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Knowledge patterns and sources of leadership: mapping the semiconductor miniaturization trajectory

Marianna Epicoco¹

Abstract

This article examines the technological capabilities that national organizations generated and accumulated throughout the long-term evolution of the miniaturization trajectory, the main direction of technological change in the semiconductor industry. Having built an original dataset of patents granted between 1976 and 2008, and using three algorithms for the analysis of citation networks, we first map the pattern of technological knowledge underlying the advancement of the miniaturization trajectory. We identify three different dimensions of that pattern and characterize them in terms of distinctive knowledge properties. Second, we analyse the geographical and organizational distribution of the knowledge pattern. The results provide evidence of significant differences in the technological capabilities of national organizations, as revealed by the magnitude and properties of the technological knowledge that those organizations generated over time. We find, *inter alia*, that while US organizations remained strong throughout the whole time period, the capabilities of European organizations were considerably eroded in the most recent years by the emergence of latecomer Asian countries like South Korea and Taiwan.

Keywords: Knowledge dynamics; Technological capabilities; Semiconductor miniaturization trajectory; Patent analysis; Citation network analysis.

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1. Introduction

Over the last six decades, the worldwide evolution of industrial leadership has been powerfully influenced by the growth of the semiconductor industry, due to the pervasive and general-purpose nature of its technologies. During the first three decades of the industry, from the 1950s to the 1970s, US firms were the uncontested leaders: they introduced the three basic innovations of the industry – the transistor, the integrated circuit and the microprocessor – and dominated the international market of semiconductors (Tilton, 1971; Braun and MacDonald, 1982; Dosi, 1984). In the 1980s, Japanese firms began to challenge that dominance (Florida and Kenney, 1990; Callon, 1995), raising concern among US policymakers and scholars. In the 1990s, the US resurgence (Macher et al., 1998; Langlois and Steinmueller, 2000) and the rise of latecomer Asian countries like South Korea and Taiwan (Chen and Swell, 1996; Mathews, 1997; Kim, 1998; Cho et al., 1998) quickly changed the scenario of the previous decade. European firms remained competitive in the semiconductor market until the early 1960s (Malerba, 1985) but, since then, have played a relatively peripheral role in the industry (Langlois and Steinmueller, 1999). The factors behind that pattern of industrial leadership have been extensively analysed in the above-mentioned literature. The main explanations have focused on the scale and pattern of domestic demand, industrial strategy and structure, government policies, and on a number of national institutions, including the financial system, the labour market, and the university system.

Although that research has greatly contributed to our understanding of the sources of leadership in the semiconductor industry, no systematic evidence has yet been provided enabling us to answer the following questions. Are there differences in the technological capabilities that national organizations generated and accumulated throughout the evolution of the industry? Are there differences in the characteristics of the main national sources of knowledge generation, namely research organizations, government agencies and different types of firms (e.g., established vs. new firms, integrated vs. specialized companies)? The answers to those questions are relevant for both researchers and policymakers since, in high-technology industries, industrial leadership largely depends on technological leadership which, in turn, significantly relies on the technological capabilities that national organizations generate and accumulate over time.

The novelty of the present article is to fill that gap in the literature by mapping the pattern of technological knowledge underlying the long-term evolution of the miniaturization trajectory and the national organizations that generated it. Studies on technological paradigms and trajectories (Dosi, 1982; 1984) show that semiconductors emerged as a result of the generation of radically new knowledge around the need to increase the miniaturization of electronic components. After the invention of the microprocessor, the realization of the “promise” contained in the new paradigm proceeded through the continuous and incremental accumulation of new knowledge along the miniaturization trajectory. Such dynamics, which can be observed *ex-post* in the space of the

semiconductor products characteristics, has driven the whole evolution of the industry, advancing for more than 50 years at a strikingly stable rate, in accordance with Moore's law.

In this study, taking the miniaturization trajectory as the basic unit of our analysis, we build an original dataset of patents granted between 1976 and 2008 for that trajectory, and investigate it via three algorithms for the analysis of citation networks. The usefulness and validity of citation network methods for mapping the technological trajectories that have characterized the evolution of specific fields has been shown by recent studies (Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009; Barbera et al., 2011; Martinelli, 2012; Bekkers and Martinelli, 2012). Here, we use and extend such methods in order to identify different dimensions of the knowledge pattern – the core inventions, the backbone and the major clusters of inventions of the miniaturization trajectory – and then characterize them in terms of distinctive knowledge properties: basicness, cumulateness and specialization. Finally, we analyse the geographical and organizational distribution of the knowledge pattern, bringing to light the main national organizations involved and their technological capabilities, as revealed by the magnitude and properties of the technological knowledge that those organizations generated over time.

The rest of the article is organized as follow. Section 2 provides a historical overview of the miniaturization trajectory, focusing on its most recent developments. Section 3 presents the data and methods. Section 4 illustrates and analyses the pattern of technological knowledge underlying the evolution of the miniaturization trajectory. Section 5 discusses the differences in the characteristics of the main national organizations at work and in their technological capabilities. Section 6 concludes.

2. The semiconductor miniaturization trajectory

The miniaturization trajectory refers to the continuous scaling down of the minimum sizes of electronic components in order to incorporate additional functionalities on the same integrated circuit (IC or chip). That trajectory has powerfully influenced all the main directions of change of the semiconductor technology: as sizes shrink, costs per chip decrease, processing speed increases, power consumption is reduced, and final electronic products become more compact and multifunctional. Figure 1 shows the evolution of the miniaturization trajectory over the last 40 years. We can see from that figure that, as the advancement of semiconductor process technologies² allowed scaling down,

² Process technology refers to the way in which semiconductor chips are manufactured. Transistor dimensions are measured in microns (μm). Therefore, it is possible to refer, for example, to a 0.5 μm IC, or to say that an IC is built with a 0.5 μm process, meaning that the smallest transistors are 0.5 μm in length. Since the 1990s, it has become common practice to use the nanometre (nm) unit. A nanometre is one billionth of a metre. The

the number of transistors (i.e., devices) that could be integrated on the same chip increased according to Moore's Law, which states that the number of devices per chip increases exponentially, doubling roughly every 24 months (Moore, 1965). That was to enable the realization of ever more complex semiconductor devices throughout the technological eras that characterized the development of the miniaturization trajectory.

Insert Figure 1 about here

A decade after the invention of the transistor, the IC integrated a complete electronic circuit on a single silicon substrate, leading to enormous increases in performance and to significant reductions in cost when compared with the manual assembly of circuits using discrete components. During the small-scale integration (SSI) era, in the early 1960s, a chip contained just a few scores of transistors, which became a few hundreds in the late 1960s, during the medium-scale integration (MSI) era. The large-scale integration (LSI) era allowed the emergence of the first microprocessor (the Intel 4004), and the first DRAM memory (the 1K Intel). The microprocessor, which can be considered as the first "computer on a chip" (Betker et al., 1997), represented a fundamental breakthrough in the semiconductor history, since it allowed the integration of a complete processor (CPU) on a single IC containing the equivalent of thousands of discrete transistors. A processor is the fundamental component of computers of whatsoever era, because its ability to execute a program gives computers the essential feature of programmability. The invention of the microprocessor resulted in a huge increase in the processing speed of computers and led to a considerable reduction in computer costs. The first commercially available microprocessor was built by Intel in the early 1970s. However, as Intel never applied for a patent covering the microprocessor, the first microprocessor patent was finally granted to Texas Instruments in 1973.

The very large-scale integration (VLSI) era offered microprocessors and memories containing well over a million transistors on a single piece of silicon. The impressive increase of IC complexity that allowed VLSI chips to be developed, demanded the invention of new design technologies in order to handle such complexity. That led to the development in the 1980s of computerized design tools, which evolved into the modern EDA (Electronic Design Automation) tools, and allowed engineers to test IC functional performances before the manufacturing stage. Since chips, prior to the 1980s, were largely designed by hand, those tools had a critical impact on the productivity of IC designers. EDA tools were first developed at the Electrical Engineering and Computer Science department of the University of

process of scaling down, even if continuous, was punctuated by leaps; for example, in 1995, there was a great leap from 600 nm to 350 nm.

California, Berkeley (UCB) and termed SPICE (Simulation Program with Integrated Circuit Emphasis). SPICE was never patented, because of an open source option. Such an option, nevertheless, helped the software to be rapidly improved and adopted within the industry, giving impetus to the growth of the Silicon Valley semiconductor design software industry (Kenney et al., 2012).

In the mid-1990s, the advancement of the semiconductor process technology pushed the miniaturization trajectory to 350-250 nm, allowing the realization of the System on a chip (SoC), which integrates a whole electronic system (e.g., a computer) onto a single chip, with both hardware and software embedded (Martin, 2003)³. The emergence of SoCs accelerated the diffusion of semiconductor devices into a steadily expanding array of new products, ranging from consumer electronics products and automotive applications to communications technologies and medical devices.

Management of the growing complexity of SoCs posed new challenges for design methodologies, which became the source of ever higher sunk costs, and created the so-called “design productivity gap”: while IC complexity and density increased rapidly following Moore’s Law, improvements in the productivity of IC designers failed to keep up (Linden and Somaya, 2003). Although, in the last few years, many efforts have been devoted to the development of new methodologies for the SoC design, there is still a considerable lack of pragmatic knowledge among practitioners (Martin and Chang, 2003). In the second half of the 1990s, the use of IP (Intellectual Property) based design and IP reuse were proposed, with pre-designed and pre-verified IP blocks being internally manufactured or licensed from third-parties. IP blocks can be embedded memories, processors, communication links, etc., which have a self-contained designed functionality. The SoC designer, who would have only limited knowledge of the internal structure of those blocks, could combine them onto a chip to implement complex functions, and reuse them in all chips requiring those specific functionalities.

