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How Well Does Knowledge Travel? The Transition from Energy to Commercial Application of Laser Diode Fabrication Technology

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This essay uses the example of laser diode fabrication technology to examine how certain scientific knowledge made the transition between nations over time and how this knowledge came to be utilized in applications not originally envisaged by its developers. We explore how scientific knowledge produced through U.S. Department of Energy research made the transition from the United States to Japan via defense research, where it flourished in mass-market applications. Specifically, we focus on the role played by academic societies, journals, and research communities, using the case of metal organic chemical vapor deposition (MOCVD) technology—one of the techniques used in laser diode manufacture—to explain how this technology came to be used in compact disc players. We show that competition in domestic markets, explicit knowledge, and elaborative research influenced how certain knowledge travelled internationally.

Introduction

This essay uses the example of laser diode fabrication technology to examine how certain scientific knowledge made the transition between nations over time and how this knowledge came to be utilized in applications not originally envisaged by its developers.

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Knowledge transfer is a core issue in the fields of economics, management studies, and business and economic history. We explore how scientific knowledge produced through U.S. Department of Energy (DOE) research made the transition from the United States to Japan via defense research, where it flourished in mass-market applications. Specifically, we focus on the role played by academic societies, journals, and research communities, using the case of metal organic chemical vapor deposition (MOCVD) technology—one of the techniques used in laser diode manufacture—to explain how this technology came to be used in compact disc players.[1]

Underlying the drastic changes in information technology that took place during the latter half of the twentieth century, diode lasers have become one of most important technologies in the optoelectronics industry and have been in widespread commercial use since the 1980s. The MOCVD technique is a key element in the laser diode fabrication process. It was developed in the mid-1970s with DOE support by scientists at Rockwell International. The main objective of the Rockwell International research was to develop a technique that would yield high-quality laser diodes. Although those scientists did not have its future commercial applications in view, the technology was subsequently utilized by Sony in the development of diode lasers for the compact disc players that went into mass production in the 1980s. By investigating articles published in academic journals and their citations, and the research communities of corporate and academic scientists, this essay demonstrates the way in which competition in domestic markets has influenced the movement of certain scientific knowledge between nations.

Knowledge Transfer

Knowledge transfer remains a controversial topic both in the fields of business and economic history and in the area of innovation studies. Broadly speaking, knowledge transfer has been viewed in terms of the transfer of technology. Technology is the embodiment of one system of knowledge, and the scientific knowledge that produces that technology is one of the topics that will be addressed in this essay. Science is knowledge relating to our understanding of physical phenomena, and it differs from technology in that technology is developed as a means to a specific end. This being the case, we will examine the issue of knowledge transfer as opposed to technology transfer.

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[1] On the technological development of laser diodes in the United States and Japan, see Hiroshi Shimizu, "Different Evolutionary Paths: Technological Development of Laser Diodes in the US and Japan, 1960-2000," *Business History* 52 (Dec. 2010): 1151-81; Shimizu, "Scientific Breakthroughs and Networks in the Case of Semiconductor Laser Technology in the US and Japan, 1960s-2000s," *Australian Economic History Review* 51 (March 2011): 71-95.

Economic historian Alexander Gerschenkron is the author of an influential study on the subject of technology transfer. According to Gerschenkron, economically backward countries are able to accelerate the process of industrialization because they have access to the technologies developed by their predecessors in the process of industrial development.[2] Nathan Rosenberg, meanwhile, argues that the success of the technology transfer process is dependent on the development of institutional infrastructure in recipient countries—in other words, that the ability of an economically backward country to accelerate the process of industrialization using technologies developed in industrially advanced nations is dependent on conditions in the backward country.[3] The conditions affecting the level of receptiveness to technology constitute one of the topics addressed in the field of management studies. Wesley Cohen and Daniel Levinthal argue that, in addition to the direct role played by research and development in the creation of technical knowledge, R&D is also instrumental in cultivating the ability to absorb knowledge from outside an organization.[4] R&D conducted within an organization facilitates rapid access to key technologies developed outside the organization and has a crucial function in linking research findings to the commercialization of these technologies.

There is a growing body of research on the different routes to knowledge transfer, and personnel transfers are one such route. Paul Almeida and Bruce Kogut assert that the mobility of scientists is of greater significance than geographical proximity to knowledge spillovers.[5] Michael Stolpe argues that highly mobile engineers are critical to knowledge diffusion even within the narrow field of liquid crystal technology.[6] In addition to the issue of scientist mobility, research is also being conducted into the impact on knowledge transfer of interactions at the individual level.[7] In this connection, the networks and communities of scientists and

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[2] Alexander Gerschenkron, *Economic Backwardness in Historical Perspective: A Book of Essays* (Cambridge, Mass., 1962).

[3] Nathan Rosenberg, "The International Transfer of Technology: Implications for the Industrialized Countries," in *Inside the Black Box: Technology and Economics*, ed. Nathan Rosenberg (New York, 1982), 245-79.

[4] Wesley M. Cohen and Daniel A. Levinthal, "Innovation and Learning: The Two Faces of R&D," *Economic Journal* 99 (Sept. 1989): 569-96.

[5] Paul Almeida and Bruce Kogut, "The Exploration of Technological Diversity and Geographic Localization in Innovation: Start-up Firms in the Semiconductor Industry," *Small Business Economics* 9 (Feb. 1997): 21-31.

[6] Michael Stolpe, "Determinants of Knowledge Diffusion as Evidenced in Patent Data: The Case of Liquid Crystal Display Technology," *Research Policy* 31 (Sept. 2002): 1181-98.

[7] Bruce Kogut and Udo Zander "Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology," *Organization Science* 3 (Aug.

engineers are viewed as important channels in the transfer of knowledge.[8] To date, the general assumption has been that knowledge spillovers are intranational as opposed to international in scope, because, as detailed above, the transfer of knowledge generally occurs through personnel transfers and interactions between individuals.[9] Lee Bran- stetter has conducted a study of knowledge spillovers between Japan and the United States and, though he finds evidence (although only a little) to suggest that Japanese firms have learned from research and development undertaken by American corporations, he questions whether such evidence will be found if knowledge spillover within the United States is controlled.

By exploring the geographical and temporal transfer of laser diode fabrication technology, we investigate how this scientific knowledge made the transition from the United States to Japan, where it flourished in mass market applications. Knowledge has the potential to travel in multiple directions, and this essay demonstrates the non-linearity of the knowledge transfer process.

Significant advances have been made in terms of patent data availability, leading to a number of studies that attempt to explore the technological trajectories of knowledge by examining patent citation networks.[10] The basic idea behind this approach is simple: if a patent is cited, it means that the technology described therein forms the basis for subsequent invention. Since we aim to examine the way in which certain technologies evolved from scientific findings to commercial application, we follow the bibliographic citation trail as opposed to patent citations. Note that the analysis herein is supported by detailed case studies.

