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Role of doctoral scientists in corporate R&D in laser diode research in Japan

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With the advancement of technology and increase in its complexity, the use of external information and resources provides companies with an important competitive advantage. In addition, the university–industry relationship has received attention with increases in the importance of science. Exploring papers on laser diodes published in Applied Physics Letters *and patents from 1960 to 2000, this study analyses the roles of corporate scientists with doctoral degrees in laser diode technology. The study focuses on the different roles played by two types of doctoral scientists: university-based and industry-based. It explores both direct and indirect contributions of doctoral corporate scientists to R&D by examining their papers and patents. The results indicate that both types achieved a higher average number of papers and patents than non-doctoral scientists. Exploring the co-authors of doctoral scientists to determine the indirect effect of doctoral scientists on corporate R&D, this study observes that the co-authors of industry-based doctoral corporate scientists published more papers or filed more patents. This study confirms that industry-based doctoral corporate scientists play an important role in promoting corporate R&D by linking corporate R&D with university research.*

Introduction

With the increasing complexity of technology, science plays an important role in technology-intensive industries. Firms internalise technological knowledge in their research and development (R&D) laboratories and place knowledge creation in a central position in their business strategies. R&D is traditionally an important source of innovation and a competitive advantage for firms (Mowery, 1983; Chandler *et al.*, 2001). Large enterprises internalise many resources and conduct scientific research in the research phase of R&D.

With increasingly complex technology, it has become quite difficult if not impossible for a firm to internalise all the resources needed for in-house R&D (Burgers *et al.*, 1993). Breakthroughs demand a range of intellectual and scientific skills that far exceed the capabilities of any single organisation; therefore, the use of external information and resources gives firms an important competitive advantage (Cohen and Levinthal, 1990; Powell *et al.*, 1996; Gulati, 1999; Chesbrough, 2003).

One important external resource is the research conducted by universities and public research institutions (Branscomb *et al.*, 1999). Industrial patents heavily cite research papers published by universities, and the industry–university relationship in

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patent citation has increased over time (Narin *et al.*, 1997). British and Japanese firms consider universities to be important sources of external technologies (Tidd and Trewhella, 2002). While industries use the research findings of universities, universities provide experimental materials, instruments and highly trained human capital (Cohen *et al.*, 2002). In a study of US industry researchers, Mansfield observed that approximately 10% of the respondents' product and process innovations could not have been developed without substantial delay in the absence of academic research input (Mansfield, 1991, 1998). The science–engineering nexus in science-based industries such as biotechnology, pharmaceuticals, medical equipment, semiconductors and electronics has attracted wide attention (Jaffe, 1986, 1989; Gambardella, 1992; Mansfield, 1998; Cohen *et al.*, 2002).

R&D not only generates new knowledge, but also enhances a firm's ability to assimilate and exploit external resources (Cohen and Levinthal, 1990). The previous literature has documented this point, and studies in economics and business management have addressed why a firm conducts scientific research and how it develops technology. Rosenberg indicated five points explaining why a firm conducts basic research (Rosenberg, 1990). First, basic research often provides first-mover advantages that more than offset any disadvantages. Second, conducting basic research helps firms understand how and where to conduct applied research. Third, research in basic science allows a firm to evaluate the outcome of applied research and to understand its implications. Fourth, basic research allows a firm to monitor and evaluate research that is being conducted elsewhere. Fifth, conducting basic research allows a firm to remain effectively plugged in to scientific communities. Science is an important frame of reference for a firm that is seeking solutions and road maps in technological development (Fleming and Sorenson, 2004). According to these studies, conducting basic research helps a firm monitor and access external knowledge and evaluate its R&D outcomes.

These investigations lead to questions regarding who conducts basic research in corporate R&D and what roles they play. Furukawa and Goto investigated the top five pharmaceutical firms in terms of the size of R&D budgets and examined the role of the firms' corporate scientists engaged in basic research (Furukawa and Goto, 2006). They found that core scientists (CSs) who have published numerous papers or whose papers have been frequently cited do not apply for a large number of patents. They do, however, promote patent applications of co-authors in their companies. Furukawa and Goto concluded that CSs serve as channels through which external knowledge flows to the researchers, thereby performing an important role in stimulating innovation by corporate scientists.

These studies provide important perspectives on basic science in firms. However, they do not fully clarify who the core scientists are and what kind of researchers they are. The main purpose of the present study lies in exploring who really plays the role of CS in corporate R&D, focusing on scientists who have a doctoral degree, for the following two reasons. First, it is reasonable to assume that corporate scientists who have been trained in higher education play an important role in corporate R&D, as the importance of science has increased. However, the previous literature on R&D in Japanese firms indicated that knowledge creation on the shop floor played an important role in corporate R&D, and that scientists and engineers who did not necessarily have a doctoral degree contributed significantly to knowledge creation in corporate R&D (Dore, 1973; Nonaka and Takeuchi, 1995). Of course, this finding does not necessarily mean that the role of doctoral level scientists is marginal. The present study attempts to clarify the role of doctoral corporate scientists in corporate R&D. Results confirm that doctoral corporate scientists play an important role in not only publishing papers and obtaining patents, but also linking corporate R&D with university research.

