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The magnitude of innovation by demand in a sectoral system: The role of industrial users in semiconductors

Pamela Adams[a,b], Roberto Fontana[b,c], Franco Malerba[b,*]

[a] Franklin College Switzerland, via Ponte Tresa 29, 6924 Sorengo, Switzerland
[b] KITeS, Bocconi University, via Roengten 2, 20136 Milano, Italy
[c] University of Pavia, Via San Felice 5, 27100 Pavia, Italy

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ABSTRACT

How relevant is innovation by demand compared to innovation by other actors in a sector? In quantitative terms, this is a yet unanswered question. The current study fills this major gap in the literature on industry studies. By taking a sectoral system perspective, this study is able to highlight the magnitude of innovation by intermediate user firms in a high technology sector: semiconductors. Using a combination of different datasets – patents, co-patents, R&D alliances and new ventures in semiconductors – this study proposes a novel quantitative approach to assessing the magnitude of innovative activity by user firms. The study reaches several findings. First, the magnitude of innovation by user firms, as measured by patents, is high in both absolute and relative terms compared to semiconductor firms and other actors in the sector. Second, the distribution of patents among different demand segments is highly uneven. Third, innovative user firms are highly heterogeneous in terms of size, diversification and vertical integration. Fourth, collaboration in R&D and co-patenting activity in semiconductors take place not just between user firms and semiconductor firms, but also among user firms themselves. Fifth, innovative user firms are quite active in entrepreneurial activity in semiconductors and their new ventures, on average, survive longer than spin-offs or other start-ups.

1. Introduction

How relevant is innovation by demand compared to innovation by other actors in a sector? In quantitative terms, this is a yet unanswered question. The current study fills this major gap in the literature. By taking a sectoral system perspective and using a combination of indicators and datasets, this study examines the magnitude of innovation by intermediate users in a high technology sector: semiconductors.

Research on sectoral systems has shown that the innovation process involves interaction among a wide variety of actors for the generation and exchange of knowledge (Malerba, 2002). These actors may include the firms within the industry, linked firms such as equipment, component and material suppliers, consumers and users, universities, research organizations, financial institutions and other public and private organizations that interact in various ways within the broader sectoral system. The roles of these different actors and their importance for innovation vary according to the sector involved. Such observations have led researchers to attempt to assess the contribution of these actors within a sectoral context. Much of this empirical work has focused on the relevance for innovation of producers, universities, and financial and public research organizations (see for example Mowery and Nelson, 1999; Malerba, 2004; Malerba and Mani, 2009). By contrast, little empirical work has been done within a sectoral systems perspective to date to assess the relevance of innovation by demand with respect to the other actors. As a result, the contribution of demand to innovation may be systematically underestimated by existing research (see the discussion by Lettl et al., 2009).

This comes as a surprise. In fact, in recent years a burgeoning literature has convincingly shown that demand, in terms of end-consumer users or intermediate user firms, plays an important role in affecting innovation in sectors. Broad studies on sectoral systems, such as the ones cited above, have also emphasized the active role of demand in sectors such as software, machine tools and semiconductors. In addition, since the pioneering work of von Hippel (1988, 2005) on lead users, numerous case studies and survey analyses have highlighted the major role of users in innovation processes across a variety of sectors. Yet despite these contributions, we still do not have clear ideas of the quantitative magnitude of innovation by demand at the sectoral level. A number of basic questions have yet to be answered. Within a sectoral system, how many innovations are developed by demand compared to other actors? What

* Corresponding author. Tel.: +39 2 58363391; fax: +39 2 5836 3399.
E-mail addresses: padams@fc.edu (P. Adams), roberto.fontana@unibocconi.it (R. Fontana), franco.malerba@unibocconi.it (F. Malerba).

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differences exist across different types and categories of demand? Does the magnitude of innovation by demand change over time? Answers to these questions are vital for both researchers and policy makers because they provide a quantitative indication of both the absolute and relative importance of innovation by demand within a sectoral system and lay the ground for comparative analyses of the relevance of demand across different sectoral systems.

The novelty of this study is to fill the gap in our understanding of the relative importance, in quantitative terms, of innovation by demand – *defined here as intermediate users* – in a sector. We will measure the magnitude of innovation by demand in one sector – semiconductors – through a series of indicators that will allow us to provide a quantitative analysis of the relevance of innovation by demand over time. After a brief discussion of what we know about the role of demand in innovation in different sectoral systems (Section 2), we present an analysis of the role of demand in the semiconductor sectoral system of innovation and introduce the four different indicators and data sets used in the study (Section 3). We then present the findings from our quantitative analysis (Section 4) of the extent and relative weight of innovation by demand in semiconductors over a 20-year period. Finally, in Section 5, we draw some conclusions.

2. Innovation by demand in a sectoral systems perspective: What we know and what we would like to know

Within the conceptual framework of a sectoral system, innovation and production are regarded as processes in which different types of actors are actively involved (Malerba, 2002). Demand, in terms of both end-consumers and intermediate user firms, is a major actor in such processes. Demand, alongside of suppliers, universities, and public and private research organizations, not only contributes to ideas and provides feedback for innovation, but also develops innovative solutions. The contribution of demand to innovation stems from its unique knowledge base with respect to other actors within a sectoral system: users and consumers have a better, deeper and more situated knowledge about uses, needs and applications.

Evidence of the role of demand in innovation comes from numerous sources. Over the past decades numerous sectoral studies have documented the role of demand in the innovation process. For example, Enos (1962) and Freeman (1968) pioneered some early work on the contribution of user innovations in the oil refining and chemical industries. Mowery and Nelson (1999) explored the sources of industrial leadership in seven industries across the United States, Japan, and Western Europe and showed that demand has played important roles in innovation in sectors as diverse as machine tools, software and computers. In a similar study, Malerba and Mani (2009) illustrated the major role of demand in developing economies in a range of industrial sectors such as ICT and software, capital goods industries and motorcycles.

These broad sectoral analyses have been complemented with a wide range of industry and case studies that explore the activities of specific user firms and user groups within sectors (Lundvall, 1992; Bogers et al., 2010). Much of this research stems from the seminal work by von Hippel (1988) on lead users. While playing different roles, users have been identified as important sources of innovation in sectors such as medical equipment (von Hippel, 1988), software (von Hippel, 2005), mountain biking and extreme sports (Schreier et al., 2007; Franke and Shah, 2003; Lüthje et al., 2006), automobiles and motorcycles (Sawhney et al., 2005) and banking services (Oliveira and von Hippel, 2011). In semiconductors, case studies on Samsung (Kim, 1997) and Ericsson (Glimstedt et al., 2010) documented the important contributions of vertically integrated user firms to innovation over the course of the industry's life-cycle. Similarly, Ernst (2005b) discussed the role of demand in the recent evolution of the semiconductor industry, and von Hippel (1977) showed the importance of user innovation in semiconductor process machinery.

Another source of evidence on the role of demand in sectoral systems of innovation comes from the many surveys that have been conducted both within and across industries over the past years. Cross-industry surveys, such as those reported in the Sappho project (Rothwell et al., 1974) and by Myers and Marquis (1969) and Cohen et al. (2002) have confirmed the prominent role of demand in innovation. Along the same lines, the Community Innovation Surveys pointed to users as a major source of innovation (Belderbos et al., 2004a,b). In addition, many studies in business-to-business marketing have analyzed buyer-seller relationships in industrial markets in an attempt to show the contribution of buyers to the process of product development through both formal and informal networks (Haakansson and Snehota, 1995). Finally, several studies have attempted to measure the extent of innovation by 'lead' users in specific sectors or product areas using detailed ad-hoc survey data. Urban and von Hippel (1988), for example, found that 24.3% of a sample of 136 users of printed circuit design software either modified or designed their own software. Similarly, Morrison et al. (2000) showed that 26% of libraries using OPAC (a software based library search system) had either customized or designed their own search systems. In a study related to surgical equipment in Germany, 22% of the surgeons in the sample declared that they had intervened to modify or develop their own versions of the equipment (Lüthje, 2004). In their study of Dutch 'high-tech' firms De Jong and von Hippel (2009) concluded that process innovations were common practice among user firms.

These various streams of research have shown that user firms may contribute to innovation in a variety of ways. '*Active' users* may simply provide knowledge and feedback to producers (Eurostat, 2004) while 'lead' users (von Hippel, 1986; Gault and von Hippel, 2009) will innovate on their own in order to develop solutions for their specific needs before the bulk of the marketplace even recognizes the same need. '*Experimental' users* (Malerba et al., 2007) are willing to try emerging technologies and attribute intrinsic merit to a product simply because it embodies a new technology. '*User entrepreneurs*' go further to take responsibility for the production and commercialization of products/services that they have first developed for their own use (Hienerth, 2006; Shah and Tripsas, 2007). '*Vertically integrated' user firms* design and produce components for their in-house use and often sell their component solutions to the open market as well.