More recently, IP based design has been followed by the development of the platform based design, which is one of the approaches to the heavy IP reuse based design of SoCs. Rather than looking at IP reuse in a block-by-block manner, platform based design aggregates groups of components into reusable platform architectures (Martin, 2003). Other recent research directions addressing the SoC design challenges are the Network-on-a-Chip (NoC) and the Programmable SoC (PSoC). The NoC approach is based on the application to the SoC design of models coming from the network design field, and focuses on the development of advanced interconnect technologies for interconnecting SoC components (Benini and De Micheli, 2002). With increasing time-to-market pressures, programmable

³ By definition, an SoC incorporates at least one or more processors, memory blocks, an Input/Output interface, and an interconnection between those three components. One of the first examples of SoCs were second generation cellular phones.

logic devices (PLDs) have been increasingly merged into SOCs, allowing the realization of PSoCs, which represent a particularly exciting and intriguing combination of in-field flexibility and programmability (Martin and Chang, 2003). PLDs are electronic components characterized by a high degree of flexibility, since they can be configured by the customer or designer after manufacturing. Those features, and the ensuing low sunk costs of production, make PLDs suitable for many applications. PSoCs are SoCs that incorporate one or more programmable logic cores.

This historical overview provides a basis for understanding why the miniaturization trajectory has dominated the whole evolution of semiconductor industry, and the nature of the technical problems involved in its evolution. In the following sections, we map the pattern of knowledge advancement underlying that evolution, in order to reveal the technological capabilities that national organizations generated over time.

3. Data and methods

Since the work of Garfield et al. (1964), citations among scientific publications have been increasingly used in network analysis studies to trace the pattern of scientific advancement. A major contribution in that direction was given by Hummon and Doreian (1989), who proposed the main path analysis: three indices for the identification of the most important streams of growth of a scientific field. In the last few years, network analysis has greatly benefited from the development of new algorithms coming from graph theory. In particular, Batagelj (2003) showed how to efficiently compute Hummon and Doreian's indices so that they can be used to analyse different characteristics of citation networks.

Citations among patents have been commonly used in the studies on innovation and technological change to weigh the importance of individual patents by counting the number of citations received (Griliches, 1990; Jaffe and Trajtenberg, 2005). However, that approach might present limitations when focus is placed on the cumulative growth of technological knowledge in a specific field⁴. More recently, a number of studies have extended Hummon and Doreian's techniques to the analysis of patent citations, in order to map the technological trajectories that have characterized the evolution of specific fields (Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009; Barbera et al., 2011; Martinelli, 2012; Bekkers and Martinelli, 2012).

In the present article, we use the network citation methods proposed by those studies, and extend them along three axes. First, we take as our unit of analysis a whole technological trajectory,

⁴ See Fontana et al. (2009) for a detailed discussion of that issue.

rather than a relatively narrow technological field, thus mapping the technological knowledge underlying the evolution of the main direction of change in an industry. Second, rather than focusing on one main algorithm of network analysis, we use three different algorithms. That allows us to identify different dimensions of the knowledge pattern and to characterize them in terms of distinctive knowledge properties. Third, we analyse the geographical and organizational distribution of the knowledge pattern. By doing so, we go beyond the analysis of technological evolution, trying to connect it with the sources of leadership in a sector.

In our context, patents granted for the miniaturization trajectory correspond to the vertices of a network and are connected to each other by a number of arcs, which symbolize citational links among patents. Each patent represents a discrete piece of technological knowledge that has passed the scrutiny of trained specialists and has been granted on the basis of relatively objective standards. Since it is a legal duty for the assignee of a patent to disclose the existing knowledge, each cited patent represents a previously existing piece of knowledge that has been incorporated and further developed by the citing patent. Citations among patents, by making explicit the epistemic links among the pieces of knowledge from which the miniaturization trajectory emerged and grew, can be used to trace the pattern of knowledge advancement of that trajectory.

As a first step, we built a patent dataset for the miniaturization trajectory. That dataset was extracted from the USPTO (United States Patent and Trademark Office)⁵ by means of a key-word search on titles, abstracts and claims of patents granted from 1976 to 2008. The key-word strategy was selected by consulting a broad range of secondary sources and by interviewing three experts⁶. The USPTO patents prior to 1976 do not have full-text access, and it is not possible to extract them by means of a key-word search. To overcome, at least in part, that limitation, and to capture patents related to the earlier phase of the miniaturization trajectory, we also included in the dataset all patents cited by patents selected via the key-word search. The final dataset (patents extracted by the key-word search and their citations) contains 41,787 vertices and 121,393 arcs. We then constructed a network of citations among patents in the dataset, and applied to it the following algorithms, implemented by the program Pajek⁷.

The first algorithm, the Critical Path Method (CPM), captures the dominant direction of knowledge accumulation that emerged over the whole time period covered by this analysis, namely the backbone of the miniaturization trajectory. By computing the total number of paths linking the

⁵ The USPTO database is freely available at www.uspto.gov/

⁶ Selecting and validating the key-word strategy have required a great deal of efforts. Professors Donatella Sciuto and Andrea Lacaita (Politecnico of Milan), and Fabrizio Rovati (STMicroelectronics) were interviewed on both the key-word strategy and the most important technological developments of the miniaturization trajectory.

⁷ Pajek is freely available at <http://pajek.imfm.si/doku.php?id=download>.

oldest vertices in a citation network to the most recent ones, that algorithm maps all possible streams of cumulative growth of knowledge, and selects the most important one. Therefore, the knowledge identified by the CPM algorithm is expected to show a relatively high degree of technological cumulateness. The CPM algorithm is based on the Search Path Count (SPC) method (Batagelj, 2003), which calculates traversal weights on arcs following Hummon and Doreian's main path analysis. Traversal weights measure the importance of paths linking entry vertices in a network (patents that are not cited within the dataset) to exit vertices (patents that do not cite other patents within the dataset)⁸. The CPM algorithm determines the path from entry vertices to exit vertices with the largest total sum of weights on the arcs.

The second algorithm, called Island, identifies the main clusters of inventions in the entire research space of the miniaturization trajectory, thus mapping the major bodies of knowledge that contributed to and benefitted from the advancement of the miniaturization process. The Island algorithm is part of main path analysis, since it is based on the calculation of SPC traversal weights on arcs. However, traversal weights are used here to identify, in the whole dataset, non-overlapping subsets of vertices that, according to the arc weights, are more closely connected with each other than with external vertices. As demonstrated in Batagelj et al. (2006), each subnetwork identified by the Island algorithm has the same topic; therefore Islands can be considered as thematic clusters characterized by a relatively high degree of specialization.

Finally, the Hubs and Authorities algorithm selects the core inventions that laid the foundations of the miniaturization trajectory (Authorities), and their best developments (Hubs). Hubs and Authorities are formal notions of the structural prominence of vertices (Brandes and Willhalm, 2002). Therefore, unlike main path analysis, which identifies the main streams of growth in a citation network, the Hubs and Authorities algorithm focuses on the structure of a citation network and determines its most prominent vertices. Consequently, the knowledge identified by that algorithm is expected to display a relatively high degree of basicness. The concept at the root of the Hubs and Authorities algorithm can be dated back to Pinski and Narin (1976), who proposed to measure the prominence of scientific journals by taking into account not simply the number of citations that a journal receives, but also the prestige (in terms of citations received) of the journals that cite it (Calero-Medina and Noyons, 2008). Journals that receive many citations from prestigious journals are

⁸ Traversal weights on arcs are calculated in the following way. In an acyclic network there is at least one entry and at least one exit. Let us denote by I and O the set of all entries and all exits, respectively. The SPC method assigns to each arc as its weight the number of the different I - O paths passing through the arc. That number is then divided by the total number of paths between entry and exit vertices in the network. That proportion represents the traversal weight of an arc. Traversal weights on arcs and vertices are calculated simultaneously, so that traversal weights on arcs always correspond to traversal weights on vertices. For more details, see de Nooy et al. (2005).

considered highly prestigious themselves and, by iteratively passing prestige from one journal to another, a stable solution is reached, which reflects the relative prestige of journals (Bollen et al., 2006). That way of measuring prestige is at the basis of the algorithms for evaluating the status of web pages developed by Kleinberg (1999) and Brin and Page (1998). Such algorithms were later adapted by Batagelj (2003) for the software Pajek. Hubs and authorities stand in a mutually reinforcing relationship: a good authority is a patent that is cited by many good hubs, and a good hub is a patent citing many good authorities (Calero-Medina and Noyons, 2008).

Patent documents are a fundamental source of data, since each patent contains information such as the organization that developed the invention (the name of the patent assignee), its location (the address of the patent assignee), the technological field, and the background of the invention, which provides an overview of the technological problems to be solved. We first studied the technical content of patents selected by network analysis algorithms, using that information to trace the pattern of knowledge advancement that drove the miniaturization trajectory. Second, we used the information relating to the patent assignees and their addresses to examine the geographical and organizational distribution of the knowledge pattern. On that basis, we highlight the main national organizations at work and their technological capabilities, as revealed by the magnitude and properties of the technological knowledge that those organizations generated along the different dimensions of the knowledge pattern.

4. Results

4.1. Firms

Figure 2 shows a reduced version of the citation network⁹. The size of vertices and the thickness of arcs represent the relative importance (the traversal weights) of patents and citational links, respectively¹⁰. That graph highlights the rich complexity of knowledge contributions from which the miniaturization trajectory emerged and grew, together with some important patents and citational links. Although the graph does not provide any information concerning the pattern of knowledge advancement, it is already possible to note that the key knowledge contributions (IBM_1985, TI_1989,

⁹ The network has been reduced in order to allow its visualization via Pajek. The reduced network has been built following Batagelj (2003). In particular, we calculated traversal weights on arcs by means of the SPC method (see Section 3), deleted all arcs with weights lower than a selected threshold, and eliminated all resulting isolated vertices.

¹⁰ For presentational purposes, only the most important vertices were labelled with their code. See Table 1.A in the Appendix for more details on the patent characteristics. Each patent document can be completely visualized at <http://patft.uspto.gov/netahtml/PTO/srchnum.htm>

IBM_1976, IBM_1984, IBM_1981, and TI_1994) were generated by IBM and Texas Instruments (TI), and focused on the testing phase of electronic systems design.