The second reason relates to the degree system in Japan. Two types of doctoral degrees – the *katei-hakase* and the *ronbun-hakase* – have been granted in Japan since the 1887 university reform.[1] While one earns the *katei-hakase* by writing a thesis in the doctoral course, the *ronbun-hakase* is usually awarded by an employee's former university after some years of research in industrial laboratories, with no matriculation or enrolment necessary, only submission of a dissertation and some articles published in well-known journals. Both degrees are reported to the Ministry of Education, Culture, Sports, Science and Technology (MECSST) when they are awarded. No formal English term describes these degrees. Therefore, following the National Science Foundation's report, *The Science and Technology Resources of Japan: a Comparison with the United States*, this study refers to the former degree as the university-based doctoral degree and the latter as the industry-based doctoral degree (Papadakis, 1988).

The industry-based doctoral degree is unique; the US has no counterpart. After being engaged in R&D for a certain period of time, industry-based corporate scientists obtain doctoral degrees on the basis of the research findings produced by their corporate R&D. The candidate is required to give a presentation at academic workshops or conferences, to publish his or her research findings, and to write a dissertation. This process is usually conducted with the assistance of university thesis examiners. Therefore, candidates usually build close relationships with university researchers. Candidates must also request permission from their firm to pursue this doctoral degree. In the present study, interviews with both doctoral and non-doctoral scientists confirmed that many companies greatly encouraged their scientists to obtain a doctoral degree.[2]

The industry-based doctoral degree in Japan is currently being reviewed, partly because of its difference from the degree systems of other countries. For example, no distinction exists between university- and industry-based degrees in the doctoral system in the US, which is currently regarded as the international standard. Of course, doctoral degrees and their awarding systems vary from country to country. For example, a higher tier of doctoral degree exists in the UK, Ireland and France. Since this level of degree is awarded in honour of exceptional research outcomes, the number of degree holders is fairly limited. No counterparts to Japan's industry-based doctoral degree exist in other countries in terms of magnitude, since many Japanese corporate scientists are awarded this degree. The current concept is that these two types of doctoral degrees should be integrated to make Japan's degree-awarding system consistent with international standards. However, research on the role of industry-based doctoral scientists in corporate R&D is extremely limited, although it could provide valuable information on which to base the decision of whether to integrate the degrees.

This study explores the roles of both university- and industry-based doctoral corporate scientists. Our main findings show that both university- and industry-based doctoral corporate scientists achieve a higher average number of papers and patents than non-doctoral scientists. The findings also show that non-doctoral corporate scientists who collaborated with industry-based doctoral scientists averaged a higher number of papers, patents and citations than non-doctoral corporate scientists who collaborated with university-based doctoral scientists. Thus, this study demonstrates that industry-based doctoral scientists play an important role in stimulating in-house knowledge creation and knowledge dissemination outside the firm's boundaries.

Data and methodology

The primary purpose of this study is to explore the role played by doctoral corporate engineers in R&D. Although the role of corporate scientists with high expertise in science has received attention with the growing importance of science, research on their roles is fairly limited, mainly because of data constraints. The *Science and Technology Indicator* survey by the MECSST allows for the investigation of an aggregated number of university- and industry-based doctors. However, to explore the role of doctoral corporate scientists, it is necessary to identify the ones with doctoral degrees and the ones without. Since all doctoral degrees are reported to the MECSST, it is possible to identify the names of all doctors. However, the MECSST does not report the organisations for which the doctoral scientists work. To complicate the issue further, the roles played by doctoral corporate scientists may vary with their areas of expertise. The *Science and Technology Indicator* provides the number of doctors for six areas of study: Science, Engineering, Agriculture, Health, Humanities and Social Sciences, and Other. As science has become more complex, scientists' expertise has advanced through specialisation and subdivisions of the sciences. Expertise varies significantly, even in those six areas of study. Of course, doctoral scientists might share basic methodology in science; however, significant differences exist in domain knowledge. For example, Computer Engineering and Material Engineering are considerably different, although both are categorised as Engineering in the *Science and Technology Indicator*. In addition, a scientist who is awarded a doctoral degree in Electrical Engineering, for example, may not necessarily be engaged in R&D in that field. Therefore, when exploring the roles of doctoral corporate scientists, it is important to identify their specialised fields of study as well as the fields in which they are engaged in corporate R&D. However, it is quite difficult to identify them by using aggregated data, such as the *Science and Technology Indicator*, because their fields of specialty are relatively specialised and segmented.