While these studies provide useful insights into the various kinds of contributions that demand and, more specifically, user firms make to the innovation process across industries and product categories, they do not assess the quantitative relevance of innovation by demand with respect to other actors. Moreover, it is not clear if and how the contribution of demand changes over time. Our objective in this article, therefore, is to examine the magnitude of innovation by demand from the perspective of a sectoral system in which different actors, with different competencies, knowledge bases, objectives, organizational structures, and behaviors, may be involved in innovation. By doing so, this study aims to shed light on some of the questions that previous studies have left unanswered. Within a sectoral system, what extent of total innovations is developed by demand? What differences exist across various types and categories of demand? Does the magnitude of innovation by demand change over time?

Our research focuses on one sector, semiconductors. We define demand in this sector as firms that mainly use semiconductor technology and semiconductor chips in either their products or their production processes. In this study, therefore, demand is synonymous with intermediate users or user firms and innovation by demand is innovation done specifically by these firms. User firms may also produce semiconductor components (and eventually sell them on the open market), making them vertically integrated user firms. But in these cases, semiconductor technology is not the major line of business nor the mission of the company. Our definition of 'user' is admittedly broader than other classifications that limit users to those that benefit directly from a technology or from components (such as semiconductors) but exclude firms that sell products or services incorporating that technology or those components (von Hippel, 2005). Our reasoning for this is that these intermediate users are key players in innovation because they have a unique knowledge base that is different from that of semiconductor supplier firms. In the sectoral system that we examine – semiconductors – user firms have knowledge bases related to application areas for semiconductor technology that are distinct, deeper and more situated with respect to the knowledge bases of semiconductor suppliers. Moreover, while knowledge on the supply side, that once was tacit, has become more codified and more easily transferable, the same is not true for application knowledge that often requires a deep understanding of complex systems or the capacity to adapt devices to the specific needs of an increasingly wider variety of final products.

Therefore, in this paper, our research explores how much of this distinct, deeper and more situated knowledge base is transformed into innovations by user firms in semiconductor technology. We do that by using a variety of indicators regarding innovation: patents, co-patents, R&D alliances, and new firm ventures. In each case, we use quantitative data on the whole population of actors, rather than surveys or case studies, to analyze the magnitude of innovative activities by intermediate user firms compared to other actors within a sectoral system.

3. The case of semiconductors: Framework and selection of indicators

3.1. The sectoral system of innovation in semiconductors

From a sectoral systems perspective, developments in semiconductors have involved a wide range of actors and networks. As a science-based industry, universities and research laboratories have been heavily involved in R&D in semiconductors. Similarly, firms in the industry, with the strong backing of financial organizations and venture capital, have invested heavily in scientific research aimed at both product and process technologies. Government agencies have supported developments in semiconductors for both military and strategic purposes. But demand has also played an important role in the growth of the semiconductor industry. In the early years of the semiconductor industry, demand from the military, aerospace, and computers was fundamental in determining both the speed and direction of technological change in semiconductors, especially in the United States (Malerba, 1985b; Langlois and Steinmueller, 1999). In the 1970s, new markets in telecommunications, automobiles and consumer electronics emerged and had a significant impact on the development of advanced capabilities by European and Japanese semiconductor producers (Malerba, 1985a).

In the decades under examination here (1980s and 1990s), two related factors increased the relevance of application knowledge for product development in semiconductors. The first was the widespread use of semiconductors in wireless communications and mass consumer products such as video games and televisions. These new markets had very different characteristics from the more traditional markets (computers and telecommunications) for semiconductors. Consumer markets were highly fragmented into a vast array of product niches, each with different requirements. Product life cycles were also much shorter due to the rapidly changing demands of consumers (Brown and Linden, 2009). Under such conditions, the stable architectural standard that had dominated in previous decades (the Wintel standard) was no longer applicable. Unlike the personal computer, consumer products more often required custom semiconductors that would allow producers to differentiate their products from those of their competitors in order to gain market share. Rather than build a system around a standardized chip, moreover, users began to demand chips that were designed for their specific systems and specifications. This required more design-in efforts by suppliers and a closer interaction between users and designers. In-depth knowledge about the features required by user firms and by system integrators became a key criterion for success in these new markets.

A second set of developments came from the technology side. The increased adoption of Complementary Metal Oxide Semiconductor (CMOS) production processes weakened the interdependence of product design and manufacturing. Because designers could work with relatively stable design rules, they were less bound by decisions concerning process technologies. The creation of standardized interfaces between components and Electronic Design Automation (EDA) tools also allowed a modular system to develop in which blocks of intellectual property ('design blocks') could be exchanged and licensed across products and companies (Ernst, 2005a). Finally, developments in CAD (Computer-Aided Design) software and in communications networks made it possible for companies to exchange huge amounts of data and design specifications (Macher and Mowery, 2004). As a result of these developments, the interdependence between product design and manufacturing was weakened in many product segments in semiconductors and specialist firms were able to enter the industry at both the design and the manufacturing stages. The so-called 'fabless' firms, and the silicon foundries they partnered with for production, began to compete with existing integrated device manufacturers (IDMs) by offering users customized designs and shorter production cycles. At the same time, user firms gained access to both the tools and knowledge bases necessary to be able to design customized chips around simple components to satisfy the rapidly changing and fragmented demands of their markets. Semiconductor chips were no longer forced to fit an industry standard, but could be made to comply with user requirements and user systems. The knowledge boundaries between users and suppliers were weakened and the barriers to access supplier knowledge were lowered.

Within this sectoral system, intermediate user firms differed along several dimensions. In terms of size, both large and small users existed according to the quantities of chips they required. A second dimension was linked to the degree of specialization in user firms. While some users were highly specialized within a particular product area (e.g. medical equipment or radio transmitters), others had more diversified product portfolios. Companies such as Samsung and Philips, for example, produced consumer goods ranging from televisions, to white goods, to mobile phones. Often, as in these two cases, such diversified firms were also vertically integrated into semiconductor production, offering a further distinction in terms of type of diversified user firm. Finally, user firms differed according to the demand market that they served: computers, automobile, telecommunications, the military, mass consumers, hospitals, etc. Because the characteristics of each of these end markets were so different, the implications of such distinctions were quite relevant within the semiconductor industry.

These developments provide a basis for understanding why semiconductors offer a rich and highly dynamic environment in which to study the importance of user knowledge in innovation over this period. Semiconductor devices became an increasingly strategic component in many user product categories. At the same time, users required more and more customization in chip design for their own systems and product lines. Yet the application specific knowledge required for designing customized semiconductor devices was often tacit and too complex for users to transfer it easily to their suppliers (Glimstedt et al., 2010). As von Hippel (1994) and Ogawa (1998) have argued, users are more likely to perform innovative activities if information about user needs is 'sticky' compared to technical information about solutions. It has also been argued that users are more likely than suppliers to innovate if their expectations of innovation related benefits are higher (Riggs and von Hippel, 1994). This was certainly the case in many areas of semiconductor devices where customized components provided strong competitive advantages to users with respect to rivals in their end markets. Furthermore, agency costs were raised by the fact that users wanted customized solutions while suppliers were seeking to develop general solutions that could be sold to a wide range of users in order to keep their development costs down and reach the economies of scale needed in such capital intensive production (Macher et al., 2007). Finally, users had gained access to the capabilities and technologies needed to design their own chips (Ernst, 2005a; Brown and Linden, 2009). User firms, therefore, had both the proper incentives and capabilities to innovate in semiconductors during the two decades under study.

3.2. Measuring the relevance of innovation by demand in semiconductors: The indicators

In order to assess the magnitude of innovation by demand within a sectoral systems perspective, we have collected and/or constructed databases that will allow us to compare and contrast the innovative activities of intermediate user firms with those of other actors in semiconductor technologies. We have identified four different types of activities, each of which provides a separate, yet complementary, indicator of the innovative capabilities of users and other actors within this sector: patents, co-patents, R&D alliances, and new venture start-ups.