Insert Figure 2 about here

Figure 3 contains the CPM path, which captures the dominant direction of knowledge accumulation that emerged throughout the whole evolution of the miniaturization trajectory¹¹. If we start from the bottom of the figure and move along the vertical axis, that graph shows the sequence of knowledge contributions that form the backbone of the miniaturization trajectory, allowing us to detail the technical problems that occupied the community of practitioners over time. The analysis of the content of CPM patents highlights the high technological cumulativeness of the integration process that evolved through the technological eras of the miniaturization trajectory, and was to lead to PCB computer systems becoming multi-chip computer systems and, finally, single-chip computer systems, with both their hardware and software being embedded¹². During that process, research efforts were focused on the testing phase of electronic systems design (as already suggested by the previous graph), in order to reduce costs stemming from the increasing integration of ICs.

By examining CPM patents in greater detail, we found that, in the first phase, going from the mid-1960s to the early 1970s (patents in the bottom layer of the figure: DATAGENERAL_1973, RCA_1969, TI_1973, IBM_1974, and WESTINGHOUSE_1966) practitioners explored various solutions for integrating PCB computer systems components. Among those contributions, we found patent TI_1973, which disclosed the first microprocessor. That is an important point for the validation of our dataset, since the microprocessor is the most significant innovation in semiconductor technology during the time period covered by this analysis, and the last radical innovation of the industry. Following the microprocessor breakthrough, the decades between the mid-1970s and the mid-1990s (patents from IBM_1976 to TI_1994) focused on the advancement of EDA tools and the development of methods for testing LSI and VLSI circuits. Two of those contributions are particularly important: patents IBM_1981 and TI_1987. The former disclosed an LSI integrated circuit system fully conformed to design rules that were new for that period (Level Sensitive Scan Design), while the latter dealt with the utilization of those same techniques for testing VLSI ICs. Patent TI_1994 is also of interest: that patent provided new methods for testing and integrating both hardware and software, and started to tackle the issue of the “design-for-reusability”, thus paving the way for the subsequent development

¹¹ See Table 2.A in the Appendix for more information on the patent characteristics.

¹² PCB computer systems are computers in which discrete electronic components are connected with each other and with passive electronic components on a printed circuit board (PCB) to create an electronic circuit with a dedicated function. Conversely, in single-chip computer systems, discrete components are manufactured and interconnected (i.e., integrated) on a single silicon substrate.

of SoCs. It should be noted here that the UCB software SPICE, as mentioned in Section 2, was never patented, yet it can be considered as the source of all those (and the subsequent phase) EDA developments.

The second half of the 1990s is the period when the most important SoC developments took place. Patents issued during those years (from INTEL_1995 to MOTOROLA_2000) focused on achieving more efficient hardware testing and software program debugging, in order to cope with the simultaneous increase of computer operating speed and microprocessor ability to execute instructions in parallel. That phase culminated with patent STM_2002, which dealt with the improvement of communication among systems components, another prominent technological aspect involved in SoC design. Analysis of the last three patents that form the backbone of the miniaturization trajectory (ACTEL_2006, ACTEL_2007, and ACTEL_2008) shows that, since the second half of the 2000s, practitioners have been focusing on the development of one of the most recent solutions proposed for facing the high sunk costs associated with the SoC design, namely PSoCs (see Section 2).

By looking at the organizations in which CPM patents were realized, we observe a relatively high degree of organizational cumulativeness. As shown in Figure 3, the main players were historically integrated semiconductor companies. Only during the early exploratory phase do we find some variety in terms of the organizations involved; together with TI, there were two established conglomerates, former vacuum tube producers (Westinghouse Electric and RCA), and Data General, one of the first minicomputer firms, then a recent Digital Equipment spin-off. During the decade from the mid-1970s to the mid-1980s, IBM dominated the exploitation of the microprocessor breakthrough. At that time, IBM was the most important computer company and IC manufacturer, and built most of the key components of its systems in house. Later, in an attempt to speed up PC time to market, IBM chose to purchase its operating systems and microprocessors from Microsoft and Intel, respectively. The subsequent decade was dominated by TI, which maintained an integrated structure until its recent decision to use foundry partners for 32 nm process technologies (LaPedus and Clarke, 2007). The main SoC advancements were generated by some of the most important US microprocessors companies, including Intel, Advanced Micro Devices (AMD) and Motorola, while developments concerning PSoCs were generated by Actel, a Silicon Valley company founded in 1985 and active in the market of PLDs. All patents selected by the CPM algorithm were generated by US companies, with the notable exception of the Italian-French STMicroelectronics (STM), which patented with its UK-based subsidiary. STM resulted from the merger of state-owned companies SGS Microelettronica and Thomson Semiconducteurs in 1987, and has its headquarters in Switzerland.

Insert Figure 3 about here

The CPM algorithm enabled us to identify, visualize and discuss the main direction of knowledge accumulation of the miniaturization trajectory, but ignored the variety of the research areas that grew complementarily. The Island algorithm, by identifying the main thematic clusters in the entire dataset, allows us to map all the major specialized bodies of knowledge that contributed to the advancement of the miniaturization process, and that benefitted from the diffusion of miniaturized semiconductor components.

Out of the more than 3,000 clusters of patents that emerged from the Island algorithm, we selected 80, on the basis of their size and relevance¹³. We found three large clusters of inventions (Main Islands). The first one concerns the same research field as that of the CPM path, and includes all the CPM patents as well. That Island (CPM Island) represents, therefore, the body of knowledge most closely connected with the backbone of the miniaturization trajectory. The second Main Island is specialized in digital optical communications systems, in which semiconductor devices, in particular light-emitting diodes (LEDs) and laser diodes, are used as transmitters. The third Main Island relates to microfluidics, which deals with the behaviour, control and manipulation of fluids at sub-millimetre scale. Microfluidic chips are widely used in inkjet printer heads, and have become common for applications in analytical chemistry research, medical diagnostics and the like, where sample sizes can be very small and analysed substances very expensive (e.g., Lab-on-a-chip). Other important Technological Islands are concerned with the development of single electronic components, especially memory devices, and semiconductor process technologies (e.g., chemical-mechanical planarization techniques, mask manufacturing methods, etc.). The remaining Islands relate to the advancement of the different technological areas in which semiconductors have been diffused over time, and include relatively established fields like consumer electronics products and automotive applications, as well as relatively new areas of inquiry at the intersection of other science domains, like optical communications technologies, microfluidics and medical devices. Figure 4 shows an example of a technological Island.

Insert Figure 4 about here

The Island algorithm maps the composition of the technological knowledge generated throughout the whole evolution of the miniaturization trajectory (from 1976 to 2008). In doing so, it privileges local connectedness among patents throughout the whole period considered, and tends to neglect important research areas with only a short history (Mina et al., 2007). To overcome that limitation, and detect the most recent developments of the miniaturization trajectory, we applied the

¹³ The Islands are available from the author upon request.

Island algorithm to a reduced dataset, starting from 2000¹⁴. Table 1 displays the geographical and organizational distribution of patents selected by the Island algorithm. Results are shown for both time periods considered here (Technological Islands₁₉₇₆₋₂₀₀₈ and Technological Islands₂₀₀₀₋₂₀₀₈). The total number of patents granted to firms from 1976 to 2008 shows that US companies generated most of the contributions, followed by Japan and European countries, while companies from the rest of Asia (Asia Excluding Japan – AEJ) play only a marginal role.

Insert Table 1 about here

By analysing those patents in greater detail, we found that Japanese companies prevailed, especially in clusters relating to consumer electronics products and automotive applications, while they also contributed significantly to the Technological Islands concerning electronic components and communications technologies. The main players were relatively established, diversified and vertically integrated electronics firms, including Hitachi, Mitsubishi, NEC, Toshiba, Matsushita, Sony and Canon. European companies, especially Siemens, Philips, STM, Bosch and Nokia, were involved in almost all Technological Islands, but they played an active role only in those clusters concerning automotive applications, consumer devices and electronic components. US companies generated most of the contributions in all Technological Islands, with the sole exception of consumer electronics products, where Japanese companies predominated. IBM, ADM, Motorola, TI and Intel contributed to many clusters, especially to CPM Island and semiconductor process technologies. Micron Technology dominated the Technological Islands concerning memory devices; Xerox was particularly active in developing MEMS applications¹⁵, HP in microfluidic chips, and AT&T in the communications field. Biotech and life science companies were major players in microfluidics and medical technologies clusters.

As shown in Table 1, if we look at the most recent clusters of inventions of the miniaturization trajectory (Technological Islands₂₀₀₀₋₂₀₀₈), the geographical and organizational distribution of knowledge changes. In particular, we can see that, while US firms preserve and consolidate their position, the contributions generated by Japanese firms decrease slightly, and the technological advantage of European firms is considerably eroded by the emergence of AEJ companies. By analysing AEJ patents, we found that the main players were the South Korean business groups Samsung, Hyundai and LG, which focused especially on clusters relating to consumer electronics products and communications

¹⁴ We followed the same procedure as that used by Mina et al. (2007).

¹⁵ Micro-electromechanical systems (MEMS) integrate mechanical elements, sensors, actuators, and electronics on the same silicon substrate. MEMS dimensions are very small, ranging from 20 μm to 1 μm , and are currently used in a variety of consumer electronics products and medical applications.

technologies. The remaining AEJ patents were spread out among a variety of different companies based in Taiwan, which were mainly involved in the development of packaging and integration technologies.

