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Changes in the technology spillover structure due to economic paradigm shifts: A driver of the economic revival in Japan's material industry beyond the year 2000

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Abstract

Innovation is believed to be a driver of the economy in the 21st century. Above all, innovation in services and devices are essential to a post-information society. Importantly, materials continue to play a significant role in innovation, particularly in incorporating new functions in new devices. Now, Japan's economy is starting a significant recovery from the "lost decade". Therefore, it is an appropriate time to review and elucidate the dynamics of material innovation before, during and after this time in order to better understand the process of innovation throughout this economic paradigm shift. In the context of innovation and economic paradigm, compound semiconductor materials lend themselves to understanding the dynamics involved because they play a critical role in introducing new functions and subsequently innovation to information communication technology. In this paper, patent applications filed by Sumitomo Electric Industries, Ltd., the world's largest firm of compound semiconductor material were investigated. Its patent applications for compound semiconductor substrates from 1980 to 2004 were examined in detail. Through this analysis, the following relationship between technology spillover and economic paradigm shift can be observed. In an industrial society, intra-technology spillover successfully led innovation. In contrast, in an information society, opportunities for both intra- and inter-technology spillovers decreased, partly because of economic stagnation, but also because of organizational inertia in business strategy. However, in a post-information society, simultaneously with the renewal of national science and technology policy and reformation of business management, inter-technology spillover emerged across industries, and the economy revived.

Keywords: Material industry; Innovation; Institution; Paradigm shift; External resources; Technology spillover; Post-information society

1. Introduction

In a post-information society, "innovation" is one of the most commonly used words in science and technology. Above all, discussion of innovation seems to be a brand new trend for policy makers and business leaders who are considering sustainability in the 21st century (Palmisano, 2004). Innovation in service and devices is becoming more focused as indicated by successful cases such as Google and "i-mode". However, there has been another type of innovation which is equally important, but has received less emphasis than these new innovative phenomena. This is ongoing material innovation. In fact, material technology has supported service and device innovation in incorporating new functions into new devices. For example, the Internet and cellular phone systems work on optical fiber and wireless communication networks. Since the networks are supported by optoelectronics devices and performance of these devices are attributed to compound semiconductor materials, neither Google nor i-mode would

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have been created without material innovation. Needless to say, communication networks are the basis of a dynamic economy. Thus, in the post-information society, it is expected that material innovation as well as service and device innovation will play more important roles than before. Therefore, it is important to understand material innovation and elucidate its dynamics in the context of the economic paradigm shifts of the last three decades.

Japan's economy including material industry showed a significant recovery from the early 2000s. This revival can be attributed to the fusion of Japanese traditional business practice and that of Western countries (Smith, 2006; The Economist, 2007). Therefore, it is necessary to take of the transformation of business management into account in examining innovation and economic revitalization.

In analyzing innovation dynamics in material industry, Japan's nonferrous metal industry has been a subject for excellent case studies, because of a long history of its intense R&D compared with that of other material industries such as the iron and steel industry and fabricated metal industry. For example, Sumitomo Electric Industries, Ltd. (SEI), a leading firm in Japan's nonferrous metal industry, stated in its annual financial reports from 1987 to 1999 that R&D is the basis for sustainable growth of its corporate business (Sumitomo Electric Industries, Ltd., 1999a). This indicates that Japan's nonferrous metal industry has consistently made R&D efforts towards diversification by technological innovation. Since technological diversification could promote innovation (Lichtenhthaler, 2005; Garcia-Vega, 2006), this strategy taken by the industry has been favorable to innovation. In fact, supported by entrepreneurship and the intra-firm venture business system, the diversification strategy was successful in creating new businesses (Hirota, 1994, 1995). Actually, an ex R&D director of SEI said that R&D planning department-led business diversification of SEI (Matsushima and Odaka, 2004). SEI in fact consisted of 25 business units in 1992, and only 15 in 1972, thus increasing by 10. Furthermore, since maintaining originality in R&D activity was a constant concern in this industry, diversification inevitably enhanced technology spillovers within a firm.

In the 1990s, under the economic stagnation known as 'the lost decade', Japan's nonferrous metal industry suffered a continuous decline in the ratio of operating income to sales (OIS), following the decrease in marginal productivity of technology (MPT). From the perspective of technology spillover, this decrease in MPT can be attributed to the exhaustion of technology spillover sources in a firm (Nakagawa and Watanabe, 2007). Table 1 shows OIS for six major firms in Japan's nonferrous metal industry over the period of 1980–2005.

Surprisingly, Table 1 demonstrates that the trend in OIS for every firm except Showa Holdings Co. Ltd. (SHO) turned to an increase between 2002 and 2005: SEI in 2004, Furukawa Electric Industries Co. Ltd. (FUR) in 2005, Fujikura Ltd. (FUJ) in 2004, Hitachi Cable Ltd. (HIT) in 2003, and Mitsubishi Cable Industries, Ltd. (MIT) in 2002. These similar trajectories indicate that firms in Japan's nonferrous metal industry have revitalized their business performance in a post-information society. As technology stock, particularly that of new businesses, had increased OIS by boosting up MPT (Nakagawa and Watanabe, 2007), it can be safely said that the trend is tightly connected with OIS.

With an aim to demonstrate a contribution of innovation to OIS, a correlation of technology stock in new business sectors and OIS is analyzed in SEI, as shown in Table 2.[3]

The result of the regression is summarized as follows:

$$\ln OIS = \underset{(-3.34)}{-3.15} + \underset{(5.16)}{0.53} \ln T_4 - \underset{(-7.87)}{0.08}t - \underset{(-5.94)}{0.27}D$$

$$adj.\,R^2 = 0.89086, \quad DW = 1.74$$

where T_4 shows technology stock of new business sectors in SEI, $t = 0$ at 1980, dummy variables $D = 1$ at 1984, 1985, 1994, 1995, 2002 when OIS presents local minimum.

Thus, there is a strong correlation between OIS and technology stock in new business sectors.

Furthermore, as technology stock boosts MPT, and the marginal productivity increases OIS (Nakagawa and Watanabe, 2007). As MPT increases the productivity growth (Griliches, 1979; Watanabe and Wakabayashi, 1996; Watanabe and Tokumasu, 2003), this correlation is not just a coincidence, but does demonstrate causality.

This paper aims to identify the sources of innovation in Japan, and make several suggestions about innovation policy in a post-information society. Empirical analysis is undertaken in relation with technology spillovers presented in patent applications. Only the case study on SEI is discussed here, because it is a leading firm in Japan's material industry, particularly nonferrous metal industry with the longest history and the highest business performance.

Many studies demonstrated that technology spillover could play an important role in innovation. For example, technology spillover can impact on R&D strategy (Watanabe et al., 2001); firms with a well-developed assimilation capacity succeed in effectively utilizing technology spillover resulting in a very productive R&D structure (Watanabe et al., 2002); cross-functional spillover could be a survival strategy for ceramics industry (Ohmura et al., 2003; Ohmura and Watanabe, 2005); and the differences of firm's sizes are one of the important factors for technology spillovers (Ornaghi, 2006). Furthermore, other studies also demonstrated that technology developments could be attributed to technology spillover (Griliches and Lichtenberg, 1984; Jaffe, 1986; Bernstein and Nadiri, 1988, 1989; Goto and Suzuki, 1989; Kwang and Watanabe, 2001; Nakanishi, 2002; Watanabe and Ane, 2003; Watanabe and Tokumasu, 2003; Nieto and Quevedo, 2005). Most of

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[3] An overview of SEI's business sectors is presented in Appendix A. An estimation of technology stock by SEI's business sector is demonstrated in Appendix B.