Core analysis rests on the construction of data on doctoral corporate scientists and their areas of expertise. This study explores corporate scientists who were engaged in laser diode R&D, partially because of data availability. Shinichi Takahashi, who worked for Nippon Telegraph and Telephone (NTT) and joined Keio University, collected information on all scientists who were awarded doctoral degrees in laser diode studies in 34 countries from 1963 to 2004 and compiled them in two bibliographies (Takahashi, 1994, 2005). The data provide the year in which the doctoral degree was awarded, name, university, country and title of thesis. Takahashi also reports two types of doctoral degrees (university- and industry-based) for those who were awarded doctoral degrees from Japanese universities. No other data source that provides such rich information on both university- and industry-based degrees in a specialised field has been identified thus far. Since the compiler was engaged in laser diode research and had expertise in that field, these bibliographies are a reliable indicator for the study of doctoral corporate scientists. Of course, the data allow the investigation of only scientists who earned doctoral degrees in laser diode research. It is possible that scientists with doctoral degrees in other areas work in corporate R&D of laser diodes, and thus do not necessarily use their specialised expertise. Therefore, this study focuses on the analysis of roles played by doctoral corporate scientists in the field of their expertise.

A laser diode, also called a 'semiconductor laser', is a device that emits a laser beam. Laser is an acronym for 'light amplification by stimulated emission of radiation'. It is an optical source of artificial light, which is typically near-monochromatic (i.e. consisting of a single wavelength) and is emitted in a narrow beam. In 1960 in the US, Theodore Mainman successfully radiated the first laser beam by using a solid pink ruby. Today many varieties of lasers exist (e.g. CO_2, YAG, He–Ne, ruby and laser diode). The power of a continuous beam ranges from a fraction of a milliwatt to more than a megawatt. The range of laser applications ranges from commercial use to military use.

Four American institutions – General Electric (GE), International Business Machines (IBM), the University of Illinois Urbana Champaign (UIUC) and the Massachusetts Institute of Technology (MIT) – simultaneously but independently developed the first laser diodes in 1962.[3] The development of the laser diode was amazing and exciting news for physicists who were involved in laser-related R&D. This invention opened huge application possibilities for lasers. Until the laser diode was invented, laser apparatus was all large-scale and required a significant amount of energy input. However, the invention of the semiconductor laser changed the notion of the laser because it was a far simpler laser that would eventually fit on a tiny chip and be efficient enough to run on a small battery. Physicists began theoretical research on laser diodes in the late 1950s. However, both the number of researchers studying laser diodes and the research outcomes were fairly limited. It was not until the late 1960s that physicists regularly published their laser research in academic journals. Both the US and Japan have been leaders in this field since the 1960s (Shimizu, 2010).

The laser diode is used mainly for information storage, such as compact disc or digital videodisc systems. It is also widely used for fibre-optic communication, which permits digital data transmission over long distances and at higher data rates than electronic communication. The laser diode was one of the most important technologies underlying the dramatic changes that took place during the last half of the twentieth century in information technology, and it has become the most widely used laser since the 1980s. The laser diode is now one of the most important devices in the optoelectronics industry.

This study examines the role of doctoral corporate scientists by exploring academic papers and patents of the Japan Patent Office.[4] Scientists and engineers publish their findings in various academic journals in laser diode technology. The variety is wide – from well-circulated journals, such as *Science* and *Science of America*, to more technical and specialised journals, such as the *Journal of Applied Physics* and the *IEE Journal of Quantum Electronics*. Because the primary purpose, the publication frequency, the readers' expertise and the citation impact differ significantly among journals, this study chooses to examine *Applied Physics Letters* to explore the roles of corporate scientists in laser diode technology for three reasons. First, it is weekly and provides up-to-date reports on new experimental and theoretical findings. This prompt report format of the *Applied Physics Letters* allows investigation of the most recent corporate and academic research more readily than full paper journals, such as the *Journal of Applied Physics*. Second, *Applied Physics Letters* has offered reports since 1962. Other important journals with the Letters format, such as *Optics Letters* and *Optics Express*, date back only to the mid-1970s. This allows longitudinal analysis of scientific research. Third, *Applied Physics Letters* has a wide circulation and a strong international reputation as the top journal in the research of laser diodes.

Electronics Letters, which has provided reports since 1965, is also one of the best-known Letters format journals in this area. Based on the Web of Science provided by Thomson Reuters that provides over 10,000 of the highest impact journals worldwide and their citations, this study investigates the number of citations published in *Electronics Letters* and *Applied Physics Letters*. The data on the number of citations were obtained in November 2009. Papers on laser diodes in *Applied Physics Letters* have been cited more frequently than those in *Electronics Letters*. The total number of papers in *Applied Physic Letters* from 1962 to 2008 is 3498, and the average number of citations is 26.81. The total number of papers in *Electronics Letters* from 1965 to 2008 is 2075, and the average citation is 14.01, with only one paper published in *Electronics Letters* ranking in the top 10 most highly cited papers in both journals. Note that this paper does not cover all papers published by corporate scientists, only those published in *Applied Physics Letters*. This is one possible limitation of using only one journal. Another possible limitation is that this paper covers only relatively good research results because *Applied Physics Letters* is the leading journal in the study of the laser diode.

