies. Based on the questionnaire, this survey reported that a number of firms were competing in the same sort of product market, thus stimulating technological change and industrial development.³¹ This pattern of competitive strategy has been discussed in the existing literature on the competitive strategy of Japanese firms.³² It has been argued that Japanese firms tended to make similar technological choices and compete in similar product markets. Much of the existing literature on the competitive strategy of firms has taken a negative view of this pattern of competition. Technology-intensive startups in the U.S. tended to target unexploited product markets and establish a unique position with a different product mix and technological choice from competitors; in contrast, Japanese firms tended to compete in the same product

²⁹ Katz, "An Analysis of Cooperative Research and Development"; Katz, et al., "R and D Cooperation and Competition."

³⁰ Griliches, "The Search for R&D Spillovers", p.14; Jaffe, "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value", pp.994-995.

³¹ Kōgyō Gijutsuin Sōmubu Gijutsu Chōsaka (Agency of Industrial Science and Technology), *Wagakuni Sangyō Gijutsu no Taishitsu to Kadai*, (Survey of Japanese Industrial Technology), pp.276-277.

³² For example, Asaba, *Nihon Kigyō no Kyōsō Genri: Dōshitsuteki Kōdō no Jisshō Bunseki*, (Competitive Theory of Japanese Firms: Empirical Study of Isomorphic Behaviour of the Firm); Shintaku, *Nihon Kigyō no Kyōsō Senryaku* (Competitive Strategy of Japanese Firms).

mix with the same technological choices as competitors. Kim and Mauborgne indicated the need for firms to exist apart from markets in which many competitors intensively compete and to find untapped product markets, called “blue oceans.”³³ Introducing the industrial organisation framework into a firm’s competitive strategy, Michael Porter argued that it is essential for firms to take unique positioning in the product market in order to hold sustainable competitive advantages.³⁴ In Porter’s account, strategy rests on choosing a unique position by offering a different mix of value than competitors. Directing his attention to Japanese firms, he also pointed out, “instead of choosing distinctive ways of competing, tailoring activities, and making trade-offs, Japanese companies tend to proliferate products and features, serve all market segments, sell through multiple channels, and emulate one another’s production approaches.”³⁵ Porter maintained that this strategy without significant differences in activities is the classic strategic mistake.

While business studies take a negative view of this pattern of competition in Japan, the previous literature about technological proximity and knowledge spillovers implied that this pattern of competition might have played an important role in inducing spillover effects. Putting this another way, the competing pattern of Japanese firms might have played an important role in inducing technological spillovers because this competition pattern assumes high technological proximity.

³³ Kim and Mauborgne, *Blue Ocean Strategy: How to Create Uncontested Market Space and Make the Competition Irrelevant*.

³⁴ Porter, *Competitive Strategy: Techniques for Analyzing Industries and Competitors*; Porter, *Competitive Advantage: Creating and Sustaining Superior Performance*; Porter, "What Is Strategy?"

³⁵ Porter et al., *Can Japan Compete?*, p.91.

Different Knowledge Travels Differently

These two points regarding spin off and technological proximity provide an important basis for this thesis. It was regarded that entrepreneurial venture business and spin off engineers play an important role in knowledge spillover in a technology intensive industry on the one hand. On the other hand, the economists supposed that a higher level of technological proximity would induce more spillovers.

Combining these two points, this thesis aims to scrutinize the technological development of the semiconductor laser in an effort to show how firms' competition shaped the nature of knowledge spillovers and induced the different types of knowledge spillovers.

The history of science and technology and economic history have explored the concept of knowledge for more years than economists. Historians have revealed the complex nature of knowledge and indicated that there were many different types of knowledge. The most familiar categorization of knowledge is pure science and applied science. Theoretical knowledge and practical knowledge is also one of the most familiar categorisations. Michael Polanyi introduced two types of knowledge: tacit knowledge and formal knowledge.³⁶ The former relates to knowledge inarticulately rooted in an individual's experience and observation. The latter relates to theoretically based knowledge that may be rationally justified. Economic historians have also categorized knowledge into several types. For example, pointing out that the growth of human knowledge is one of the deepest and most elusive elements in economic history, Joel Mokyr introduced two types of knowledge: propositional and prescriptive.³⁷ The former category, labelled Ω -knowledge, consists of the stock of beliefs about natural phenomena and regularities. The latter (λ -knowledge) includes the set of instructions or techniques for applying propositional knowledge in economic production. Scholars in business management

³⁶ Polanyi, *The Tacit Dimension*. Following from Polanyi's categorization, Nonaka and Takeuchi examined how new knowledge was created in firms. Nonaka and Takeuchi, *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*.

³⁷ Mokyr, *The Gifts of Athena: Historical Origins of the Knowledge Economy*, pp.1-27.

studies also have examined different types of knowledge. Pointing out that the traditional categorisation of innovation as either incremental or radical is incomplete and potentially misleading, Henderson and Clark introduced two distinctive types of knowledge: component knowledge and architectural knowledge.³⁸ The first is “knowledge about each of the core design concepts and the way in which they are implemented in a particular component.”³⁹ The second is “knowledge about the ways in which the components are integrate and linked together into a coherent whole.”⁴⁰ Examining organisational capability to utilise certain knowledge, Teece classified knowledge into two depending on inter-organisational transferability: one is contractually non-separable from the firm possessing it and the other is contractually separable.⁴¹

This thesis assumes that depending on types of spillover knowledge from other firms, the nature of knowledge spillovers may vary. This section classifies knowledge into two categories; current technological domain specific knowledge and lateral utilization knowledge, and it introduces two types of knowledge spillovers. Current technological domain-specific knowledge (domain-specific knowledge) relates to knowledge about a technology that one is currently developing for a certain target. Lateral utilization knowledge relates to knowledge about how one would use technology for a new target.

Take carbon fibre technology, for example. Carbon fibre is a highly durable and flexible carbon filament thread, which is stronger and much lighter than steel. It is widely used in airplane parts, high-performance vehicles, sporting equipment, wind generator blades, and other demanding mechanical applications.

If one is currently developing carbon fibre for the wing of an airplane, all technological knowledge created from R&D in this domain is classified as domain-specific knowledge. For instance, knowledge about the material composition of

³⁸ Henderson and Clark, "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms", p.11.

³⁹ Ibid., p.11.

⁴⁰ Ibid., p.11.

⁴¹ Teece, "Towards an Economic Theory of the Multiproduct Firm."

carbon fibre for wings is classified into domain-specific knowledge. Knowledge about the manufacturing process of carbon fibre for wings is also classified in this category. In other words, all knowledge created in this domain is classified into domain-specific knowledge. On the other hand, knowledge about how to apply the carbon fibre, which one is currently developing for the wing, to a different target, is lateral utilization knowledge. For instance, one may want to apply the carbon fibre to a tennis racket. In this case, knowledge concerning how one uses the carbon fibre in a tennis racket is classified into lateral utilization knowledge.

This thesis presumes that the conditions in which knowledge spillover occurs vary depending on the types of knowledge spillovers. The previous literature in economics on knowledge spillover indicated that technological proximity plays an important role in inducing spillover effects. For instance, Griliches contended that more technological spillovers emerged if the firms that adopted similar technology and targeted similar markets conducted R&D in the same technological areas.⁴²

While the previous literature assumed that higher technological proximity would induce more technological spillover effects, this thesis argues that higher technological proximity induces a higher level of domain-specific knowledge spillover but reduces the possibility of lateral utilization knowledge spillover.

One can easily learn from others who have conducted R&D in a similar technological domain. In this spillover, what one can learn from the others is domain-specific knowledge. In other words, one can learn domain-specific knowledge more from others who are researching in a similar domain with a similar technological choice than others who are researching in a different area with a different technological choice.

On the other hand, a higher technological proximity does not necessarily bring about lateral utilization knowledge spillover. Furthermore, it reduces the possibility of lateral utilization knowledge spillover. It is necessary to have a certain complementary knowledge to obtain knowledge about how to apply current

⁴² On the overview of relationship between spillover and technological proximity, see Griliches, "The Search for R&D Spillovers."

technology for a different domain. If the carbon fibre manufacturer tries to begin to apply carbon fibre to make tennis rackets, it needs to learn from those who have researched this field and accumulated complementary knowledge. If everyone conducts R&D in the same technological domain, it reduces the possibility that one can access complementary knowledge and learn how to apply technology in a different field. It must be noted that it is difficult to induce any knowledge spillover from others, if their research area and technological choice are completely different. However, it is reasonable to assume that high technological proximity would increase domain-specific knowledge spillover and reduce the possibility of lateral utilization knowledge spillover.

Research Question

There are two important governmental reports on the optoelectronics industry and the semiconductor laser: the JTEC report and the AIST report. As showed above, examining the world optoelectronics industry, JTEC reported that Japanese firms were competitive in high volume consumer product markets, while U.S. firms were competitive in the custom market. The simple but fundamental question underlying this study is how the patterns of competitive advantages reported by the JTEC emerged in the U.S. and Japan. In other words, the fundamental research questions are the following.

- **Research Question 1:** How did Japanese firms come to be competitive in the high volume market?
- **Research Question 2:** How did the U.S. firms come to be competitive in the niche markets?

Surveying key industrial technologies in 1983, AIST designated semiconductor laser technology as one of the most competitive key industrial technologies in optoelectronics. Based on a questionnaire survey, this report

indicated that the firms' fierce competition in the same semiconductor laser market played an important role in technological development.⁴³ The JTEC survey combined with the AIST's survey revealed that Japanese firms competed in the consumer electronics market with the same technological choices, whereas U.S. firms assumed competitive advantages in niche markets.⁴⁴ These points lead to questions concerning how Japanese firms came to have a similar strategy in the same market, and how the U.S. firms came to be competitive in niche markets. These research questions are broken down into sub research questions. They will be examined in detail in each chapter starting from the third chapter, *Human Capital and Research Networks*.

Scrutinizing the development of semiconductor lasers based on the research questions, this thesis shows that Japanese firms and the U.S. firms obtained different types of knowledge spillovers in R&D competition. More concretely, while the U.S. firms acquired lateral utilization knowledge spillover, Japanese firms obtained domain-specific knowledge spillover more than lateral utilization knowledge. It proposes two points:

- The U.S. firms tended to bring knowledge spillovers which enriched and exploited potential and untapped product markets by utilizing the fundamental technology of the semiconductor laser.
- The pattern of competition of Japanese firms induced spillovers enhancing the development of the fundamental technology of the semiconductor laser instead of exploiting niche product markets.

This paper draws a somewhat ironic conclusion from the case of

⁴³ Kōgyō Gijutsuin Sōmubu Gijutsu Chōsaka (Agency of Industrial Science and Technology), *Wagakuni Sangyō Gijutsu no Taishitsu to Kadai, (Survey of Japanese Industrial Technology)*. pp.276-277.

⁴⁴ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, p.xv; Kōgyō Gijutsuin Sōmubu Gijutsu Chōsaka (Agency of Industrial Science and Technology), *Wagakuni Sangyō Gijutsu no Taishitsu to Kadai, (Survey of Japanese Industrial Technology)*. pp.276-277.

semiconductor laser technology in the U.S and Japan. Since the U.S. firms were in a better position to learn how to apply the semiconductor laser for untapped markets, they differentiated their R&D and targeted niche markets. The more that firms differentiated their R&D for untapped markets, the more lateral utilization knowledge was spilt over in the industry through developed inter-organisational networks and the high mobility of engineers in the U.S. As a result, because the firms differentiated their R&D for small niche markets, the development of fundamental semiconductor laser technology for mass markets was retarded in the U.S. The highest volume market was eventually taken by Japanese firms, which had difficulty in accessing lateral utilization knowledge. Many Japanese firms were competing to develop epitaxy technology, which was the most economically and strategically important semiconductor laser technology. The pattern of competition of Japanese firms induced knowledge spillovers to enhance the development of fundamental semiconductor laser technology instead of exploiting niche product markets.

1.2. Semiconductor Laser⁴⁵

The semiconductor laser, which is also called “Laser Diode”, is a tiny electronics device mainly used in optical communication and optical information storage. Figure 1-1 depicts an actual sized semiconductor laser. Its height is around one centimetre. The diameter of the packaged semiconductor laser is around five millimetres.

Figure 1-1: Semiconductor Laser



Copyright (C) 1998, Matsushita Electronics Corporation.

Laser stands for light amplification by stimulated emission or radiation. It is an optical source of artificial light, which is typically near-monochromatic, single wavelength and emitted in a narrow beam. Theodore H. Mainman succeeded in radiating a laser beam by using a solid body pink ruby in 1960 in the U.S. It was the first laser emission in the world. The semiconductor laser was invented in 1962. Now there are many varieties of lasers; CO₂ laser, YAG laser, He-Ne laser, ruby laser, semiconductor laser, and so on. The power in a continuous beam ranges from a fraction of a milliwatt to more than a mega watt. The range of laser application is broad from commercial uses to special military uses.

Examples of applications⁴⁶

- Materials working
- Measurement and inspection

⁴⁵ On the mechanisms of semiconductor laser, see Appendix VI.

⁴⁶ Hecht, *The Laser Guidebook*. pp. 7-8.

- Reading, writing, and recording of information
- Displays
- Communications
- Holography
- Spectroscopy and analytical chemistry
- Remote sensing
- Surveying, marking, and alignment
- Laser weaponry
- Laser-induced nuclear fusion
- Isotope enrichment
- Spectroscopy and atomic physics
- Measurement
- Plasma diagnostics

There are four reasons for taking semiconductor laser technology as a case study. The first reason is the fact that the semiconductor laser is quite technology intensive. Table 1-1 shows the R&D intensity of technology intensive industry in Japan measured by R&D expense divided by sales. It illustrates that the Communication, Electronics, and Electric Measurement industry in which the semiconductor laser is classified, come to the second highest R&D intensity industry next to the pharmaceutical industry. Moreover, laser technology was regarded as one of the greatest inventions of 20th century. It became the symbol of “high tech” of the century.

Table 1-1: R&D Intensity in Japan

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Total	1.54	1.67	1.84	2.03	1.99	2.31	2.57	2.59	2.6	2.72	2.78
Total Manufacturing Sector	1.74	1.92	2.15	2.31	2.34	2.69	3.03	3.14	3.15	3.29	3.36
Pharmaceutical	5.45	5.85	5.56	6.59	6.49	7.04	6.89	6.96	6.94	7.5	8.02
Communication, Electronics and Electric Measurement	3.94	4.21	4.72	4.85	4.6	5.25	5.63	5.78	5.66	6.1	6.12
Electric Machine and Instrument	3.35	3.8	4.17	4.4	4.45	5.1	5.5	5.61	5.53	5.89	5.36
Precision Machine	3.02	3.47	3.97	4.02	4.08	4.49	4.59	4.91	4.85	5.16	5.94
Grease and Paint	2.48	2.56	2.66	2.83	3.09	3.14	3.42	3.85	3.74	3.93	3.9
General Chemicals and Chemical Textile	1.85	2.01	2.17	2.32	2.47	2.8	3.56	3.76	3.92	4.09	4.01
Automobile	2.38	2.82	3.02	2.89	2.9	2.96	3.2	3.17	3.31	3.48	3.65

Source: Monbu Kagaku Shō, (Ministry of Education Culture Sports Science and Technology). *Kagaku Gijutsu Shihyō 2004 Ban, (Science and Technology Report)*, p.526.

The second is related to the presence of laser technology. The laser was invented in the late 1950s. Now the laser is widely used both in daily life and on battlefields. The application areas of laser light are highly diversified, and include measurement, information processing, alignment and construction, optical communications, medical work, and instrumentation, printers, material processing, pointers, radar, and also bombs. Table 1-2 demonstrates the presence of optoelectronics production in GDP in Japan. It shows that the optoelectronics presence in GDP steadily increased from 1983 and reached 1.08 percent of GDP in 1997. Optoelectronics was the basis of competitiveness of various industries such as the consumer electronics industry and the computer industry. Optoelectronics is one of the best representatives of the development of technology intensive industries in Japan.

Table 1-2: Optoelectronics Production and Presence in GDP (Billion Yen)

	1983	1984	1985	1986	1987	1988	1989
Optoelectronics	466	642	847	1,042	1,690	2,086	2,614
The Presence in Real GDP (%)	0.15	0.19	0.25	0.29	0.45	0.53	0.63

1990	1991	1992	1993	1994	1995	1996	1997
3,169	3,467	3,682	3,727	4,060	4,309	4,767	5,272
0.73	0.77	0.82	0.82	0.89	0.92	0.97	1.08

Source: Keizai Kikaku Chō, (the Economic Planning Agency Government of Japan). *Kokumin Keizai Keisan Nenpō*, (Annual Report on National Accounts), 2000. Denpa Shinbun Sha, *Denshi Kōgyō Nenkan* (Annual Report on the Electronics Industries), 1983-1998. Current Price.

Semiconductor laser technology is the key technology of optoelectronics production. In the optoelectronics market, the semiconductor laser has the biggest share in sales among various types of lasers. Table 1-3 shows laser sales in Japan from 1980.

Table 1-3: Laser Sales in Japan (Million Yen)

	1980	1981	1982	1983	1984	1985	1986	1987
Semiconductor Laser	925	2,290	4,569	15,894	20,550	40,797	39,459	34,528
Gas Laser	2,080	2,188	2,382	4,999	6,658	8,027	7,614	7,282
Solid body Laser	300	1,564	827	1,282	3,883	3,663	2,920	2,229

1988	1989	1990	1991	1992	1993	1994	1995
29,411	33,641	40,200	38,067	42,965	44,479	54,624	71,102
8,512	12,546	15,595	16,114	12,004	10,747	14,915	19,681
2,976	3,310	636	4,094	3,683	3,300	4,900	5,283

Source: Denpa Shinbun Sha, *Denshi Kōgyō Nenkan (Annual Report on the Electronics Industries)*, 1980-1995. Current Price.

Even though there is no statistical data allowing us to investigate in the 1970s, it is assumed that the gas laser had the biggest share before 1981.⁴⁷ The gas laser was the dominant form until 1981. Table 1-3 shows that the semiconductor laser occupied the biggest market share from the beginning of the 1980s and steadily increased its sales. In other words, the semiconductor laser became dominant in the optoelectronics market from the beginning of the 1980s. In spite of the presence and significance of semiconductor laser technology and the optoelectronics industry, however, the literature about it is very limited.

The third reason is related to its competitiveness. The industrialisation of laser technology started in the 1970s. There have been no systematically recorded statistics indicating the size of the optoelectronics market and its national share. However, the Optoelectronics Industry Development Association (OIDA) and the

⁴⁷ Suematsu Yasuharu, a professor of Tokyo Institute of Technology, noted, “Research and development in semiconductor lasers began in 1962. However, few researchers paid attention to the semiconductor laser. The research on the gas laser was dominant in the 1960s. When we talked about the academic society of quantum electronics, it meant the academic society of the gas laser.” Suematsu, *Handōtai Rēzā ga Tsūshin o Kaeru, (Semiconductor Laser Will Change Communication)*, p.13.

Optoelectronics Industry and Technology Development Association (OITDA)'s 1993 survey allow us to estimate the size of the market and the market share of Japan.⁴⁸ OIDA estimated that the world optoelectronics market totalled approximately \$70 billion in 1993.⁴⁹ OITDA's statistics indicated that Japanese firms' optoelectronics production was around \$35 billion.⁵⁰ From these statistics, it is possible to estimate that Japanese firms had approximately a 50% share in the world optoelectronics market. Japan Technology Evaluation Centre (JTEC) in the U.S. provided a more aggressive estimation in 1996. It indicated, "Japan now dominates some 90% of the world optoelectronics markets and can be expected to continue its dominance for a number of years."⁵¹ The most widely circulated electronics journal in Japan said,

"Much of Japanese industrial technology was based on technological import from the western countries. Based on high level production technology, skilled labour, high quality control, and high flexibility to environmental change, Japan improved the imported technologies and exported them to the western countries. This is true in the automobile, TV, and semiconductor industry." "Optoelectronics, however, is the technology that is made in Japan and can contribute to the world."⁵²

⁴⁸ OIDA is the U.S. industry association representing 50 members, including both large and small companies. It was established to promote optoelectronics worldwide and advance the competitiveness of its members in July 1991. OITDA is an industry association of Japan's optoelectronics industry. It was established in 1980. Saxonhouse estimated the size of market with OIDA and OITDA surveys. Saxonhouse, "Optoelectronics in Japan: Some Economic Considerations."

⁴⁹ Optoelectronics Industry Development Association, "Optoelectronic Technology Roadmap; Conclusions and Recommendations."

⁵⁰ Hikari Sangyō Gijutsu Shinkōkai (Optoelectronics Industry and Technology Development Association), *Hikari Sangyō no Dōkō*, (*Trends in Optoelectronics Industry*).

⁵¹ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, p.xv.

⁵² Hikari Sangyō Kondankai (Optoelectronics Industry Conference), "Hikari Gijutsu no Ayumi to Hikari Sangyō no Genjō, (History of Optoelectronics Technology and Present State of the Optoelectronics Industry)", pp.34-51.

In 1986, *Fortune* indicated that Japanese firms developed the most advanced technological competence among technology leading countries in the optoelectronics field (Table 1-4). *Fortune* asked ten scholars, business executives, government officials, and foundation leaders in each field to rank the state of research and development in the U.S., Japan, Western Europe, and the USSR on a scale of 1 to 10. Table 1-4 shows the average points that the U.S., Japan, Western Europe, and the USSR received in each technical field.

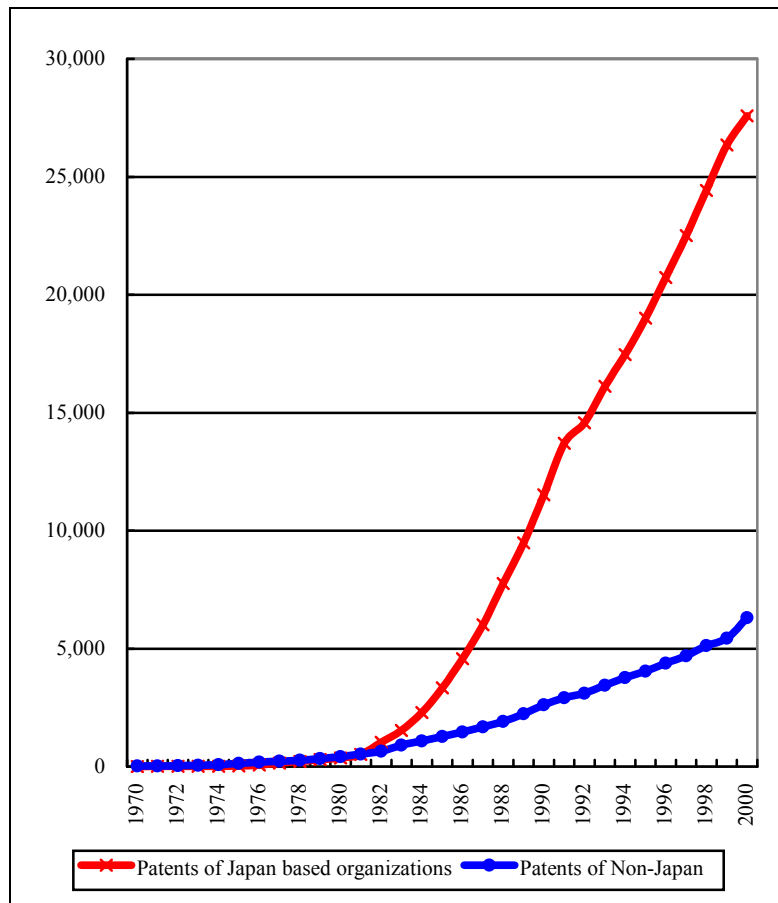
Table 1-4: Competitive Advantage of the Nations in Technical Field

Technical Field	United States	Japan	West Europe	USSR
Computer	9.9	7.3	4.4	1.5
Biochemical	8.9	5.7	4.9	1.3
New Materials	7.7	6.3	6	3.8
Optoelectronics	7.8	9.5	5.7	3.6

Source: Bylinsky, "Where the U.S. Stands", pp.18-36. Average of ten experts' rankings.

It must be noted that this Fortune's survey seemed not to follow a systematic method to carry out questionnaire survey. For example, how Fortune selected scholars, business executives, government officials, and foundation leaders were not presented in the article. The instructions and questionnaires were not shown either. However, it is important to note that the competitive advantage of Japan in optoelectronics was presented in such a well-circulated non-academic journal.

The number of patents in semiconductor laser technology sheds light on the technological competitiveness of the optoelectronics industry of Japan. Figure 1-2 shows the number of patents in semiconductor technology both in the world and in Japan. It shows that Japanese firms, research institutions, and individual inventors began to get patents from the 1970s and became active in getting patents in semiconductor lasers from the 1980s.

Figure 1-2: World Patents and Japan Patents (Accumulative)

Source: *Derwent Innovations Index*. Calculated by the number of semiconductor laser patents in developed countries, which the Derwent Innovations Index covers, this graph sorted the patents by whether the patent is from a Japan base institution or not, not by the place where each patent assignee is located.

It also indicates that Japan's annual number of semiconductor laser patents exceeded that of patents excluding Japan's in 1977 for the first time. Japan's total cumulative number of semiconductor laser patents has exceeded that of cumulative patents excluding Japan's from 1981 onwards. This graph indicates that the turning point was 1981. Until 1981 the slope of both total patents excluding Japan's and Japan's patents were quite similar. The slopes, however, diverged from 1981. Japan's accumulated patents exceeded those of the world from 1981, and the trends highly diverged. Based on these data, it is possible to suppose, Japanese firms gained technological competitiveness in semiconductor laser technology from the beginning of the 1980s. Showing the top twenty organisations obtaining patents in

semiconductor laser from 1970-2000, the following table lists organisations playing important roles in the technological development of semiconductor lasers in Japan.

Table 1-5: Top Twenty Firms in Japan

	1970s			1980s			1990s		
	Firm	Number of Patens	Share (%)	Firm	Number of Patens	Share (%)	Firm	Number of Patens	Share (%)
1	Hitachi	52	17.8082	NEC	1468	15.9721	NEC	1644	9.7752
2	NEC	42	14.3836	Matsushita Elec Ind	1009	10.9781	Mitsubishi Electric	1257	7.4741
3	NTT	42	14.3836	Fujitsu	883	9.6072	Matsushita Elec Ind	998	5.9341
4	Matsushita Elec Ind	35	11.9863	Mitsubishi Electric	811	8.8238	Hitachi	907	5.393
5	Fujitsu	27	9.2466	Hitachi	785	8.541	Fujitsu	857	5.0957
6	Mitsubishi Electric	23	7.767	Toshiba	544	5.9188	Toshiba	835	4.9649
7	Sharp	13	4.521	Sharp	454	4.9396	Sony	826	4.9114
8	Canon	12	4.096	Canon	430	4.6785	Canon	776	4.6141
9	Toshiba	9	3.822	NTT	309	3.362	Sharp	602	3.5795
10	Agency of Industry	8	2.397	Ricoh	263	2.8615	NTT	602	3.5795
11	Sony	7	2.973	Oki Electric Ind	179	1.9476	Ricoh	464	2.7589
12	Sumitomo Electric Ind	3	1.274	Sony	173	1.8823	Sanyo	411	2.4438
13	Sanyo	2	0.6849	Seiko Epson	156	1.6973	Fuji Photo Film	321	1.9087
14	KDD	1	0.3425	Agency of Industry	149	1.6212	Nikon	284	1.6887
15				Sanyo	128	1.3927	Oki Electric Ind	283	1.6827
16				Fuji Photo Film	104	1.1315	Furukawa Electric	257	1.5281
17				Sumitomo Electric Ind	96	1.0445	Seiko Epson	240	1.427
18				Omron Tateishi	88	0.9575	Sumitomo Electric Ind	240	1.427
19				Konica	87	0.9466	Olympus	206	1.2249
20				Fuji Electric Mfg	83	0.9031	Semiconductor Energy Lab	166	0.987
Total			94.5205			89.2068			72.3986

Source: *Derwent Innovations Index*. It counts the number of patents obtained by the firms with the Derwent Innovation Index. The share is calculated from the total number of patents obtained by Japanese organisations in each period and the number of patents obtained by each firm.

This table indicates that the main actors were big electronics enterprises through these periods. The main actors such as NEC, Hitachi, Fujitsu, Toshiba, Mitsubishi, and Matsushita, were highly ranked through 1970s to 1990s. This study explores how these firms were competing and came to be competitive from the 1980s.

The fourth reason is related to research ability and commercial sensitivity. Research that examines the micro activities of a firm such as corporate R&D activity, human resource management, and cost structure may confront a commercial sensitivity problem. The commercial sensitivity may affect data availability. Commercial sensitivity in this industry, however, is not critical for this study for two reasons. Japan's patent policy was a 'first to file system' and 'automatic publication policy.' Under this patent system, firms had a strong incentive to apply for a patent first. As a result, patent data can show much of the firms' R&D activities. Of course, patent is not the R&D activity itself but the outcome of R&D activities. Yet, it still reveals the technological areas in which firms competed. This patent system reduces the commercial sensitivity problem. In addition, the firms competed to publish their R&D results in their corporate technical journals and in academic journals. These publications also allow investigating the firms' R&D activities. Of course, the firms published only the successful R&D results. However, it still shows the areas in which the firms focused their R&D and competed with each other. Second, more than 20 years have passed since many of the epoch-making technological innovations in semiconductor lasers emerged. Although semiconductor laser technology is still key for optoelectronics, many of the technologies developed from the 1960s to 1980s, which is the main focus of this study, have already become "classic." Many of the corporate engineers have already retired from their business. Some of them have got positions at a university and started their second career as an academician. They were willing to speak about their experiences in R&D to develop such "classical technologies." Twenty years old technologies are already "classical" in this industry, even though some of them are still alive. Of course, it may be difficult to touch current on-going important R&D activities and the amount of R&D investment on a certain specific project. This sensitivity is not limited to this study.

Although the sensitivity remains in certain areas, it is not crucial for data availability for this study.

Semiconductor lasers are being used in various application areas such as medical use, light for high-speed cameras, material processing, optical sensors, laser pointers, measurement, optical disks, printers, barcode readers, and optical fibre. The two biggest application areas have been optical communication and optical information storage. Long wavelength semiconductor lasers ($1.3\mu\text{m}$ - $1.55\mu\text{m}$) are used for optical communication appliances such as optical fibres.⁵³ Short wavelength semiconductor lasers ($0.47\mu\text{m}$ – $0.85\mu\text{m}$) are used for optical information storage and processing such as optical discs and laser printers. The following table shows the production of optical communication and information storage / processing. The parenthesis shows the share in total optoelectronics production and denotes that these two areas were the main market of semiconductor lasers.

Table 1-6: Two Main Markets of Semiconductor Lasers (Million yen)

	1985	1990
Optical Communication	252,714 (30%)	556,993 (18%)
Optical Information Storage/ Processing	514,722 (61%)	2,464,815 (78%)

Source: Tsūshō Sangyō Shō, (Ministry of International Trade and Technology), *Denshi Kōgyō Nenkan (Annual Report on the Electronic Industry)*, 1993, p.615.

These two semiconductor laser markets are different, although semiconductor lasers are the key devices in both markets. The long wavelength semiconductor lasers were used in important social infrastructure such as long-distance telecommunication and high broadband networks. Many industrialised countries had their own telecommunication firms. Because the state-owned telegraph and telecommunication company developed optical communication system and used domestic firms for telecommunication-related manufacturing for its social infrastructural appliances, the political economy of relations between the government, the telecom company and the suppliers played a role in these markets. The short wavelength semiconductor lasers, which were for optical information

⁵³ Regarding wavelength, see Appendix VI.

storage, laser printers, barcode readers, medical use, pointers, and laser sensors, were more consumer and industrial appliances in which governmental intervention did not play an important role. Since it goes far beyond the scope of this study to offer an exhaustive description of the development of semiconductor lasers, this study mainly focuses on the development of semiconductor lasers for consumer and industrial appliances, not for appliances for social infrastructure.

1.3. Epitaxy Technology

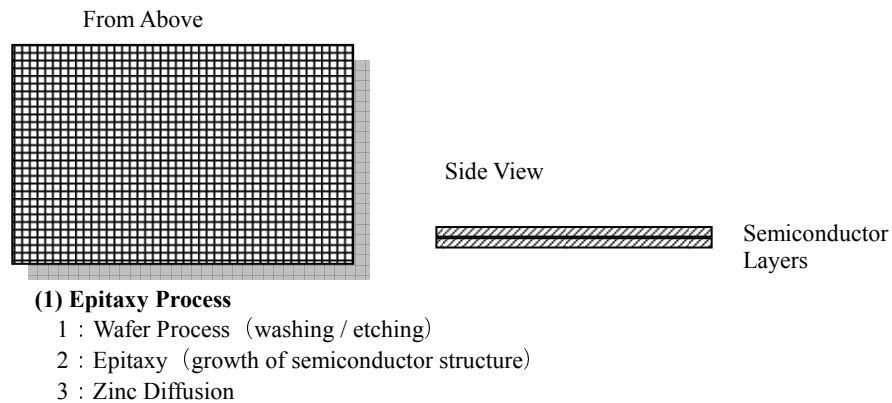
Since the semiconductor laser is composed of many sub technologies, this thesis focuses on the development of epitaxy technology. The *Optoelectronics Handbook* indicated, “The most important process technology in semiconductor lasers is epitaxy technology, which determines most of the quality of semiconductor laser.”⁵⁴ The Japan Patent Office classified semiconductor laser technology into five categories: device, material, manufacturing, drive, and system technologies.⁵⁵ According to the Japan Patent Office’s classification, epitaxy technology is classified as a manufacturing technology. Surveying industrial technologies, the AIST reported that Japanese firms were competitive in semiconductor laser technology and in epitaxy technology in particular.⁵⁶

Semiconductor laser manufacturing is categorized into three processes. The first, the epitaxy process, involves making a semiconductor wafer by depositing a very thin layer of single crystal materials over a substratum (Figure.1-3). This process is the most important process in semiconductor laser manufacturing, since the semiconductor layers seriously affect the quality and longevity of the semiconductor laser. This process varies with combinations of semiconductors used for the semiconductor laser.

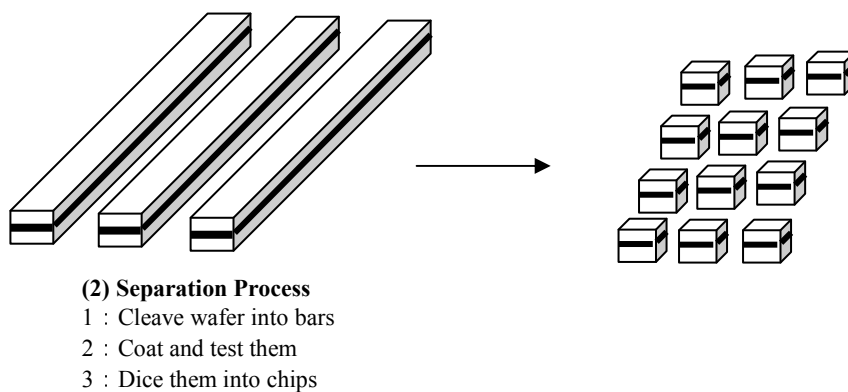
⁵⁴ Ōyō Hikari Electronics Handbook Henshū Iinkai (Applied Optoelectronics Handbook Editorial Committee), *Ōyō Hikari Electronics Handbook (Applied Optoelectronics Handbook)*, p.105.

⁵⁵ Tokkyochō (Japan Patent Office), *Korede Wakaru Handōtai Rēzā: Motto Tsukaō Motto Ikasō Konna Gijutsu (Handbook of Semiconductor Laser)*.

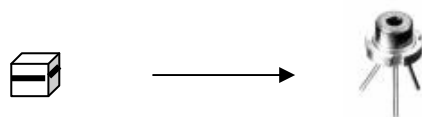
⁵⁶ Kōgyō Gijutsuin Sōmubu Gijutsu Chōsaka (Agency of Industrial Science and Technology), *Wagakuni Sangyō Gijutsu no Taishitsu to Kadai, (Survey of Japanese Industrial Technology)*, pp.276-277.

Figure 1-3: Epitaxy Process

In the second process, the semiconductor wafer with layers is cleaved into bars with a diamond cutter. Then the bars are diced into semiconductor laser chips.

Figure 1-4: Separation Process

Through these first two steps, a semiconductor laser chip is manufactured. The last process is a packaging process so that the semiconductor laser chip can be used as an electronic device. Leads are attached to the semiconductor tip, and the tip is sealed in the package. After packaging, the final performance testing of optical and electrical functions is conducted.

Figure 1-5: Packaging Process

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(3) Palletize/ Mount/ Test

- 1 : Bar Cleavage/ Edge Coating
- 2 : Palletizing
- 3 : Wire Connecting
- 4 : Cap Sealing

The optoelectronics handbook noted, “Epitaxy technology is the most important semiconductor laser manufacturing technology because the performances of the semiconductor laser are highly dependent on epitaxy technology.”⁵⁷ This epitaxy process is important for two specific reasons.⁵⁸ First, it determines the basic performance of a semiconductor laser (e.g., longevity and reliability). The semiconductor laser amplifies the laser beam with a thin layer (0.5 to 20 microns) of different semiconductor materials. The quality of the layer, therefore, is important to basic performances. Second, this process is necessary for achieving high economies of scale to increase the size of the wafer, thus determining how many semiconductor laser chips can be produced in a single manufacturing process. Since it was believed that the semiconductor laser would be one of the most important devices in the optoelectronics industry, it was indispensable to produce a long-life and highly reliable semiconductor laser at a reasonable price. Furthermore, since the sunk costs in the technology-intensive industry are high, firms have an incentive to produce on a large scale, in order to achieve high economies of scale. Epitaxy technology was

⁵⁷ Ibid., p.105.

⁵⁸ On epitaxy technology, see Hirata, *Wakaru Handōtai Rēzā No Kiso to Ōyō*, (*Handbook of Semiconductor Laser, Basics and Application*), pp.113-119.

the key technology for the production of the semiconductor laser on a large scale. Therefore, epitaxy technology was economically and strategically important to competing firms.

The three epitaxy technologies, LPE, MBE, and MOCVD, were competing by the mid 1980s. Each epitaxy technology had advantages and disadvantages. Table 1-7 briefly summarises the technological features and status of these three technologies in the late 1970s.

Table 1-7: Three Epitaxy Technologies: LPE, MBE, and MOCVD

Epitaxy Technology	Description	Status in the late 1970s
LPE (liquid-phase epitaxy)	Material precipitates from a molten solution to a film on the wafer	LPE-grown semiconductor laser demonstrated by RCA in 1963. Status quo technology for the last ten years. Equipment was relatively cheap.
MBE (molecular beam epitaxy)	Materials are evaporated from multiple sources and deposited on a wafer in a high-vacuum chamber.	MBE-grown semiconductor laser demonstrated by Bell Labs in 1975. Excellent control of deposition process was the main advantage. Expensive equipment and long set-up times were main concerns.
MOCVD (metal-organic chemical vapour-phase deposition)	Source gases react and deposit material in a film on the wafer.	MOCVD-grown semiconductor laser demonstrated by Rockwell in 1977. Potential advantages were high throughput and good control of deposition process. Hazardous gases were a concern.

Source: Adopted and modified from Wood and Brown, "Commercializing Nascent Technology: The Case of Laser Diodes at Sony." Table 3. p.174.

1.4. Approach and Contribution

How does the thesis approach the questions? The remainder of this chapter firstly, shows research design, perspectives, and methodology. Then, it presents sources, contributions to the previous studies, and an outline of the arguments.

Research Design

First, this study does not aim at establishing a theoretical predictive model of technological change, even though the dominant goal of empirical economics studies is to establish a predictive model. The reason is the difficulty in the analysis of technological change. Theoretical predictive model analysis does not fit with the study of technological change. The predictive model is built on the assumption that the economic actor maximises his/her utility function under constraints.⁵⁹ Technological changes, however, are the result of the attempts that actors make to overcome constraints.⁶⁰ The predictive model that assumes constrained maximisation or satisfaction does not suit well to the analysis of technological change. This thesis assumes that actors try to overcome constraints rather than just accept them and try to maximise their utility function under the constraints. Of course, it does not mean that actors always can successfully overcome the constraints. Sometimes they may fail to overcome them. Sometimes they may not try to challenge them. It, however, assumes that the actors do not accept their constraint as given and as something that they cannot change. They try to create a favourable environment for themselves rather than accept the environment as given.

Second, this study takes an historical approach. Innovations do not emerge in a vacuum. Technological trajectories depend on the specific knowledge of the

⁵⁹ On the rationality of organisation, see Simon, *Administrative Behavior: A Study of Decision-Making Processes in Administrative Organisation*. 3rd ed.

⁶⁰ Schumpeter distinguished managerial functions from entrepreneurial functions. On the one hand, managers maximise subject to constraints. On the other hand, entrepreneurs try to overcome constraints. Schumpeter, "The Creative Response in Economic History."

society and particular constellations of institutional constraints that vary radically both through time and in cross-section in various economies.⁶¹ It is, therefore, necessary to understand the specific knowledge and institutions within which specific innovations emerged. An historical approach also enables us to study the dynamic process of technological change. Also, this study takes a case study as a research design for two reasons. First, a case study is better for making a detailed contextual analysis of a complex issue. Yin indicated that the case study method was an empirical inquiry that allowed us to investigate an historical phenomenon, when the boundaries between phenomenon and context were not evident.⁶² Furthermore, one of the prime advantages of a case study is that it can be used for the heuristic purpose of inductively identifying additional variables and generating hypotheses. A case study allows us to investigate how firms came to compete in the same product market with the same technological choice from the very complex interaction among various actors. A case study permits us to disentangle the complex strategic decision making process. Of course, since the case study is not an almighty methodology, it

⁶¹ Douglas North articulated that institutions play a significant role in the economy. See Gomulka, *The Theory of Technological Change and Economic Growth*; North and Thomas, *The Rise of the Western World; a New Economic History*; North, *Institutions, Institutional Change, and Economic Performance*, *The Political Economy of Institutions and Decisions*. His perspective is called New Institutional Economics (NIE). This perspective is new because there is an older school of institutionalism in economics. The old intuitionism originated in the work of Thorstein Veblen, John R. Commons, Clarence Wendell and Allen Gruchy. On NIE and OIE see Harriss et al., *The New Institutional Economics and Third World Development*.

Sociologists also pay great attention to the impact of social context on economic behaviour. For instance, Granovetter and Swedberg, *The Sociology of Economic Life*; Smelser and Swedberg, *The Handbook of Economic Sociology*. This sociological perspective is rooted in Max Weber. On the one hand, many economic historians pay close attention to institutions that shape transaction costs in an economy. On the other hand, there are various different perspectives in sociology. For example, on the one hand, James Coleman took rational behaviour theory and discussed how macro phenomena emerge from an aggregation of individual actions which are taken in a certain social context. Coleman, *Foundations of Social Theory*. On the other hand, Berger and Luckmann argued that actors' interactions inter-subjectively create actors' rationality. Berger and Luckmann, *The Social Construction of Reality; a Treatise in the Sociology of Knowledge*.

In spite of the fact that their perspectives are not monolithic, all of these writers indicated that it is necessary to examine the social context to understand how economic actors behave and how macro economic phenomena emerge.

⁶² Yin, *Case Study Research: Design and Methods*, pp.4-9.

has limitations. One of the limitations is that this thesis has a limited ability to induce a general law or proposition because it examines a single case. The other major limitation is that since a case study cannot control for extraneous variables, numerous plausible hypotheses are generally present. Therefore, it is difficult to induce a general law or proposition. Despite these limitations, this study takes the case study method because the main purpose of this study lies not in inducing a general law or proposition but in examining how a certain social phenomenon emerged from complex social interaction.

Perspectives

R&D is one of the most important processes in a technology intensive industry. The output of R&D is technological knowledge, which has unique characteristics. This section reviews three points that are important bases of this study. They are sunk costs and economies of scale, the spillover effect and uncertainty, and competition through time.

The first point is sunk costs and economies of scale. R&D in a technology intensive industry requires a large amount of investment. R&D assets such as research facilities and research engineers are immobile. R&D investments, once made, tend to be largely irreversible. Once a firm invests in R&D, it, therefore, becomes a sunk cost.⁶³ Sutton showed the two-stage game in which the present study captures sunk costs. At the first stage, firms incur fixed outlays, which are associated with acquiring a single plant of minimum efficient scale (setup costs), and developing and establishing a product line. These fixed outlays incurred at the first stage of the game are treated as sunk costs in analysing the behaviour of firms at the second stage of the game. Because many R&D investments are sunk costs, economies of scale are an important factor determining the competitiveness of a firm.

⁶³ On sunk costs, see Sutton, *Sunk Costs and Market Structure: Price Competition, Advertising, and the Evolution of Concentration*.

Efficiency gains can only be achieved at a higher level of minimum efficient scale.⁶⁴ As a result, a technology intensive industry becomes capital intensive. Because of the high level of sunk costs, a technology intensive industry tends to be oligopolistic. Competition among firms tends to be “Schumpeterian” competition. The important point is summarised as follows; R&D in a technology intensive industry incurs sunk costs. As a result, competition in the industry tends to be oligopolistic.

The second point is technological spillover and uncertainty. The output of corporate R&D inherently includes technological knowledge. Arrow indicated that technological knowledge is inherently a public good.⁶⁵ He directed his attention to the nature of technological knowledge, which was the main output of R&D, and indicated two important points: non-rivalness and non-excludability. First, an unlimited number of agents can use the same technological knowledge at the same time. Second, once a firm has released technological knowledge in public, it is difficult for the firm to exclude other firms from using the knowledge. The patent system provides an inventor with a set of exclusive rights to make or sell his/her invention for a fixed period of time. One of the other aims of the patent system is to publicise important inventions. Therefore, once an invention is patented, it becomes a source of spillover. When there are technologically related research efforts of other firms, a given firm may take advantage of knowledge produced by other firms and achieve R&D results with less research effort than otherwise. Griliches argued that technological spillover plays an important part in technological development.⁶⁶ He argued that technological spillover is one of the sources of increasing returns in R&D.

While technological spillover plays an important role in R&D, R&D in a

⁶⁴ Chandler, *The Visible Hand: The Managerial Revolution in American Business*.

⁶⁵ Arrow also emphasised that knowledge is characterised by a greater degree of uncertainty, indivisibility, and asymmetry than are other types of economic goods. They will be introduced in the following discussion. On non-excludability and externality of technological information, see Arrow, "Economic Welfare and the Allocation of Resources for Invention."

⁶⁶ Griliches, "The Search for R&D Spillovers"; Griliches, *R&D, Patents, and Productivity*, *A National Bureau of Economic Research Conference Report*.

technology intensive industry is highly uncertain.⁶⁷ The uncertainties can be classified into three. The first is that it is uncertain how much R&D investment would be needed to attain a desirable R&D result.⁶⁸ The second is that it is uncertain whether a desirable R&D result would be attained or not and when it would be attained. The third is that it is uncertain whether the firm can reach a desirable R&D result quicker than its rivals do. The third point depends on the strategy of rival firms. On the one hand, given the amount of R&D investment of rivals, an individual firm can increase the level of R&D investment and increase the probability that it reaches the desirable R&D result quicker than its rivals do, even though the probability does not rise linearly in proportion to the increase in R&D investment. On the other hand, if rival firms increase the level of R&D, the probability that an individual firm can reach the desirable R&D result decreases. The inherent uncertainties in R&D means that R&D investment is somewhat of a gamble because outcomes are not always perfectly predictable. Because of these uncertainties, not only big business but also small venture businesses are involved in R&D competition. Moreover, because of these uncertainties in R&D, learning by researching has significance. The learning curve effect plays an important role in R&D. Therefore, it is important for a firm to rush into promising R&D to shift onto a new learning curve.

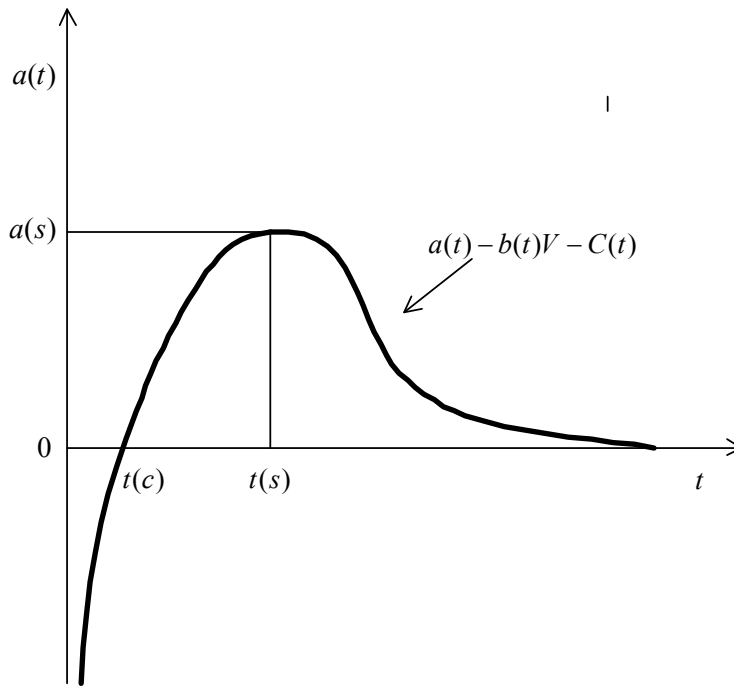
The third point is competition through time. The way in which firms compete in R&D is different from the pattern of price competition. The main reason why firms invest in R&D is to gain monopoly rents. Suppose that there is a business opportunity that will provide successful R&D with certain monopoly rents (V). The timing of a firm's conduct of R&D for the opportunity determines the amount of rents that the firm can gain. If a firm conducts R&D after t , the monopoly rent will be discounted by the current value whose discount rate is r , and will yield $b(t)V (= e^{-rt}V)$. If a firm does not conduct R&D right away, the gain will be

⁶⁷ On uncertainty in R&D, see Kamien and Schwartz, *Market Structure and Innovation*, *Cambridge Surveys of Economic Literature*.

⁶⁸ On uncertainty and innovation, see Freeman and Soete, *The Economics of Industrial Innovation*, pp.242-264.

decreased because t becomes bigger. In sum, late R&D decreases the amount of gain that the firm can get. On the other hand, the R&D costs may be decreased if the firm starts R&D later because it can take advantage of the technological development exogenously produced in a society. In other words, R&D costs deducted by current value, $c(t)$, is gradually diminished as t increases. Therefore, the timing of R&D is important for firms. Firms have an incentive to postpone R&D until technology is developed in a society on the one hand. On the other hand, if a firm starts R&D later than rival firms do, the possibility that the firm can get monopolistic rents will be decreased. Barzel modelled this dilemma as shown in Figure 1-6.⁶⁹ This model aimed to show that R&D competition caused excessive investment in R&D, which was beyond the level of socially desirable R&D investment. His model shows the nature of R&D competition well. Barzel assumed that the total profit $a(t)$ that a firm gains from R&D started in t as $a(t) = b(t)V - c(t)$. Figure 1-6 describes that a firm gets the highest total profit $a(s)$ if it starts R&D in $t(s)$. If a firm starts its R&D when technology is not well developed in a society $t(c)$, the profit that a firm gets will be small because R&D costs are immense. However, if a firm starts its R&D later $t(s)$, profit will be diminished.