Table 1
Operating income to sales for six major firms in Japan's nonferrous metal industry (1980–2005)

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
SEI	5.28	5.29	4.26	2.69	3.96	4.37	4.50	4.49	4.25	4.70	4.93	4.34	3.62
FUR	2.18	3.48	3.50	2.92	2.66	3.10	4.01	3.87	3.12	2.87	3.22	2.98	2.18
FUJ	3.36	5.22	5.14	4.12	2.54	2.91	3.87	4.35	2.84	3.50	4.53	3.81	2.51
HIT	6.72	8.46	8.09	6.78	6.96	5.51	5.33	5.86	5.67	6.21	5.88	4.88	3.62
MIT	1.64	5.33	6.20	0.68	1.55	2.69	3.80	5.73	5.02	6.09	6.30	6.07	5.67
SHO	3.54	4.65	3.95	3.26	3.30	3.15	3.69	5.30	4.17	3.75	4.83	4.59	3.20
	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
SEI	3.49	3.23	3.34	4.00	3.69	2.95	2.61	3.93	1.88	−1.30	−1.50	−0.26	1.17
FUR	2.09	1.81	1.13	1.11	1.75	0.43	0.86	5.18	2.48	−0.08	−0.27	−0.46	2.17
FUJ	2.09	0.99	1.86	3.79	3.62	1.14	0.73	4.82	5.16	1.32	0.04	0.59	3.93
HIT	2.90	3.93	4.45	4.48	4.10	2.62	3.04	5.15	0.47	−1.91	−0.16	1.13	1.42
MIT	5.07	3.03	1.48	2.04	1.31	0.46	−1.45	−2.03	−3.50	−2.98	0.57	0.88	2.09
SHO	0.88	−0.50	−0.07	−0.35	0.60	−1.88	−0.19	0.84	0.92	1.61	2.60	1.43	0.47

OIS (%).
SEI: Sumitomo Electric Industries, Ltd.; FUR: Furukawa Electric Co., Ltd.; FUJ: Fujikura Ltd.; HIT: Hitachi Cable Ltd.; MIT: Mitsubishi Cable Industries, Ltd.; SHO: Showa Holdings Co., Ltd.

Table 2
OIS and technology stock in new business sectors in SEI (1980–2004)

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
OIS (%)	5.63	5.32	4.95	4.08	3.64	3.67	4.28	4.45	4.41	4.48	4.63	4.66	4.30
T_4 (yen M)	8835	9577	10,315	11,057	12,407	13,902	15,565	18,147	21,167	24,263	29,054	34,423	37,785
	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	
OIS (%)	3.82	3.45	3.36	3.53	3.68	3.55	3.08	3.17	2.81	1.50	−0.31	−1.02	
T_4 (yen M)	41,717	45,812	48,324	50,553	51,108	50,040	48,834	48,872	50,473	51,981	52,978	54,535	

OIS: 3 years moving average.
T_4: technology stock in new business sectors.

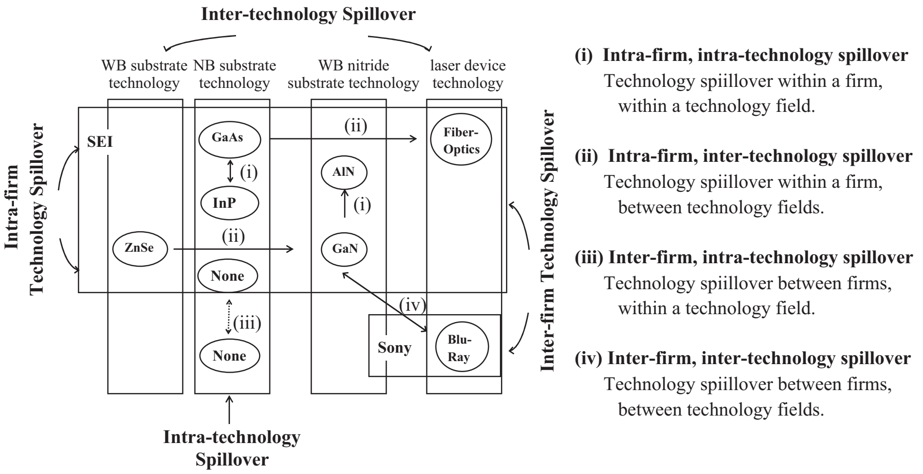

Fig. 1. Schematic diagram of technology spillovers.

these studies showed some mechanism about inter-firm spillovers; however, did not show a systematic view of the spillover effects in innovation and firm's MOT.

From an organizational point of view, technologies can spillover within a firm, and between firms. These types of technology spillovers are defined as "intra-firm technology spillover'' and ''inter-firm technology spillover.'' For instance, technology spillover within SEI is an ''intra-firm technology spillover'', but one between SEI and Sony is an ''inter-firm technology spillover.''

On the other hand, from a technological point of view, technologies can spillover within a technological field, and between technological fields. For instance, technology spillover within ''compound semiconductor material technology[4] ''is an ''intra-technology spillover'', but spillover between ''compound semiconductor material technology'' and ''laser fabrication technology '' is an ''inter-technology spillover.''

Combining these two types of technology spillovers, technology spillovers are classified as four. ''Intra-firm, intra-technology spillover'', ''Intra-firm, inter-technology spillover'', ''Inter-firm, intra-technology spillover'', and ''Inter-firm, inter-technology spillover.'' Fig. 1 illustrates a schematic diagram of these four types of technology spillovers.

Each of the four types of technology spillovers shows distinctive characteristics:

(i) *Intra-firm, intra-technology spillover*: this type of spillover can be frequently observed. In SEI, a manufacturing technology of compound semiconductor materials spilled over from GaAs to InP.
(ii) *Intra-firm, inter-technology spillover*: this type can also be observed. In SEI, thin film manufacturing technologies of compound semiconductor spilled over to substrate manufacturing technology.
(iii) *Inter-firm, intra-technology spillover*: this type can hardly be observed except in basic researches.
(iv) *Inter-firm, inter-technology spillover*: this type can be observed in joint researches with other firms. For example, a laser fabrication technology in Sony spilled over to compound semiconductor material technology in SEI.

From a managerial point of view, technology spillover structures reflect strategic options in firms' technology development. In-house R&D activities play a different role from external contracted R&D (Beneito, 2006).

As this paper does not focus on university–industry and government–industry relationship; however, those relationship can play important roles for innovation (Audretsch and Lehmann, 2005; Kelly and Nakosteen, 2005; Watanabe, 1999, 2006; Tanabe and Watanabe, 2003, 2005).

Section 2 presents three hypotheses about technology spillovers of material manufacturing, Section 3 presents empirical analysis, Section 4 presents the discussion and Section 5 is for conclusions.

2. Hypotheses

First, in the 1980s in Japan, the market was full of attractive goods such as Walkman, word processors, and home video-cassette recorders. Since the market was fiercely competitive, and manufacturing technology was believed to be a key success factor for survival, firms put their resources into R&D, intensively. Material industries as suppliers to machinery industry were also competing with each other in technology development. In order to extend their markets, and enhance their positions in the market, some of the firms adopted a diversification strategy through R&D. Hirota (1994, 1995) identified that success of SEI Ltd., in diversification and technology development can be attributed to the organization's tradition of entrepreneurship and its ''*Kaihatsu–shitsu''* (Development Group) system. ''*Kaihatsu–shitsu*'' is a department in R&D groups of SEI, where researchers themselves develop and carry out their business plans for commercialization. Hirota (1995) mentioned that ''*Kaihatsu–shitsu*'' is a system of corporate venture business, because business development in the department depends on the entrepreneurship of researchers themselves. Eventually, SEI extended its business units from 10 in 1972 to 25 in 1992, increasing the total number by 15 business units. Another noteworthy character of those days was that firms were hesitant to cooperate in R&D because of the fierce competition: they did not want to expose what they were developing, even to their customers.[5]

Consequently, the range of technology spillover needed to be limited within a firm, within a technology. Thus, a hypothesis can be presented as follows:

Hypothesis 1. Intra-technology spillover was the main driving force for technology development in the 1980s. Different kinds of technologies scarcely crossed over.

In the 1990s, the era of an information society began with the bursting of the bubble economy in Japan. Industries had to endure the economic stagnation called ''the lost decade''. This stagnation caused a decrease of OIS and R&D intensity; as some studies demonstrated, consequently caused the decrease of MPT (Dean and Meyer, 1996; Roller and Sinclair-Desgagne, 1996; Green wood and Jovanovic, 1999; Hobjin and Jovanovic, 2001; Larsen and Lomi, 2002; Matsumoto et al., 2002; Takayama et al., 2002; Nakagawa and Watanabe, 2007). More significant is the fact that competitive advantage in the former decade did not work well. Certainly, firms noticed the unfavorable change and tried to cope with it. For example, Sumitomo EIectric Industries, Ltd. (1996) reported that ''*Kaihatsu–shitsu*'' had not been newly established in any business

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[4] Compound semiconductor: semiconductor made of two or more chemical elements, e.g., GaAs, InP. Thin film manufacturing technology and substrate manufacturing technology are process technologies on compound semiconductor materials. Laser fabrication technology is a technology to fabricate lasers from compound semiconductor materials.