Laser Diodes and Their Manufacture

The first laser diodes were developed simultaneously by four American institutions working independently—General Electric (GE), International Business Machines (IBM), the University of Illinois Urbana-Champaign (UIUC), and the Massachusetts Institute of Technology (MIT) in 1962.

1992): 383-97; J. C. Spender, "Making Knowledge the Basis of a Dynamic Theory of the Firm," *Strategic Management Journal* 17 (Winter 1996): 45-62.

[8] Bruce Kogut Bruce and Paul Almeida, "Localization of Knowledge and the Mobility of Engineers in Regional Networks," *Management Science* 45 (July 1999): 905-17; Stolpe, "Determinants of Knowledge Diffusion," 1181-98.

[9] Lee G. Branstetter, "Are Knowledge Spillovers International or Intranational in Scope? Macroeconometric Evidence from the U.S. and Japan," *Journal of International Economics* 53 (Feb. 2001):53-79.

[10] Roberto Fontana, Alessandro Nuvolari, and Bart Verspagen, "Mapping Technological Trajectories as Patent Citation Networks: An Application to Data Communication Standards," *Economics of Innovation and New Technology* 4 (June 2009): 311-36; A. Mina, R. Ramlogan, G. Tampubolon, and J. S. Metcalfe, "Mapping Evolutionary Trajectories: Applications to the Growth and Transformation of Medical Knowledge," *Research Policy* 36 (June 2007): 789-806.

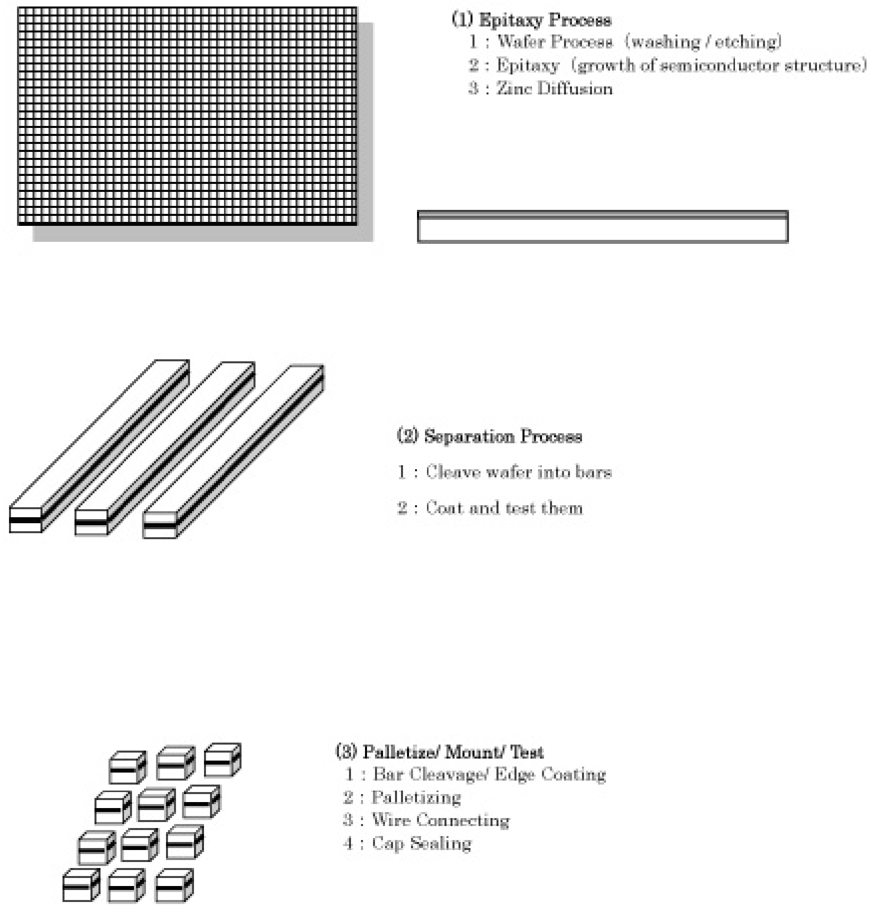
Laser diodes (also known as semiconductor lasers) emit laser beams. Laser was originally an acronym that stands for "light amplification by stimulated emission of radiation." Many different lasers are currently in use, including CO2, YAG, He-Ne, ruby, and laser diodes. Continuous laser beams have powers ranging from a fraction of a milliwatt to over a megawatt, and laser applications range from commercial products to specialized military uses. Laser technology is seen as a general purpose technology (GPT); diode lasers, meanwhile, find wide use in medicine, as a light source for high-speed cameras, in material processing, optical sensors, laser pointers, measurement, optical disks, printers, barcode readers, and optical fiber communications. In numerical terms, laser diodes are the most common type of laser, with laser diode technology underpinning the dramatic changes that occurred in information technology during the latter half of the twentieth century.

The compact disc player, which went on sale in 1982, was the first major commercial application of laser diode technology. Unlike the analogue records that it superseded, the compact disc player uses a laser beam (produced by a laser diode) to read audio data that has been encoded onto the surface of a compact disc by means of patterned indentations known as "pits." Compact disc players have become cheaper and increasingly compact since their commercial launch in 1982. But compact disc players did not generate significant economic value from the outset: sales of compact discs did not overtake sales of vinyl records until 1986. Nonetheless, there can be little doubt that compact discs were a key driver in the subsequent digitalization process. With the commercial launch of CD-ROMs (Compact Disc Read-Only Memory) in 1985, it became possible to store data other than audio files onto compact discs. Recordable compact discs (CD-R), which made it possible to write data onto compact discs, became commercially available in 1989. This was followed by Digital Versatile Discs (DVD), an optical disc format with a higher density than compact discs that made it possible to store images and other high-volume data. Laser diodes, the core component of the optical disc player, have subsequently found wide use in laser pointers, displays, and scanners, among other mass market applications.

This essay focuses on the development of the compact disc player as the first commercial application of laser diode technology to generate significant economic results. The compact disc player was developed as the result of competitive research and development primarily involving Sony and other Japanese electronics manufacturers. The laser diode technology that is critical to compact disc player manufacture was not, however, developed by Japanese corporations. That technology derives from American research that was conducted during the 1960s.

The fabrication of laser diodes broadly breaks down into three processes (see Fig. 1). The first, the epitaxy process, involves making a semiconductor wafer by depositing a very thin layer of single crystal materials over a substratum. This process is the most important of the three, because the semiconductor layers affect the quality and longevity of

Figure 1
Laser Diode Manufacturing Process



Source: Compiled from Hirata Shoji, *Wakaru Handotai Reza no Kiso to Oyo* [Handbook of Semiconductor Lasers, Basics and Applications] (Tokyo, 2001).

the resultant laser diode, which vary according to the combinations of semiconductors used. In the second process, the semiconductor wafer is cleaved into bars using a diamond saw; these bars are then diced into semiconductor laser chips. The final packaging process is designed to enable the semiconductor laser chips to be used as an electronic device. Leads are attached to the semiconductor tip, and the tip is sealed into the package. This process is followed by performance testing of optical and electrical function.