This study examines all papers on laser diodes published in *Applied Physics Letters* from 1960 to 2000 and checks all authors' names to identify whether they had doctoral degrees by matching their names with Takahashi's two bibliographies (1994, 2005). Since many firms [e.g. Hitachi, Nippon Electric Corporation (NEC), Toshiba, Mitsubishi Electric, Fujitsu, Sony, Sharp, Panasonic, Nichia Chemical and NTT] are involved in laser diode research in Japan, this study explores only the top five firms in terms of the number of patent applications in the field of laser diodes from 1965 to 2000. Those firms are NTT, NEC, Fujitsu, Hitachi and Panasonic.

Two steps are taken to explore the research of doctoral corporate scientists. The first step involves comparing the number of papers and patents that a firm's doctoral corporate scientists published with those of other scientists and engineers from that firm. If a firm's doctoral scientists published more papers and patents than other scientists from that firm, it can be assumed that doctoral scientists contribute directly to corporate R&D. The second step involves exploring the co-authors of doctoral scientists to determine the indirect effect of doctoral scientists on corporate R&D. According to Furukawa and Goto (2006), a corporate scientist who publishes more papers or is cited more than other scientists does not necessarily publish more patents than other scientists. However, since the co-authors of CSs are likely to file more patents than other scientists, they concluded that CSs serve as gatekeepers who enhance the absorptive capacity of the firm by linking external knowledge to corporate R&D. Following their argument, this study explores doctoral corporate scientists, their co-authors and other corporate scientists.

Doctors in laser diodes

This section explores the number of doctoral degree holders in Japan in the field of laser diode technology. Figure 1 indicates the number of university- and industry-based doctors in faculties of science and faculties of engineering in Japan from 1960 to 2000. It also indicates the total number of university students. The number of university- and industry-based doctors in science and engineering shows a modest increase until the mid-1970s. Then the numbers became flat until the mid-1980s,

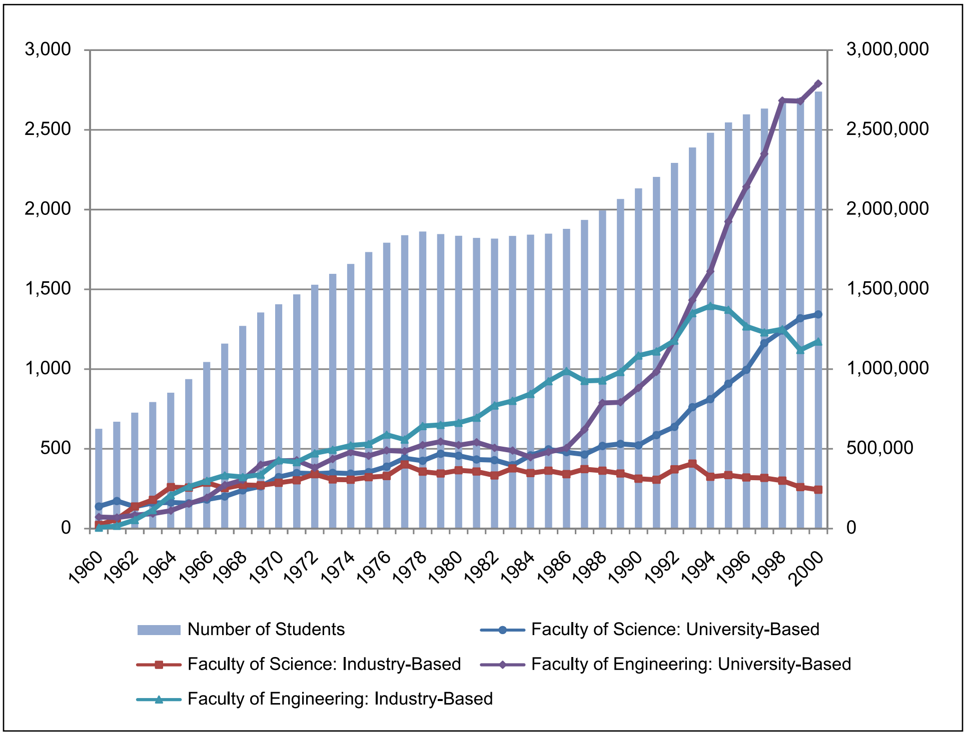

Figure 1. University-based and industry-based doctors in faculties of science and faculties of engineering
Source: Research Institute for Higher Education, Hiroshima University, *Statistics of Japanese Higher Education*, Ministry of Education, Culture, Sports, Science and Technology, *Kagaku Gijyutsu Shihyo*.

except for industry-based doctors in faculties of engineering, which showed a steady increase. The number of university-based doctors in both faculties of science and engineering began to increase in the mid-1980s. As Figure 1 illustrates, an increase in the number of university students was a factor in the increase of university-based doctors. The change in the number of students and doctors was attributed to the university reform that began in 1990. The 1991 *Amendment of University Establishment Standards* deregulated universities. Before this amendment was introduced, the establishment of new schools and the reorganisation of existing universities were highly regulated by the Ministry of Education, Science and Culture (currently MECSST). After this deregulation, more new schools were established and the number of university students increased. The important point regarding industry-based doctors is their high proportion within the total number of doctors in Japan. The number of industry-based doctors in faculties of science was similar to that of university-based doctors until the mid-1980s, when industry-based doctors in faculties of engineering were outnumbered by university-based doctors until the early 1990s. The percentage of industry-based doctors among the total number of doctors in Japan has not been marginal over time, although it began decreasing at the beginning of the 1990s.