[5] The discussion in this paper focuses only on the technology development for commercial purposes. There were some research consortia including competitor firms. However, those consortia conducted relatively basic research for future applications; it is not appropriate to discuss this issue in this paper.

units since 1990, because it could not cope with some issues in SEI, such as the termination of the diversification strategy, the lack of sufficient financial sources, and the diminishing competitiveness with venture businesses mainly from the United States (Sumitomo Electric Industries, Ltd., 1996). In order to cope with such challenges as mentioned above, the material industry changed its R&D strategy from diversification to selection and concentration (Sumitomo Electric Industries, Ltd., 1999b). In order to select promising R&D projects, SEI developed a new R&D evaluation system in 1991, which enabled R&D managers to evaluate future outcomes and therefore to offer stop/go criteria (Osawa and Murakami, 2002; Osawa, 2003). However, OIS in materials firms, as well as in SEI, continued to decrease until the early 2000s.

As the number of R&D projects decreased, the opportunities for intra-technology spillover were supposed to have decreased. These new evaluation systems required researchers to design precise R&D strategy including alliances with external firms; there was a possibility for inter-technology spillover. However, there were no significant changes in MPT, nor OIS (Nakagawa and Watanabe, 2007). Thus, Hypothesis 2 can be presented as follows:

Hypothesis 2. Intra-technology spillover diminished over time. Inter-technology spillover was emerging, but yet weak in the 1990s.

In the early 2000s, deliberate government and corporate measures were put in place to revitalize the Japanese economy. In 2001 and in 2006, the Japanese government started the second and the third Science and Technology basic plans, in which government encouraged academia–industry cooperation. In 2002, SEI's new R&D director announced renewal of R&D strategies, which defined roles of corporate R&D, and encouraged researchers to learn from outside of the firm. Since it is said that organizational integration is significant to market success (Millson and Wielmon, 2006), there is no doubt that these national policies and corporate strategies supported technological revitalization. A symbolic event in academia–industry cooperation announced in 2005 was the partnership agreement between the National Institute of Advanced Industrial Science and Technology (AIST), a public research organization, and SEI. Consequently, as demonstrated in Table 2, OIS and technology stock of new business sectors in SEI began to increase. Therefore, opportunities for technology exchanges among organizations and industries increased in the early 2000s.

In the context of these changes in the society Hypothesis 3 is as follows:

Hypothesis 3. In place of intra-technology spillover, inter-technology spillover played a significant role in material innovation in the early 2000s.

3. Empirical analysis

3.1. Patent applications on compound semiconductors

Innovation in compound semiconductor materials in SEI is one of the best examples for a case study, because this is a typical case of SEI's material innovation due to the following reasons:

(i) SEI's major product, GaAs substrate, has maintained its position holding the world's top market share over the last two decades.
(ii) SEI's R&D history on compound semiconductors, which started in the 1960s, is longer than any of its competitors.
(iii) SEI advocates that its vigorous innovation efforts on the compound semiconductor business greatly contributed to its success.
(iv) Compound semiconductor materials played important roles in an information society. For example, microwave ICs in cellular phone, lasers equipped in CD and DVD drivers are classified as compound semiconductor devices.
(v) SEI's compound semiconductor business is recognized as a successful case of the intra-firm venture business system, "*Kaiahatsu–shitsu*" (Hirota, 1994, 1995). As has been pointed out before, this system encouraged researchers' entrepreneurship and therefore successfully combined R&D with business.

Before analyzing technology spillovers, it is worth explaining manufacturing technology and applications of semiconductor materials in general. Semiconductor materials can be roughly divided into two: single-element semiconductors such as silicon and germanium, and compound semiconductors such as gallium arsenide (GaAs) and gallium nitride (GaN). It is more complex and difficult to manufacture compound semiconductors

Table 3
Major materials and characteristics of narrow and wide bandgap semiconductors

	Narrow bandgap (NB-type)	Wide bandgap (WB-type)
Major materials	GaAs, GaP, GaSb, InP, InAs, CdTe, InGaAs, AlGaAs	ZnSe, PbSnTe, GaN, SiC, AlGaInN, AlGaN
Colors of light emission	Infra-red to red, yellow	Green, blue, violet to ultraviolet, (white)
Laser, LED applications	Optical communication, CD, DVD	Blu-Ray disc recorder, traffic signal
Substrate manufacturing method	Liquid solidification (easy)	Vapor deposition (difficult)

Table 4
Number of patent applications on compound semiconductor substrates filed by SEI (1980–2004)

Material	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
GaAs	9	11	24	48	33	44	57	51	38	37	26	19	14
GaP	0	1	0	0	0	1	0	0	0	0	0	1	0
GaSb	0	0	1	0	0	0	0	0	0	0	0	0	0
InP	0	0	0	0	5	4	3	8	9	9	2	1	1
InAs	0	0	0	0	2	1	4	7	0	0	0	0	0
CdTe	0	0	0	0	0	13	11	13	2	2	4	7	2
InGaAs	0	0	0	0	0	1	0	4	0	0	0	0	0
AlGaAs	0	0	0	0	0	0	1	0	0	1	0	0	0
ZnSe	0	0	0	0	0	0	0	4	2	0	2	0	0
PbSnTe	0	0	0	0	0	0	0	0	0	2	0	0	0
GaN	0	0	0	0	0	0	0	0	0	0	0	0	0
SiC	0	0	0	0	0	0	0	0	0	0	0	0	0
AlN	0	0	0	0	0	0	0	0	0	0	0	0	0
AlGaInN	0	0	0	0	0	0	0	0	0	0	0	0	0
AlGaN	0	0	0	0	0	0	0	0	0	0	0	0	0
Unidentified	0	0	0	2	1	0	4	6	8	4	2	3	1

Material	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
GaAs	5	10	14	8	7	6	4	5	6	9	5	22
GaP	0	0	0	0	0	0	0	0	0	0	0	0
GaSb	0	0	0	0	0	0	0	0	0	0	0	0
InP	3	1	0	0	1	4	0	0	2	4	2	1
InAs	0	0	0	0	0	0	0	0	0	0	0	0
CdTe	0	0	0	0	0	0	0	0	0	0	0	0
InGaAs	1	1	0	1	0	0	0	0	0	0	0	0
AlGaAs	0	0	0	0	0	0	0	0	0	0	0	0
ZnSe	2	7	12	10	9	11	17	4	4	7	1	1
PbSnTe	0	0	0	0	0	0	0	0	0	0	0	0
GaN	0	0	0	0	0	2	3	3	1	12	15	16
SiC	0	0	0	0	0	2	4	0	2	0	4	4
AlN	0	0	0	0	0	0	0	0	0	0	0	7
AlGaInN	0	0	0	0	0	0	0	0	0	0	0	2
AlGaN	0	0	0	0	0	0	0	0	0	0	0	1
Unidentified	1	0	1	1	1	0	1	0	0	0	0	0

than single-element semiconductors, because the former contains two or more elements, while the latter contains one. Briefly speaking, compound semiconductor devices are manufactured in the following three steps. Firstly, a single-crystal substrate is prepared. Secondly, a multi-layered thin film is grown on the substrate. Lastly, electronic circuits are fabricated on the thin film. Performance of devices is mainly dominated by quality of the materials and structure design of the devices. The thin film and the circuit have inner structures; the substrate does not. Therefore, contrast to the thin film and the circuit, the quality of the substrate is defined only by material manufacturing technology. Therefore, it is reasonable to focus on the substrate for analyzing material innovation.

In terms of characteristics, compound semiconductor materials can be roughly categorized into two: narrow bandgap (NB-type), and wide bandgap (WB-type) semiconductors.[6] Major materials and characteristics of both types of compound semiconductors are summarized in Table 3.

Patent applications are a good example in investigating technology spillovers, because they describe technological contents, referred technologies, and inventors. Technology spillover paths can be identified by tracking the date of application, inventors, and technological description.[7] SEI filed 863 patent applications made by 205 researchers from 1980 to 2004 on compound semiconductor substrates. The numbers of patent applications in each material are demonstrated in Table 4.

Looking at Table 4, we note that GaAs is the most well-researched material during the entire period examined, and that ZnSe and GaN are also mainly researched materials in

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[6] "Bandgap" is one of the important characteristics of semiconductors. "Strictly speaking, the term "narrow bandgap semiconductor" is not commonly used in this sense, while "wide bandgap semiconductor" is a broad term. In this paper, however, semiconductors other than wide bandgap semiconductors are called "narrow bandgap semiconductors" for convenience.

[7] This paper examined patent applications filed in JPO, because SEI is a Japanese firm; it is reasonable to suppose that SEI first filed applications to JPO. Therefore, patent application IDs presented hereinafter address JPO patent application IDs.