The optoelectronics handbook notes: “Epitaxy technology is the most important laser diode fabrication technology because the performance of the laser diode is highly dependent on epitaxy technology."[11] This epitaxy process is important for two specific reasons.[12] First, it determines the basic performance of a laser diode (its longevity and reliability): the laser diode amplifies the laser beam with a thin layer (0.5 to 20 microns) of different semiconductor materials, which means that layer quality is of critical importance to basic laser diode performance. Second, epitaxy enables manufacturers to achieve the economies of scale necessary to increase wafer size, thus determining how many laser diode chips can be produced in a single fabrication process. Since researchers believed that the laser diode would become one of the most important devices in the optoelectronics industry, the goal for manufacturers was thus to produce low-cost, long-lasting, highly reliable semiconductor lasers. Moreover, the high sunk costs in technology-intensive industries give firms the added incentive to produce on a large scale in order to achieve economies of scale. Epitaxy technology is the core technology in the mass production of laser diodes, and it thus became economically and strategically important to competing firms.

Broadly speaking, epitaxial silicon is grown using one of the following three methods: liquid phase epitaxy (LPE), molecular beam epitaxy (MBE), and metal organic chemical vapor disposition (MOVCD), also known as vapor phase epitaxy (VPE).

The LPE growth method came into being as the result of research undertaken at the Radio Corporation of America (RCA) beginning in 1963; it enables semiconductor crystal layers to be grown using relatively simple, inexpensive apparatus.[13] The method is known as liquid phase epitaxy because the crystals are grown by depositing constituent chemicals that have been dissolved in a solvent onto a solid substrate and then lowering the temperature of the solvent (or melt) to create a supersaturation. The LPE technique was the standard method for growing crystals during the 1960s and the 1970s.

The MBE technique for growing crystals was invented at Bell Laboratories by Alfred Y. Cho in 1975. This technique involves heating constituent chemicals in an ultra-high vacuum furnace, where the crystals are grown by utilizing the thermal energy produced by this heating process to radiate molecules and atoms onto a solid substrate.[14] The crystals are

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[11] Oyo hikari electronics handbook henshu iinkai, *Oyo Hikari Erektronicusu Handobukku* [Applied Opto Electronics Handbook] (Tokyo, 1989), 105.

[12] On epitaxy technology, see Hirata Shoji, *Wakaru Handotai Reza No Kiso to Oyo* [Handbook of Semiconductor Lasers, Basics and Application] (Tokyo, 2001).

[13] Herbert Nelson, "Epitaxial Growth from the Liquid State and Its Application to the Fabrication of Tunnel and Laser Diodes," *RCA Review* 24 (1963): 603-15.

[14] Alfred Y. Cho and Horace C. Casey, "GaAs-AlGaAs Double-Heterostructure Lasers Prepared by Molecular Beam Epitaxy," *Applied Physics Letters* 25 (Sept. 1974): 288-30.

grown in ultra-high vacuum, which allows the direction and composition of the crystals to be precisely controlled and the growth of thin-layer crystals. Although the MBE technique offers outstanding control over the crystal growth process, the necessity of maintaining ultra-high vacuum makes mass production difficult.

The MOCVD method was developed in 1977 by Russell Dupuis and Daniel Dapkus at Rockwell International.[15] MOCVD uses alkyl compounds combining Group V element hydrogen compounds with Group III elements, methyl and ethyl, where constituent chemicals are transmitted to the substrate surface as vapor. Again, crystal growth can be precisely controlled, because constituent chemicals are transmitted to the substrate surface in the gas phase. Moreover, since MOCVD does not require ultra-high vacuum, it is possible to upscale the apparatus, thus offering excellent high-volume output performance. The apparatus is extremely expensive to design, however, because the technique involves highly toxic gases.

Sony used this MOCVD technique to develop and mass produce laser diode oscillation. It began producing laser diodes for compact disc players in 1984 and has achieved significant economic results. The MOCVD technique discussed here is the dominant technology in laser diode fabrication; it is also used in the research and development of quantum well and other high-performance lasers, because it allows for microscopic control of the crystal growth process. As stated earlier, however, Sony cannot claim credit for the development of the MOCVD technique. The foundations for this technology were laid through groundbreaking research that began in the United States during the 1970s.[16] The critical scientific breakthrough was made in 1977 by Dupuis and Dapkus at Rockwell International. The next section examines the processes via which this scientific breakthrough led to technical innovation at Sony.[17]

The Transfer of MOCVD Knowledge from Rockwell to Sony

Russell Dupuis and Daniel Dapkus were members of a team engaged in laser diode research being led by Nick Holonyak at the University of Illinois at Urbana-Champaign (UIUC) research laboratories. Dupuis and Dapkus earned their doctorates in 1972, and 1970, respectively, and were

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[15] Russell D. Dupuis and P. Daniel Dapkus, "Room-Temperature Operation of $Ga_{(1-X)}Al_xAs/GaAs$ Double-Heterostructure Lasers Grown by Metalorganic Chemical Vapor Deposition," *Applied Physics Letters* 31 (Oct. 1977): 466-68.

[16] For a detailed history see: Russell D. Dupuis and M. R. Krames, "History, Development, and Applications of High-Brightness Visible Light-Emitting Diodes," *Journal of Lightwave Technology* 26 (May 2008): 1154-71.

[17] For details of the MOVCD method employed by Sony in the development of compound semiconductor devices and mass production technologies, see: Okochi Memorial Foundation, *The 1989 (36th) Okochi Memorial Prize Winners Report* (1990), 108-14.

research contemporaries at the UIUC labs.[18] Holonyak, who pioneered the world's first continuous-wave laser diode in 1962, was followed by a long line of renowned laser diode researchers produced by the University of Illinois.[19] Holonyak attended the Device Research Conference, and numerous graduates gathered around him, forming a group once known as the Holonyak School.[20]

After earning his doctorate from the University of Illinois, Dupuis joined a team of researchers working at Texas Instruments in 1973. Dapkus, meanwhile, moved to Rockwell from Bell Laboratories, where he had been conducting research into light-emitting diodes.

The goal of Holonyak and his team of researchers at UIUC was to accomplish visible wavelength laser oscillation. Laser wavelength is a function of the band-gap of the semiconductor constituents. These optically pumped semiconductor lasers (OPSL) used a III-V semiconductor chip as the gain media. In the early 1970s, neither MBE nor MOCVD were realistic technologies, and LPE was the principal method for growing crystals. The LPE approach was not without problems, however: the difficulty of growing uniform layers on large substrates and of automating the LPE process meant that crystal growth was dependent on researcher proficiency. Specifically, it proved exceptionally difficult to produce thin films with a high degree of reproducibility.