Table 1 indicates the number of doctors in the top 10 countries from 1960 to 2000. The first doctoral degrees in the field of laser diodes were awarded to two scientists

Table 1. Doctors in laser diodes

	1965	1970	1975	1980	1985	1990	1995	2000
US	5	26	49	84	130	251	529	812
Japan	0	7	17	42	88	155	287	414
Germany	0	6	20	35	52	93	191	329
UK	0	4	10	18	35	78	179	276
France	2	5	7	15	29	85	165	266
Russia (USSR before 1991)	3	28	58	79	110	141	176	203
China	0	0	0	0	2	14	39	71
Korea	0	0	0	0	5	19	38	66
Canada	0	0	1	2	4	8	26	54
Spain	0	5	9	11	18	22	33	47

Source: Takahashi (1994, 2005).

by the P.N. Lebedev Physics Institute of the USSR Academy of Sciences and by the University of Paris in 1963. The first doctoral degree issued by a Japanese university in laser diode technology was awarded to Yasuo Nannichi in 1966. Based on the research at NEC, where he was working to develop reliable laser diodes, Nannichi was awarded an industry-based doctoral degree by the University of Tokyo. The number of laser diode technology doctoral degrees issued clearly increased from 1980 to 1990 in all countries. The US took a clear lead in the number of doctors in this field, and Japan had the second largest number after the US in the 1980s. Of course, a simple international comparison of the number of doctors requires careful interpretation because degree systems vary from country to country. The important point is that the number of doctors has increased significantly since the 1980s.

Figure 2 plots the number of university- and industry-based doctors in laser diode technology in Japan. The number of industry- and university-based doctors shows a similar pattern. From 1960 to 2000, industry-based doctors outnumbered university-based doctors. Compared with the general trend demonstrated in Figure 2, university-based doctors show a higher presence in laser diode research than in other fields, suggesting that not only universities but also firms actively conducted basic research on laser diodes.

The role played by doctoral corporate scientists

As Figure 2 reveals, the number of industry-based doctors was slightly larger than the number of university-based doctors. Of course, not all industry-based doctors necessarily worked for private firms; some may have worked for national research institutions or academic institutions. However, the majority of them were engaged in corporate R&D. By exploring corporate scientists who were engaged in laser diode R&D at five firms, this section examines the role of doctoral corporate scientists. The five firms – NTT, NEC, Fujitsu, Hitachi and Panasonic – were selected on the basis of the number of patent applications filed in laser diode technology. Table 2 indicates the number of corporate scientists and engineers who published papers on laser diodes in *Applied Physics Letters* and the number of scientists who filed patents in the field of laser diodes. As to the number of researchers, both university- and industry-based doctoral corporate scientists were marginal, compared with non-doctoral scientists,