Table 5
Researcher who filed on two or more materials by year of application

Researcher	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
R1	GaAs	GaP	GaAs, GaSb	GaAs	GaAs	GaAs	GaAs	GaAs, InP	GaAs, InP	GaAs	GaAs	
R2	GaAs	GaAs	GaAs	GaAs	GaAs, InP	GaAs	GaAs	GaAs	GaAs			
R3	GaAs	GaAs, GaP		GaAs		GaAs		GaAs		GaAs		
R4		GaAs	GaAs	GaAs	GaAs, InAs, InP	GaAs, CdTe, InAs, InP	GaAs, CdTe, InAs	GaAs, CdTe, InAs, InP				
R5		GaAs	GaAs	GaAs	GaAs, InP	GaAs, GaP, InP, InAs, CdTe	GaAs, CdTe, InAs	GaAs, CdTe, InAs, InP				
R6		GaAs, GaP	GaAs	GaAs	GaAs							
R7			GaAs	GaAs								
R8		GaAs	GaAs	GaAs	GaAs	GaAs, InGaAs, InP	GaAs	GaAs	GaAs	GaAs	GaAs	
R9		GaP	GaAs	GaAs	GaAs, InP		InP					
R10				GaAs	GaAs	GaAs, InGaAs	GaAs	GaAs GaAs	InP	GaAs		
R11				GaAs	GaAs	GaAs						
R12				GaAs	GaAs	GaAs, InGaAs	GaAs, AlGaAs, InAs	GaAs, InAs, InGaAs				
R13				GaAs				ZnSe	ZnSe			
R14				GaAs		GaAs	GaAs					
R15			GaAs	GaAs, InP	GaAs	GaAs	GaAs, InP	GaAs				
R16				GaAs	GaAs, InAs	GaAs, InAs, InP, GaP	GaAs, InAs	GaAs, CdTe, InAs, InGaAs, InP	GaAs, CdTe, InP	GaAs, CdTe, InP, PbSnTe GaAs	CdTe	GaAs, CdTe
R17				GaAs	GaAs, InP		InP	GaAs, InP	GaAs, InP	GaAs	GaAs	
R18					GaAs, InAs	GaAs, InAs, GaP, InP	GaAs	GaAs	GaAs, CdTe, InP	GaAs, InP	GaAs	GaAs, CdTe
R19					GaAs	GaAs, CdTe, InP		GaAs, ZnSe		GaAs	GaAs	
R20						GaAs, InGaAs	GaAs, AlGaAs, InAs	GaAs, InAs, InGaAs	GaAs, InP	GaAs, PbSnTe	CdTe	GaAs
R21							GaAs, InAs	GaAs, InAs	GaAs, InP	InP	GaAs	GaAs
R22							GaAs		GaAs	GaAs	GaAs	
R23							GaAs		GaAs	GaAs		
R24							CdTe	GaAs	CdTe	CdTe, GaAs		CdTe
R25								GaAs	GaAs	InP	GaAs	
R26									GaAs			
R27									GaAs			
R28										GaAs		
R29											GaAs	GaAs
R30												GaAs
R31												GaAs
R32												
R33												
R34												
R35												
R36					InP							
R37										InP		

Table 5 (*continued*)

Researcher	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
R38										InP, PbSnTe	GaAs	GaAs, CdTe,
R39										InP		GaAs
R40											InP,GaAs	
R41							CdTe					
R42										CdTe		
R43												
R44												
R45								ZnSe				
R46												
R47												
R48												
R49												
R50												
R51												
R52												
R53												
R54												
	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
R1	GaAs	ZnSe	ZnSe	ZnSe								
R2												
R3												
R4												
R5							ZnSe					
R6												
R7	InP											
R8			GaAs	GaAs			GaAs		GaAs			
R9												
R10						ZnSe			ZnSe			
R11											GaN	AlN
R12												
R13												
R14			ZnSe									
R15												
R16	InGaAs	GaAs	GaAs	nGaAs	GaAs	GaAs	GaAs	GaAs, GaN				GaAs
R17						InP						
R18		GaAs	GaAs GaAs	GaAs	GaAs	GaAs				GaAs		GaAs
R19					ZnSe	ZnSe	ZnSe	ZnSe	ZnSe	ZnSe		ZnSe
R20												
R21			GaAs	GaAs	GaAs	GaAs, InP	GaAs					GaAs, InP
R22									GaN		GaN	GaN
R23	GaAs									GaAs, InP	GaAs	GaAs
R24			ZnSe							ZnSe		
R25												
R26					GaAs	GaAs					InP	GaN
R27		InP	GaAs			GaAs	GaAs	GaAs	GaAs	InP		AlN
R28		GaAs			InP							

R29											InP	
R30						InP						
R31			GaAs						InP			
R32	GaAs	GaAs				ZnSe						
R33			GaAs							InP	GaAs	
R34			GaAs			GaAs			GaAs	GaAs		GaAs, InP
R35					GaAs						SiC	
R36			GaAs						InP			
R37							GaAs					
R38				GaAs								
R39												
R40		GaAs										
R41				ZnSe								
R42	nGaAs	ZnSe	ZnSe	ZnSe	ZnSe	ZnSe	ZnSe	ZnSe	ZnSe	ZnSe	ZnSe	AlGaInN, AlGaN, AlN
R43		GaAs	GaAs	nGaAs	GaAs	GaAs, InP						
R44			GaAs									
R45											GaN	
R46				ZnSe		ZnSe	ZnSe	GaN		GaN		GaN
R47										ZnSe	GaN	GaN
R48	nGaAs	InGaAs	ZnSe	ZnSe							GaN	GaAs
R49										GaN	GaN	AlGaN. AlN
R50										GaN	GaN	AlN
R51												AlN,GaN
R52												AlGaN. AlN
R53												AlGaN. AlN
R54												AlGaN. AlN

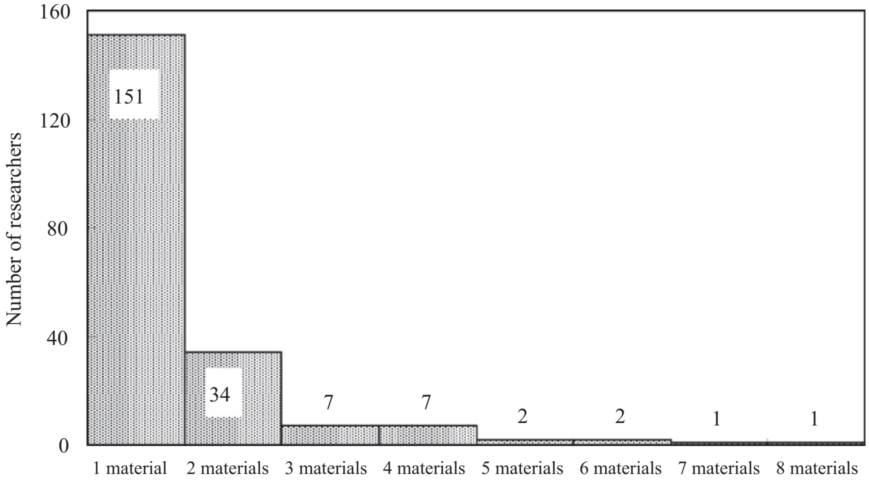

Fig. 2. Number of researchers by number of materials in patent applications.

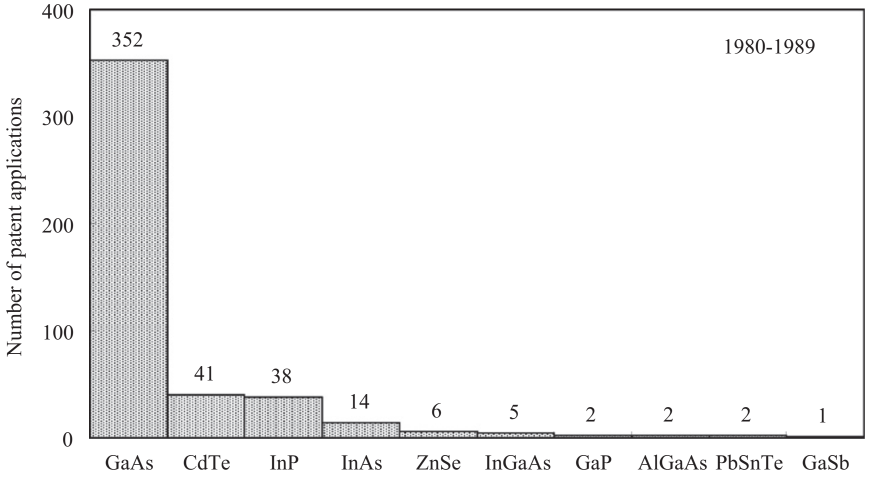

Fig. 3. Number of patent applications on compound semiconductor materials filed by SEI (1980–1989).

the 1990s and the early 2000s. Therefore, it is reasonable to focus on these three materials for further analysis.