While research continued into the automation of the so-called pushrod setup used in LPE, scientists continued to look for new methods of crystal growth. One such was the molecular beam expitaxy technique pioneered by Cho at Bell Laboratories in 1975.

At around this time, Harold Manasevit, working at Rockwell International, was attempting to grow gallium nitride (GaN) on a sapphire substrate using the LPE technique. In 1971, Manasevit and his team also successfully demonstrated the MOCVD growth of GaN films on sapphire.[21] Though this represented a major scientific breakthrough, the crystals produced were of extremely poor quality.[22] In 1975, Dapkus, now working at Rockwell International, purchased a computer-controlled MOCVD

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[18] Based on findings from an interview with Russell D. Dupuis conducted by the author in Georgia, 3 Aug. 2009.

[19] The University of Illinois has produced the world's largest number of semiconductor laser doctorates. Shinichi N. Takahashi, "A Bibliography of Doctoral Theses on Semiconductor Lasers Ii" (Yokohama, 2005); Takahashi, "A Bibliography of Doctoral Theses on Semiconductor Lasers" (Yokohama, 1994).

[20] Based on findings from an interview with Kenichi Iga (professor at Tokyo Institute of Technology), conducted by the author in Tokyo, 30 July 2009.

[21] Harold M. Manasevit, F. M. Erdmann, and William I. Simpson, "The Use of Metalorganics in the Preparation of Semiconductor Materials," *Journal of The Electrochemical Society* 118 (1971): 1864-68.

[22] Dupuis and Krames, "History, Development, and Applications of High-Brightness Visible Light-Emitting Diodes."

reactor for growing semiconductor crystals for use in basic research on photovoltaic cells. This purchase was funded by a research grant from the U.S. Energy Research and Development Administration (ERDA) and was ultimately intended for use in basic research on photovoltaic cells. Since Dapkus was using this computer-controlled MOCVD system for research into laser diode crystal growth, however, he brought Dupuis over to Rockwell International in 1975. Dapkus and Dupuis had intended to use this ERDA-funded MOCVD for laser diode research from the outset. During the 1970s it was still extremely costly to introduce MBE and MOCVD apparatus for crystal growth. Researchers, however, had no idea as to the viability of producing laser diode crystals capable of laser light oscillation even if this apparatus was introduced, and there was enormous uncertainty involved in the research and development effort. The availability of ERDA funding for the purchase of an MOCVD reactor was thus critical.

Although Manasevit had successfully demonstrated the MOCVD growth of gallium nitride at Rockwell International, when Dupuis and Dapkus commenced their research, the MOCVD approach was not being considered for the growth of III-V semiconductor crystals.[23] They embarked on their research in 1975 and in 1977 succeeded in demonstrating continuous visible light oscillation from aluminum gallium arsenide (AlGaAs) grown by MOCVD at room temperature.[24] They were the first to demonstrate continuous wave operation of laser diodes grown by MOCVD, thus making a major scientific breakthrough.[25]

During the 1970s, laser diodes were produced using the liquid phase epitaxy (LPE) technique. It was, however, difficult effectively to control the growth of the crystals critical to laser diode function. In addition, scientists believed that the growth of thin-layer crystals was essential to the production of high-performance lasers. The MOCVD and MBE methods of depositing single crystals were developed to address these challenges. Nonetheless, the initial investment outlay was extremely high, and it was that cost that prompted Dupuis and Dapkis to use ERDA funding to purchase an MOCVD system for use in basic photovoltaic research—which led to the successful demonstration of continuous wave operation of laser diodes grown by MOCVD in 1977.

The articles documenting the success of Dupuis and Dapkus in demonstrating continuous wave operation of laser diodes at Rockwell

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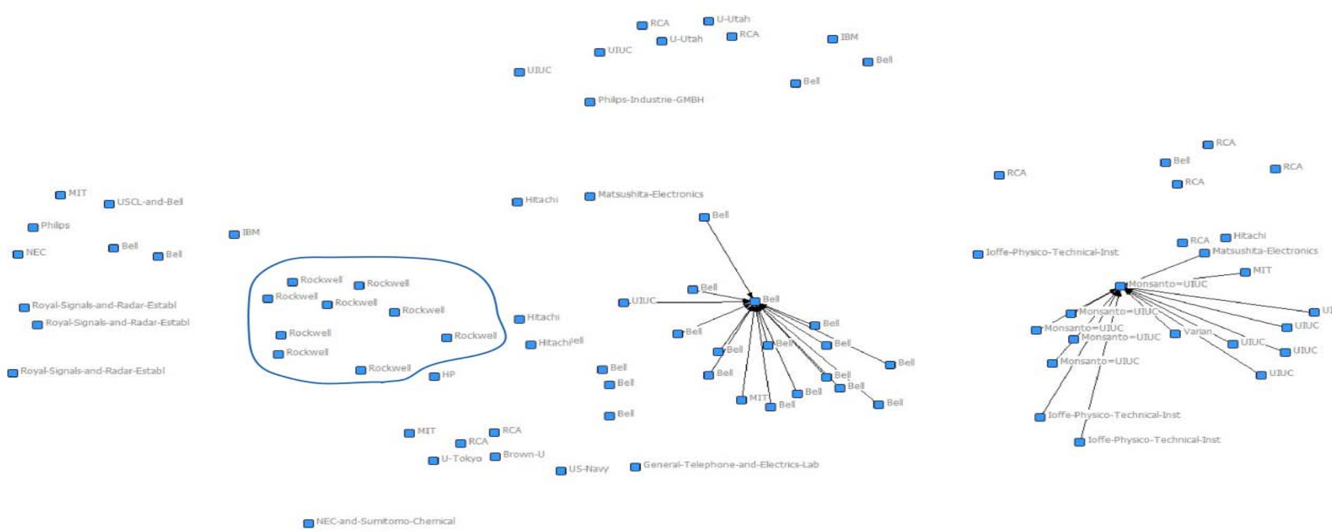
[23] Ibid.

[24] Dupuis and Dapkus, "Room-Temperature Operation of $Ga_{(1-X)}Al_xAs/GaAs$ Double-Heterostructure Lasers."

[25] Dupuis, who pioneered this research, has received numerous awards for his contributions to MOCVD research, including the IEEE Edison Medal (2007) and the National Medal of Technology (2002).

International were published between 1977 and 1978. Figure 2 shows these articles, together with the articles that led to subsequent MOCVD innovations at Sony. The area bordered in blue indicates the breakthroughs achieved by Dupuis and his colleagues at Rockwell International, while the area on the lower right-hand side of Figure 2 shows the research undertaken by Monsanto and UIUC. This research involved light-emitting diodes, and these articles formed the basis for the innovations made by Sony in later years. Holonyak was pioneering the development of visible light laser diodes at UIUC, and the research into light-emitting diodes was the precursor to this. LPE was the dominant method for crystal growth at that time. Likewise, researchers at Bell Laboratories had embarked on research that was to have an indirect impact on the innovations later made by Sony.