3.2.1. Patents

3.2.1.1. Previous studies. A number of studies have been done on the semiconductor industry using patent data. Hall and Ziedonis (2001) used a combination of patent data, financial data on R&D and capital expenditures, and qualitative interviews with companies to analyze the reasons behind the increase in patenting by semiconductor firms following the strengthening of U.S. patent rights in the early-1980s. They found that the surge in patenting that followed this change was caused mainly by large-scale, integrated device manufacturers (IDMs) that were seeking to expand their patent portfolios in order to improve their leverage with other patent owners in the industry. Design firms also showed an increase in patenting activity, but for very different reasons: strong patent rights were needed in order to protect market niches and secure venture capital funding. Macher et al. (2007), on the other hand, used patent data to examine the globalization of the innovative activities of semiconductor firms. Combining data on investments in R&D, technology alliances, and patenting activity, this study showed that the relevance of offshore innovation-related activities by U.S. semiconductor firms up until 2003 was modest. They also found that semiconductor design activities up until this time were highly concentrated in the U.S., notwithstanding the growth of design capacity in other regions around the world. In a more recent analysis, Dibiaggio and Nasiriyar (2009) used patent data, weighted by the number of citations received by each patent, to conduct an analysis of the knowledge integration capabilities of semiconductor firms. They concluded that the ability of firms to exploit complementarities between knowledge elements was a major source of innovative performance, but that not all firms in the semiconductor industry had the same type of knowledge integration capabilities.

The research focus of each of these studies was on the patenting behavior of semiconductor firms. The authors therefore began by selecting a sample of firms whose major line of business was semiconductors and then analyzed the patent portfolios of these companies. Hall and Ziedonis (2001) identified a universe of 95 publicly traded U.S. companies whose main business, as defined by their SIC code (3674), was semiconductors and related devices. Their sample excluded non-U.S. semiconductor companies, systems manufacturers and companies in other lines of business including user firms and other organizations active in semiconductor technology research. Similarly, Macher et al. (2007) started with a defined set of 217 U.S. and non-U.S. semiconductor firms and then examined the patent portfolios of these companies across more than 80 technology classes related to semiconductors. The authors went further to distinguish between the trends for the IDM and systems firms and the fabless firms in their sample. Yet given their focus on the location, rather than the extent, of R&D activities of semiconductor firms, they did not analyze the relevance of patenting activity across different types of firms or include actors other than semiconductor firms in their sample. Finally, Dibiaggio and Nasiriyar (2009) analyzed patent data for 112 firms across 62 technology classes. These authors also identified different types of companies according to their level of vertical specialization (system integrators, fabless firms and diversified integrators). They then measured the innovative performance of the firms in their sample by the number of patents held by the firm, weighted by the number of citations received by each patent in the 5 years following the date of application. Yet because the objective of their study was to analyze the impact of knowledge integration on innovative performance, they did not provide any specific evidence of the magnitude of user innovation in semiconductors with respect to other actors in the sector.

3.2.1.2. Patent selections and classification used in this study. In order to be able to study the magnitude of innovation across different actors in the semiconductor industry, we adopted a different approach to the selection of patent data. Rather than starting with a population of firms in the industry, we began by identifying a single class of patents from within the broader set of semiconductor technologies. For our purposes we selected the International Patent Classification (IPC) class H01L (Semiconductor devices) for analysis. The patent data were drawn from the NBER patent data base (Hall et al., 2001) which contains information on United States Patent and Trademark Office (USPTO) data for the period 1984–2006. The patents were classified according to the year of application, rather than the date granted, in order to approximate better the date of actual invention. We also used 2003 as a cut-off year for the data; given that it takes an average of 3 years between the application and the granting of a patent in semiconductors (Popp et al., 2004), this cut-off avoided gaps in the data for the last 3 years for patents that may not have been granted at the time the dataset was created.[1]

The choice of technological class H01L was made for several reasons. The literature identifies approximately 62 technology classes in which semiconductor manufacturers tend to patent (Dibiaggio and Nasiriyar, 2009). These classes represent a wide range of intermediate products and processes related to semiconductors. Because our objective is to understand the specific magnitude of user firms' patents with respect to those of semiconductor firms

[1] Some declines in patent numbers in this technology class were noted in our data for the last years, 2002 and 2003. These declines, however, may not be due to a real decline in patent numbers, but rather to the fact that applications completed in these years had not yet been granted at the time the database was completed.

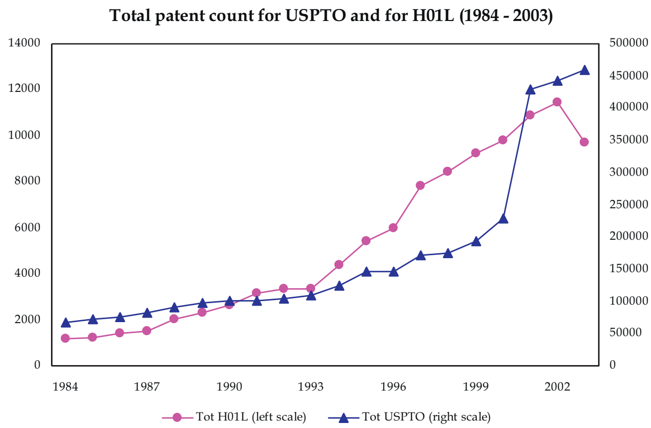

Fig. 1. Total USPTO patents and total H01L patents in our sample.

and other actors, we decided to focus on a technology product patent class in which both supplier and user firms would patent, rather than on patents for either intermediate products or steps in the manufacturing process that might favor one group or the other.[2] This is especially true because products are more likely to be patented than process innovations (as has been highlighted by empirical analyses since Levin et al., 1987 and Cohen et al., 2000). Examining patents for semiconductor devices makes the comparison between the innovative activity of user firms and semiconductor firms most direct and unbiased. With this selection, we obtained a sample of 105,318 patents from 1984 to 2003.

The research results of Hall and Ziedonis (2001) showed that the increasing propensity to patent within the semiconductor industry matched, and even exceeded, the broader industry trends in patenting that followed the legal changes to the system in the early 1980s. Fig. 1 tracks the number of patents in the technology class chosen here, H01L, against the total number of patents listed by the USPTO. The trend illustrated for our subset of data is consistent with the results reported by Hall and Ziedonis for the overall semiconductor industry, thus confirming the validity of this dataset for our purposes.

In this study, we examine user organizations and distinguish between different kinds of firms and organizations in a sectoral systems perspective. In this sense, we depart from Lettl et al. (2009) who, in a recent study using patent data in medical equipment technology, analyzed the magnitude of patents held by "independent inventors" or individual users compared to corporate companies.

Next, in accordance with the work currently being done within the NBER-PDP project (Bessen, 2009), we codified the names of the applicants listed in the patents, taking into account, in cases of firms, parent companies as well as subsidiaries and divisions. This process produced a total of 3644 organizations in our sample. Firms were then assigned to categories according to their main line of business using their SIC codes.[3] Five major categories were created for the study: Semiconductor Firms, User Firms, Academics and Professionals, Linked Industries and Other Industries (see Appendix A). 'Semiconductor firms' are companies whose main line of business is listed as semiconductors (SIC code 3674). This category includes both Integrated Device Manufacturers (IDMs) such as Intel, Infineon and STM, and 'fabless' firms focused on semiconductor design activities such as Nvidia, Cirrus, and Xilinx.

The 'User Firms' category consists of companies who sell products or services that 'use' or incorporate semiconductors. While they may design and even produce semiconductors for their own use, and may even sell these devices on the open market, this is not their principal line of business. For our purposes, a selection of user categories was made according to the main demand segments identified by the International Electronics Manufacturing Initiative (iNEMI) in its annual Road Maps over the course of the past two decades. Our 'User Firms' category therefore consists of companies whose main line of business falls within one of the following industry groups according to the company's main SIC code: Industrial Machinery, Consumer Electronics, Computer Equipment, Telecommunications, Automotive, Instrumentation and Aerospace/Defense (see Table A1 in Appendix A). It is important to note that diversified electronics firms such as IBM, Philips and Samsung, are categorized in this study as 'User Firms'. It should also be noted, however, that the patents of the semiconductor subsidiaries of these diversified electronics firms were separated out and placed in the previous category of 'Semiconductor Firms'. For example, the patents of Samsung Electronics (SIC code 3674) were counted in the 'Semiconductor Firms' category, whereas those of Samsung Ltd. (SIC code 3661) were classified under 'User Firms'. Our assumption here is that the knowledge base of the patenting product divisions of user firms that have independent semiconductor subsidiaries is more similar to that of other patenting user firms that do not have independent subsidiaries, than to that of their own semiconductor subsidiaries. This is due to the tacit nature and "stickiness" of application specific knowledge. Therefore the distinction between the semiconductor patents of the product divisions and those of the subsidiaries of a vertically integrated firm is important. Our methodological choice also mirrors the logic of the companies themselves that have made strategic decisions to patent certain semiconductor devices by their semiconductor subsidiaries and other devices by their main product divisions.