⁶⁹ Barzel, "Optimal Timing of Innovations." Dasgupta and Stiglitz also modelled competition through time and examined the speed of R&D. Dasgupta and Stiglitz, "Industrial Structure and the Nature of Innovative Activity."

Figure 1-6: Timing of R&D and Profit

Suppose that two firms, A and B, start their R&D in the same technology area. Firm A starts its R&D in $t(s)$ and firm B starts a little bit before $t(s)$. In this case, firm B can pre-empt monopolistic rents that firm A could have if only firm A conducts R&D in this area. A firm can pre-empt monopolistic rents if it starts its R&D before rivals start their R&D. Firms rush to invent for monopolistic rents unless $a(t)$ reaches zero at $t(c)$. Scholars of business management also suggest that competition through time is one of the most important characteristics of the technology intensive industry.⁷⁰ As described above, both economies of scale and the learning curve effect play an important role in R&D competition. As a result, firms have an incentive to jumpstart R&D to achieve economies of scale and to reach a superior learning curve. Both economies of scale and the learning curve effect can

⁷⁰ The importance of timing issues in high technology competition is manifested not only in product innovation races but also in decisions about the optimal timing of investments in new plant and equipment. Utterback, *Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change*.

reduce R&D costs. In other aspects, competition through time occurs because the first mover advantage is significant in technology intensive industry.⁷¹

How to Measure Technological Innovation

How does this study measure technological change? In spite of the fact that technology is one of the indispensable factors for sustainable growth, how to measure technological innovation continues to be debated. There are four major ways of measuring technological innovation.⁷² There is, however, no single indicator for measuring technological change. It is, therefore, important to note that each measurement can only shed light on certain aspects of technological change.

First, the Solowian tradition has regarded technological change as residual factors, which were not explained by its growth model.⁷³ However, it does not capture changes in the technology of the production function. Moreover, the residual is not equal to technological innovation. For instance, when capital and labour are used more intensively at times, the residual can vary even if the technology does not change. Moreover, technological innovation is not the only source affecting the residual. Organisational innovation and managerial innovation may affect the residual.⁷⁴ In other words, the residual does not necessarily indicate technological innovation. This measurement is widely used to analyse macro economic phenomena in particular. Total factor productivity (TFP), which addresses any effects in total output not caused by inputs or productivity, is commonly used to assess technological change in national accounting. However, it is not possible to use this measure to distinguish a certain technological change from other because it

⁷¹ On first mover advantages, see Lieberman and Montgomery, "First-Mover Advantages."

⁷² There are some other ways of measuring such as scientific papers citations and patent citations. On their advantages and disadvantages, see Patel and Pavitt, "Patterns of Technological Activity: Their Measurement and Interpretation", p.51.

⁷³ Solow, "A Contribution to the Theory of Economic Growth."

⁷⁴ On organisational innovation, see Chandler, *Strategy and Structure: Chapters in the History of the Industrial Enterprise*.

measures aggregate technological change.

The second way is to measure the amount of R&D input. This is a widely used indicator to measure technological innovation in science-based industries such as the chemicals industry. Mowery and Rosenberg indicated that science based R&D grew in importance as sources of technological change.⁷⁵ It allows the investigation of certain technological changes in a certain sector. It is, however, the input that this method measures as a proxy. It is not the measurement of the output of R&D activities. Only if technological innovation is randomly given and is a function of the amount of input, will this method be adequate to measure technological innovation. In addition, this method is not good at measuring technological innovation in non-R&D based industries. Moreover, it underestimates production technology, which emerged not in R&D but in production facilities. This study does not take this method to measure technological change because it does not assume that technological innovation is randomly given and that technological innovation is a function of the amount of input.

The third method is to measure productivity growth, which is closely related to the Solowian tradition. By definition, innovation brings about productivity growth. Therefore, productivity growth is used as a proxy to measure technological innovation. Technological innovation, however, is not the only source contributing to productivity growth. Organisational innovation is another source of productivity growth of the firm. For example, Chandler scrutinised the history of four big enterprises in the U.S. and indicated that innovation in organisational structure contributed to the increase in productivity growth of the firm.⁷⁶ Managerial innovation can be also a source of productivity growth. U.S. manufacturing firms began to introduce PERT (Programme Evaluation and Review Technique), which was originally developed in 1958 by the U.S. Department of Defence's US Navy Special Projects Office in 1958 for the Polaris submarine ballistic missile production project, for their production management. PERT is a production management

⁷⁵ Mowery and Rosenberg, *Paths of Innovation: Technological Change in 20th-Century America*.

⁷⁶ Chandler, *Strategy and Structure: Chapters in the History of the Industrial Enterprise*.

method intended to identify a critical path in the production process and to increase the productivity of a large-scale and complex production process. Innovation in human resource management may also increase productivity growth. For instance, the introduction of scientific management in the shop floor increased productivity.⁷⁷ Since productivity growth captures all innovations such as technological innovation, organisational innovation, and managerial innovation, it would be a good measurement of innovation if it intends to capture innovation of the firm as a whole. Because this study focuses on technological change, it does not use the productivity growth of the firm as a measurement of technological innovation. The productivity growth of the firm captures too many other types of innovation for this study. In addition, if a firm produces various products, productivity growth is not better at identifying a certain specific technological change. It is difficult to identify which technological innovation contributed to the productivity growth if the firms produce various products with various technologies.

The fourth measuring method is patents.⁷⁸ This study uses patents to measure technological change. A patent is an exclusive right granted by an authorised governmental agency to a person or an institution for a fixed period in exchange for the regulated, public disclosure of certain details of a technological invention or a useful new artifact. After an examination of the novelty and potential utility of the claimed invention, the grant is given to the inventors.

Patents have been widely used to examine technological change in a certain area of technology or industry because patents provide important information such as the names of inventors, the name and address of the assignee, technological classification, and application date.⁷⁹ Since patent documentation is systematically

⁷⁷ On scientific management, see Taylor, *The Principles of Scientific Management*; Taylor, *Scientific Management, Comprising Shop Management, the Principles of Scientific Management*.

⁷⁸ Regarding patents as indicator of inventive activity, see Griliches, "Patent Statistics as Economic Indicators: A Survey"; Basberg, "Patents and the Measurement of Technological Change: A Survey of the Literature"; Pakes and Griliches, "Patents and R&D at the Firm Level: A First Look."

⁷⁹ On the argument, see Griliches, "Patent Statistics as Economic Indicators: A Survey"; Griliches, "R&D and Productivity: Econometric Results and Measurement Issues."

kept by a governmental agency, it allows the construction of complete time series analysis. It is possible to assume that the patent system and attitudes as to the use of the patent system remain substantially constant during the period of analysis, 1970-1990. Moreover, because this study focuses on technological change in a certain area, technological changes in the semiconductor laser area, patents, which are classified by technological area, are a useful and practical measure of technological change.

As mentioned above, there is no single method to measure technological change. Every method has advantages and disadvantages. Patent measurement has several disadvantages too.⁸⁰ The first disadvantage is related to institutional differences. There are two different types of institutional differences: difference in the patenting system and in the importance of patenting. The first difference relates to the patenting system itself.⁸¹ For instance, the U.S. takes a first to invent system and publication-after grant policy on the one hand. On the other hand, Japan and many other OECD countries take a first to file system and automatic publication policy. This difference may affect the patenting decision making of firms. The second institutional differences stems from inter-industry difference. There is a difference in the relative importance of patenting among industries even in the same country. For example, patenting is less important in the leather craft industry than in the biochemical industry. These two institutional differences make comparative analysis difficult. Even though the main aim of this study is not to compare technological change in different industries or different countries, it must be noted that patent data should be carefully investigated when it examines cross-national patent data.

The next disadvantage is that not all technologies can be patented. For instance, basic science is for the most part unpatentable yet this was likely to have been important in the industry. Patent data may underestimate any production technology that cannot be patented. This thesis, therefore, examines the state of

⁸⁰ On patent data, see Patel and Pavitt. "Patterns of Technological Activity: Their Measurement and Interpretation."

⁸¹ On the institutional difference of the patent system between the U.S. and Japan, see Kotabe, "A Comparative Study of U.S. And Japanese Patent Systems."

scientific advancement and knowledge accumulation in basic research in semiconductor laser technology, which are the fundamental bases of technological development, by investigating the number of Ph.D and academic papers in semiconductor laser technology and the inter-organisational research networks. This thesis examines the opinion of technical experts such as scientists, engineers, and corporate managers as well. There are many experts' surveys to identify technological innovations in many industries. Even though this method is qualitative more than quantitative, it is useful to identify technological innovations that had a strong impact. It is, however, costly to carry out this method. Usually the agents carrying out this survey are government, industrial organisations, or journalists. Unfortunately, no experts' survey has been done in laser technology in Japan. There are, however, many publications pointing out major technological innovations. Scientists, engineers, and corporate majors frequently pointed out major technological innovations in corporate reports, academic journals, and newspapers. Their identification of technological innovations is consistent with each other. Therefore, it is possible to use these data to complement patent data to identify technological innovations in laser technology in Japan.

Another disadvantage is that firms do not necessarily patent all of their inventions. They may strategically keep their invention secret. If it is easy for competitors to imitate and invent a new technology based on a published patent, the firm may keep its invention secret. However, this problem does not create serious problems in this study. This disadvantage will be critical in any cross industrial comparative analysis because the possibility of imitation based on patent varies with the technological area. Since this thesis focuses on a specific technological area, which is semiconductor laser technology, the possibility of imitation can be assumed constant. The qualitative sources mentioned above allow identifying technological innovations that were strategically kept secret.

The last disadvantage of patent data is that some patents do not have any economic impact. Therefore, this study examines not only the number of patents but

also the citation of patents, which allows an examination of the quality of patent.⁸² A patent document contains citation to previous patents. A patent examiner cites previous patents to limit and to validate the scope of novelty of invention. Patent citations are supposed to indicate previous work on which the current invention builds or relies, or which embodies results that are related to those of the current invention. Because a government authority performs a citation, the patent citation is not contaminated by unnecessary citations to friends, colleagues, or a famous authority, which could happen sometimes in a bibliographic citation. The above arguments about patent citation data conclude that it is possible to assume that a highly cited patent is an important technology.

One new thing in this study is that it mainly uses patent citation data. Because of the lack of a patent citation database in the Japan Patent Office, there have not been studies about technological change in Japan using patent citation data. The Japan Patent Office provides the Industrial Property Database that allows the investigation of patent application and registration in Japan. However, it does not provide a database that allows investigating a patent citation. This study is the first attempt in the line of arguments about technological change in Japan to use patent citation data in the analysis. It uses the Derwent Innovations Index to investigate patent citation in Japan. This is a database of citations appearing in patents from six major patenting authorities. It provides details of citations, both patent and literature, reviewed by the examiner during the examination of a patent application.

⁸² On the relationship between patent citation and important technology, see Trajtenberg, "A Penny for Your Quotes: Patent Citations and the Value of Innovations"; Schankerman and Pakes, "Estimates of the Value of Patent Rights in European Countries During the Post-1950 Period"; Narin et al., "Patents as Indicators of Corporate Technological Strength"; Carpenter and Narin, "Validation Study: Patent Citation as Indicators of Science and Foreign Dependence"; Carpenter et al., "Citation Rates to Technologically Important Patents."

Sources

This research is based on six different groups of sources. Since each source has its own advantages and disadvantages, these sources are selected to cover the disadvantages and to shed light on the technological development from various aspects.

The first group is governmental and industrial association reports on technology and industry. This thesis uses some governmental reports on the optoelectronics industry and semiconductor laser technology. Both the U.S. and Japanese government and industrial associations investigated the technology intensive industries and released reports on optoelectronics and semiconductor laser technology since the 1980s when the optoelectronics industry became one of the most important technology intensive industries and semiconductor laser technology was regarded as the fundamental technology in the industry. There are two reports that provide extensive research and important insights on the optoelectronics industry and semiconductor laser technology. One was provided in 1996 by the U.S. research association, the Japan Technology Evaluation Centre (JTEC). The other was produced in 1983 by the Japanese Agency of Industrial Science and Technology (AIST). Because these reports were supported by government funds, they might be biased to the government or a certain group of people. For instance, as Gotō pointed out, U.S. governmental reports tended to claim that the government should launch government-funded research projects.⁸³ However, because the budget of governmental research is usually sufficiently substantial to conduct large sample questionnaires, interviews and site visiting, their fact-finding provides an important basis of this study. In addition to these reports, this thesis makes use of monthly reports published by banks. Banks published monthly reports, in which the research and planning department analysed both macro economic and industrial trends. They also picked up either some industries or some firms and analysed them. The banks published the reports not only for their customers but also for business purposes. The banks made their business decisions based on the research done by their

⁸³ Gotō, *Inobēshon to Nihon Keizai, (Innovation and Japanese Economy)*, pp.14-15.

research and planning department. The reports enable us to examine how business communities saw laser technologies.

The second group is data for analysing the inside of the firms. Corporate technological journals and annual reports are the two main sources in this group. Many of the Japanese manufacturing firms publish their own periodical technological journals. The main objective of publishing these technological journals is to release R&D outcomes and to place advertisements for the latest technologies. The directors of the R&D division announced their R&D goals in the journals. The engineers released their research and development results in them. Corporate technical journals thus allow us to study the R&D activities of individual firms. Corporate technical journals show the R&D focuses, the engineers' main concerns, and the ways in which engineers tried to solve their technological problems. It must be noted that the corporate technical journals do not cover all the R&D activities of firms. Because the main purpose of a corporate technical journal is to advertise the R&D achievements of firms, the published articles might be biased toward the successful R&D results. However, the journals provide an important clue on the R&D focus of firms by looking at the featured articles published in the journals. Corporate annual reports allow analysing the inside of individual firms from a different perspective. The annual reports of the listed company are all available to the public. They describe financial conditions (a balance sheet and a statement of balance and losses), corporate governance, business schemes, organisational structures, and lists of corporate executives. It is important to know both the financial conditions and the state of the related business in a firm in particular because all of the laser manufacturers internalised many varieties of related businesses. The laser R&D plans were closely connected with other related business in the firms. In sum, the corporate annual reports are useful data to analyse the internal resources and setting of the firms. There is one more source in this group of data. It is books, journals, and corporate history books in which engineers and top business managers look back on their achievements. Since they are a secondary source, it is important to inquire carefully into their reliability. They, however,

permit us to examine how engineers and top managers saw their R&D and laser business.

The third group of sources is for analysing not only the inside of the firms but also the communities in which the engineers were involved. There are two sources in this group. The first source is academic journals such as the *Journal of Applied Physics (JAP)* and *Journal of Applied Physics Letters (JAPL)*. The corporate engineers published their R&D results not only in their corporate technical journals but also in academic journals. In addition, the engineers presented their work at both academic workshops and annual meetings. Many scientists also participated in technological development competitions in laser technology. The academic journals permit scrutiny of R&D goals and activities in the communities. While the corporate technological journals allow an analysis of R&D concerns and activities in individual firms, the academic journals can show the communities' concern. This study also uses *A Bibliography of Doctoral Theses on Semiconductor Lasers* to examine the research community of the semiconductor laser. This bibliography includes all doctoral theses on semiconductor lasers all over the world and describes them in quantitative terms of the development of specific knowledge of semiconductor laser in universities and research institutions in the world from 1963 to 2005. The entry items are (1) the author name, (2) the name of awarding university or institution, (3) the awarding year, (4) the title of each thesis, and (5) the name of research institution or company for which the doctor degree holder was working. The third chapter uses this bibliography to estimate the human capital accumulation in developed countries.

The fourth source of this study is, as noted earlier, patents.⁸⁴ This study uses mainly two different sources of patent. The first is the patent application database of the Japan Patent Office and the patent database of the European Patent Office. Both patent databases provide all patent applications in semiconductor laser technology from 1976. It is a good source for corporate R&D activity because patent application

⁸⁴ On the patent system in Japan, see Okada and Asaba, "The Patent System and R&D in Japan"; Kotabe, "A Comparative Study of U.S. And Japanese Patent Systems."

data is a relatively straight forward measurement of corporate R&D output. However, it does not capture the quality of technological invention. This study uses the Derwent Innovations Index to capture the quality of a patent. The Derwent Innovations Index is a patent database provided by Thompson Wila-Derwent, which is a supplier of information services that support the management of intellectual property right as they pertain to patents, trademarks and industrial designs. The Derwent Innovations Index comprises eleven million inventions from forty patent-issuing authorities⁸⁵ and covers all laser related patents issued in Japan. It allows the investigation of the content, publication date, priority application, inventor, patent assignee, patent title, cited articles, cited patent, and citing patent. Because the Japan Patent Office does not provide patent citation data, the Derwent Innovations Index is a valuable source to examine the quality of patents obtained in Japan.

The fifth group of sources is quantitative data. The data consists of two different groups. The first group of quantitative data is macro economic statistics and general social trends. This group of data provides the general background in which laser technology was developed. Statistical data recorded by MITI includes the general macro economic data. The statistics recorded by the Ministry of Education, Culture, Sports, Science and Technology provide the number of graduates in physics and the trends of the physics department in both private and national universities. The second group is about the outcomes of behaviours of the firms. The data in this group are the number of patents, the number of certain technological articles both in the firms' technological journals and in the academic journals, production scale, and corporate financial data. The Patent Office of Japan provides several important patent data such as the number of patents in a certain technology, the number of patent applications, the number of patents for each firm and for each technology. Statistics recorded by the Japan Patent Office and Ministry

⁸⁵ The followings are the coverage of Derwent Innovations Index. Argentina, Australia, Austria, Belgium, Brazil, Canada, China, Czech Republic, Czechoslovakia, Denmark, European Patents, Finland, France, Germany, Hungary, Ireland, Israel, Italy, Japan, South Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Philippines, Portugal, Romania, the Russian Federation, Singapore, Slovakia, South Africa, Spain, Sweden, Switzerland, Taiwan, the United Kingdom, and the United States.

of Economy, Trade and Industry and yearbooks published by the industry associations provide consistent quantitative data such as production scale, cumulative production, prices, and specification of products. This thesis uses ICARUS, which is a database of U.S. and Canadian firms, to examine business domain and financial data of American firms. This study also uses the *Japan Company Handbook* to show Japanese firms' business domain. The thesis uses these statistical data for a mainly descriptive purpose to analyse laser technology development.

The last group is interview data.⁸⁶ The author interviewed nineteen Japanese corporate engineers and managers, and government officials with direct knowledge of the manufacturing and engineering process in semiconductor laser technology in Japan between September 2004 and February 2006. The interview data allows the investigation of R&D in the firms. Many of the actors who participated in the technological competition over laser technology are still working. Even though this research uses the interview data for a supplementary purpose, it allows the examination of the strategic thinking behind their behaviours and their expectations of other actors' behaviours. This qualitative data also helps analyse two insights for the analysis. Firstly, it gives important insights about how corporate engineers saw rival firms' R&D and how they learnt from their rivals. Secondly, it helps analyse the consensus-making process through competition. Firms developed their strategic technological choices taking the rival firms' strategies into account. The interviews can show how firms saw their rivals and how this cross-reference shaped their strategy. Furthermore, technology intensive firms undertook several R&D projects. Large firms such as IBM, Xerox, Bell, Hitachi, and Toshiba, usually undertake numerous R&D projects at the same time. Even the small-specialized firms such as TRG and Microtron ran several R&D projects. It is not easy to access firm-specific R&D records. For instance, it is difficult to access data on how much money and resources were allocated into a specific R&D project in the firm. Research that aims to scrutinize corporate R&D projects tends to confront this difficulty of accessing

⁸⁶ On the interview, see Appendix III: List of Interviewees.

specific R&D project data. This thesis tries to fill this gap by interviewing corporate engineers, even though the interviews could not fully reveal the specific R&D project of the firms. The corporate technical journals are also an important source to access specific R&D projects of firms, as the technical journals sometimes did a special feature on a certain R&D project to which the firm gave particularly high propriety. By interviewing corporate engineers and scrutinizing the corporate technical journals, this thesis tries to reveal firms' semiconductor laser R&D projects.

Contribution

How do the research questions of this study fit in to previous debates? How can the thesis contribute to the debates?⁸⁷ Firstly, there has a few studies examining the development of the optoelectronics industry. The optoelectronics industry became one of the most important sectors in the national economy of Japan from the 1980s. The semiconductor laser was the most important electric device in the optoelectronics industry. By examining the development of semiconductor laser technology, this thesis aims to provide a better understanding about how Japanese technological intensive industry came to be competitive from the 1970s. Saxonhouse and Miyazaki's studies are two of the first studies on the optoelectronics industry. Saxonhouse surveyed the optoelectronics industry in Japan and provided the first important outline of the industry.⁸⁸ Paying attention to the argument of core competence⁸⁹, Miyazaki attempted to measure *ex ante* firm's technological core competence in the optoelectronics industry. Exploring how technological competences were built in firms, she showed several factors influencing core competence building such as the importance of top management, and path dependency. While her argument focused on the competence building process in a

⁸⁷ The second chapter reviews the previous arguments more broadly to indicate how this study fits in the broader line of previous debates on Japanese Economic History.

⁸⁸ Saxonhouse, "Optoelectronics in Japan: Some Economic Consideration."

⁸⁹ On the core competence of firms, see Hamel and Heene, *Competence-Based Competition*.

firm, this study is primarily concerned with interactions of firms' strategic technological choice.

Secondly, this thesis directs its attention to the relationship between competition and technological innovation. There is a good deal of discussion in the literature on the organisational setting of Japanese firms under the framework of the "Japanese management system", which will be reviewed in the second chapter, *Literature Review: Technological Development in Post-war Japan*. However, the amount of work on the relation between competition, spillover, and technological change has been limited, even though competition is an important factor for technological innovation. The organisational setting is an important supply side mechanism pushing technological change to a certain pattern. It is, however, important to examine the dynamic process in which supply side mechanisms evolved and interacted with each other through competition. This thesis contributes to these studies by examining how competition became fierce in a certain market and how fierce competition contributed to technological innovation in technology intensive industry in Japan.

The third point is related to the relationship between the theoretical research on the economics of a technology intensive industry and technological change and previous research on technological change in post-war Japan. Technology intensive industries became important from the 1960s. Economists have begun to study the industry and to provide useful perspectives. The interaction between the theoretical research and the previous research about technological change in post-war Japan, however, has been quite limited.⁹⁰ One of the possible reasons lies in the fact that much of the previous literature about technological change in Japan directed their attentions to outlining the unique feature of the "Japanese management system." This study aims to bridge the theoretical research about the economics of a technology intensive industry and the empirical research about the competitiveness

⁹⁰ Of course, there are some exceptions. For example Aoki, *Information, Incentives, and Bargaining in the Japanese Economy*; Aoki and Dore, *The Japanese Firm: The Sources of Competitive Strength*. However, the English-language work on competition and technological change based on the theoretical framework has been limited.

of a technology intensive industry in Japan.

The last point lies in the sources used in the thesis. As will be shown in the following section, some of the most important data for this study is patent data. The number of studies employing patent data has been recently growing. There are many studies examining industrial and technological development in Japan with patent data.⁹¹ However, many of them employ U.S. patent data provided by the National Bureau of Economic Research (NBER) to examine Japanese firms.⁹² Since the Japan Patent Office does not provide citation information, the previous studies have faced difficulty of accessing Japanese patent citation data. As discussed above, both patent data and patent citation data can allow systematic and consistent investigation of the timing of technological change and its impact. This thesis is one of the first attempts to examine technological change in Japan by using patent and Japanese patent citation data.

Structure of the Argument

This thesis consists of six chapters. The first chapter, *Introduction*, has introduced why this study scrutinises semiconductor laser and presented the methodology.

The second chapter, *Literature Review: Technological Development in Post-war Japan*, reviews previous arguments about technological development in post-war Japan. Through the literature review, it aims to show how the research questions of the thesis fit in the line of the previous arguments and how this study contributes to the arguments.

⁹¹ For example, Nagaoka, "Assessing the R&D Management of a Firm in terms of Speed and Science Linkage: Evidence from the US Patents"; Branstetter and Sakakibara, "Japanese Research Consortia: A Microeconometric Analysis of Industrial Policy"; Branstetter and Sakakibara, "When Do Research Consortia Work Well and Why? Evidence from Japanese Panel Data."

⁹² On the NBER patent data, see Hall, Jaffe, and Tratjenberg, "The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools."

As Griliches indicated, the R&D output of firms mainly depends on the three factors, the state of aggregate knowledge in the industry, the level of conventional inputs of the firm and the specific knowledge capital of the firm.⁹³ The third chapter, *Human Capital and Research Networks*, accordingly examines the first factor, which is the state of aggregate knowledge in the industry. Physicists began to research semiconductor lasers from the late 1950s. Based on the journal citation and the bibliography of doctoral theses on semiconductor lasers, this chapter shows

- [3-1] The U.S. and the U.S.S.R. were the two leading countries in human capital accumulation in semiconductor laser technology.
- [3-2] Although Japan accelerated its human capital accumulation from the 1970s, it was not the leading country in human capital accumulation in semiconductor laser technology.
- [3-3] Inter-organisational collaboration in semiconductor laser technology was more developed in the U.S. than in Japan and Europe.

These findings also suggest that Japan attained technological development in semiconductor lasers and gained a significant market share in semiconductor lasers and their application areas from the beginning of the 1980s in spite of the fact that the human capital accumulation and the research network in semiconductor laser were not specially advanced in Japan compared to those in The U.S. and Europe.

The fourth chapter, *Semiconductor Laser Research Consortium: OMCS Project*, examines the research consortium launched in 1977. As will be reviewed in the second chapter, the government-led growth view maintained that the governmental research consortia played important roles in the technological development of the technology intensive industry. Examining the research consortium launched in 1979 with patent citation data, this chapter shows:

- [4-1] Important technology was not produced in the consortium, compared to

⁹³ Griliches, "The Search for R&D Spillovers", pp.9-10.

the in-house R&D of the participating firms.

- [4-2] The consortium stimulated corporate private R&D in areas where the participating firms undertook joint R&D.

The fourth chapter argues that the consortium provided an important path dependency for technological development and industrial development. However, the consortium does not provide a full explanation for the technological development and the competitiveness of the industry. The fifth chapter, *Competition, Knowledge Spillover, and Innovation* examines how the firms competed under the conditions which the research consortium and industrial association provided and how technological change emerged in competition by scrutinising an important technological change, which was semiconductor epitaxy technology, LPE, MBE, and MOCVD. First, this chapter presents the following points:

- [5-1] Most Japanese firms simultaneously engaged in R&D competition in both MBE and MOCVD, while some American firms adopted neither MBE nor MOCVD.
- [5-2] Japanese firms competed in MBE and MOCVD areas over relatively longer periods than the U.S. firms did.

Based on these findings, this chapter introduces two different types of knowledge and shows how the R&D strategies of the firms and the patterns of competition in the U.S. and Japan affected the nature of knowledge spillovers and how the different trajectories of technological development emerged through different patterns of R&D competition and different institutional settings.

The last chapter, *Conclusions and Implications*, first summarises the arguments and presents discussions and implications of the arguments. Concretely, it presents the implications of the findings for arguments relating to vertical integration, competition and technological change. Then it shows some points for further research.

2. Literature Review: Technological Development in Post-war Japan

This chapter reviews the previous literature on technological development in postwar Japan.¹ In particular, it focuses on the literature on technological development in technology-intensive industry after 1973.² This chapter aims to show how the research questions of the thesis fit in the line of previous arguments and how the thesis will contribute to these arguments.

This literature survey takes three steps. The first involves a review of basic studies about economic growth and the development of technology-intensive industry after 1973. It provides the basic background regarding Japanese technology-intensive industries' attainment of high competitiveness and the characteristics of technological innovation during this period. The second step (starting at 2.2. *Four Perspectives on Technological Change and Economic Growth*) reviews the four categories of the previous arguments on technological development in Japan's technology-intensive industries. The third step (starting at 2.3. *Previous Studies and Research Questions*) reveals how this thesis aims to contribute to these previous arguments.

¹ For an overview of postwar Japanese economic history, see Nakamura, *The Postwar Japanese Economy: Its Development and Structure*; Tolliday, *The Economic Development of Modern Japan, 1945-1995*; Katz, *Japan, the System That Soured: the Rise and Fall of the Japanese Economic Miracle*.

² On technological development in prewar period, Westney analyzed social institutional change such as the educational system, the transportation system, and the information system in Meiji Japan. Westney, *Imitation and Innovation: The Transfer of Western Organisational Patterns to Meiji Japan*. Morris-Suzuki reviewed the technological development of Japan from the 17th to the 21st century. Morris-Suzuki, *The Technological Transformation of Japan: From the Seventeenth to the Twenty-First Century*. Odagiri also concretely summarised technological development after the Meiji Restoration and used case studies to describe technological developments in the textile, iron and steel, electrical and communications equipment, and automobile industries. Odagiri and Gotō, *Technology and Industrial Development in Japan: Building Capabilities by Learning, Innovation, and Public Policy*, *Japan Business and Economics Series*.

2.1. Economic Growth and Two Exogenous Shocks

Angus Maddison showed that Japan's GDP per capita in 1990 was \$1.135 (1990 international dollars), which was only about one-fourth that of the U.K. or the U.S. and on a par with the Philippines and Mexico.³ However, Japan attained high economic growth, becoming the second largest economic power after the U.S. after World War II. As early as 1961, Reischauer described Japan as a "model for underdeveloped countries that wished to modernise."⁴ However, two incidents--the cancellation of the Bretton Woods Agreements and the oil crises--shocked Japan's economy.

Two Shocks and Rise of Technology Intensive Industries

During the Vietnam War, the U.S. economy faced chronic inflation and an accumulated deficit in the international balance of payments. The U.S. balance of trade with Japan went into the red in the late 1960s, with an accumulated deficit of two billion dollars. President Richard Nixon announced his comprehensive macroeconomic policy in 1971. The following year, the Smithsonian Agreement brought about a re-evaluation of the Japanese yen, with an appreciation of 16.88%. This was the first shock for the Japanese economy. The second shock came the following year, when the Organisation of Petroleum Exporting Countries (OPEC) carried out a major oil boycott during the Arab-Israeli war, refusing to sell oil to countries that supported Israel. The price of oil quadrupled from 1973 to 1975. With no oil reserve in Japan, Japanese firms were unable to avert the rising price of oil.

The rising oil prices and the re-evaluation of the yen had three important consequences. First, many studies indicate that these two shocks changed the industrial organisation of the Japanese economy. Prior to the cancellation of the

³ Maddison, *Monitoring the World Economy, 1820-1992*, Development Centre Studies, Table 1-3, p. 24.

⁴ Nakayama and Reischauer, "Nihon Kindaika No Rekishiteki Hyōka (History of Japanese Modernisation)", p. 89.

Bretton Woods Agreements, the competitive advantage of Japanese firms in the international market was low prices due to an abundant supply of cheap labour.⁵ These two shocks, however, made it difficult for Japanese firms to compete in the international market. Hashimoto pointed out that energy-consuming and labour-intensive industries (e.g., petrochemicals, metal-working, ceramic, textile, and paper and pulp industries) decreased their profit rate in 1973.⁶ All of these industries had been key industries in the high economic growth since the mid-1950s. The strengthening of the yen decreased exports and boosted domestic demand. Changes in the exchange rate impacted cash flow. Strong yen, trade surplus, low bank rate policy, and capital market liberalisation induced cash flow into the Japanese capital market. It became easy for firms to raise money from the capital market, stimulating investment in plants and equipment. Second, firms began focusing on the quality of their products. It became difficult for them to pursue cost leadership strategies because of the strong yen. Thus, they shifted their product mix from low-priced labour-intensive products that competed with NIEs to high-quality technology-intensive products. Gotō contended that Japanese firms developed many incremental energy-saving technologies in an effort to reduce rising energy costs and maintain a competitive advantage in pricing.⁷ The government also set up two major collaborative projects in support of firms' R&D in energy-saving technology. The Sunshine Project, set up in 1974, aimed to develop alternative sources of energy. The Moonlight Project was launched in 1978 in an effort to develop energy-saving technology.⁸ Third, firms engaged in direct foreign investment to shift their production base overseas. They transferred their labour-intensive production facilities to the U.S. and Southeast Asia, and shifted their domestic R&D and

⁵ For example, Nakamura, *The Postwar Japanese Economy: Its Development and Structure*, pp. 205-227.

⁶ Hashimoto, Hasegawa, and Miyajima, eds. *Gendai Nihon Keizai*, (*Contemporary Japanese Economy*), p.171. For the changes in comparative advantage in post oil crisis Japan, see Komiya and Itoh, "Japan's International Trade and Trade Policy, 1955-1984", pp.200-201.

⁷ Gotō, *Inobēshon to Nihon Keizai* (*Innovation and Japanese Economy*), pp. 104-108.

⁸ Regarding to these national projects, see Shimamoto, *Nashonarupurojekuto no Seido Sekkei: Sanshain Keikaku to Taiyōkō Hatsuden Sangyō no Seisei* (*Institutional Design of National Project: Sunshine Project and Development of Solar Power Generation Industry*).

production from labour-intensive to technology-intensive.⁹

Despite the shock from the cancellation of the Bretton Woods Agreement and the oil crises, the Japanese economy sustained its growth even though the growth rate slowed. Because of the shift in their product mix from low-priced to high-quality products, Japanese firms became competitive in various areas with the U.S. and the advanced European countries from the 1970s to the 1990s. Japanese automobile, consumer electronics, robotics, and semiconductor industries began exporting their products to the U.S. market in the 1980s.

U.S. economists began to analyse the competitiveness of U.S. industries to regain competitiveness against Japanese products. For instance, Ezra Vogel's 1979 book, *Japan as Number One: Lessons for America*, received widespread attention both in the U.S. and in Japan.¹⁰ Former U.S. Commerce Department bureaucrat Clyde Prestowitz explained how the U.S. had allowed Japan to take the lead.¹¹ Noting that "the profit-maximizing firms of the United States have faced off against the empire-building firms of Japan," Lester Thurow warned of the upcoming battle involving Japan, Europe, and America.¹² U.S. President Ronald Reagan set up the Commission on Industrial Competitiveness to analyse U.S. industrial competitiveness.¹³ In 1985, this commission published a report indicating that Japan was the biggest rival of U.S. technology-intensive industries.¹⁴ MIT conducted a project, funded by U.S. automobile firms, to examine the technological competence of the automobile industry. The main goal was to examine why the U.S. automobile

⁹ It was pointed out in the second half of the 1980s that the yen's continuing strong appreciation would decrease domestic employment and weaken the manufacturing sector, because manufacturing industry would shift facilities overseas. On the hollowing out problem in Japan, see Nakamura and Shibuya, "The Hollowing Out Phenomenon in the Japanese Industry."

¹⁰ Vogel, *Japan as Number One: Lessons for America*.

¹¹ Prestowitz, *Trading Places: How We Allowed Japan to Take the Lead*.

¹² Thurow, *Head to Head: The Coming Economic Battle among Japan, Europe, and America*, p. 151.

¹³ United States President's Commission on Industrial Competitiveness, *Global Competition: The New Reality: The Report of the President's Commission on Industrial Competitiveness*.

¹⁴ *Ibid.*

industry was losing competitiveness and how the Japanese automobile industry was gaining competitiveness.¹⁵ In 1995, the U.S. Council on Competitiveness released its report, *The New Challenge to America's Prosperity: Findings from the Innovation Index*.¹⁶ The report predicted that Japan would become the leading country in technological innovation, even though it had been struggling from the long depression.

Incremental Innovation

A vast amount of literature has analysed technological development in Japan's technology-intensive industries. Change within Japanese companies tended to be directed toward incremental technological change. For example, examining the Japanese automobile industry, Cusumano pointed out that the technology originally invented in Western nations was improved by Total Quality Control (TQC) at the shop floor level in Japan.¹⁷ In their comparative statistical research, Kagono et al. analysed the technological change of U.S. firms and Japanese firms, revealing that U.S. firms tended to focus on product change, whereas Japanese firms focused on process change, which was usually more incremental than product change.¹⁸ They also asserted that Japanese firms focused on process innovations more than product

¹⁵ Abernathy, Clark, and Kantrow, *Industrial Renaissance: Producing a Competitive Future for America*; Clark and Fujimoto, *Product Development Performance: Strategy, Organisation, and Management in the World Auto Industry*; Finan, *Matching Japan in Quality: How the Leading U.S. Semiconductor Firms Caught up with the Best in Japan*; Cusumano, *The Japanese Automobile Industry: Technology and Management at Nissan and Toyota*.

¹⁶ Porter, Stern, and Council on Competitiveness, *The New Challenge to America's Prosperity: Findings from the Innovation Index*.

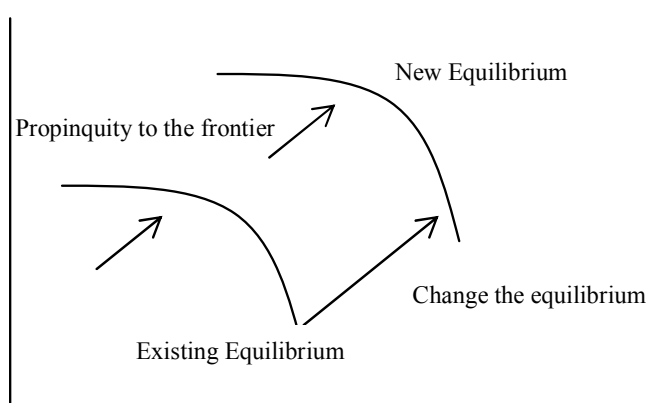
¹⁷ For the first TQC movement in Japan, Cusumano, *The Japanese Automobile Industry: Technology and Management at Nissan and Toyota*, pp.324-327. It is believed that Edward Deming also contributed to incremental innovation and high productivity growth within Japanese manufacturing sectors. Deming was first invited to Japan to give a lecture on quality management in 1950. He contributed to the Japanese manufacturing by introducing statistical quality control method. On Deming's method, see Walton, *The Deming Management Method*.

¹⁸ Kagono et al., *Strategic vs. Evolutionary Management: A U.S.-Japan Comparison of Strategy and Organisation*, pp. 90-96.

innovations. Some of the literature uses the terms “process innovation” and “incremental innovation” interchangeably, although they are two distinct concepts.

Regarding innovation as creative destruction, Schumpeter classified innovation into (1) the introduction of a new product, (2) the introduction of a new production method, (3) the finding of a new market, (4) the introduction of new material, and (5) the introduction of a new organisation, or a mix of one or more of these.¹⁹ He regarded innovation as the transfer to a new technological production frontier. Kirzner developed a counterargument to Schumpeter’s definition and expanded the notion of innovation.²⁰ Although he did not clearly define innovation, he contended that limiting innovation to creative destruction ignores small incremental technological changes that also contribute to economic growth. Big technological change impacts the current production frontier, but small changes increase efficiency and thus help move production to the existing production frontier. While Schumpeter emphasised innovation’s destruction of the current equilibrium, Kirzner maintained that small technological changes move production to the equilibrium, thus playing an important role in economic growth (Figure 2-1).

Figure 2-1: Technological Innovation and Production Frontier



¹⁹ Schumpeter, *Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process*, pp. 62-77.

²⁰ Kirzner, *Competition and Entrepreneurship*, pp.125-131.

Developing a theory similar to that of Kirzner, Joel Mokyr claimed that technological progress was crucial for high and sustainable growth.²¹ He established the concept of micro- and macro-inventions. Micro-inventions are small incremental steps that improve, adapt, and streamline existing techniques or products already in use; they reduce costs, while increasing durability and function. Macro-inventions are radical new ideas that emerge *ab nihilo*. No pattern in their progression can be recognised, but luck and genius play important roles. Once a macro-invention has occurred, it inevitably sets the ground for micro-inventions. For Mokyr, micro- and macro-inventions are the two complementary elements through which technology progresses in an evolutionary fashion. He classified technological change in terms of (1) improvement of existing techniques or products or (2) production of something new.²² Nelson and Winter also paid attention to incremental innovation, which is relatively minor changes to the existing product, and argued that interplay between major and incremental innovation over the course of product and technological change was important.²³

Based on these conceptualisations, the previous research about technological change in Japan indicated that Japanese firms tended to produce incremental innovation more than radical innovation.²⁴ In other words, technological innovations in Japan tended to be incremental and evolutionary, while those in the U.S. tended to be radical and revolutionary.

²¹ Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress*, p. 55.

²² Many works in business management studies have developed different categorisation of innovation. For example, Abernathy and Clark introduced four types of innovation depending on continuity of technology and current competitive advantage of firms; Niche Creation innovation, Architectural innovation, Regular innovation, and Revolutionary innovation. Abernathy and Clark, "Innovation: Mapping the Winds of Creative Destruction."

²³ Nelson and Winter, *An Evolutionary Theory of Economic Change*. Tushman and Anderson put an emphasis on the interplay between radical and incremental innovation. Tushman and Anderson, "Technological Discontinuities and Organisational Environments."

²⁴ For example, Lynn, *How Japan Innovates: A Comparison with the U.S. in the Case of Oxygen Steelmaking*; Clark and Fujimoto, *Product Development Performance: Strategy, Organisation, and Management in the World Auto Industry*; Cusumano, *The Japanese Automobile Industry: Technology and Management at Nissan and Toyota*.

2.2. Four Perspectives on Technological Change and Economic Growth

The following section reviews four main perspectives on technology development in Japan's technology-intensive industries after the double exogenous shocks: (1) technology transfer, (2) government-led growth, (3) cultural issues, and (4) Japanese management. A review of these perspectives will clarify how this thesis contributes to previous arguments.

Technology Transfer: Late Comer Advantage?

The first perspective concerns technological transfer. World War II shut down the information flow regarding the latest technologies. Ōkawa et al. developed an important argument for the relationship between technological backwardness and economic growth.²⁵ Technology transfer was the strategy that the Japanese firms and government took to catch up with Western countries.²⁶ Based on the new knowledge acquired from the U.S. about advanced technology, Japanese firms planned to introduce advanced technology from overseas. Japanese automobile, electronics, and petrochemical industries bought advanced technologies from companies in various countries such as the U.S., Germany, Italy, and Austria. For example, Toshiba made a technology transfer agreement with General Electric (GE). Mitsubishi Electric also entered into a similar agreement with Westinghouse Electric, as Fuji Electric did with Siemens.²⁷ In the automobile industry, agreements were made between Nissan and Austin, Hino and Renault, and Isuzu and Hillman.²⁸ Japanese petrochemical

²⁵ Ōkawa, Shinohara, and Meissner, *Patterns of Japanese Economic Development: a Quantitative Appraisal*.

²⁶ On technological importation in post-war Japan, see Wakasugi and Gotō, "Kyōdō Kenkyū Kaihatsu to Gijutsu Kakushin (Collaborative R&D and Technological Innovation)." Saxonhouse examined technology transfer in the cotton textile industry from the late 19th century to the early 20th century. Saxonhouse, "Mechanisms for Technology Transfer in Japanese Economic History."

²⁷ On the electronics industry and its technology transfer, see Chokki, "Denki (History of the Electric Industry)."

²⁸ The automobile firms transferred technology from European automobile manufacturers

firms introduced advanced technologies from Germany, the U.S., and Italy.²⁹

According to Gerschenkron's framework, the latecomer can start industrialisation by using advanced technologies already developed by other countries.³⁰ As a result, its industrialisation and economic growth occurs more quickly than that of early starters. Following this perspective, it is possible to assume that Japanese firms acquiring advanced technology from overseas could experience high growth.

Much of the previous literature on technological transfer in post-World War II Japan seemed to confirm Gerschenkron's theory. For instance, Lynn showed that Japanese iron and steel firms acquired the basic oxygen furnace (BOF) from Austria and made incremental modifications at the plant level, bringing about high productivity growth.³¹ Madeley analysed the technology transfer from Britain's Wolseley Motors and Rootes Motors to Japan's Ishikawajima Shipbuilding and Engineering Company and Isuzu Motors.³² A licensing agreement facilitated Ishikawajima's entry into the automobile industry. Ishikawajima struggled to manufacture a Fiat automobile by reverse engineering, because the firm's technological competence was not at a sufficient level to produce automobiles. The licensing agreement contained provisions for the direct transfer of Wolseley's production facilities, technology, business management methods, and know-how to Ishikawajima. Madeley insisted that licensing agreements had a significant impact on the development of the automobile industry. Japanese automobile firms accessed advanced technology through licensing agreements and accumulated technological competence, even though the agreements did not provide satisfactory outcomes for the British firms that had planned to expand their market shares in Japan. Madeley

because they believed that compact cars would be necessary for Japan's narrow roads. Shimokawa, "Jidōsha (History of the Automobile Industry)."

²⁹ On the petrochemical firms and their technology transfers, see Kudō, "Sekiyu Kagaku (History of the Petrochemical Industry)."

³⁰ Gerschenkron, *Economic Backwardness in Historical Perspective: A Book of Essays*.

³¹ Lynn, *How Japan Innovates: A Comparison with the U.S. In the Case of Oxygen Steelmaking*.

³² Madeley, "A Case Study of Anglo-Japanese Cooperation in the Motor Vehicle Industry Ishikawajima, Woosely, Isuzu and Rootes."

suggested that technology transfer provided opportunities not only for incumbent firms but also for new entrants in the automobile industry as well as in the petrochemicals industry.³³ Introducing advanced petrochemicals technologies from overseas, new entrants could establish a comparative advantage against the incumbents if they bought in advanced technologies and successfully accumulated technological competence through licensing. Of course, the incumbent firms also planned to introduce advanced technology to update their existing technologies. As a result, firms competed to introduce the most advanced technology from overseas.

Technology inflow from overseas to Japan was not limited to technology transfer. Scientific management such as production quality control, plant layout, and floor arrangement of the production facility were also introduced. TQC, which was introduced in 1962, had become popular with Japanese firms by the 1970s.³⁴ Tsutsui made a similar point in *Manufacturing Ideology: Scientific Management in Twentieth-Century Japan*, regarding the selective adoption of Western scientific management.³⁵

These occurrences in Japan were compatible with Abernathy's conceptualisation of dominant design and technological innovation.³⁶ Abernathy perceived technological innovations as emerging with a certain pattern in historical dynamics. He defined two different types of innovation--process innovation and product innovation. The ratio of product innovation outnumbers that of process innovation before a certain dominant design appears. The dominant design is the product design with main components and mechanisms underlying fundamental characteristics that do not change from one model to another. Once a dominant design appears, the number of product innovations decline and that of process

³³ On the technology transfer in the petrochemical industry, see Kudō, "Sekiyu Kagaku (History of the Petrochemical Industry)."

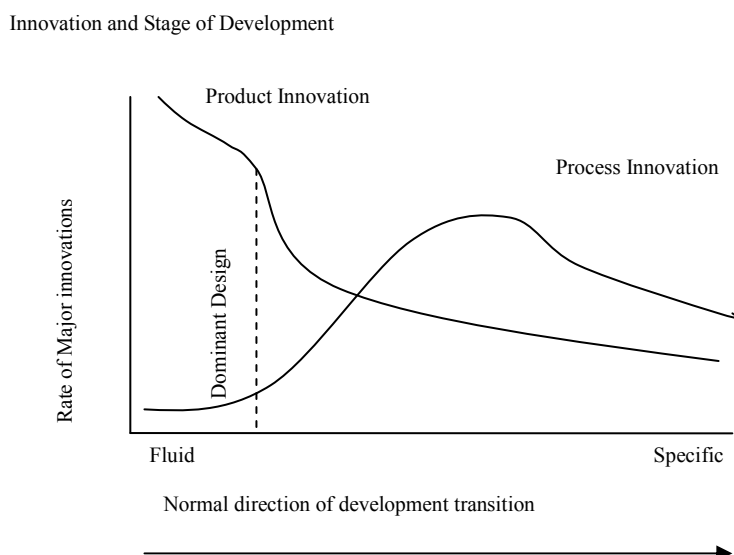
³⁴ On the history of Quality Control in Japan, see Ishikawa, *TQC towa Nanika- Nihonteki Hinshitsu Kanri (What Is TQC? Japanese Quality Control)*.

³⁵ Tsutsui, *Manufacturing Ideology: Scientific Management in Twentieth-Century Japan*.

³⁶ Abernathy, *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*.

innovations increase. (Figure 2-2)³⁷

Figure 2-2: Dominant Design, Product Innovation, and Process Innovation



Abernathy, *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*, p.72

From Abernathy's perspective, it is possible to assume that Japanese firms transferred many fixed dominant designs of technology from overseas; as a result, the number of incremental processes increased. In other words, by modifying transferred advanced technology, Japanese industries acquired incremental technology and experienced high economic growth.

This technology transfer view, however, does not fully explain the technological change that occurred after the late 1970s, since technology transfers from overseas were declining. Japanese firms started introducing insignificant technology such as a 'golf wear' design in the 1960s.³⁸ The total amount of technology exports exceeded that of technology imports in 1972. Since then, the

³⁷ Examining the patterns of paradigm change in natural science, Kuhn developed similar arguments to Abernathy. Kuhn, *The Structure of Scientific Revolutions*.

³⁸ Gotō, *Inobēshon to Nihon Keizai (Innovation and Japanese Economy)*, p. 80.

difference between imports and exports has increased. Moreover, the biggest importer of Japanese technology has been the U.S.--not the developing countries. Furthermore, Gotō and Wakasugi argued that the importance of technology transfer was exaggerated in the previous literature. They pointed out that the ratio of investment for technology transfer to total investment in plants and equipment was 15% even in its peak in 1958.³⁹

Government Led Growth?

The second perspective is the government intervention theory. Chalmers Johnson's *MITI and the Japanese Miracle* kicked off the debate.⁴⁰ Johnson asserted that the expert coordination of the economy by the Ministry of International Trade and Industry (MITI) bureaucrats had a strong impact on Japan's economic growth.⁴¹ *MITI and the Japanese Miracle* has attracted attention from various areas of studies such as political science, economics, and economic and business history. It also attracted politicians' and bureaucrats' attention in many countries. However, it must be noted that his argument has sometimes been oversimplified. In his analysis, he carefully constructed his argument and did not argue that Japan's economic growth was entirely attributed to MITI's industrial policy.

MITI and the Japanese Miracle has drawn attention for two reasons. The first is Johnson's portrayal of wartime Japan. He argued that the Japanese system originated during the interwar period, with important elements forming during the 1930s and others during the years of total war. The final consolidation, ironically,

³⁹ Gotō and Wakasugi, "Technology Policy", p. 184.

⁴⁰ Johnson, *MITI and the Japanese Miracle: The Growth of Industrial Policy, 1925-1975*.