Figure 2
The Situation in 1978

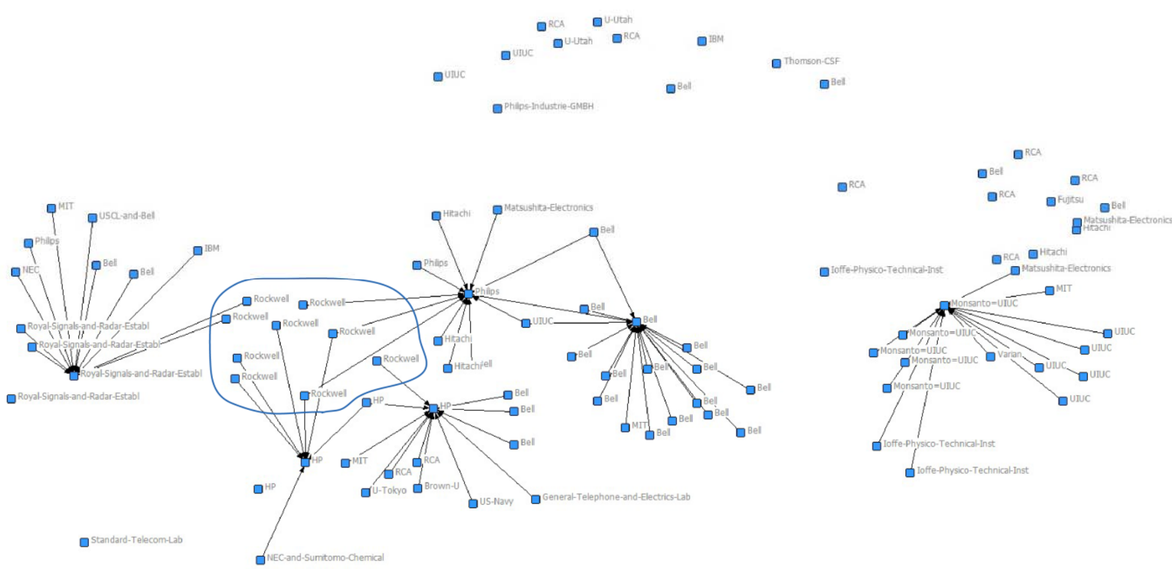


Source: Compiled from the Web of Science, based on Okochi Memorial Foundation, *1989 (36th) Okochi Memorial Prize Winners Report* (1990), 108-14.

The research into MOCVD technology was given an enormous boost by the successful demonstration of continuous wave operation of MOVCD-grown laser diodes at room temperature at Rockwell International. This research into laser diodes grown by MOCVD was underpinned by studies into techniques for controlling crystal growth and the formation of thin layers on the surface of crystal wafers. Scientists believed that if the active layer of the laser diode was made as thin as possible and its quantum efficiency utilized, a significant reduction in the threshold current of the laser diode could be achieved. It was hoped that lowering the threshold current would not only increase the lifespan of laser diodes, but also enhance laser diode performance. It was for this reason that Dupuis and his colleagues joined forces with Holonyak and his team of researchers at UIUC to conduct research into quantum well lasers after their 1977 success with continuous wave operation of MOVCD-grown laser diodes.[26] At this point, Dupuis and Dapkus were more interested in finding ways to utilize the advanced control of crystal growth afforded by the MOCVD method to develop high-performance laser diodes than in its potential for mass production.

From 1977 onward, other researchers began attempting to elaborate on the MOCVD research being undertaken by Dupuis. Gerald B. Stringfellow, who had been conducting research into light-emitting diodes and semiconductors at Hewlett Packard, began work to improve the efficiency of continuous wave lasing and to lengthen the lifespan of laser diodes grown by MOCVD. Figure 3 shows the research being undertaken by Hewlett Packard, Philips, the Royal Signals and Radar Establishment

Figure 3
The Situation in 1980



Source: Compiled from the Web of Science based on the *1989 (36th) Okochi Memorial Prize Winners Report*, 108-14.

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26 Nick Holonyak et al., "Low-Threshold Continuous Laser Operation (300-337k) of Multilayer Mo-Cvd $Al_xGa_{1-X}As$-GaAs Quantum-Well Heterostructure," *Applied Physics Letters* 33 (Oct. 1978): 737-39; Russell D. Dupuis et al., "Room-Temperature Laser Operation of Quantum-Well $Ga_{(1-X)}Al_xAs$-GaAs Laser Diodes Grown by Metalorganic Chemical Capor Deposition," *Applied Physics Letters* 32 (March 1978): 295-97.

(RSRE, a U.K. Ministry of Defense organization), and other companies on the basis of the Rockwell International research. While Hewlett Packard and Philips were working to develop light-emitting diode display devices, semiconductor lasers for optical disc players, and other commercial applications, the aim of the RSRE research into MOCVD crystal growth was to build the foundations for U.K. defense, which hints at the versatility of the MOCVD technique. Sony initiated its laser diode research and development in the late 1970s with the goal of using laser diodes as the light source for compact disc players. Sony was aiming to establish the technical standards for compact discs with a view to commercial production of compact disc players and to develop laser diodes in-house, because the diodes constituted the essential technology.

The compact disc player was to become the first mass market application for laser diodes, which meant that NEC, Toshiba, Hitachi, Sharp, and Mitsubishi Electric were all engaged in the R&D race alongside Sony. Japan's electronics manufacturers were working to develop a laser structure capable of achieving efficient laser oscillation. While research into the MBE and MOCVD methods of crystal growth had finally got under way at Bell Laboratories and Rockwell International, Japanese firms were using LPE exclusively. Nonetheless, some research into the MBE and MOCVD techniques was being conducted in Japan at this time: Hajime Asahi was working on MBE at Nippon Telegraph and Telephone Public Corporation, and Hiroshi Kukimoto was engaged in MOCVD research at Tokyo Institute of Technology.

Following the successful demonstration of continuous wave operation of laser diodes grown by MOCVD at Rockwell International, in 1977, Sony began work to develop a new method of crystal growth at its central research laboratory. Limitations on resources made it impossible to conduct parallel research on both MBE and MOCVD technologies. It was for this reason that on his return from the United States, where he had been engaged at Bell Laboratories, Makoto Kikuchi elected to work on the MOCVD technique at Sony's central research laboratory. Sony assigned only a single researcher to MOCVD, however, and the company remained focused on research into laser diodes grown by LPE.