Technologies are transferred by researchers (Ohmura and Watanabe, 2006), thus, it can easily be assumed that those who conducted research on two or more materials delivered the technology spillover among the materials. Table 5 demonstrates a list of researchers in SEI who have filed patent applications on two or more semiconductor substrate materials, with types of materials included in the patent applications from 1980 to 2004.

Table 5 demonstrates that 54 researchers conducted research on two or more kinds of materials. Looking at Table 5 closely, we also note that a few specific researchers filed most of the patent applications. In fact, as summarized in Fig. 2, they account for only 27% of all 205 researchers who are studying compound semiconductor substrates in SEI.

Thus, technology spillovers in SEI can be attributed to those few researchers who studied many kinds of materials for the patent applications. Therefore, the focus is on the researchers for further analysis.

3.2. *Technology spillovers in the 1980s: NB-type semiconductor materials*

Table 4 in Section 3.1 suggests that NB-type materials were mainly researched during the entire period examined. In fact, 141 researchers filed 654 patent applications related to NB-type materials. Particularly, 455 of these applications were filed in the decade from 1980 to 1989. In order to analyze technology spillovers in the 1980s, the numbers of patent applications by material from 1980 to 1989 are compared in Fig. 3.

Recall that in Table 3 in Section 3.1 GaAs, CdTe, InP, InAs, InGaAs, and GaSb are categorized as the NB-type semiconductors, and ZnSe and PbSnTe as the WB-type. Fig. 3 suggests that NB-type semiconductors were the main targets of the technology development in the 1980s. Typical examples of the researchers who filed for two or more materials are found in Table 5 in Section 3.1. For example, researcher R16 filed GaAs and InAs in 1984, GaAs, InAs, InP, and GaP in 1985, GaAs and InAs in 1986, GaAs, CdTe, InAs, InGaAs, and InP in 1987, GaAs, CdTe and InP in 1988, GaAs, CdTe, InP, and PbSnTe in 1989 in the 1980s. Thus, it is understandable that technology spillovers in the 1980s were limited in NB-type substrate manufacturing technology. Table 5 also shows that some other researchers such as R4, R5, R8, and R2 show the same pattern.

As for inter-technology spillovers, only two researchers, R4 and R16, had targeted oxide optics device before they filed GaAs (e.g., "JP, S55-184887", "JP, S56-60379").

Therefore, NB-type semiconductor substrates were developed by delivering spillovers of manufacturing technology among NB-type semiconductor substrates, while other kinds of technology hardly spilled over to the NB-type. Thus, it can be safely said that intra-technology spillovers drove technology developments in the 1980s, demonstrating Hypothesis 1.

3.3. *Technology spillovers in the 1990s: NB-type and WB-type semiconductor materials*

In the same way as in Section 3.2, Fig. 4 compares the numbers of patent applications by material from 1991 to 1999.

Fig. 4 illustrates that GaAs and ZnSe were the major materials for R&D in the 1990s. In fact, 36 researchers filed patent applications on compound semiconductor substrates and 11 of them filed particularly on ZnSe among those substrates. Technology spillovers in the 1990s show significant differences from those in the 1980s. Looking at Table 5 in Section 3.1, we note that there are six researchers who filed for two materials in a single year: R16 (GaAs and CdTe, 1990–92; GaAs and InGaAs, 1996), R18 (GaAs and CdTe, 1992) and R21 (GaAs and InP, 1998); no researcher filed on more than two materials in the 1990s. It suggests that each material was almost independently developed with less intra-technology spillovers.

Given a few examples of inter-technology spillovers from ZnSe, its manufacturing technology is mainly attributed to that of NB-type semiconductor materials. In fact, researchers R1, R5, R10, R13, R14, R19, R24, R32, R41, R42, and R48 filed patent applications on NB-type semiconductor substrates before they first filed on ZnSe, which suggests that the NB-type technology spilled over to WB-type. In contrast, there were no cases in which the ZnSe substrate technology spilled over to other materials except R46 (2000), R42 (2003), and R48 (2004) which spilled over to GaN.

Furthermore, there were three cases of inter-technology spillovers from thin film manufacturing. For example, a researcher filed patent applications on the thin film technology for GaAs (e.g. "JP, H04-287587", 1992) before he filed ZnSe a substrate patent application, "JP, H06-50521". This case demonstrates an existence of inter-technology spillovers from the thin film technology to the substrate technology.

From the technological point of view, it is understandable that inter-technology spillovers from thin film affected the development of ZnSe substrate. As summarized in Table 3 in Section 3.1, ZnSe substrate could not be manufactured by the NB-type substrate technology, but by vapor deposition technology. As the vapor deposition technology is commonly used in manufacturing thin film, it is logical that there was a possibility of inter-technology spillovers from the thin film technology.

In addition to the discussion about the inter-technology spillover to ZnSe, it must be noted that both the NB-type and thin film technologies came from the inside of SEI, not from external organizations. Therefore, inter-technology spillovers were emerging but they were limited within a firm.

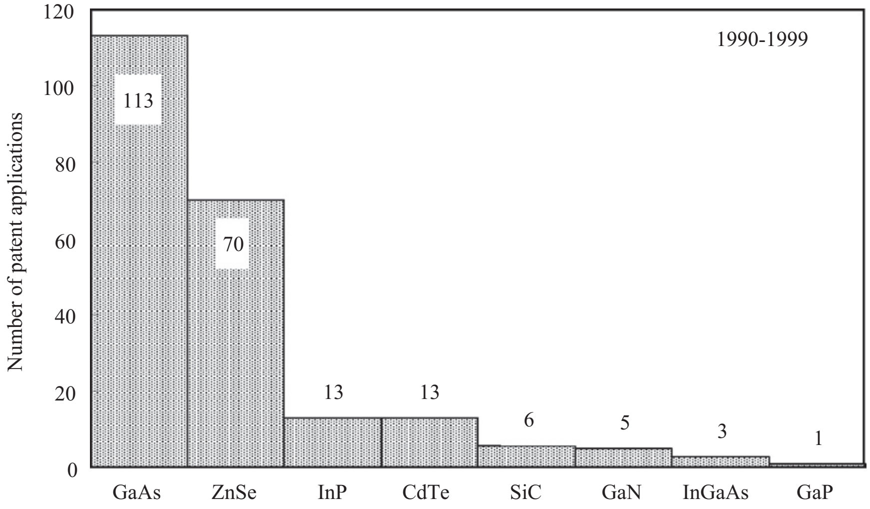

Fig. 4. Number of patent applications of compound semiconductor materials filed by SEI (1990–1999).

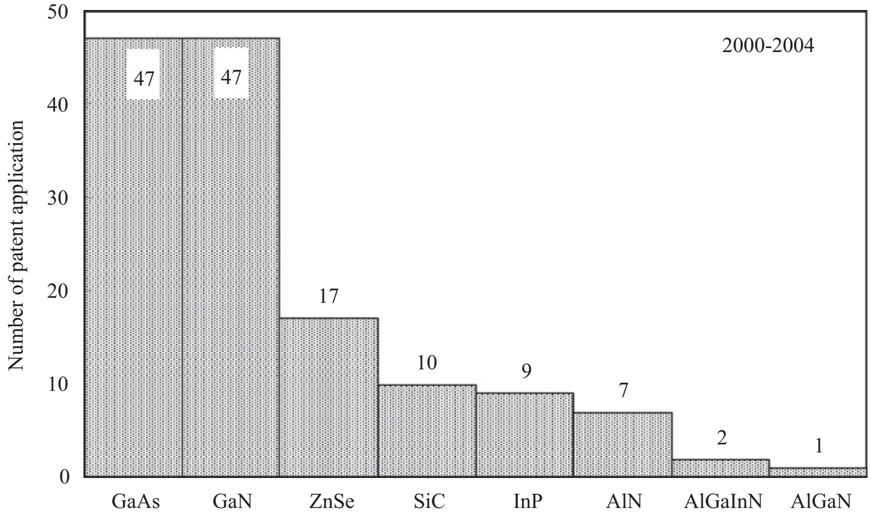

Fig. 5. Number of patent applications of compound semiconductor materials filed by SEI (2000–2004).

To sum up the results in this section, there were fewer opportunities for intra-technology spillovers in the 1990s than the 1980s. Inter-technology spillovers were emerging, yet only from the inside of a firm, not from external organizations. Thus, Hypothesis 2 is demonstrated.

3.4. Technology spillovers in the early 2000s: WB-type semiconductor materials

Fig. 5 compares the numbers of patent applications by material from 2001 to 2004.