The 'Academics and Professionals' category consists of academic institutions and public and private research organizations, while the 'Linked Industry' group includes firms from industries that may either be suppliers of materials, parts or machinery to semiconductor producers, or that provide services to the industry. The

[2] In this context, the challenge was to identify the most suitable technological class(es) for our purpose. In this respect we decided that the most conservative 'test bed' for our hypotheses would be a semiconductor class closely related to semiconductor devices. As a direct one-to-one correspondence between technological classes and devices is difficult to establish, our major concern was to strike the right balance between semiconductor and user firms concerning the likelihood to patent in the selected class(es). On the one hand we did not want to risk to 'oversample on semiconductor firms' (i.e. to focus on technological classes in which users firms are clearly less likely to be involved than semiconductor manufacturers). For this reason we decided to exclude classes such as B01J, B23K, B24B, B41J, B41M, B65H, related to semiconductor materials or manufacturing processes (i.e. substrate and layer processing, packages and mountings, assembly, testing, and handling). On the other hand, we did not want to risk to 'oversample on users' and include in the sample technological classes closely related to the final product such as electrical devices (H01), audiovisuals (H03F,G,H), telecommunications (H04), optics (G02), information technology (G06), where semiconductor manufacturers are in principle less likely to directly patent. The selected class was H01L which includes a wide array of devices, not included in the other classes, such as: discrete components or specific parts of integrated circuits (i.e. LEDs, transducers, diodes, capacitors, bipolar transistors, thyristors, unipolar transistors); integrated circuits (i.e. CMOS, BICMOS, optoelectronic IC, wafer scale integration, analogue circuits, digital circuits, also with matrix arrays eg. memory, programmable logic and gate arrays); memories. All other things being equal, we would expect semiconductor firms, rather than users, to patent more in this class. If, instead, we find that users are able to patent in semiconductor devices, it means that they are indeed involved in innovation in semiconductor devices.

[3] Company SIC codes were drawn from the Hoover Business Directory, which is a standard, and widely accepted source for classifications in such research analyses and is available in most university library systems. Hoover assigns a SIC code according to their assessment of the main business of the company. We checked the Hoover code for each company separately (one by one), making sure to clarify if the listing was for the parent or a specific subsidiary in cases where more than one listing for a company was included in Hoover (i.e. the case of Samsung reported above).

'Other Industries' group is a residual category that includes all of the remaining organizations from the sample.

This way of classifying semiconductor patents is different from, yet complementary to, other large-scale studies that examine the quantitative dynamics of technical change within and across sectors and that distinguish between industries that produce patented innovations and industries that use them. Evenson and Johnson (1997) and Johnson (2002), for example, reclassify patents in a technology class in terms of sectors responsible for the manufacture of the invention and sectors of use. In this study, by contrast, we classify the firms that patent within a technological class as either firms in the industry, users, or other organizations active within a sectoral system. Normaler and Verspagen (2008) use patent citation data to analyze knowledge flows among sectors. They distinguish between technology-producing and technology-using sectors and then measure the pervasiveness of certain upstream technologies among using sectors. In this study, we measure the patenting behavior of user firms within a technology in order to gauge the contribution of downstream knowledge to innovation.

3.2.2. Co-patents

An additional dimension of innovation by users refers to the joint innovative activity either between users and firms in the semiconductor industry and other organizations, or among users themselves. One indicator of this joint activity is co-patenting. Co-patenting occurs when different firms or different units (i.e. divisions) within the same organization engage in joint research and patent together. Because co-patents represent an outcome of 'real interactions' among the partners, they involve joint investments, a commonality of interests, and face-to-face sharing of information. From this perspective, the evidence concerning knowledge flows gathered from data on co-patenting is qualitatively different from the evidence based on patent citations (Ejermo and Karlsson, 2006; Frietsch and Schmoch, 2006; Hagedoorn, 2003). For this dataset, we identified all co-patent agreements in the H01L technological class between 1984 and 2003. Our sample includes patents registered between different firms (inter-firm) and excludes co-patents between firms within the same group (intra-firm). The actors involved as authors of these co-patents were then identified and categorized according to the classification used above for patents (semiconductor firms, user firms, academics and professional organizations, linked industries, or other industries). It should be noted that the total number of co-patents registered in this technology class over this period is significantly smaller than the total number of patents: our sample contains a total of 5650 co-patents.[4] In relative terms the share of co-patents over total patents in this technological class increased from an average of 3.8% between 1984 and 1988 to 6.6% between 1989 and 1993 to stabilize around 5.6% between 1999 and 2003. These results are consistent with other recent studies of the relevance of co-patenting in high-technology sectors (Hagedoorn, 2003; Frietsch and Jung, 2009). Although these numbers are relatively small, this data still provides an additional and complementary view of the patterns of innovation in semiconductors.

3.2.3. Strategic alliances

Another indicator of the involvement of users in innovative activity in semiconductors is the number of R&D alliances in semiconductors in which users participated (Grant and Baden-Fuller, 2004). Macher et al. (2007) examined R&D alliances in their analysis of the semiconductor industry. Their analysis, however, was limited to the R&D alliances of semiconductor firms. By contrast, this study again begins by focusing on a patent class (semiconductor devices) and then examines the activities of all actors involved in R&D alliances, including both semiconductor and user firms.

Our data is drawn from the Thomson Financial Database on joint ventures and strategic alliances. This database contains data on international alliances for the period 1985–2002. Although this time range is somewhat shorter than the one used for our patent data, it still represents a relevant base from which to observe trends in semiconductors during the period under study. Thomson has classified the alliances in the database by both sector and type (marketing, commercial, distribution, R&D, etc.), according to the stated purpose and contents of the agreement. For our purposes we have selected only those cases that were classified as R&D alliances in semiconductors. This selection produced a total of 2062 R&D alliances for the period 1985–2002. We then identified the partners involved in each agreement and classified them according to the same methodology used above for patents and co-patents. The data do not contain information about the revenues or investments involved in the alliances and therefore, we do not have an indication of their relevance. Yet the raw numbers do give us an indication of the extent of user involvement in innovative activities through alliances with other actors within the sector.

3.2.4. Entrepreneurial new ventures

The last indicator regards entrepreneurial start-ups in semiconductors. While not all start-ups are innovative, most new ventures in such a technologically dynamic industry represent an entrepreneurial activity that transforms innovative ideas into products through the opening of a design house or a production facility. Broadly speaking, these new ventures in semiconductors can also be associated to innovative activity by demand in a truly Schumpeterian fashion. Therefore, we analyze the background of the founders of start-ups in semiconductors to assess how many were founded by former employees of intermediate user firms. We also assess the innovativeness of these new ventures and their survival rates.

The dataset was constructed by the authors from information collected from published sources regarding start-up firms in the semiconductor industry between 1997 and 2007.[5] Again, this time frame is slightly different from that used for patents and alliances. Yet there is sufficient overlap to allow us to observe trends within the same historic period. Detailed information was collected for 1010 start-ups including the year of entry into semiconductors, the type of activities conducted by the firms, the background of the founders, and the eventual year of exit from the industry. This database was then integrated with the database on patents: a subset of firms with at least one patent over the 10 year period was identified. This subset contains a total of 407 companies and was defined as our sample of 'innovative' start-ups. Using the information collected on the founders, the start-ups were finally classified as either spin-offs (companies founded by people that had previously worked in another semiconductor company or that had strong backgrounds in semiconductor software and/or semiconductor design and production), other start-ups (start-ups founded by people previously active in university research, banking, finance or business consulting), and 'user' start-ups (companies with founders coming from industries that sell products which

[4] This is the total after excluding missing values and agreements involving individual inventors.

[5] The main source of information for constructing this dataset was the magazine Semiconductor Times published by Pinestream Communication (a consulting company). Each month the magazine reports information on new start-ups active in the semiconductor industry. This information was further integrated with specific details on the companies' founders and their backgrounds collected from other sources (see Fontana and Malerba (2010) for further details on the construction of the sample).

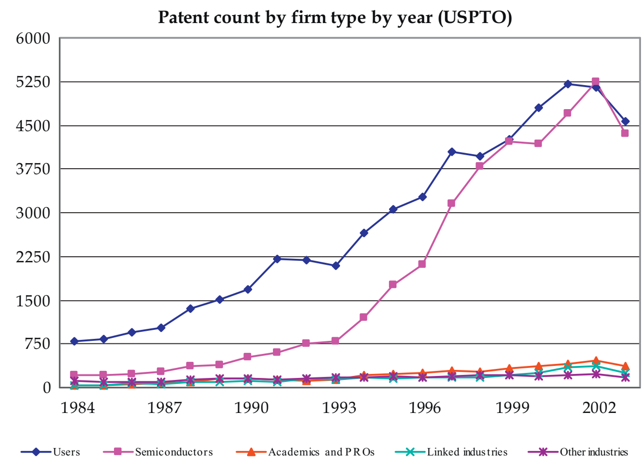

Fig. 2. Total H01L patent count by firm type by year (1984–2003).