Sony proposed a laser structure known as EBH, or etched buried hetero. This unique structure could be produced only by utilizing the crystal growth properties afforded by LPE. In 1980, the EBH structure offered the advantages of low power consumption and outstanding coupling efficiency with optical systems, but there were problems with the instability produced by external noise during oscillation. Other Japanese electronics manufacturers including NEC, Toshiba, Hitachi, and Mitsubishi Electric were also proposing new laser structures and were competing to develop structures with improved power consumption, imaging characteristics, and lifespan. The favorable properties of the buried hetero (BH) and channeled substrate planar (CSP) structures were demonstrated by Hitachi, while Mitsubishi Electric demonstrated the advantages of the transverse junction stripe (TJS) structure. Laser spots remained unstable however, and there were additional problems in terms of yield.

Sony's choice of technology was altered by a Sharp innovation. Sharp developed a laser diode structure known as VSIS, or V-channeled Substrate Inner Stripe. The VSIS structure not only offered outstanding performance in terms of laser oscillation and lifespan, but its potential for mass production far outstripped that of rival laser structures. Most of the companies working to develop laser diodes for compact disc players brought sample laser diode products to Sony, but the properties of Sharp's VSIS structure eclipsed all other contenders.[27] The superior performance of the VSIS structure was unmistakable, and the majority of compact disc players available in October 1982 were equipped with a VSIS semi-conductor laser.

Research and development at Sony had reached an impasse, however. Laser diode research for optical communications began in the 1960s; because Sony had no optical communications business it was a late entrant to the R&D race. The performance offered by Sony's EBH laser was clearly inferior to that of Sharp's VSIS structure, although both were grown by LPE.

The net result was that in 1981 Sony terminated its research into LPE-grown laser diodes and shifted to MOCVD. This was a major decision for the company. Although Sony had continued its research into MOCVD at its central research laboratory, in practical terms the decision to suspend the work on LPE-grown laser diodes in 1981 meant that the company was resolved not to equip the compact disc players due to go on the market in 1982 with its own laser diodes.

Figure 4 illustrates the links between contemporary research and MOCVD innovation at Sony in 1981. The area circled in red indicates the research into MOCVD being undertaken at Sony's central research laboratory. In 1981, Yoshifumi Mori used research into MOCVD technology undertaken at Rockwell Innovation to demonstrate continuous wave operation of a 780 nanometer (nm) laser diode at Sony's central research laboratory. This was basic research, but its goal was to develop laser diodes for compact disc players. Accordingly, rather than using the quantum well structure to increase functionality, the main point of the work was to develop laser diodes with a wavelength of 780nm (for use in compact disc players) and superior mass production.

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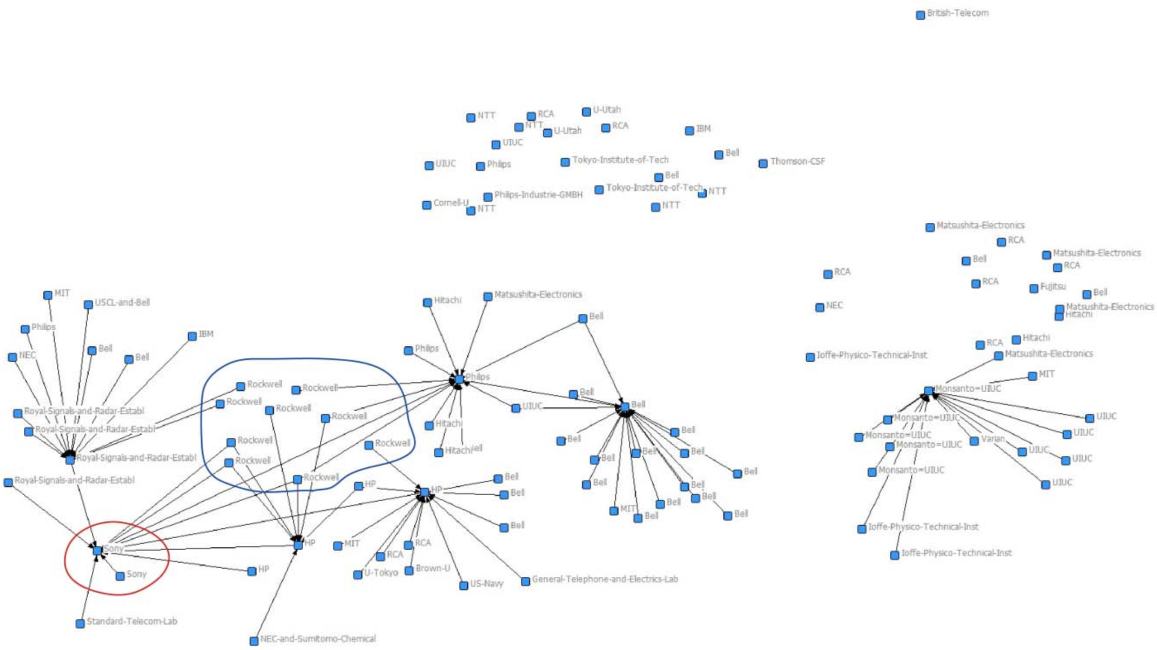
[27] Based on findings from interviews with Takayoshi Mamine, who was engaged in the development of semiconductor lasers for compact disc players at Sony (but on the staff of the University of Tokyo at the time of this interview) conducted by the author in Tokyo on 2 Nov. 2005 and 15 July 2009.

Figure 4
The Situation in 1981



Source: Compiled from the Web of Science based on the *1989 (36th) Okochi Memorial Prize Winners Report*, 108-14.

It is important to note here that the research into MOCVD technology being undertaken at Sony was based not only on the research conducted by Dupuis and his team at Rockwell International in 1977, but also on the work to elaborate this breakthrough that was undertaken by Philips, Hewlett Packard, and RSRE in later years. Moreover, the articles on this research were not in the top one percent of bibliographic citation rankings. The research did, however, serve to link the scientific breakthroughs made at Rockwell International with the innovations made by Sony. Even with development work being undertaken during the 1970s and the 1980s that had a specific commercial purpose, the research aimed at elaborating scientific breakthroughs made by external organizations played a key role in linking this groundbreaking research with corporate innovation.

The fact that Sharp's VSIS structure had a major impact on Sony's decision to shift the focus of its research effort from LPE to MOCVD technology is important to understanding the innovation process. Sharp's research on the VSIS structure is plotted on the left hand side of Figure 4. It is worth noting that no direct citation of this VSIS research is made in connection with the MOCVD research that was conducted by Sony. The links among research citations reveal an increase in research analyzing innovations made on the basis of bibliographic information such as the articles published by Sharp and patent citation links from the 1980s onward.[28] Due caution is required when analyzing the innovation process solely on the basis of bibliographic data, however. Such data had a significant impact on Sony's decision to shift the focus of its research to MOCVD technology, but it is difficult to determine how decisions on research projects were made on the basis of bibliographic data alone—that is, as separate from the flow of knowledge in linked citations. In order to understand the innovation process careful consideration needs to be given to the process by which the decisions influencing it were taken rather than relying on the bibliographic data in isolation.