⁴¹ Johnson, however, was not the first scholar to point out the importance of MITI's industrial policy. For example, scrutinizing the petrochemicals industry and the importance of MITI's industrial policy, Kawade and Bōno claimed, "The government played a significant role in the petrochemicals industry.... The government played as Almighty God when firms planned to industrialise petrochemical products. Due to the Foreign Exchange and Foreign Trade Control Law, gaining permission from the government was the top priority for firms." Kawade and Bōno, *Sekiyukagaku Kōgyō (the Petrochemical Industry of Japan)*, pp. 172-173. However, since Johnson's argument was one of the first studies on MITI's industrial policy written in English, it attracted a great deal of attention.

culminated in the occupation era, when civilian bureaucrats no longer had to bow to military priorities. Johnson suggested that mobilisation for war had aided rather than obstructed healthy post-war economic development. The second reason is his argument about the importance of MITI bureaucrats. He suggested that Japan's economic growth was a model for developed countries because it provided important policy implications for governmental officials of developed countries to attain economic growth.

Counterarguments to Johnson's theory arose after the publication of his *MITI and the Japanese Miracle* in 1982. These counterarguments consist of three main points: the scope of MITI's industrial policy, MITI's capability of formulating industrial policy, and the effect of the industrial policy.

Abe reviewed the debate on MITI and indicated that to what extent MITI's industrial policy was successful should be assessed on a case-by-case basis.⁴² MITI's policy was effective in some industries but it was not successful in others. He concluded that MITI's industrial policy played an important role when it could create social consensus on a targeting industry. Friedman argued that MITI's industrial policy did not fully explain Japan's economic growth because its scope was limited.⁴³ He found Johnson's theory misleading because it could be interpreted that MITI's industrial policy brought about Japan's economic growth. Friedman contended that the development of the machine tool industry, a leading industry in post-war Japan, was not solely attributable to MITI's industrial policy. Komiya also noted that many new industries gained competitiveness in the international market and started exporting their products in the 1960s.⁴⁴ He indicated that the government did not help in the development of new industries such as the sewing machine, camera, bicycle, motor bicycle, piano, fastener, transistor radio, colour television, tape recorder, magnetic tape, audio equipment, fishing equipment, watch, ceramics,

⁴² Abe, "The State as the 'Third-Hand': MITI and Japanese Industrial Development after 1945."

⁴³ Friedman, *The Misunderstood Miracle: Industrial Development and Political Change in Japan*.

⁴⁴ Komiya, Okuno, and Suzumura, *Industrial Policy of Japan*, pp.7-8.

electronic calculator, electric wire, machine tool, numerical control machine tool, electronic communication tool, and robotic industries. These facts indicated that although technology transfer may explain incremental technological change until the 1970s, it does not explain more recent technological change. Johnson's argument became popular because it gave a simplistic impression that MITI's industrial policy accounted for Japan's economic growth in its entirety. However, Friedman pointed out that MITI targeted the steel and iron, shipbuilding, petrochemicals, and automobile industries. Other industries achieved competitiveness without the help of MITI's industrial policy.

The second point of the counterarguments against *MITI and the Japanese Miracle* concerns MITI's capability of formulating industrial policy. Using the Japanese aluminium industry as an example, Samuels argued that since MITI had a limited number of researchers to examine individual industries, the officials depended heavily on trade associations and firms in formulating industrial policy.⁴⁵ Of course, the importance of trade associations in the policy planning process was not limited to Japan; for example, Lynn and McKeown indicated that trade associations provided U.K. policymakers with important information about industry.⁴⁶ Trade associations in Japan as well as in the U.S. cooperated with their own government and helped with policymaking in the 1930s. And although trade associations in the U.K. and the U.S. were regarded as lobbyists for their own interests, Lynn and McKeown argued that Japanese trade associations were not just a lobbying group.⁴⁷ Okimoto also pointed out that Japanese trade associations were an important connector between MITI and individual firms.⁴⁸ Both Yonekura and Kikkawa developed similar counterarguments against Johnson's theory.⁴⁹ Concluding that trade associations played an important role in the policymaking

⁴⁵ Samuels, "The Industrial Destructuring of the Japanese Aluminum Industry."

⁴⁶ Lynn and McKeown, *Organizing Business: Trade Associations in America and Japan*.

⁴⁷ Ibid.

⁴⁸ Okimoto, *Between MITI and the Market: Japanese Industrial Policy for High Technology: Studies in International Policy*, pp.112-176.

⁴⁹ Yonekura, "The Functions of Industrial Associations"; Kikkawa, "Enterprise Groups, Industry Associations, and Government: The Case of the Petrochemical Industry in Japan."

process, they perceived information asymmetry between MITI's officials and the industries. MITI's officials were unable to comprehend and examine the situation of individual industries. The trade associations, organised by representatives of the firms, dissolved the asymmetric information problem. Yonekura and Kikkawa contended that the interests of individual firms were incorporated into the policy through industry associations. Indicating that MITI formulated its policy through interaction with the firms at the trade associations, their arguments provided a counterargument against the government-led growth theory.

The last counterargument against the government-led view lies in the fact that government intervention became more indirect and weaker after the 1970s.⁵⁰ The government-led view asserts that economic growth was brought about by strong government intervention, but it does not explain the technological development that occurred after the 1970s. As Japanese industries gained more competitiveness in the international market, the U.S. government and industries started criticising MITI's direct intervention in the market economy. After the 1970s, MITI changed its industrial policy from direct to indirect intervention, such as organizing government-funded research consortia and providing subsidies to important R&D of the industry.⁵¹ The best-known cooperative R&D project in Japan is the Very Large Scale Integrated (VLSI) circuit project, which was launched in 1975 to help Japanese firms compete with their rivals.⁵²

The previous literature asserted that the impact of indirect industrial policy was limited in scale and scope, compared to the direct intervention of the 1950s and 1960s. Callon conceded that MITI's industrial policy was effective until the 1970s.⁵³

⁵⁰ Regarding to the industrial policy in technology intensive industries after the 1970s, see Patrick et al., *Japan's High Technology Industries: Lessons and Limitations of Industrial Policy*.

⁵¹ On the changes in MITI's industrial policy, see Komiya, Okuno, and Suzumura, *Industrial Policy of Japan*, Chapters 3 and 6. Regarding to the government financing and indirect policy in the technology intensive industries, see Okimoto, "Regime Characteristics of Japanese Industrial Policy", pp.60-66.

⁵² On the VLSI project, see Sakakibara, "Soshiki to Inobēshon: Jirei Kenkyū Chō LSI Gijutsu Kenkyū Kumiai (Organisation and Innovation: Case Study, VLSI Consortium)."

⁵³ Callon, *Divided Sun: MITI and the Breakdown of Japanese High-Tech Industrial Policy*,

However, after examining the impact of four research consortia funded by MITI, he asserted that MITI's industrial policy became less effective and the private sectors gained initiative in the national economy after the 1970s. Studying government-funded collaborative research, Okimoto concluded that a causal connection between industrial policy and competitiveness in high technology was not clear, even though industrial policy facilitated the development of Japan's high-technology industries.⁵⁴

Cultural Issues

The third perspective involves Japanese culture's effect on the pattern of technological change in Japan. Although this perspective is sometimes problematic, it is incredibly persistent and is quite strongly tied to the idea that Japanese capitalism is deviant.

James C. Abegglen's *The Japanese Factory* has been the most prevalent work that takes a comparative cultural approach, in which Japanese management is explained by the reference to traditional Japanese values.⁵⁵ For example, Herbig's *Innovation Japanese Style: A Cultural and Historical Perspective* emphasised the cultural differences between Japan and the Western countries.⁵⁶ Herbig contended that Japanese creativity is different from that of the West: "Western creativity reflects frontier thinking and is based on the concept of individual freedom, which favours the discovery of new ideas and product breakthroughs... Japanese creativity is responsive, eclectic, focused, and practical. Japanese creativity is like growing rice. Japanese rice farming is an arduous, time-consuming process of cultivation."⁵⁷ He explained that the Japanese economic system is rooted in rice farming. "The continuation and success of an irrigated wet-rice growing culture has had a long-term effect on the Japanese social system and lifestyle--patience, perseverance,

1975-1993.

⁵⁴ Okimoto, *Between MITI and the Market: Japanese Industrial Policy for High Technology, Studies in International Policy*, p. 230.

⁵⁵ Abegglen, *The Japanese Factory*.

⁵⁶ Herbig, *Innovation Japanese Style: A Cultural and Historical Perspective*.

⁵⁷ *Ibid.*, pp. 10-11.

diligence, cooperation, passivity, conservative, fatalism, energetic, courageous, self-reliant, tenacious, patient, humble, and law-abiding--because this kind of farming required elaborate irrigation systems that could not be easily built and maintained or protected by single families; communities had to work together in large units in order to survive. Through centuries of agrarian experience, the Japanese developed customs of mutual help, collective coordination, risk sharing, and flexible adaptation to continual and incremental environmental change.”⁵⁸

Teramoto and Yamamoto also considered the cultural perspective as it applied to the technological strategies of Japanese firms.⁵⁹ They indicated that Japanese firms did not develop a clear unique competitive strategy. Then they argued that the essence of business strategy originated in military strategy. Because the Japanese did not have much war experience compared to European countries and China, Teramoto and Yamamoto concluded that Japanese firms could not effectively develop business and technological strategies, since the Japanese love peace and avoid fighting.⁶⁰

This cultural perspective has four main problems. First, culture is an umbrella concept that covers many phenomena. Although difficult, defining culture is necessary in order to avoid the fallacy of circular reasoning.

The second problem is that the cultural perspective is based on historical information that is not always completely factual. For instance, Teramoto and Yamamoto concluded that the Japanese loved peace, since Japan had not experienced war as much as European countries and China. However, in reality, Japan experienced many civil wars from the eighth century to the early seventeenth century. And although the Tokugawa period provided two hundred years of peace, Japan did go to war against major powers (e.g., the Sino-Japanese War in 1894-1895 and the Russo-Japanese War in 1904-1905), until it was defeated in World War II. A look at historical facts causes one to question the statement that Japan lacks war

⁵⁸ Ibid., pp. 151-152.

⁵⁹ Teramoto and Yamamoto, *Gijutsu Keiei no Chōsen (the Challenge of Management of Technology)*.

⁶⁰ Ibid., pp.113-118.

experience and the conclusion that its people love peace.

The third problem is closely related to the second one, but from a different line of argument. Economic historians assert that the unique features of Japan's economic system (which will be discussed later) originated in the wartime economy. Based on comparative institutional analysis, Aoki and Okuno examined the origins of the Japanese management system.⁶¹ Aoki stressed the importance of examining institutional settings, incentive systems, and complementarities of institutions. Okazaki and Okuno also emphasised path-dependence and strategic complementarity of institutions.⁶² They argued that the Japanese management system was formed in the interwar period.⁶³ For instance, the lifetime employment and seniority systems were established in the interwar period, when skilled labour was scarce. Noguchi also believed that the Japanese management system, which he called "the 1940 system," originated in the trans-war period.⁶⁴ These arguments agree on three points: (1) the Japanese management system was the outcome of economic rational behaviour; (2) the wartime economy changed the strategic complementarities of institutions; and (3) the institution set in the wartime economy brought about high economic growth. These conclusions are not new. For example, Nakamura had already pointed out that many of the components of the Japanese management system originated in the wartime economy.⁶⁵ From this viewpoint, the economic system radically changed during the war, and these changes were the outcome of economically rational strategies.

The last problem is that the cultural perspective tends to regard culture as static. Herbig believed that rice-farming customs emphasising cooperation and

⁶¹ Aoki and Okuno, eds. *Keizai Shisutemu no Hikaku Seido Bunseki (Comparative Institutional Analysis: A New Approach to Economic Systems)*. On comparative institutional analysis, see Aoki, *Toward a Comparative Institutional Analysis, Comparative Institutional Analysis*.

⁶² Okazaki and Okuno, eds. *The Japanese Economic System and Its Historical Origins, Japan Business and Economics Series*.

⁶³ Ibid.

⁶⁴ Noguchi, *1940 Nen Taisei: Saraba "Senji Keizai" (1940 System: Good by "Wartime System")*.

⁶⁵ Nakamura, *The Postwar Japanese Economy: Its Development and Structure*, pp. 15-21.

harmony in the community shaped economic behaviour. Of course, it is possible that some rice-farming customs could still survive in the twentieth century Japan and affect technological change. However, as Granovetter argued, a better understanding of economic phenomena requires acknowledgement that culture is dynamic.⁶⁶ For instance, since the number of workers in farming has steadily decreased since 1950, it is safe to assume that change in the industrial structure minimized the relative importance of the “rice-farming culture.”

Japanese Management

The last perspective is Japanese management, which has attracted much attention. Economists, economic historians, and scholars in business management studies began to analyse how Japanese technology intensive industries (e.g., automobile, electronics, and semiconductor industry) gained competitive advantage in the international market from the 1970s.⁶⁷ The previous studies have argued that the organisational structure and managerial mechanism of Japanese firms played an important role in the development of technology intensive industries. Many of their arguments address the relationship between the Japanese management system and its technological competence.

Since Japanese management has been massively studied, it is beyond the scope of this study to provide extensive review.⁶⁸ Aspects of the Japanese management system are varied; however, two main characteristics--human resources management and long-term interfirm relationships--have been pointed out as important factors in the pattern of technological change in Japan.

⁶⁶ Granovetter, "Economic Action and Social Structure: The Problem of Embeddedness."

⁶⁷ Abegglen's *the Japanese Factory* is one of the first works on Japanese Management and its competitive advantage. Abegglen, *The Japanese Factory: Aspects of its Social Organisation*

⁶⁸ On the Japanese management system, see Imai et al., *Business Enterprise in Japan: Views of Leading Japanese Economists*; Aoki and Dore, *The Japanese Firm: The Sources of Competitive Strength*.

Human Resource Management

One important aspect of human resources management is lifetime employment and the seniority system.⁶⁹ The long-term employment relationships in Japan have been regarded as one of the important components of “the Japanese Management system.” Lifetime employment is the employers’ practice of recruiting employees directly from high school or university every spring and then retaining them until retirement between 55 and 60 years of age. The coverage varies from a low average of approximately 20% in the smaller enterprises with fewer than 50 employees to a high average of approximately 70% in larger enterprises and government departments.⁷⁰ Japanese organisations offered lifetime employment not as a legal guarantee, but as part of an informal, psychological contract with the expectation of employee dedication to the company in return. The original basis of the seniority system was the value placed on experience and skills. Hashimoto and Raisian pointed out that Japanese firms’ salaries were more correlated with seniority than those of firms in other countries.⁷¹ The long-term relationships have been quite often explained by the lack of competitive labour markets for mid-careers in Japan. Some have explained it in terms of traditional Japanese values stressing groupism and loyalty.⁷²

The literature has pointed out that lifetime employment and seniority systems enhanced incremental innovation for two reasons. First, under these systems, workers had a strong incentive to stay at their firms. The worker who quit a job had

⁶⁹ On Japanese labour management, see Aoki, "The Ranking Hierarchy of the J-Firms as Incentive Scheme"; Koike, "Intellectual Skills and Long-Term Competition." On lifetime employment and seniority-based systems, see Aoki and Okuno, eds. *Keizai Shisutemu no Hikaku Seido Bunseki (Comparative Institutional Analysis: A New Approach to Economic Systems)*, pp. 123-152; Itami, "The "Human-Capital-Ism" of the Japanese Firm as an Integrated System"; Sako and Sato eds, *Japanese Labour and Management in Transition*. Dore, *British Factory, Japanese Factory: The Origins of National Diversity in Industrial Relations*.

⁷⁰ Whitehill, *Japanese Management: Tradition and Transition*, pp.130-131.

⁷¹ Hashimoto and Raisian, "Employment Tenure and Earnings Profiles in Japan and the United States."

⁷² Itoh provided a counterargument to these explanations. He concluded that inactive labour market in Japan was the result of Japanese firms’ human resource management strategy. Itoh, "Japanese Human Resource Management from the Viewpoint of Incentive Theory."

to start over again, from the point of view of seniority. Under this system, the individual worker's salary depended greatly on the firm's performance. Workers could gain by aiming to achieve the collective goals of their firms. In other words, lifetime employment and the seniority system facilitated cooperation among workers. Under the lifetime employment system, people working in the same firm knew one another well; their interaction reduced information asymmetry among different divisions and allowed smooth cooperation within a firm. Kusunoki and Numagami observed that the redeployment of engineers within a firm was undertaken flexibly and frequently.⁷³ They concluded that such transfers enhanced smooth cooperative interaction among R&D and its related divisions. Aoki also concluded that Japanese firms tended to develop cooperative interaction between their R&D and production divisions, thus increasing the efficiency of R&D and production information flows among related divisions.⁷⁴ Chokki pointed out that while the relationship between the R&D department and the production department became close in the 1960s, it later became much more intense.⁷⁵ Kenny and Florida also pointed out that constant interaction between employees with different skills made it easier to solve collaborative problems.⁷⁶

The literature contains evidence that the skill formation pattern in Japanese firms played an important role in Japan's technological development. According to Koike, labourers in Japanese firms acquired skills through on-the-job training.⁷⁷ Because lifetime employment and the seniority system reduced the risks of losing training investments, substantial amounts of formal and informal training were conducted in Japanese firms. As a result, many of the skills that the workers acquired were firm specific and tacit. The ongoing training and the seniority system provided the context for continuous improvement and quality control activities.

⁷³ Kusunoki and Numagami, "Intrafirm Transfers of Engineers in Japan."

⁷⁴ Aoki, *Information, Incentives, and Bargaining in the Japanese Economy*. See pp. 69-86.

⁷⁵ Chokki, "Denki (History of the Electric Industry)", pp.32-34.

⁷⁶ Florida and Kenney, *The Breakthrough Illusion: Corporate America's Failure to Move from Innovation to Mass Production*, pp. 154-155.

⁷⁷ Koike, *Understanding Industrial Relations in Modern Japan*, pp. 273-274. For job training and learning in Japanese firms, see Koike, "Learning and Incentive Systems in Japanese Industry."

Since Japanese firms rarely hired workers midway through the year, the opportunity to exchange firm-specific knowledge was limited.

Examining several different highly technology-intensive product R&D processes of Japanese firms, Takeuchi and Nonaka suggested that Japanese firms limited the size of their R&D projects to encourage intense interaction.⁷⁸ The new product development process was composed of several different phases (e.g., design phase, prototype-testing phase, production phase, marketing phase). All phases were flexibly connected and coordinated in Japanese firms, based on the close relationship among divisions; interaction among the phases was more intense than that in the U.S. firms. Flexible coordination accelerated the R&D process. However, firms confronted a huge information flow that each unit had to process. Takeuchi and Nonaka pointed out that a new development project had to be small enough to maintain face-to-face interaction so that the flexible coordination of R&D processes could be achieved.⁷⁹ They implied that the Japanese new product development process did not fit well with big projects that involved numerous people.

Assembler-Supplier Long-Term Relation

The second point involves long-term interfirm relationships.⁸⁰ Close interfirm relationships between suppliers and assemblers have been addressed in much of the previous literature on technological development in post-war Japan. For instance, examining the relationship between automobile parts suppliers and assemblers, Asanuma showed that the long-term relationship was an important institutional mechanism for coordinating design and assuring timely supply.⁸¹ Clark and Fujimoto observed that automobile manufacturers such as Toyota and Nissan

⁷⁸ Takeuchi and Nonaka, "Seihin Kaihatsu Purosesu no Manegimento (the Management of New Product Development)."

⁷⁹ Ibid.

⁸⁰ On long-term relationships, see Hashimoto, *Sengo no Nihon Keizai (History of Post War Japanese Economy)*.

⁸¹ Asanuma, "Manufacturer-Supplier Relationships in Japan and the Concept of Relation-Specific Skill."

had long-term relationships with certain suppliers.⁸² Aoki indicated that relationships among assemblers and suppliers extended over a long period.⁸³ Some long-term relationships were based on cross-share holdings.⁸⁴ Others were based on assembler-supplier relationships called “Keiretsu.” One type of Keiretsu is a large horizontally organised industrial conglomerate, called “Zaibatsu”, such as Mitsubishi, Mitsui, and Sumitomo, some of which originated in pre-war Japan.⁸⁵ Another type is a vertically quasi-integrated firm, such as Toyota, Matsushita Electric, and Kajima. Both were a contentious issue in the trade negotiations between the U.S. and Japan. The U.S. government criticised that the firms in Keiretsu tended to conduct business exclusively within the same Keiretsu group. The U.S. government indicated that the strong ties in Keiretsu groups kept foreign firms out, even if the firms moved their production facilities or sales branches overseas.

The literature has developed three points regarding the effects of long-term relationships on technological change. The first is that long-term interfirm relationships reduced the information asymmetry among firms and restrained opportunistic behaviour. Examining the interfirm relationship in the automobile industry, Nishiguchi found that assemblers such as Toyota, Nissan, and Honda maintained relationships with multiple parts suppliers simultaneously and ranked them according to their past performance.⁸⁶ If suppliers engaged in opportunistic behaviour, the assembler would downgrade their ranking or sever the relationship. Highly ranked suppliers were allowed to become involved in assemblers’ R&D from the blueprint phase. Nishiguchi’s argument indicated that under the condition that

⁸² Clark and Fujimoto, *Product Development Performance: Strategy, Organisation, and Management in the World Auto Industry*, pp. 136-143.

⁸³ Aoki, *Information, Incentives, and Bargaining in the Japanese Economy*, pp.204-257.

⁸⁴ On cross-share holding, see Sheard, "Interlocking Shareholding and Corporate Governance in Japan."

⁸⁵ On Zaibatsu, see Morikawa, *Zaibatsu: the Rise and Fall of Family Enterprise Groups in Japan*.

⁸⁶ Nishiguchi, *Strategic Industrial Sourcing: The Japanese Advantage*, pp.116-119. Fujimoto also indicated the same point. Fujimoto, *The Evolution of a Manufacturing System at Toyota*, pp.133-135. On the Japanese automobile industry, see Shimokawa, *The Japanese Automobile Industry: A Business History*.

longer relationships resulted in more benefits for the supplier, the incentive to refrain from opportunistic behaviour increased. Imai, Nonaka, and Takeuchi argued that long-term relationships promoted information sharing and cooperation among firms. Assemblers shared their new product development plans from the blueprint stage with the top-ranked suppliers. Such actions were risky for the assemblers because their blueprints could potentially be disclosed to the public. However, the assemblers took that risk, since long-term relationships decreased the incentive to engage in opportunistic behaviour. Cooperation between assemblers and suppliers accelerated technological change and enhanced the flexibility of new technology development.⁸⁷ Aoki made a similar argument that the relationship among assemblers and suppliers was quasi-integration, which increased the efficiency of production and information diffusion.⁸⁸

The second point is that the interfirm relationships stimulated competition among suppliers. Examining the technological development of the automobile industry, much of the previous literature pointed out that the assemblers ranked their own suppliers based on past performance.⁸⁹ The higher-ranked supplier received more benefits from its assembler than low-ranked suppliers did. Benefits included technological support, human resources, financial support, and a certain number of orders from the assembler. Low-ranked suppliers had to meet severe demands not only in price and quality but also in tightly appointed dates of delivery to raise their ranking, even if the order was not profitable. The result was fierce competition among the suppliers to raise their ranking. Additionally, the pace of innovation and new product development were accelerated. It was possible for assemblers to run several new product development projects simultaneously without internalising many resources because they had several suppliers working together.

While long-term relationships facilitated technological innovation, they also

⁸⁷ Imai, Nonaka, and Takeuchi, "Managing the New Product Development Process: How Japanese Companies Learn and Unlearn."

⁸⁸ Aoki, *Information, Incentives, and Bargaining in the Japanese Economy*, pp. 204-257.

⁸⁹ For instance, Nishiguchi, *Strategic Industrial Sourcing: The Japanese Advantage*, pp. 116-119; Fujimoto, *The Evolution of a Manufacturing System at Toyota*, pp. 130-143.

disturbed the development of radical innovation. It was believed that long-term interfirm relationships were less flexible, and as a result Japanese firms were vulnerable to radical technological change.⁹⁰ They could not flexibly change their business partners because of the long-term relationships they had established. Even though the assemblers had multiple parts suppliers, they did not frequently change their main supplier. As a result, it was difficult for Japanese firms to react flexibly to radical technological change and to produce radical innovation by changing their business partners. In contrast, since U.S. firms flexibly changed their business partners throughout the market, radical technological innovation by changing their business partners was relatively easy.

⁹⁰ For example, Kagono et al., *Strategic vs. Evolutionary Management: A U.S.-Japan Comparison of Strategy and Organisation*; Cusumano, *The Japanese Automobile Industry*; Aoki, "Toward an Economic Model of the Japanese Firm."

2.3. Previous Studies and Research Questions

As indicated in the first chapter, one contribution of this thesis lies in the sources that this research uses. This section, however, focuses on the relationship between the previous studies about technological change in Japan and the research question in this thesis.

Firstly, as reviewed above, the technology intensive industries came to be competitive from the 1970s. Regarding the economic growth of post-war Japan, the government-led perspective remains strong, though many counterarguments exist. One reason is that the high economic growth period from 1955 to 1973 has received more attention than the period after the oil crises. However, previous arguments indicated that MITI's intervention changed from direct to indirect, and its impact decreased after the 1970s. The optoelectronics industry also became an important sector of the national economy. This thesis examines the optoelectronics industry, which started industrialising and gained technological competitiveness after the oil crises. By examining the development of semiconductor laser technology, this thesis aims to provide a better understanding of how Japanese technology intensive industries have become competitive since the 1970s.

Second, this study analyses relationships among competitors, the spillover effect, and technological innovation. Much discussion in the literature addresses the organisational setting of Japanese firms under the framework of "the Japanese management system." The organisational settings are important supply side mechanisms pushing technological change to a certain pattern. Much of the previous literature has revealed how a certain set of organisational settings affected an individual Japanese firm's R&D and led it toward a certain pattern such as incremental innovation.

This thesis focuses on interactions among the competing firms by looking at spillover effects. It is important to examine the dynamic process in which the firms interacted through competition and to explore how a certain pattern of technological change emerged from their interactions. There is no literature discussing the pattern

of technological development in post-war Japan in terms of the knowledge spillover effect in market competition.⁹¹ This thesis contributes to the studies by examining why competition was fierce, and how fierce competition contributed to technological innovation in Japanese industries.

Additionally, this thesis pays strong attention to the fact that the firms chose similar strategies and fiercely competed in the same areas. The AIST surveyed key industrial technologies in 1983; their report concluded that firms' competition in the same type of semiconductor laser contributed to technological development.⁹² Certain externalities, which would not have existed with only one firm in the market, were induced through this competition. By examining this pattern of competition, the spillover effect, and its impact on technological development, this thesis aims to contribute to information about competition and technological innovation. This topic has not been addressed nearly as much as the organisational setting of Japanese firms, framed as the Japanese management system.

The third point involves the relationship between theoretical research on the economics of the technology-intensive industry and technological change, and previous research on technological change in post-war Japan. These industries became increasingly important after the 1960s, and economists began to study them and to provide useful perspectives. The interaction between the theoretical research and the previous research about technological change in post-war Japan, however, has been quite limited. One possible reason lies in the fact that much of the previous literature about technological change in Japan was limited to the unique features of the Japanese management system, to the exclusion of the possibility that new findings in the economics of technology-intensive industry could be enlightening. This study aims to bridge the gap between theoretical research about the economics

⁹¹ Examining the technological development of the pocket calculator industry, Numagami, Asaba, Shintaku, and Amikura studied the spillover effects among the competing firms. However, no English-language literature discusses spillover effects among the firms. Numagami et al., "Taiwa to Shite no Kyōsō (Competition in the Market as a Dialogue)."

⁹² Kōgyō Gijutsuin Sōmubu Gijutsu Chōsaka (Agency of Industrial Science and Technology), *Wagakuni Sangyō Gijutsu no Taishitsu to Kadai (Survey of Japanese Industrial Technology)*, p. 276.

of technology-intensive industries and empirical research about the competitiveness among those industries in Japan. Based on the important features of the technological industry described in the first chapter, this study examines how the semiconductor laser technology of Japanese firms became technologically competitive.

Lastly, the previous literature discussing research networks and technological change in post-war Japan has been limited. While there is much literature examining the government funded joint research projects, which the fourth chapter *Semiconductor Laser Research Consortium* will review, the literature on non-governmental joint research and research networks in post-war Japan has been very limited. One of the possible reasons lies in the fact that Japanese engineers acquired important skills through OJT. It is reasonable to suppose that research networks did not play an important role in technological change in Japan. However, technology intensive industries rely substantially on the application of new science-based technologies to products or production processes. Therefore, this study aims to provide a better understanding of the relationship between research networks and technological change by examining the state of aggregate knowledge and research networks in the industry.

3. Human Capital and Research Networks

Science plays an important role in technology-intensive industry. As Griliches indicated, the R&D output of firms mainly depends on three factors, the state of aggregate knowledge in the industry, the level of conventional inputs of the firm and its specific knowledge capital of the firm.¹ Scientific advancement and knowledge accumulation in basic research and development are the fundamental bases of technological development. This chapter discusses the research community and the state of aggregate knowledge in semiconductor laser technology.

As the first chapter has shown, Japanese firms came to be competitive in semiconductor laser research and development in the early 1980s. One might speculate that the competitiveness of Japanese firms could be attributed to the Japanese research community's superiority in certain ways over those of the U.S. and Europe. This chapter, however, shows that this assumption is incorrect.

This chapter consists of three sections. The first section describes the brief history of semiconductor laser research and examines the semiconductor laser research that physicists began in the 1950s in the U.S., Japan, the U.S.S.R., and Europe. The second section studies the human capital accumulation in semiconductor laser in the U.S., Japan, and Europe. Japan was still behind the U.S. and the U.S.S.R. in human capital accumulation in semiconductor laser technology, but began accelerating its accumulation in the 1970s. The third section investigates the collaborative research networks in those regions from 1963 through 1985. Previous literature in both history of science and technology and economics of

¹ Griliches formulated the notion of externalities and productivity growth as follows.

$$Y_i = BX_i^{1-\gamma} K_i^\gamma K_a^\mu$$

where Y_i is the output of the i th firm which depends on the level of conventional inputs X_i , its specific knowledge capital K_i , and on the state of aggregate knowledge in this industry K_a . Note that constant returns are assumed in the firm's own inputs, X_i and K_i . Griliches, "The Search for R&D Spillovers", pp.9-10.

technology has argued that inter-organisational collaborative networks are important institutions through which organisations can access complementary knowledge. This section shows that the inter-organisational research network in Japan was more limited in its scope and scale than those in the U.S. and Europe. Through the analyses of human capital accumulation and research networks in semiconductor laser technology, this chapter concludes that no evidence exists to show that Japan was more advanced or had a better research community than its counterparts. The findings in this chapter suggest that Japan attained technological development in semiconductor lasers and gained significant market share in the semiconductor laser and its application areas from the beginning of 1980s in spite of the fact that the human capital accumulation and the research network in semiconductor lasers were not specially advanced in Japan compared to those in the U.S. and Europe.

3.1. The Beginning of Semiconductor Laser Research

The first theoretical conception of the laser originated with Albert Einstein, who presented the photoelectric effect in 1905, which became a fundamental theoretical backbone of the laser.² Extending this theory, in 1917 Einstein predicted stimulated emission of radiation. This first theoretical finding, however, remained untouched until after World War II.

Toward the end of the 1930s, German torpedoes began sinking U.S. ships. The U.S. government and military turned to the problem of how to protect their ships.³ The U.S. military began to mobilize physicists into the war and set clear research goals for them. It was the first time that governments used physics for their military strategic purposes on a large scale. The U.S. military set two goals for the physicists: (1) to develop the nuclear bomb and (2) to develop microwave radar. The first project was called “Manhattan Project.” In 1939, there was a rumour that the Nazis were developing an atomic bomb. It was necessary for the U.S. to build an atomic weapon before its enemies such as German or Japan did. The U.S. government initiated the Manhattan project under the Army Corps of Engineers in June 1942. The main target of the second project was to develop microwave for radars and weapons. Under the guidance of the government, the physicists began to develop various radio wave weapons such as electronically guided anti-aircraft guns and radar-guided bombing system with electromagnetic waves. All of them were microwave applications. The physicists struggled to develop (1) shorter wavelength and (2) higher output microwaves. A shorter wavelength could transmit more information. Higher output could reach a further point.

This research in microwaves would lead to laser technology after the war.

² This thesis is “Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen (On the Motion-Required by the Molecular Kinetic Theory of Heat- of Small Particles Suspended in a Stationary Liquid).”

³ On the wartime research in applied physics, see Townes, *How the Laser Happened: Adventures of a Scientist*, pp.33-46.

With the financial support of the U.S. Air Force, Army, and Navy, in 1953 Charles H. Townes, a physicist at Columbia University, applied Einstein's theory to invent the first maser, which was a device operating on principles similar to those of the laser, but producing microwave rather than optical radiation.⁴ This maser was not capable of continuous output, which was indispensable for the practical use of the photoelectric effect. U.S.S.R. physicists Nikolay Basov and Aleksandr Prokhorov independently solved this problem with the idea of Townes's maser and attained continuous output.⁵ Based on these discoveries, physicists at many research institutes (e.g., MIT Lincoln Laboratories, IBM, Westinghouse, Siemens, RCA Labs, GE, Bell Laboratories, and Technical Research Group (TRG)) competed to amplify shorter wavelength light to produce visible light because the shorter the wavelength light, the more information could be transmitted.

The winner of the competition was Gordon Gould, a graduate student of Columbia University. In 1957, he came up with a stimulated emission with shorter wavelength light and noted his idea in his notebook. He named this idea LASER (Light Amplified by Stimulated Emission of Radiation). But since Gould did not publish his idea and did not promptly apply for a patent, other physicists did not recognize his finding.⁶ They continued researching to develop shorter wavelength light. Townes and Arthur Schawlow also investigated the possibility of an optical maser, a prototype of the gas laser. They published the first detailed proposal for building an optical maser in *Physical Review* in 1958.⁷

Theodore H. Mainman, an electronic engineer at Hughes Aircraft Research

⁴ On Townes and his works, see *ibid.*

⁵ Townes, Basov, and Prokhorov won the Nobel Prize in Physics in 1964 for fundamental work in the field of quantum electronics.

⁶ Gould brought his idea of a laser to TRG in New York. TRG and Gould presented their research proposal to the Department of Defense Advanced Research Project Agency to receive research funding. The agency accepted their research proposal and offered one million dollars to support Gould's research at TRG. Gould and Townes went to court to claim their invention. Since Townes and his colleague Arthur L. Schawlow presented the laser light and applied for a patent in 1958, Gould went to court and appealed that the laser was his idea. The final judgment supported Gould's appeal in 1977. *Ibid.*, pp.101-104 and pp.120-124.

⁷ Schawlow and Townes, "Infrared and Optical Maser."

Laboratories in California, used a solid body pink ruby to amplify visible light in 1960.⁸ It was the first successful light amplification by stimulated emission of radiation. Because Mainman used a pink ruby to amplify the laser beam, it was named the “ruby laser.” Many various lasers were developed after Maiman’s success.⁹

These lasers were an important breakthrough in applied physics in the 20th century. It was regarded as “the greatest invention of the 20th century.” However, it was necessary for the practical use of the laser to overcome many technical obstacles. Among the technical problems, two problems especially needed to be solved for the practical use of the laser. The first was the size of the laser. The lasers developed by these physicists required a large-scale amplification facility to produce a laser beam. It was necessary to scale down the amplification facility. Otherwise, the application areas for the lasers would be seriously limited due to the large size facility. The second obstacle was the costs of production. For instance, Theodore Maiman used a solid body pink ruby, which was not cheap material, to amplify the laser beam. It was necessary to cut the production costs by both scaling down the amplification facility and reducing the material costs.

It was predicted that a semiconductor laser might be able to solve these problems. A semiconductor laser needed a very small size amplification system of only one inch cubed. It used a semiconductor, which was supplied at a very reasonable price compared to other materials used for lasers, as its amplification mediation.

The first theoretical idea of a semiconductor laser emerged in a letter written in 1953 by John von Neumann, a Hungarian mathematician.¹⁰ Neumann believed it

⁸ Despite the fact that Mainman successfully amplified the laser beam, his laser did not receive much attention. For instance, *Physical Review* rejected his article on the laser. *Physical Review Letters* also rejected his report of the ruby laser. *Nature* reviewed his laser with only three hundred words.

⁹ For example, Ali Javan, William Bennet, and Donald Herriot developed the first gas laser by using helium and neon (He-Ne) in 1960. C. Kumar and N. Patel worked with carbon dioxide and developed carbon monoxide lasers which they mixed with nitrogen, helium, and water to fine-tune the laser properties.

¹⁰ Grundmann, *Nano-Optoelectronics: Concepts, Physics, and Devices*, Nanoscience and

would be possible to attain stimulated emission with the use of a semiconductor; however, he did not present this idea at any academic society. The first publicly released material on light amplification using a semiconductor was a patent for a “semiconductor maser” granted to Nishizawa Junichi, a physicist at Tohoku University, in 1957. This maser, run with principles similar to those of the laser, reinforced the feasibility of stimulated emission in semiconductors. GE applied for a patent for the same idea in the U.S. eighteen days after Junichi’s application in Japan.

Two years after the invention of the first laser in 1960, four different research groups almost simultaneously developed the semiconductor laser.¹¹ In September 1962, Gunther Fenner, a member of the research group headed by Robert N. Hall at the GE Development Centre, successfully operated the first semiconductor laser.¹² A few weeks later, Nick Holonyak at the University of Illinois at Urbana-Champaign, Marshall I. Nathan at the IBM Research Laboratory in Yorktown Heights, and Robert Rediker at the Lincoln Laboratory Massachusetts Institute of Technology independently developed the semiconductor laser.¹³ They were big breakthroughs in semiconductor laser technology. All the semiconductor lasers developed by those institutions, however, worked only a few seconds at the very low temperature of minus 196 degrees centigrade. Subsequently, physicists began competing to develop a semiconductor laser that would work at room temperature with high stability.

Physicists began to research semiconductor lasers from the end of the 1950s. However, both the number of the researchers researching semiconductor lasers and the research outcomes were fairly limited. It was not until the late 1960s that physicists regularly released their research in academic journals. Figure 3-1 shows the number of articles on the semiconductor laser published in the *Journal of*

Technology, p.3.

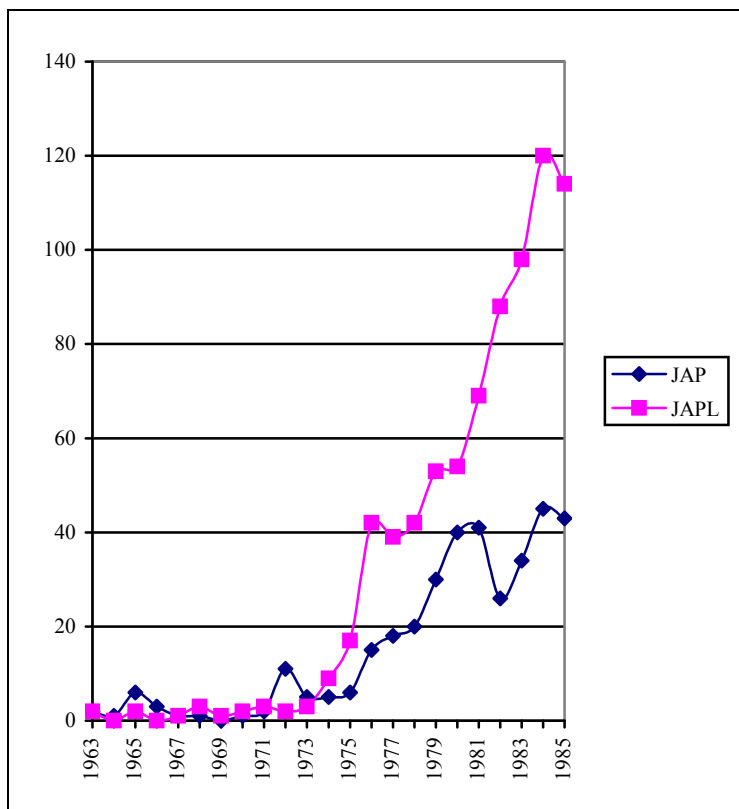
¹¹ Holonyak and Bevacqua, "Coherent (Visible) Light Emission from Ga(As₁-X_{px}) Junctions"; Quist et al., "Semiconductor Maser of GaAs"; Nathan et al., "Stimulated Emission of Radiation from GaAs P-N Junctions"; Hall et al., "Coherent Light Emission from GaAs Junctions."

¹² Hall et al., "Coherent Light Emission from GaAs Junctions."

¹³ Quist et al., "Semiconductor Maser of GaAs"; Nathan et al., "Stimulated Emission of Radiation from GaAs P-N Junctions"; Holonyak and Bevacqua, "Coherent (Visible) Light Emission from Ga(As₁-X_{px}) Junctions."

Applied Physics and *Journal of Applied Physics Letters*, two widely recognized international journals in applied physics published by the American Institute of Physics. Since 1931, two issues of the *Journal of Applied Physics* have been published per month to provide a better understanding of the physics underlying modern technology. Since 1962, the weekly journal *Applied Physics Letters* has offered up-to-date reports on new experimental and theoretical findings in applied physics.

Figure 3-1: Number of Semiconductor Laser Publications



Source: Compiled from *Journal of Applied Physics* 1931-1985, *Journal of Applied Physics Letters* 1963-1985.

In both journals, the first papers about the semiconductor laser were published in 1963. But it was not until the 1970s that physicists regularly released their findings on the semiconductor laser, indicating that during this time they were beginning to conduct their research in “open science,” features the principle of research outcome

disclosure.¹⁴

¹⁴ On the discussion about the open science, see Dasgupta and David, "Toward a New Economics of Science"; David, "Common Agency Contracting and the Emergence of "Open Science" Institutions."

3.2. Accumulation of Human Capital

The state of aggregate knowledge in the industry strongly affects the R&D output of a firm. This section looks at the state of knowledge in semiconductor laser technology by examining the number of physicists who received doctoral degrees in semiconductor laser studies. Since semiconductor laser technology requires highly complex and detailed expertise in applied physics, the number of doctoral degree-holders in semiconductor laser can serve as an indicator of human capital accumulation in semiconductor laser technology. The *Bibliography of Doctoral Theses on Semiconductor Lasers* reveals the number of doctoral degrees in semiconductor laser technology issued throughout the world.¹⁵

It must be noted that there might be several biases in using the number of doctoral degrees to estimate the accumulation of human capital. Firstly, because countries did not necessarily adopt the same educational and academic system, there are institutional differences in their academic systems. For instance, there are two types of doctoral degree in Japan. The first is the doctoral degree that one can receive by completing the required courses and a doctoral thesis in a certain period of time, which is usually from 5 to 8 years. This type of doctoral degree is listed as “the first (Kō).” The second, which is listed as “the second (Otsu)”, is for those who do not receive “the first” doctoral degree. This type of doctoral degree is given to those who did not receive “the first” doctoral degree but published prominent scholarly achievements, which can be conceived as an equal achievement to a doctoral thesis. This distinction reflects the fact that the doctoral degree used to be regarded as an honour given to someone regarded as a prominent scholar in his field.¹⁶ Therefore, the number of doctoral degree holders might be biased toward being smaller in this social and academic system, compared to the U.S., which had

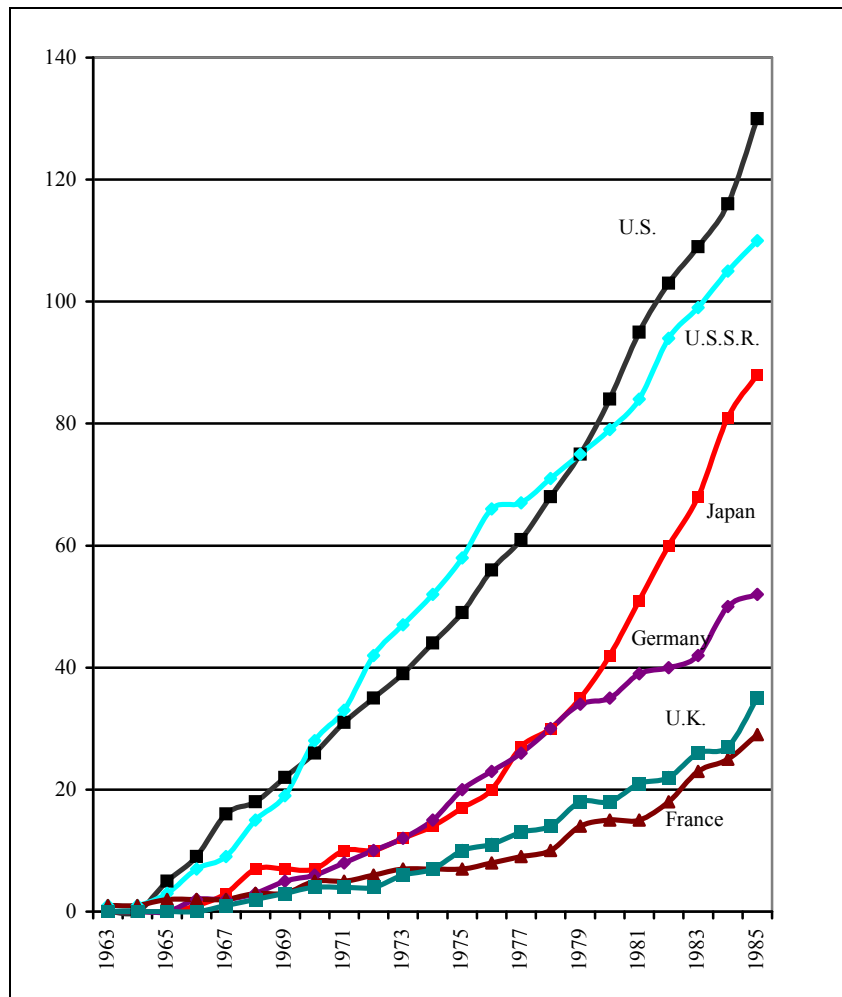
¹⁵ Takahashi, *Bibliography of Doctoral Theses on Semiconductor Lasers*; Takahashi, *Bibliography of Doctoral Theses on Semiconductor Lasers II*.

¹⁶ For the overview of the academic system in science and technology area and how to use published papers in those fields, see Ueda et al., eds. *Rikōgaku Bunken no Tokushoku to Riyōhō* (*Handbook of Literature in Science and Technology*).

no such distinction in the doctoral degree. However, this institutional difference was bigger in the arts and social science areas than in the natural science.

Secondly, since scientists and engineers who have been involved in semiconductor laser research are not necessarily limited to those with doctoral degrees, it would be preferable to examine the number of bachelor and master degrees in semiconductor laser technology. However, no systematic and consistent data identifies the number of students specialising in semiconductor laser in undergraduate and master degree programs because it is difficult to trace students' specialities in more detail than physics in undergraduate and master courses. Another possible limitation might be the institutional difference in academics (e.g., in the procedures and conditions in conferring a doctoral degree). Researchers in different countries might have different preferences for receiving a doctoral degree. Despite these points, the *Bibliography of Doctoral Theses on Semiconductor Lasers* has provided the best systematic and consistent data about human capital accumulation in semiconductor laser thus far.

Figure 3-2 plots the cumulative number of doctoral degree holders in semiconductor laser technology in the top seven countries in terms of the number of doctoral degree holders in the world. The first doctor degrees in semiconductor lasers were granted in France and Russia in 1963. The first such degree in Japan was granted in 1966.

Figure 3-2: Accumulative Number of Doctoral Degrees

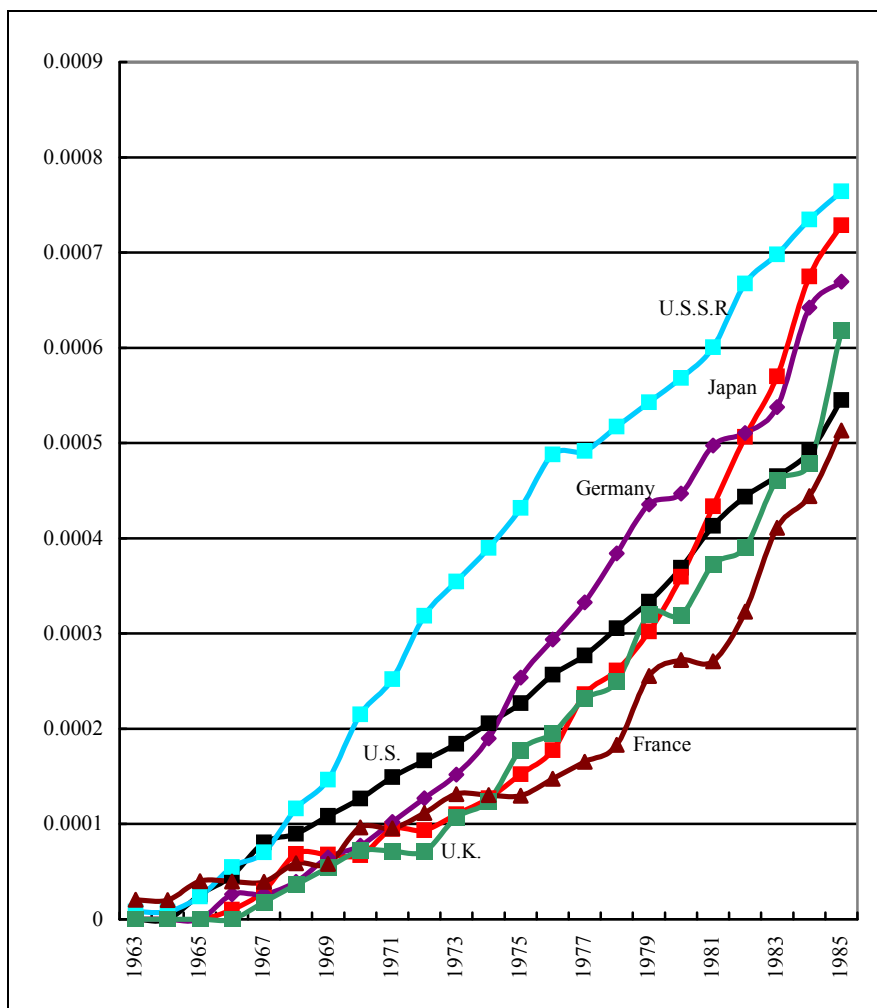
Source: Takahashi, *Bibliography of Doctoral Theses on Semiconductor Lasers II*.

Clearly, the U.S. and the U.S.S.R. have been the two leaders in human capital accumulation in semiconductor lasers since 1965. Japan was one of the countries in the second group in the 1960s, and in the 1970s, the number of doctoral degrees began increasing in Japan. Japan was diverging from the second group and increasing at the same ratio as the two leading countries. However, a certain difference existed in the total number of doctors between the leading countries and Japan, even though the difference was decreasing somewhat.

The following figure shows the accumulative number of doctoral degrees per capita. This figure provides a slightly different view on human capital accumulation

in semiconductor lasers. The U.S. was not the leading country in the human capital accumulation per capita. Japan became the second largest country after U.S.S.R. in 1983. However, it did not stand out from other rival countries until the 1980s.

Figure 3-3: Accumulative Number of Doctoral Degrees Per Capita



Source: Takahashi, *Bibliography of Doctoral Theses on Semiconductor Lasers II*. U.S. Census Bureau, *International Data Base (IDB)*.