Fig. 5 illustrates that GaAs and GaN were the most well-researched substrate materials in the early 2000s. Additionally, compared with the 1990s, the number of NB-type materials decreased from five to two, while WB-type increased from three to six. In the early 2000s, compared with GaAs, GaN patent applications rapidly increased, while GaAs did so slowly. Thus, it is reasonable to focus on GaN for further analysis. Table 5 shows researchers who filed on only one or two materials in a single year, except one case in which R41 filed for three materials in 2004. Looking at Table 5, we also note that R11, R16, R22, and R26 had filed NB-type materials, and R45, R47, and R48 had filed on ZnSe before they filed GaN patent applications. Therefore, similar to the case of ZnSe, the GaN technology is attributed to the spillover from manufacturing technologies to other materials. Consequently, both intra- and inter-technology spillovers from the inside of the firm affected the technology development of GaN substrate, similar to the 1990s.

Unlike ZnSe, however, it is noteworthy that GaN provided a conduit for inter-technology spillovers from external organizations. There were some researchers who filed patent applications both on GaN substrate and on GaN laser. These patent applications were jointly filed by researchers of SEI and other organizations. In fact, the researcher R56 filed laser patent applications with either Sony or Sharp. SEI filed 42 joint patent applications on GaN substrate and devices. In fact, 11 of them were filed with Sony,[8] and seven with Sharp as co-applicants. It is noteworthy that these patent applications were filed intensively during the three years from 2001 to 2003. Table 6 presents all the patent applications on GaN substrate and device, filed by SEI, including joint and non-joint applications from 2001 to 2003.

Since SEI filed more than twice as many patent applications with Sony as with Sharp, further analysis is focused on SEI–Sony joint applications, particularly two researchers R56 (SEI) and SO3 (Sony), who filed the most of the joint applications by SEI and Sony. Patent applications filed by them are shown in Table 6. Fig. 6 illustrates the technology spillovers between technologies and those between firms generated by R56 and SO3.

Fig. 6 suggests that technology spillovers occurred bilaterally between device (laser) and substrate technologies, transmitting bilaterally to and from SEI and Sony. Consequently, it can be safely said that developments of both laser and substrate technologies were driven by inter-technology spillovers.

Actually, a laser development on GaN substrate started in 1998, when SEI filed two epoch making patents: "JP, H10-171276" and "JP, H10-183446". These patents claimed a new technology of GaN substrate for laser fabrication. As they were not fully suited for commercial use however, SEI became motivated to support joint research with electronics firms. An R&D planning director of SEI remarked, "In order to develop substrates of sufficient quality, we needed technology for laser fabrication." On the other hand, electronics device firms were eager to use GaN substrate for developing lasers. Therefore, it makes sense that joint research with the electronics device industry was one of the strategic options.

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[8] The four applications: JP, 2003-417113, -417114, -417115 and -417116 are eliminated because they are the divisional applications of JP, 2001-315703.

Table 6
Patent applications by SEI on GaN substrate and devices (2001–2003)

Year	Patent application ID	Technology	Co-applicant	Inventor[a]
2001	JP, 2001-166904	Substrate	None	R22, R55
	JP, 2001-315703	Laser	Sony	R56, SO1, SO2, SO3, SO4, SO5
	JP, 2001-315704	Laser	Sony	R56, SO6, SO7, SO8
	JP, 2001-315705	Laser	Sony	R56, SO7
	JP, 2001-330068	Laser	Sharp	R56, SH1, SH2, SH3, SH4, SH5
	JP, 2001-330181	Laser	Sharp	R56, SH1, SH2, SH3, SH5
2002	JP, 2002-8130	Substrate	None	R22, R55
	JP, 2002-27981	Laser	Sony	R56, SO9
	JP, 2002-27982	Laser	Sony	R56, SO3
	JP, 2002-27983	Laser	Sony	R56, SO3
	JP, 2002-27984	Laser	Sony	R56, SO3, SO6
	JP, 2002-27985	Laser	Sony	R56, SO3
	JP, 2002-103723	Substrate	None	R56, R57
	JP, 2002-127727	Substrate	None	R58, R59
	JP, 2002-137722	Device and Substrate	None	R56, R57
	JP, 2002-152172	Substrate	None	R45
	JP, 2002-152334	Substrate	None	R45
	JP, 2002-152338	Substrate	None	R45
	JP, 2002-197548	Device and substrate	Other	R56, R60, R57
	JP, 2002-219059	Substrate	None	R61
	JP, 2002-230925	Substrate	None	R56, R58, R61, R62, R63
	JP, 2002-269387	Substrate	None	R56, R58, R62, R63
	JP, 2002-353274	Substrate	None	R62
	JP, 2002-353274	Substrate	None	R58
2003	JP, 2003-1255	Laser	Sharp	R56, SH1, SH3, SH5, SH14
	JP, 2003-9890	Substrate	None	R63, R61
	JP, 2003-22059	Substrate	None	R63, R61
	JP, 2003-80256	Substrate	None	R45
	JP, 2003-80375	Substrate	None	R45
	JP, 2003-90317	Substrate	Other	R63, R64, R65
	JP, 2003-116203	Device and substrate	None	R56, R57, R66
	JP, 2003-119334	Laser	Sharp	R56, SH1, SH2, SH3, SH5, SH6, SH7
	JP, 2003-120130	Laser	Sharp	R56, SH8, SH9, SH10, SH11
	JP, 2003-123180	Laser	Sharp	R56, SH12
	JP, 2003-128059	Substrate	Sony	R22, R61, R63, SO3, SO10
	JP, 2003-128061	Substrate	Sony	R22, R67, SO3, SO10
	JP, 2003-153621	Laser	Sharp	R56, SH11, SH13
	JP, 2003-158143	Device and substrate	Other	R57, R59, R60, R66
	JP, 2003-273551	Substrate	None	R11, R47, R56, R57, R59, R68, R69
	JP, 2003-275935	Substrate	None	R22, R48
	JP, 2003-281647	Substrate	Sony	R22, R67, SO3, SO10
	JP, 2003-345910	Substrate	None	R22, R70, R71, R48

[a] Researchers SOxx, SHxx, and Rxx present those from Sony, Sharp, and other organization including SEI, respectively.

Furthermore, after the period from 2001 to 2003 when many joint applications were filed, Sony independently filed patent applications which utilized SEI's GaN substrate for laser fabrications. For example, "JP, 2004-302642", and "JP, 2004-320274" are Sony's non-joint patent applications which claim the laser structure on the SEI's GaN substrate. These patent applications are pieces of evidence that further illustrate the substrate technology spilled over to Sony and was incorporated into the device fabrication technology.

The discussion above proves that substrate and device technologies drove the co-evolution of each other. SEI's innovation was attributed to Sony's technology and similarly Sony's innovation was driven by SEI technology. Eventually, SEI successfully released GaN substrate for laser application in 2003. Sony also launched a new game machine "PlayStation 3" in 2006, with a GaN laser inside.

So far, it is demonstrated that inter-technology spillovers not only converge technologies, but also incorporate external technologies. These results lead us to the conclusion that inter-technology spillovers help technologies co-evolve. Additionally, considering that Sony is an electric machinery firm, this is also a case of inter-industry technology spillovers.

To sum up the results in this section, a joint research with another industry partner has enhanced technology development in the early 2000s. However, no clear intra-technology spillover was present. Thus, Hypothesis 3 is demonstrated.