Other relevant results that we obtained from the analysis of Technological Islands₂₀₀₀₋₂₀₀₈ concern the greater importance of the clusters concerning optical communications systems, SoC design challenges, and semiconductor sensor applications. Furthermore, we found an increased weight of relatively new, small and specialized companies, especially in the areas relating to the SoC design challenges. Those bodies of knowledge were considerably developed by the fabless semiconductor firms Xilinx, Altera and Broadcom, and by the EDA company Cadence Design Systems, a UCB spin-off. The contributions of such firms mainly focused on PSoCs and PLDs, which employ technologies characterized by higher flexibility, lower sunk costs and faster development times. Conversely, those SoC challenges that require more complex technologies and closer coordination between design and manufacturing (IP test and verification, communication among IP blocks, and NoCs), were disclosed by historically integrated semiconductor firms, including IMB, TI, ADM, STM, and Intel. Fabless semiconductor firms partially contributed to the fields of electronic components, IC testing, and communications technologies as well. The most active firms in those fields were Cirrus Logic, Cisco Systems, and Broadcom. Fabless firms and other specialized companies were mostly located in the Silicon Valley.

4.2. Research organizations and government agencies

The CPM algorithm identified the backbone of the miniaturization trajectory, while the Island algorithm mapped all major specialized bodies of knowledge contained in the whole research space of the miniaturization trajectory. The Hubs and Authorities algorithm allows us to further explore the pattern of knowledge advancement by disclosing the core inventions that laid the foundations of the miniaturization trajectory (Authoritative patents) and their best developments (Hub patents). Tables 2 and 3 report the ten highest ranked Hub and Authoritative patents.

Insert Tables 2 and 3 about here

Authoritative patents were generated in the 1980s, and Hub patents in the late 1990s. Both Hubs and Authorities deal with parallel computing systems¹⁶, and focus on the technological problems

¹⁶ Parallel computing is a form of computation in which many calculations are carried out simultaneously, operating on the principle that large problems can be divided into smaller ones, which are then solved concurrently, i.e. in parallel (Li et al., 2009).

concerning the development of parallel processors, in order to increase the processing capacity and operating speed of computers. The main applications of parallel processors are supercomputers, which are used for the solution of advanced computational problems. The term supercomputer is relative, since it refers to computers that are at the cutting edge of current processing capacity. The level of performance required to make a computer a supercomputer has grown rapidly over time, and today's supercomputers typically become tomorrow's ordinary computers. That is why research on parallel processors, by continuously pushing forward the frontier of computer processing capacity, has emerged as the basic knowledge of the miniaturization trajectory. While Authoritative patents focus mostly on increasing the number of processors operating in parallel, Hub patents are especially dedicated to the task of integrating on the same chip ever more advanced processors "capable of massively parallel processing of complex scientific and business applications" (Patent No. 5794059).

As shown in Table 2, four of the ten highest ranked Authoritative patents were generated by some of the most prestigious US research universities, including the Massachusetts Institute of Technology (MIT), the Johns Hopkins University, Duke University, and Purdue University. Military government agencies supported the realization of Authoritative Patents No. 4380046, 4523273 and 4720780¹⁷. As reported in the Government Interest field of those patents, the funding agencies were the NASA, the Air Force, and the Navy, respectively. A clear description of the technological objective of those contributions can be found in the background of the invention of Patent No. 4380046, which points out the need to meet the "increasing requirements for multidimensional data processing computers that are fast enough to operate in real time on two or more dimension data (such as two dimensional imaging data) and compact enough to be carried on board in satellites, missiles or spacecraft". Patents falling within the Government Interest class, and aimed at increasing the operating speed of processors, emerged in the CPM Island as well (Patents No. 4079455, 4597080, and 4720780). Those contributions were generated in the 1980s by RCA, TI, and the Johns Hopkins University, with the support of the Army, the Air Force, and the Navy, respectively. The other core inventions of the miniaturization trajectory were generated by Thinking Machines, a major supercomputer manufacturer strongly involved in US military activities, and by a number of US aerospace and defence companies, including Goodyear Aerospace, Hughes Aircraft and Martin Marietta. Other knowledge contributions disclosed during the 1970s and the 1980s by US companies active in the fields of defence, aerospace, and supercomputers also emerged in the CPM Island¹⁸. As

¹⁷ Patents filed with the USPTO may contain a field labelled "Government Interest", which provides data that indicate any interest or right of the US government on a particular patent. That interest may arise for several reasons, but most frequently, at least in our case, it indicates that the invention received financial support from the government.

¹⁸ Those companies were Goodyear Aerospace (Patents No. 3800289, 3812467, 3936806), RCA (Patents No. 3462742, 4079455), Data General (Patents No. 3737866, 4071890), International Telephone and Telegraph

indicated in Table 3, IBM generated absolutely all the Hub patents, proving to be the organization capable of best developing the basic knowledge that was to lay the foundations of the miniaturization trajectory.

Further relevant information about the knowledge generated by research organizations and government agencies is provided by the analysis of Technological Islands. As shown in Table 1, US organizations were far more active than their foreign counterparts during both the time periods considered here (1976-2008 and 2000-2008), although a slight decline can be observed for the most recent years. That decline seems to be caused, at least in part, by the dynamism of AEJ research organizations. We also calculated the share of patents generated by US research organizations and government agencies out of the total US patents selected by Technological Islands₁₉₇₆₋₂₀₀₈. We found that such a share amounts to 12.2%, while the share of patents falling within the Government Interest class is 6.3%¹⁹.

US universities and research organizations were particularly active in the generation of those relatively new clusters of inventions at the intersection with other science domains where semiconductor components were diffused: optical communications systems, microfluidics, mass spectrometry²⁰, medical devices, and semiconductor sensors applications. Stanford University and Bell Laboratories played an important role in the Technological Islands relating to optical communications systems, with a focus on laser systems. The University of Pennsylvania stood out in microfluidics clusters, while the Charles Stark Draper Laboratory and the California Institute of Technology focused mainly on mass spectrometry-related Technological Islands. In the clusters on medical devices, the main contributions were generated by the MIT and the Georgia Tech Research Corporation, an organization that supports R&D at the Georgia Institute of Technology.

As for the US government, the analysis of Technological Islands₁₉₇₆₋₂₀₀₈ highlights that, in the 1970s and 1980s, the interest of national agencies was especially directed at the areas concerning electronic components and, to a lesser extent, optical communications systems. The main agencies of those decades were the Department of Energy (DOE) and its predecessor (the Atomic Energy Commission), the Department of Navy, the Air Force, and the Army. Since the 1990s, the US

(Patents No. 4507748, 4580215), Litton Systems (Patent No. 3988717), Raytheon (Patent No. 4691161), Rockwell International (Patent No. 5544311), Control Data (Patent No. 4527249), Cray Research (Patent No. 4636942), and Floating Point Systems (Patent No. 4891751).

¹⁹ Those include patents granted to firms (37.3%), universities (29.3%), public agencies (28%), and patents without any assignee (5.3%). If patents granted to public agencies and universities are excluded, the percentage of patents in the Government Interest class falls to 2.7% of the total US patents emerging from Technological Islands₁₉₇₆₋₂₀₀₈.

²⁰ Mass spectrometry is an analytical technique for the determination of the elemental composition and chemical structures of molecules. Mass-spectrometers were large, heavy, and expensive. The research efforts of that Island are devoted to disclosing methods for manufacturing miniaturized high performance mass-spectrometers, such as the Mass Spectrometer on a Chip.

government's activity shifted towards the same clusters that research organizations focused on (microfluidics, optical communications systems, medical devices, mass spectrometry, and semiconductor sensor applications). The major players were the Advanced Technology Program (ATP), the National Science Foundation, the Department of Navy, the National Institutes of Health, the NASA, the DARPA, and the DOE.

The contributions of research organizations and government agencies in Japan and Europe, when compared to those of the US, were far less considerable, amounting to only 6% and 4.4% of the total Japanese and European patents (respectively) that emerged from Technological Islands₁₉₇₆₋₂₀₀₈. In Japan, the most active organization was the METI Agency of Industrial Science and Technology (AIST), while the sporadic contributions of European organizations were mainly generated by the British Ministry of Defence, the French *Commissariat à l'Energie Atomique*, and the British Atomic Energy Authority. Finally, with regard to AEJ countries, the share of patents owned by research organizations out of the total patents granted to AEJ countries is 16.2%²¹. In South Korea, two main organizations emerged, especially in the clusters relating to communications technologies: the ETRI (Electronics and Telecommunications Research Institute) and the KAIST (Korea Advanced Institute of Science and Technology). In Taiwan, the main contributions were generated by the ITRI (Industrial Technology Research Institute), which focused in particular on developing electronic components and semiconductor process technologies.

5. Discussion

Table 4 outlines the results that have been illustrated in Section 4. Overall, we found significant differences in both the characteristics of the main national organizations at work and their technological capabilities, as revealed by the magnitude and properties of the technological knowledge that those organizations generated throughout the evolution of the miniaturization trajectory.

First, compared to their counterparts in Japan and Europe, US universities and government agencies were far more active. As shown by the list of the 10 highest ranked Authoritative patents, those organizations played a critical role in generating – or supporting the generation of – the basic knowledge on parallel processors that, by continuously pushing forward the frontier of computer performance, was to lay the foundations of the miniaturization trajectory. The results relating to Technological Islands (1976-2008) reveal that US universities and government agencies also

²¹ Those data refer to Technological Islands₂₀₀₀₋₂₀₀₈, since data referring to the whole period (1976-2008) are not significant for AEJ countries.

contributed significantly to generating the specialized bodies of knowledge underlying the new market segments in which semiconductor components were diffused (optical communications systems, microfluidics, and medical devices). Earlier historical studies have highlighted the importance of US universities and federal R&D funding in determining US strength in the semiconductor industry (e.g., Dosi, 1984; Macher et al., 1998; Mowery and Nelson, 1999). Our results provide, on the one hand, empirical evidence supporting that conclusion and, on the other hand, offer a finer grained analysis of the role played by those organizations during the evolution of the industry. Our data concerning the most recent evolution of Technological Islands (2000-2008) also show that, unlike Japan and Europe, AEJ countries have been following a path that relied considerably on the contribution of public research.

