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

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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.

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

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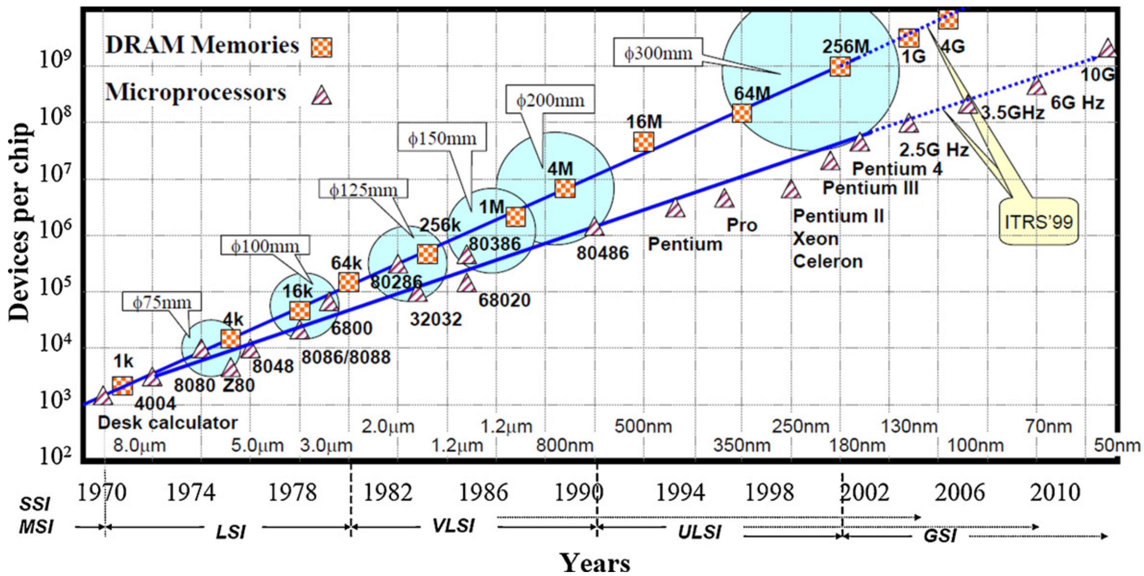

Fig. 1. Moore's Law and miniaturization trajectory.

Source: Zheng (2008).

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; Barberá 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, cumulativeness 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. Fig. 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 technologies[1] allowed scaling down, 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.

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

[1] 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 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.