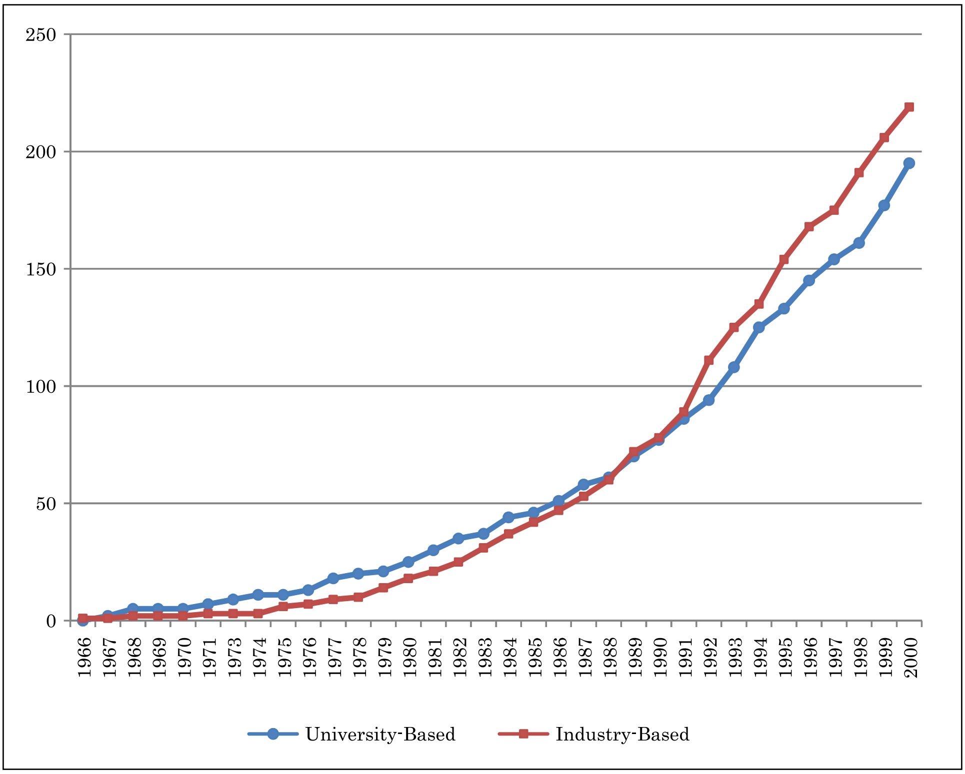

Figure 2. University-based and industry-based doctors in laser diodes
Source: Takahashi (1994, 2005).

and industry-based corporate scientists outnumbered university-based corporate scientists.

The following tables present the number of papers and patents that corporate scientists obtained in order to explore the research of doctoral corporate scientists. If a firm's doctoral scientists published more papers and patents than other scientists from that firm, it can be assumed that doctoral scientists contributed directly to

Table 2. University-based, industry-based, and non-doctoral scientists/engineers

		Scientists/engineers publishing paper			Scientists/engineers publishing both paper and patent		
	Total	University-based	Industry-based	Non-doctoral	University-based	Industry-based	Non-doctoral
NTT	131	5	23	103	3	21	58
NEC	73	3	15	55	3	12	47
Fujitsu	86	7	12	67	6	2	20
Hitachi	53	0	10	43	0	5	12
Panasonic	62	0	13	49	0	11	21
Total	405	15	73	317	12	51	158

Source: *Applied Physics Letters*, 1960–2000; Japan Patent Office.

corporate R&D. In contrast, if the co-authors of doctoral corporate scientists published more papers or filed more patents, it can be assumed that doctoral corporate scientists acted as both a percolator producing knowledge absorbed by the firm and a diffuser spreading knowledge outside the firm's boundaries.

Table 3 looks at paper publication, and Table 4 at patent filing. The number of citations obtained by an early paper or patent does not necessarily have the same significance as that attained by a more recent paper or patent. In this study, the number of citations obtained by each paper and patent is therefore standardised by dividing that number by the average number of citations in that year. The Kruskal–Wallis test, a non-parametric method to test the equality of population medians among groups, is used to examine the statistical difference among doctoral and non-doctoral corporate scientists. The reason for choosing the Kruskal–Wallis test is its ability to compare multiple unpaired groups in nonparametric data. The purpose of the analysis is to show the significances of group differences among industry- and university-based doctoral researchers. For this purpose, the Kruskal–Wallis test is more appropriate than any pair-wise comparison method because there is no intrinsic ordering in every single data group composed of nonparametric count data, not even its dis-normality. In addition, the Kruskal–Wallis test provides a result showing whether at least two of the sample medians are significantly different. In this context, there might be some counterarguments that populations other than industry- and university-based doctoral researchers would show a statistical significance. Hence, we also test and verify statistical significance with another data window, which eliminates other populations in the order of the permutations, and that test shows similar result so far.

Both tables indicate that, on average, industry-based doctors published the most papers and filed the most patents. University-based doctors achieved a higher average number of paper citations. Industry-based doctors ranked higher in patent citations; non-doctoral corporate scientists ranked lowest in both, i.e. the number of papers and citations. Although these tables indicate some difference in performance between university- and industry-based doctoral corporate scientists, they demonstrate that doctoral corporate scientists were engaged more and achieved higher performance in scientific research in their corporate R&D than non-doctoral scientists. It is interesting to observe that both university- and industry-based doctoral corporate scientists had more patents and citations than non-doctoral scientists/engineers. This finding suggests that doctoral corporate scientists were highly engaged in research not only in conducting basic research and publishing papers, but also in patenting their research outcomes.

The next step in determining the role of doctoral corporate scientists in corporate R&D is to examine the performance of doctoral scientists' co-authors. By observing that the co-authors of CSs were likely to file more patents than other scientists, Furukawa and Goto (2006) concluded that the CSs serve as gatekeepers who enhance the absorptive capacity of the firm by linking external knowledge to corporate R&D. Tables 3 and 4 indicate that both university- and industry-based scientists achieve higher performance in paper publications and patent filing than scientists without a doctoral degree in the field of laser diodes. However, the co-authors' performance indicates a clear difference between non-doctoral scientists collaborating with industry-based doctors and those collaborating with university-based doctors. Non-doctoral scientists who collaborated with industry-based doctoral scientists averaged a higher number of papers, patents and citations than non-doctoral scientists as well as non-doctoral scientists collaborating with university-based doctoral scientists. As shown in