Second, our results provide evidence that a relatively stable and small group of large and established firms predominated over smaller and newer firms, both in the US and elsewhere. Nevertheless, when we analysed the most recent evolution of Technological Islands (2000-2008), we found an increased importance of Silicon Valley-based fabless and EDA companies, which played an especially active role in the specialized bodies of knowledge concerning SoC design challenges. That result seems to be consistent with Linden and Somaya (2003), who suggest that the process of vertical specialization spurred by the emergence of SoC technologies is associated with an increased dynamism of smaller and specialized firms. However, we found that, compared to fabless and EDA companies, foundries, IP providers and other networked firms analysed by Linden and Somaya (2003) played only a minor role. Our data also show that fabless and EDA companies mainly focused on those SoC design technologies that are characterized by higher flexibility, lower sunk costs and faster development times (PSoCs and PLDs). We found little evidence supporting the increased importance of Taiwanese small design companies. This seems to confirm Chang and Tsai (2002), who found that Taiwan did not attempt to challenge the US technology leadership in IC design, but rather focused on being a superior quick follower, through knowledge assimilation and utilization. According to our data (Technological Islands 2000-2008), Taiwanese companies were, instead, mainly involved in the development of integration and packaging technologies.

Third, compared to their foreign competitors, US firms largely dominated the generation of new technological knowledge throughout the whole time period considered in this study. The main US players were relatively integrated semiconductor firms, together with a few “systems” manufacturers, like IBM. As shown by the evolution of the CPM path, those firms pursued a strategy that first bet on the last radical innovation of the industry (the microprocessor), and later focused on the cumulative solution of the testing challenges arising from the design of increasingly integrated microprocessor systems. Furthermore, those same firms played a dominant role in many important specialized bodies of knowledge, including semiconductor process technologies and electronic components

(Technological Islands 1976-2008), as well as in the most recent developments of the miniaturization trajectory concerning SoCs design challenges (Technological Islands 2000-2008). As the list of the 10 highest ranked Hub patents shows, IBM generated on its own all the most important developments of the basic knowledge that was to lay the foundations of the miniaturization trajectory (integration of parallel processors).

Conversely, in Japan and in European countries, the main players were relatively integrated and diversified electronics firms. Both Japanese and European firms followed a strategy that was markedly different from that of US companies, largely focusing their efforts on generating specialized bodies of knowledge relating to consumer electronics products and automotive applications (Technological Islands 1976-2008). Although those firms extended their competences to other specialized bodies of knowledge as well (electronic components and communications technologies), they only generated part of the relevant knowledge there. Compared to European firms, Japanese companies showed higher technological capabilities, but gained an advantage over US firms only in consumer electronics technologies. Our data for the most recent evolution of Technological Islands (2000-2008) show that AEJ firms, especially South Korean electronics companies, have been following the same strategy of specialization in consumer and communications technologies as that pursued by Japanese and European companies. Those data also show that the emergence of AEJ firms considerably eroded the technological advantage of European firms which, in the most recent years, experienced a deep decline in their technological capabilities. US and Japanese firms, instead, were able to preserve their areas of technological advantage, and there is even evidence that US firms consolidated their position.

Those results are broadly consistent with earlier historical studies that have analysed the evolution of national competitive advantage in the semiconductor industry (Langlois and Steinmueller, 1999; 2000). Langlois and Steinmueller (2000) found that the US resurgence during the 1990s was greatly determined by a renewed focus of US semiconductor firms on what had long been their distinctive capabilities in higher margin, design-intensive chips, especially microprocessors and related chips, where innovation is a critical factor of competition. The same authors (Langlois and Steinmueller, 1999) have highlighted the strength of Japanese electronics companies in consumer electronics products, and the relative success of European firms in consumer and automotive applications. Our results show, in addition, that by focusing on the design of microprocessor systems, US semiconductor firms maintained command over the most important stream of knowledge accumulation that emerged throughout the whole evolution of the miniaturization trajectory. Our results also suggest that, unlike their foreign competitors, US firms extended their knowledge bases well beyond their distinctive areas of competitive advantage, including also areas where they do not

have a competitive advantage as, for example, memory devices²². US firms also remained strong in technological areas such as semiconductor process technologies in which latecomer countries, in particular Taiwan, conquered considerable market shares.

There are, nevertheless, organizations that fall outside the patterns discussed above, implementing strategies that "bucked" the general trends observed. Surprisingly, we found that, besides universities and government agencies, a number of US aerospace, defence, and supercomputer companies also played an active role in the 10 highest ranked Authoritative patents. By generating the basic knowledge on parallel processors that was to lay the foundations of the miniaturization trajectory, those firms pursued a strategy which was markedly different from that of their US and foreign competitors. This strategy aimed at improving computer performances, in terms of processing capacity, operating speed and compactness, and was also followed by other defence, aerospace and supercomputing companies appearing in the CPM Island. Those results seem to suggest that US military demand played a key role in shaping the strategy of those firms; firstly, because of the distinctive characteristics of those firms, whose main buyer is typically the government and, secondly, because of the considerable involvement of US public agencies as sponsors and customers for parallel processors technologies for national security purposes (Metropolis and Nelson, 1982; Williams, 1985; Mackenzie, 1991). Should that be the case, we can conclude that US military demand had a critical impact, not only during the early years of the semiconductor industry, as previous studies have highlighted (Dosi, 1984; Malerba, 1985; Langlois and Steinmueller, 1999), but even during the industry's relatively more recent evolution (the time period covered by this analysis).

Furthermore, our data appear to corroborate the finding that military agencies played a key role even on the supply side (Dosi, 1984), as shown by the military character of the US agencies involved in the generation of both the basic knowledge on parallel processors (Authoritative patents) and the many clusters of inventions that emerged throughout the whole time period considered (Technological Islands 1976-2008). It should also be noted that the present study may have underestimated the extent of the contribution of military agencies, because the early period of the miniaturization trajectory, when the involvement of US military agencies was more prominent, is not completely covered by our dataset. Moreover, it is well known that military agencies extensively financed university research on semiconductors, but that often does not emerge from the analysis of patent documents.

A second surprising result relates to the behaviour of STM. There seems to be evidence, in fact, that this Italian-French semiconductor firm bucked the general declining trend experienced in the most recent years by European firms. The presence of STM patents in the main path of knowledge

²² The market for memory devices was dominated by Japanese firms at an early stage and, later, by Korean firms (Langlois and Steinmueller, 1999).

accumulation and in many connected specialized bodies of knowledge (electronic components, semiconductor process technologies and SoC design challenges) shows that the strategy pursued by STM differed from that of the other European companies, being instead similar, in many aspects, to that of US semiconductor firms.

The findings discussed so far have to be considered with some caution, due to the limitations of the use of patents and patent citations as a unit of measure²³. First, patent citations may not perfectly reflect the knowledge bases that organizations rely on. For example, Alcacer and Gittelman (2006) found that the magnitude of citations added by USPTO patent examiners is high, and they raise concern about the unknown noise that such citations, which typically are not separately reported, can add to the data. In response to such concern, Barbera et al. (2011) have recently tested patent citations methods and, in particular, the network citation methods used in the present analysis, showing their validity in studying technological evolution. That seems to suggest that, at least for what concerns the analysis of technological evolution, the bias introduced by examiners' citations is not bad *per se*.

Second, the extent of inventive activity and technological capabilities is not fully revealed by patenting activity (see, for example, Arundel and Kabla (1998) and Nelson (2009)). It is, in fact, well known that not all inventions are patentable, and most of those inventions concern basic research discoveries. Moreover, not all patentable inventions are patented due, for example, to an open source preference, as in the case of the UCB SPICE (see Section 2). In consequence, our analysis may significantly underestimate the relative role played by universities which, by definition, are more involved in basic research, and typically rely less often than firms on patents to appropriate returns on R&D.

Third, patents are often used for strategic objectives, and patent strategies differ both over time and across firms, even within the same industry or technological area (Hall and Ziedonis, 2001; Ziedonis, 2004). Due to the rapid pace of technological change and short product life cycles, firms in the semiconductor industry tend to rely more heavily on lead time, secrecy, and manufacturing or design capabilities than on patents to profit from innovation (Hall and Ziedonis, 2001). Nonetheless, the number of US semiconductor-related patents has risen sharply since the early 1980s, exceeding the overall increase in US patenting (Kortum and Lerner, 1998). In exploring that apparent paradox, Hall and Ziedonis (2001) found that the surge in semiconductor patents was not accounted for either by increases in R&D spending (the propensity of semiconductor firms to patent has also increased), or by technological/managerial improvements. Rather, the primary reason was the more aggressive patenting by US semiconductor large manufacturers (capital-intensive firms). Those firms responded

²³ See Pavitt (1985), Griliches (1990), Jaffe and Trajtenberg (2005) for a discussion about the use and limitations of patent documents.

strategically to the strengthening of US patent rights in the 1980s, by building larger portfolios of their own “legal rights to exclude”, in order to reduce the holdup problem posed by external patent owners and negotiate access to external technologies on more favourable terms. Having analysed the behaviour of a sample of 67 US semiconductor firms, Ziedonis (2004) found that a firm's patenting strategy depends on the fragmentation of its markets for technology, and on the firm's own level of investment in technology-specific assets. More particularly, Ziedonis (2004) found that capital-intensive firms patent more than five times as aggressively in response to average levels of fragmentation in markets for technology than is the case for firms of average capital-intensity.

Those findings have relevant implications for the present analysis, suggesting that our results may to some extent be biased by the different patenting strategies pursued by organizations. That is particularly important for the results concerning the dominance of large US semiconductor firms vs. smaller US design companies which, according to Hall and Ziedonis (2001), did not engage in the same “patent portfolio races” as US capital-intensive firms. Moreover, according to Ziedonis (2004), those smaller firms also patent less aggressively than capital-intensive firms in response to equal levels of fragmentation in markets for technology. Unfortunately, we do not have comparable studies on the patenting strategies pursued by non-US firms that patented at the USPTO. In consequence, we are not able to determine whether our results concerning the relative dominance of US firms vs. non-US firms have been affected as well by the different patenting strategies at work.