The following table indicates the top ten research institutions in the cumulative number of doctoral degrees specialising in semiconductor laser studies.

Table 3-1: Top 10 Institutions in the Cumulative Number of Doctoral Degrees Granted 1965-1985

	1965	1970	1975	1980	1985
P.N. Lebedev Physics Institute (USSR)	3	20	30	36	48
A.F. Ioffe Physicotechnical Institute (USSR)	0	5	12	22	37
University of Illinois at Urban-Champaign (US)	1	9	17	23	33
Tokyo Institute of Technology (Japan)	0	1	3	9	28
The University of Tokyo (Japan)	0	3	7	13	19
University of California, Berkeley (US)	1	2	4	11	18
California Institute of Technology (US)	0	1	3	8	18
Massachusetts Institute of Technology (US)	0	3	7	12	18
Osaka University (Japan)	0	1	4	7	14
Humboldt University, Berlin (Germany)	0	1	2	5	13

Source: Takahashi, *Bibliography of Doctoral Theses on Semiconductor Lasers II*.

The P.N. Lebedev Physics Institute and the University of Illinois at Urbana-Champaign (UIUC) were the two leading institutions until the mid-1970s, when the A.F. Ioffe Physicotechnical Institute overtook UIUC. The Tokyo Institute of Technology increased the number of doctoral degrees granted in the late 1970s and ranked fourth in 1981. The human capital accumulations in the semiconductor laser at the institutional level indicate that Japanese institutions were not at the head, but they were among the leading institutions. The evidence indicates two important points:

- [3-1] The U.S. and the U.S.S.R. were the two leading countries in human capital accumulation in semiconductor laser technology.
- [3-2] Although Japan accelerated its human capital accumulation from the 1970s, it was not the leading country in human capital accumulation in semiconductor laser technology.

3.3 Collaborative Research and Networks

Many studies in the history and sociology of science and technology suggest that science and technology are dependent on each other, and both scientific and technological knowledge involve interaction among scientists and engineers.¹⁷ Technological spillover, which creates positive externalities for innovation, is an important factor of technological progress and requires that scientists and engineers collaborate, sharing complementary knowledge. The previous research suggests that networking among scientists and engineers enhances knowledge spillover and contributes to technological development.¹⁸

No single measurement casts light on every aspect of collaboration between scientists and engineers. This thesis uses co-author publication as a proxy measure for collaboration among scientists and engineers. Co-publication can be considered evidence of collaborative research.¹⁹ It, however, has limitations in measuring collaborative research in academics.²⁰ First, co-publication does not capture informal collaborative research, which usually does not appear in academic journals.²¹ Collaborative research can take various forms from a formally organized research consortium to casual conversation among scientists and engineers. Secondly, co-

¹⁷ Bijker, Hughes, and Pinch, *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*; Latour, "Give Me a Laboratory and I Will Raise the World"; MacKenzie, "Missile Accuracy: A Case Study in the Social Processes of Technological Change"; Merton, "Priorities in Scientific Discovery: A Chapter in the Sociology of Science"; Mulkay, *Science and the Sociology of Knowledge, Controversies in Sociology*; Fleming and Sorenson, "Science As a Map in Technological Search." For the recent literature on the relationship between science and technology, see Murray, "Innovation as Co-Evolution of Scientific and Technological Networks: Exploring Tissue Engineering."

¹⁸ David, "Knowledge Property and the System Dynamics of Technological Change"; Dietz and Bozeman, "Academic Careers, Patents, and Productivity: Industry Experience as Scientific and Technical Human Capital."

¹⁹ Smith, "The Trend toward Multiple Authorship in Psychology."

²⁰ On the previous researches on collaborative research and their problem, see Katz and Martin, "What is Research Collaboration?"

²¹ On informal know-how trading, see Von Hippel, "Cooperation between Rivals: Informal Know-How Trading." Von Hippel interviewed engineers of competing firms in the U.S. steel minimill firms and observed the informal know-how trading among them.

publication does not measure collaborative research that was not successful, since the published article is usually a result of successful research. Thirdly, co-publication does not allow the investigation of micro-level qualitative aspects of collaborative research, although it is possible to infer the intensity of a collaborative research network by counting the number of co-publications from a given pair of scientists. It is, for example, difficult to see the process of collaborative research and the contribution of each collaborator. Furthermore, Katz and Martin maintained that the definition of “collaborative research” is not perfectly definable because collaborative research can be conducted at several levels (e.g., individual, research group, institutional, and country).²²

Despite these limitations, co-publication data has been the most widely used method to analyse collaborative research. It provides systematic and consistent data, and it is less expensive than interviews or questionnaires. To examine co-publication, this thesis uses the *Journal of Applied Physics* and the *Journal of Applied Physics Letters*, which are widely recognized international journals in applied physics. Since these journals are published by an American academic society, U.S.S.R. researchers did not publish their studies in these journals for political reasons. Therefore, it should be noted that these journals do not provide any data about collaborative research in the U.S.S.R. Table 3-2 shows the number of articles and co-publications on the semiconductor laser in the *Journal of Applied Physics* and the *Journal of Applied Physics Letters* over the period 1962-1985.

²² Katz and Martin pointed out the problem of the definition. Katz and Martin, "What is Research Collaboration?", pp.11-13.

Table 3-2: Number of Articles and Co-Publications 1962-1985

	JAP	JAPL
Total Number of Articles on Semiconductor Laser	356	761
Number of Co-Publications	280	691
Number of Single Author Publications	76	70
Number of Intra-Organisational Co-publications	241	602
Number of Inter-Organisational Co-Publications ²³	39	89

Source: *Journal of Applied Physics*, 1962-1985. *Journal of Applied Physics Letters*, 1962-1985.

This table reveals that the most of the articles were co-publications. From 1962 to 1985, 356 papers in the *Journal of Applied Physics* and 761 papers in the *Journal of Applied Physics Letters* were about semiconductor laser technology. Seventy-nine percent of all semiconductor laser papers (i.e., 280 papers) were co-publications in the *Journal of Applied Physics*. The *Journal of Applied Physics Letters* had a higher percentage of co-publications (91 percent). These figures suggest that co-publication was dominant in semiconductor laser research.

Collaborative research, however, was limited to the scientists and engineers who belonged to the same institution. Katz and Martin maintained that many different levels of collaboration exist.²⁴ They introduced *inter* and *intra* distinctions of collaboration. This thesis focuses on inter-organisational collaboration. The last two rows in Table 3-1 indicate both intra- and inter-organisational co-publications in the *Journal of Applied Physics* and the *Journal of Applied Physics Letters*. From 1962 to 1985, 39 inter-organisational co-publications (11 percent) appeared in the *Journal of Applied Physics*, and 89 (12 percent) were published in the *Journal of Applied Physics Letters*.

Table 3-3 shows the number of organisations involved in inter-

²³ A research consortium was launched in Japan in 1979. The consortium published 2 articles in the *Journal of Applied Physics Letters* in 1984 and in 1985. Since they were published under the name of the consortium, this chapter does not count them as inter-organisational co-publications. The consortium will be closely examined in the next chapter.

²⁴ Katz and Martin, "What is Research Collaboration?", pp.5-8.

organisational collaborative research and the number of inter-organisational co-publications. It counts the number of inter-organisational co-publication on semiconductor laser technology published in *Journal of Applied Physics* and *Journal of Applied Physics Letters* from 1962-1985.

Table 3-3: Number of Organisations and Inter-Organisational Co-Publications 1962-1985²⁵

	JAP	JAPL
The U.S.		
Number of Organisations Involved in Inter-Organisational Co-Publications	16	23
Number of Inter-Organisational Co-Publications	32	70
Japan		
Number of Organisations Involved in Inter-Organisational Co-Publications	2	14
Number of Inter-Organisational Co-Publications	2	8
Europe		
Number of Organisations Involved in Inter-Organisational Co-Publications	8	17
Number of Inter-Organisational Co-Publications	5	14

Source: *Journal of Applied Physics*, 1962-1985. *Journal of Applied Physics Letters*, 1962-1985.

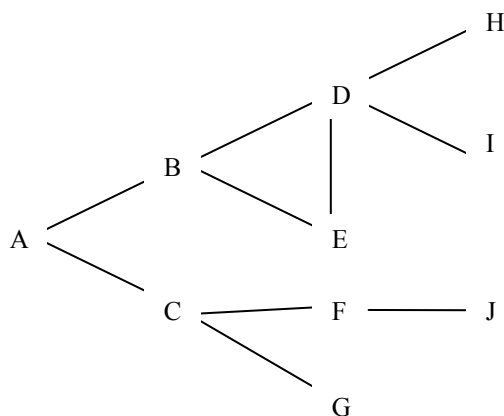
The first row for each region indicates the number of institutions involved in inter-organisational co-publication. The second row signifies the number of inter-organisational co-publications in the journals from 1962 to 1985. These figures reveal that the U.S. institutions dominated inter-organisational collaborative research in both journals.

There are two different types of collaborative connections in the inter-organisational collaboration network; direct collaborative connection and indirect connection, which can provide participating organisations with different types of

²⁵ Because some of the inter-organisational co-publications in the JAPL were inter-regional, they are counted in each region. Therefore, the total number of inter-organisational co-publications in the JAPL does not match with Table 3-2.

benefits.²⁶ The direct connection refers to the number of direct linkages maintained by an organisation. Organisations can share the R&D facility and avoid excessive investment through direct collaboration. Direct connections can also provide knowledge spillovers. The indirect connection is the number of organisations that a given organisation can indirectly reach in the network through its partners and their partners. The indirect connection of the network can provide informal access to complementary knowledge and information leakage, while it cannot provide formal resource-sharing benefits.²⁷ Figure 3-3 illustrates an example of the inter-organisational network. Organisation A has two direct connections with organisations B and C on the one hand. It has seven indirect connections with organisation D, E, F, G, H, I, and J on the other hand.

Figure 3-4: Direct and Indirect Connections



Figures 3-4, 5, and 6 illustrate collaborative networks in the U.S., Japan, and Europe.²⁸ Calculating from all inter-organisational co-authored papers on

²⁶ Gautam nicely reviews direct ties and indirect ties of the network. Gautam, "Collaboration Networks, Structural Holes, and Innovation: A Longitudinal Study."

²⁷ Noting that strong social relationships would not supply much diversified knowledge, Granovetter argued that the weak ties would enable the reaching of knowledge that was not accessible via strong ties. Granovetter, "The Strength of Weak Ties."

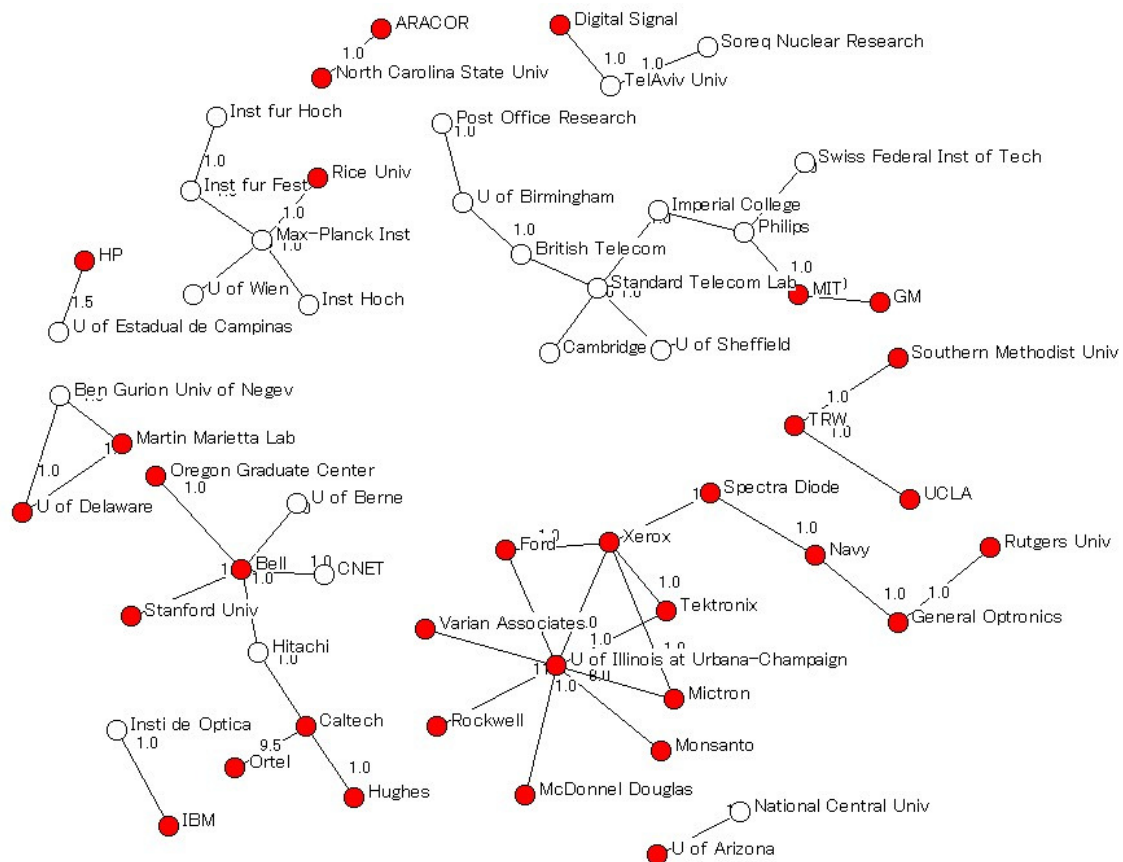
²⁸ These figures were processed with a network analysis software, UCINET. Borgatti, Everett, and Freeman, *UCINET 6.0 Version 1.00*. Appendix II lists all the institutions involved in inter-organisational co-publication. It also indicates the number of

semiconductor laser technology published in the *Journal of Applied Physics* and the *Journal of Applied Physics Letters* from 1965 to 1985, these figures plot the organisations that were involved in inter-organisational collaborative research. Organisations involved in the collaborative research are connected with their partners. These figures visualize both the direct connections and the indirect connections of the social networks in those regions, which allow one to see the actual collaborative networks. The coloured circles denote the organisations in the region titled in the figure. The colourless circles denote the organisations in other regions. The number indicated on the connection signifies the number of inter-organisational co-publications that the organisations published in the *Journal of Applied Physics* and the *Journal of Applied Physics Letters* from 1965 to 1985. A greater number of the circles indicate that the inter-organisational collaborative network was widely developed. If the network was smaller in scope but denser, we observe the smaller number of the circle and the greater number of the lines connecting to the circles.

Figure 3-5: The U.S. Collaborative Organisational Networks

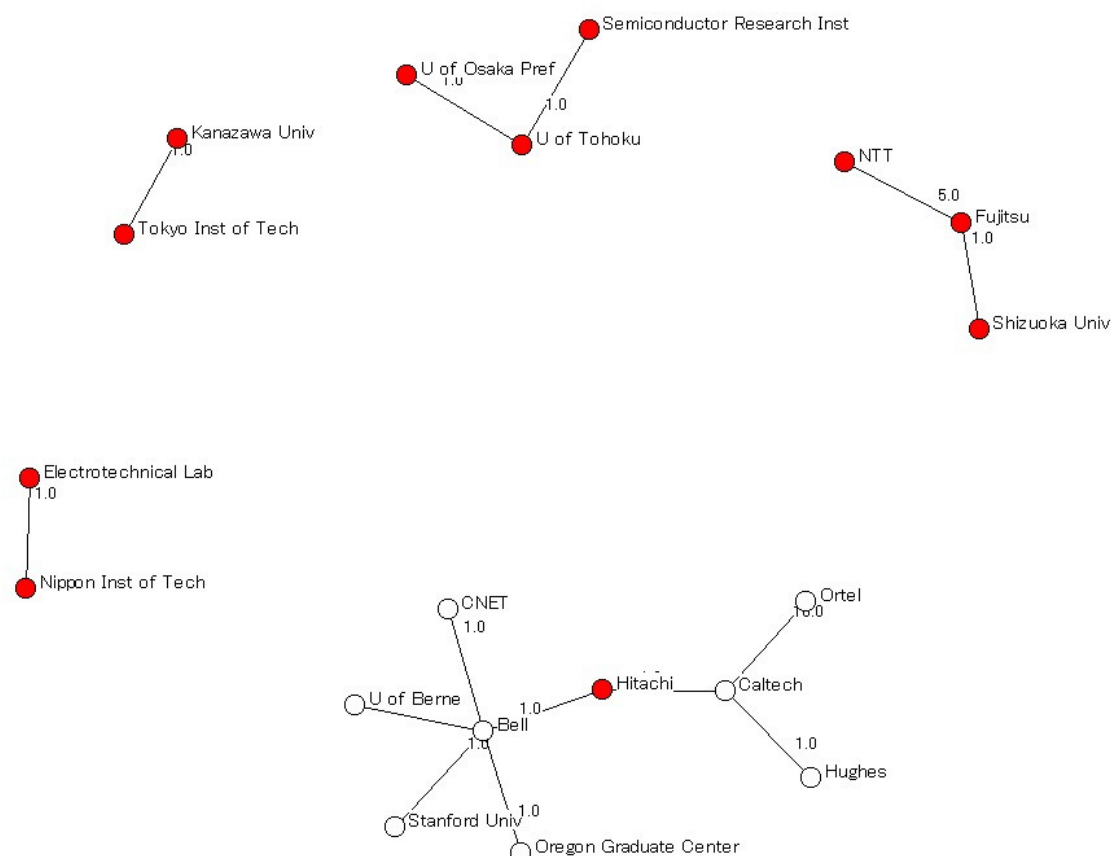
interorganisational-co-publications that each institution published in the journals.

3. Human Capital and Research Networks



Source: *Journal of Applied Physics*, 1965-1985 and *Journal of Applied Physics Letters*, 1965-1985. Borgatti, Everett, and Freeman, *UCINET 6.0 Version 1.00*.

This figure demonstrates the collaborative research network of the U.S. organisations. The University of Illinois Urbana-Champaign was an important hub connecting the organisations. Both Bell laboratories and Xerox were also a hub connecting the research organisations. No such research institution existed either in Japan or in Europe. The U.S. organisations developed thicker and wider networks, compared to those of Japan and Europe (Figures 3-5 and 3-6).

Figure 3-6: Japanese Collaborative Organisational Networks

Source: *Journal of Applied Physics*, 1965-1985 and *Journal of Applied Physics Letters*, 1965-1985. Borgatti, Everett, and Freeman, *UCINET 6.0 Version 1.00*.

Figure 3-5 shows that the collaborative networks in Japan were much more scattered than those of the U.S. were.²⁹ The number of organisations and the number of the lines linking organisations together were smaller than those of the U.S. were. Furthermore, all of the connections were one-to-one institutional relationships, and most of the networks were domestic.³⁰ Hitachi was the only institution that

²⁹ It should be noted that one informal research workshop about the semiconductor compound was organized by a few physicists. This workshop, called “Shimoda Workshop,” was annually held a few days each winter, beginning in the early 1980s. Approximately 50 young engineers from different rival firms and different universities came to this workshop to discuss technology. Interviewee D, E, and G. On the interviewees, see Appendix III.

³⁰ Examining international and intranational knowledge spillover in the U.S. and Japan, Branstetter found strong evidence of intranational knowledge spillovers in both the U.S. and Japan. The evidence that Japanese firms benefit positively from research undertaken by U.S.

Table 3-4 summarizes the inter-organisational collaborative networks. The first and second rows show the scale of the research network. The large number of inter-organisational co-publications suggests that much technological knowledge was developed in the networks. Both the number of co-publications and the number of institutions reflect the scale of the research networks. The number of links denotes the lines connecting the institutions. The large number of links indicates that the network was densely and widely developed.

Table 3-4: Scale and Scope of Research Networks

	The U.S.	Japan	Europe
Number of Inter-Organisational Co-Publications	199	18	34
Number of Institutions	56	19	34
Number of Links	49	14	28

Source: *Journal of Applied Physics*, 1965-1985 and *Journal of Applied Physics Letters*, 1965-1985.

This table indicates that the collaborative research networks of the U.S. organisations were more intense and wider in scope. The U.S. organisations were involved in inter-organisational collaborative research more than Japanese and European firms were.

This evidence reveals one important point:

- **[3-3]** The formal inter-organisational collaboration in semiconductor laser technology was more developed in the U.S. than in Japan and Europe.

Why was inter-organisational collaboration in semiconductor laser technology more developed in the U.S. than in Japan and Europe? One of the central motivations behind inter-organisational collaboration is to gain complementary knowledge. As a firm grows complementary knowledge in its R&D divisions, it gets less motivation to conduct inter-organisational collaboration. Given that, the difference in the inter-organisational collaboration between the U.S., Japan, and

Europe might be attributed to differences in the resource allocation of the firms in those regions. If Japanese firms tended to internalise complementary technological knowledge more than the U.S. and European firms did, Japanese firms would have less incentive to conduct inter-organisational collaboration than did the U.S. and European firms. Since there has been no empirical study discussing it, this question still needs more detailed empirical examination. It might be attributed to socio-cultural factors such as research community ethos. It might be attributed to the career and incentive structure of corporate engineers and university scientists. The central point of this section is, however, that inter-organisational collaboration, an important route to access outside complementary knowledge, was not used much in Japan compared to the U.S. and Europe.

3.4. Conclusion

This chapter examines human capital accumulation and research networks in the U.S., Japan, and Europe. First, it shows that physicists began semiconductor laser research in the 1950s, but not until the 1970s did physicists regularly publish their research in academic journals. Second, the U.S. and the U.S.S.R. were the two leading countries in human capital accumulation in semiconductor laser technology. While the number of doctoral degrees began increasing in the mid-1970s in Japan, the total number was still behind these two countries. Third, this chapter examines the collaborative research networks in the U.S., Japan, and Europe. The fact that the majority of papers published in the *Journal of Applied Physics* and the *Journal of Applied Physics Letters* were co-publications suggests that technological knowledge about the semiconductor laser was developed mainly through teamwork among physicists. And the fact that the inter-organisational co-publication in these journals was quite limited suggests that interaction among the physicists was mainly limited to intra-institutional collaboration. Finally, the chapter examines the collaborative networks in the U.S., Japan, and Europe. Even though it must be noted that the co-authored papers allows us to examine only the formal inter-organisational collaborative research, it reveals that networks in Japan were smaller and more dispersed in scale and scope than those in the U.S. and Europe. These findings are summarized as follows.

- [3-1] The U.S. and the U.S.S.R. were the two leading countries in human capital accumulation in semiconductor laser technology.
- [3-2] Although Japan accelerated its human capital accumulation from the 1970s, it was not the leading country in human capital accumulation in semiconductor laser technology.
- [3-3] The formal inter-organisational collaboration in semiconductor laser technology was more developed in the U.S. than in Japan and Europe.

These findings indicate that the U.S. firms were in a better position to access outside complementary knowledge. It casts doubt on the argument that Japan had a better research community than its counterparts, while the human capital accumulation in semiconductor laser technology in Japan began rapidly increasing in the mid-1970s. These findings also suggest that Japan attained technological development in semiconductor lasers and gained significant market share in the semiconductor laser and its application areas from the beginning of the 1980s in spite of the fact that the human capital accumulation and research networks in semiconductor lasers were not specially advanced in Japan compared to those in the U.S. and Europe. The fifth chapter, *Competition, Knowledge Spillover, and Innovation*, will revisit these points to discuss patterns of knowledge spillover in the U.S. and Japan. It will analyse how the less developed research network was one of the important institutional conduits leading firms to compete in the same product markets.

4. Semiconductor Laser Research Consortium: the OMCS Project

As shown in the previous chapters, the U.S., European, and Japanese firms began basic R&D in semiconductor lasers from the 1960s. However, the firms' R&D was still at a nascent level in the 1970s.¹ In this context, the Japanese government launched a research consortium in 1979, which aimed to develop the basic technologies for semiconductor lasers. Examining various optoelectronics technological areas such as optical fibre, optical storage, and optical sensors, the JTEC report put an emphasis on the fact that the government-launched joint research consortium of 1979, Optical Measurement and Control System (OMCS), had played an important role in spurring the technological and industrial development of the semiconductor laser.² It, however, did not clearly explain how the research consortium contributed to the competitiveness of Japan's semiconductor laser technology.

A consortium is an organised form of collective action, which brings together multiple organisations (e.g., firms, universities, and government research institutions) under one organisational umbrella, and the participants conduct cooperative R&D. A central challenge of research consortia is the promotion of inter-organisational learning for the benefit of all participants. Whereas the previous research has listed such advantages of cooperative R&D as cost- and risk-sharing,³ this chapter pays attention to technological spillover and competition enhancement.

¹ Examining the commercialising process of nascent technology, Wood and Brown divided the process into three stages: appropriation, implementation, and manufacture. The R&D in semiconductor lasers was categorized as being in the first stage, which involves monitoring, assessing, and capturing new technologies. On the phases of R&D, see Wood and Brown, "Commercializing Nascent Technology: The Case of Laser Diodes at Sony."

² Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, pp.xviii-xix.

³ For example, Katz et al., "R and D Cooperation and Competition"; Odagiri, Nakamura, and Shibuya, "Research Consortia as a Vehicle for Basic Research: The Case of a Fifth Generation Computer Project in Japan."

It focuses on the fact that the participating firms were rivals in the product market and addresses the following points:

- **[4-1]** The participating firms underinvested in R&D of the consortium because they were rivals in the product market. As a result, no important technology was produced in the consortium.
- **[4-2]** The fact that direct rivals were participating in the consortium became the institutional conduit for competition and stimulated competition in certain technological areas.

4.1 Previous Research and Approach

Research Consortia

Since the late 1960s, governments of developed countries have adopted joint research projects.⁴ The best-known cooperative R&D project in Japan is the VLSI (Very Large Scale Integrated circuit) project, which was launched in 1975 to help Japanese firms compete with their rivals. Another example is the SEMATECH (Semiconductor Manufacturing Technology), which imitated the VLSI project and was established in the U.S. in 1988.⁵

Analysing research consortia since the 1970s, economists have indicated that the R&D incentive of a firm and the public R&D incentive tend to be divergent.⁶ In other words, the private R&D of a firm in the market economy is not likely to achieve a socially desirable level of R&D. Arrow contended that technological knowledge, which is the main output of R&D, can be non-exclusively used by others.⁷ Expanding on Arrow's argument, Spence asserted that non-excludability produced market failure in corporate R&D.⁸ If a single firm undertakes

⁴ Aldrich and Sasaki have done a comparative study of research consortia in the U.S. and Japan. Aldrich and Sasaki, "R&D Consortia in the United States and Japan." Ham, Linden, and Appleyard also examined research consortia in the U.S. and Japan in semiconductor technology. Ham, Linden, and Appleyard, "The Evolving Role of Semiconductor Consortia in the United States and Japan."

⁵ On the VLSI project see, Sakakibara, "Soshiki to Inobēshon: Jirei Kenkyū Chō LSI Gijutsu Kenkyū Kumiai (Organisation and Innovation: Case Study, VLSI Consortium)." On the SEMATECH project, see Grindley, Mowery, and Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of High-Technology Consortia." Yamamura examined the differences in Antitrust law and discussed how the differences affected joint research projects in the U.S. and Japan. Yamamura, "Joint Research and Antitrust: Japanese vs. American Strategies."

⁶ Katz reviewed the sources of the divergence: technological spillover, access to complementary technologies and products, government policies, and ability to sell R&D results. Katz et al., "R and D Cooperation and Competition", pp.138-139.

⁷ Arrow also emphasised that knowledge is characterised by a greater degree of uncertainty, indivisibility, and asymmetry than other types of economic goods. On non-excludability and externality of technological information, see Arrow, "Economic Welfare and the Allocation of Resources for Invention."

⁸ On market failure in R&D, see Spence, "Cost Reduction, Competition, and Industry Performance."

R&D and if technological information produced by the R&D is distributed to other firms, resources necessary for the R&D will be socially utilized. However, the firm does not have a strong incentive to become involved in the R&D because of the non-excludability of technological information. The R&D incentive of a firm depends on the extent of appropriability of R&D benefits and business opportunity. It is difficult for a firm to garner all the profit from the R&D results. Therefore, the benefits available to the innovator are usually smaller than the social benefits from R&D.⁹ Since the appropriability of innovation is not always perfect to a firm, it has an incentive to lower the level of R&D investment. As a result, a socially desirable level of R&D is not realised.

By contrast, a separate line of research has indicated that private R&D investments may be excessive, beyond the socially desirable level of R&D investments. Dasgupta and Stiglitz contended that when multiple firms undertake R&D in the same technological area, the first successful firm is likely to take most of the profit from R&D.¹⁰ If rival firms increase their level of R&D investments, the possibility that other firms will win the R&D race diminishes. Therefore, firms have an incentive to rush to increase their level of R&D investments. R&D competition then becomes socially redundant and involves excessive investment.

Although their arguments differ, economists seem to agree that private R&D competition leads to market failure. Thus, some contend that a research consortium may offer a solution. If firms can share R&D costs through a research consortium and if they can secure appropriability of technology in the consortium, the desirable level of R&D investment can be achieved. A research consortium can also solve redundant excessive investment in the same technological areas. This argument offers justification for governments to launch research consortia. Previous

⁹ For example, Bernstein and Nadiri empirically examined the divergence between the social returns and the returns that the firm could gain from R&D. They showed that the social benefits were greater than the private benefits. Bernstein and Nadiri, "Interindustry R&D Spillovers, Rates of Return, Andproduction in High-Tech Industries." Katz summarized four different sources of divergence between private and social incentives to conduct R&D. Katz et al., "R and D Cooperation and Competition", pp.138-139.

¹⁰ This phenomenon is sometimes called diseconomies of common pool. See Dasgupta and Stiglitz, "Industrial Structure and the Nature of Innovative Activity."

research maintained that a research consortium could allow sharing fixed costs of R&D, realize economies of scale in R&D, secure appropriability of technology, and help attain a socially desirable level of R&D.

Katz, however, developed a counterargument against this viewpoint.¹¹ Indicating that a research consortium does not necessarily solve market failures, he discussed that the portfolio of participating firms plays an important role in the performance of joint research. When the level of product market competition among participating firms is intense and when the level of spillover potential in a research consortium is low, firms underinvest in the consortium.

Using Katz's arguments as a basis, Branstetter and Sakakibara examined large-sample Japanese government-sponsored research consortia and came to two conclusions: (1) higher potential spillover produced a higher level of R&D productivity; (2) a higher level of competition in the product market among the participants decreased the research productivity of the research consortium and the participants.¹² They also concluded that government sponsorship in Japan generally increased the R&D productivity of the participating firms because of the high level of spillover potential and the low level of product market competition. With this study, Branstetter and Sakakibara provided an important ground sketch of the research consortia in Japan. Unfortunately, however, since their data covers only the consortia launched from 1980 to 1990, the OMCS project launched in 1977 was not included in their study.

The OMCS project had two unique characteristics that research consortia examined by Branstetter and Sakakibara did not have. The first involved the characteristics of the participating firms. Branstetter and Sakakibara pointed out that in selecting participants for the consortia, MITI has generally sought to bring together firms with complementary research assets since the early 1980s. In other words, beginning in the early 1980s, MITI has avoided selecting rival firms whose

¹¹ Katz, "An Analysis of Cooperative Research and Development"; Katz et al., "R and D Cooperation and Competition."

¹² Branstetter and Sakakibara, "When Do Research Consortia Work Well and Why? Evidence from Japanese Panel Data", p.157.

research assets are substitutive. However, in selecting participants for the OMCS project, MITI selected direct rivals in the product market. The second characteristic involved the organisational structure of the research consortium. The OMCS project was the first consortium to have a joint laboratory in which participating firms worked together.¹³ Since a central challenge of research consortia is the promotion of inter-organisational learning from which participants can benefit, this organisational structure designed to promote interaction among the participating engineers was important.

Approach

The previous research about the OMCS has been limited. The only detailed studies of the OMCS project were conducted by Merz and İzuka.¹⁴ Since both Merz and İzuka were the OMCS participating engineers, their studies provided important and valuable insights on the OMCS. However, no attempt has been made to examine the OMCS from the standpoint of economics.

The approach for analysing the research consortium basically follows Katz, Branstetter, and Sakakibara: it focuses on the level of product market competition among participating firms and the level of spillover potential in a research consortium. It also follows the basic framework to analyse the collective action along the lines developed by Mancur Olson. Focusing on the logical basis of organized collective action, Olson provided a theoretical framework to analyse collective action.¹⁵ Since a research consortium, in which participants pursue the same R&D goal in a certain period, is certainly collective action, it takes his

¹³ The VLSI project also had a joint laboratory in which the participating firms worked. However, no research team existed in which the engineers from the different participating firms worked together in the VLSI project. Wakasugi and Gotō, "Kyōdō Kenkyū Kaihatsu to Gijutsu Kakushin (Collaborative R&D and Technological Innovation)."

¹⁴ Merz, "The Optoelectronics Joint Research Laboratory: Light Shed on Cooperative Research in Japan"; İzuka, "Erekutoronikusu Bunya ni Okeru Dōgyōshakan no Kyōdō Kenkyū Kaihatsu (Joint Research Project among Competing Firms in the Electronics Area)."

¹⁵ Olson, *The Logic of Collective Action; Public Goods and the Theory of Groups*; Olson, *The Rise and Decline of Nations: Economic Growth, Stagflation, and Social Rigidities*.

perspective on collective action to study the OMCS project.

First, it describes the foundation and structure of the OMCS project in order to examine the level of spillover potential. Then, using patent and patent citation data, this thesis examines the extent to which the consortium produced important technological innovation.¹⁶ Because of the lack of a patent citation database in the Japan Patent Office, no studies use patent citation data to analyse technological change in Japan. Research about research consortia in Japan has simply used the number of patent applications as an indicator of R&D output.¹⁷ This study is the first attempt to use patent citation to examine research consortium and technological change in Japan. It uses the Derwent Innovations Index, a database of citations appearing in patents from six major patenting authorities. This thesis also uses interview data to show how the OMCS project was organised and operated, how participating engineers were engaged the joint research, and how this joint project affected the participating firms' in-house R&D.

¹⁶ Regarding to the advantages and the disadvantages of using patent as a measurement of technological change, see *How to Measure Technological Innovation* in the first chapter, *Introduction*.

¹⁷ For example, Branstetter and Sakakibara, "Japanese Research Consortia: A Microeconomic Analysis of Industrial Policy"; Branstetter and Sakakibara, "When Do Research Consortia Work Well and Why? Evidence from Japanese Panel Data."

4.2 Optoelectronics Measurement and Control System Project

OMCS Research Theme

The 1949 Foreign Exchange Law protected the Japanese economy against direct investment from overseas. In the early 1960s, the U.S and some European governments demanded that the Japanese government push economic liberalisation. In 1962, the International Monetary Fund asked the Japanese government to accept Article 8 of the IMF.¹⁸ It was projected that this economic liberalisation would have a major impact on Japanese firms. When economic liberalisation was introduced, foreign capital would begin buying Japanese firms without permission from MITI. Both the government and the industries faced serious issues regarding how to gain competitiveness under these new conditions.

The government and the industries realised that the R&D capability of technology-intensive industries was not strong enough to compete against international players. It was necessary (1) to catch up with the technological level of the western nations and (2) to develop domestic technologies that could compete against international players and contribute to long-term economic growth. Thus, in 1966, MITI initiated the Industrial Technology Research and Development Project, which was a government-sponsored joint research schema called the “Large Scale Project.” This project aimed to launch research consortia that would promote new and innovative industrial technological development contributing to the growth of national economy and social welfare.

With the assistance of corporate engineers, Sakurai Kenjirō and Shimada Junichi, MITI’s officials, planned to launch a Large Scale Project consortium in the optoelectronics area in 1977.¹⁹ The plan was for this research consortium to develop

¹⁸ Article 8 of the IMF pledges: (1) avoidance of restrictions on current payments, (2) avoidance of discriminatory currency practices, (3) convertibility of foreign-held balances, (4) furnishing of information, (5) consultation between members regarding existing international agreements, and (6) obligation to collaborate regarding policies on reserve assets.

¹⁹ The description of the research consortium in this thesis relies on Mitsubishi Sōgō

a semiconductor laser, which was regarded as a new technology that would be competitive against international players.

The main objective of the consortium was to develop an optoelectronics measurement and control system that could be used in a large manufacturing facility. The project leader, Shimada Junichi, coined a new technological concept, the Opto Electronic Integrated Circuit (OEIC), and set it as the core R&D target.²⁰ Since the semiconductor laser was regarded as a key device for the OEIC, semiconductor laser technologies became an important and practical R&D target for the consortium.

Participation and Budget

MITI officials named the consortium “Optical Measurement and Control System (OMCS)” and appropriated 18 billion Japanese yen in 2005 value (15.7 billion Japanese yen in 1986 value) for this project.²¹ Because of the variety of consortia in various areas, the budgets varied. However, the budget of the OMCS project was slightly larger than the average budget of Large Scale Projects (Table 4-1).

Kenkyūjo, (Mitsubishi Research Institute), *Hikari Kankei Kenkyū Kaihatsu Purojekuto no Gijutsu Sangyō Shakai eno Inpakuto ni kansuru Chōsa*, (Report on the Impact of Optoelectronics Research Consortia on Technology, Industry, and Society); Merz, "The Optoelectronics Joint Research Laboratory: Light Shed on Cooperative Research in Japan"; Shimada, "Ai to Kanashimi no Hikari Ōpuro, Purojekuto Rīdā no Memo Yori, (Optoelectronics Large Project - Project Leader's Memo)."

²⁰ Shimada, "Ai to Kanashimi no Hikari Ōpuro, Purojekuto Rīdā no Memo Yori, (Optoelectronics Large Project - Project Leader's Memo)", p.5.

²¹ Mitsubishi Sōgō Kenkyūjo, (Mitsubishi Research Institute), *Hikari Kankei Kenkyū Kaihatsu Purojekuto no Gijutsu Sangyō Shakai eno Inpakuto ni kansuru Chōsa*, (Report on the Impact of Optoelectronics Research Consortia on Technology, Industry, and Society), p.11.

Table 4-1: OMCS and Other Large Scale Projects 1962-1992

	Real R&D Expense (Million Yen)	Project Term (Year)	Number of Participating Firms	Annual R&D Expense per Participant (Million Yen)
OMCS	18.730	7	14	191.224
Sample	30			
Average	17.128	8.167	18.6	112
Median	14.188	8	15	118

Source: Kawatetsu Tekuno Risāchi, (Kawatetsu Technology Research). “Kokka Purojekuto no Unei/ Kanri Jōkyō Bunseki Chōsa Hōkokusho II, (Evaluation Report on Operation and Management of National Projects).” The R&D expenses indicate real R&D expenses in 2005 Japanese yen value. Appendix IV includes this table converted into 2005 U.S. dollar value.

When MITI planned the consortium, nine Japanese electronics firms (NEC, Fujitsu, Hitachi, Toshiba, Mitsubishi Electric, Matsushita Electric Industries, Sony, Sharp, and Sanyo) had already been involved in R&D in semiconductor laser since the late 1960s. However, none of them had yet developed a commercialised semiconductor laser. The firms’ R&D in semiconductor laser was still on the nascent “precompetitive” stage.

Since this project focused on the semiconductor laser, first, MITI selected five leading firms in semiconductor laser: NEC, Fujitsu, Mitsubishi Electric, Toshiba, and Hitachi.²² Matsushita Electric Industries was also selected as a participant. Then MITI selected nine other participating firms that planned to develop semiconductor-related technologies, such as a fibre and information system. Although Sony, Sanyo, and Sharp had begun R&D in semiconductor lasers, they were not selected because they had researched only the short-wavelength semiconductor laser. The five leading firms and Matsushita Electric Industries were researching both the short-wavelength and the long-wavelength semiconductor laser. Table 4-2 lists the participating

²² When the consortium was launched, MITI consulted with these firms about the consortium and made participation overtures. Regarding how MITI started this project, see Ibid.

institutions of the OMCS project.

Table 4-2: Participating Firms

Five Main Participating Firms	
Fujitsu	Major maker of telecommunication and information equipments
Hitachi	Leading general electric machinery maker
Mitsubishi Electric	Third largest integrated electric machinery company
NEC	Major manufacturer of telecommunications and electronic machines
Toshiba	Second largest general electric machinery maker
Other Participating Firms and Research Institution	
Fuji Electrics	Specializes in generator, transformers and magnet switches
Fujikura	Fourth largest manufacturer of electric wires and cables
Furukawa Electric	Non-ferrous metal processor with top stress on electric cables and wires
Matsushita Electric	Largest electric appliance enterprise
Nippon Sheet Glass	Second largest sheet glass manufacturer
Shimadzu	Top maker of scientific equipment and related industrial machines
Sumitomo Electric Industries	Largest maker of electric wires and cables
Oki Electric Industries	Telecommunication and electronics manufacturer
Yokogawa Electric	Top manufacturer of industrial measuring instruments
Electrotechnical Laboratory	MITI's research institution

Source: Tōyō Keizai Shinpōsha. *Japan Company Handbook*.

Much of the previous literature has discussed firms' motivations for participation in joint research.²³ The evaluation report on the consortium pointed out

²³ Odagiri, Nakamura, and Shibuya summarised the previous literature discussing the motivations to participate in joint research and grouped them into five points: cartelisation factor, spillover factor, complementarity factor, subsidization factor, and national commitment factor. Odagiri, Nakamura, and Shibuya, "Research Consortia as a Vehicle for

that the participating firms had different motivations.²⁴ For example, some firms sought a better connection with MITI by participating in this project. Some firms that had not begun R&D in semiconductor lasers planned to develop their optoelectronics business by participating in the consortium and learning skills and capabilities in semiconductor laser technology from other participants.²⁵

Research funding was an important factor as well.²⁶ Because the Japanese government planned to liberalise its economy in the 1960s, it was necessary for the firms to become competitive against international big players before economic liberalization occurred. Many technology-intensive firms established central R&D laboratories in the 1960s, in an effort to develop advanced research and to enhance basic R&D capability, which was regarded as a weakness of Japanese firms. In the context of the high economic growth of the 1960s, a “central R&D laboratory boom” occurred. The participating firms of the OMSC project had established their central R&D laboratories in the late 1950s. But after the Bretton Woods cancellation by the U.S. and the oil crisis, the Japanese economy stagnated in the 1970s. Under the recession, it became difficult for the firms to continue allocating sufficient money to basic research, which had inherently high uncertainty. Therefore, it was important to obtain subsidization from the government by participating in a joint research project. MITI recognized the situation that the firms were facing. The evaluation report indicated that it was also important to provide financial support to the participating firms so that they could invest in an R&D facility when they

Basic Research: The Case of a Fifth Generation Computer Project in Japan", pp.192-193.

²⁴ Mitsubishi Sōgō Kenkyūjo, (Mitsubishi Research Institute), *Hikari Kankei Kenkyū Kaihatsu Purojekuto no Gijutsu Sangyō Shakai eno Inpakuto ni kansuru Chōsa*, (*Report on the Impact of Optoelectronics Research Consortia on Technology, Industry, and Society*).

²⁵ Examining motives for participating in cooperative R&D, Sakakibara discussed that the skill-sharing motive could be competition enhancing, while cost-sharing R&D cooperation could be competition suppressing in terms of their roles in R&D competition. Sakakibara, "Heterogeneity of Firm Capabilities and Cooperative Research and Development: an Empirical Examination of Motives."

²⁶ Odagiri et al. called it subsidization. Odagiri, Nakamura, and Shibuya, "Research Consortia as a Vehicle for Basic Research: The Case of a Fifth Generation Computer Project in Japan", p.193.

confronted difficulty in investing in basic and uncertain R&D.²⁷ Compared with the private R&D investment of the participating firms, the research fund provided by the consortium was quite substantial. As shown in Table 4-1, the annual R&D expense per participant firm was 191 million yen in 2005 value.

Surveying the optoelectronics industry of Japan, the OITDA reported the amount of R&D investment and the number of the firms in semiconductor lasers. First, the survey reported that twenty firms manufactured semiconductor lasers in Japan in 1990.²⁸ According to the OITDA's survey, only one firm reported R&D investment in semiconductor lasers over 200 million yen (Table 4-3).²⁹

Table 4-3: R&D Investment and Number of Firms in 1990

R&D Investment	Number of Firms
10 million – 50 million	6
50 million – 100 million	4
100 million – 500 million	7
500 million – 1 billion	4
1 billion – 2 billion	1
2 billion – 5 billion	0
5 billion – 10 billion	0
10 billion – 20 billion	1
20 billion – 50 billion	0
Over 50 billion	0

Source: Denpa Shinbun Sha, *Denshi Kōgyō Nenkan (Annual Report on the Electronics Industries)*, 1993, p.629.

Because the survey did not reveal individual respondents, these figures do not

²⁷ Mitsubishi Sōgō Kenkyūjo, (Mitsubishi Research Institute), *Hikari Kankei Kenkyū Kaihatsu Purojekuto no Gijutsu Sangyō Shakai eno Inpakuto ni kansuru Chōsa, (Report on the Impact of Optoelectronics Research Consortia on Technology, Industry, and Society)*, p.v.

²⁸ Denpa Shinbun Sha, *Denshi Kōgyō Nenkan (Annual Report on the Electronics Industries)*, 1993, p.623.

²⁹ Ibid., p.629.

necessarily signify the OMCS participants' R&D investment. However, since all of the participating firms were members of the OITDA, this survey can provide a rough estimation for total R&D investment in semiconductor lasers. Most of the firms' investments ranged from 10 million to 1 billion Japanese yen. The OMCS appropriated 19 million yen in 2005 value for this project. These figures suggest that the research fund for the consortium was significant for the participants, especially when they had difficulty in raising money for their central research laboratory in 1970s.

Research Organisation

This project consisted of two different types of research unit: the individual laboratory and the joint laboratory. The participating firm organised an individual laboratory in its own R&D facility and received research funds for project-related work. Every individual laboratory was assigned a specific R&D target. In the joint laboratory, engineers from different participating firms collaborated and conducted joint R&D. NEC, Hitachi, Toshiba, Mitsubishi Electric, Fujitsu, Matsushita Electric Industries, Oki Electric Industries, Furukawa Electric, and Sumitomo Electric Industries sent several engineers to the joint laboratory to work together in each sub-research group. Since no interaction occurred among the individual laboratories, the joint laboratory was where the actual collaborative research was conducted. The joint laboratory had six sub-research groups. Each group researched basic technologies of the semiconductor laser. Table 4-4 indicates the joint research laboratories, their leaders, and the researchers. Epitaxy technology, which was one of the most important research targets in the OMCS and will be examined in the next chapter, was researched in the number 2 and 3 laboratories.

Table 4-4: Sub Research Groups in Joint Research Laboratory

Research Laboratory Number	1	2	3	4	5	6
Research Theme	Bulk Crystal Growth	FIBI MBE	Epitaxy	Interface Physics	Dry Etching	Material Evaluation
Research Leader	T. Fukuda (Toshiba)	T. Hashimoto (Fujitsu)	M. Ishii (Mitsubishi)	H. Nakajima (Hitachi)	K. Asakawa (ETL)	K. Ishida (NEC)
Number of Researchers						
Fujitsu	1	4				1
Furukawa	1				1	1
Hitachi	1			3		1
Matsushita	2	1	1	2		
Mitsubishi	2		3			1
NEC			2		2	2
Oki			1	2		1
Sumitomo		1	3	1		
Toshiba	3		1			1
Total	10	6	11	8	3	8

The number of researchers shown in this table was in 1985. The parentheses indicate the participating firm that sent the research leader. Source: Merz, "The Optoelectronics Joint Research Laboratory: Light Shed on Cooperative Research in Japan."

This organisational setting was designed to promote interaction among engineers from the different firms. The OMCS project was the first research consortium funded by MITI in which engineers from different firms worked together in the same joint laboratory. Before the OMCS project, the research units in the joint laboratory were usually composed of engineers from the same firms. This organisational setting of the consortium was particularly designed to promote the interaction of technological knowledge among the participating firms. Therefore, the

level of potential spillover was high.

All engineers and administrative staff worked full-time in the consortium. However, all of them also belonged to a participating institution. When the consortium ended, the engineers and administrative staff were expected to return to the firms or the institution that had sent them to the consortium. The OMCS project was planned as an eight-year project, starting in 1979. The term was, however, shortened one year, and the OMCS ended in 1985.

4.3. Underinvestment of the Participating Firms

Focusing on the logical basis of organized collective action, Mancur Olson has provided a theoretical framework to analyse collective action.³⁰ In *the Logic of Collective Action*, Olson argued the participants are motivated to act collectively and to contribute to the group, only when a benefit is strictly reserved for the individual participant. If the benefits are not properly reserved for the group members, the participants will have an incentive to free ride. In other words, he showed that common interest is not enough to motivate the participants to contribute to the group. The free rider problem leads to the non-production or under-production of a collective good. The participants have an incentive to contribute to the group in collective action when (1) benefits outweigh the costs and (2) the participant is provided with selective incentives. A type of selective incentive is a social incentive, which only works in smaller groups. A social incentive is the “desire to win prestige, respect, friends, and ... other psychological objectives.”³¹

According to Olson’s argument, to what extent the participants of consortia in general have a disincentive to corporate and pursue a collective goal depends on its benefits and costs, and the selective incentive. First, the benefits to contribute to the group R&D were not strictly and properly reserved to the participating firms in the OMCS project. The results of the collaborative R&D were published as either patent or academic papers. Since both patents and academic papers were open to the public, non-participants could access these R&D results. Furthermore, the patents under the name of the government could not be used for cross-licensing, even though the participating firms could use them for their business. The U.S. government introduced the Bayh-Dole Act in 1980, which allowed for the transfer of exclusive control over many government funded inventions to universities and businesses operating with federal contracts for the purpose of further development

³⁰ Olson, *The Logic of Collective Action: Public Goods and the Theory of Groups*.

³¹ *Ibid.*, p.61.

and commercialisation.³² The contracting universities and businesses were permitted to exclusively license the invention to other parties. The Bayh-Dole Act was designed to increase appropriability of collaborative R&D and stimulate government-funded collaborative R&D. In other words, it was designed to reserve the benefits of cooperation to the participants. However, there was no institution like the Bayh-Dole Act to stimulate contributions to collaborative research in Japan until 1999. Appropriability of the collaborative R&D for the participating firms was limited to the tacit knowledge that the participating engineers could exclusively acquire from the collaborative research. Therefore, it is possible to conclude that the incentive of the participating firms to contribute to the group R&D was not significant in the consortium due to the low appropriability.

Furthermore, the costs of fully engaging in the consortium were high. Katz indicated that participating firms underinvest in a consortium when they are competing in the product market.³³ If participating firms were competing in the same product market, they would confront the risk that an important confidential R&D result might be leaked out to the rival firms through the collaborative R&D. The main participants dedicated to semiconductor laser R&D in the OMCS were competing in the product market. The way in which MITI selected the participating firms suggests that competition in the product market among the firms was quite high. MITI selected the five leading firms in semiconductor laser technology for the consortium (Hitachi, NEC, Toshiba, Mitsubishi Electric, and Fujitsu). One additional firm, Matsushita Electric Industries, participated in the consortium for semiconductor laser research. When MITI planned OMCS, nine firms had already started R&D in semiconductor laser. Six of those nine firms participated in the consortium. Furthermore, their business background was quite similar. All were competing in various consumer electronics markets. Branstetter and Sakakibara suggested that in selecting participants for consortia formed beginning in the early

³² On the Bayh-Dole act, see Bremer, "University Technology Transfer Evolution and Revolution", pp.20-21.