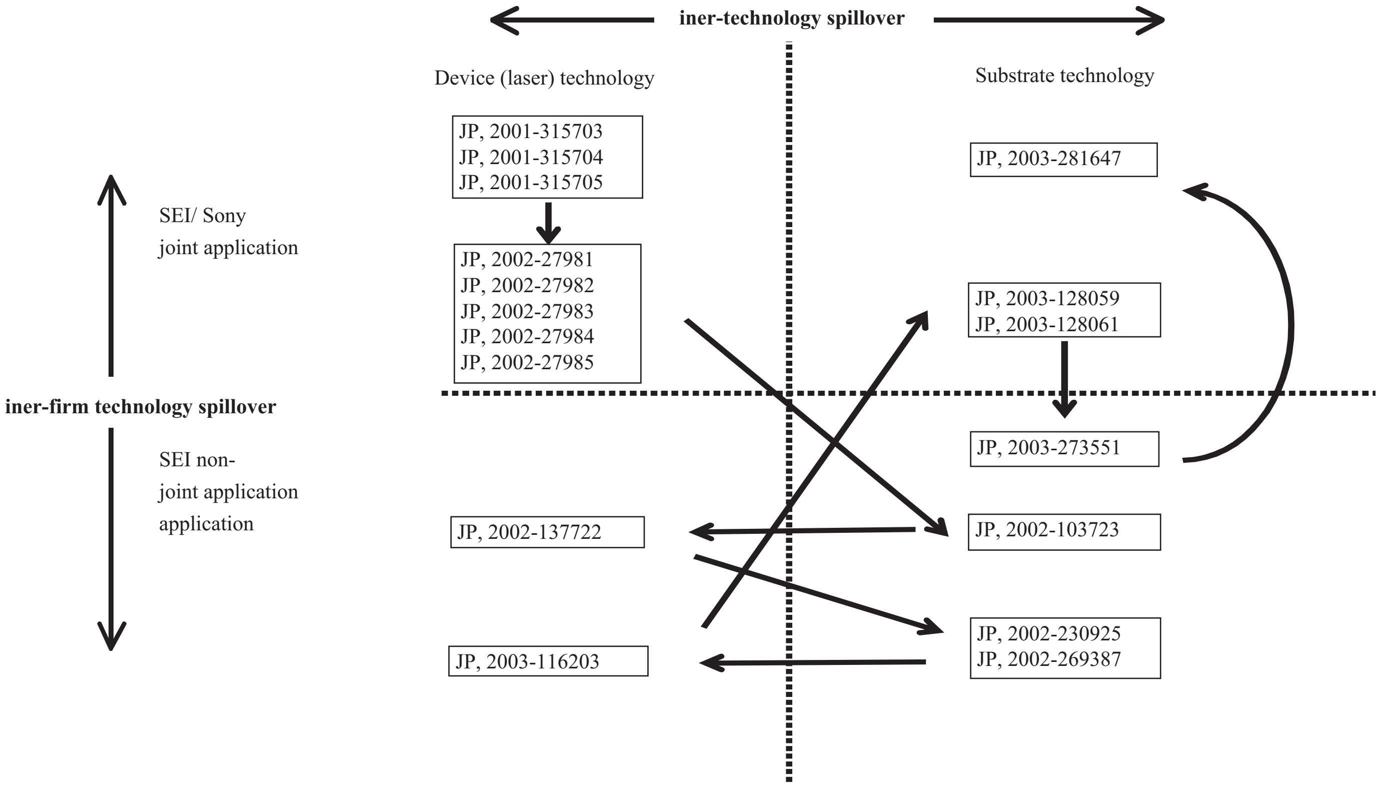

Fig. 6. Development of GaN laser and substrate technologies.

4. Discussion

The results in Section 3 show that technology spillovers structure changed from intra- to inter-technology spillovers from the 1980s, 1990s, and through the early 2000s. However, they do not demonstrate a relationship between innovation and socio-economic change. In this section innovation dynamics in the 1980s, 1990s, and the early 2000s is discussed in relation to the paradigm shifts between an industrial, an information, and a post-information society.

In an industrial society, materials firms hardly disclosed manufacturing technology even to their customers. It was partly because manufacturing technology was a critical factor for innovation, and partly because they were fiercely competing with each other in terms of the quality of their products. The same was also true of electronics firms. Additionally, materials firms actually did not need external learning, because material innovation was conducted through applications of their own technology, as presented in the GaAs case. In addition to the above, the not-invented-here (NIH) syndrome, the reluctance of universities to contribute to industries, and the active basic research in firms themselves were all characteristics of the socio-economic paradigm of that time. In conclusion, technology spillovers in the 1980s analyzed in Section 3.2, presents the features of an industrial society. This analysis showed that technology spillovers in the 1980s were dominated by intra-technology spillovers.

As Japan transitioned to an information society, a decade long stagnation resulted in decreasing R&D intensity. Additionally, there was a change of R&D strategy from diversification to "selection and concentration" which diminished opportunities for intra-technology spillovers. However, firms were still reluctant to learn from the outside. This means that firms could not utilize the dominant features of an information society for stimulating innovation. In short, sluggish innovation in this society can be demonstrated as a transient phenomenon from intra-technology-driven innovation to inter-technology-driven innovation. Both intra- and inter-technology spillovers existed however, their effects were not significant. Consequently, the technology spillover structure in the 1990s elucidated in Section 3.3 represents this transition to information society.

In a post-information society, manufacturing technology was becoming less important for innovation. Instead, consumer behavior was increasing in its significance. New functions had to be quickly incorporated into new devices. Therefore, materials firms had to develop new materials for new applications with little experience in these new areas. They needed feedback from customers to achieve this. Electronics device firms had to develop new devices with unknown materials. However, they could not do this quickly in isolation. Therefore, both materials and device firms needed each other's cooperation.

In conclusion, the technology spillover structure in the early 2000s, demonstrated in Section 3.4, illustrates the transition to a post-information society.

Furthermore, as innovation cannot be created only by manufacturing technology itself, innovation in the early 2000s shows the distinctive feature of a co-evolution of R&D, business strategy, market, and national science and technology policy. In fact, in 2001, when Sony and SEI filed their first joint patent applications, the new R&D director in SEI announced encouraging external learning. In 2003, when Sony–SEI joint research successfully finished, the R&D group reformed its management system as a part of business administration reform, and encouraged external learning. In 2005, SEI and the AIST concluded a partnership agreement for further cooperation. Thus, it is likely that there exists bilateral causality between corporate business strategy and management of technology. A director of the SEI Research Planning Department claims that some successful cases in joint R&D-inspired management to enhance external learning. On the other hand, this reform encouraged researchers to carry out joint research. Furthermore, in terms of national science and technology policy, this agreement is a symbolic case of academia–industry collaboration. Therefore, it is inferred from these facts that innovation and institutional elements such as business strategy, and national policy form a manifold, interdependent, co-evolutionary system.

5. Conclusion

Noteworthy findings from this study include:

(i) The structure of technology spillover has changed according to the economic paradigm shifts in Japan. This change has extended the boundary of spillovers: from unilateral to bilateral, from intra-technology to inter-technology, from intra-firm to inter-industry.
(ii) These changes reflect not only changes of business strategies, but also institutional changes in the context of Japan, including national policy and market structure.
(iii) Intra-technology spillover in the material industry is, essentially, an application of manufacturing technology from one material to another. Thus, it naturally reaches a limit when it has covered all of the possible materials for application.
(iv) Inter-technology spillover is a fusion of technologies. The materials and device industries utilized each other's technology for their own development.
(v) Innovation is promoted by the transformation of institutional elements. For example, material technology, device technology, national policy, business strategy, market, and so on.

These findings suggest some very specific policy implications for material innovation. Most importantly, a firm should use and share crossover knowledge not only with customer industries, but also with other various institutional elements to stimulate and sustain innovation. In other words, a firm in the material industry should extend the technology spillover boundaries, not within customer industries, but also to manifold elements which form the institutional infrastructure. This is the way to create breakthrough innovation in a post-information society.

This paper has demonstrated changes in the technology spillover structure related to Japan's economic paradigm shifts over the last three decades. Further research focused on the dynamics in technology spillovers could provide greater insight into the changing roles of intra- and inter-technology spillovers in a dynamic marketplace.

Appendix A. Business sectors in SEI Ltd.

Appendix A provides an overview of the business in the SEI, Ltd. SEI was established in 1896 as a manufacturing firm of electric wires and cables. Since then, SEI's business strategy has consistently focused on the diversification by innovation. For instance, wire-drawing technology was applied to stainless steel wire business, powder alloy products business derived from extrusion dies made of powder alloy, and communication cable business changed to that of fiber optics and compound semiconductors.

From a technological point of view, SEI's business can be divided into four sectors, as presented in Table A1.

Appendix B. Estimation of technology stock by business sector

Appendix B presents an estimation of technology stock by business sectors in SEI. As technology spillovers among

Table A1
SEI's business sectors and major products

Business sector	Major products
Wire and cables	Electric power cables, Optical fiber cables, Magnet wire, Wiring harnesses, Ultra fine copper wire, Superconducting cables Electric wire for electric equipment and automotives, Submarine cables
Special stainless wires	Steel wires, Stainless steel wires, Steel cords.
Powder alloy products	Powder metallurgical parts, End mills and drills, Bonding tools, Cemented carbide insert, Synthetic diamond
New business sectors	Cable accessories, Brake system, Optical data link, Traffic control system, Porous metal, Polyimide tube, Fluororesin products, Printed circuit, Compound semiconductors.