Finally, in the absence of a unified global patent database, this study has used the USPTO, the most representative database. Although that may, to some extent, have biased the results of our analysis towards US organizations, patenting in the US market is still important for foreign countries in order to protect areas of competitive advantage, and US patenting activity by foreign organizations remains a good measure of the technological capabilities of foreign countries (Pavitt, 1985). Moreover, as Figure 5 shows, the patenting activity of the USPTO seems to reflect very closely the pattern of industrial leadership in the semiconductor industry: early US dominance, the Japanese challenge during the 1980s, the US resurgence in the 1990s, the rise of AEJ countries, as well as the relatively peripheral role of European countries.

Insert Figure 5 about here

6. Conclusion

The semiconductor miniaturization trajectory is one of the most stable and influential dynamics that have characterized the evolution of modern computing, communications and manufacturing systems. Using an original dataset of patents and three algorithms for the analysis of citation networks, this article has mapped the pattern of technological knowledge underlying that trajectory. We first identified three different dimensions of the knowledge pattern – the core inventions, the backbone and the major clusters of inventions of the miniaturization trajectory – and then characterized them in terms of distinctive knowledge properties: basicness, cumulateness and specialization. We subsequently analysed the geographical and organizational distribution of the knowledge pattern, disclosing the main national organizations involved and their technological capabilities, as revealed by the magnitude and properties of the technological knowledge that those organizations generated over time.

The results provide evidence of significant differences in both the characteristics of the main national organizations and their technological capabilities. First, compared to their counterparts in Japan and Europe, US universities and government agencies were far more active. They played a critical role in generating both the basic knowledge on parallel processors that was to lay the foundations of the miniaturization trajectory, and the specialized knowledge underlying the new market segments in which semiconductor devices were diffused (optical communications systems, microfluidics, and medical devices).

Second, a rather stable and small collection of large and established firms predominated over smaller and newer firms, both in the US and elsewhere. However, in the US, the main players were relatively integrated semiconductor firms, together with a few “systems” manufacturers like IBM, while in Japan, Europe and in AEJ countries, integrated and diversified electronics firms largely prevailed. As discussed in Section 5, the dominance of US large manufacturers over smaller design companies may be due, at least in part, to the different patenting strategies that those firms pursued in response to the strengthening of US patent rights in the 1980s (see Hall and Ziedonis, 2001; Ziedonis, 2004). Moreover, we found evidence of a more recent dynamism of Silicon Valley-based fabless and EDA companies, which seems to be linked to the process of vertical specialization spurred by the emergence of SoC technologies.

Third, compared to their foreign competitors, US firms dominated the generation of new technological knowledge during the whole time period considered. By betting on the last radical innovation of the industry (the microprocessor), and by focusing on the cumulative exploitation of the technological opportunities contained in such innovation (integration of microprocessor systems), US semiconductor firms maintained command over the main stream of knowledge accumulation that emerged throughout the whole evolution of the miniaturization trajectory. Furthermore, those firms

accumulated higher technological capabilities in important specialized bodies of knowledge that grew complementarily (semiconductor process technologies, memory devices, SoC design challenges). Conversely, Japanese and European electronics companies followed a different strategy, largely focusing their efforts on generating specialized knowledge concerning consumer electronics products and automotive applications. Japanese companies showed higher capabilities than European firms, but gained an advantage over US firms only in consumer electronics technologies. Our results also show that the emergence of AEJ companies significantly eroded the technological advantage of European firms which, despite certain exceptions, experienced, in the most recent years, a deep decline in their technological capabilities. Japanese firms, instead, were generally able to preserve their areas of technological advantage.

The outlier behaviour of a number of US aerospace, defence, and supercomputer companies suggests that US military demand played a key role in shaping the strategy of those firms. This strategy, in fact, was very different from that of the other firms and, as in the case of US universities and government agencies, aimed at generating the basic knowledge of the miniaturization trajectory in order to push forward the frontier of computer performances. The US agencies that were involved in the generation of both such a basic knowledge and many clusters of inventions were also military organizations.

Although our findings are subject to a number of caveats (see Section 5), they have important implications for the literature on the sources of leadership in the semiconductor industry. First, they provide empirical evidence that US universities and federal R&D funding were, and still are, a major source of technological leadership, while offering a finer grained analysis of the role played by those organizations during the evolution of the industry. Moreover, as discussed in Section 5, we may have underestimated the contribution of both universities and government agencies, especially military agencies, which massively funded university research on semiconductors. We also show that the poor performance of universities and government agencies in Japan and Europe contributed to determining the relative weakness of those countries compared to US. Second, the technological areas where national firms accumulated their capabilities largely correspond to their distinctive fields of competitive advantage, as analysed by previous studies (Langlois and Steinmueller, 1999; 2000; see Section 5 for more details). More generally, this suggests that, in the long-term, competitive outcome is strongly rooted in technological capabilities that national firms are able to generate and accumulate over time. However, we also found that, unlike their foreign competitors, US firms extended their knowledge bases well beyond their characteristic areas of industrial strength, including also areas where they do not have a competitive advantage. Third, it appears that US military demand had a critical impact, not only during the early years of the industry, as previous studies have highlighted (Dosi, 1984, Malerba, 1985; Langlois and Steinmueller, 1999), but even during its (relatively) more

recent evolution (the time period covered by this analysis). Fourth, our results seem to corroborate the conclusion that military agencies played a key role even on the supply side (Dosi, 1984), by directly generating, or financing the generation of, significant pieces of knowledge.

Furthermore, this article shows for the first time that investigating the dynamics of technological knowledge through citation network methods can be a useful tool for highlighting the sources of knowledge generation and the technological capabilities of organizations in a sector. Rather than selecting a sample of organizations and analysing their patent portfolio, as is common in the literature (see, for example, Patel and Pavitt, 1997), this study started by mapping the knowledge pattern of a whole technological trajectory, allowing the identification of the main organizations at work and their capabilities on the basis of the knowledge that organizations generated along this pattern. Moreover, our approach allows organizations' capabilities to be detailed by also taking into account, for the first time, the properties of the knowledge involved.

Our findings suggest the following policy implications. First, Japan and European countries might benefit from strengthening their university research and *public laboratory system*. Discussing the specific characteristics of the different scientific systems, and the connected policies supporting their strength, is beyond the scope of this article and has been the focus of other studies (see, for example, Dosi et al., 2006; Bonaccorsi, 2007). However, with respect to the case of semiconductors, we suggest here that policies should put more emphasis on stimulating the potential of public research for generating new knowledge in those technological areas that are at the intersection of different science domains (e.g., physics, biology, medicine) in which semiconductor components were diffused in the most recent years, and in which it is expected that they will be diffused even more in the coming years (e.g., medical devices, nanotechnologies, photovoltaics). In those fields, where the technological opportunities created by basic and explorative knowledge are particularly important, public research can play a unique role.

Second, active sectoral-specific industrial policies might help European firms to close the technological gap they have cumulated in recent years. European countries are heterogeneous, and devising specific public policies for the whole European context would require deeper and more situated analyses. Here, we limit ourselves to suggesting a number of general policies that might be considered. Those include supporting the acquisition and assimilation of external knowledge, as well as the diffusion and exchange of technological knowledge. Policies aimed at increasing firms' capabilities in generating new technological knowledge could be important too. That may include supporting university spin-offs and university-industry R&D projects, procurement policies for selected and broadly-targeted technologies, and R&D public projects, based on peer review assessment of merit, whose results are widely diffused within the industry. Even in this case, it seems to be important to focus policies on the new and emerging areas of application and experimentation of

semiconductors, where technological opportunities are expected to be high. These recommendations, like those mentioned above, are especially important in view of the current economic crisis, which is leading many European governments to underinvest in research and “knowledge infrastructures”.

Third, this analysis seems to provide evidence that, even in a relatively established paradigm like semiconductors, government demand can play an important role in shaping the priorities of industrial firms, motivating them to generate new knowledge in those domains in which performances matter more than costs. This, in turn, emphasizes that the structure or the “quality” of government demand is as important as its magnitude in supporting innovation. That appears to be particularly important for emerging technological areas and potentially new technological paradigms, especially when there is a collective interest in their development, as in the case of sustainable technologies. In that respect, government policies aimed at creating or stimulating market niches willing to pay a significant premium for some superior characteristics of products could be particularly useful (see, for example, Kemp, 1994; Kemp et al., 1998). Finally, government policies turn out to play an important role even on the supply side, by generating or stimulating the generation of new knowledge in the most complex and uncertain areas of inquiry through effective R&D projects and funding.

By analysing the dynamics of the technological knowledge underlying the long-term evolution of the semiconductor miniaturization trajectory, this study sheds light on the sources of leadership of what is generally accepted as the most important technology of the second half of the past century. Studying the knowledge dynamics pushing the emergence of potential radically new technologies or paradigms could provide exciting opportunities for further research.

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Tables

Table 1 Geographical and organizational distribution of Technological Islands (%)

	Firms		Research organizations and government agencies		Total	
	1976-2008	2000-2008	1976-2008	2000-2008	1976-2008	2000-2008
USA	70.7	72.9	77.5	67.5	67.1	69.5
JP	16.5	15.9	8.6	0.8	14.6	14.3
EU	10.5	4.7	4.3	6.5	9.2	4.6
AEJ	1.1	5.0	2.7	13.8	1.2	5.3
Other Countries	1.3	1.5	7.0	11.4	1.8	2.0
No Assignee	-	-	-	-	6.1	4.2
Total	100	100	100	100	100	100

Note: The procedure used to build this table is based on the address of the patent assignee listed on the patent, and does not take into account ownership relations between organizations (e.g., mother and daughter firms, or mergers, acquisitions and split-ups). In the table, the upper-left cell, for example, shows that 70.7% of all firms engaged in all Technological Islands₁₉₇₆₋₂₀₀₈ are based in the US.