³³ Katz, "An Analysis of Cooperative Research and Development"; Katz et al., "R and D Cooperation and Competition", p.145.

1980s, MITI generally sought to bring together non-direct rival firms with complementary research assets. However, in selecting the participants for the OMCS project, MITI selected direct rivals in the product market. Table 4-5 describes the participants and their semiconductor laser application products in 1984.

Table 4-5: Semiconductor Laser-Related Product Markets of Participants

	Laser Printer	Video Disc	Rewritable Disc	Compact Disc
Toshiba			●	●
NEC	●		●	●
Hitachi	●	●	●	●
Fujitsu	●			
Matsushita			●	●
Mitsubishi	●			●

Source: Yano Keizai Kenkyūjyo, (Yano Research Institute). *Kakudai Suru Rēzā Sangyō no Shijō Jittai to Kongo no Juyō Tenbō (Survey on Semiconductor Laser Market and Its Prospects)*, p.15

This table suggests that these participants were competing in the semiconductor-related final product market. It must be noted that they were also competing in the semiconductor laser market. The participating firms intended to develop semiconductor lasers not only for their own use, but also for sales to assemblers. The participants, therefore, were competing not only in the final product market but also in the device market.

The evidence suggests that the high level of competition in the product market reduced the level of commitment and produced non-cooperative behaviour on the part of firms. In other words, the participating firms underinvested in the consortium, as Katz predicted they would. First, the evaluation report of the consortium noted that the firms were reluctant to send their star scientists to the consortium.³⁴ Since the star scientists were allocated to undertake important in-

³⁴ Mitsubishi Sōgō Kenkyūjo, (Mitsubishi Research Institute), *Hikari Kankei Kenkyū Kaihatsu Purojekuto no Gijutsu Sangyō Shakai eno Inpakuto ni kansuru Chōsa, (Report on the Impact of Optoelectronics Research Consortia on Technology, Industry, and Society)*,

house R&D, new graduates and non-star scientists were sent to the consortium. The interview results show³⁵,

“We did not send someone who was the ace engineer of the company.” [Interviewee:G]

“The participating firms sent less important engineers to the consortium. They sent engineers who were thought in their firm as less likely to contribute to the profit-making business activity of the firms.” [Interviewee: D]

Second, the participating engineers were usually not allowed to use R&D results and technological data produced in their own R&D departments. They were asked to limit their communication with others to published information such as an academic paper, a presentation at an academic society, or a corporate technical journal. One interviewee suggested,

“It was not easy to manage collaborative research because the rival firms participated in the same research group.” [Interviewee: N]

This non-cooperative behaviour promoted by the high level of competition in the product market vitiated the joint research efforts of the consortium. Patent citation data indicates that no important technology was produced in the consortium. The OMCS project produced 352 patents from 1982 to 1988.³⁶ Through the Derwent Innovations Index, 286 of these patents were identified.³⁷ The most highly cited

pp.80-81.

³⁵ On interviewees, see Appendix III.

³⁶ Nihon Sangyō Gijutsu Shinkō Kyōkai, (Japan Industrial Technology Association), *Kōgyō Gijutsuin Shokan Kokuyū Tokkyō Sō Risuto (the List of Agency of Industrial Science and Technology Holding Patent)*.

³⁷ Approximately 100 patents are not identified in the Derwent Innovations Index because the database coverage is limited in Chemical, Engineering, and Electrical and Electronic

patent had 11 citations by 2005. The average number of citations of the consortium patents was 0.93. Compared to the patents in semiconductor lasers that the participating firms obtained from their private R&D before, during, and after the consortium, the number of OCMS patent citations was disappointing.

Table 4-6: Patent Citation: OMCS and Participating Firms' Private R&D

	Number of Observations	Mean	Median	Standard Deviation	Max
OMCS Patents (1982-1988)	286	0.9021	0	1.4950	11
Patents obtained by Participating Firms's Private R&D					
Before OMCS 1970-1981	316	4.8418	0	9.2805	55
During OMCS 1982-1988	4,633	1.8619	0	5.1745	65
After OMCS 1989-2000	9,090	2.1072	0	5.0856	71

Source: *Derwent Innovations Index*. With the Derwent Innovations Index, this table identifies the patents obtained by the OMCS project and the participating firms' private R&D. Then it examines the number of citation each patent received until 2004.

Assuming that a highly cited patent is an important technology, it seems that no important technological invention was produced in the consortium. Although the organisational setting was designed to facilitate the interaction of technological knowledge, non-consortium research produced more important technologies than the consortium. From Table 4-6, it is possible to conclude the following point.

- **[4-1]** Important technology was not produced in the consortium, compared to the in-house R&D of the participating firms.

areas. It does not cover such areas such as textiles, paper, physics, and performing operations. Because this consortium focused on the development of semiconductor laser, many of the patents are classified in the Electrical and Electronic area. Still, we cannot investigate the citation of some patents with the Derwent Innovations Index.

As the evaluation report pointed out, the fact that the participating firms underinvested in the consortium was one reason for this disappointing result of the OMCS project. Star engineers of the participating firms were conducting private R&D in their firm. The patenting rule of the consortium was another factor that negatively affected the consortium. The participating firms did not have an incentive to patent an important R&D result under the patenting rule of the government-sponsored consortia. MITI sponsored two types of research: contract research and subsidisation research. With contract research, the government provided all necessary funds to the research consortium. The patents from the contract research consortium were assigned not to the participating firms but to the government.³⁸ With subsidisation research, the government provided half of the research funds. The participating firms, however, could be an assignee of the patents resulting from the subsidised research. Since the OMCS project involved contract research, the patents from the consortium were assigned to the government and thus could not be used for cross-licensing. It was necessary for a firm to be a single assignee of a patent in order to use a patent for cross-licensing. The participating firms, therefore, were motivated to patent important R&D results under their own name.³⁹

The previous research about SEMATECH suggests another factor dampening the cooperative R&D in the OMCS project. Grindley, Mowery, and Silverman suggested that one of the factors underlining SEMATECH's success was the source of funding. Half of SEMATECH's budget was federal funding. The other half was from the participating firms. Their analysis has implied that the reduced federal support brought flexibility in consortium management and industry involvement in programme management. They noted, "in order to retain industry involvement in and commitment to SEMATECH, its member firms must retain primary control over

³⁸ As described earlier, no Japanese law was equivalent to the Bayh-Dole Act at that time.

³⁹ Interviewee C said, "Actually, I guess it was not difficult for the participating firms to patent R&D results from the consortium under the name of their own because many of them were doing almost the same R&D at their own R&D laboratory. I do not know to what extent it happened. We did not check it and did not try to do it. Even if we tried, it would not have been possible. Moreover, it was OK for MITI because our primal goal was to promote industrial development. We could not do what firms did not want."

the consortium's research agenda" and "efforts by federal sponsors to tighten control of SEMATECH'S research agenda for agency missions may have a chilling effect on industry contributions of funding and personnel."⁴⁰ As described above, the OMCS project was a government-sponsored consortium. It is, therefore, possible to suppose that the government funding diminished the OMCS participants' commitment to the consortium and induced non-cooperative strategy in the firms in the consortium.

⁴⁰ Grindley, Mowery, and Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of High-Technology Consortia", p.750.

4.4. Competition Enhancement Effect

The findings of this chapter show that important technology was not produced in the consortium compared to the in-house R&D of the participating firms. It must be, however, noted that both the previous literature on consortia and several anecdotal evidences suggest that the OMCS potentially promoted R&D competition among the participants.

Reviewing the various research consortia in Japan, Kodama maintained that the participating companies tended to set up duplicative in-house R&D to absorb the benefits from cooperative R&D in consortia.⁴¹ Assuming that external knowledge is an important source of innovation, Cohen and Levinthal discussed that it was important for firms to have their own R&D to gain absorptive capacity to use external knowledge. R&D not only generates new knowledge but contributes to the firms' absorptive capacity. Since accumulating absorptive capacity in one period helps its more efficient accumulation in the next, it was reasonable for the participating firms to invest in the areas where they undertook the collaborative R&D in the OMCS project. The participating engineer noted,

“The participating firms started the in house R&D project in the same area, if the collaborative research went well or seemed to go well in the area. If the research turned out to be unsuccessful in a certain area, the participating firms tended to stop in house R&D in that area.” [Interviewee: S]

The participating firms eventually tended to conduct in house R&D in the

⁴¹ Kodama, "Direct and Indirect Channels for Transforming Scientific Knowledge into Technical Innovations." Branstetter and Sakakibara, and Sakakibara also suggested that firms tended to increase in-house R&D in the area where they undertook the collaborative R&D. Branstetter and Sakakibara, "Japanese Research Consortia: A Microeconomic Analysis of Industrial Policy", p.215; Sakakibara, "The Diversity of R&D Consortia and Firm Behavior: Evidence from Japanese Data", p.184 and 192.

same technological areas (e.g. epitaxy technology). Since many competing firms in semiconductor laser technology and targeting the same product markets participated in the consortium, this effect was spread to the product markets. It intensified the in-house R&D competition of the participating firms in the areas where the participating firms conducted R&D and their research turned out to be good or seemed to be good. The evaluation report of the research consortia in the optoelectronics industry noted that the research in the consortium on epitaxy technology (MOCVD) promoted the in-house R&D of the participating firms and intensified R&D competition in those areas.⁴²

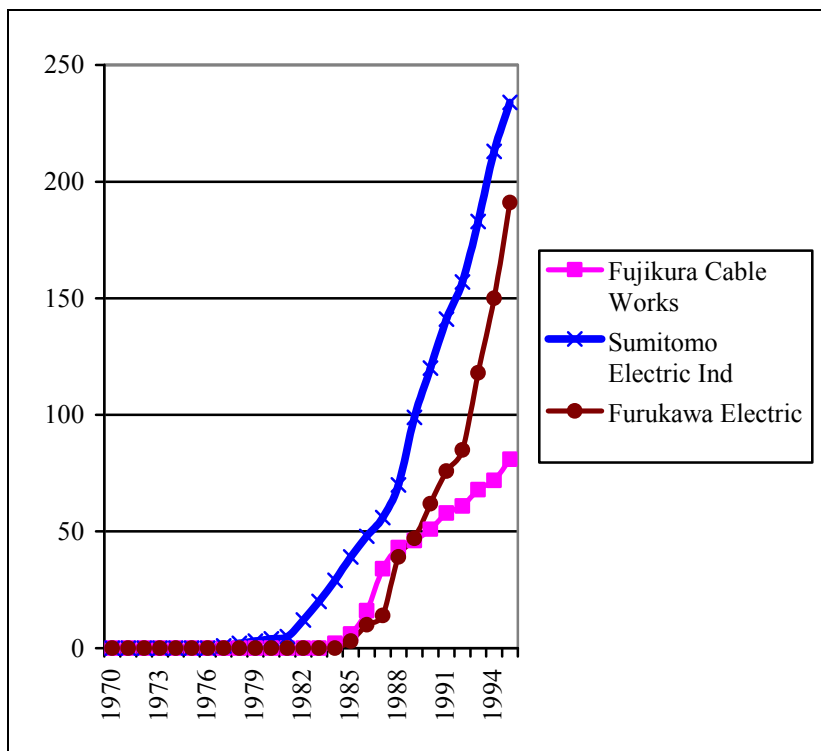
Furthermore, this consortium promoted the new entries to semiconductor laser R&D competition. The main firms conducting R&D in long-wavelength semiconductor laser were limited to the firms, which were subcontractors of Nippon Telegraph and Telephone Public Corporation (NTT), which was a government-owned telecommunication corporation, before the OMCS got started. The main four NTT subcontractors were NEC, Fujitsu, Hitachi, and Oki Electric. Since the relationship between NTT and its subcontractors was fixed based on long-term consideration, it was a barrier for potential entrants. NTT provided secure demand to the group of subcontractors called the “NTT family.” In other words, this discouraged potential entrants from investing in semiconductor laser R&D. However, non-NTT family firms such as Sumitomo Electric Ind, Furukawa Electric and Fujikura Cable Works, which had not begun semiconductor laser R&D, could participate in the OMCS project. By participating in the OMCS project, these firms accumulated know-how and information about semiconductor lasers and began in-house semiconductor laser R&D.⁴³ Merz, who was a visiting engineer of the OMCS project, reported that the firms such as Oki and Sumitomo, which were late comers in semiconductor laser R&D, could acquire advanced R&D capability in a relatively

⁴² Mitsubishi Sōgō Kenkyūjo, (Mitsubishi Research Institute), *Hikari Kankei Kenkyū Kaihatsu Purojekuto no Gijutsu Sangyō Shakai eno Inpakuto ni kansuru Chōsa*, (Report on the Impact of Optoelectronics Research Consortia on Technology, Industry, and Society), p.88.

⁴³ Ibid., p.23 and 74.

short period by participating in the project.⁴⁴ Figure 4-1 shows the cumulative number of patents in semiconductor lasers that Sumitomo, Furukawa and Fujikura obtained. It shows that these firms began to obtain patents in semiconductor lasers from the beginning of the 1980s.

Figure 4-1: Cumulative Number of Patents in the Semiconductor Laser



Source: Calculated from *Derwent Innovation Index*. The figures show the number of patents obtained by the firms through the Derwent Innovation Index and calculates the cumulative total.

These firms, which participated in the project to provide complementary knowledge, optical fibre technology, to the consortium, had not engaged in R&D in semiconductor lasers before the OMCS project was launched. However, they began independent in-house R&D in the areas in which they undertook collaborative R&D in order to exploit and appropriate technological knowledge and information created

⁴⁴ Merz, "The Optoelectronics Joint Research Laboratory: Light Shed on Cooperative Research in Japan", p.82.

by the joint R&D. Because of this duplicative in-house R&D, the firms increased the number of their own patent applications in the same technological areas in which they were doing the research in the consortium.⁴⁵

Lastly, many of the interviewees suggested that the consortium produced an important externality. The fact that the government launched a consortium in semiconductor lasers with a large amount of money created the expectation that semiconductor lasers would be an important technology of the future. This expectation was not limited to the participating firms: it spread across the electronics-related industry. The project leader of the OMCS called this phenomenon the “flag ship effect.”⁴⁶ He pointed out,

“The consortium played an important role as a flagship. The fact that MITI launched the consortium announced to the industry that semiconductor laser would be a key technology in the optoelectronics market.” [Interviewee:D]

This factor takes place when the government launches a consortium in a certain technological area, signalling that the government is committed to promoting the industry. Since the OMCS was carried out as a major national project, it conveyed the message that optoelectronics would become an important technology in the future. Previous studies on the industrial policy of MITI⁴⁷ have pointed out

⁴⁵ From the resource-based view of the firm, it can be assumed that the consortium homogenized in-house R&D of certain areas in which the firms conducted R&D in the consortium. On the resource-based view, see Barney and Hesterly, *Strategic Management and Competitive Advantage: Concepts and Cases*; Penrose, *The Theory of the Growth of the Firm*.

⁴⁶ Shimada, "Ai to Kanashimi no Hikari Ōpuro, Purojekuto Rīdā no Memo Yori, (Optoelectronics Large Project - Project Leader's Memo)." Odagiri et al. referred to this effect as the national commitment factor. Odagiri, Nakamura, and Shibuya, "Research Consortia as a Vehicle for Basic Research: The Case of a Fifth Generation Computer Project in Japan", p.193. Brahm discussed how the aggregate strategic targeting actions of national governments affected the nature and intensify of rivalry in contemporary international high-technology industries. Brahm, "National Targeting Policies, High-Technology Industries, and Excessive Competition."

⁴⁷ On the industrial policy of Japan, see Komiya, Okuno, and Suzumura, *Industrial Policy of*

this effect, and interviewees have verified its existence in the OMCS project. No R&D division in the firms was exclusively designed for the optoelectronics technology before the OMCS project was launched. Optoelectronics was a somewhat vague concept for the firms because how it would be used for their business was not clearly defined. The laser was a “great solution looking for problems.” But when MITI launched the OMCS project, the project leader coined a new concept, the Optical Electronic Integrated Circuit (OEIC), and set it as an R&D target. The OEIC became an influential concept in the industry. Throughout the 1960s and 1970s, electrical firms competed to develop the Integrated Circuit (IC). When MITI set the OEIC as an R&D target, the OEIC came to be regarded as the next generation IC. The idea was to change the existing electronic IC to an optical electronic IC. It provided a clear concept about how optoelectronics would be used and how big the potential market would be. The project leader also noted,

“When MITI planned the consortium, there were academic societies for optoelectronics. However, the firms did not have any optoelectronics division. The fact that MITI launched the OMCS project, invested a significant amount of resources, and targeted the semiconductor laser as the next generation’s important device set the firms off organising a division for semiconductor laser and intensifying their own research.” [Interviewee:D]

It is also clear that firms began to set up the new research groups and business units for semiconductor laser technology because the fact that the government invested a large amount of money in semiconductor laser R&D provided firms with the justification for setting up new research groups and business units specially designated for semiconductor laser technology.⁴⁸ Before the OMCS

Japan.

⁴⁸ Mitsubishi Sōgō Kenkyūjo, (Mitsubishi Research Institute), *Hikari Kankei Kenkyū Kaihatsu Purojekuto no Gijutsu Sangyō Shakai eno Inpakuto ni kansuru Chōsa*, (Report on the Impact of Optoelectronics Research Consortia on Technology, Industry, and Society),

project got started, the in-house semiconductor laser R&D of firms was usually conducted as a small research subgroup in the central R&D division.

These anecdotes indicate that the effect of national commitment existed in the optoelectronics industry, even though the question remains, then, as to what the national commitment effect contributed to technological and industrial development.

4.5. Conclusion

MITI started the Large Scale Project to promote technological competitiveness in the international market, when economic liberalization was promoted by the government and it was necessary for firms to increase their R&D capability. In the late 1970s, the semiconductor laser was regarded as a domestic technology that would become a key industry of the national economy; thus, MITI launched the OMCS as a Large Scale Project to facilitate R&D in semiconductor lasers in 1979.

Unlike the other consortia funded by MITI, the main participating firms were direct rivals. As Katz indicated, the fact that the participants were competing in the product market affected the OMCS project. First, it dampened the joint R&D in the consortium. The high level of competition in the product market among the participating firms induced non-cooperative behaviours in the consortium. The participants underinvested in the OMCS project. Patent citation data shows that important technology was not produced in the consortium, compared to the private R&D results of the participating firms. The evaluation report of the consortium reported that the OMCS project could not develop the OEIC, which was the final target.⁴⁹

Competition among participating firms in the product market significantly affected the industry. The fact that MITI selected competing firms dampened the R&D of the consortium, but it stimulated competition in semiconductor laser technology among the firms. Examining research consortia in various technological areas, Sakakibara asserted that the technological and industrial diversity among the participating firms increased R&D expenditures of the individual participants.⁵⁰

⁴⁹ Ibid., p.ii.

⁵⁰ Sakakibara, "The Diversity of R&D Consortia and Firm Behavior: Evidence from Japanese Data", p.192. Examining motives for participating in cooperative R&D, Sakakibara also discussed that the skill-sharing motive could be competition enhancing, while cost-sharing R&D cooperation could be competition suppressing in terms of their roles in R&D competition. However, because the participating firms had different motives

According to Sakakibara's study, if the participating firms of the OMCS project had not been competing in the same technological area, they would have increased the level of R&D commitment and the number of patents in their own product market area more than if the participants were rivals. However, if the participating firms had not been direct rivals, the private R&D efforts of the participating firms would have been scattered and dispersed in the product markets, because their target product market would differ from one another. It must be noted that since the participants were direct rivals in the product market, the competition-enhancing effect spread throughout the industry in the case of the OMCS project.

The finding that the participants underinvested in the consortium because they were rivals in the product market supports the previous literature. However, the fact that the participants began to increase the number of patents in the area in which they were undertaking the joint research suggests that the consortium stimulated market competition in certain technological areas and could contribute to technological development.

However, these findings do not necessarily show any direct causality in terms of the research consortium causing the technological development of semiconductor lasers and enhancing the technological competitiveness of the firms.⁵¹

While the research consortium was not in itself the single factor leading to the technological development of semiconductor lasers in Japan, this thesis reveals that the consortium provided important path dependency for technological development and industrial development. It stimulated competition in semiconductor laser technology (e.g., material technology and epitaxy technology).

to participate in the OMCS and their motives might have changed through the time periods, it was not clear which motives, cost-saving motive or skill-acquiring motive, was more important for the participants. Sakakibara, "Heterogeneity of Firm Capabilities and Cooperative Research and Development: an Empirical Examination of Motives."

⁵¹ Studying government funded collaborative research, Okimoto came to the same conclusion that a causal connection between industrial policy and competitiveness in high technology was not clear yet, even though the industrial policy facilitated the development of Japan's high-technology industries. Okimoto, *Between MITI and the Market: Japanese Industrial Policy for High Technology, Studies in International Policy*, p.230.

The next chapter examines how the firms competed under the conditions provided by the research consortium, by scrutinising important technological changes in epitaxy technology.

5. Competition, Knowledge Spillover, and Innovation

As discussed in the fourth chapter, the OMCS project was not successful in producing important technology, compared to the firms' in-house R&D. However, it stimulated private in-house R&D in the technological area on which the research consortium focused. New entrants accumulated R&D competence through participation in collaborative research in the consortium and participated in semiconductor laser R&D competition. This chapter explores how the firms competed under the conditions that the research consortium provided and how Japanese firms gained competitiveness in the high volume product market.

The JTEC report and the AIST survey provide important perspectives for this chapter. Reviewing the optoelectronics industry in the U.S. and Japan, JTEC found “Japan clearly led in consumer optoelectronics, that both countries were competitive in communications and networks, and that the United States held a clear lead in custom optoelectronics.” “Japan’s lead in high-volume consumer optoelectronics and related technologies gave it a dominant share of the overall global optoelectronics market.”¹ Surveying key industrial technologies in 1983, the AIST designated semiconductor laser technology as one of the most competitive key industrial technologies in optoelectronics. The AIST survey pointed out that firms were competing in the same sort of products and that through fierce R&D competition, the firms increased R&D investments to develop their own technology.² These points revealed by these reports are important issues in the exploration of the technological development of semiconductor lasers.

How did this pattern of competitive advantage indicated by the JTEC report emerge? Examining the R&D strategy of the U.S. and Japanese firms, this section

¹ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, p.xv.

² Kōgyō Gijutsuin Sōmubu Gijutsu Chōsaka (Agency of Industrial Science and Technology), *Wagakuni Sangyō Gijutsu no Taishitsu to Kadai*, (*Survey of Japanese Industrial Technology*), pp.276-277.

aims to explore this issue with the following questions. [1] Why did Japanese firms compete in the same technological area with the same technological choice longer than their counterparts in the U.S.? [2] How did the pattern of the strategic behaviour of the firms affect technological change in the semiconductor laser?

Through scrutinizing patent data, it aims to show how certain patterns of competition among the firms affected the areas in which knowledge spillover effects emerged and resulted in the different paths of technological development in the U.S. and Japan. More concretely, the U.S. firms tended to bring about lateral utilization knowledge spillovers, which enriched and exploited potential and untapped product markets by utilizing the fundamental technology of semiconductor laser technology. In contrast, the pattern of competition of Japanese firms induced domain-specific knowledge spillovers, which enhanced the development of the fundamental technology of the semiconductor laser instead of exploiting niche product markets.

This chapter is developed in five sections. Scrutinizing how the semiconductor laser was invented and what the R&D targets were, the first section shows that both American and Japanese firms were targeting the same R&D goals in the 1970s. The second section reveals that it became necessary to develop new semiconductor laser technology to catch new growing product markets for semiconductor lasers. This section also shows that Japanese firms adopted the same technological choices and competed in the same areas, while their rivals in the U.S. assumed different strategies. Examining the economic conditions and the level of downward integration of the competing firms, the third section demonstrates that the growing electronics industry and the higher level of downward integration allowed Japanese firms to compete in the same technological area for a longer period than their rivals. The fourth section examines how the R&D strategies of the firms and the patterns of competition in the U.S. and Japan affected the nature of knowledge spillovers and how different trajectories of technological development emerged through different patterns of R&D competition and different institutional settings. The last section draws ironic conclusions from the development of epitaxy technology in the U.S. and Japan.

5.1. Invention of the Semiconductor Laser and LPE

Scrutinizing how the semiconductor laser was invented and what the R&D targets were, this section reveals that both American and Japanese firms were targeting the same R&D goals in the 1970s.

Invention of the Semiconductor Laser

The first semiconductor laser was invented in the 1960s. Three American institutions--GE, IBM, and MIT simultaneously but independently developed the first semiconductor lasers in 1962.³ A research group at GE headed by Robert N. Hall developed the first semiconductor laser on September 16, 1962. Within a month, physicists in the two other institutions independently demonstrated their own versions of the semiconductor laser. The development of the semiconductor laser was amazing and exciting news for physicists who were involved in laser-related R&D.

This invention opened huge possibilities for lasers. Until the semiconductor laser was invented, laser apparatuses, as noted earlier, were all large-scale. For instance, the ruby laser, which was the first laser in the world, needed a five-meter square amplification apparatus. It also required a significant amount of energy input. The laser seemed exotic, complex, and dangerous “high tech” in the early 1960s. However, the invention of the semiconductor laser changed the notion of the laser, since it was a far simpler laser that would eventually fit on a tiny chip and be efficient enough to run with a small battery.

However, this invention did not necessarily lead to smooth technological development. Suematsu Yasuharu, who was one of the star scientists in the optoelectronics technology, noted,

³ On the invention of four semiconductor lasers, see Dupuis, "The Diode Laser-the First Thirty Days Forty Years Ago."

“Semiconductor laser R&D began in 1962. However, it did not come to the attention of many engineers because of the poor performance of the semiconductor laser. The mainstream of laser R&D was still the Gas laser through the 1960s.”⁴

The semiconductor laser was still on a very nascent level, even though it was believed that it would have huge potential. Japanese firms started semiconductor laser R&D from the beginning of the 1960s. However, their research was still at a very basic level. The number of research personnel for semiconductor laser R&D was fairly limited through the 1960s.

Room Temperature Operation by Bell Labs

The semiconductor lasers developed by GE, IBM, and MIT worked properly only at minus 196 degree Celsius (i.e., liquid nitrogen temperature). Unless the semiconductor laser could work at room temperature, its potential would be fairly limited. Therefore, after the invention of the first semiconductor laser, the focus of R&D in semiconductor laser technology was to develop a semiconductor laser that could work at room temperature.

It took eight years for the engineers to solve this technological problem. This period was later called “the winter years of semiconductor lasers”. The first semiconductor laser working at room temperature was developed in 1970 by a Bell Laboratory research team.⁵ The new semiconductor laser was named Double-Heterostructure Laser (DH).

Even though the semiconductor laser developed by Bell did not work stably, it was one of the turning points in the technological development of the semiconductor laser, stimulating competition as many firms developed reliable and

⁴ Suematsu, *Handōtai Rēzā ga Tsūshin o Kaeru (Semiconductor Lasers Will Change the World)*, p.13.

⁵ Panish, Hayashi, and Sumski, "Double-Heterostructure Injection Lasers with Room-Temperature Thresholds as Low as 2300 A/cm²."

stable semiconductor lasers that could work at room temperature. The newspapers reported that this newly invented DH laser would fundamentally change Optical Engineering and that it would be the same as the transistor, which had produced a fundamental change in Electronic Engineering.⁶ Reporting that the newly invented semiconductor laser had huge potential, they described that it would enable people to transmit huge amounts of data by optical fibre. The newspapers also reported that this laser would make it possible to do face-to face communication with TV phones. After the invention of the DH laser, the laser technology became widely known among the public in the U.S. and in Japan. For instance, MITI reported on laser technology and its huge limitless potential for product markets.⁷ Twentieth Century Fox released the first *Star Wars* series in 1977. In the movie, the director, George Lucas, used many special effects. Lucas showed laser light as one of the futuristic technologies. Laser became thought of as the technology of the future.

The semiconductor laser developed by the Bell research team opened the possibility of using the semiconductor laser for optical communication.⁸ Optical communication was clearly an important application area that most of the firms were targeting. Many organisations were competing to develop semiconductor lasers, which could work stably with greater longevity at the room temperature. Based on patent data, the following tables show the firms that were involved with semiconductor laser R&D in the beginning of the 1970s (1970-1975).⁹

⁶ *Asahishinbun (Asahi Newspaper)*, September 1st, the evening edition.

⁷ Tsūshō Sangyō Shō, (Ministry of International Trade and Technology), *Denshi Kōgyō Nenkan (Annual Report on the Electronic Industry)*, 1976, pp.513-524.

⁸ In the same year as the DH laser was invented, the U.S. glass manufacturer, Corning Glass Works, invented an essentially complementary technology to the semiconductor lasers. Corning Glass Works invented the first practical optical fibre for communication in 1970. The optical fibre was also an important invention to open the possibility of using the semiconductor laser. The Japan Electronics Apparatus Industry Association stated that “the laser diode attained a continuous amplification at room temperature in 1970. It is projected that it will be used in optical telecommunication and data communication soon.” *Nihon Denshi Kikai Kōgyō Kai, Denshi Kōgyō 30 nenshi (A 30 year history of Electronics Industry)*, p. 269.

⁹ In addition to those firms, many research institutions began their research in the beginning of the 1970s. The main research institutions in these areas were UIUC, MIT, NASA, US Navy, and Tokyo Institute of Technology. On the research institutions, see the third chapter.

Table 5-1: U.S. Firms in Semiconductor Laser R&D 1970-1975

The U.S. firms	Business Description
American Optical Corp	Eyewear company
Bell Telephone Lab	Telecommunication company
Eastman Kodak	Cameras, printers, accessories manufacturer
Energy Conversion Devices	Electronic components, storage batteries manufacturer
GE	Electronics conglomerate
Hughes Aircraft	Defence and aerospace
IBM	Computer and information technology
McDonnell Douglass	Commercial airplane and defence
3M	Consumer and industrial technology
Motorola	Communication and electronics
Northern Rockwell	Business conglomerates defence
Quantronix Corp	Manufacturer of lasers for scientific and industrial applications
RCA	Consumer electronics
Texas Instruments	Semiconductor and computer technology
Union Carbide	Petrochemical, chemical and polymers
Western Electric	Electrical engineering company, the manufacturing arm of Bell
Westinghouse Electric	Nuclear reactor
Xerox	Printers and office products

Source: Calculated from *Derwent Innovations Index*. The Derwent Innovations Index identifies all of the U.S. firms and research institutions that obtained a patent in semiconductor laser technology from 1970-1975. This table lists all of the firms that obtained more than two patents from 1970-1975.

Table 5-2: Japanese Firms in Semiconductor Laser R&D 1970-1975

Japan	Business Description
Hitachi	Consumer and industrial electronics
Kansai Paint	Consumer / industrial paints and coatings
Matsushita Electronic Industry	Consumer and industrial electronics
Matsushita Electronics	Consumer and industrial electronics
Mitsubishi Electric	Consumer and industrial electronics
NEC	Consumer and industrial electronics
NTT	Telecommunication company
Sanyo Electric	Consumer and industrial electronics
Sharp	Consumer electronics
Sony	Consumer electronics
Toshiba	Consumer and industrial electronics

Source: Calculated from *Derwent Innovations Index*. This table is created with the same procedure for Japanese firms as Table 5-1.

These tables show that a greater number of firms was involved in semiconductor laser R&D in the U.S., compared to those in Japan. Furthermore, the business backgrounds of the U.S. firms were much more diversified than those of Japan. For instance, Hughes Aircraft and MacDonnell Douglass were aircraft and aerospace manufacturers. IBM and Xerox were computer and office equipment manufacturers. While Texas Instruments, Minnesota Mining and Manufacture, and Energy Conversion Devices were specialized industrial and electric device manufacturers, GE and RCA were more integrated industrial and consumer electronics manufacturers. This reflects the fact that American consumer electronics and computer firms diversified their business domains based on the high economic growth through the 1960s and the beginning of the 1970s.¹⁰ By contrast, only electronics or telecommunication firms were involved in semiconductor laser R&D in the beginning of the 1970s in Japan.

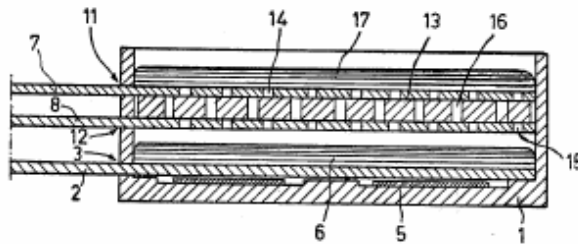
Even though various firms were involved in semiconductor laser R&D in the beginning of the 1970s, they were competing for the same R&D target. Since the laser beam amplification was noisy and unstable and the life span of the semiconductor was short in the 1970s, all of the firms were competing to develop stable and long-life semiconductor lasers, which could work at room temperature.

LPE (liquid phase epitaxy) was the only dominant epitaxy technology in the 1970s.¹¹ The Bell Laboratory research group used LPE to amplify laser beam at room temperature in 1970. Because the other firms followed Bell's technological choice, they adopted LPE for the epitaxy process. Figure 5-1 depicts an example of LPE technology.

¹⁰ On the diversification in the consumer electronics industry, see Chandler, "The Competitive Performance of U.S. Industrial Enterprises since the Second World War." Chandler, *Inventing the Electronic Century: the Epic Story of the Consumer Electronics and Computer Industries*. Chapter 2.

¹¹ On epitaxy technology, see 1.3. Epitaxy Technology in the first chapter.

Figure 5-1: LPE Technology



Abstract of US3933123

A method of and a device for the epitaxial deposition of a layer on a monocrystalline substrate from a material in the liquid state. During the deposition process, apportioned quantities of a second material are added to the material in the liquid state, using a jig with a plurality of vertically spaced, fixed, and slidable walls for controlling the addition. Application inter alia for the provision of semiconductor layers, for example, of material of the type AIIIBV, in particular from mixed crystals.

Source: Elie, "Liquid Phase Epitaxy." US3933123.

First, semiconductor materials are melted into liquidised metal and poured into a space divided by carbon separators (small cells in the middle of the box in Figure. 5-1). The bars stuck in the box are substratum, which becomes a semiconductor laser wafer. Second, the temperature of the semiconductor materials is lowered so that they become crystallised. Third, when the substratum is slid from right to left, different semiconductor materials attach to the substratum in order. As a result, semiconductor layers are formed on the substratum.

Since LPE did not require a special production facility, high-quality layers could be produced with minimal capital investment, compared to alternative techniques. The firms were competing to develop a semiconductor laser that could work longer with high reliability amplification by using LPE technology.

5.2. New Market and Technological Change

Using the same epitaxy technology, the U.S., European, and Japanese firms were competing to develop a reliable semiconductor laser that could work at room temperature.

Showing that a new product market emerged in semiconductor laser technology, this section reveals that it became necessary to develop new epitaxy technology to catch the new growing demand for semiconductor lasers. This section also shows that Japanese firms adopted the same technological choices and competed in the same areas, while their rivals in the U.S. assumed different R&D strategies.

New Market and New Technology

It was believed that the semiconductor laser would be a key electronics device in the optoelectronics industry. After the invention of the DH laser by the Bell research team in 1970, firms were competing to develop a reliable long-life semiconductor laser with LPE, a relatively uncomplicated epitaxy technology.

The main application area in the beginning of the 1970s was long-distance telecommunication. At that time, the electronic wire was used for long-distance telecommunication. However, electronic wire long distance-telecommunication did not provide sufficient quality. The problem that long-distance telecommunication confronted was energy loss. Because of the energy loss, the electronic wire cable for long-distance telecommunication needed a relay device, called a repeater, every few kilometres. Too many relay devices caused a time lag, background noise and cutting-off of the long-distant telecommunication. The engineers believed that the laser optical fibre would resolve these problems by reducing the energy loss. Since it was estimated that optical fibre would need only one-relay device every 180 kilometres, they believed that the optical fibre would enable clear, instant, and stable long-

distance telecommunication. It was predicted that optical fibre would take the place of electric wire for long-distance telecommunication if a practical optical fibre and a reliable semiconductor laser could be developed. The Japan Electronics Apparatus Industry Association stated,

“The semiconductor laser attained a continuous amplification at room temperature in 1970. It is projected that it will be used in optical telecommunication and data communication soon.”¹²

However, the size of the long-distance telecommunications market was not very large, even though it was an important social infrastructure. Once the semiconductor lasers had been set up in the long-distance telecommunication infrastructure, much of the additional demand would be replacement of the existing cable. Additionally, the product markets of the semiconductor laser were not clear until the late 1970s, even though optical communication (e.g. optical fibre) was regarded as one of the applications of semiconductor lasers. Hayashi Izuo, who was one of the Bell Laboratories’ engineers successfully developing semiconductor laser amplification at room temperature in 1970, noted in 1972,

“It is difficult to estimate how the semiconductor laser will be developed. First, it is because we are still uncertain about the technological possibility. Second, we do not know what kind of product market will be found. Since the laser was invented, many various and dreamy potentialities have been pointed out. However, many of them have not been realized yet. Even though many technological problems remain unsolved in the semiconductor laser technology, the biggest problem lies in whether appropriate and effective potential uses can be

¹² Nihon Denshi Kikai Kōgyō Kai, *Denshi Kōgyō 30 nenshi (A 30 year history of Electronics Industry)*, p. 269.

found.”¹³

While many firms competed to develop a semiconductor laser for optical fibre, Stanford University and 3M started researching laser technology for information storage on photographic videodisc in 1961.¹⁴ In those days, information was stored in an analogue signal. Their attempt was to store data in a digital signal. Unfortunately, their efforts were unsuccessful at that time because laser technology was still immature. Even though their research attracted little attention at the time, this was the first attempt to use optoelectronics technology for information storage.

Ten years after Stanford and 3M’s attempt, some firms began to do research on videodisc technology in the early 1970s and developed several videodisc systems based on progress in laser technology. Taking different formats, Philips, Music Corporation of America (MCA), Nippon Victor, RCA, and Telefunken were competing to develop the videodisc.¹⁵ Japanese firms such as Mitsubishi, Toshiba, and NEC, also began to develop the videodisc.

Announcing that it had developed an analogue pulse videodisc, called VLP (Video Long Play) system, in September of 1972, Phillips released the videodisc player in 1973.¹⁶ It was the first commercial laser application to an optical disc. Phillips’s videodisc demonstrated that laser technology would be used in the information storage area, in spite of the fact that this videodisc did not achieve commercial success.

All of the firms that were trying to develop the videodisc in the beginning of the 1970s adopt Helium-Neon (He-Ne) laser, which was a type of small gas laser and more primitive laser than the semiconductor laser, for the source of light. The reason why they selected the He-Ne laser instead of the semiconductor laser was its reliability. The reliability of the semiconductor in continuous amplification at room

¹³ Hayashi, "Handōtai Rēzā o Omou (Semiconductor Laser)", p.355.

¹⁴ The system of the photographic videodisc read a signal recorded on the disc by the strength of the penetration light from a mercury lamp. Nakajima and Ogawa, *Zukai Konpakuto Disuku Tokuhon (Handbook of Compact Disc)*, p. 55.

¹⁵ Ibid., p. 57.

¹⁶ On the videodisc see, Ibid.

temperature was still less reliable than that of He-Ne laser in the beginning of the 1970s.

As the firms committed to semiconductor laser R&D, it became clearer that the semiconductor laser would eventually be used for optical information storage such as videodiscs, compact discs and laser discs. By the end of the 1970s, it was obvious that the semiconductor laser would involve huge application areas. For example, the *Electronics Industry Year Book of 1979* noted,

“It is expected that electronics products such as POS (point of sales) system and Video Disc will be widely used in shops and homes. It is projected a huge new market will appear based on the economies of large-scale production, if the semiconductor laser is used in these products. He-Ne laser is currently used in these products. However, firms and research institutions are actively conducting R&D in semiconductor lasers so that it can be used in these products.”¹⁷

Information storage was a new product market for the semiconductor laser. As expectations for the information storage market grew, it became clear that it would be necessary to develop manufacturing technology that would allow the production of reliable semiconductor lasers on a large scale for the mass markets. It had become apparent that LPE would prove difficult in the mass production of the semiconductor laser, even though LPE was a relatively uncomplicated technology and its production facilities tended to be inexpensive.

When the firms were targeting high volume markets, engineers were confronting some technical problems that would be caused by using LPE. First, because it was necessary for an engineer to slide the substratum to form the layer with LPE, no systematic way to control the thickness of the layer existed in LPE technology. Since thickness control depended on the speed at which an engineer slid

¹⁷ Tsūshō Sangyō Shō, (Ministry of International Trade and Technology). *Denshi Kōgyō Nenkan (Annual Report on the Electronic Industry)*, 1979, p.679.

the substratum, it highly relied on the tacit knowledge of skilled engineers. Second, the size of the substratum that LPE could use was limited. It was impractical to control the thickness of the layer with a large substratum by using LPE. The square measure of the semiconductor wafer had a strong impact on the economies of scale, since the larger wafer could allow production of more semiconductor laser chips at once.

It was necessary to improve the current LPE technology or change epitaxy technology from LPE to a new one in order to meet the growing demand for the semiconductor laser. Such problems in large-scale production became more obvious as many firms and research organisations realized that demands for the semiconductor laser would probably be enormous. The optoelectronics device market survey in 1982 reported,

“The price of a semiconductor laser is five hundred thousand yen in 1980. Since the price is high, it is important to reduce the production costs to develop and expand potential product markets.”¹⁸

“It is anticipated that the semiconductor laser product markets will be fully grown after 1985. Therefore, it is necessary for the semiconductor laser manufacturers to establish semiconductor laser mass production technologies and facilities.”¹⁹

Two other epitaxy technologies, MOCVD and MBE, were likely solutions. The thickness control of both MOCVD and MBE were automatically operated. The square measure of the wafer with MBE and MOCVD was larger than that with LPE. Both MOCVD and MBE were, however, still nascent technologies in the 1970s, even though both had already been invented and were public.²⁰

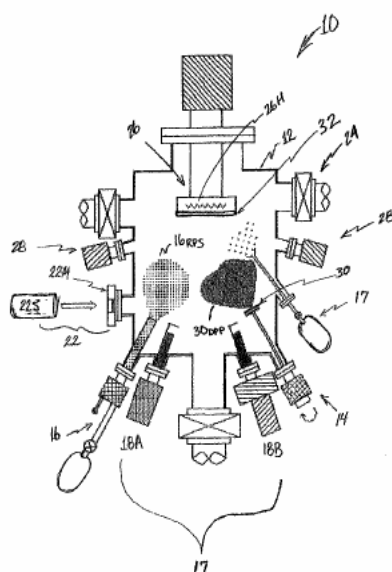
¹⁸ Sōgō Giken, *Oputodebaisu Shijō Yōran (Optoelectronics Device Handbook)*, p.44.

¹⁹ Ibid., p.44.

²⁰ The first patent in MOCVD was taken by Monsanto in 1959. The first academic report on

The engineers of Bell Laboratory published the first academic report on MBE in 1969.²¹ Figure 5-2 exemplifies the deposition process of MBE.

Figure 5-2: MBE Technology



Abstract of WO2004020686

A hybrid beam deposition (HBD) system and methods according to the present invention utilizes a unique combination of pulsed laser deposition (PLD) and equipment and techniques that provide a radical oxygen rf-plasma stream to increase the flux density of available reactive oxygen at a deposition substrate for the effective synthesis of metal oxide thin films. The HBD system and methods of the present invention further integrate molecular beam epitaxy (MBE) and/or chemical vapor deposition (CVD) techniques and equipment in combination with the PLD equipment and technique and the radical oxygen rf-plasma stream to provide elemental source materials for the synthesis of undoped and/or doped metal oxide thin films as well as the synthesis of undoped and/or doped metal-based oxide alloy thin films.

Source: White, Ryu, and Lee, "A Hybrid Beam Deposition System and Methods for Fabricating Metal Oxide ZnO Films, P-Type ZnO Films, and ZnO-Based II-VI Compound Semiconductor Devices" WO20004020686

First, semiconductor materials are evaporated in small pots. Then the evaporated molecules are jetsprayed, one by one, in an ultra-high vacuum chamber in a certain order and form semiconductor layers on the substratum. MBE allowed the production of a thin semiconductor layer because it used molecules. Moreover, it was believed that MBE might solve the problem of mass production that LPE was expected to confront in the early 1980s. However, the speed of the deposition process on the substratum was slow, and the production facility was expensive

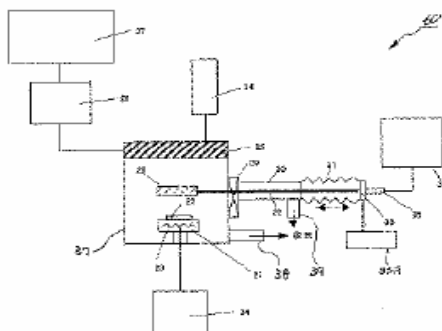
MOCVD was published by Rockwell engineers in 1969.

²¹ Arthur and LePore, "GaAs, GaP, and GaAs_xP_{1-x} Epitaxial Films Grown by Molecular Beam Deposition."

because it required an ultra-high vacuum chamber.

While MBE employed molecules for the deposition process, MOCVD used metal organic chemical vapour. Figure 5-3 depicts an example of the deposition process of MOCVD.

Figure 5-3: MOCVD Technology



Abstract of JP2006005062

PROBLEM TO BE SOLVED: To provide a MOCVD apparatus that can effectively and stably form a crystal on the front surface of a substrate, and that can obtain a semiconductor laser element having excellent characteristics with high-production efficiency.

SOLUTION: The MOCVD apparatus includes a substrate supporting means (21) for supporting a substrate (22), and a first heating means (23) for heating the substrate in a chamber (37). Furthermore, the MOCVD apparatus includes a second heating means (28) for high-frequency heating, a hold room (30) that is connected and provided in the exterior of the side wall of a chamber to hold the second heating means (28), and a means (35A) for moving the second heating means between the interior of the chamber and the hold room (30). The pressure of the hold room interior can be controlled independently with the chamber.

Source: Miura, "MOCVD Apparatus" JP2006005062.

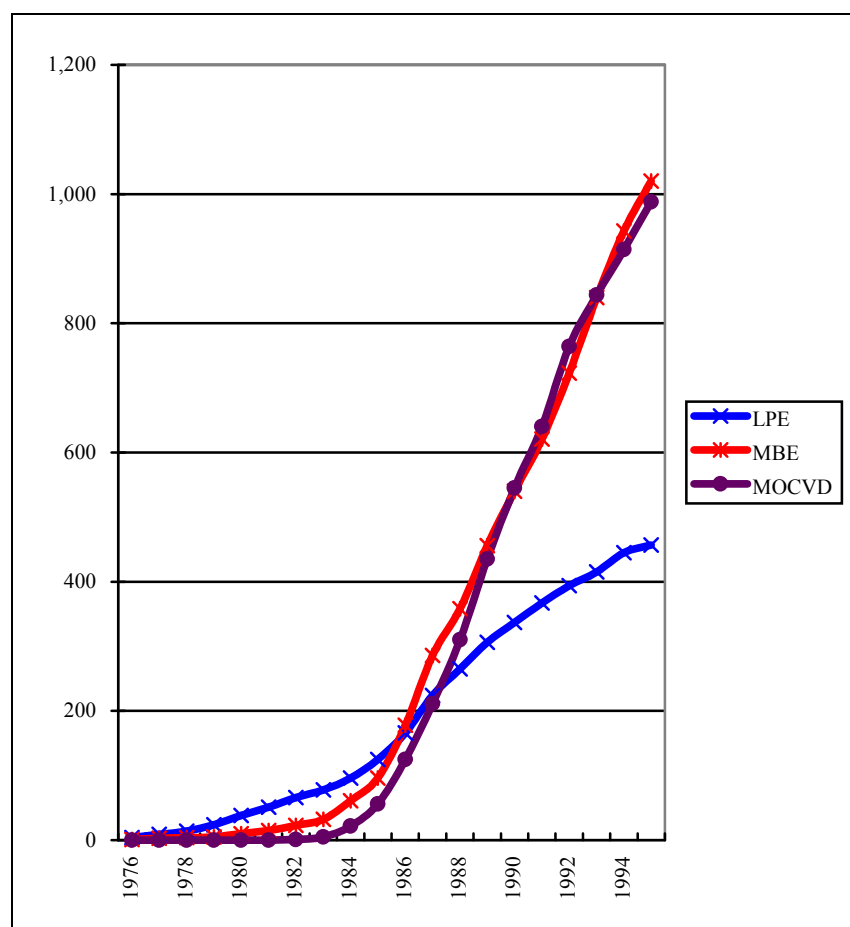
First, gases, which are metal organic materials, are sent to the small boxes (Figure. 5-3). Combined with the gas in the box, semiconductor materials become metal organic chemical vapour. This vapour is then sent to the ultra-vacuumed room (coloured in Figure. 5-3), in which the substratum is set so that the vapour forms semiconductor layers on the substratum. MOCVD effectively controls layer thickness. It also allows the use of a bigger wafer so that economies of scale can be achieved. Therefore, it was believed that MOCVD would be a solution to the mass production problems of LPE. However, the production facility of MOCVD was as

expensive as MBE. Furthermore, MOCVD uses metal organic chemical vapour, which can endanger human life.

Technological Change from LPE to MBE and MOCVD

As the expectation about high volume product markets was greatly growing, it became much clearer that either MBE or MOCVD would be the dominant epitaxy technology.²² Many firms began to shift their R&D focus from LPE to either MBE or MOCVD. Figure 5-4 reveals the number of patents in LPE, MBE, and MOCVD from 1976 to 1995 with patent data registered in European Patent Office, demonstrating that the cumulative number of patents in both MBE and MOCVD exceeded that of LPE in the mid-1980s. Clearly, the focus of R&D changed from LPE to MBE and MOCVD in the mid-1980s.

²² For instance, a technological review in 1985 suggested that MOCVD or MBE would be the dominant epitaxy technology soon. Mechatronics Henshūbu, *Saisentan no Optoelektronikusu*, (*the Optoelectronics Frontier*), p.24.