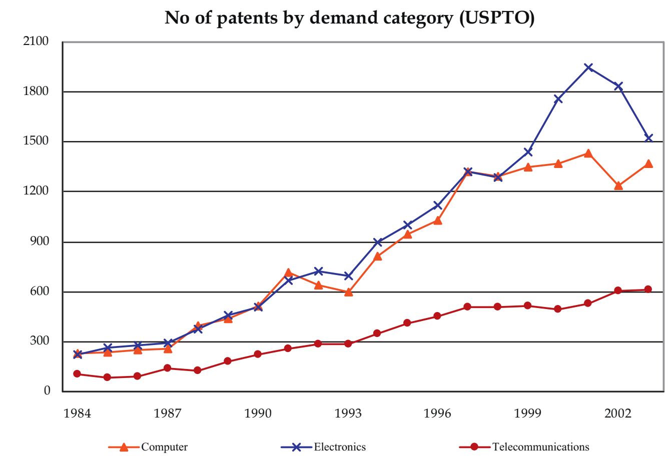

Fig. 3. Total H01L patents by user industry category. Computer, electronics, and telecommunications.

incorporate or use semiconductors, such as computers, consumer electronics, telecommunications, and automotive).

4. Findings

4.1. Patents

The first significant finding of our research is that not only have user firms been active in patenting in semiconductor technology, they have actually dominated patenting in semiconductor devices for most of the time period considered. Fig. 2 illustrates the trends in patenting by firm type over the 20 year period.

The plotted lines for 'Users' and 'Semiconductors' show a growth rate that is consistent with the increase in patenting activity registered in this industry in the late 1980s (Hall and Ziedonis, 2001). What is noteworthy is that the number of user firms' patents exceeded those of any other category, including 'Semiconductor firms', for the entire period up until the late 1990s. User firms, therefore, not only had contextual strategic knowledge about semiconductors and applications, but were using this knowledge to design and patent innovative devices. By contrast, academic and professional organizations, as well as firms in 'Linked' or 'Other industries', demonstrated consistently low levels of patenting activity over the period in this technological category.

These findings appear even more evident in Table 1 which presents the total number of patenting firms and the total number of patents in both absolute and percentage terms for each category of firm type over the 20 year period.

User firms alone accounted for between 60.2% and 69.2% of all H01L patents between 1984 and 1994, and for more than 50% up until 1997. This means that companies whose main line of business was not semiconductors registered the majority of patents for semiconductor devices during this period. Semiconductor firms, on the other hand, accounted for less than 20% of all patents in semiconductor devices up until 1991 when their share began to grow steadily to reach 45.7% in 1999. Table 1 also confirms the relatively low rate of patenting activity for firms in the 'Academic/Professional Organizations' and 'Linked Industries' categories. In each of these categories the trend has been a general decline in patenting activity over the years from a high point of between 4% and 7% to a low point of 2.6% for Linked firms and 3.6% for Academics and Professionals. The 'Other Industries' category also showed modest levels of patenting activity across the two decades, accounting for only 3% of total patents.

Table 1 also shows that the dynamics of patenting in semiconductors changed sharply in the mid-1990s. Although the percentage of user firms' patents fell between 1994 and 2004, both the number of user firms patenting and the number of patents granted to user firms rose steadily over this period. At the same time, semiconductor firms registered higher levels of growth in patenting. The number of semiconductor firms with patents more than doubled from 121 to 302, while the number of patents granted to semiconductor firms increased by 263%, from 1202 patents in 1994 to 4358 patents in 2003. The alignment reached by 2000 onwards that put user firms and semiconductor firms both close to the 45% level, therefore, was due more to an increase in the propensity of semiconductor firms to patent than a decrease in the propensity of user firms to patent. Such observations are consistent with the findings of Hall and Ziedonis (2001), summarized above in Section 3, that both new design firms entering the market and established large-scale manufacturers began 'ramping up' their patent portfolios in the mid-1990s.

The second finding of our study is that the general increase in patenting activity was not evenly distributed across the different intermediate user industries. Figs. 3 and 4 present the number of patents per year for user firms, broken down by user categories. It is evident from these figures that patenting behavior across these different groups varied significantly. User firms from the 'Computer' and 'Consumer Electronics' groups showed both higher levels of, and a steady increase in patenting activity over the 20-year period compared to firms in the other 'user' groups: from a low of just

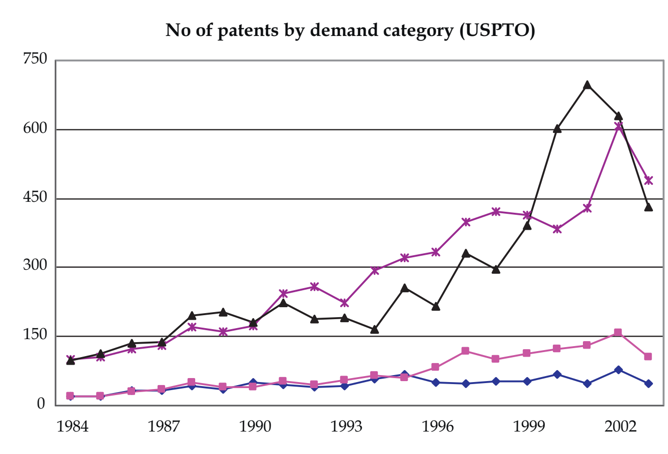

Fig. 4. Total H01L patents by user industry category. Defense, automotive, instrumentation, and industrial machinery.

Table 1
Share of total H01L patents by firm type by year.

Year	Semiconductor firms			User firms			Linked firms			Academic and PROs			Other	TOT
	%Patents	#Firms	#Patents	%Patents	#Firms	#Patents	%Patents	#Firms	#Patents	%Patents	#Firms	#Patents	#Patents	%Patents
1984	17.64%	37	211	66.39%	125	794	2.76%	18	33	3.85%	24	46	112	
1985	17.20%	43	214	67.28%	127	837	3.30%	25	41	3.70%	26	46	106	
1986	16.98%	56	238	67.12%	149	941	5.06%	38	71	3.92%	34	55	97	
1987	18.10%	45	277	66.86%	148	1023	3.46%	28	53	5.03%	37	77	100	
1988	17.56%	75	359	66.59%	173	1361	4.40%	50	90	5.09%	56	104	130	
1989	17.08%	65	395	65.50%	170	1515	4.28%	52	99	6.57%	65	152	152	
1990	19.72%	87	516	64.35%	180	1684	4.74%	54	124	5.58%	62	146	147	
1991	18.72%	82	595	69.23%	192	2200	3.34%	49	106	4.31%	63	137	140	
1992	22.36%	100	751	64.87%	186	2179	4.47%	58	150	3.63%	57	122	157	
1993	23.71%	98	792	62.63%	186	2092	4.22%	51	141	4.10%	60	137	178	
1994	27.41%	121	1202	60.25%	205	2642	3.79%	57	166	4.65%	67	204	171	
1995	32.69%	143	1770	56.53%	227	3061	3.01%	53	163	4.30%	81	233	188	
1996	35.12%	161	2102	54.80%	237	3280	2.94%	59	176	4.24%	71	254	173	
1997	40.20%	188	3146	51.60%	296	4038	2.11%	62	165	3.64%	77	285	191	
1998	45.12%	205	3798	47.05%	300	3960	2.17%	64	183	3.21%	85	270	206	
1999	45.73%	237	4217	46.26%	315	4266	2.27%	74	209	3.47%	102	320	210	
2000	42.71%	252	4183	48.97%	354	4797	2.50%	82	245	3.79%	110	371	199	
2001	43.26%	300	4704	47.90%	438	5208	3.13%	98	340	3.77%	133	410	211	
2002	45.89%	316	5254	44.99%	450	5150	3.16%	98	362	4.01%	134	459	223	
2003	44.79%	302	4358	47.03%	379	4576	2.59%	73	252	3.83%	119	373	171	
TOT	37.48%			52.54%			2.98%			3.97%			3.03%	100.00%

Table 2
Concentration ratio of top patentees by firm category (1984–2003).

USPTO patents	C1	C4	C10	C20	Total patents	Total firms
All semiconductor firms	16%	40%	62%	75%	41657	920
All user firms	8%	26%	49%	67%	58393	1759
Automotive	20%	55%	83%	96%	1514	65
Aerospace and defense	31%	61%	86%	93%	944	58
Industrial machinery	40%	75%	83%	87%	5939	382
Computer equipment	26%	81%	95%	98%	17318	148
Consumer electronics	16%	43%	69%	82%	19458	758
Instrumentation	25%	59%	79%	86%	6067	265
Telecommunications	41%	86%	96%	98%	7153	83

under 300 patents per year in 1984, they grew to a high of just under 2000 (Electronics) and just over 1400 (Computers) patents in 2000. These two user groups, in fact, were the real drivers of the increase in 'User firms' patents over the period. The next three intermediate user industry groups, 'Instrumentation', 'Industrial machinery', and 'Telecommunications', also showed steady increases, but at lower growth rates than the first two groups. Firms from the 'Defense' and 'Automotive' industries, on the other hand, registered consistently low levels of patenting activity, although 'Automotive' did show a slight jump in growth in the second-half of the 1990s. Therefore, although user firms, on aggregate, patented more than the other broad categories, patenting behavior across user groups was not homogeneous.