Table 3. Papers and citations

	University-based	Industry-based	Non-doctoral	Non-doctoral collaborating with university-based	Non-doctoral collaborating with industry-based	Non-doctoral collaborating with both university-based and industry-based	Kruskal–Wallis test: chi-squared with ties
Number of observations	15	73	113	15	137	51	
Average number of papers	2.60	3.11	1.55	1.47	2.47	3.06	59.99***
	(2.47)	(2.26)	(1.09)	(1.02)	(2.00)	(2.53)	
Average number of citations	29.76	25.74	16.31	25.23	25.63	18.06	29.07***
	(32.06)	(14.26)	(14.83)	(12.91)	(19.03)	(12.18)	
Average number of citations (standardized)	1.09	1.01	0.60	1.06	1.02	0.67	31.94***
	(1.43)	(0.54)	(0.58)	(0.54)	(0.79)	(0.42)	
Average number of max paper citation	38.00	41.33	19.66	29.80	38.15	27.20	45.68***
	(30.96)	(25.27)	(22.33)	(17.04)	(31.50)	(19.15)	
Average number of max paper citation (standardized)	1.38	1.63	0.73	1.26	1.48	0.99	49.57***
	(1.40)	(1.02)	(0.92)	(0.74)	(1.24)	(0.63)	

Notes: Numbers in parentheses signify standard deviation. Asterisks (***) denote significance at the 1% level.
Source: *Applied Physics Letters*, 1960–2000; Web of Science.

Table 4. Patents and citations

	University-based	Industry-based	Non-doctoral	Non-doctoral collaborating with university-based	Non-doctoral collaborating with industry-based	Non-doctoral collaborating with both university-based and industry-based	Kruskal–Wallis test: chi-squared with ties
Number of observations	15	73	113	15	138	51	
Average number of patents	4.77	6.65	1.87	0.10	3.68	3.46	45.26***
	(6.09)	(12.55)	(4.74)	(0.37)	(7.56)	(9.38)	
Average number of patent citations	0.21	0.30	0.08	0.00	0.17	0.17	41.46***
	(0.30)	(0.61)	(0.23)	(0.01)	(0.37)	(0.45)	
Average number of patent citations (standardized)	0.09	0.13	0.07	0.00	0.14	0.08	29.06***
	(0.12)	(0.19)	(0.18)	(0.01)	(0.35)	(0.19)	
Average number of max patent citation	1.60	2.01	0.63	0.03	1.14	0.89	47.15***
	(1.70)	(2.79)	(1.14)	(0.12)	(1.75)	(2.01)	
Average number of max patent citation (standardized)	0.160	0.191	0.121	0.044	0.184	0.140	30.88***
	(0.09)	(0.15)	(0.11)	(0.07)	(0.16)	(0.13)	

Notes: Numbers in parentheses signify standard deviation. Asterisks (***) denote significance at the 1% level.
Source: Japan Patent Office, Tamada Database.

Tables 3 and 4, all the Kruskal–Wallis tests were empirically significant at the 1% level: the mean rank of papers, patents and their citation are statistically different among the groups of scientists.

These results imply that industry-based doctoral scientists play a more important role in promoting basic research in corporate R&D than university-based doctoral scientists. This difference is mainly because industry-based scientists obtain doctoral degrees on the basis of their research outcomes from their corporate R&D, while university-based scientists obtain their doctoral degrees on the basis of research conducted in the university laboratory. Since industry-based scientists gain not only the formal and comprehensive knowledge required to obtain a doctoral degree, but also firm-specific and tacit knowledge embedded in the firm for corporate R&D, they play a more important role in linking external knowledge and in-house R&D than university-based scientists.

Conclusions

Exploring papers on laser diodes published in *Applied Physics Letters* and patents from 1960 to 2000, this study analyses the ways in which doctoral corporate scientists in laser diode technology contribute to R&D in their field of expertise. First, the results indicate that both university- and industry-based doctoral scientists achieved more papers and patents than non-doctoral scientists, thus demonstrating that doctoral scientists significantly contribute to their firms' R&D. This result differs from that of Furukawa and Goto (2006), who investigated the top five pharmaceutical firms in terms of the size of their R&D budget. They found that scientists who published many papers or obtained the maximum citations do not necessarily hold more patent applications than corporate scientists who did not publish as many papers. This difference may be attributed to the fact that the phases in R&D are more clearly defined and divided in the pharmaceutical industry than in other manufacturing sectors, such as automobiles and electronics. For instance, researchers conducting basic research in the initial phase of pharmaceutical research are not usually highly engaged in manufacturing technology development. In contrast, interaction between research and development is quite frequently observed in other manufacturing sectors. Therefore, it is likely that scientists engaged in basic research in the pharmaceutical industry patent fewer inventions than researchers conducting basic research in other manufacturing sectors. Furthermore, the difference in patenting between 'substance patenting' in the pharmaceutical industry and 'device patenting' in the optoelectronics industry may play a role in this difference as well. After Japan introduced the substance patent system in 1976, patenting activity moved to a much earlier stage in the development process, whereas patenting in laser diode technology is closer to the market. Therefore, careful consideration is necessary to further our understanding of the role played by corporate scientists.