Figure 5-4: The Number of Patents in LPE, MBE, and MOCVD

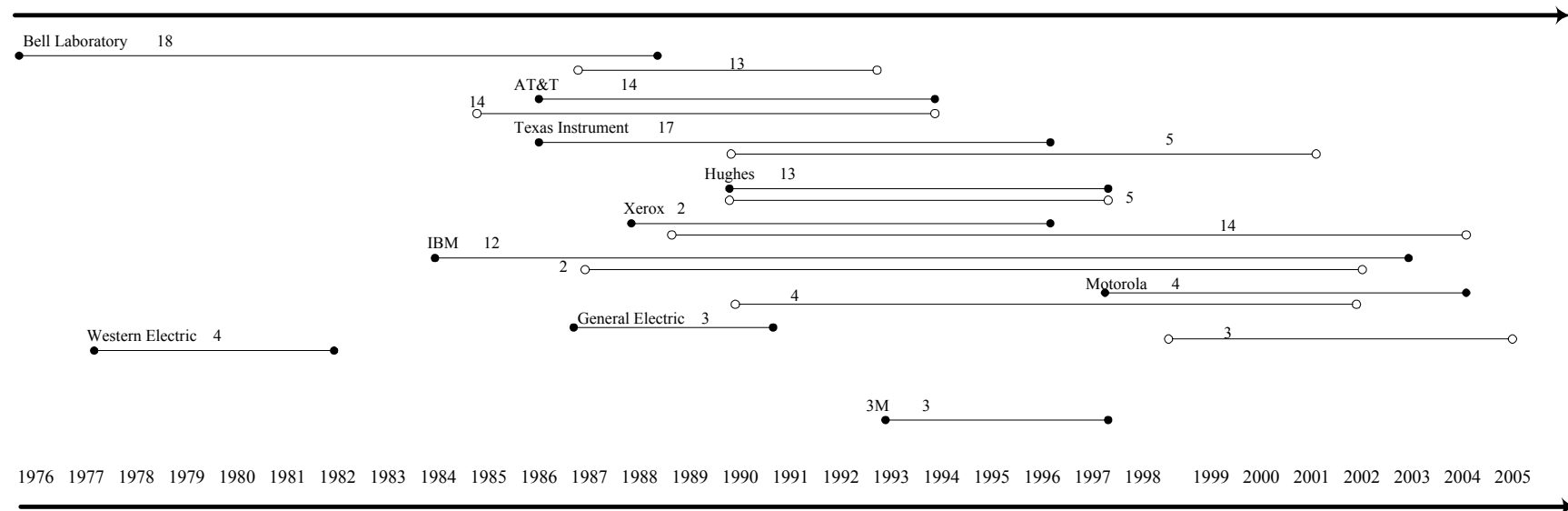
Source: Europe Patent Office. Using the Patent Database of the European Patent Office, this figure counts the number of patents in LPE, MBE, and MOCVD and calculates the cumulative numbers.

In the process of the technological change from LPE to MBE and MOCVD, the strategic behaviour of Japanese firms was clearly different from that of American firms. Japanese firms simultaneously made the same technological choices as their domestic rivals, while the U.S. firms made different choices.

Figures 5-5 and 6 reveal the differences in technological choices among firms in the U.S. and Japan. These tables present: (1) the names of the firms involved in semiconductor laser R&D competition, (2) whether or not they conducted R&D in epitaxy technology, and (3) when they began and ended R&D in epitaxy technology. Concretely, they list all of the firms that obtained patents in

semiconductor lasers more than once from 1970 to 1980, and when they obtained their first and last patents in MBE and MOCVD. It is assumed that the firms listed in the tables began R&D in semiconductor lasers with LPE before they acquired patents in MBE or MOCVD. Additionally, if the firms did not obtain a patent in MBE or MOCVD, it is assumed that they did not participate in R&D competition in epitaxy technology.

Figure 5-5: Technological Choice of U.S. Firms



The followings did not obtain any patent in either MBE or MOCVD.

Energy Conversion
National Semiconductor
Northen Electric
Exxon
International Standard Electric
RCA
Westinghouse Electric
Standard Tel & Cable
Perkin-Elmer
Rockwell

MBE



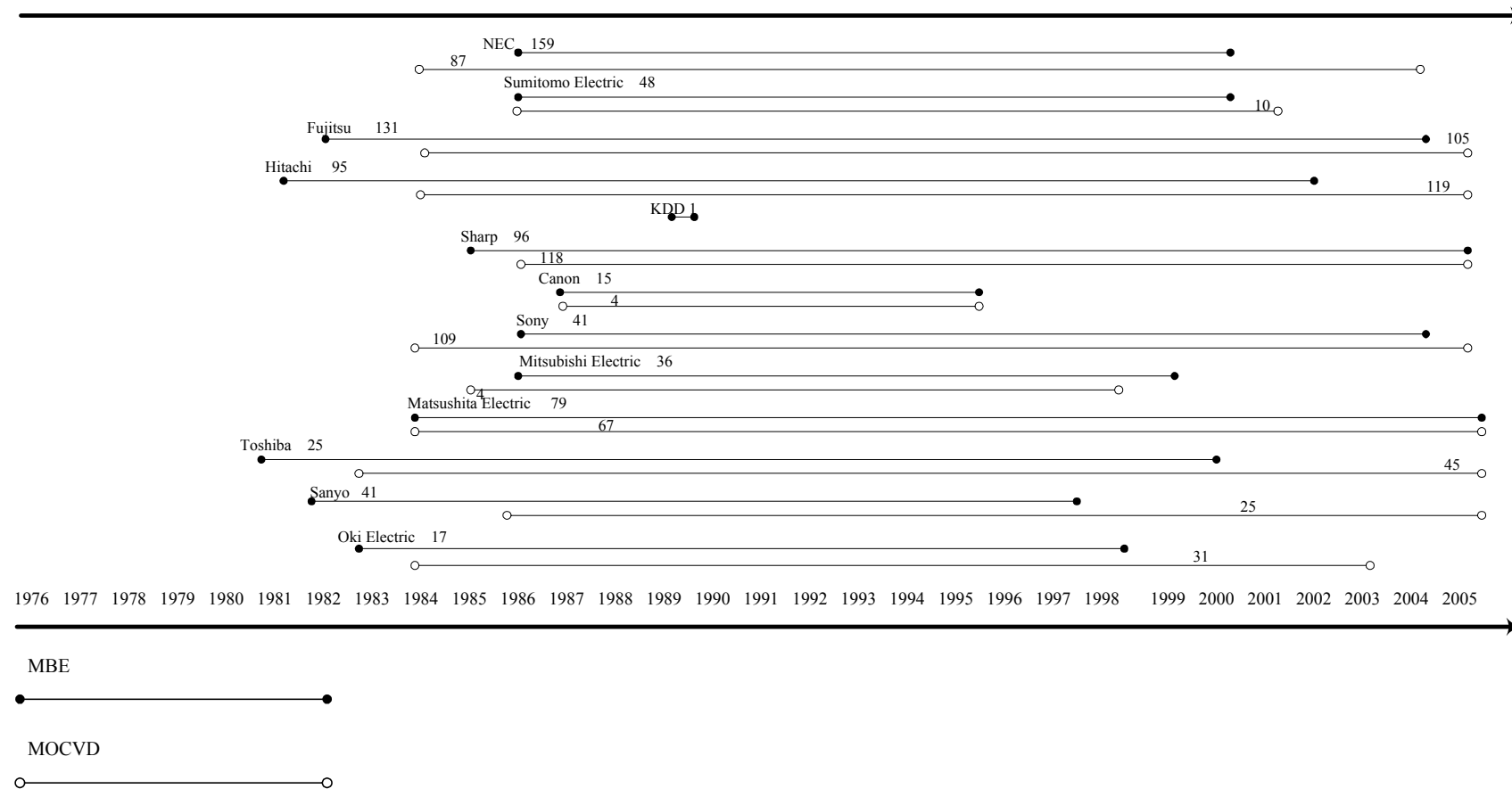
MOCVD



The line shows the first year and the last year that the firm obtained patent in MBE or MOCVD.
The number denotes the number of patents the firm obtained.

Source: Europe Patent Office, Patent Database. ICARUS.

Figure 5-6: Technological Choice of Japanese Firms



The line shows the first year and the last year that the firm obtained patent in MBE or MOCVD.
The number denotes the number of patents the firm obtained.

Source: Europe Patent Office, Patent Database. ICARUS.

These figures demonstrate two important points: the technological choice of the firms and the timing of start and exit. First, most Japanese firms began to patent in both MBE and MOCVD, while some American firms (e.g., RCA, Rockwell, and Energy Conversion) did not acquire any patents in MBE or MOCVD. Western Electric and 3M became involved only in MBE. KDD, a private telecommunication company, was the only Japanese firm that did not conduct R&D in MOCVD; and KDD apparently was not actively involved in MBE R&D either, since it obtained only one patent in MBE. Clearly, American firms' pattern of technological choice was in complete contrast with that of Japanese firms. It is possible to assume that the firms that did not engage in R&D in either MBE or MOCVD did not target an economically important area of semiconductor laser. If the firms targeted high volume markets, it was necessary for them to develop epitaxy technology, which was indispensable for the mass production of semiconductor laser. This point is summarized in the following statement:

- [5-1] Most Japanese firms simultaneously engaged in R&D competition in both MBE and MOCVD, while some American firms adopted neither MBE nor MOCVD.

The second point is the timing of firms' exits from R&D competition. It assumes that a firm stopped R&D and exited from R&D competition in the area if it did not acquire a patent in the area for a certain period. These figures also indicate the period between the year of the first patent and that of the last patent, indicating the period in which the firms were participating in R&D competition in MBE and MOCVD. These reveal that many American firms began obtaining patents later than Japanese firms did, and they exited from competition earlier than Japanese firms did. This point is summarized in the following statement:

- **[5-2]** Japanese firms competed in MBE and MOCVD areas over relatively longer periods than the U.S. firms did.

The findings of the fourth chapter partially explain the first point **[5-1]**. It discussed how the OMCS project provided participating firms with an incentive to invest in the technological area that the consortium targeted for development. The epitaxy technologies, MBE and MOCVD, were important R&D targets in the OMCS. It is, therefore, possible to assume that the consortium made Japanese firms' technological choices homogeneous and its R&D start times simultaneous in those areas. One yet unanswered question is related to why **[5-2]** Japanese firms competed in MBE and MOCVD over relatively longer periods than the U.S. firms did.

5.3. Economic Context and Vertical Integration

Examining the economic conditions in both Japan and the U.S. and the level of vertical integration of the competing firms, this section explores why Japanese firms competed in the same technological area with the same technological choices for a longer term than their counterparts in the U.S. did. Showing an industry undergoing tremendous change in both Japan and in the U.S., this section presents the following points. The first is that Japanese firms were in a favorable economic condition for R&D investment, while American electronics firms were declining from the mid 1970s. The second is that the higher level of downward integration of Japanese firms provided greater incentive in both MBE and MOCVD than the U.S. firms.

Growth and Decline of the Industry

As reviewed in the second chapter, the Bretton Woods cancellation and the oil shocks had a strong impact on economic growth. These two shocks made it difficult for Japanese firms to compete in price in the international market. Japan experienced its first post-war economic decline in industrial production. The key industries such as textiles and the steel and iron industry, which were labour and energy intensive, lost their competitiveness. The technology intensive industries obtained competitiveness and became key industries after these shocks. This structural economic change slowed economic growth, which had attained more than 10 percent GDP growth in the 1960s.²³ Even though Japan slowed its economic growth after the shocks, Japan attained annual growth rates no better than 4 to 6% in the 1970s and 1980s, which was for example, higher than that of the U.S.

Through this structural change, the Japanese electronics industry became one of the most rapidly growing industrial sectors in Japan. Realising that it would

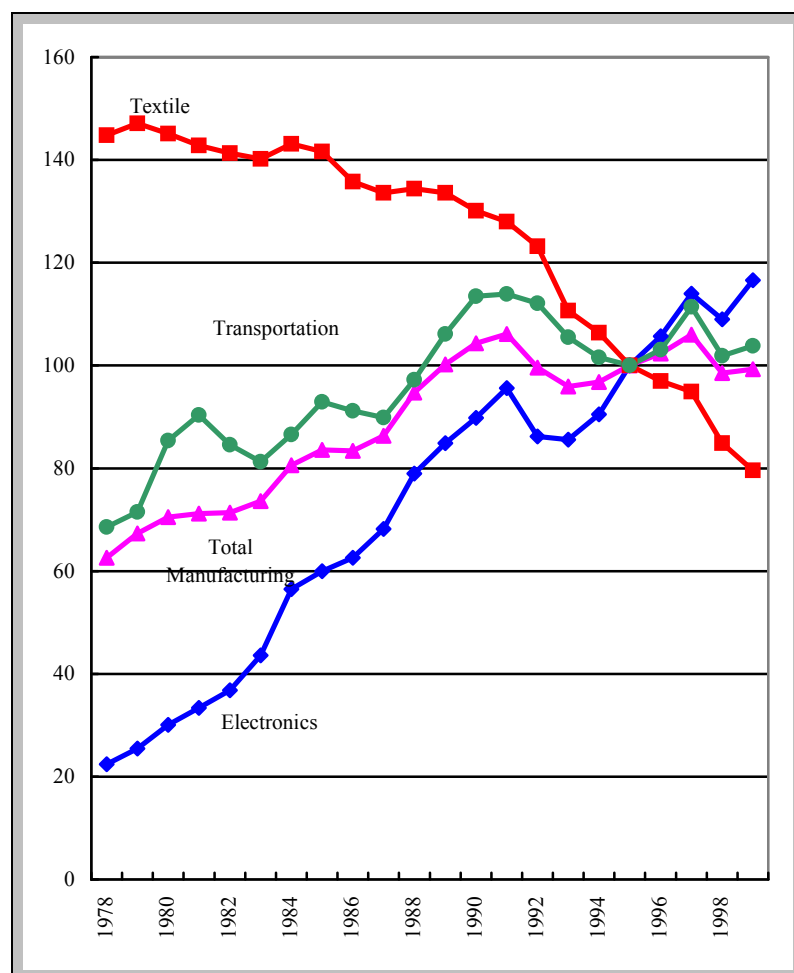
²³ Maddison, *Monitoring the World Economy, 1820-1992*, calculated from p.183.

be necessary to shift their business to less energy-intensive production, Japanese manufacturing firms increased R&D and plant/equipment investments in technology intensive areas. In 1972, the R&D component of U.S. GDP was 2.32 %, while that of Japan was 1.86.²⁴ In 1982, the same figure for the U.S. was 2.48, while that of Japan had increased to 2.38. Steadily increasing from 1972, the percentage in Japan reached 3.02 in 1996, while the U.S. reached 2.55 and has never reached 3 percent. R&D investment in microelectronics technology in the late 1970s and 1980s led to new growth industries in consumer electronics and computers, and to higher productivity in pre-established industries. Showing the transition of the Japanese manufacturing sector's production price index for value added (1995=100)²⁵, Figure 5-7 shows that the electronics industry was steadily growing from the 1970s. The energy and labour intensive industries such as the textile and the steel and iron industry were stagnated through these periods. In contrast, the electronics industry achieved the highest growth in the 1970s and 1980s, compared to other manufacturing sectors. In this rapid growth, Japanese electronics firms released new products such as portable cassette players, videocassette recorders, and fax machines.

²⁴ Kagaku Gijutsu Chō Kagaku Gijutsu Seisaku Kenkyūsho (National Institute of Science and Technology Policy), *Kagaku Gijutsu Shihyō: Nihon no Kagaku Gijutsu Katsudō no Taikeiteki Bunseki (Science and Technology Index: Systematic Analysis of Japan's Science and Technology Activities)*, p.277.

²⁵ This index is the value added by factors of production in transforming inputs purchased from other producers into output.

Figure 5-7: Japanese Manufacturing Sector Production Price Index for Value Added (1995=100)



Source: Yano Tsunekita Kinenkai, *Sūji de miru nihon no 100 nen: Nihon Kokuseizukai Chōki Tōkeiban*, Calculated from Table 6-1, p.245.

While the Japanese electronics industry was growing in the 1970s and 1980s, American electronics firms were facing unfavourable conditions for R&D investments.²⁶ The Bretton Woods cancellation and the oil shock hit the U.S. economy. In 1973, the U.S. economy was hit by recession, the worst since the 1930s. Examining American big businesses, especially the chemical and electronics

²⁶ Examining the political economy in the U.S. consumer electronics industry, Curtis showed the decline of U.S. consumer electronics and the rise of foreign cartels. Curtis, *The Fall of the U.S. Consumer Electronics Industry: An American Trade Tragedy*.

industries, Alfred Chandler showed how they responded to the economic changes.²⁷ The increased production costs and the sharp rise in raw material costs reduced the profitability of the diversified businesses. Furthermore, competition against foreign rivals became fiercer in the 1980s. In the computer and office equipment industry, American firms such as IBM and Xerox held a significant market share both in the U.S. and abroad. However, rival firms such as Siemens and Fujitsu, NEC, and Hitachi were increasing their presence in the U.S. market.²⁸

American electronics firms faced fiercer competition than the computer and office equipment-manufacturing firms did. Japanese firms such as NEC, Hitachi, Toshiba, Mitsubishi, Matsushita, and Sony were increasing their presence in the global market. Table 5-3 shows the changes in world market share in 1960-1986 in computers, office equipment, electrical equipment and electronics, in which many firms that were involved in semiconductor laser R&D were classified. This table indicates that the U.S. firms were losing their share in the global market in these industries from the 1970s. The market share of U.S. electronics in the global market was dropping from 71% in 1960 to 27% in 1986, while that of Japan was rising from 8% to 35%. Two U.S. companies among the top twelve in terms of worldwide sales of electrical equipment in 1970 not longer listed in 1986 were ITT and the RCA. Chandler noted, "by 1990, two more - Westinghouse as a victim of overdiversification and Western Electric as the result of the break-up of its parent, AT&T, in an antitrust suit - would not be among the top twelve."²⁹

²⁷ Chandler and Daems, *Managerial Hierarchies: Comparative Perspectives on the Rise of the Modern Industrial Enterprise*; Chandler, "The Competitive Performance of U.S. Industrial Enterprises since the Second World War."

²⁸ On the overdiversification of the U.S. firms and their performance, see Ibid., pp.38-39.

²⁹ Ibid., p.38.

Table 5-3: Changes in World Market Share in 1960-1986

	<i>Number of Firms in Top Twelve</i>					<i>Percentage of Sales of Top Twelve</i>				
	1960	1970	1975	1980	1986	1960	1970	1975	1980	1986
<i>Computers and Office Equipment</i>										
United States	7	9	8	8	8	95	90	90	86	84
Japan	0	1	1	2	2	0	3	3	7	10
Italy	1	1	1	1	1	3	4	4	4	4
United Kingdom	1	1	1	1	1	2	2	2	3	2
France	0	0	1	0	0	0	0	2	0	0
<i>Electrical Equipment and Electronics</i>										
Japan	2	3	3	3	4	8	17	18	21	35
United States	6	5	5	5	3	71	59	49	44	27
South Korea	0	0	0	0	2	0	0	0	0	13
Netherlands	1	1	1	1	1	10	12	15	11	11
Germany	2	2	2	1	1	10	12	15	11	10
France	0	0	1	2	1	0	0	5	12	6
United Kingdom	1	1	0	0	0	4	5	0	0	0

Source: Adopted from Table 1: Changes in 'world market share' in major industries. Franko, "Global Corporate Competition; Who's Winning, Who's Losing, and the R&D Factor as One Reason Why", pp.451-453.

American electronics firms were trying to restructure their overdiversified business and focusing their business on profitable businesses. Chandler indicated that only those firms that unbundled unprofitable businesses could maintain their position in the worldwide markets.³⁰

For instance, the sales and operational profit of GE were seriously decreasing.³¹ Confronting foreign rivals and economic stagnation, only a handful of GE's 350 business units held a leading position in their markets, which were lighting, power systems, and motors. The only businesses that were becoming profitable on a global market were plastics, gas turbines, and aircraft engines. Becoming Chairman and Chief Executive Officer of GE in 1981, John Francis "Jack" Welch Jr. tried to transform its business into more profitable and introduced a strategy that demanded each division should set out to be the number one or two in its market. In his book, he phrases it as "fix it, sell it, or close it".³² Jack Welch relinquished unprofitable businesses, which were not or were regarded not to be the number one or two in the market.

RCA, which was a consumer electronics manufacturer established in 1919 by GE, became one of the largest companies in the world in the 1960s.³³ Based on success in radio, TV, and the consumer electronics appliance manufacturing business, RCA diversified far beyond its original focus on electronics and communications from the mid 1950s. Taking steps toward becoming a conglomerate, the company acquired Hertz (rental cars), Banquet (frozen foods), Coronet (carpeting), Random House (publishing) and Gibson (greeting cards).³⁴ RCA was becoming one of the largest companies in the world in the 1960s led by David Sarnoff, who became president of RCA in 1930. RCA, however, was plagued by financial problems from the mid 1960s due to the increased costs of material and production and the loose

³⁰ Chandler, "The Competitive Performance of U.S. Industrial Enterprises since the Second World War", pp.38-39.

³¹ On GE's business and its restructuring, see Slater, *Jack Welch and the GE Way: Management Insights and Leadership Secrets of the Legendary CEO*.

³² For "fix it, sell it, or close it" policy, see Welch, *Jack: Straight from the Gut*, pp.106-110.

³³ For an overview of RCA business history, see Sobel, *RCA*.

³⁴ *Ibid.*, pp.184-198.

management of the diversified businesses. RCA posted a financial loss in 1966 and that trend continued to flow for the rest of the decade. RCA dissolved its businesses in 1986. GE merged with RCA and sold its consumer electronics business to a French electronic consumer manufacturer, Thomson SA. The entertainment division of RCA was sold to a German media company Bertelsmann AG. RCA's R&D laboratories was transferred to SRI International (Stanford Research Institute International), which was a nonprofit research organisation performing client-sponsored R&D for government agencies, commercial businesses, and private foundations. Chandler concluded, "Losses in consumer electronics resulted from U.S. companies' over diversification, especially by the dominant firm, RCA."³⁵

In these historical contexts, the U.S. firms that had been involved in semiconductor laser R&D took a different R&D strategy from Japanese firms. Many of the U.S. firms did not participate in epitaxy technology R&D competition. While Japanese electronics firms were growing, the U.S. electronics firms relinquished unprofitable business division and focused their managerial resources into areas in which their divisions had already emerged as profitable.

Vertical Integration and R&D Strategy

The level of vertical integration of the firms also influenced the R&D strategy of the firms. Analysis of the competing firms' level of vertical integration reveals that Japanese firms involved in semiconductor laser R&D competition had more incentive to compete in the same technological area than their American rivals did.

The point of departure of this section lies in the observation that Japanese firms were more vertically integrated than American firms. Tables 5-4 and 5-5 list the firms involved in semiconductor laser R&D and their final products. A black dot denotes that the firm produced or planned to produce a final product from the 1980s

³⁵ Ibid., p.39.

through 1990. Showing whether the firms were manufacturing only semiconductor laser or whether they were involved in producing a final semiconductor laser product, these tables demonstrate the level of downward vertical integration of firms in the semiconductor laser business. Since there is no survey and business directory that covers all firms manufacturing semiconductor lasers in the world, this thesis uses three international surveys on semiconductor laser products conducted in 1984, 1987, and 1991.³⁶ It also uses corporate technical journals published by firms from 1970-1990 as a complementary source. However, it must be noted that corporate technical journals can play only a supplemental role in comparing the level of vertical integration because not all of the listed firms publish their own technical journals. A black circle is marked, if the three surveys indicated that a firm manufactured the product. A white square denotes that R&D information on the product was released in corporate technical journals. If both the surveys and corporate journals showed that firms manufactured the product, then only a black circle is marked in the tables.

³⁶ Arthur, "Optical Disc Storage & Document Image Processing Systems: A Guide and Directory 1991", pp.39-82. Hendley, "CD-Rom and Optical Publishing System", pp.140-142. Yano Keizai Kenkyūjyo (Yano Research Institute), *Kakudai Suru Rēzā Sangyō no Shijō Jittai to Kongo no Juyō Tenbō*, (*Survey on Semiconductor Laser Market and Its Prospects*), pp.10-16.

Table 5-4: Semiconductor Laser and Final Products of the U.S. Firms 1984, 1987 and 1991³⁷

Firms	Final Products								
	Optical Fibre	CD-ROM	Rewritable	WORM	Document Image Processing Systems ³⁸	Compact Disc	Laser Printer	Research Instrument Others	Technical Journal / Corporate History
Bell	<input type="checkbox"/>							<input type="checkbox"/>	<i>AT & T Bell Laboratories Technical Journal</i>
Xerox							●		<i>Dealers of lightning</i>
RCA						<input type="checkbox"/>			<i>RCA: A Historical Perspective</i>
IBM	<input type="checkbox"/>	●	<input type="checkbox"/>	<input type="checkbox"/>	●		●		<i>IBM Journal of Research and Development</i>
GE						<input type="checkbox"/>		<input type="checkbox"/>	<i>GEC Journal of Science and Technology/ GEC Journal of Research</i>
Hughes Aircraft									NA
Motorola									<i>Technical Disclosure Bulletin</i>
Perkin-Elmer									NA
HP		<input type="checkbox"/>	●	<input type="checkbox"/>	●		<input type="checkbox"/>	<input type="checkbox"/>	<i>Hewlett-Packard Journal</i>
North American Rockwell									NA
Westinghouse									NA

³⁷ Regarding CD-ROM, Rewritable Disc, WORM (Write-Once-Read-Many), Optical Storage Subsystems, Jukeboxes, Document Image Processing Systems, data is collected from Arthur, "Optical Disc Storage & Document Image Processing Systems: A Guide and Directory 1991", pp.39-59.

³⁸ This colum includes 1.PC/Microcomputer, based DIP (Document Image Processing) Systems, 2. Workstation/Unix based Office DIP Systems, 3. Minicomputer & Mainframe based DIP Systems, 4. Special Purpose DIP Systems, 5. Large Format DIP Systems, and 6. Data Storage & Cold Systems. On these systems, see Arthur, "Optical Disc Storage & Document Image Processing Systems: A Guide and Directory 1991", pp.55-59.

Western Electric									NA
Energy Conversion									NA
Texas Instrument									NA
International Standard Electric									NA
Exxon									NA
3M									<i>A century of Innovation: 100</i>
Standard Cable									NA
National Semiconductor									NA

Source: Arthur, "Optical Disc Storage & Document Image Processing Systems: A Guide and Directory 1991", pp.39-82. Hendley, "CD-Rom and Optical Publishing System", pp.140-142. For Compact Disc, and Laser Printer/ Scanner, Yano Keizai Kenkyūjyo (Yano Research Institute), *Kakudai Suru Rēzā Sangyō no Shijō Jittai to Kongo no Juyō Tenbō*, (*Survey on Semiconductor Laser Market and Its Prospects*), pp.10-16.

Table 5-5: Semiconductor Laser and Final Products of Japanese Firms 1984, 1987 and 1991

Firms	Final Products								
	Optical Fibre	CD-ROM	Rewritable	WORM	Document Image Processing Systems	Compact Disc	Laser Printer/Scanner	Research Instrument Others	Technical Journal / Corporate History
NEC		●	□	□	□	●	●		<i>NEC Technical Journal</i>
Hitachi		●	●	●	□	●			<i>Hitachi Hyōron</i>
KDD	□								<i>KDD Technical Journal</i>
Fujitsu		□	□	□			●		<i>Fujitsu Scientific and Technical Journal</i>
Mitsubishi		□	□	●		●	●		<i>Mitsubishi Denki Gihō</i>
Toshiba		●	□	●	□	●			<i>Toshiba Gihō</i>
Matsushita (Panasonic)		●	●	●	□	●	●		<i>Matsushita Technical Journal</i>
Sharp		□	□	□		●			<i>Sharp Technical Journal</i>
Sony		●	●	●		●			<i>Made in Japan, Akio Morita and Sony</i>
Sumitomo	□								<i>Sumitomo Electric Review</i>
Sanyo		●	□	□		●			<i>Sanyo Technical Review</i>
NTT	□								<i>Electrical Communications Laboratories Technical Journal</i>
Rohm									<i>Rohm Data Book</i>
Oki									<i>Progressive spirit: the 120-year history of Oki Electric</i>

Source: Arthur, "Optical Disc Storage & Document Image Processing Systems: A Guide and Directory 1991", pp.39-82. Hendley, "CD-Rom and Optical Publishing System", pp.140-142. For Compact Disc, and Laser Printer/ Scanner, Yano Keizai Kenkyūjyo (Yano Research Institute), *Kakudai Suru Rēzā Sangyō no Shijō Jittai to Kongo no Juyō Tenbō*, (Survey on Semiconductor Laser Market and Its Prospects), pp.10-16.

Table 5-5 reveals that many Japanese firms were manufacturing optical storage products (e.g., Compact Disc and CD-ROM). Table 5-4 indicates differences between the U.S. firms' final product selections. Compared to Japanese firms, far fewer firms manufactured the final products. Japanese firms were more involved in various final products than the U.S. firms were. Many Japanese firms were involved in manufacturing multiple final products; however, in the U.S. only IBM, HP, and Xerox were involved in more than one area of the final products.

The difference in the level of downward vertical integration affected the strategic technological choice of the competing firms. Japanese firms, which integrated downward process more than the U.S. firms, internalised both semiconductor laser manufacturing and final product assembly. In other words, Japanese firms had secure in-house demand for semiconductor lasers. They undertook complex negotiations on the specification and price of the semiconductor lasers not through market transaction but through organisational decision-making.³⁹ They could also negotiate on the timing and amount of semiconductor laser supply through their administrative hierarchy. Furthermore, the firms could strategically source semiconductor lasers of their own internally, even if their semiconductor lasers were slightly less competitive in price or quality than those of their rivals. Exploring the integrated circuit industry, Hashimoto pointed out that the vertically integrated Japanese firms were better positioned to invest in integrated circuit R&D because their in-house demand reduced the risk that they could not profit from their R&D.⁴⁰ As Hashimoto indicated in the integrated circuit industry of Japan, the secure in-house demand for semiconductor laser was another important factor that allowed Japanese firms to invest in semiconductor laser R&D where many firms were competing with a similar technological choice.⁴¹

³⁹ On hierarchical decision-making and market transaction, see Williamson, *Markets and Hierarchies: Analysis and Antitrust Implications: A Study in the Economics of Internal Organisation*; Williamson, "The Economics of Organisation: The Transaction Cost Approach"; Coase, *The Firm, the Market, and the Law*; Coase, Winter, and Williamson. *The Nature of the Firm: Origins, Evolution, and Development*.

⁴⁰ Hashimoto, *Nihon Keizai Ron (Japanese Economy)*, p.126.

⁴¹ Examining technological choice in the U.S. and Japanese digital watch industries in the

Since the U.S. firms did not integrate the downstream manufacturing process much, they negotiated on the specification and price of semiconductor lasers through market transactions. The large and firm-specific investments could give rise to a hold-up problem. However, since both MBE and MOCVD were important core semiconductor laser technologies for the emerging high-volume markets, it was necessary to establish large scale manufacturing facilities. The low level of downward integration made it difficult for the U.S. firms to invest in MBE and MOCVD, when they were focusing their businesses on the profitable areas in the 1970s and 1980s as presented above. The firms sought to select profitable smaller markets and assumed a product-differentiation strategy in order to avoid the hold up problem. If they could not do so, they exited from the competition. Bell, IBM, and Xerox, which integrated multiple final product manufacturing processes or planned to manufacture final products, were competing in both MBE and MOCVD for relatively longer periods than the other less integrated firms.

1970s, Numagami pointed out that Japanese firms had a greater incentive to undertake parallel R&D projects than the U.S. firms did. Under the system of flexible market transaction, the firms could flexibly respond to technological change in the industry by changing their transaction partner on the one hand. On the other hand, under inflexible market transaction, which Japanese firms were facing, the firms tended to run parallel R&D projects so that they could respond to technological change of the industry through the administrative control. Numagami, "Flexibility Trap: A Case Analysis of U.S. and Japanese Technological Choice in the Digital Watch Industry." This argument suggests important points about the difference in technological choice between U.S. firms and Japanese firms. However, it does not fit well with the situation, which the semiconductor laser manufacturers were facing in the 1970s and 1980s. The argument assumes that there are several device manufacturers in the market that can supply different technologies so the firms could change their part suppliers. However, there were no device manufacturers in the market that could supply semiconductor lasers with either MBE or MOCVD.

5.4. Competition and Knowledge Spillover

The previous section discussed how Japanese firms could compete in the same technological areas with their rivals because they had a secure in-house demand for the semiconductor laser. The U.S. firms--many of which were less integrated--tended to differentiate their R&D.

This section discusses how the R&D strategies of the firms and the patterns of competition in the U.S. and Japan affected the nature of knowledge spillovers and how different trajectories of technological development emerged through different patterns of R&D competition and different institutional settings.

This section pays attention to two types of knowledge: domain-specific knowledge and lateral utilization knowledge.⁴² It assumes that the nature of knowledge spillover may vary depending on what types of knowledge are spilt. Then, it examines how different types of knowledge spillover emerged through the firms' different R&D strategies and different institutional settings and how the nature of knowledge spillover resulted in the different trajectories of technological development in the U.S. and Japan.

Competition and Knowledge Spillover in Japan

Why did not Japanese firms differentiate their technological choice and target niche markets by exploiting the current semiconductor laser? One of the reasons was that it was necessary for the firms to satisfy growing in-house demand for semiconductor lasers. The corporate technical journals clearly indicate that the primary R&D goal was to provide semiconductor lasers to in-house assembly lines for final products.⁴³ Since it was projected that the demand for optoelectronics

⁴² On the knowledge spillovers and these types of knowledge see 1.1. *Knowledge Spillover and Technological Change* in the first chapter.

⁴³ Much of the research in the corporate technical journal indicated that the firms were researching and developing the semiconductor laser primarily to satisfy their in house

products such as compact discs, laser printers, and POS scanners would be enormously growing, it was necessary for the firms to have a stable and secure semiconductor laser supply, as these were the most important devices for these products. The interviewees noted,

“Because the semiconductor laser was one of the most important devices, we believed that it was necessary to source it internally in order have a secure and reliable laser supply. If we were behind rivals in R&D for the key device, it would be a serious disadvantage for the firm.” [Interviewee: B]

“Because the semiconductor laser was the key component, we believed that it was indispensable to source it internally, even if it would be not profitable in the short term.” [Interviewee: K]

“In-house users played very important roles. We sourced internally other components and designed the system configuration of final products. So, even if we could not currently develop the best semiconductor laser, we could possibly cover the poor quality by modifying other components and changing the system configuration of the final product. Therefore, even if we could not currently develop the best semiconductor laser, we hoped that we would win R&D competition in next generation semiconductor laser technology, and we kept investing in semiconductor laser R&D.” [Interviewee: H]

Second, lateral utilization knowledge spillover, which was needed to apply the semiconductor laser for the new untapped markets, was limited among Japanese

demand. For example, Kondō et al., "Konpakuto Dhisuku Purēyāyō MPL-2 gata Hikari Pikkuappu (MLP-2 Optical Pick Up for Compact Disc Player) ", p.742; Aiki et al., "Laser Diodes for Optical Information Processing Systems", p.45.

firms, while Japanese firms obtained domain-specific knowledge spillover from rival firms because they were competing in the same technological areas with a similar technological choice. Japanese firms were competing in the same technological areas for longer than U.S. firms. Since a number of firms were competing in the same technological area for a certain amount of time, the aggregated amount of R&D investment in the area became larger. The increase in R&D investment enhanced the possibility of successful R&D results.

Furthermore, this pattern of technological choice of the firms affected the knowledge spillover. Many Japanese firms were undertaking parallel R&D in MBE and MOCVD from the beginning of the 1980s. Competition among the firms making the same technological choice induced domain-specific knowledge spillover more than lateral utilization knowledge spillover because the firms were competing in the same technological areas with similar technological choice.

Reverse engineering and patent publication were important sources of the knowledge spillover. Reverse engineering is an important method for a firm to learn from its competitors, especially when the technology is composed of complex sub-technologies. It is a good source for domain-specific knowledge in particular because it involves taking apart an object to determine how it works, for the purpose of duplicating or enhancing the object. Corporate engineers of Japanese firms that were engaged in semiconductor laser R&D purchased competitors' semiconductor lasers, tested their quality, disassembled them, and examined the structure and the mechanisms as a means of enhancing their own semiconductor lasers.⁴⁴ The responses to the interview questions (5) "How did you approach technological knowledge created by other organisations?" and (6) "Did you have any particular organisation in which you paid attention to their research?" provide some insight into the nature of the spillover effect in Japan. Examples include the following:

"We bought every semiconductor laser provided by the other firms

⁴⁴ For instance, see Mamine, "Handōtai Rēzā Kaihatsu no Ayumi, (History of the Development of Semiconductor Laser)", p.70.

and did reverse engineering for them.” [Interviewee: K]

“We did reverse engineering for semiconductor lasers on the market. But we tested only semiconductor lasers from Japanese firms because U.S. made semiconductor lasers were customized for special needs.” [Interviewee: H]

“The semiconductor lasers from the U.S. and European firms were out of our sight because the performance of their semiconductor lasers was not high enough for our needs.” [Interviewee: G]

These suggest that reverse engineering became an important source of domain-specific knowledge spillover because the firms were competing in the same product market with similar technological choices.

The previous literature on the U.S. and Japanese patent systems has discussed how far the Japanese patent system played an important role in the knowledge flow.⁴⁵ The individual countries had several differences in their patent systems from those of other developed countries, although the developed countries are attempting to standardize patent systems. Much of the previous literature on the Japanese patent system indicated that Japanese firms had a higher tendency to patent their R&D outcome compared to U.S. firms. It concluded that the institutional features of the Japanese patent system induced innovators to disclose technological information sooner than under the U.S. patent system and promoted technological diffusion and technological progress. Ordoover pointed out several institutional features in the Japanese patent system including the “first-to-file” rule, pre-grant disclosure, pre-grant opposition, and licensing and royalties.⁴⁶ One of the biggest

⁴⁵ Aoki and Prusa, "Product Development and the Timing of Information Disclosure under U.S. and Japanese Patent Systems"; McDaniel, "Legal Features of the Japanese Patent System and Impacts on Technology Diffusion"; Ordoover, "A Patent for Both Diffusion and Exclusion."

⁴⁶ Ordoover, "A Patent for Both Diffusion and Exclusion."

institutional differences in the patent system between the U.S. and Japan is the file principle. The Japan Patent Office employed the “first-to-file” principle, which has been employed by most countries in the world (except for the U.S., Canada, and the Philippines). In this system, a patent is granted to the first person filing an application for the patent. Therefore, the firms have an incentive to apply for a patent for their R&D output, even though it discloses technological information. The U.S. and Canada employed the “first-to-invent” rule, which grants the patent to the person who first invented the item. As will be described in the following section, it is a rational strategy for firms not to patent a strategically important R&D outcome in order not to disclose it to the public to increase the appropriability of the R&D under the “first-to-invent” system.

The previous literature has revealed that patent information plays an important role in monitoring rival firms’ R&D and learning from rivals.⁴⁷ As the previous literature on the patent system projected, Japanese firms increased the number of patents in semiconductor laser technology as shown in the first chapter. The increased number of patents in semiconductor laser technology from the firms competing in the same technological areas with similar technological choice provided a great source to induce domain-specific knowledge spillovers to Japanese firms.

The patent citation of Japanese firms implies this knowledge flow. Table 5-6 shows the patent citations that Japanese firms obtained for their own patents and show the transition of knowledge flow from the 1970s and 1980s.

⁴⁷ Gotō, *Inobēshon to Nihon Keizai*, (*Innovation and Japanese Economy*), p.41 and pp.146-147.

Table 5-6: Patent Citation by Japanese Firms

	1970-1979	1980-1989
Number of Patents	164	3490
Number of Cited U.S. firms' Patents	62 (61.4%)	1609 (34.2%)
Number of Cited Japanese firms' Patents	21 (20.8%)	2477 (52.7%)
Other	18 (17.8%)	613 (13%)

Source: *Derwent Innovations Index*. The Derwent Innovation Index was used to identify all of the patents that U.S. firms and Japanese firms obtained in these time periods. Then, it was used to check the citations that individual patents obtained up to 2006. Lastly, the cited and citing patent's assignee was investigated to show the citation linkage.

The table shows the number of cited patents that Japanese firms received in the 1970s and the 1980s. First, this table shows that Japanese firms cited U.S. firms' patents (61.4%) more than Japanese patents (20.8%) in the 1970s. This reflects two facts. The first is that American firms such as Bell and IBM were leading research organisations in semiconductor laser R&D in the 1970s. Japanese firms followed and learnt from these U.S. leading firms in the 1970s. The second is that Japanese firms could learn from the U.S. firms in the 1970s because all American and Japanese firms were competing for the same technological target. However, Japanese firms cited their firms' patents more than the U.S. firms' patents in the 1980s. This suggests that Japanese firms obtained technological spillovers from Japanese rival firms more than from U.S. firms in the 1980s. It is the result of the pattern of competition whereby Japanese firms were competing in the same technological area through the 1970s and 1980s, while the U.S. firms were differentiating their R&D targets from the 1980s.

The research network of Japanese firms also played an important role in determining the nature of knowledge spillovers. As much of the previous literature indicated, the nature of the research network can significantly affect a firm's R&D activity and the trajectory of technological development.⁴⁸ A research network can

⁴⁸ Podolny and Stuart, "A Role-Based Ecology of Technological Change"; Merton, "Priorities in Scientific Discovery: A Chapter in the Sociology of Science"; Bijker, Hughes, and Pinch, *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*; Latour, *Science in Action: How to Follow Scientists and Engineers through Society*; Latour, Woolgar, and Salk, *Laboratory Life: The Construction of Scientific Facts*.

function as an important institutional conduit through which one may be able to access complementary knowledge. As shown in the third chapter, formal inter-organisational networks were fairly limited in Japan, compared to those of the U.S. and Europe. The inter-organisational collaboration was much smaller in Japan than in the U.S. and Europe.

Moreover, all of the participating firms in the collaborative research were electronics or telecommunication enterprises competing in the same product markets with a similar technological choice. As shown in Figure 3-6 in the third chapter, the only firms participating in formal inter-organisational collaboration were NTT, Fujitsu, and Hitachi, all of which were electronics and telecommunication firms competing in the same technological areas. This suggests that it was rare for Japanese firms to access complementary knowledge through a research network.

The more the firms competed in the same technological areas with the same technological choice, the more the knowledge stock regarding epitaxy technologies was accumulated, which brought increasing returns to the firms' R&D in those areas. Through competition among the firms targeting the same R&D goals with similar technological choice, Japanese firms solved the technological problems of MBE and MOCVD. The AIST reported that Japanese firms were leading in epitaxy technology around the world. Because epitaxy technology was important for mass production of the semiconductor laser, Japanese firms became competitive particularly in high volume consumer electronic semiconductor laser-related products such as optical information storage products, which were the biggest market in the optoelectronics industry.⁴⁹

As described above, many firms such as Hitachi, Toshiba, Mitsubishi Electric, Matsushita, NEC, Fujitsu, Sony, Sharp, and Sanyo were competing to develop reliable and long-lifespan lasers for high volume growing optical information storage market using MBE or MOCVD. First, developing a reliable laser, named VSIS, using LPE, which was the status quo epitaxy technology, Sharp

⁴⁹ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, pp.6-9.

gained a 70% market share for its 780 nano meter semiconductor laser, which was mainly for compact discs and dominated the laser in the beginning of the 1980s.⁵⁰ The first compact disc released in 1982 by Sony used the VSIS laser. The second biggest producer was Mitsubishi Electric at that time. Starting R&D in MOCVD from the end of the 1970s, Sony developed a reliable MOCVD and began pilot production of semiconductor lasers using MOCVD in 1984.⁵¹ With the MOCVD, Sony's semiconductor laser gained a significant market share from 1984. After the epitaxy technology for mass production was fully developed, many Japanese firms were still competing in the high volume market. In November 1993, newspaper reported that a Japanese electric and chemical component manufacturer, Nichia Chemical industries, Co. Ltd, had invented a blue colour laser, which was regarded as a big technological breakthrough for information technology.⁵² Through competition in the same technological areas among many firms, technological breakthroughs in semiconductor lasers for the high volume market emerged one after another in Japan. The firms were competing to develop a shorter wavelength laser, which could allow high volume information storage, and holding a significant market share in this sector, as the JTEC report indicated.⁵³

⁵⁰ Wood and Brown, "Commercializing Nascent Technology: The Case of Laser Diodes at Sony", pp.178-179.

⁵¹ Ibid.

⁵² On Nichia Chemical Industries and its blue laser, see Fujii, "Nichia Chemical Industries Co.,Ltd.: How Can a Growing Firm Sustain its Strategic Position? "

⁵³ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, pp.6-9.

Competition and Knowledge Spillover in the U.S.

While domain-specific knowledge spillover was enhanced among Japanese firms, lateral utilization knowledge spillover emerged in the U.S. Although various factors can affect the knowledge spillover, this section directs its attention to the patent system, the research networks, and the venture businesses in the U.S. and discusses how these affected the nature of technological knowledge spillovers.

First, comparing the U.S. and Japanese patent systems, the previous literature concluded that the institutional features of the Japanese patent system induced innovators to disclose technological information sooner than under the U.S. patent system and promoted technological diffusion and technological progress.⁵⁴ The patent system in the U.S. and Canada was different from the Japanese patent system. The U.S. and Canada employed the “first-to-invent” rule, which grants the patent to the person who first invented the item, while Japan and other countries (except for the Philippines) used the “first-to-file” rule. In the “first-to-invent” principle, an inventor who can demonstrate priority with dated and witnessed laboratory notes, disclosures, etc., and can diligently reduce it to practice will be able to patent an invention, even if someone has already filed claiming that invention. Compared to the first-file rule, the incentive to file is much less in this system because the first inventor, not the first filer, is rewarded so that the inventor’s time and money are not diluted. It is a rational strategy for firms not to patent a strategically important R&D outcome in order not to disclose it to the public to increase the appropriability of the R&D under the “first-to-invent” system. American and Canadian firms, therefore, had less incentive to patent their R&D outcome than did Japanese firms. From the conclusion of the previous literature, it is possible to premise that the technological knowledge spillover through patents was not developed in the U.S., compared to Japan.

Second, the semiconductor laser research network in the U.S. was much

⁵⁴ Aoki and Prusa, "Product Development and the Timing of Information Disclosure under U.S. and Japanese Patent Systems"; McDaniel, "Legal Features of the Japanese Patent System and Impacts on Technology Diffusion"; Ordober, "A Patent for Both Diffusion and Exclusion."

more developed than that of Japan and Europe, as presented in the third chapter. The participating organisations were more diversified in terms of their technological and business background than the participants of the Japanese research network (Figure. 3-6) The business background of the participating firms was diverse. For example, both Ford and General Motors were motor vehicle and car body manufacturers, and Micron was specialising in the production of voltage magnetrons. Pioneering systems engineering, TRW was developing missile systems and spacecraft. This suggests that the U.S. firms, which were involved in semiconductor laser R&D, accessed more complimentary knowledge through the research network than Japanese firms could.

Third, venture business played an important role in determining the nature of knowledge spillovers. The monthly report of the Industrial Bank of Japan reported, “Small and middle size business ventures played a central role in the U.S. optoelectronics industry except for a few large scale telecommunications companies and optical fibre manufactures.”⁵⁵ The JTEC reported:

“Due to the vibrant entrepreneurial industry base that is an integral part of the U.S. economy and which is apparently nearly absent in Japan, numerous small companies have spun-off from their larger, parent companies.”⁵⁶

“These small businesses, which generally specialize in the manufacture of photonic components, are rarely positioned to compete head-to-head with the larger, systems-oriented companies; instead, they tend to specialize by filling narrow niches. As companies become established, the niches expand with the manufacture of additional specialized, unique devices produced to

⁵⁵ Nippon Kōgyō Ginkō (the Industrial Bank of Japan), “Hikari Sangyō no Shōrai Tenbō (the Prospects for the Optoelectronics Industry)”, p.77.

⁵⁶ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, p. xvii

fill the needs of particular subsets of customers.”⁵⁷

Many technology-intensive startups spun off from intellectual hubs, which were observed in the collaborative networks examined in the third chapter. For instance, Spectra Diode Labs, Inc was founded in 1983 as a joint venture between Xerox and Spectra Physics, Inc. Spectra Diode Labs developed and manufactured high-power solid-state semiconductor lasers. Lytel was founded by a star spin-off engineer from RCA, in New Jersey in 1986. Many ventures were involved in collaborative research with such intellectual hubs as RCA and the University of Illinois Urbana-Champaign. The startups that spun off from the intellectual hubs were regarded as the source of knowledge spillovers.⁵⁸ The venture firms tended to invest in applied semiconductor laser technology instead of the fundamental technology of the semiconductor laser, since they had spun off from the intellectual hubs to target niche and custom product markets.⁵⁹ This suggests that lateral utilization knowledge spillover was enhanced in American firms more than domain-specific knowledge spillover.

Numerous small startups such as Lasertron, Sensors Unlimited, and Ortel launched into business to manufacture highly specialized laser, modulator, or detector devices, all of which were niche markets (Table 5-7).⁶⁰

⁵⁷ Ibid, p.xvii.

⁵⁸ On the relationship between the technology-intensive venture business and the knowledge spillovers, see Dorfman, "Route 128: The Development of a Regional High Technology Economy"; Florida and Kenney, "Venture Capital, High Technology and Regional Development."

⁵⁹ Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, p.10.

⁶⁰ Ibid., p.7

Table 5-7: Example of Venture Business in Semiconductor Lasers

Company	SIC Code Business Description
Lasertron	Industrial and commercial machinery and equipment, not elsewhere specified
Ortel ⁶¹	Printed circuit boards
Sensors Unlimited ⁶²	Drawing and insulating of nonferrous wire
Judson Technologies ⁶³	Search detection, navigation, guidance, aeronautical and nautical systems and instruments manufacturing
Varian Associates ⁶⁴	Public relations services
Spectra Diode Labs	Manufacturing high power semiconductor laser ⁶⁵
Mictron Inc	Industrial and commercial machinery and equipment, not elsewhere specified
Tektronix Inc	Instruments for measuring and testing of electricity and electrical signals

Source: Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*, p.7. ICARUS⁶⁶.

The spin-off engineers played an important role in these venture business. The spin-off engineers from big companies and the engineers' mobility across firms are important sources of technology transfer and knowledge spillovers. Examining career patterns within the industrial, academic, and governmental sectors and their relation to the publication and patent productivity in the U.S., Dietz and Boseman

⁶¹ Ortel is now a division of Emcore established in 1984, which is a manufacturer of semiconductors and related devices. ICARUS.

⁶² Sensors Unlimited is now one division of Optical and Space Systems in Goodrich Corporation, which was established in 1870 and whose business is aircraft parts and auxiliary equipment manufacturing. ICARUS.

⁶³ EG&G Judson is currently Judson Technologies, LLC, which was established in 2000 and whose business is search, detection, navigation, guidance, aeronautical and nautical systems and instruments manufacturing. ICARUS.

⁶⁴ In 1999, Varian Semiconductor Equipment Associates, Inc spun-off of Varian Associates.

⁶⁵ SIC Code is not available for Spectra Diode Labs in ICARUS.