Table B1
Number of patent applications by business sector in SEI (1980–2004)

Business sector	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
W and C	417	476	550	626	697	734	646	753	530	548	574	476	519	451	449	496	423	439	422	450	364	452	505	314	285
SSW	27	27	21	78	42	85	46	44	42	29	14	20	35	56	38	34	14	30	25	21	24	20	4	4	1
PAP	116	237	161	193	176	187	222	264	165	164	149	172	121	115	108	122	69	82	111	64	39	31	60	16	17
NBS	400	541	493	751	755	975	882	1461	1130	1010	1213	1195	939	913	702	682	636	783	808	804	783	885	1149	1082	1229

internal business sectors played important roles in increasing MPT, it is informative to elucidate technology stock of SEI by its business sector. Since R&D expenditure of each business sector is not available, it is estimated from the number of patent applications of the business sector. Hereinafter, the word "patent application" indicates the one which is filed with the Japan patent office (JPO).

All 38,669 patent applications filed by SEI in the period from 1980 to 2004 were examined in detail and classified by business sector. Table B1 provides a breakdown of SEI patent applications (P) by business sector and its trend from 1980 to 2004.

Patent applications can be formulated as a production function of R and $T(R)$,

$$P = F(R, T(R)) \cong F(R) = AR^{\alpha} \tag{B.1}$$

Applying the trends in R and P in SEI for the period 1980–2004 to this equation, the production function, F, is empirically identified as follows:

$$\ln P = \underset{(-0.84)}{-0.56} + \underset{(11.77)}{0.84}\ \ln R - \underset{(-11.36)}{0.05}\ D_t \ln R + \underset{(5.19)}{0.16}\,D$$

$$adj.\ R^2 = 0.906,\ DW = 2.27 \tag{B.2}$$

$D_t = 1/(1 + \mathrm{e}^{(-0.7t)}), \quad t = 0 \quad \text{at } 1991$

D : Dummy variable (1983, 1985, 1991, 2002, 2004 = 1, other years = 0).

A dummy variable, D, is set at specific events in SEI's R&D activity: business launching in semiconductors and fiber optics in 1983 and in 1985; an intensive R&D in high-temperature superconductors in 1991; significant increase in patent applications encouraged by leadership of a new R&D director and an intensive R&D in automotive equipment in 2002 and 2004.

With an inverse function of F, F^{-1}, R is expressed as the following functions:

$$R = F^{-1}(P) \tag{B.3}$$

$$\ln P = (0.84 - 0.05D_t)\ln R + (0.16D - 0.56) \tag{B.4}$$

$$\ln R = \frac{\ln P}{(0.84 - 0.05D_t)} + \frac{(0.56 - 0.16D)}{(0.84 - 0.05D_t)} \tag{B.5}$$

Therefore,

$$R = AP^B$$

where

$$A = \mathrm{e}^{((0.56 - 0.16D_y)/(0.84 - 0.05D_t))}$$

$$B = 1/(0.84 - 0.05D_t)$$

As SEI's R&D activity in each sector is administrated by one group: "Development Planning Department", there is little difference in R&D management among business sectors. Therefore, it is reasonable to suppose that the correlation between R&D expenditure and patent applications in each business sector traces a similar trajectory to that of SEI as a whole.

$$A_j \equiv a_j A \tag{B.6}$$

where $j = 1,2,3,4$ represent SEI's business sectors, W&C, SSW, PAP, and NBS, respectively. Supposing that $A_j \equiv a_j A$ and $B_j \equiv B$ for $j = 1,2,3,4$, with $P = \sum_{j=1,2,3,4} P_j$ and $R = \sum_{j=1,2,3,4} R_j$, you have $a_1 = 1.6$, $a_2 = 1.0$, $a_3 = 0.6$, $a_4 = 1.2$.

Now that the R&D expenditure for each business sector has been estimated as above, technology stock in each business sector can be estimated as presented in Table B2, illustrated in Fig. B1.

This paper estimated R&D expenditure of a firm from patent application data, while Nakagawa and Watanabe (2007) did it from publications. Fig. B2 shows the result of the estimation by publications. Comparing Fig. B1 with Fig. B2, we note that technology stock estimated by publications on SEI Technical Review shows a larger gap between the new business sectors and cable and wireless sector than the one by patent applications. This difference is caused by the difference of activities between publishing and patent applications.

As SEI Technical Review is a technical journal of SEI and publication of a paper is judged by its technological achievements. As technology in new business is growing at high speed and old business like cable/wire is matured, it is understandable that publications in new business are much more than those in old business. On the other hand, as a patent is an intellectual property right, its applications

Table B2
Technology stock in SEI by business sector (1980–2004)

Business sector	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
W and C	12.38	13.42	14.45	15.49	16.85	18.73	20.59	23.02	25.56	27.30	28.86	29.49	29.60	30.35	30.34	30.52	31.49	32.03	33.19	34.00	34.15	34.29	34.54	34.17	33.90
SSW	0.30	0.32	0.35	0.37	0.40	0.40	0.50	0.63	0.75	0.85	0.85	0.84	0.81	0.73	0.64	0.63	0.74	0.84	0.86	0.80	0.75	0.73	0.69	0.66	0.63
PAP	1.01	1.10	1.18	1.27	1.57	1.90	2.02	2.15	2.24	2.41	2.67	2.78	2.77	2.74	2.72	2.68	2.60	2.53	2.50	2.39	2.20	2.16	2.08	1.84	1.58
NBS	8.84	9.58	10.31	11.06	12.41	13.90	15.57	18.15	21.17	24.26	29.05	34.42	37.78	41.72	45.81	48.32	50.55	51.11	50.04	48.83	48.87	50.47	51.98	52.98	54.53

10^3 million yen at 2000 fixed prices.

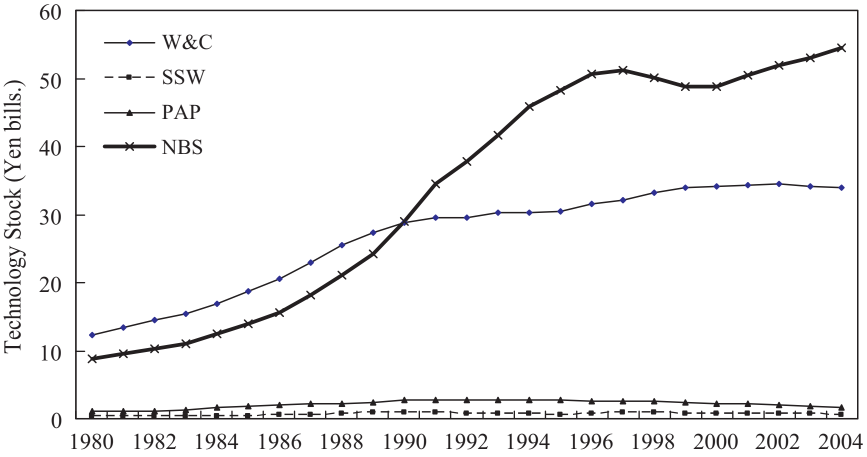

Fig. B1. Trends in technology stock in SEI by its business sector (1980–2004), fixed prices at 2000.

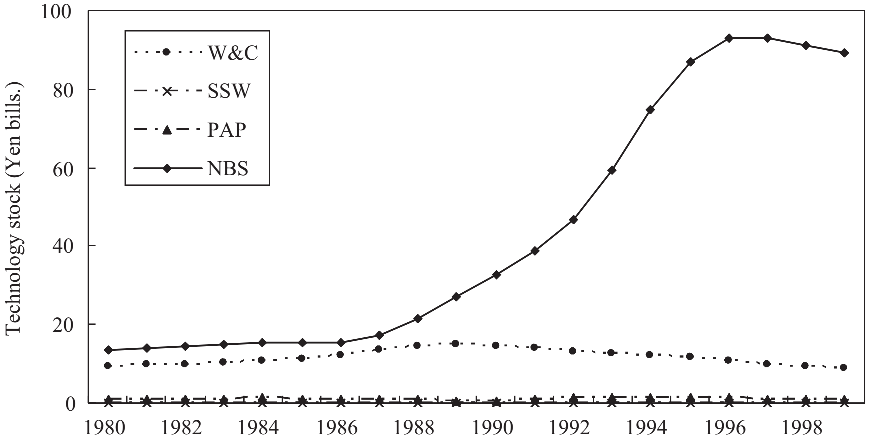

Fig. B2. Trends in technology stock by business sector in SEI (1980–1999). Estimated by publications. *Source*: Nakagawa and Watanabe (2007).

are encouraged even for a small improvement in an old business. This difference in the attitude explains the difference in the gap in these numbers. In this paper, in order to catch the details in R&D activity, the number of patent applications is adopted as an index of R&D activity.

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