Second, the results of this study show that non-doctoral corporate scientists and engineers who collaborated with industry-based scientists were likely to publish more papers and file more patents than scientists who did not collaborate at all with doctoral scientists, or than scientists who collaborated with only university-based doctoral scientists. These results suggest that industry-based doctoral scientists play an important role in creating knowledge and spreading it outside the firm's boundaries. Although the science–technology relationship is often naively presented as a linear model, it has been clear for more than 30 years that these relationships are intricately intertwined and mutually dependent (Constant, 1973; Rosenberg, 1982). Thus, it is highly advantageous for a firm to have a researcher in R&D who can facilitate such interactions between science and technology. Industry-based doctoral scientists are more likely to access the university research community and to learn from findings produced by universities than other scientists, because to obtain a doctoral degree they must access university researchers to present papers at academic workshops or conferences and to publish papers.

Existing studies confirm that relationships with university research play an important role in increasing corporate R&D productivity (Fabrizio, 2006). These relationships allow a firm to gain access to cutting-edge basic research and university researchers' expertise (Rappert *et al.*, 1999). Access to strong basic science facilitates corporate R&D (Nelson, 1982; Cockburn and Henderson, 2001). Although the university–industry relationship has been developed much more modestly in Japan than in the US (Branscomb *et al.*, 1999), the results of this study suggest that the system of industry-based doctoral degrees has been one of the important elements in promoting the university–industry relationship.[5] The findings imply that industry-based corporate scientists absorb external knowledge and promote in-house R&D by linking in-house R&D with the scientific community, based on both the tacit and firm-specific knowledge embedded in corporate R&D and formal expertise, and by gaining access to university research, as required for the attainment of a doctoral degree.

Furthermore, the industry-based doctoral degree system provides an incentive to work with non-doctoral corporate scientists in basic research and facilitates the relationship between corporate R&D and university research.[6] The corporate scientist who obtains a doctoral degree has a greater opportunity to earn a research position at a university. In fact, many industry-based doctoral scientists who were engaged in laser diode R&D held academic positions at universities after retirement from their firms (Takahashi, 2005). After transferring to the university, many maintained a link with the firms for which they had worked. Therefore, industry-based doctoral scientists play an important role in linking corporate R&D with the university, even after they retire from the firm.

The findings of this study have important policy implications. Reform of the doctoral degree programme in Japan has recently been discussed.[7] One argument is that the Japanese degree system should be reformed to meet the global standard because no counterpart to the industry-based doctoral degree system exists in other countries. The government indicated that one possibility is to abolish the industry-based doctoral degree and consolidate it into the university-based doctoral degree.[8] The industry-based doctoral degree system has not previously been examined from the perspective of knowledge transfer between corporate R&D and university research. However, the results of the present study imply the feasibility of reviewing the degree system and upgrading the national innovation system in the light of the roles played by industry-based scientists in corporate R&D, particularly in the technology-intensive and science-based industries. In terms of the channels through which corporate scientists reach university research communities and expertise, the industry-based doctoral system plays an important role in linking corporate R&D with university research. The results of this study imply that the industry-based doctoral degree system enhances the relationship between industry R&D and university research in science and technology-intensive industries.

Investigating papers and patents in the area of laser diodes, this study confirms that industry-based doctoral corporate scientists play an important role in promoting corporate R&D by linking corporate R&D with university research. However, note that detailed study on the career of industry-based doctoral corporate scientists would provide greater insight into their actual role in corporate R&D. For further understanding of the role of doctoral corporate scientists, it is also important to investigate the relationship between the distribution of doctoral scientists in corporate R&D and firms' R&D performance. Furthermore, investigation of doctoral scientists in other disciplines and in other countries would definitely help clarify their role in corporate R&D, if data availability allows.

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Notes

1. On the history of the Japanese degree system, see Kaigo and Terasaki (1969), Amano (1980) and Terasaki (2003).
2. The author conducted 70 interviews with US and Japanese scientists, engineers and managers engaged in laser diode R&D between 9 September 2004 and 27 December 2010. A list of interviewees and interview data are available on request.
3. On the invention of the four semiconductor lasers, see Dupuis (2004).
4. Following the patent classification that the Japan Patent Office (Tokkyocho, 1999) used to investigate laser diode technology, this study used the following international patent classifications: H01S/096, H01S3/133, H01S3/18, H01S3/04S, H01S3/08 and H01S3/23.
5. Odagiri (1999) also found that university–industry linkage was not necessarily ineffective in Japan.
6. The linkage between corporate R&D and universities maintained by industry-based doctoral scientists was confirmed in the interviews.
7. For a recent discussion on the reform of the university-based doctoral degree system, see, for example, Central Council for Education, Subdivision on Universities, Graduate School Section, *Shakaijinto no Enkatsuna Hakasego Shutoku ni Tsuita*, 18 November 2009.
8. Central Council for Education, the Subdivision on Universities, Graduate School Section, *Shinjidai no Daigakuin Kyoiku no Tenkai ni Mukete*, 12 May 2005.

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