⁶⁶ ICARUS is a database containing profiles of 1.4 million public and private U.S. companies and 175,000 public and private Canadian companies. An ICARUS report typically contains information such as contact information, details of sales and number of employers, activities (US SIC and NAICS).

showed that intersectoral changes in jobs through the career provided access to new social networks and scientific and technical human capital, which resulted in higher productivity.⁶⁷ Much of the previous literature on technology intensive startups indicated that star spin-off engineers played a significant role in knowledge spillovers and industrial development in the technology intensive industry in Silicon Valley in California and Route 128 in Massachusetts.⁶⁸ Unlike Silicon Valley and Route 128 there was no clear regional cluster in the semiconductor laser industry. However, it was widely observed that star engineers moved from one company to another in the semiconductor laser industry. For instance, Receiving a Ph.D in both Physics and Electrical Engineering from Caltech in 1936, an American physicist, Simon Ramo, who is now known as “the father of the Intercontinental ballistic missile (ICBM)” began his engineering career in microwave research at GE from 1936 until 1946.⁶⁹ He was hired by Hughes Aircraft in 1946. In 1953, Simon Ramo launched a venture business, Ramo-Wooldridge Electronic Corporation, with Dean W. Wooldridge, his colleague at Hughes Aircraft. Ramo-Wooldridge was involved in ICBM R&D with the U.S. Air Force. Ramo-Wooldridge merged with Thompson Products to become TRW⁷⁰, which supported Gordon Gould’s laser research. This mobility permeated into the industry throughout the period of optoelectronics R&D.

This high mobility of star engineers in the U.S., which allowed firms to access complementary knowledge, was in complete contrast with that of Japan. As the previous literature on the Japanese labour market indicated, it was quite rare that for star engineers to transfer from one company to another in Japan in the semiconductor laser industry. Investigating the role played in the process of

⁶⁷ Dietz and Bozeman, "Academic Careers, Patents, and Productivity: Industry Experience as Scientific and Technical Human Capital."

⁶⁸ Dorfman, "Route 128: The Development of a Regional High Technology Economy"; Koepp, *Clusters of Creativity: Enduring Lessons on Innovation and Entrepreneurship from Silicon Valley and Europe's Silicon Fen*; Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*.

⁶⁹ Robinson, *United States Business History, 1602-1988: A Chronology*. p.291. On Simon Ramo in detail, see his book, Ramo, *The Business of Science: Winning and Losing in the High-Tech Age*.

⁷⁰ For overview of TRW’s history, see Dyer, *TRW: Pioneering Technology and Innovation Since 1900*.

innovation by corporate “star” scientists. Furukawa and Gotō argued that the highly cited core scientists served as channels through which external knowledge flows to firms.⁷¹

Assuming that highly cited engineers were “stars”, this thesis identifies top engineers by looking at the number of academic papers and citations. Then it investigates the changes in their affiliations indicated in their academic papers in order to examine the mobility of top engineers. The analysis of the changes in the affiliation of the top engineers allows the investigation of top engineers’ mobility in the U.S. and Japan. This thesis uses two databases for this analysis; *Web of Science* and *Scitation*. Thomson Scientific covers approximately 6,125 journals and provides an online database, *Web of Science*, allowing identifying citation trends and highly cited engineers in semiconductor laser technology from 6,125 active journals in the natural sciences. However, it does not provide detailed affiliation information. Therefore, using another database, *Scitation*, the thesis attempts to identify the affiliation of the top fifty highly cited engineers. Because *Scitation* covers all of the important academic journals in applied physics and provides not only reference and citation information but also authors’ detailed affiliation information, it is possible to trace the mobility of engineers by investigating their affiliations.

Calculated by the number of academic papers published from 1960 to 1990 and the number of their citations until March of 2007, Table 5-8 show the top fifty highly cited engineers in semiconductor laser technology in the U.S. and Japan based institutions from 1960 to 1990. Examining their affiliations, this table shows the mobility of the highly cited engineers.⁷² If the engineer changed his/her affiliation once (e.g. from Bell Laboratory to UC Berkeley) from 1960 to 1990, this thesis counts two for its affiliation. If the engineer did not change his/her affiliation at all in this time period, the thesis counts one for its affiliation. This table clearly shows that the mobility of the highly cited engineers was higher in the U.S. than

⁷¹ Furukawa and Gotō, "The Role of Corporate Scientists in Innovation."

⁷² See Appendix V for the full list of the top fifty engineers and their affiliations.

Japan.⁷³

Table 5-8: Mobility of Top Fifty Engineers

	Engineers of U.S. Organisation	Engineers of JPN Organisation
Number of observation	50	50
Average number of affiliations held by engineer	2.1	1.1
Variance	1.69	0.09
Median	2	1
Maximum	5	2

Source: *Web of Science. Scitation.*

It must be noted that such academic paper citation does not necessarily capture all of the top engineers, since the publicising activity of engineers is highly dependent on his/her organisation's policy. Some firms may encourage their engineers to publish R&D outcomes in academic journals. Other firms may prohibit their engineers from publishing R&D outcomes. Therefore, the author asked the interviewees whether they knew star engineers in the semiconductor laser area who changed their affiliation from 1960 to 1990. The following table lists the top four most frequently indicated U.S. star engineers by the interviewees.

Table 5-9: U.S. Star Engineers

Name	Affiliations
Botez, D	UC Berkeley--- IBM--- RCA---TRW--- Univ of Wisconsin
Dupuis, R.D.	UINC--- Bell--- Rockwell--- Texas Instruments
Tsang, W. T,	UC Berkeley--- Bell
Panish, M.B	Oak Ridge National Lab--- AVCO--- Bell

Source: *Scitation. Interview.*

Won-Tien Tsang, who received a Ph.D in semiconductor laser technology in 1976

⁷³ This finding is compatible with the findings on hypermobility of high-tech labor in California observed by Florida and Kenney. Florida and Kenney, *The Breakthrough Illusion: Corporate America's Failure to Move from Innovation to Mass Production*, pp.79-83.

from the University of California, Berkeley and devoted in his research at Bell Laboratory, was the only star engineer who did not change his affiliation during his professional career.

Over the course of their careers, Morton B. Panish, Dan Botez, and Russell D. Dupuis changed their affiliations. Morton B. Panish began his engineering career at Oak Ridge National Laboratory in 1954.⁷⁴ He moved to Research and Advanced Development Division of AVCO Corporation in 1957 and researched very high temperature chemistry. He moved to Bell Laboratory's Materials Science Research Department in 1964 and developed the first semiconductor laser that worked at room temperature with Hayashi Izuo in 1970. Dan Botez, who received a Ph.D in semiconductor laser and LPE technology in 1976 from the University of California, Berkeley and became one of the highly cited engineers in semiconductor laser technology, began his engineering career at IBM in 1976.⁷⁵ From 1977, he moved to RCA, David Sarnoff Research Centre, and developed novel types of semiconductor lasers, two of which became commercial products. In 1984, he spun off from RCA and founded Lytel Inc in New Jersey. In 1986, jointing TRW Inc, Botez continued his research in high-power semiconductor lasers. In 1998, he founded Alfalight in Madison, Wisconsin, whose business was to design and manufacture high-power semiconductor lasers for the industrial, defence, and telecommunication markets. Russell D. Dupuis, who was also one of the highly cited star engineers, received a Ph.D in 1973 from University of Illinois at Urbana-Champaign under the guidance of Nick Holonyak, who was one of the most highly cited engineers in semiconductor laser technology.⁷⁶ Transferring between several firms; AT&T Bell Laboratories,

⁷⁴ The author contacted Dr. Morton B. Panish. He kindly sent me his Curriculum Vitae and professional highlights. The following descriptions about his career are based on the CV and professional highlights.

⁷⁵ The author contacted Professor Dan Botez. He also kindly sent me his Curriculum Vitae. The following descriptions about his career are based on the CV.

⁷⁶ Nick Holonyak, Russell Dean Dupuis, and George Craford were given the National Medal of Technology by Technology Administration, US Department of Commerce, which is the U.S. federal agency working to maximise technology's contribution to America's economic growth, in 2002 for contributions to the development and commercialisation of light-emitting diode (LED) technology, with applications to digital displays, consumer electronics,

Rockwell International, and Texas Instruments, Dupuis proceeded to research semiconductor laser technology.

All of the interviewees agreed that the mobility of engineers was quite limited in Japan. The following table lists the top four Japanese engineers who were not captured by *Web of Science* but were indicated as a “star” by the interviewees.

Table 5-10: Japanese Star Engineers

Name	Affiliations
Hayashi, I.	Tokyo Univ--- Bell--- NEC--- OMCS--- Optoelectronics Technology Research
Nishizawa, J	Tohoku Univ
Suematsu, Y	Tokyo Institute of Technology
Nannichi, Y	NEC

Source: *Scitation*. Interview.

Nannichi Yasuo, Nishizawa Junichi, and Suematsu Yasuharu did not change their affiliations in the course of their engineering careers.⁷⁷

One exception was Hayashi Izuo. He began his professional career at the University of Tokyo Department of Science and Technology in 1946 and became a visiting scholar at MIT in 1963.⁷⁸ He transferred to Bell Laboratory in 1964 and developed the first semiconductor laser that worked at room temperature in 1970, which was one of the important breakthroughs in this field. He moved to the Central Research Division of NEC from 1971 to 1982. He was appointed as technical director of the OMCS project from 1982-1987.

automotive lighting, traffic signals, and general illumination. The following description on the career of Russell Dean Dupuis is based on the Biography of Russell D. Dupuis provided for the medal by Technology Administration.

⁷⁷ Nannichi Yasuo was invited to Brazil, Universidade Estadual de Campinas, to support the United Nation’s project to update information technology in Brazil and to construct optical fibres for long distance communication in 1977. He spent one year in Brazil. However, since he was on loan to Brazil and he was expected to come back to NEC, this one-year change is not included in this analysis.

⁷⁸ For his career, see, Itō, "Dai 1 kai Ōyō Butsuri Gakkai Gyōseki Jyushōsha Sōkai (the Profile of Japan Society of Applied Physics Prizewinners) ", pp.384-385.

As previously stated, American firms adopted different technological choice in epitaxy technology, which was the strategically important technology regarding the semiconductor laser. It is possible to suppose that they could access lateral utilization knowledge spillover so that they could differentiate their R&D to target untapped product markets or customized niche markets. As they differentiated their semiconductor laser R&D, lateral utilization knowledge was more accumulated in the U.S. On the other hand, R&D investment in the fundamental semiconductor laser technology was scattered and dispersed in the U.S. due to the strategic behaviour of the less integrated semiconductor manufacturers.

5.5. Conclusion

Examining epitaxy technology, which was the most fundamental technology in semiconductor lasers, this chapter explored how Japan gained competitiveness in high volume markets and how American firms held the lead in niche markets, asking these two research questions. How did Japanese firms come to compete in the same technological area with the same technological choice for a longer term than their counterparts in the U.S. did? How did this pattern of the strategic behaviour of the firms affect technological change in semiconductor lasers?

It discussed two points. First, it shows the economic conditions and the firms' level of vertical integration, which determined their R&D incentive. The less vertically integrated American firms had a stronger incentive to differentiate their products and to position themselves in niche markets. In contrast, Japanese firms, which integrated the downward process, had less incentive to differentiate their product and to find a niche market because they had secure in-house demand for their semiconductor lasers. They could strategically adopt their in-house-made semiconductor lasers, even when rival firms achieved successful R&D. The organisational transaction facilitated asset-specific R&D investment. As a result, Japanese firms competed in the same technological area longer than their American counterparts.

Second, the competition patterns differed in the areas in which knowledge spillovers emerged. Numerous venture firms spun off from the parent firms and targeted niche markets in the U.S. Therefore, knowledge spillover emerged in the areas where semiconductor laser technology was applied and exploited to fill untapped markets. While the U.S. firms assumed an R&D differentiation strategy, Japanese firms targeted the same market with the same technological choice. Epitaxy technology, the most economically and strategically important semiconductor laser technology, was their R&D target. This pattern of competition of Japanese firms induced domain-specific knowledge spillover, which enhanced the

development of fundamental semiconductor laser technology instead of exploiting niche product markets, while it reduced the level of lateral utilization knowledge spillover and precluded the firms from differentiating their R&D to target niche markets. American firms differentiated their semiconductor laser R&D and tended to target untapped small markets. Based on the rich inter-organisational networks in semiconductor laser research, the firms could access complementary knowledge to differentiate their R&D and target niche markets.

This chapter draws a somewhat ironic conclusion from the case of semiconductor laser epitaxy technology in the U.S and Japan. Since the U.S. firms were in a better position to learn how to apply the semiconductor lasers to untapped markets, they differentiated their R&D and targeted niche markets. As a consequence the R&D efforts were dispersed into different technological domains in the U.S. As a result, knowledge about epitaxy technology, which was the fundamental technology of semiconductor lasers, was not developed in the U.S. In other words, because the American firms were in a better position to learn how to apply the laser to new areas, they targeted untapped markets instead of competing to develop the core technology of semiconductor lasers for the high volume market. The highest volume market was eventually taken by Japanese firms.

Pointing out that American firms were poor imitators, Nathan Rosenberg questioned why Japanese were so much better at imitation than the Americans.⁷⁹ He pointed to effective solutions to the myriad small problems that are key to efficient mass production techniques as one of the important factors in the imitations made by Japanese industries. He argued that American engineers and scientists thinking about the innovation process focused excessively upon the upstream process. Comparing R&D activity in Japan and the U.S., Mansfield came to a similar conclusion, namely that there was a clear difference in R&D resource allocation between the U.S. firms and Japanese firms.⁸⁰ The American firms devoted their R&D resources to improve product technologies more than process technologies. On the other hand, the

⁷⁹ Rosenberg and Steinmueller, "Why are Americans Such Poor Imitators?"

⁸⁰ Mansfield, "Industrial R&D in Japan and the United States: A Comparative Study"

Japanese firms allocated their resources to process technologies rather than product technologies.

The findings of this thesis imply that the developed research networks and the nature of knowledge spillover channelled U.S. firms to allocate their resources in a certain direction. It is reasonable to assume on the one hand that if the firms could access complementary knowledge and obtain lateral utilization knowledge, they tended to allocate their resources to product technologies in order to apply their technology to a new product market.

While the U.S. firms assumed an R&D differentiation strategy, Japanese firms targeted the same market with the same technological choice. Japanese firms, which had difficulty of accessing lateral utilization knowledge, focused their R&D efforts on epitaxy technology. The inter-organisational research network through which the firms could have accessed complementary knowledge to differentiate their R&D, was not developed in Japan. As a result, many Japanese firms were channelled to compete in developing epitaxy technology, which was the economically and strategically most important semiconductor laser technology. The pattern of competition of Japanese firms induced knowledge spillovers to accelerate the development of core semiconductor laser technology instead of exploiting niche product markets.

6. Conclusions and Implications

Summarizing the arguments of this study, this chapter presents a discussion of the implications of the findings for (1) economic growth and R&D investment, (2) vertical integration and technological change, (3) competition and technological change, and (4) diseconomies of duplicated R&D. Last, it discusses some limitations of this study with a view to future research.

6.1. Summary of the Arguments

This thesis has scrutinised the development of semiconductor laser technology from 1960 to 1990 and examined how the pattern of competitive advantage indicated by the JTEC report emerged.

The first two chapters presented the research questions, methodology, and literature review. The first chapter revealed that the semiconductor laser became one of the most important electronic devices in the optoelectronics industry and that Japanese firms gained high competitiveness in semiconductor lasers. Reviewing previous arguments about the technological development of post-war Japan, the second chapter showed that the arguments about competition and technological change have been limited, although the literature does contain much discussion of the organisational setting of Japanese firms under the framework of the “Japanese management system.”

The third chapter examined the state of aggregate knowledge in the industry. Analysis of doctoral theses and academic papers on the semiconductor laser revealed that physicists began semiconductor laser research in the 1950s. However, it was not until the 1970s that physicists regularly released their findings on the semiconductor laser. Although Japan accelerated its human capital accumulation beginning in the 1970s, it was not the leading country in human capital accumulation in semiconductor laser technology. Co-authored academic papers indicate that inter-organisational collaborative research was less common in Japan than in the U.S. and Europe. The findings presented in this chapter are summarized as follows.

- **[3-1]** The U.S. and the U.S.S.R. were the two leading countries in human capital accumulation in semiconductor laser technology.
- **[3-2]** Although Japan accelerated its human capital accumulation from the 1970s, it was not the leading country in human capital accumulation in semiconductor laser technology.

- **[3-3]** Inter-organisational collaboration in semiconductor laser technology was more developed in the U.S. than in Japan and Europe.

Based on these findings, the third chapter concluded that the state of aggregate knowledge and human accumulation in the semiconductor laser in Japan was not necessarily superior to those in the U.S. and Europe.

While the third chapter examined the human capital accumulations and the research networks in semiconductor laser technology, the fourth and fifth chapters focused on the industrialization of the semiconductor laser. The JTEC indicated that the research consortium launched in 1977 played an important role in the development of the optoelectronics industry in Japan. However, the JTEC report did not present clearly how the consortium contributed to this development. Analysing the technological spillover effect among the participating firms and competition in the product market revealed the following points.

- **[4-1]** Important technology was not produced in the consortium, compared to the in-house R&D of the participating firms.
- **[4-2]** The consortium stimulated corporate private R&D in areas where the participating firms undertook joint R&D.

The consortium provided important path dependency for technological and industrial development. It stimulated the participating firms' in house R&D in the areas where they were involved in the joint research in the consortium. However, it was not the only reason for technological development and competitiveness in the industry.

The fifth chapter examined how the firms competed under the conditions provided by the research consortium. It also scrutinised important technological changes that occurred with the emergence of new epitaxy technology (i.e., LPE, MBE, and MOCVD). Concretely, by examining patents of epitaxy technology, this chapter presented the following points.

- [5-1] Most Japanese firms simultaneously engaged in R&D competition in both MBE and MOCVD, while some American firms adopted neither MBE nor MOCVD.
- [5-2] Japanese firms competed in MBE and MOCVD over relatively longer periods than American firms did.

Based on these findings, this chapter first examined the economic conditions and the level of vertical integration of competing firms in order to examine how Japanese firms competed in the same technological areas with the same technological choices for a longer term than their counterparts in the U.S. The differences in the level of downward vertical integration affected the expected returns from the firms' R&D. The less integrated U.S. firms had a stronger incentive to differentiate their products and to position themselves in a niche market since they had to sell their products to the assembler through market transactions. In contrast, because of their downward integration, Japanese firms had less incentive to differentiate their product and to find a niche market since they had secure in-house demand for their semiconductor lasers. The integrated firms could strategically source the semiconductor laser internally.

Differences in inter-organisational networks and technological choice between U.S. and Japanese firms brought about the different types of knowledge spillover. The competition among the firms that took the same technological choice and targeted the same product markets enhanced domain-specific knowledge spillover. The U.S. firms, which assumed an R&D differentiation strategy, brought about lateral utilization knowledge into the industry.

6.2. Contribution

This study aims to make four contributions. The first lies in the sources used for this thesis. In addition to academic journals in applied physics, corporate technical journals, corporate annual reports, and interview data, some of the most important data in this study were patent and patent citation data. The number of studies examining technological change in Japan with patent and citation data has been recently growing. However, they use U.S. patent data to examine technological change of Japanese firms. The lack of a good patent database in the Japan Patent Office has been a big obstacle. Therefore, much of the previous literature discussing technological innovation in Japan used either certain specifications of products or sales of certain products to explore technological change, since their primary focus was product market competition. However, product data does not necessarily reveal R&D competition, which usually precedes competition in the product market. Both patent data and patent citation data, provided by the Derwent Innovation Index in the British Library, has allowed systematic and consistent investigation of the timing of technological change and its impact. Since this research aimed to investigate R&D competition in semiconductor laser technology, patent data was a primary source. This study is the first attempt to examine technological change in R&D competition in Japan by using Japanese patent and patent citation data. One interesting finding was that the joint R&D in the OMCS, which has been recognized as successful and which became a prototype consortium for the U.S., was not successful compared to the in-house R&D of the participating firms. Supporting Katz's argument about competition among the participants in the product market, this finding reveals a double-edged implication. On the one hand, if the participating firms were direct rivals in product markets, they will underinvest in joint research, which eventually dampens the performance of joint research. On the other hand, if the participating firms were rivals in product markets, the competition enhancing effects will be spread to their product markets.

The second contribution is to the economics and business history literature

on technological development in Japan. A vast amount of literature has explored how Japanese firms gained technological competitiveness in the technology-intensive industries beginning in the 1970s. The optoelectronics industry became an important sector in the national economy of Japan in the 1980s, and the semiconductor laser was the most important electrical device in the industry. However, a very few detailed study has been done on the development of the optoelectronics industry.¹

Third, this study aimed to bridge theoretical research on the economics of the technology-intensive industry and empirical research on the competitiveness of the technology-intensive industry in Japan. Much of the previous research about technological change in Japan focused on the unique organisational and institutional features of the “Japanese management system.” Organisational settings are important supply-side mechanisms pushing technological change to a certain pattern. However, it is important to examine the dynamic process by which the supply-side mechanism evolved through competition. This thesis aims to provide a better understanding of the nature of knowledge spillover and the trajectory of technological development. Introducing two different types of knowledge; current technology domain-specific knowledge and lateral utilization knowledge, it shows how different types of knowledge spillover emerged through research networks and firms’ technological choice in the U.S. and Japan. This study is one of the first attempts to examine the pattern of technological change in post-war Japan by directing its attention to knowledge spillover.

¹ Saxonhouse and Miyazaki’s studies are two of the first studies on the optoelectronics industry. He surveyed the optoelectronics industry in Japan and provided the first important outline of the industry. Saxonhouse, “Optoelectronics in Japan: Some Economic Consideration.” Miyazaki, *Building Competence in the Firm: Lessons from Japanese and European Optoelectronics*.

6.3. Discussions and Implications

This section presents some discussions and implications induced by the argument of this thesis. First, it discusses the economic context in which the technological development of the semiconductor laser occurred. Then it presents implications about competition, vertical integration, spillover, and technological change.

Economic Growth and R&D Investment

The economic context in which the firms were competing to develop semiconductor lasers must be noted. Japan attained high economic growth, called an “economic miracle,” from 1955. It became the second-largest capitalist country in GNP in 1968. This trajectory of high and rapid economic growth was halted by the significant increase in yen value resulting from the cancellation of the Bretton Woods system and the soaring oil price soar caused by the Fourth Arab-Israeli War in 1973. However, the Japanese economy grew until 1991. R&D investment in semiconductor laser technology was undertaken in the context of steady economic growth.

Compared to the Japanese economy, the growth of the U.S. and European economies were low. U.S. post-war prosperity ended in the early 1970s. Key industries such as the automobile and steel industries began to confront competition with foreign manufacturers in the domestic market. The U.S. economy suffered from soaring inflation and inactive economic growth throughout the 1970s, reaching the most severe recession since the Great Depression in 1982. Even though the real GDP began to grow and the unemployment rate began to drop in 1982, many key industries lost their competitiveness. The European economy attained steady growth from 1976 to 1979. However, Japan achieved a relatively higher rate growth. Table

6-1 shows GDP growth rate in Japan, the U.S. and European countries after 1973.

Table 6-1: GDP Growth Rate

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Japan	8	-1.2	3.1	4	4.4	5.3	5.5	2.8	2.8	3.1
U.S.	7.1	-1.4	-0.6	2.6	2.4	3.2	2.7	-2.1	-1.5	1.9
European Union 15 countries ²	6.2	0.4	0.1	4.8	3.9	4.6	3.8	0.8	1.9	-0.1

Source: For the U.S. and European Union 15 countries, calculated from OECD Data obtained in Economic Social Data Service (ESDS)³. GDP Growth Rate for Japan is taken from *Japan Statistical Yearbook 2007*. Key Statistics p.3.

This table shows that Japan attained a higher rate of growth through the ten years after the oil crisis in 1973, compared to the U.S. and European countries. Since R&D investment in technology-intensive industry entails high uncertainty, firms tend to reduce their R&D in technology-intensive areas when they face financial difficulty. Therefore, it is possible to suppose that Japanese firms were experiencing a macro-economic environment that favoured R&D investment. While the spillover effect is an important source of technological development, it may reduce the R&D incentive of the firm. Because the R&D result of the firm might be used by its competitors, the post-innovation rents decrease when many firms compete in the same technological area. The existence of technological spillovers may reduce the degree of expected R&D returns, while it increases R&D productivity. However, since the economy was growing and the demand for the semiconductor laser was significantly increasing, the possibility that the firms could appropriate R&D results was high. When demand exceeds supply, it is possible for the rest of the firms to appropriate a certain amount of rents by meeting unsatisfied demands. Therefore, the growing economy and increasing demand enhanced the degree of expected returns

² European Union 15 countries are Belgium, France, West Germany, Italy, Luxembourg, Netherlands, Denmark, Republic of Ireland, United Kingdom, Greece, Portugal, Spain, Austria, Finland, and Sweden.

³ ESDS International aims to promote and facilitate increased and more effective use of international datasets in research, learning and teaching and provides a range of international datasets.

from R&D. Additionally, it must be noted that the pattern of R&D competition of Japanese firms was supported by the growing national economy.

Furthermore, much of the previous literature on post war Japanese firms indicated that Japanese firms took a longer-term strategy compared to the U.S. firms, which tended to be more conscious of short-term results than Japanese firms. For example, Kagono et al. found that U.S. managers were extremely sensitive about short-term results such as the stock price and the profit gained on each share compared to Japanese managers.⁴ One of the reasons for this pointed out by much of the previous literature lies in the difference in corporate governance between the U.S. and Japanese firms. Much of the previous literature on finance and corporate governance in post-war Japan indicated that the dominant fund raising method of post-war Japanese firms was indirect financing instead of direct financing from markets.⁵ As a result of indirect financing and cross-share holdings, Japanese managers were relatively free from the risk of a takeover bid. In contrast, U.S. firms had to be cautious about the possibility of a takeover bid. Kagono et al. indicated that U.S. firms had to steadily raise earnings on a quarterly basis in order to discourage takeover because U.S. firms were more based on direct financing.⁶ Kagono et al. also pointed out that "The sensitivity toward stock prices and concomitant emphasis on short-term performance are attributable not only to the threat of takeover. Both are also encouraged by bonus systems, stock option plans, and intra-company control systems. In Japan, the stock option arrangement has not been broadly adopted, and with a high percentage of stable shareholders and government restrictions on ownership by foreign investors, there is much less threat of a takeover than in the United States."⁷ These arguments are quite consistent with the findings that U.S. firms tended to focus their semiconductor laser business on

⁴ Kagono et al., *Strategic vs. Evolutionary Management: A U.S.-Japan Comparison of Strategy and Organisation*, p.153.

⁵ For example, Okazaki, "Sengo Nihon no Kinyū Shisutemu (Finance System of post-war Japan)." Regarding to the main bank system and corporate governance, see Teranishi, "the Main Bank System."

⁶ Kagono et al., *Strategic vs. Evolutionary Management: A U.S.-Japan Comparison of Strategy and Organisation*, p.155.

⁷ Ibid., p.155.

untapped niche markets, which were more profitable, and Japanese firms competed in the same high volume areas, which were growing faster.

Vertical Integration and Technological Change

A central argument of this thesis relates to the pattern of competition, spillover effects, and technological development. It contends that the level of vertical integration affected the pattern of competition, which brought a different pattern of knowledge spillover and technological development. This idea has implications for the previous literature on vertical integration and technological change.

Much of the literature in economics and in economic and business history focuses on vertical integration and technological change. There is a clear debate concerning the relationship between the level of integration and technological development.

Examining industrial development in the U.S. from 1870 to 1940, Alfred Chandler proposed that technological development was closely correlated to the degree of vertical integration.⁸ Vertically integrated firms were in the best position to develop innovation. Examining the British cotton industry, William Lazonick came to the same conclusions as Chandler. His argument maintained that economies of scale were essential to technological development and argued that less integrated firms could not compete effectively in many areas.⁹ Florida and Kenney argued that firms with high levels of vertical integration could realise technological innovation and attain economic growth based on economies of scale, as long as coordination between R&D and manufacturing activities was well-operated; their argument also contended that the high level of vertical integration contributed to technological

⁸ Chandler, *The Visible Hand: The Managerial Revolution in American Business*.

⁹ Lazonick, *Competitive Advantage on the Shop Floor*; Lazonick, *Business Organisation and the Myth of the Market Economy*.

development.¹⁰

Examining the 1970s developments in productive technology and consumer demand, Piore and Sabel challenged the paradigm of big enterprise and mass production. They argued that the less vertically integrated small European firms could produce technological development and economic growth based on skilled craftsmen and the flexible division of labour.¹¹ Sabel and Zenith also contended that production through small flexible networks could be an alternative to mass production.¹²

The case of technological development of semiconductor lasers has implications for these debates about vertical integration and technological change. First, it confirmed that the low level of vertical integration in the U.S. provided firms with an incentive to differentiate their products. In contrast, vertically integrated firms could continue to invest in the same technological area as their rivals longer than the less integrated firms could because they retained secure in-house demand. These strategic R&D choices of competing firms aggregately affected the areas in which knowledge spillovers emerged. The spillover effects emerged in the U.S. in the areas where the firms exploited the untapped product market by utilizing the semiconductor laser. Therefore, knowledge spillover enriched the technological development of customized semiconductor laser applications in the U.S. In contrast, knowledge spillover enhanced fundamental semiconductor laser technology in Japan because the firms with high technological proximity were competing to develop a high-quality semiconductor laser for high volume markets and reduce production costs at the same time.

These findings suggest that the level of vertical integration affects the areas where technological change occurs. The less integrated firms introduced technological innovation to differentiate their product for the market so that they

¹⁰ Florida and Kenney, *The Breakthrough Illusion: Corporate America's Failure to Move from Innovation to Mass Production*.

¹¹ Piore and Sabel, *The Second Industrial Divide: Possibilities for Prosperity*.

¹² Sabel and Zeitlin, "Historical Alternatives to Mass Production: Politics, Markets, and Technology in Nineteenth-Century Industrialization."

could achieve a sufficient level of expected returns from their R&D. Competition among the less integrated firms eventually promoted technological development mainly in the custom or niche market. Highly integrated firms competed in the same technological areas and produced technological change in high volume production areas. The findings of this thesis suggest that vertically integrated firms were well-positioned for the technological development of core technology. Figuratively speaking, semiconductor laser technology was the trunk of a tree that had numerous branches. The branches were semiconductor laser application areas.¹³ The spillover effects in the U.S. emerged mainly to enrich the branches of the tree. Numerous new small branches emerged by exploiting the trunk. The spillover effects in Japan emerged to enrich the trunk more than creating new branches.

This study's findings suggest that the pattern of competition and spillover in the U.S. was not suitable to enhance technological development of the core technology from which many product markets could have spun off. The numerous startups that spun off from the intellectual hubs and produced a technological breakthrough in semiconductor laser technology may have been an illusion. Examining the U.S. technology-intensive industries, Florida and Kenney pointed out that American firms often failed to capitalise on technological breakthroughs.¹⁴ Their argument showed that the U.S. firms often failed to connect R&D with production; thus, they could not industrialize the technological breakthroughs produced in R&D. The findings in this thesis partly support this argument. Immediately after a breakthrough emerged, startups spun off from the parent company in order to exploit and retain business in the small niche market. It was rational for the U.S. firms, which could access complementary knowledge to target untapped markets, to allocate its resource to target untapped markets, which were usually more profitable than the product markets in which many firms already competed.¹⁵ As a result, semiconductor laser technology was diffused in numerous

¹³ On the list of the application areas, see the first chapter, *Introduction*.

¹⁴ Florida and Kenney, *The Breakthrough Illusion: Corporate America's Failure to Move from Innovation to Mass Production*.

¹⁵ Discussing competition between a leading firm with an established product and its

small niche markets in the U.S. However, the development of core technologies such as epitaxy technology was retarded.

Through the technological competition for high volume market among vertically integrated firms, Japanese firms induced domain specific knowledge spillover, which enhanced the trunk of the semiconductor laser technology tree. Although it would be rash to draw any definite conclusions from these points, they definitely need further examination; these findings may lead to new insights about vertical integration, spillover effects, and technological development.

Competition and Technological Change

The third implication involves policy, which is related to the relationship between competition and technological change. On the basis of his historical studies, Lazonick pointed out that governments should develop industrial policies to increase the market concentration ratio in their national economies so that competitive firms could be highly integrated.¹⁶ By contrast, Piore and Sabel contended that the government needed to promote competition and cooperation so that small firms could engage in technological development through the flexible division of labour. Porter also came to a different conclusion than Lazonick.¹⁷ Because he believed competition facilitated technological change, he insisted that the government frame a policy to promote competition.

The findings in this study support part of Porter's policy implication.

challengers, Christensen argued that the leading firm could be left behind by a new technological revolution brought by its rivals because it had an incentive to allocate its resources to current established products. The strategic choice of U.S. firms in the optoelectronics industry suggests that the patterns of knowledge spillover and access to complementary knowledge influenced firms' resource allocation and played important roles in long-term technological change and their competitive advantage. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*; Christensen and Bower, "Customer Power, Strategic Investment, and the Failure of Leading Firms."

¹⁶ Lazonick, *Business Organisation and the Myth of the Market Economy*, p.302.

¹⁷ Porter, *The Competitive Advantage of Nations*, pp.126-128.

Competition in the same technological area among the firms that internalised the downstream process accelerated technological development in the case of semiconductor laser technology; thus, firms quite possibly develop competitiveness through competition. This fact, however, does not necessarily imply that competition always contributes to technological development and industrial growth. If the less vertically integrated firms compete in the same technological area, it is possible that they will assume a product-differentiation strategy at an earlier stage than the vertically integrated firms will. The competing firms' R&D strategies affect the areas in which spillover effects and technological development emerge. Therefore, it is necessary for policy makers to examine the firms' level of vertical integration and the areas in which technological spillover would emerge. It is also important for policy makers to set target technological areas in which to attain technological development because a firm's R&D strategy determines the areas in which technological development will emerge. If it is necessary to attain technological development in the core parent technology, from which many technological spinoffs would later emerge, it is rational to stimulate competition among vertically integrated firms. However, if the target is to enhance breakthroughs in the application areas, it would be rational to promote spinoffs from the intellectual hubs.

Firms may strategically choose to participate in competition to access technological spillover and to gain competitiveness, instead of differentiating their products and avoiding competition. As Cohen and Levinthal argued, it is necessary for firms to be involved in R&D to absorb new knowledge created by other firms.¹⁸ Participating in competition in the same technological areas as competitors plays an important role for firms in accumulating principal technological competence. When viewed from the importance of competition, this perspective is consistent with Hayek's notion of competition.¹⁹ Hayek regarded competition as a discovery procedure and emphasised the efficiency of information transaction in a market

¹⁸ Cohen and Levinthal, "Absorptive Capacity: A New Perspective on Learning and Innovation"; Cohen and Levinthal, "Innovation and Learning: The Two Faces of R&D."

¹⁹ Concerning his conceptualisation of knowledge, see Hayek, "Competition as a Discovery Procedure"; Hayek, "The Meaning of Competition."

economy. Knowledge of individual firms is limited. An individual firm does not own enough knowledge about the whole economy and does not necessarily know what the best technology is and what kind of product mix is suitable for the market. Each firm has distinct, limited knowledge. From Hayek's perspective, competition is the process by which each firm pursues its business opportunities through its own knowledge. Through competition, firms gain knowledge about what is the most useful production system, which is the most satisfying product mix, and what kind of organisation is suitable for their business strategy. If many firms are competing in the same technological area for a certain period of time, this discovery procedure is enhanced.

The case of technological development of the semiconductor laser suggests that firms whose level of vertical integration was high could keep investing in the competitive device market relatively longer than firms with low levels of vertical integration, and this enriched the discovery procedure of the firms and enhanced technological changes in the area. Many business management studies have contended that a firm should avoid competition by constructing barriers against its competitors.²⁰ For example, Kim and Mauborgne stressed the necessity for firms to stay away from markets in which many competitors were intensively competing and to find untapped product markets, called "blue oceans".²¹ They argued that firms should assume a "blue ocean strategy," avoiding competition and seeking unexploited markets. They noted, "Blue ocean strategy challenges companies to break out of the red ocean of bloody competition by creating uncontested market space that makes the competition irrelevant."²² Introducing the framework of industrial organisation into the competitive strategy of firms, Michael Porter argued that firms must take unique positioning in the product market to hold sustainable

²⁰ For example, Porter, *Competitive Strategy: Techniques for Analyzing Industries and Competitors*; Porter, *Competitive Advantage: Creating and Sustaining Superior Performance*; Porter, "What Is Strategy?"

²¹ Kim and Mauborgne, *Blue Ocean Strategy: How to Create Uncontested Market Space and Make the Competition Irrelevant*.

²² Ibid., p.x.

competitive advantages.²³ Directing his attention to Japanese firms, he also pointed out “few Japanese companies have strategies... Instead of choosing distinctive ways of competing, tailoring activities, and making trade-offs, Japanese companies tend to proliferate products and features, serve all market segments, sell through multiple channels, and emulate one another’s production approaches. Continuous operational improvement is confused with strategy.”²⁴

It was pointed out that Japanese firms’ profitability was quite low, even though sales and production were growing. For instance, the chair of the Japan Petrochemical Industry Association reported that the petrochemical industry of Japan began its operation in 1958, attained significant growth, and became the second largest after the U.S. in only ten years. However, because competition became excessive, the industry became “growth without profit.”²⁵ Previous literature has observed fierce competition and growth without profit in various industries in post-war Japan.²⁶ As Porter indicated, governmental and industrial reports suggested that it was necessary for firms to differentiate their business and not to be drowned in fierce competition.²⁷

However, this study suggests that it would be rational for a firm to participate in competition in order to accumulate technological competence when many firms were competing to develop the core technology, because important technological breakthroughs would result. In other words, it would be rational for firms to compete in the same area, as long as knowledge spillover brings increasing returns to firms’ R&D and the product market is expected to grow. If a firm retreated from competition in the early stage of technological development, it would be left behind

²³ Porter, *Competitive Advantage: Creating and Sustaining Superior Performance*, pp.41-44. Porter, "What Is Strategy?"

²⁴ Porter et al., *Can Japan Compete?*, p.91.

²⁵ Japan Petrochemical Industry Association, *Sekiyu Kagaku Kōgyō 10 nenshi (10 year history of Japanese Petrochemical Industry)*, preface.

²⁶ Regarding to fierce and “excessive” competition, see Itoh et al., “*Industry Policy of Japan. Chapter 8. On “growth without profit” in the petrochemical industry*, see Shimizu, “Sangyō Seisaku to Kigyō Kōdō no Shakai Teki Ghōsei (The Interaction between the Industrial Policy and the Firms’ Strategy in the Petrochemical Industry of Japan).”

²⁷ Japan Petrochemical Industry Association, *Sekiyu Kagaku Kōgyō 10 nenshi (10 year history of Japanese Petrochemical Industry)*.

in important technological breakthroughs. Moreover, a firm that avoided R&D competition and targeted the custom niche product markets could be left behind and lose its competitive advantage. In Kim and Mauborgne's term, a firm that followed "blue ocean strategy" might be trapped and left behind by breakthroughs in the core technology provided by the competition, in which the firm failed to participate.

Concentrated Resource Allocation and Diseconomies of Duplicated R&D

This thesis has pointed out the economies of duplicated R&D investment, which produced domain-specific knowledge spillover effect to enhance semiconductor laser technology. Because of duplicated R&D in epitaxy technology--strategically and economically the most important technology in semiconductor laser--Japanese firms could acquire domain-specific knowledge spillovers from their competitors.

However, this strategy does not always produce spillover or bring favourable outcomes to the firms. For example, competition in the same technological area may cause excessive investment in R&D, beyond the level of socially desirable R&D investment.²⁸ Additionally, duplicated R&D strategy may bring about two different effects in the environment where technological change is frequently changed.²⁹ First, it might reduce the level of R&D competition. Indicating divergent strategies reduce the ability of oligopolistic firms to coordinate their strategy, Michael Porter maintained that strategic symmetry among the rivals decreases industry rivalry.³⁰ From this point of view, it is possible to suppose that firms chose the duplicated R&D strategy to band together with competitors in an effort to limit the level of

²⁸ Dasgupta and Stiglitz have shown that the R&D investment of firms could result in excessive investment. Dasgupta and Stiglitz, "Industrial Structure and the Nature of Innovative Activity."

²⁹ In Abernathy's account, this duplicated R&D strategy might play different roles until the dominant technology emerged. Abernathy, *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*.

³⁰ Porter, "The Structure within Industries and Companies' Performance."

competition. Based on game theory, Chen and MacMillan discussed that it is rational for a firm to assume the same strategy as its competitors because doing so preserves the current market position and prevents devastating competition.³¹

Also, if firms engaged in duplicated R&D investment and focused on a certain technological area, they might become vulnerable to radical environmental change. A clear dilemma exists between competition with high technological proximity, which is a source of domain-specific knowledge spillover effects, and vulnerability to radical environmental change. If firms make similar technological choices and compete in the same technological area, domain-specific knowledge spillovers in the industry--a source of increasing returns of technological development--will increase. If they make different technological choices and compete in different technological segments, the industry will be relatively less vulnerable to radical environmental change, while domain-specific knowledge spillovers in the industry will be scarce. Since R&D investments are irreversible and the absorptive capacity entails R&D path-dependency, it is possible to suppose that this pattern of strategic choice reduces flexibility in R&D strategy. The technological choice of firms entails path-dependency and can lock in the pattern of knowledge spillover in the industry.³²

Thus, it was risky for the Japanese semiconductor laser industry to have firms making similar technological choices and competing in the same technological areas. Japan was behind the U.S. and U.S.S.R. in human capital accumulation in semiconductor laser technology when the firms began semiconductor laser R&D. The fact that the firms made similar technological choices and competed in similar technological areas played an important role in focusing R&D resources of the firms into certain technological areas and in attaining catching up to the technological level of the advanced nations. As shown in the fourth chapter, the OMCS launched

³¹ Chen and MacMillan, "Nonresponse and Delayed Response to Competitive Moves: The Roles of Competitor Dependence and Action Irreversibility."

³² Regarding increasing returns, lock in, and path dependency, see Arthur, *Increasing Returns and Path Dependence in the Economy, Economics, Cognition, and Society*; Arthur, "Competing Technologies, Increasing Returns, and Lock-in by Historical Events"; Katz and Shapiro, "Network Externalities, Competition and Compatibility."

by the government contributed to focus the R&D resources of firms into certain areas. Examining government sponsored collaborative research in Japan, Sakakibara's argument suggested that it might be risky to run a large-scale government funded research consortium because the participating firms tended to take similar technological choice.³³ However, while the duplicated R&D competition might have been risky, the concentrated resource allocation gained leverage to induce spillover effects and to overtake the U.S. in the short term.

The final point is related to the timing of the duplicated R&D strategy. The findings of this thesis do not necessarily suggest that duplicated R&D competition always leads to high competitiveness of the industry. It depends on the phase of technological development and industrial development.

Semiconductor laser technology was still nascent and not industrialized on a large scale when firms began to compete in epitaxy technology. Examining the U.S. automobile industry from 1896 to 1975, Abernathy argued that the appearance of dominant design in the technological system played an important role determining the ratio of product innovation and process innovation.³⁴ The dominant design is a product design whose main components and mechanisms underlying fundamental characters do not vary from one model to another. In Abernathy's account, when Japanese firms began duplicated R&D investments, a dominant design did not appear in semiconductor laser technology, since the most important technology for large-scale production had not yet been developed. Winning the R&D competition for the dominant design is desirable, since it enables firms to collect monopoly rents. And it is important for firms to invest in R&D in order to accumulate absorptive capacity in the important technological areas.³⁵ Thus, it was rational that many firms were competing in important technological areas.

However, if this pattern of competition was taken in technological areas

³³ Sakakibara, "The Diversity of R&D Consortia and Firm Behavior: Evidence from Japanese Data", p.184 and 192.

³⁴ On the dominant technology, see Abernathy, *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry*.

³⁵ Cohen and Levinthal, "Absorptive Capacity: A New Perspective on Learning and Innovation"; Cohen and Levinthal, "Innovation and Learning: The Two Faces of R&D."

where the dominant design had already appeared, the returns from duplicated R&D and spillover effects would decrease. Figuratively speaking, a tree cannot grow higher once it reaches a certain height; at that point, it is necessary to nurture its branches and fruits. Thus, in a sense, Japanese firms undertook duplicated competition at the right time in the case of semiconductor laser technology. However, the pattern of competition among the startups spun off from the intellectual hubs might have resulted in greater market positions in high-volume product markets if undertaken in the later stage of technological development. These facts suggest that duplicated R&D is not necessarily always favourable to technological development, and the outcome of a certain pattern of competition may depend on the phase of technological development.

Finally, the phase of industrial development also influences the economies of duplicated R&D competition. Some of the Japanese electronics firms were losing their competitiveness and Korean firms such as LG Electronics and Samsung Electric gained competitiveness based on cost advantages from the 1990s. Economies of scale play a significant role in the consumer electronics industry, especially in the manufacturing process of the consumer goods industry. Since R&D in a technology intensive industry needs a large amount of sunk costs, it is necessary to attain economies of scale in the manufacturing process to cover the large amount of direct costs. In terms of economies of scale, on the one hand, it was not rational that many firms should compete in the same area because production facilities were scattered in the industry and the production scale of individual firms became small. It was necessary to increase the concentration ratio of the industry to achieve higher level of economies of scale. On the other hand, the fact that many firms were competing in the same area stimulated domain-specific knowledge spillover effects, which could bring increasing returns to R&D. Therefore, the duplicated R&D competition on the one hand brought domain-specific knowledge spillover effects to the industry and eventually resulted in the development of semiconductor laser technology. On the other hand, it could dampen the economies of scale in production. Once the fundamental technologies are developed and the technology has become

fully commercialised, the diseconomies of duplicated R&D competition would become much greater. It is possible to surmise that the institutional settings and the strategic behaviours of the firms in Japan historically played an important role in the phase of the technological and industrial development of semiconductor laser technology and resulted in the technological competitiveness.³⁶

Limitations and Further Research

This section discusses some limitations of this study and provides some perspectives for future research. First, this study examined human capital accumulation through an analysis of doctoral theses on the semiconductor laser. It also discussed co-authored academic papers that focused on the semiconductor laser research network. The analysis of co-authored academic papers is a widely used method of exploring the research community network.³⁷ But since co-authored academic papers capture only the formal research network, it is also necessary to examine the more informal research community network, which might play an important role in the knowledge spillovers.³⁸

Second, this study used academic papers and patent data to examine technological change and knowledge spillover effects. It must be noted that this thesis examines only the explicit knowledge codified in the academic papers and patents. This codified technological knowledge is not, however, necessarily all

³⁶ Introducing the concept of “national innovation system”, Nelson and Winter indicated that the institutional settings of a country had a strong impact on the pattern of innovation of firms. Nelson and Winter, *An Evolutionary Theory of Economic Change*. Examining the development of synthetic dye technology, Murmann showed how technological capability of firms and national institutions coevolved. Murmann, *Knowledge and Competitive Advantage: the Coevolution of Firms, Technology, and National Institutions*.

³⁷ On the analysis of co-authored academic papers, see Smith, "The Trend toward Multiple Authorship in Psychology."

³⁸ Examining the “Transversely Excited Atmospheric Pressure CO₂ Laser” research network, Collins discussed that it was difficult to capture the nature of much scientific knowledge, which entailed tacit and invisible knowledge, with conventional techniques such as analysis of co-authored paper and citation. Collins, "The TEA Set: Tacit Knowledge and Scientific Networks."

knowledge created in R&D. As it is said, “we can know more than we can tell”, knowledge can be unconscious, unexternalisable, and intransmittable, which is usually defined as tacit knowledge.³⁹ Unlike explicit knowledge--which can be explicitly expressed and codified into figures, sentences, or formula expressions--tacit knowledge is implicit and cannot easily be codified.⁴⁰ It is necessary to examine knowledge that cannot be codified in the academic papers and patents in order to comprehend knowledge spillovers. Although it is not easy to access tacit knowledge by definition, more wide-ranging and deeper interviews would help reveal the real nature of R&D competition and technological spillover.

Third, this study maintains that the level of vertical integration affected the pattern of R&D investments. However, it does not specify how differences in the level of vertical integration historically emerged in the U.S. Europe, and Japan. It is necessary to scrutinize the broader social context to examine how differences in the level of vertical integration emerged in the U.S., Europe, and Japan in order to reveal the whole picture of the development of the optoelectronics industry.

Lastly, this study discussed change and competition in the technological development of the semiconductor laser as a case study in which various social and economic factors came into play. The case study approach allows the disentanglement of the complex relationship between technological change and competition, and helps identify important factors such as level of vertical integration and spillover effects. However, scrutinizing only the semiconductor laser case does not reveal a general pattern of technological change driving Japanese technology-intensive industry to gain competitiveness. Thus, the case study method has limitations. The next step from this study is to expand the scope of analysis. Specifically, technological change and competition in other technological areas (e.g.,

³⁹ The arguments about knowledge--what we know, what we do not know--have been deeply considered in various areas such as history of science, philosophy of science, and phenomenology. Reviewing the details of these arguments is far beyond the scope of this thesis. On tacit knowledge, see Polanyi, *Personal Knowledge: Towards a Post-Critical Philosophy*; Polanyi, *The Tacit Dimension*.

⁴⁰ On the distinction of explicit and implicit knowledge, see Nonaka and Takeuchi, *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*, pp.8-11 and pp.83-90.

the long-wavelength semiconductor laser and the optical fibre in the optoelectronics industry) must be examined in order to present the whole picture of the development of the optoelectronics industry, which is one of the most important sectors of technology-intensive industry.

Appendix I: Number of Doctorates Awarded in Semiconductor Laser in the World

(1) 1963-75

	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Australia	0	0	0	0	0	0	0	0	0	0	0	0	0
Austria	0	0	0	0	0	0	0	0	0	0	0	0	1
Belarus	0	0	0	0	0	0	0	0	1	2	0	0	0
Belgium	0	0	0	0	0	0	0	0	0	0	0	0	0
Brazil	0	0	0	0	0	0	0	0	0	0	0	0	0
Canada	0	0	0	0	0	0	0	0	0	1	0	0	0
China	0	0	0	0	0	0	0	0	0	0	0	0	0
Czechoslovakia	0	0	0	0	0	0	0	0	0	0	0	0	0
Denmark	0	0	0	0	0	0	0	0	1	0	0	0	0
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0
France	1	0	1	0	0	1	0	2	0	1	1	0	0
Germany	0	0	0	2	0	1	2	1	2	2	2	3	5
Greece	0	0	0	0	0	0	0	0	0	0	0	0	0
India	0	0	0	0	0	0	1	0	0	0	0	2	0
Ireland	0	0	0	0	0	0	0	0	0	0	0	0	0
Israel	0	0	0	0	0	0	0	0	0	0	0	0	0
Italy	0	0	0	0	0	0	0	0	0	0	0	0	0

Japan	0	0	0	1	2	4	0	0	3	0	2	2	3
Korea	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0	0	0	0	0
Norway	0	0	0	0	0	0	0	0	0	0	0	0	0
Philippines	0	0	0	0	0	0	0	0	0	0	0	0	0
Poland	0	0	0	0	0	0	0	0	0	1	0	0	0
Portugal	0	0	0	0	0	0	0	0	0	0	0	0	0
Russia and USSR	1	0	2	4	2	6	4	9	5	9	5	5	6
Singapore	0	0	0	0	0	0	0	0	0	0	0	0	0
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0
Sweden	0	0	0	0	0	0	0	0	0	0	0	1	0
Switzerland	0	0	0	0	0	3	2	0	0	0	1	1	2
Tadzhikistan	0	0	0	0	0	0	0	0	0	0	0	0	0
Taiwan	0	0	0	0	0	0	0	0	0	0	0	0	0
United Kingdom	0	0	0	0	1	1	1	1	0	0	2	1	3
United States	0	0	5	4	7	2	4	4	5	4	4	5	5
Yugoslavia	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	2	0	8	11	12	18	14	17	17	20	17	20	25

Source: Takahashi, *Bibliography of Doctoral Theses on Semiconductor Lasers II*.