Table 2 Authoritative patents

Patent Number	Issue Year	Title	Assignee Name
4598400	1986	Method and apparatus for routing message packets	Thinking Machines Corporation (Cambridge, MA)
4380046 ^a	1983	Massively parallel processor computer	None
4621339	1986	SIMD machine using cube connected cycles network architecture for vector processing	Duke University (Durham, NC)
4523273 ^a	1985	Extra stage cube	Purdue Research Foundation (Lafayette, IN)
4720780 ^a	1988	Memory-linked wavefront array processor	The Johns Hopkins University (Baltimore, MD)
4873626	1989	Parallel processing system with processor array having memory system included in system memory	Massachusetts Institute of Technology (Cambridge, MA)
4739474	1988	Geometric-arithmetic parallel processor	Martin Marietta Corporation (Bethesda, MD)
4805091	1989	Method and apparatus for interconnecting processors in a hyper-dimensional array	Thinking Machines Corporation (Cambridge, MA)
4314349	1982	Processing element for parallel array processors	Goodyear Aerospace Corporation (Akron, OH)
3970993	1976	Cooperative-word linear array parallel processor	Hughes Aircraft Company (Culver City, CA)

^a US Government Interest

Table 3 Hub patents

Patent Number	Issue Year	Title	Assignee Name
5794059	1998	N-dimensional modified hypercube	International Business Machines Corporation (Armonk, NY)
5963745	1999	APAP I/O programmable router	International Business Machines Corporation (Armonk, NY)
5842031	1998	Advanced parallel array processor (APAP)	International Business Machines Corporation (Armonk, NY)
5828894	1998	Array processor having grouping of SIMD pickets	International Business Machines Corporation (Armonk, NY)
5822608	1998	Associative parallel processing system	International Business Machines Corporation (Armonk, NY)
5717943	1998	Advanced parallel array processor (APAP)	International Business Machines Corporation (Armonk, NY)
5963746	1999	Fully distributed processing memory element	International Business Machines Corporation (Armonk, NY)
5966528	1999	SIMD/MIMD array processor with vector processing	International Business Machines Corporation (Armonk, NY)
6094715	2000	SIMD/MIMD processing synchronization	International Business Machines Corporation (Armonk, NY)
5734921	1998	Advanced parallel array processor computer package	International Business Machines Corporation (Armonk, NY)

Table 4 Outline of the main results

Network Analysis Algorithms	Knowledge Pattern	Knowledge properties	Technical problem	Prevailing geographical location and organizational form
CPM	Backbone	Cumulativeness	Testing and integration of microprocessor systems	US firms
Hubs and Authorities	Core inventions	Basicness	Parallel processors	US universities and government agencies US firms
Island	Major clusters of inventions	Specialization	Testing and integration technologies	US firms
			Microfluidics	US firms US universities and government agencies
			Communications technologies	US and JP firms US universities and government agencies
			Semiconductor process technologies	US firms
			Single electronics components	US, JP and EU firms
			Consumer electronics products	JP, US, EU and AEJ firms
			Automotive applications	US, JP and EU firms
			Medical devices	US firms US universities and government agencies
			SoC design challenges	US firms

Figures

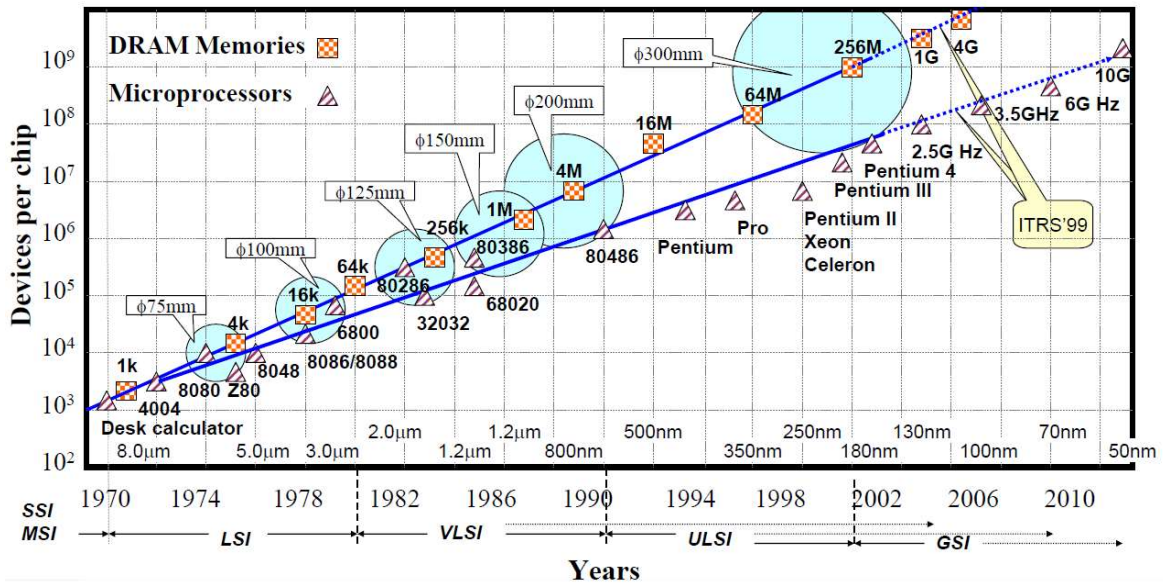


Fig. 1. Moore's Law and miniaturization trajectory
Source: Zheng (2008)