The third finding is that a large part of the innovative activity by users in semiconductors was concentrated in the hands of large diversified firms, and that the concentration of innovation was high. Table 2 lists the number of patents in each industry that belonged to the top firm (C1), as well as to the top 4 firms (C4), top 10 firms (C10) and top 20 firms (C20) in each category. For purposes of comparison, we have also listed the concentration levels for the broader categories of 'Semiconductor Producers' and 'Users,' as well as the number of patents registered in each demand category. Two groups in particular, 'Computers' and 'Telecommunications', had the highest levels of concentration: the top 4 companies accounted for 81% of patents in computers and 86% of patents in telecommunications, while the top 20 companies accounted for 98% of all patents in both categories. Consumer electronics, on the other hand, appears to have been more fragmented with the top 4 companies accounting for only 43% of all patents and the top 20 for 82%.

A closer look at the list of firms in the data reveals that the majority of user firms' patents were held by diversified systems firms. The top 10 'User Firms' – IBM, Toshiba, NEC, Mitsubishi, Samsung, Hitachi, Motorola, Matsushita, Sharp and Canon – were all large systems producers that were, or had been at some point during this period, vertically integrated into semiconductors. These 10 companies alone detained 47% of the patents in the users' category. Yet, while large systems firms dominated the list in terms of number of patents per firm, they were not the only users to patent. Many other smaller user firms (not directly integrated into semiconductor production, or with limited capabilities in semiconductor production), also patented in semiconductors, albeit at much lower levels. This is evident in the data in Table 2. The top 20 companies in Consumer electronics, for example, detained 82% of total patents, or 15,955 patents. That means, however, that another 738 consumer electronics firms, including many non-vertically integrated producers, accounted for the remaining 3503 patents in this category.[6] As is the case in most industries, the distribution of patents is skewed with large companies holding substantial patent portfolios, and smaller companies holding only a few, or even a single patent. But these numbers clearly demonstrate that users firms with semiconductor divisions or subsidiaries were not the only user firms to patent in semiconductor technology during this period.

[6] Similar calculations can be made for the other categories: if we consider firms outside of the top 20, 245 firms in Instrumentation accounted for 849 patents, 362 firms in Industrial Machinery had 772 patents, 128 firms in Computer Equipment had 346 patents, 63 firms in Telecommunications had 143 patents, 45 firms in Automotive had 60 patents, and 38 firms in Aerospace and Defense had 66 patents.

Table 3
Total H01L co-patents between user firms and the other categories by sub-periods.

Year	User firms		Semiconductor firms		Linked firms		Academic and PROs		Other
	%Co-patents	#Co-patents	%Co-patents	#Co-patents	%Co-patents	#Co-patents	%Co-patents	#Co-patents	#Co-patents
1984–1988	40.26%	157	16.15%	63	22.05%	86	8.97%	35	49
1989–1993	48.33%	595	14.87%	183	16.82%	207	10.89%	134	112
1994–1998	48.98%	789	25.45%	410	9.50%	153	8.13%	131	128
1999–2003	42.62%	1158	36.36%	988	9.05%	246	7.47%	203	122

In each year, the % is the share of the co-patents over the total co-patents involving at least a user firm.

Table 4
Total H01L co-patents between semiconductor firms and the other categories by sub-periods.

Year	User firms		Semiconductor firms		Linked firms		Academic and PROs		Other
	%Co-patents	#Co-patents	%Co-patents	#Co-patents	%Co-patents	#Co-patents	%Co-patents	#Co-patents	#Co-patents
1984–1988	73.26%	63	1.16%	1	8.14%	7	1.16%	1	14
1989–1993	52.44%	183	5.16%	18	15.47%	54	7.16%	25	69
1994–1998	61.10%	410	11.77%	79	11.18%	75	10.73%	72	35
1999–2003	64.70%	988	15.59%	238	8.32%	127	8.38%	128	46

In each year, the % is the share of the co-patents over the total co-patents involving at least a semiconductor firm.

Actually, one may claim that our classification of user firms has been quite "conservative" and may have underestimated the extent of user firm patenting in semiconductor technology. In fact, as mentioned above, in cases where user firms had an independent semiconductor subsidiary, the patents of this subsidiary were separated out and assigned to the 'Semiconductor firms' category. As a result, the contribution of user knowledge to patenting in semiconductors may have been underestimated because, undoubtedly, the semiconductor subsidiaries of these companies also had "application knowledge advantages" over "pure" semiconductor players in the market stemming from their internal access to knowledge generated in the downstream product divisions of their companies.

In sum, patent data indicates clearly that users were a strong source of patents in semiconductors throughout the two decades under examination. Not only were they able to give ideas and feedback to suppliers, but they were also able to design and patent innovative solutions in a product field (semiconductor devices) outside of their 'core' business. The magnitude of their patenting activity far exceeded that of the other actors in the industry whose core business was not semiconductors: Academics and Professionals, Linked Industries and Other Industries.

4.2. Co-patents and alliances

The previous findings that showed that user firms are directly involved in patenting in semiconductors are confirmed by our data on co-patents. Table 3 lists the total number of co-patents involving at least one user firm, subdivided by the category of the other partner involved in the co-patent. Therefore, co-patents between a user firm and another user firm are included in the column 'User Firms', while co-patents involving a user firm and a semiconductor firm are listed under the column 'Semiconductor Firms' in Table 3. Table 4 repeats the same exercise for all co-patents involving at least one semiconductor firm.[7]

It is clear from these tables that a steady growth in co-patenting occurred in this technology over the two decades under examination, although the total number of co-patents was still relatively small compared to the number of patents registered over the same period. This growth was most marked in the last 5 years between 1998 and 2003. It is also noticeable that the largest share of co-patents came from the user category: at least one user firm was involved in a total of 4714 co-patents. This compares with semiconductor firms that were involved in only 2417 co-patents in semiconductor devices. Moreover, the growth in co-patenting was driven by co-patents between user firms (1627 co-patents) and between user firms and semiconductor firms (1480 co-patents). It is also interesting to note that, in the last 5 years in particular, user co-patents were split rather evenly between other user firms and semiconductor firms (36.29% and 39.28% respectively), while more than two-thirds of semiconductor co-patents (66.04%) were done with user firms. The trend toward vertical specialization in the industry during this period, therefore, seems to have favored greater levels of cooperation between semiconductor firms and user firms in device technology.

Another indication of the magnitude of innovation by demand in semiconductors comes from our data on R&D alliances. Figs. 5 and 6 provide three types of information concerning alliances. The two histograms in Fig. 5 report the trend in the total number of alliances and, more specifically, alliances involving at least one 'user firm'. Both trends are consistent with overall patterns in alliances as reported by Hagedoorn (1993) and in alliances in semiconductors as reported by Macher et al. (2007). The solid line over the graph, which should be read from the right hand scale, traces this trend in percentage terms: the share of alliances involving at least one user firm hovered between a low of 40% to a peak of almost 70% in the mid-1990s. Again, the prevalence of user participation in joint research is noteworthy.

Fig. 6, on the other hand, takes the subset of alliances involving at least one semiconductor firm and looks at how many of these involved user firms or other actors as partners. It is clear from this figure that, except for the very early years in the sample, semiconductor firms formed more R&D alliances with user firms than with any other type of organization, including other semiconductor firms. This evidence supports the idea of a high involvement, both in absolute and in relative terms, of 'user firms' in knowledge exchange as represented by participation in R&D related alliances in semiconductors. Recent studies on high technologies have underlined the importance of strategic alliances as a way for partners to learn 'from and about' each other (Yasuda, 2005; Vanhaverbeke et al., 2002). We take these findings as further, albeit indirect, evidence that semiconductor firms viewed formal alliances as a means to access the tacit and 'sticky' nature of application specific knowledge in user firms in order to design increasingly customized devices (Glimstedt et al., 2010).

[7] The data in both Tables 3 and 4 excludes intra-firm co-patents (patents by firms belonging to the same group).