As described above, the compact disc players available in 1982 were equipped with a Sharp VSIS semiconductor laser. Nonetheless, because the laser diode is the essential compact disc player technology, and it was anticipated that major technological developments would be made in this area over the coming years, all manufacturers were keen to develop their own laser diode technology in order to equip the compact disc players they produced with a company-made device as opposed to the VSIS system.

At issue was the crystal growth technology. In the first instance, there was some doubt as to whether the LPE technique was in fact suited to mass production, an issue that manufacturers were concerned could become critical when demand for compact disc players increased exponentially, as it was expected to do. The focus thus turned to MBE and MOCVD. MBE allows for precise control of the crystal growth process and was considered the easiest technique for producing lasers with good properties in the laboratory. At issue, however, was the adaptability of the MBE method to mass production. By contrast, the MOCVD technology made it possible to produce wafers with a large surface area and was thus considered to offer superior qualities for mass production.

Sony ended its research into laser diodes grown by LPE in 1981 and began concentrating its development resources on MOVCD-grown laser diodes. At this stage, no one had succeeded in developing a laser diode grown by MOCVD, though, following Sharp's development of the VSIS structure, Sony's rivals had gradually begun focusing on the development of next-generation laser diodes grown by either MOCVD or MBE.

Sony made the shift to MOCVD ahead of other Japanese electronics manufacturers, but struggled to grow lasers with a 780 nm wavelength capable of stable oscillation by MOCVD. In 1981, however, the company refined its MOCVD-grown lasers and succeeded in developing lasers that offered outstanding mass production quality using a laser structure known as TAPS (tapered stripe). This triumph enabled Sony to begin equipping

[28] For example, Bjorn L. Basberg, "Patents and the Measurement of Technological Change: A Survey of the Literature," *Research Policy* 16 (Aug. 1987): 131-41; Zvi Griliches, "Patent Statistics as Economic Indicators: A Survey," *Journal of Economic Literature* 28 (Dec. 1990): 1661-707; Adam B. Jaffe and Manuel Trajtenberg, *Patents, Citations, and Innovations: A Window on the Knowledge Economy* (Cambridge, Mass., 2002).

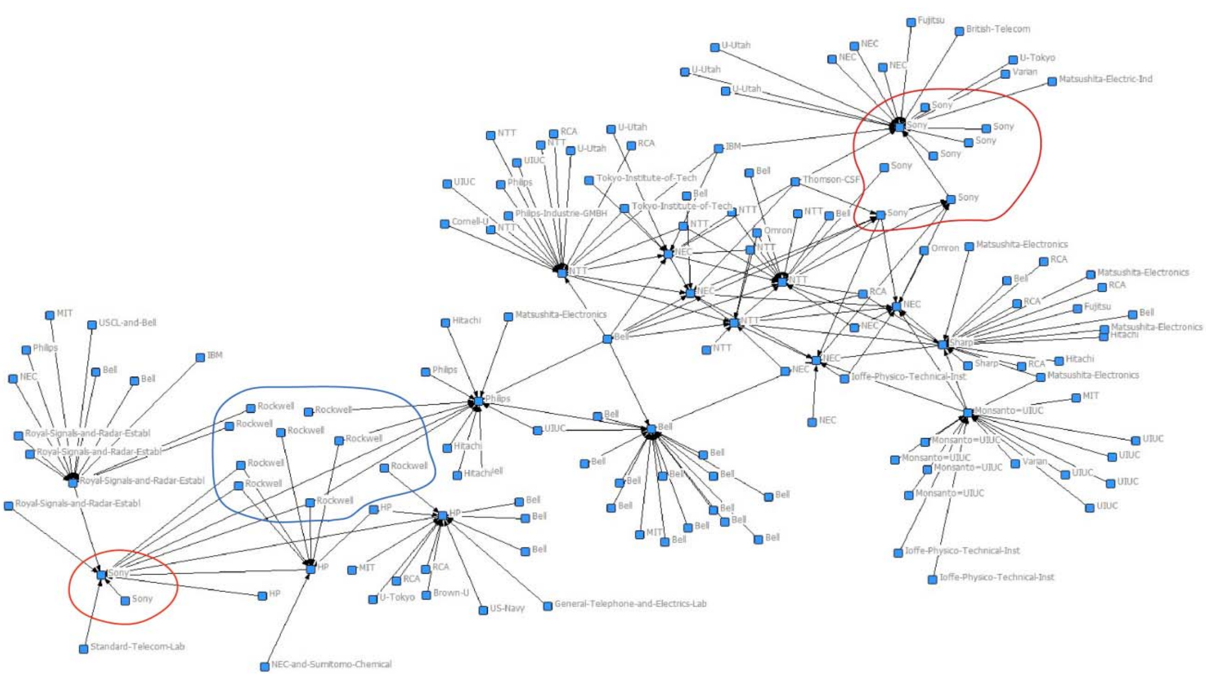
its compact disc players with its own laser diodes rather than the Sharp VSIS device in 1985.

Following the commercial launch of the compact disc player, Japanese firms began competing to shorten the wavelength of their laser diodes, because reducing the oscillation wavelength would make it possible to read and write large volumes of data. Oscillation wavelength is dependent on the band-gap of the semiconductor constituents. The laser diodes used in compact disc players had a wavelength of 780 nm and were made of gallium arsenide (GaAs). In the bid to shorten diode wavelength, attention turned to aluminum gallium indium phosphide (AlGaInP), the goal now being to develop a light source for DVDs.

Sony was thus at the head of pioneering research and development into new III-V laser diodes fabricated using the MOCVD technique. In 1984, it successfully demonstrated continuous wave lasing of an AlGaInP diode in the 650 nm bandwidth at minus 196 degrees Centigrade—a world first—and they achieved continuous wave lasing at room temperature the following year. This was a major innovation that led to the mass production of light-emitting diodes fabricated using MOCVD.

Later research conducted at Sony using the MOCVD technique is circled in red at the top right of Figure 5, and indicates the innovations in mass production technology for shortwave light-emitting diodes and diode lasers. Once this technology was established, Sony began making product innovations for its DVD and LED applications.

Figure 5
The Situation in 1986



Source: Compiled from the Web of Science based on the *1989 (36th) Okochi Memorial Prize Winners Report*, 108-14.

Again, as illustrated by Figure 5, the citations given for Sony's research include numerous citations for NEC, which was conducting similar research into reducing wavelength using the AlGaInP material; they succeeded in demonstrating continuous wave lasing at much the same time as Sony. There are also numerous citations from the University of Utah, because Gerald Stringfellow, one of the pioneering basic MOCVD researchers, moved from Hewlett Packard to the University of Utah to continue his research. This implies that Stringfellow's research was critical to the research and development work on MOCVD technology being undertaken at Sony.