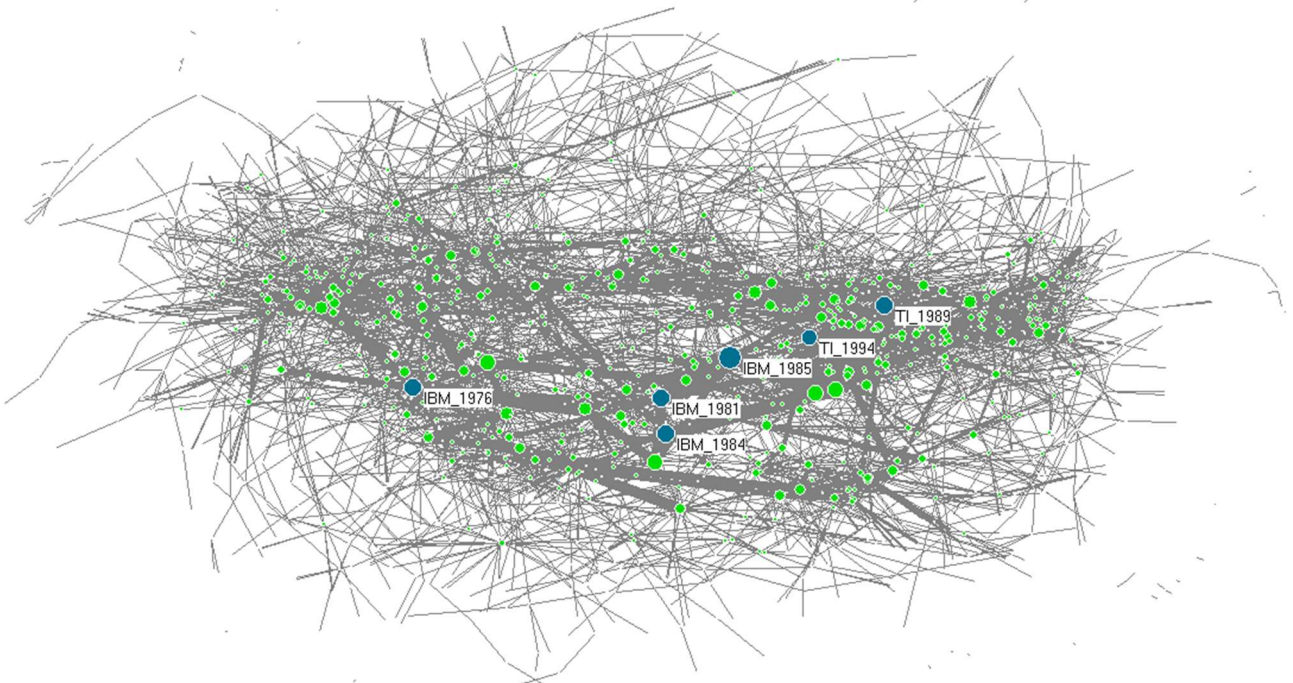


Fig. 2. Citation network

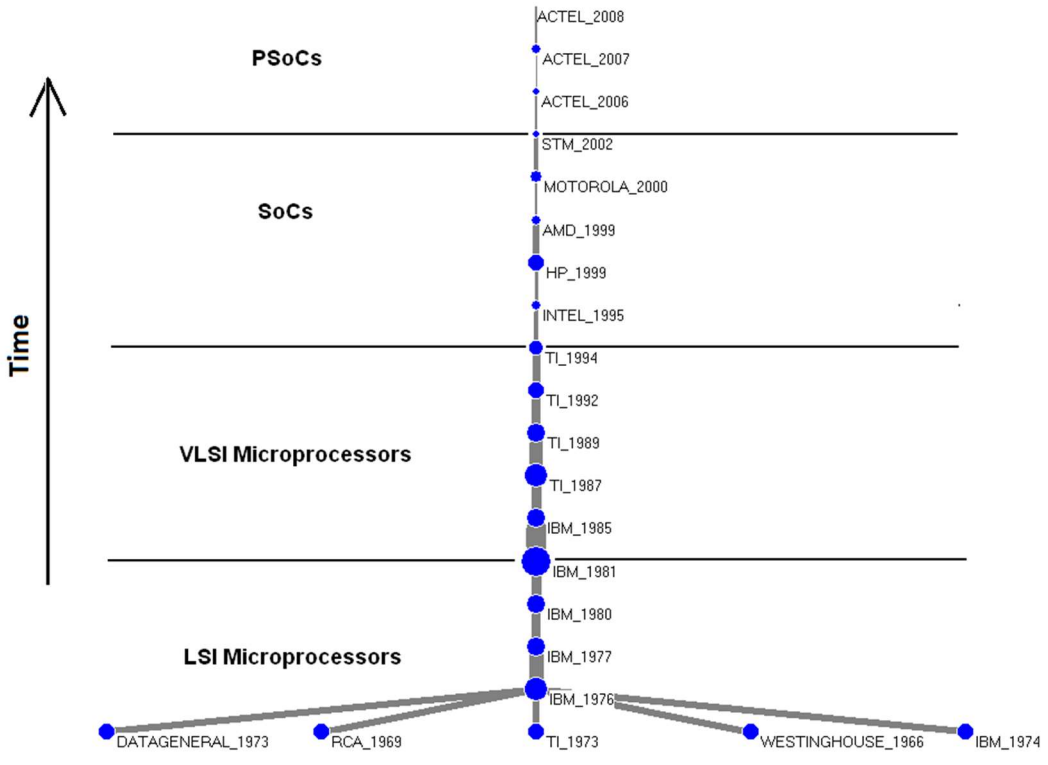


Fig. 3. CPM

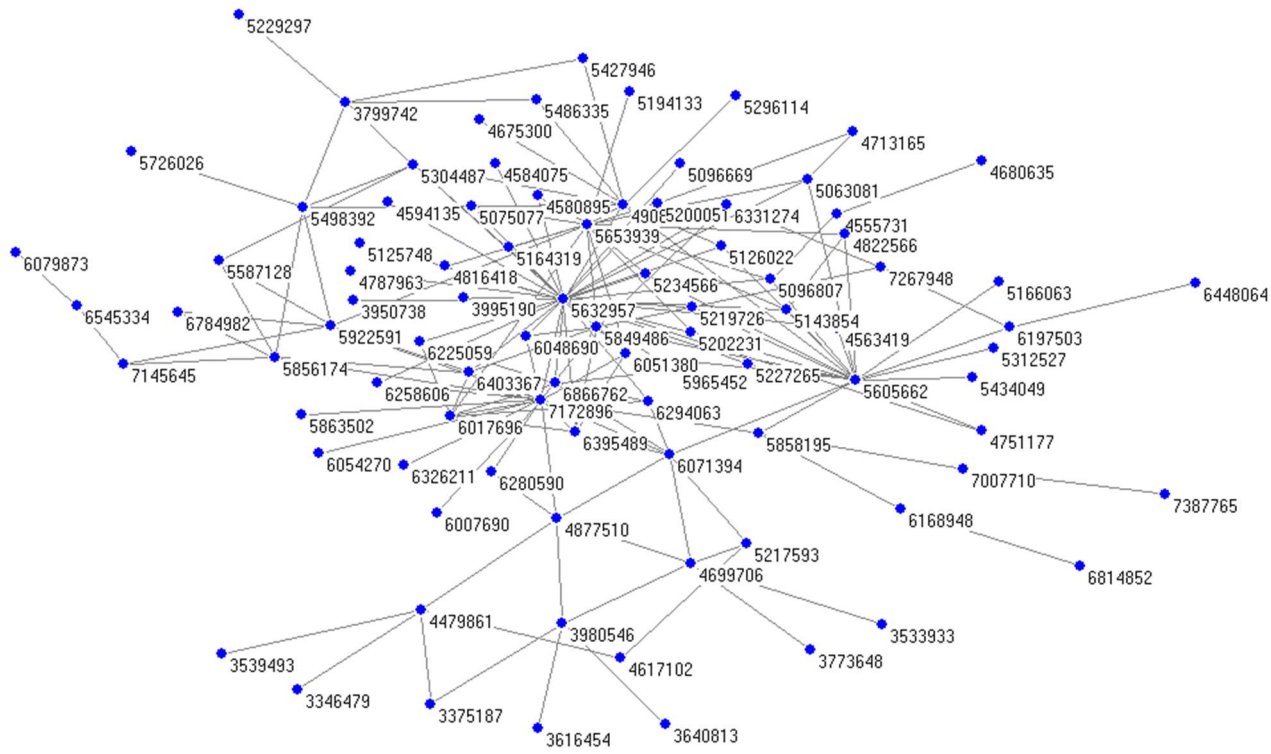


Fig. 4. Main Island “Microfluidics”

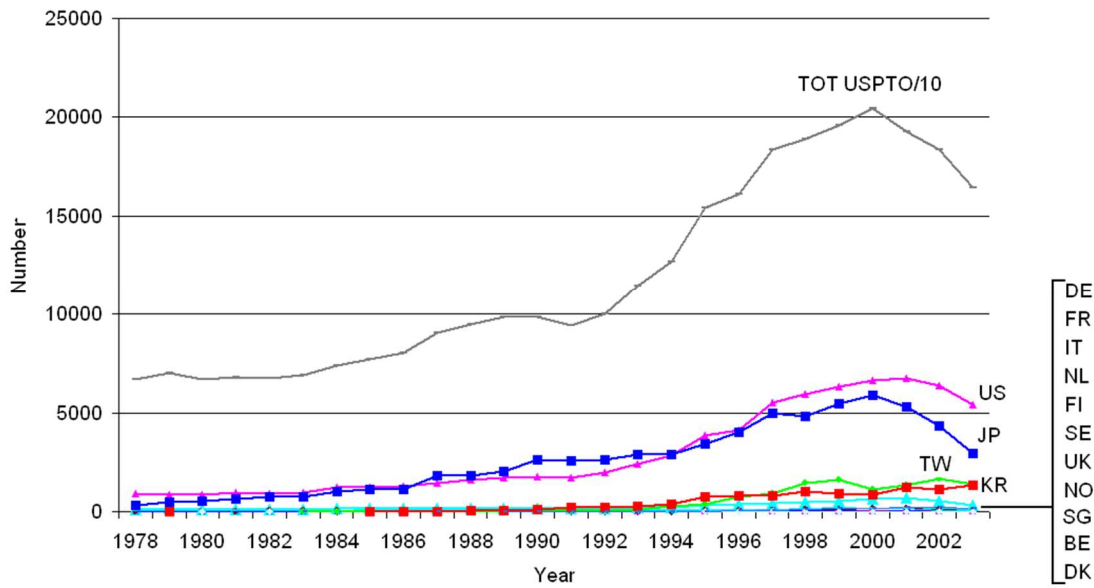


Fig. 5. Semiconductor patents granted by the USPTO by priority year at the national level
Source: Eurostat

Appendix

Table 1.A Most important patents of the citation network

Patent Code	Patent Number	Issue Year	Title	Assignee Name
IBM_1985	4503537	1985	Parallel path self-testing system	International Business Machines Corporation (Armonk, NY)
TI_1989	4872169	1989	Hierarchical scan selection	Texas Instruments Incorporated (Dallas, TX)
IBM_1976	3983538	1976	Universal LSI array logic modules with integral storage array and variable autonomous sequencing	International Business Machines Corporation (Armonk, NY)
IBM_1984	4441075	1984	Circuit arrangement which permits the testing of each individual chip and interchip connection in a high density packaging structure having a plurality of interconnected chips, without any physical disconnection	International Business Machines Corporation (Armonk, NY)
IBM_1981	4298980	1981	LSI Circuitry conforming to level sensitive scan design (LSSD) rules and method of testing same	International Business Machines Corporation (Armonk, NY)
TI_1994	5329471	1994	Emulation devices, systems and methods utilizing state machines	Texas Instruments Incorporated (Dallas, TX)

Table 2.A CPM patents

Patent Code	Patent Number	Issue Year	Title	Assignee Name
WESTINGHOUSE_1966	3287703	1966	Computer	Westinghouse Electric Corp. (Pittsburgh, PA)
RCA_1969	3462742	1969	Computer system adapted to be constructed of large integrated circuit arrays	Rca Corporation (Delware)
DATAGENERAL_1973	3737866	1973	Data storage and retrieval system	Data General Corporation (Southboro, MA)
TI_1973	3757306	1973	Computing system CPU	Texas Instruments Incorporated (Dallas, TX)
IBM_1974	3798606	1974	Bit partitioned monolithic circuit computer system	International Business Machines Corporation (Armonk, NY)
IBM_1976	3983538	1976	Universal LSI array logic modules with integral storage array and variable autonomous sequencing	International Business Machines Corporation (Armonk, NY)
IBM_1977	4051353	1977	Accordion shift register and its application in the implementation of level sensitive logic system	International Business Machines Corporation (Armonk, NY)
IBM_1980	4225957	1980	Testing macros embedded in LSI chips	International Business Machines Corporation (Armonk, NY)
IBM_1981	4298980	1981	LSI Circuitry conforming to level sensitive scan design (LSSD) rules and method of testing same	International Business Machines Corporation (Armonk, NY)
IBM_1985	4503537	1985	Parallel path self-testing system	International Business Machines Corporation (Armonk, NY)
TI_1987	4710931	1987	Partitioned scan-testing system	Texas Instruments Incorporated (Dallas, TX)
TI_1989	4872169	1989	Hierarchical scan selection	Texas Instruments Incorporated (Dallas, TX))
TI_1992	5103450	1992	Event qualified testing protocols for integrated circuits	Texas Instruments Incorporated (Dallas, TX)
TI_1994	5329471	1994	Emulation devices, systems and methods utilizing state machines	Texas Instruments Incorporated (Dallas, TX))
INTEL_1995	5479652	1995	Microprocessor with an external command mode for diagnosis and debugging	Intel Corporation (Santa Clara, CA)
HP_1999	5867644	1999	System and method for on-chip debug support and performance monitoring in a microprocessor	Hewlett Packard Company (Palo Alto, CA)
AMD_1999	5978902	1999	Debug interface including operating system access of a serial/parallel debug port	Advanced Micro Devices, Inc. (Sunnyvale, CA)
MOTOROLA_2000	6145122	2000	Development interface for a data processor	Motorola, Inc. (Schaumburg, IL)
STM_2002	6415344	2002	System and method for on-chip communication	STMicroelectronics Limited (Almondsbury, GB)
ACTEL_2006	7034569	2006	Programmable system on a chip for power-supply voltage and current monitoring and control	Actel Corporation (Mountain View, CA)
ACTEL_2007	7256610	2007	Programmable system on a chip for temperature monitoring and control	Actel Corporation (Mountain View, CA)
ACTEL_2008	7446560	2008	Programmable system on a chip for temperature monitoring and control	Actel Corporation (Mountain View, CA)