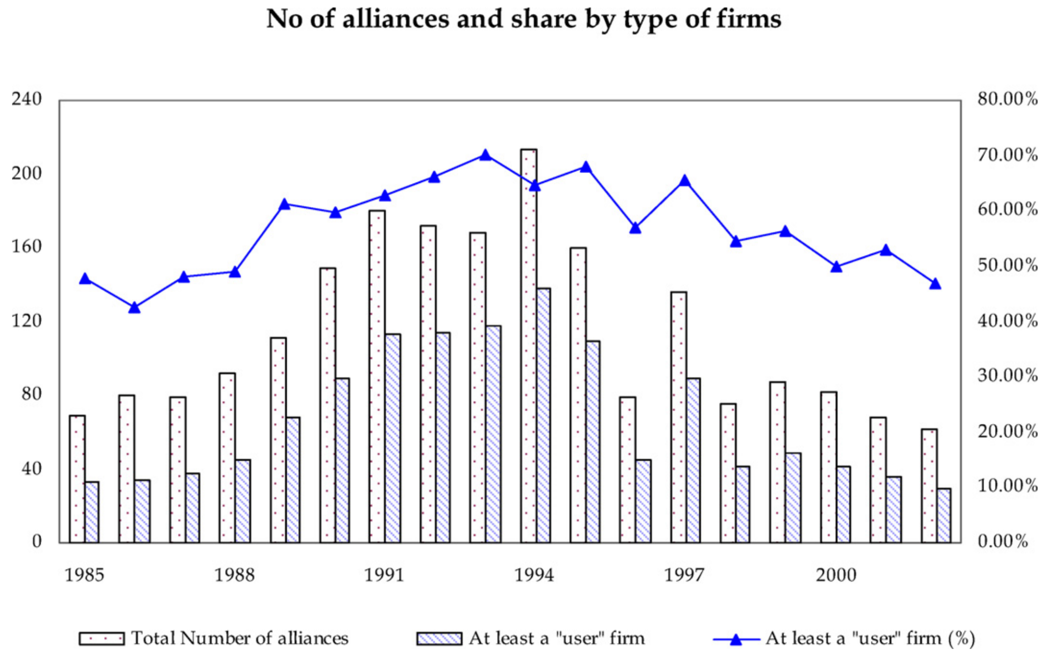

Fig. 5. Number of alliances and share of user firms (1985–2002).

4.3. Entrepreneurship 'by users'

Our last indicator regards the number and behaviour of start-up companies in the semiconductor industry over the past decade (1997–2007). Table 5 lists the total number of entries by company type. The subset of 'innovative' start-ups for each category refers to entrants that had at least one patent. The largest number of start-ups were spin-offs from semiconductor firms (412), while user start-ups totalled 346 new ventures and other start-ups accounted for 252 new ventures. The trend for user industry start-ups mirrored the trends in the other two categories, with a significant growth of entrants between 1998 and 2003 and a subsequent drop in the number of new firms in the following years. Entrepreneurship by user industries, therefore, was clearly an important phenomenon in semiconductors.

Application-specific knowledge seems to have provided user firms with a rich source of entrepreneurship: 34% of start-ups over this decade were founded by people with a background in user firms. User-based ventures also showed the highest likelihood of having at least one patent: 44% of user start-ups had at least one patent, compared with 42% of other start-ups and 36% of spin-offs. Not only were employees from user industries able to profit from their knowledge in specific application areas to start new ventures, they were also at least as likely as the others to base their ventures on patented innovations.

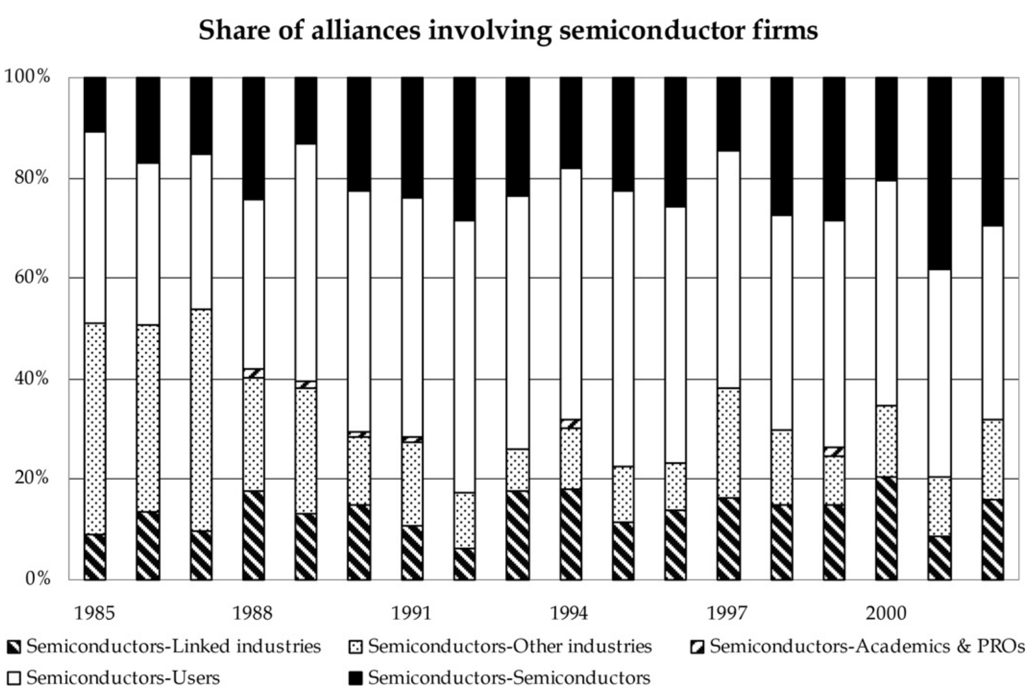

Fig. 6. Share of alliances involving at least a semiconductor firm.

Table 5
Entry of start-ups by type of entry (1997–2007).

	Spin-offs		User industry start-ups		Other start-ups	
	Total	Innovative[a]	Total	Innovative[a]	Total	Innovative[a]
1997	38	19	33	20	32	15
1998	39	14	35	16	26	11
1999	53	20	40	11	35	10
2000	59	21	53	23	46	20
2001	49	13	40	15	35	15
2002	43	16	44	23	20	8
2003	52	18	33	15	19	13
2004	45	12	30	10	17	7
2005	21	9	25	12	10	3
2006	10	5	13	7	9	3
2007	3	2	0	0	3	1
Total	412	149	346	152	252	106

[a] With at least one patent.

Table 6
Start-up background and survival.

	Survived	Dead	Total	% Survived
Spin-off	113	36	149	76%
User industry start-ups	129	23	152	85%
Other start-ups	73	33	106	69%
Total	315	92	407	77%

Chi-square statistics = 9.4643. The null hypothesis of independence between firm background and survival can be rejected at 1% significance level.

Finally, user start-ups performed better than spin-offs and other start-ups in terms of survival. Table 6 shows that 85% of user start-ups had survived at the end of the decade, compared to only 69% of other start-ups and 76% of spin-offs.

5. Conclusions and implications

By taking a sectoral system perspective in which innovation is related to the various actors active in a broad technology such as semiconductors, this study has examined a simple and important, but as yet unexplored, issue: the magnitude of innovation by users in a high technology sector. Several results emerge from this analysis. First, the magnitude of innovation by user firms, as measured by patents, was quite high in both absolute and relative terms compared to firms in the industry over the entire period under examination. This finding is quite novel and somewhat surprising. While it has long been pointed out that demand plays an important role in innovation, that users have made important process innovations in semiconductors, and that 'lead users' develop innovations on their own, these results demonstrate that a broad range of intermediate users were a major source of patents in a product field (semiconductor devices) outside of their 'core' business. Second, the distribution of innovation among firms from different intermediate user industries was highly uneven; this finding points to differences across final demand groups in terms of the requirements, the intensity of use, and the strategic content of semiconductors. It may also be the result of differences in the propensity to patent across demand categories. While the explanation of such findings is beyond the scope of this study, they point to interesting issues for future research. Third, innovative users were highly heterogeneous in terms of size, diversification and vertical integration. Large user firms, most of which were vertically integrated, had substantial patent portfolios. Yet there is also evidence of a vast number of smaller user firms that were able to patent in this technology, albeit at lower rates. The finding is striking because, by classifying companies whose main line of business is not semiconductors but who produce chips as vertically integrated user firms rather than as diversified semiconductor producers as in most studies, and by grouping them together with smaller, non-vertically integrated user firms, we were able to fully acknowledge the relevance of users' contextual knowledge about final applications for innovation in semiconductor devices. Fourth, collaboration in R&D and co-patenting activity in semiconductors took place not just between users and semiconductor firms, but also among users themselves. While such activities are less a direct indicator of innovation, they show that user firms contribute in different ways to the generation of new knowledge in semiconductors, to the introduction of new technologies, and to the launch of new products and designs. The magnitude of co-patenting and alliances involving user firms also shows that such firms represented a major source of complementary knowledge about devices for both other user firms and semiconductor firms. Finally, employees from user firms were quite active in entrepreneurial activities that involved patents in semiconductors. Their ventures, on average, also survived longer than spin-offs from incumbent firms in the industry. This finding indicates the relevance of application and market knowledge for entry and survival.