Although the scientific breakthroughs made at Rockwell International in 1977 mark a critical starting point in the development of compound semiconductor devices and mass production technology for MOCVD at Sony, these revolutionary demonstrations went through a lengthy process before they could be translated into innovations for Sony. During that process research aimed at elaborating the scientific breakthroughs achieved at Rockwell International and competition to commercialize that technology were spurring electronics manufacturers to research new crystal growth techniques. Though American organizations including Rockwell International, Hewlett Packard, Monsanto, and the University of Illinois were engaged in important research, it was Japanese manufacturers who translated the research into commercial products.

Conclusions

As demonstrated above, the MOCVD technique for fabricating laser diodes was developed by Rockwell International in the United States. This was followed, in 1977, by the first demonstration of laser diode oscillation at the University of Illinois by Dupuis and Dapkus, who had introduced a computer-controlled MOCVD reactor bought using a Department of Energy research grant. These were major scientific breakthroughs. It was Sony, however, that succeeded in commercializing these American breakthroughs in the world's first mass market application.

In tracking the transfer of knowledge from Rockwell International to Sony, this essay has focused on bibliographic research citations. The goal of the research using MOCVD conducted by Dupuis and Dapkus at Rockwell International was not the mass production of laser diodes but an increase in functionality based on the fabrication of the quantum well structure. The development of MOCVD-grown laser diodes at Sony, meanwhile, was based on the superior mass production offered by the MOCVD technique. In other words, findings from research undertaken at Rockwell International were put to use in applications that researchers had not originally envisaged.

This transfer of knowledge from Rockwell International to Sony did not happen overnight, however. Sony began conducting research that acted as a spur for the MOCVD technique in 1977, the year in which

Dupuis and Dapkus successfully demonstrated laser diode oscillation. This research was based on knowledge generated at Rockwell International.

Three factors had a critical impact on the transfer of MOCVD knowledge. The first was the race for priority among manufacturers. Although researchers at Rockwell International succeeded in demonstrating laser diode oscillation in 1977, the research effort at Sony did not go into high gear until the 1980s. The development by Sharp of the VSIS structure provided the catalyst for Sony to speed up its research into MOCVD-grown laser diodes. In other words, the development of a rival product using an alternative technology spurred MOCVD research in Japan. In the 1970s, Japan's electronics manufacturers were all pursuing research using LPE. The transfer from the United States to Japan of the knowledge produced at Rockwell International did not occur until the 1980s, and that timing was set by innovations based on alternative technologies. Researchers are engaged in a fierce struggle to establish priority in their research findings by being the first to publish revolutionary findings in academic journals and other venues.[29] The race for research and development priority among manufacturers is equally intense. It is more important for manufacturers to be at the forefront of the research and development effort than to have precedence in procuring finance and resources, or in production, distribution, and marketing operations. As with scientific papers, manufacturers cannot acquire a patent for their inventions unless they have the novelty of being the "world's first." When numerous manufacturers are pursuing research and development at the same time, only the first manufacturer to acquire a patent is able to have monopoly use of the technology. Patents that are based on rehashed research will necessarily be narrow in scope and are unlikely to confer competitive advantage. Although numerous patents generate no economic value, manufacturers play an important role in translating such technology into products capable of generating high added value; the acquisition of patents does not necessarily have a direct impact on a company's competitiveness. The acquisition of patent rights is of considerable importance to companies with knowledge-based assets, however.

Being first in the research and development race is critical in science-based industries, and the struggle for priority is thus intense. The way in which this competitive research and development evolved had a major impact on the transfer of MOCVD knowledge. Hans Gersbach and Armin Schmutzler argue that knowledge spillovers are influenced by endogenous factors as opposed to external conditions, and that competition in product markets will determine the extent to which spill-

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[29] Partha Dasgupta and Paul A. David, "Toward a New Economics of Science," *Research Policy* 23 (Sept. 1994): 487-521.

over occurs.[30] According to Gersbach, knowledge spillover increases when a large number of companies are engaged in a bid to differentiate their products, as opposed to a price war, and the market is expanding significantly. In the case of the MOCVD technology analyzed here, heavy competition among Japan's electronics manufacturers had a significant impact on the transfer of MOCVD knowledge from the United States to Japan.

The second factor influencing the transfer process is scientific knowledge. Broadly speaking, there are two types of knowledge: tacit knowledge and explicit knowledge. For researchers, scientific papers and patents are of critical importance in the struggle for priority; they constitute explicit knowledge. Because explicit knowledge plays a larger role in science-based industries than in manufacturing and assembly-based industries such as the auto industry and the machine tool industry, where tacit knowledge specific to individual companies is more significant, scientific papers and patents are very influential in the transfer of knowledge. As might be expected, strategic disclosure of important research findings is a choice for manufacturers. Nonetheless, it is difficult for manufacturers in the heat of the race for priority to conceal all their research. In the event that a rival company in second or third place acquires the rights to the same technology, the leader will effectively lose its right to exclude.

The transition of the knowledge produced at Rockwell International from tacit to explicit knowledge and its potential usability was a major factor in the transfer of this knowledge between nations. The knowledge maintained a high degree of integrity in the form of scientific papers and patents as it crossed international borders.[31] Nonetheless, the knowledge about enhancing laser diode function that was produced at Rockwell International evolved into a mass market application as the result of development work undertaken by Sony. MOCVD is a highly versatile technology that was transferred to Japan with its integrity intact via academic papers, where it underwent further development, primarily for uses other than those intended by its original developers.

To date, personnel transfers and interpersonal communication have been viewed as important to the knowledge transfer process.[32] This is thought to be partly attributable to the key role played by tacit knowledge.

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[30] Hans Gersbach and Armin Schmutzler, "Endogenous Spillovers and Incentives to Innovate," *Economic Theory* 21 (Jan. 2003): 59-79.

[31] Peter Howlett and Mary Morgan, *How Well Do Facts Travel? The Dissemination of Reliable Knowledge* (New York, 2011).

[32] Almeida and Kogut, "The Exploration of Technological Diversity and Geographic Localization in Innovation," and "Localization of Knowledge and the Mobility of Engineers in Regional Networks"; Kogut and Zander, "Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology."

There can be little doubt that tacit knowledge is critical to science-based industries. However, as has been demonstrated in the case of the transfer of knowledge from Rockwell International to Sony, explicit knowledge is becoming an increasingly critical factor in the knowledge transfer process.

The third factor is the role played by the research conducted with a view to elaborating on Rockwell International's research findings. Scientific breakthroughs do not translate directly into product innovations. Elaborative research is essential for the commercialization process. The research aimed at improving the efficiency of laser diode oscillation and extending the lifespan of diode lasers that was undertaken by Stringfellow and his team played a key role in the research and development work on the MOCVD technique that was conducted at Sony. Stringfellow's efforts to elaborate on the breakthroughs made at Rockwell International thus formed an important springboard for Sony's research and development work.