Appendix I: Number of Doctorates Awarded in Semiconductor Laser in the World (2) 1976-1990

	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Australia	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Austria	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1
Belarus	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Belgium	0	0	0	0	0	0	0	0	1	0	0	1	3	1	2
Brazil	0	1	1	0	2	1	0	0	0	0	0	0	0	1	2
Canada	0	0	1	0	0	0	0	2	0	0	0	1	0	1	2
China	0	0	0	0	0	0	0	0	0	2	1	0	1	6	4
Czechoslovakia	0	0	0	0	0	2	1	1	1	0	0	0	1	0	3
Denmark	0	0	1	1	0	1	1	0	2	1	3	1	2	0	4
Finland	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
France	1	1	1	4	1	0	3	5	2	4	4	12	13	8	19
Germany	3	3	4	4	1	4	1	2	8	2	3	6	9	6	17
Greece	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
India	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ireland	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0
Israel	0	0	0	0	0	0	1	0	0	0	1	1	1	0	1
Italy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Japan	3	7	3	5	7	9	9	8	13	7	10	13	10	21	13
Korea	0	0	0	0	0	0	0	1	1	3	3	3	3	4	1
Netherlands	0	0	0	0	0	0	0	1	0	0	1	0	1	1	2
Norway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Philippines	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Poland	1	0	0	1	0	0	0	1	0	1	1	0	1	0	0
Portugal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Russia and USSR	8	1	4	4	4	5	10	5	6	5	7	4	6	10	4
Singapore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sweden	0	0	0	0	2	1	0	0	1	1	1	1	3	1	2
Switzerland	1	0	0	1	0	1	2	0	2	2	1	2	0	1	0
Tadzhikistan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taiwan	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1
United Kingdom	1	2	1	4	0	3	1	4	1	8	8	6	14	7	8
United States	7	5	7	7	9	11	8	6	7	14	23	19	17	26	36
Yugoslavia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	26	20	23	31	26	39	37	36	46	54	67	74	87	96	123

Sourer: Takahashi, *Bibliography of Doctoral Theses on Semiconductor Lasers II*.

Appendix II: Institutions and Co-Publications

Journal of Applied Physics

Institutions	Number of Co-Publications
University of Illinois at Urban-Champaign (U.S.)	8
Monsanto (U.S.)	
Universidade Estadual de Campinas (Brazil)	1
Hewlett-Packard (U.S.)	
University of Rhode Island (Island)	1
Siemens (Germany)	
University of Illinois at Urbana-Champaign (US)	8
Rockwell (U.S.)	
Standard Telecommunication Laboratories (UK)	1
University of Sheffield (UK)	
Fujitsu (Japan)	2
NTT (Japan)	
National Central University (China)	1
University of Arizona (US)	
British Telecom (UK)	1
University of Birmingham (UK)	
TRW (US)	1
Southern Methodist University (US)	
Oregon Graduate Center (US)	1
Bell Laboratories (US)	
University of Illinois at Urbana-Champaign (US)	7
Xerox (US)	
British Telecom (UK)	1
Standard Telecommunication (UK)	
TRW (US)	1
University of California Los Angeles (US)	
TRW (US)	1

Digital Signal Corporation (US)	
Tel-Aviv University (Israel)	1
Soreq Nuclear Research Center (Israel)	
North Carolina State University (US)	1
Aracor (US)	
CNET (France)	1
Bell (US)	
AT&T Bell (US)	
Ben Gurion University of the Negev (Israel)	1
Martin Marietta Laboratories (US)	
University of Delaware (US)	

Source: *Journal of Applied Physics*, 1965-1985

Journal of Applied Physics Letters

Institutions	Number of Co-Publications
Ortel Corporation (US)	18
California Institute of Technology (US)	
Rockwell International (US)	14
University of Illinois at Urbana-Champaign (US)	
University of Illinois at Urbana-Champaign (US)	11
Xerox Palo Alto Research Center (US)	
University of Illinois Urbana-Champaign (US)	7
Monsanto Company (US)	
Fujitsu Laboratories Ltd (Japan)	3
Nippon Telegraph and Telephone Public Corporation (Japan)	
Corporate Solid State Laboratory, Varian Associates, Incorporated (US)	2
University of Illinois at Urbana-Champaign (US)	
Hewlett-Packard Laboratories (US)	1
Universidade Estadual de Campinas (Brazil)	
University of Osaka Prefecture (Japan)	1

Tohoku University (Japan)	
University of Berne (Switzerland)	1
Bell Laboratories (US)	
Max-Planck-Institut für Festkörperforschung (Germany)	1
Rice University (US)	
Swiss Federal Institute of Technology (Switzerland)	1
Philips (the Netherlands)	
Post Office Research Centre (UK)	1
University of Birmingham (UK)	
Hughes Research Laboratories (US)	1
California Institute of Technology (US)	
Imperial College (UK)	1
Standard Telecommunications Laboratory (UK)	
Cambridge University (UK)	1
Standard Telecommunications Laboratory (UK)	
Hitachi Ltd (Japan)	1
California Institute of Technology (US)	
Electrotechnical Laboratory (Japan)	1
Nippon Institute of Technology (Japan)	
Institut für Halbleitertechnik und SFB 202, Rheinisch-Westfälische Technische Hochschule Aachen (Germany)	1
Max-Planck-Institut für Festkörperforschung (Germany)	
Institut für Festkörperphysik der T.U.Berlin (Germany)	
General Optronics Corporation (US)	1
Naval Research Laboratory (US)	
Universität Stuttgart (Germany)	1
AEG-Telefunken (Germany)	
Max-Planck-Institut für Festkörperforschung (Germany)	1
Technische Universität Wien (Austria)	
Instituto de Optica (Spain)	1
IBM Research Laboratory (US)	

Imperial College (UK)	1
Philips (the Netherlands)	
Massachusetts Institute of Technology (US)	1
General Motors Research Laboratories (US)	
University of Illinois at Urbana–Champaign (US)	1
McDonnell Douglas Astronautics Company (US)	
Tel Aviv University (Israel)	1
Soreq Nuclear Research Center (Israel)	
General Optronics Corporation (US)	1
Rutgers University (US)	
Thomson–CSF (France)	1
Centre National D'Etudes et Telecommunications (France)	
Kanazawa University (Japan)	1
Tokyo Institute of Technology (Japan)	
Thomson-CSF (France)	1
Centre Universitaire d'Orsay (France)	
Massachusetts Institute of Technology (US)	1
Philips (the Netherlands)	
Naval Research Laboratory (US)	1
Spectra Diode Laboratories (US)	
University of Illinois at Urbana–Champaign (US)	1
Xerox Palo Alto Research Center (US)	
Tektronix (US)	
Bell Communications Research (US)	1
Hitachi Ltd (Japan)	
University of Illinois at Urbana–Champaign (US)	1
Ford Microelectronics Inc (US)	
Xerox Palo Alto Research Center (US)	
University of Illinois at Urbana–Champaign (US)	1
Mictron Inc (US)	
Xerox Palo Alto Research Center (US)	

Bell Communications Research (US)	1
Stanford University (US)	
Fujitsu Laboratories Ltd (Japan)	1
Shizuoka University (Japan)	
Spectra Diode Laboratories (US)	1
Xerox Palo Alto Research Center (US)	
Tohoku University (Japan)	1
Semiconductor Research Institute (Japan)	

Source: *Journal of Applied Physics Letters*, 1962-1985

Appendix III: List of Interviewees

Interviews were conducted with corporate engineers and managers, and government officials with direct knowledge of manufacturing, manufacturing process engineering, and the OMCS project. The questioning first focused on a set of fixed questions after asking for a description of the interviewee's job title and responsibilities. The fixed questions were:

- (1) What was the most important technological breakthrough in semiconductor laser technology throughout the 1970s and 1980s?
- (2) How do you think the Japanese semiconductor laser came to be competitive?
- (3) What did you and your colleagues think about the OMCS project when it was launched?
- (4) What did you and your colleagues think about epitaxy technologies?
- (5) How did you approach technological knowledge created by other organisations?
- (6) Did you have any particular organisation you paid attention to their research?
- (7) Who were the star scientists in semiconductor laser throughout the 1970s and 1980s?

The interviewees who participated in the consortium were asked another set of fixed questions. The questions involved (1) the relationship between the in-house R&D and the joint R&D in the OMCS project; (2) who was sent to the OMCS project; and (3) to what extent the engineers from the different participating firms cooperated in the OMCS project. After addressing these points, more detailed and individual points were addressed.

Interviewees were first selected by looking at such journals as *Oyo Butsuri (Journal of Applied Physics of Japan)* and *Elekttronikusu (Electronics)*. The author directly contacted them, mainly by email and by letter. Second, the author contacted

Interviewee A, B, and H through the Hitotsubashi University network. Third, some were recommended by other interviewees.

The response rate was quite high. Except for one refusal, which involved a schedule conflict, no one refused to be interviewed.

Interviewee	Organisation in 1979	Position in 1979	Current Organisation	Current Position	Participated / Not	Date	Time	Place
A	Hitachi	Engineer	Cube IT (R&D Consulting Firm)	President	Not	09/09/04	11:30-15:00	Tokyo
B	Sanyo Electric	Engineer	Sanyo Electric	General Manager	Not	25/10/05	13:30-15:30	Osaka
C	Sanyo Electric	Engineer	Sanyo Electric	Manager	Not	25/10/05	13:30-15:30	Osaka
D	MITI	General Manager	National Institute of Advanced Industrial Science and Technology, Grid Technology Research Center	Emeritus Advisor	Director	26/10/05	14:00-17:30	Tokyo
E	MITI	Manager	Optoelectronic Industry and Technology Development Association	Director	Manager	27/10/05	10:00-12:00	Tokyo
F	Fujitsu	Engineer	Optoelectronic Industry and Technology Development Association	Deputy General Manager/ Senior Staff	Engineer	27/10/05	10:00-12:00	Tokyo
G	Toshiba	Manager	Tokai University	Professor	Not	27/10/05	15:30-	Shizuoka

							21:30	
H	Matsushita Electric	Engineer	Matsushita Electric	General Manager	Not	28/10/05	10:00-13:30	Tokyo
I	Matsushita Electric	Engineer	Kōchi University of Technology	Professor	Engineer	31/10/05	12:30-14:30	Kochi
J	Matsushita Electric	Engineer	Matsushita Electric	Manager	Engineer	01/11/05	11:30-12:30	Kyoto
K	Sony	Engineer	The University of Tokyo	Project Professor	Not	02/11/2005	10:30-12:30	Tokyo
L	Sharp	Engineer	Fuji Photo Film	Divisional Manager	Not	13/02/06	10:00-12:00	Kanagawa
M	Fujitsu	Engineer	National Institute of Advanced Industrial Science and Technology	Senior Advisor	Engineer	15/02/06	10:00-12:00	Ibaraki
N	Toshiba	Engineer	Tōhoku University	Professor	Research Leader	16/02/06	14:00-16:00	Tokyo
O	NEC	General Manger	Toyama New Industry Organisation	Director	Advisor	17/02/06	14:00-16:00	Tokyo
P	Mitsubishi Electric	Engineer	Kanazawa Institute of Technology	Professor	Research Leader	21/02/06	11:00-13:30	Ishikawa
Q	NTT	Engineer	Osaka University	Professor	Not	22/02/06	15:00-17:00	Tokyo

Appendix

R	NTT	Engineer	Keiō University	Professor	Not	01/09/2006	15:00- 17:00	Kanagawa
S	Oki Electric	Engineer	Fuji Photo Film	Senior Research Scientist	Engineer	04/09/2006	14:00- 15:30	Kanagawa

Appendix IV: Consortium Expenditure in U.S. Dollars

Table 4-1: OMCS and Large Scale Projects

	Real R&D Expense (Million U.S. Dollar)	Project Term (Year)	Number of Participating Firms	Annual R&D Expense per Participant (Million U.S. Dollar)
OMCS	170	7	14	1.736
Sample	30			
Average	155.531	8.167	18.6	1.017
Median	128.836	8	15	1.071

Source: Kawatetsu Tekuno Risāchi, (Kawatetsu Technology Research). "Kokka Purojekuto no Unei/ Kanri Jōkyō Bunseki Chōsa Hōkokusho II, (Evaluation Report on Operation and Management of National Projects)". R&D Expense is 2005 U.S. dollar value. The exchange rate is 2005 average rate: 1 US Dollar = 110.12445 Japanese Yen.

Appendix V: Top Fifty Engineers and their Affiliations

Top Countries in Semiconductor Laser Technology

Country	Record Counted	Share of 1391 Record Counted (%)
Japan	431	30.9849
The U.S.	367	26.3839
The U.K.	104	7.4766
U.S.S.R.	92	6.6139
France	68	4.8886
Federal Republic Germany	41	2.9475

Source: *Web of Science*. "Record Counted" means that Japan obtained 431 papers that were cited at least once. Calculated by the number of academic papers published from 1960 to 1990 and the number of their citations until 2006, this table presents the distribution of highly cited engineers. From 1960 to 1990, Web of Science captures 1391 records, which are based on the number of papers and citations, and shows that both Japan and the U.S. were two leading countries in terms of the number of highly cited engineers.

The Top Fifty Highly Cited U.S. Based Engineers 1960-1990

Engineer	Record Counted	Affiliation
Scifres, DR	32	Univ of Illinois Urbana Champaign--- Xerox--- Spectra Diode
Yariv, A	29	Bell--- Caltech
Striefer, W	25	Stanford Univ--- Univ of Rochester---- Xerox---- Univ of New Mexico----
Welch, DF	21	Cornell Univ ----Spectra Diode
Wang, S	16	UC Berkeley
Cross, PS	14	Institut für Angewandte Festkörperphysik der Fraunhofer-Gesellschaft--- Bell--- HP--- Spectra Diode
Katz, J	14	Caltech
Olsson, NA	12	Bell
Burnham, RD	11	Univ of Illinois Urbana-Champaign--- Xerox--- Spectra Diode--- Xerox--- Amoco Research Center
Margalit, S	11	Technion-Israel Institute of Technology Israel --- Caltech
Agrawal, GP	8	Indian Institute of Technology--- Ecole Polytechnique--- City College of City Univ of New York--- Bell--- Univ Rochester
Kapon, E	8	Tel Aviv Univ--- Caltech--- Bell
Tang, CI	8	Cornell Univ
Whinnery JR	8	UC Berkeley
Goldberg, L	7	Naval Research Laboratory
Lau KY	7	Bell--- Hughes--- Caltech --- Ortel--- Columbia Univ

Fuhr, PL	6	NASA
Harnagel, GL	6	Xerox--- Spectra Diode
Haus, HA	6	MIT
Sakamoto, M	6	Spectra Diode
Bowers, JE	5	Univ of Minnesota--- Stanford Univ --- Bell
Chen, YC	5	Exxon --- GTE Laboratories--- Perkin-Elmer
Chow, WW	5	Univ of Arizona--- Univ of New Mexico--- Hughes
Hall, DG	5	Univ of Tennessee--- McDonnell Douglas--- Univ of Rochester
Henry, CH	5	Bell
Paoli, TL	5	Stanford Univ--- Bell--- Xerox
Patonay, G	5	Emory Univ
		NASA--- Tel Aviv Univ--- Caltech--- Bell---Technion---Israel Institute
Salzman, J	5	of Technology
Vahala, K	5	Caltech
Berger, J	4	HP--- Spectra Diode
Byer, RL	4	Stanford Univ--- Bell--- Xerox
Chen, KL	4	UC Berkeley
Dienes, A	4	Caltech--- Bell --- UC Berkeley--- UC Davis
Endriz, JG	4	Stanford Univ--- RCA--- Spectra Diode
Ezekiel, S	4	MIT
Hsin, W	4	UC Berkeley
Lee, TP	4	Bell
Lindsey, C	4	Caltech --- Univ of Hawaii
TWU, Y	4	UC Berkeley--- Bell
Vanderziel, JP	4	Bell
Weller, JF	4	Naval Research Laboratory
Yang, JJ	4	TRW
Abshire, JB	3	NASA
Beach, R	3	Columbia Univ--- Lawrence Livermore National Laboratory
		Univ of Missouri-Rolla--- McDonnell Douglas--- Bell---Univ of
Begley, DL	3	Illinois at Urbana-Champaign
Holonyak, N	3	Univ Illinois Urbana Champaign
Cella, T	3	Bell
Chun, MK	3	General Electric--- Naval Research Laboratory
Defreez, RK	3	Oregon Graduate Center
Dutta, NK	3	Cornell Univ--- Bell

Source: *Web of Science. Scitation.*

Top Fifty Highly Cited Japan Based Engineers 1960-1990

Engineer	Record Count	Affiliation
Kimura, T	22	NTT
Yamamoto, Y	22	NTT
Saruwatari, M	19	NTT
Ikeda, M	17	NTT
Mukai, T	17	NTT
Imasaka, T	14	Kyushu Univ
Ishibashi N	14	Kyushu Univ
Otsuka K	12	NTT

Kobayashi, K	11	NEC
Kobayashi, S	11	NTT
Mito, I	11	NEC
Saito, S	11	NTT
Imanaka, K	10	Oki --- Omuron
Ohtsu, M	10	Tokyo Institute of Technology
Inoue, K	10	NTT
Kawano, K	9	NTT
Mitomi, O	9	NTT
Mukai, S	9	Electrotechnical Laboratory
Nakazawa, M	9	Tokyo Institute of Technology--- NTT
Tsuchida, H	9	Electrotechnical Laboratory
Kikuchi, K	8	Univ of Tokyo
Ogura, M	8	Electrotechnical Laboratory---AIST
Sakakibara, Y	8	Mitsubishi Electric
Susaki, W	8	Mitsubishi Electric
Yamamoto, S	8	KDD
Itoh, H	7	Electrotechnical Laboratory
Kakimoto, S	7	Mitsubishi Electric
Kawaguchi, H	7	NTT
Machida, S	7	NTT
Shimura, M	7	Omron
Sugie, T	7	NTT
Suzuki, K	7	NTT
Suzuki, T	7	Niigata Univ
Asatani, K	6	NTT
Imamoto, H	6	Electrotechnical Laboratory--- Omron
Ito, R	6	Hitachi
Mitsuhashi, Y	6	Electrotechnical Laboratory
Mochizuki, K	6	KDD
Nakajima, Y	6	Mitsubishi Electric
Nakayama, T	6	Polytechnic Institute of Brooklyn--- Mitsubishi Electric
Sato, F	6	Omron
Suzuki, M	6	Tokyo Inst Polytech
Takada, A	6	NTT
Wakabayashi, H	6	KDD
Watanabe, M	6	Electrotechnical Laboratory
Yajima, H	6	Electrotechnical Laboratory
Fujii, H	5	NEC
Hashimoto, M	5	Tokyo Inst Technology
Iwamura, H	5	NTT
Kawata, S	5	NEC
Kimura, Y	5	NTT

Source: *Web of Science. Scitation.*

Appendix VI: Laser and Semiconductor Laser

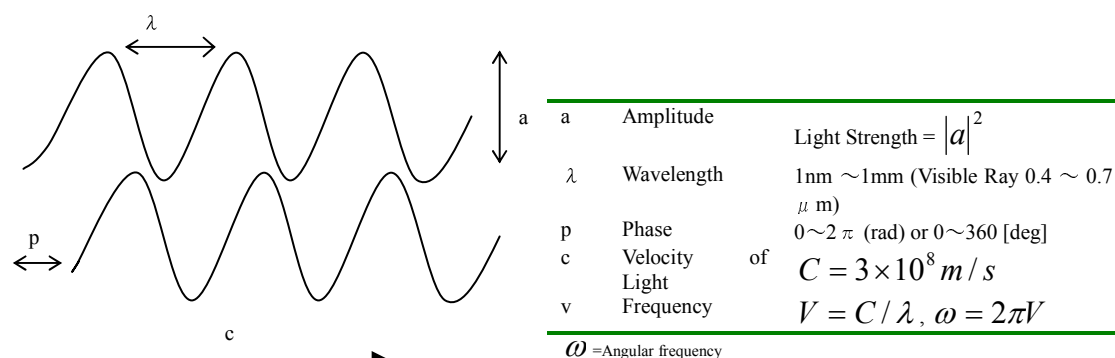
Two Natures of Light: Waves and Particles

Light has two natures; waves and particles. Light simultaneously exhibits these two natures. Physicists found the former aspect first and found the latter aspect later. Both of these aspects are important natures for laser technology. This section briefly explains these natures.

Light has been one of the challenging topics in physics from Euclid. Euclid studied how mirror reflected light in water. He was thinking light refraction. He put a ring in a jar. One could not see the ring when one saw diagonally the jar. One could see it only from just above. However, if one filled the jar with water, one could see the ring from the diagonal. This was the first experiment regarding light in physics. From AC two century, physicists began to study various aspects of light such as refraction, diffraction, and velocity.

In the late nineteen-century, a Scottish physicist brought a breakthrough in the research of light. Based on Faraday's law of induction, James Clerk Maxwell developed a set of equations expressing the basic laws of electricity and magnetism and presented in 1864.¹ He indicated that light was an electromagnetic disturbance in the form of wave propagated through the electromagnetic field according to electromagnetic laws. In short, he revealed that light is a visible electric wave. Figure 1 represents the characteristics of light in terms of electric wave.

Figure 1: Light as Electric Wave



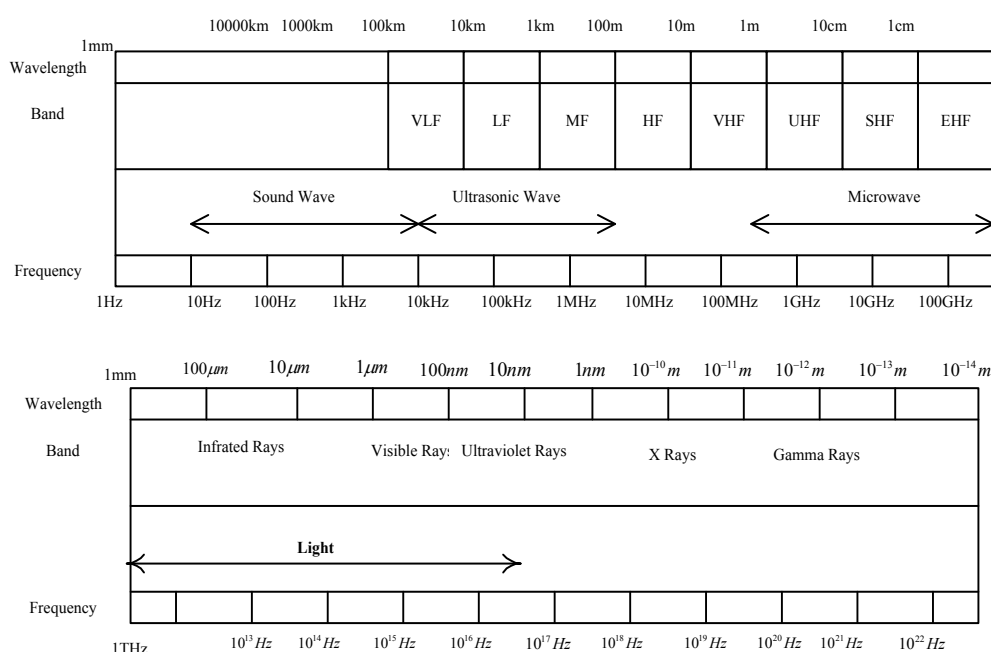
Source: Hirata, *Wakaru Handōtai Rēzā No Kiso to Ōyō*, (*Handbook of Semiconductor Laser, Basics and Application*), p.14.

Amplitude (a), wavelength (λ), phase (p), and velocity of light (c) are four factors, which one can feel when we see light. Amplitude is related with light strength. The higher amplitude light, the brighter we see. Wavelength is related with colour of light. If light has longer wavelength, the colour becomes blue. Shorter wavelength

¹ Maxwell, *A Dynamical Theory of the Electromagnetic Field*.

light becomes red. Phase corresponds with the colour of interference. Why we see different colours in light reflected in water is because natural light has different phases. As described above, Maxwell indicated that light was visible electric wave. When electricity vibrates, electric wave occurs. Frequency is an indicator of the number of electric vibrations in one second. Light is a wavelength that vibrates five hundred billion times per second. The visibility of light depends on wavelength. Figure 2 shows the relationship between wavelength and classification of electric wave.

Figure 2: Wavelength and Light



Source: Mizuno, *Optoelectronics Handbook*, p.16.

About forty years after Maxwell's theory, German physicists revealed the other nature of light. In 1900, a German physicist, Max Karl Ernst Planck, presented that light had elementary units ($h\nu$), which could not be separated into a smaller unit.² This finding suggested that light had a nature as particle. Since this Planck's new theory was revolutionary, it took five years to recognize the scientific importance of this new theory. In 1905 based on Planck's theory, Albert Einstein published "On a Heuristic Viewpoint Concerning the Production and Transformation of Light" and clearly revealed the second nature of light that had not been found. Einstein presented that light was particle flying at the speed of light (c). This thesis proposed the idea of "light quanta", currently called photons, and showed photoelectric effect. He also introduced the concept of population inversion.³ This

² This " h " is called Planck's constant and " ν " is the frequency of the radiation.

³ On population inversion, see Figure 7 and 8.

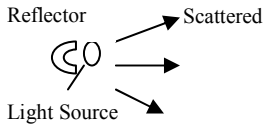
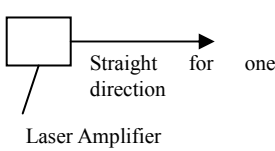
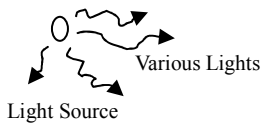
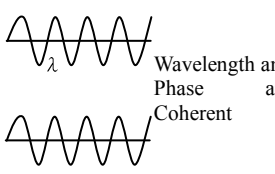
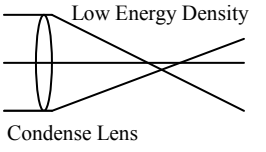
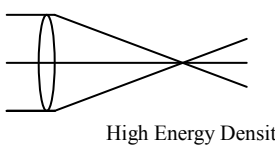
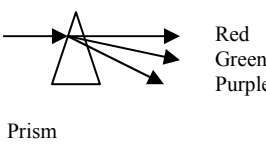
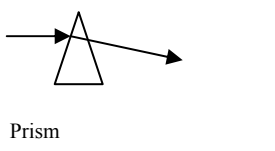
was one of the most important findings in opening up the current quantum physics.

Maxwell found that light was an electric wave in 1867. Einstein indicated that light was a kind of particles in 1905. The findings showed that light had two aspects; wave and particle. These findings provided indispensable theoretical background for the invention of laser.

Features of Laser Light

Laser has unique characteristics, which natural light does not have. It has four distinctive characteristics, directivity, coherency, energy density, and mono-wavelength (Table 1).⁴ Because of these four characteristics, laser is widely used in various areas.

Table 1: Four Characters of Laser Light

	Natural Light	Laser Light	Application Examples
Directivity	 <p>Reflector Scattered Light Source</p>	 <p>Straight direction for one Laser Amplifier</p>	Optical Communication Laser Scanner Optical Disc Laser Rader
Coherency	 <p>Various Lights Light Source</p>	 <p>Wavelength and Phase are Coherent</p>	Holography Measurement
Energy Density	 <p>Low Energy Density Condense Lens</p>	 <p>High Energy Density</p>	Laser Processing Laser Weld Laser Scalpel Laser Weapon
Wavelength	 <p>Red Green Purple Prism Light is separated by spectrometer according to its wavelengths.</p>	 <p>Prism</p>	Spectroscopic Analysis

Source: Tanikoshi, *Lēsār no Hanashi, (Handbook of Laser)*, p 39.

The first point is directivity. Laser light goes straight for one direction, while natural light goes to several directions. The second point is about coherency. While

⁴ Tanikoshi, *Lēsār no Hanashi, (Handbook of Laser)*.

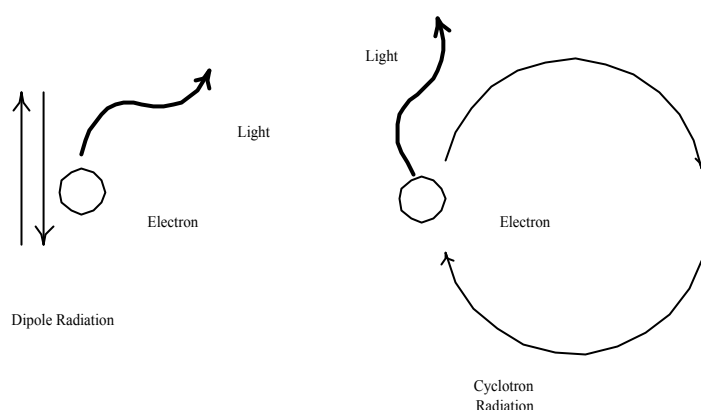
the wavelength and phase of natural light are inconsistent, those of laser light are coherent. The third point concerns energy density. Because of its directivity, laser light can focus on a precise point. As a result, it attains high energy density. This characteristic enables laser light to use in material processing. The last point is its wavelength. While natural light includes various wavelengths, laser is mono-wavelength light.

Laser is used in various areas such as optical communication, material processing, and bombing. Lasers are classified into five categories based on the medium used to amplify light; solid body laser, gas laser, liquid laser, chemical laser, and semiconductor laser. Since different lasers vary their wavelength, input and output power, and manufacturing costs, they are widely used in various areas. Because semiconductor laser is compact and easy to operate, there are various application areas. For instance, it is used in compact disc player, digital videodisc player, barcode recorder, pointer, measurement, printer, and optical fibre. Semiconductor laser is also used for lightning for another laser. Both optical communication and optical storage, however, were the main application areas of semiconductor laser, even though there are many small application areas. There are two types of semiconductor lasers according to its wavelength of laser. Long wavelength semiconductor laser is used in optical communication. Short wavelength semiconductor laser is used in optical storage.

Making Laser Beam

This section briefly explains how laser technology uses these natures of light in order to produce light. One can make light with many different ways such as striking a match, turning on the light and catching fireflies. All of these ways use the same principle to make light. As described, light is an electric wave. Therefore, one can make light by vibrating electron. Figure 3 shows two classic models.

Figure 3: Two Classic Models of Light Radiation



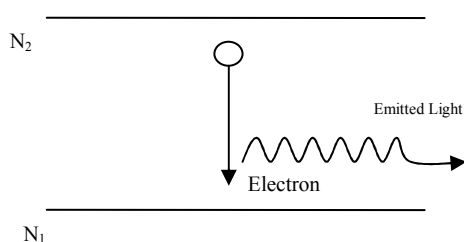
Source: Hirata, *Wakaru Handōtai Rēzā No Kiso to Ōyō*, (*Handbook of Semiconductor Laser, Basics and Application*), p.22.

Dipole radiation makes light by vertically vibrating electron. Cyclotron radiation

circularly vibrates electron and makes light. One can make light by vibrating electron around five hundred trillion times per second.

Why does vibrated electrons make light? Electrons stay either at N_1 or at N_2 . Electron at N_1 has lower energy than that of N_2 . Electrons do not stay in the middle of them. Electrons at N_1 are called the ground state. Electrons at N_2 are called the excited state. The electrons radiate light, which is the energy gap between N_1 and N_2 , when the electrons of N_2 fall down to N_1 (Figure 4).

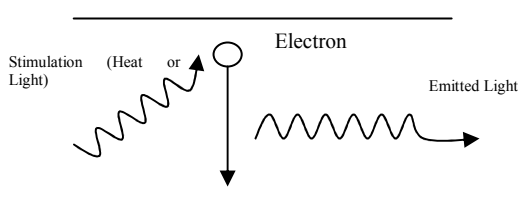
Figure 4: Natural Emission



This emitted light is natural light. Its directivity and coherence, therefore, are scattered and various. Almost of all the light in our daily life such as solar light, electric light, and candlelight, is natural emission light.

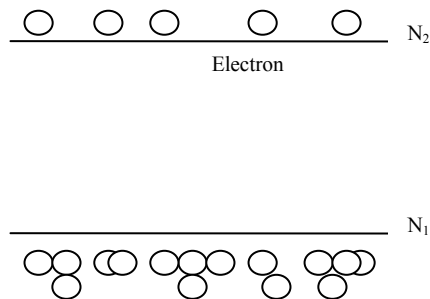
There is another type of emission, called stimulated emission. In stimulated emission, light stimulates N_2 electron to fall down to N_1 (Figure 5).

Figure 5: Stimulated Emission



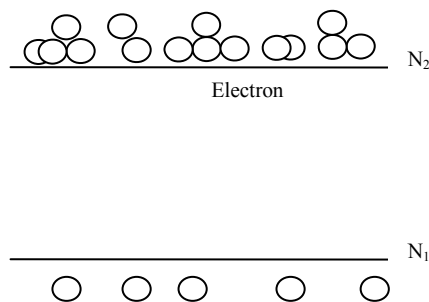
The stimulated light has the same amplitude and wavelength as the light stimulating the electron. This is a unique characteristic of stimulated emission. Laser uses this unique nature of stimulated emission.

Stimulated emission does not occur in natural environment. There are two requirements to make laser beam; (1) population inversion and (2) feedback. Population inversion is of fundamental importance for laser because stimulated emission occurs only in this special circumstance. Figure 6 illustrates the state in which the number of electrons located at N_1 is more than that of N_2 . This state is called thermodynamic equilibrium. In natural environment, electrons are always in thermodynamic equilibrium.

Figure 6: Thermodynamic Equilibrium

Source: Hirata, *Wakaru Handōtai Rēzā No Kiso to Ōyō*, (*Handbook of Semiconductor Laser, Basics and Application*), p.31.

Stimulated emission does not occur in this circumstance. It is indispensable to increase the number of the electrons in higher energy orbit (N_2) for attaining stimulated emission. This state in which the number of the electrons at N_2 exceeds half of all electrons is called population inversion.

Figure 7: Population Inversion

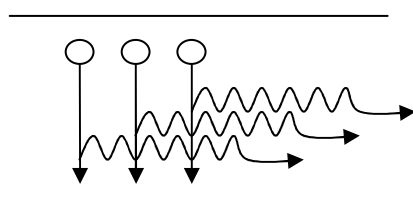
Source: Hirata, *Wakaru Handōtai Rēzā No Kiso to Ōyō*, (*Handbook of Semiconductor Laser, Basics and Application*), p.32.

In natural environment, the number of the electrons located in lower energy orbit (N_1) exceeds that of the electron in higher energy orbit (N_2). When Einstein proposed the mechanism of population inversion in 1905, it was believed that population inversion could not be attained. However, it became proven that population inversion could be attained by strongly activating material. For instance, exposing material to strong light or strongly discharging electricity causes population inversion. It is necessary to give artificially high energy to atom. For example, Maiman used xenon flashlight to achieve population inversion for his ruby laser in 1960.⁵ When the number of the higher electrons exceeds half of the all electrons, stimulated emission occurs. In population inversion, the light emitted

⁵ Xenon is one kind of electric filament type light bulbs. Xenon has higher output than other filament type bulbs such as krypton bulb and halogen bulb have.

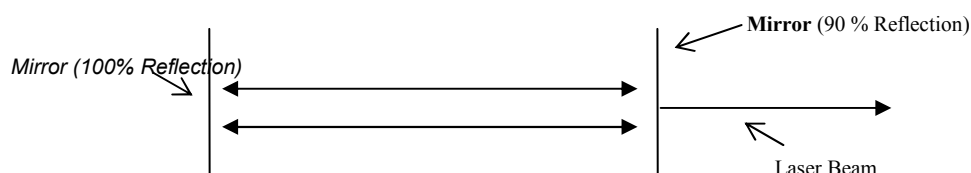
from the stimulated electron stimulates other electron. It causes the emission of another photon of the same energy. In other words, the secondly stimulated electrons emit the light that has the exactly same wavelength. This phenomenon is called “stimulated emission.” When this stimulated emission happens repeatedly, the light becomes stronger. This is the basic mechanism of laser light.

Figure 8: Stimulated Emission Radiation



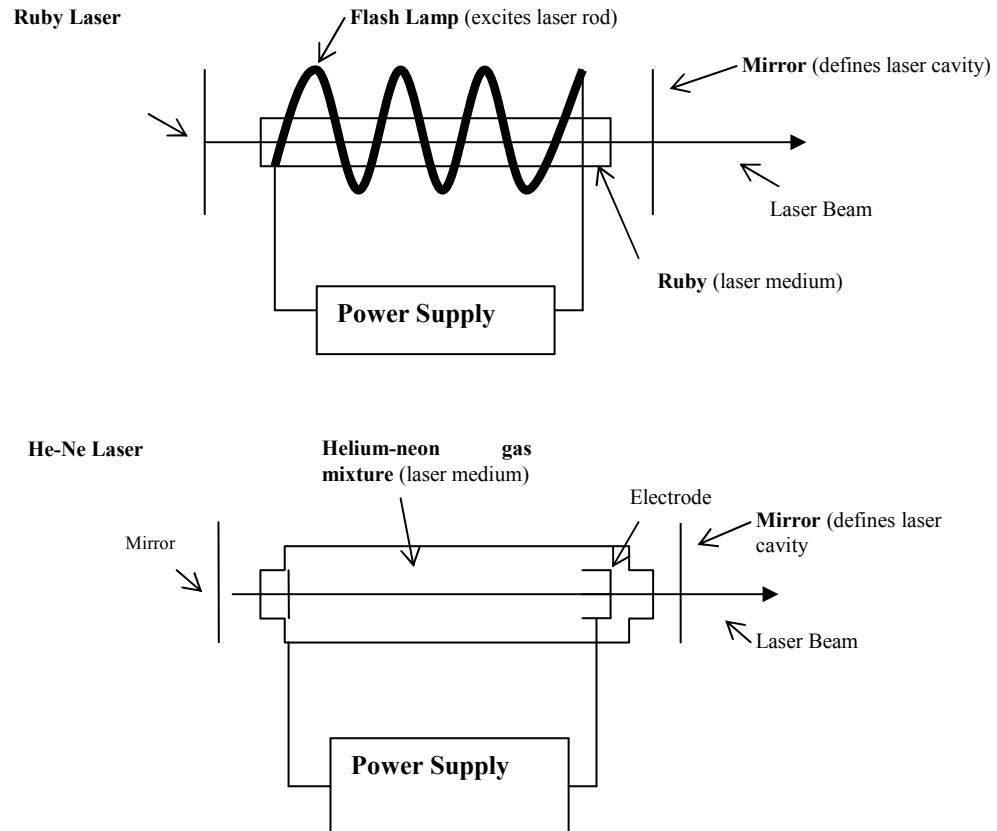
The second requirement to make laser beam is feedback. The device for laser must have a feedback structure to amplify stimulated emission. The feedback is attained with two parallel mirrors, called Fabry-Perot. Stimulated emission is amplified and concentrated between those two mirrors. Then, laser beam comes out from one of the mirrors, which the beam penetrates (Figure 9).

Figure 9: Feedback Structure



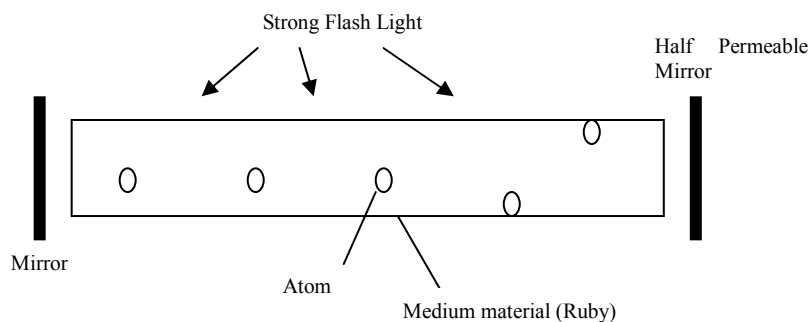
Source: Hirata, *Wakaru Handōtai Rēzā No Kiso to Ōyō*, (*Handbook of Semiconductor Laser, Basics and Application*), p.33.

What kinds of devices are needed to amplify laser beam? Laser device is consisted of three key elements. The first is the laser medium to generated light. The second is the power supply to deliver energy to the medium needed to stimulate electrons to emit light. The third is the mirrors to concentrate the light to stimulate the emission of laser radiation. All three elements can take various forms. Figure 10 shows the basic three elements of ruby laser and He-Ne laser, which have simpler structure than semiconductor laser. First, flashlight radiates pulse light. The pulse light excites atoms in the medium material. Then, laser beam goes out from the cavity.

Figure 10: Ruby Laser and He-Ne Laser

Source: Hecht, *The Laser Guidebook*, p. 4

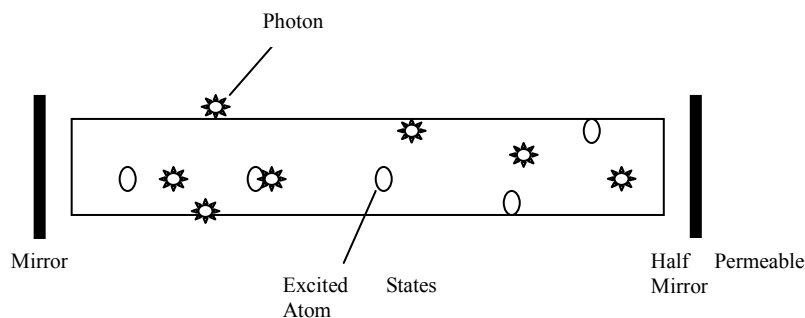
How does the mechanism produce laser beam in a lightning device? Figure 11, 12 and 13 show the basic mechanisms of amplifying laser beam in Ruby laser. First, flashlight radiates pulse light. It excites atoms in the medium material.

Figure 11: Mechanism of Ruby Laser 1

Source: Yano Keizai Kenkyūjyo, (Yano Research Institute). *Kakudai Suru Rēzā Sangyō no Shijō Jittai to Kongo no Juyō Tenbō*, (*Survey on Semiconductor Laser Market and Its Prospects*), p.19.

The excited atoms emit photons in order to keep energy balance. Since the wavelength and phase of this emitted light are inconsistent, this light is natural emission light. Since the photons move at random, many of them go out from the material. Some of the photons stimulate atoms to emit photons more. This effect is called stimulated emission. In this special situation, the atoms emit the stimulated emission light whose wavelength and phase are consistent.

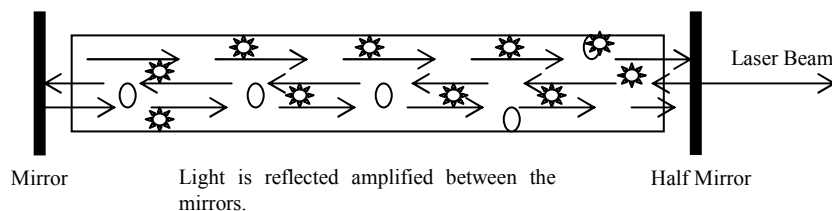
Figure 12: Mechanism of Ruby Laser 2



Source: Yano Keizai Kenkyūjyo, (Yano Research Institute). *Kakudai Suru Rēzā Sangyō no Shijō Jittai to Kongo no Juyō Tenbō*, (Survey on Semiconductor Laser Market and Its Prospects), p.19.

It is necessary to amplify this stimulated emission light to produce laser beam. The light can be amplified by setting one mirror against the other half mirror to reflect the light. By the reflection between two mirrors, the number of excited atoms increases. This process is called light pumping. As a result, the stimulated emission light becomes stronger. And the stimulated emission light goes out as laser light through a small hole of the half mirror whose reflective rate and transmission rate are 50% respectively.

Figure 13: Mechanism of Ruby Laser 3



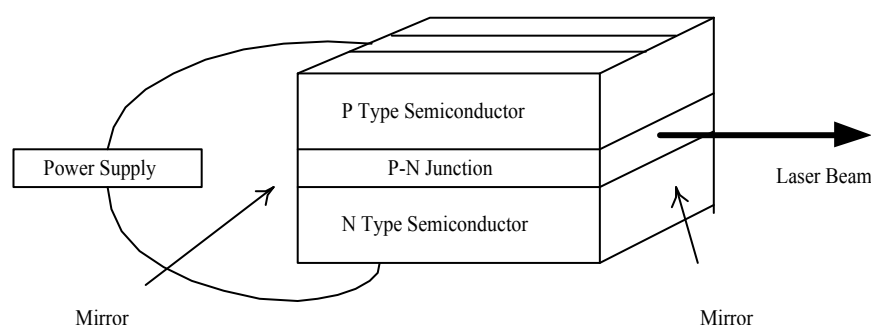
Source: Yano Keizai Kenkyūjyo, (Yano Research Institute). *Kakudai Suru Rēzā Sangyō no Shijō Jittai to Kongo no Juyō Tenbō*, (Survey on Semiconductor Laser Market and Its Prospects), p.19.

Semiconductor Laser

What is the mechanism of semiconductor laser? Semiconductor laser is a tiny electronics device mainly used in optical fibre and optical information storage. Figure 15 depicts an actual sized semiconductor laser. Its height is around one centimetre. The diameter of the packaged semiconductor laser is around 5 millimetres.

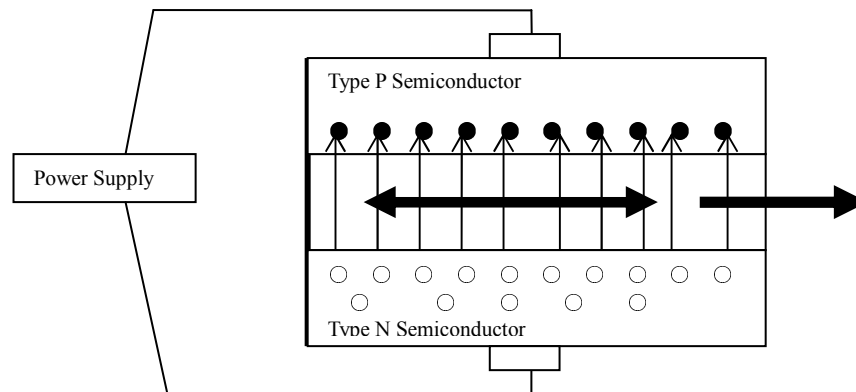
Figure 14 illustrates the basic structure of semiconductor laser. Semiconductor laser has the same basic structure as other lasers such as ruby laser and He-Ne laser described above. It has the same three key elements; the laser medium, the power supply and the mirrors. Semiconductor laser uses semiconductor as the laser medium. It consists of two outer semiconductor layers separated by a middle layer, called p-n junction. The middle layer is called an active layer. The two outer semiconductor layers are called a cladding layer. This structure is packaged in the circular package as illustrated in Figure 15.

Figure 14: Semiconductor Laser



Source: Hirata, *Wakaru Handōtai Rēzā No Kiso to Ōyō*, (*Handbook of Semiconductor Laser, Basics and Application*), p.34.

Semiconductor laser literally uses semiconductor materials such as silicon, germanium, or selenium as the laser medium to generate laser beam. The basic mechanism to radiate laser beam is the same as the other lasers. Figure 15 exemplifies the mechanism of semiconductor laser amplification.

Figure 15: Semiconductor Laser

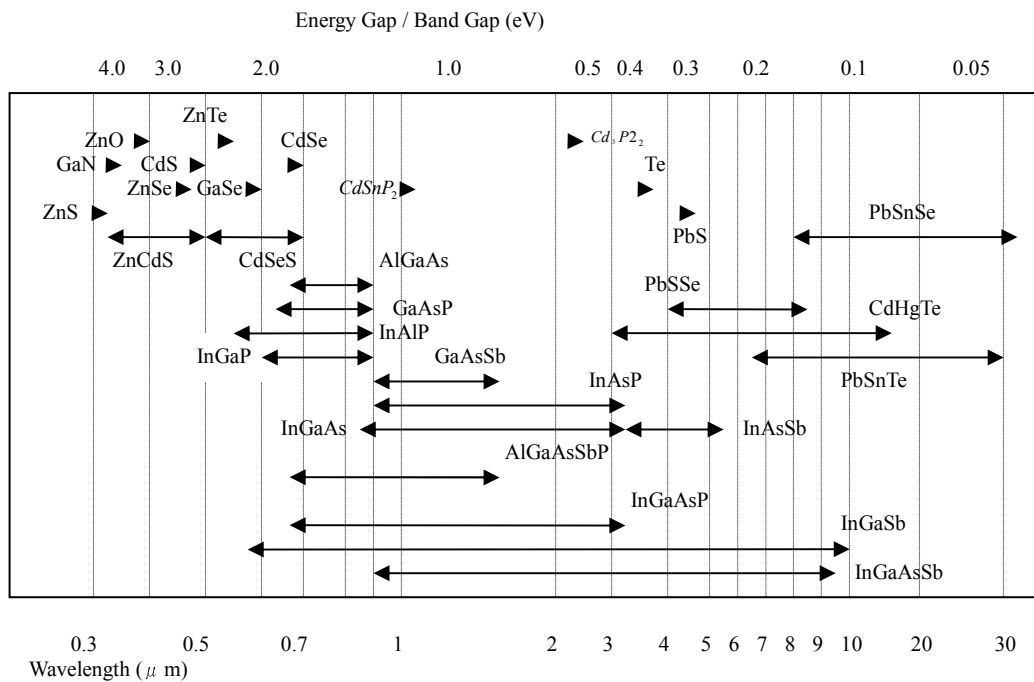
Source: Andō, Kōji. *Hikari to Hikari no Kiroku; Hikari Hen, (Light and Optical Memory)*, p.185.

Semiconductor has three technological characteristics.

- (1) Semiconductors have medium electric resistance rate between conductor and non-conductor at room temperature. ($1 \times 10^{-3} \sim 1 \times 10^{10} \Omega \text{ cm}$)
- (2) While semiconductor's resistance rate becomes infinite at the extreme low temperature, it becomes low resistance rate in inverse proportion to the temperature goes up.
- (3) When semiconductor has impurities or when it is exposed to light, its resistance rate varies.

Various materials can be used to produce semiconductors. For instance, not only single material such as silicon (Si) and germanium (Ge), but also compound such as GaAs and GaP can be semiconductor material. According to its materials, semiconductors vary its intrinsic resistance.

Different semiconductor materials amplify at different wavelengths when they are used for laser amplification. Figure 16 shows some examples of semiconductor materials and their wavelength.

Figure 16: Semiconductor Materials and Wavelengths

Source: Suzuki, "Kitai Fukuramu Handōtai Rēzā no Gijutsu Kakushin (Technological Innovation of Semiconductor Laser)", p.278.

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