Our findings are relevant in a number of ways. While the role of intermediate users in innovation has been examined through case studies and surveys, this study contributes to the literature by introducing an approach that allows researchers to use quantitative indicators of innovation by user firms with respect to the other actors within a sectoral system. The methodology applied in this study is based on a novel approach that has two basic characteristics. The first is the use of the technology class as a point of departure. By starting with a technology class rather than a predefined list of firms in the industry, we were able to identify all of the actors that were actively patenting in that technology and then to examine the characteristics of these actors. This is a fundamental difference from previous approaches and, as detailed above, has permitted us to show the relevance of intermediate user firms within a specific sectoral system. The second characteristic of our approach is the use of multiple indicators of innovative activity: patents, co-patents, R&D alliances and new firm formation. The combination of these different indicators is important in order to shed light on complementary aspects of the role demand in the innovation process: invention and patenting, cooperation in research, and the launching of new entrepreneurial ventures. The use of databases for each of these indicators also begins to map an alternative to a reliance on survey data to quantify different types of innovative activities across actors and over time.

This methodology is applicable in other sectoral systems in which patents are a good (albeit not perfect) indicator of innovation. In sectors such as pharmaceuticals and ICT, in fact, it would provide a good basis for a quantitative assessment of the magnitude of innovation by users compared to other actors and other firms in these industries. The limit of this methodology, however, is that it is impossible to apply it in sectoral systems where patenting is not a major indicator of invention and innovation, or where patents are not used extensively. It would therefore be difficult to make comparisons across sectors in which the intensity and dynamics of patenting differ extensively. A final limitation of this study is that it does not give any indication of the importance or value of the activities measured. While it is true that demand-based firms have a greater number of patents and alliances, are they of larger or smaller value than those belonging to firms in the industry? A next step in the research will be to develop indicators that include value as well as number for each type of activity.

This study has also added to our knowledge of the semiconductor industry. Most studies of the industry have focused on the effects of the emergence of new markets for semiconductors in the 1980s and increasing vertical specialization within the industry on the innovative activities of semiconductor firms (Macher et al., 2007; Brown and Linden, 2009; Ernst, 2005a). Our study highlights the importance of looking at the influence of these factors not only on the supply side, but also on the demand side. Developments in technology and the growing need for closer interactions between component designers and the heterogeneous product markets in which they were active allowed user firms to play a significant role in innovation in semiconductor technology during this period. By starting from a definition of the technology to be examined, rather than a definition of the firms in the industry, the study was able to uncover this important finding.

Our findings have important implications for both management and public policy. For management, the implication is the importance of taking into full consideration both the characteristics and the boundaries of knowledge within an industry when thinking about innovation. In our case, the increased codification of formerly tacit knowledge within the value chain, the development of technical standards that promoted stability and exchange across interfaces, and a growing importance of "sticky" application-specific knowledge in product design paved the way for a major role for demand in innovation in the semiconductor industry. Thus changes in the characteristics and boundaries of knowledge may shift the locus of innovation and push firms to rethink their innovation strategies and innovative alliances (von Hippel, 1998).

For public policy, the implications relate to the issue of demand-led innovation that has gained considerable attention in policy circles such as the OECD and the European Commission. The policy discussion has so far been focused on either the role of public agencies in mission-oriented technology policies and their spillovers to the economy, or diffusion-cum-innovation policies in which the goal has been to stimulate demand for innovative products. Policymakers have adopted tools ranging from public procurement, to regulation, to standardization and lead-market initiatives with the objective of stimulating the "demand for innovation". This paper indicates a different approach to the issue. Our results show that in order to stimulate innovation and technological change in an economy or an industry, public policy should focus not only on the demand for innovation, but also on "innovation by demand". To this end, mechanisms will be needed to valorize the application and technological knowledge that user firms possess and to stimulate them to introduce innovations and new technologies. The shift in perspective from supporting demand for innovation to supporting innovation by demand could be significant, and may add an important policy input for the growth and dynamics of an economy.

Further research along the lines highlighted in this study may involve two areas. In semiconductors, it would be interesting to examine the trends in user patents across a broader spectrum of technologies (in addition to H01L) and a longer time frame. It would also be interesting to investigate the reasons for the heterogeneous patenting behavior in different user groups. Finally, a comparative analysis of two or more sectoral systems would allow researchers to understand and develop hypotheses about differences in the relevance of user firm knowledge when technological or sectoral contexts differ.

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Appendix A.

See Table A1.

Table A1
Industries included in five macro categories identified on the basis of their main organization SIC code.

Semiconductors	Semiconductors and related devices	3674
User industries	Industrial and commercial machinery (also including electric, gas and sanitary services)	3511, 3519, 3523, 3531, 3537, 3541, 3542, 3544, 3545, 3555, 3559, 3562, 3563, 3567, 3568, 3569, 3585, 3586, 3599, 4911, 4931, 4953
	Computer equipment	3571, 3572, 3575, 3577, 3578, 3578, 3579
	Electronic and other electrical equipment and components	3612, 3613, 3621, 3625, 3629, 3632, 3634, 3635, 3641, 3643, 3645, 3646, 3647, 3651, 3652, 3671, 3672, 3675, 3676, 3677, 3678, 3679, 3691, 3694, 3695, 3699
	Telecommunication (also including communication services)	3661, 3663, 3669, 4812, 4813, 4822, 4833, 4841, 4899
	Automotive (also including transportation equipment)	3711, 3714, 3721, 3724, 3732, 3743, 3799
	Instrumentation (also including medical instruments)	3812, 3821, 3822,3823, 3825, 3826, 3827, 3829, 3861, 3873, 3841, 3842, 3845, 3851
	Aerospace-defense	9661, 3761, 3764, 3769, 3483, 3489
Academic and research organizations	Colleges, universities and professional schools	8221
	Research, development, and testing services	8731, 8732, 8733
	Administration of general economic programs	9611

Table A1 (*Continued*)

Semiconductors	Semiconductors and related devices	3674
Linked industries	Mining	1011, 1021, 1041, 1094, 1311, 1389
	Lithographic, gravure	2752, 2754
	Chemicals and allied products	2812, 2813,2819, 2821, 2824, 2833, 2834, 2869, 2879, 2899
	Rubber and miscellaneous plastic product	3011, 3053, 3081, 3083, 3086, 3089
	Primary metal industries	3312, 3313, 3315, 3316, 3317, 3325, 3331, 3339, 3351, 3356, 3357, 3366, 3399
	Depositary institutions	6029
	Non depositary credit institutions	6141, 6153, 6162
	Security and commodity brokers, dealers, exchanges and services	6211, 6282
	Insurance carriers	6311, 6331
	Insurance agents, brokers and services	6411
	Software	7371, 7372, 7373, 7374, 7375, 7377, 7379
	Health services	8011, 8052, 8071, 8099
	Engineering services	8711
Other industries	Fruits and tree nuts	179
	Construction	1521, 1541, 1623, 1629, 1799
	Wine manufacturing	2084
	Textile mill products	2253, 2282
	Office furniture	2521, 2522, 2599
	Paper and allied products	2621, 2657, 2671
	Printing, publishing and allied industries	2721, 2731, 2741
	Petroleum refining and related industries	2911
	Stone, clay, glass, and concrete products	3211, 3229, 3231, 3241, 3253, 3255, 3271, 3292
	Fabricated metal products, except machinery and transportation equipment	3423, 3433, 3443, 3444, 3448, 3462, 3463, 3469, 3471, 3491, 3493, 3499
	Miscellaneous manufacturing industries	3944, 3999
	Railroad transportation	4011
	Local and suburban transit and interurban highway passenger transportation	4142
	Motor freight transportation and warehousing	4215
	Water transportation	4412
	Transportation by air	4581
	Transportation services	4724, 4731
	Wholesale trade	5012, 5013, 5032, 5044, 5045, 5047, 5049, 5051, 5063, 5064, 5065, 5072, 5084, 5099, 5153, 5169, 5171, 5182, 5191, 5198
	Retail trade	5311, 5411, 5511, 5571, 5722, 5734, 5999
	Real estate	6552
	Holding and other investment offices	6722, 6726, 6794, 6799
	Miscellaneous personal services	7299
	Business services	7311, 7312, 7359, 7363, 7389
	Automotive repair, services, and parking	7549
	Motion picture	7822, 7829
	Amusement and recreation services	7997
	Management and public relations services	8741, 8742, 8748
	Non classificable	9999

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