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From Fabless to Fabs Everywhere? Semiconductor Global Value Chains in Transition

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> "Everyone wants to build their own semiconductor factories, but is that realistic? If it was that easy, there would be chipmaking plants everywhere in the world already.."
> (CC Wei, CEO, TSMC, 17 December 2022)

4.1 Introduction

It is a common phenomenon that an integrated circuits (IC) – known as a semiconductor chip – used in a personal computer (PC), a mobile phone, an electric vehicle, or simply a remote-controlled toy dog is produced along a complex and highly globalized value chain. Semiconductor firms located in various economies and regions jointly finish the necessary tasks of design, wafer fabrication, assembly, packaging, and testing chips before their distribution to downstream manufacturers of final devices. In today's semiconductor GVCs, no economy has an autonomous and fully integrated semiconductor sector that needs neither foreign technologies nor materials. As will be evident throughout this chapter, all economies are interdependent in the global semiconductor industry. But not all of them need to have, or are capable of running, efficient chipmaking factories known as "fabs". Indeed, over the last three decades, the internationalization and fragmentation of semiconductor production has been largely driven by the "fabless revolution" starting in the late 1980s. The evolving sophistication of semiconductor technology and the desire for economic efficiency have further intensified the international division of labor in this high-tech industry.

One key driver has been the exponentially higher cost of building new fabs. From about $200 million in 1983, a bleeding-edge fab in the early 2020s cost well over $20 billion to build and as much to operate in the next ten years. This multibillion-dollar price tag

for a new fab has therefore become a major entry barrier in the industry.
At the 1991 In-Stat Forum held in Arizona, Jerry Sanders, the co-founder and former chairman of Advanced Micro Devices (AMD), proudly claimed that “Real men have fabs”! The statement reflects his belief (and that of AMD’s then market-leading competitor Intel) that integrating chip design and chip manufacturing was crucial for a top-tier semiconductor company, and massive investment in fabs was necessary for succeeding in this highly competitive industry. However, technological innovation in chip design and production has led to changing industrial organization and the rise of semiconductor GVCs. Instead of building expensive fabs, many start-ups in Silicon Valley entered the industry by specializing in IC designs and outsourcing chip manufacturing tasks to established firms in the US and elsewhere. In short, they were “fabless” chip design firms right from the start. During the period of 1985 to 1994, about 250 fabless firms emerged in Silicon Valley alone.

The rise of these fabless semiconductor firms challenged the then conventional integrated device manufacturing (IDM) model, where a large American semiconductor firm, such as IBM Microelectronics, Intel, and Texas Instruments, internalized all tasks necessary for producing chips in their in-house fabs; it also accelerated the spatial fragmentation of production and the globalization of the semiconductor industry. Represented by such industry leaders as Apple, Nvidia, and Qualcomm, fabless now has become a mainstream business model in the global semiconductor industry. Even AMD, the company co-founded by Jerry Sanders and several others from Fairchild Semiconductor in May 1969, has spun off all fabrication facilities and turned into fabless as of 2009. The transformation saved AMD from the brink of bankruptcy. In 2020, fabless semiconductor firms’ revenue totalled $153 billion, about one third of the entire industry and far higher than “merely” 7.6% in 2000.

The emergence of the fabless model has enhanced the functional and geographical specialization of the industry at the level of tasks. For instance, American fabless firms are specializing in IC designs and marketing, while semiconductor firms in East Asia are responsible for wafer fabrication and downstream production activities. As a result, wafer fabrication in the global semiconductor industry has become highly concentrated in Chinese Taipei; Republic of Korea; the People’s Republic of China (PRC); Japan; and Singapore; which together accounted for some 80% of the world’s total wafer fabrication capacity in the 2018-2023 period. TSMC has emerged as the world’s largest pureplay foundry from this “fabless revolution” and accounted for well over 85% of the most advanced chips produced in 2022.

Global Value Chain Development Report 2021 concludes that geopolitical tensions stemming from the trade tensions between the United States and the PRC since 2018, along with the COVID-19 pandemic, have been driving geographic reconfigurations of global value chains. The semiconductor industry is no exception. The massive disruptions worldwide during the COVID-19 pandemic led to severe chip shortages that became the key concern of policy makers and business leaders in relation to the resilience of the existing semiconductor GVCs. As the rivalry between the world's two largest economies, the US and the PRC, has intensified in both political and economic spheres, this high concentration of semiconductor fabs in East Asia is now regarded as a major vulnerability in trade disputes and geopolitical tensions. Semiconductors are a backbone of modern industries, and the advancement in semiconductor technology determines how far human beings can go in artificial intelligence, autonomous mobility, and next-generation telecommunications. Maintaining a domestic manufacturing capacity for the most advanced chips has seemingly become a critical imperative for national security among major economies.

To strengthen the resilience of semiconductor supply chains by building domestic chip manufacturing capacity, governments of major economies have resorted to industrial policy by providing massive fiscal subsidies and tax incentives. The 2022 CHIPS and Scientific Act of the US promises a $52 billion subsidy for revitalizing American semiconductor manufacturing and strengthening its competitiveness in IC research and design. To reduce the European Union's reliance on American and East Asian semiconductor manufacturers, the European parliament approved the €43 billion European Chips Act on 18 April 2023, which intends to increase the share of semiconductors manufactured in Europe from 10% to 20% by 2030. Made in the PRC 2025, an official document on the strategy of the PRC's future industry development unveiled in 2015, lists semiconductors as one of the key future industries and sets a target of 70% self-sufficiency for semiconductor production by 2025.

Other economies are also seeking greater self-sufficiency in chip making. Japan used to capture more than 50% of the world's semiconductor revenue in the 1980s, but this share dropped precipitously during the two "lost decades". In the current global race in building new fabs, the Japanese government has designated semiconductors as critical to economic activity and national security and set aside ¥2 trillion to subsidize firms up to 50% of their investment in fabrication facilities, chipmaking equipment, and semiconductor materials. Republic of Korea has set its sights on expanding its K-Semiconductor Belt with tax credits to attract up to $450 billion private investment by 2030. And even though India is not a major player in the semiconductor industry, the Modi government approved the Semicon India Program in December 2021, with a $10 billion incentive scheme for developing a sustainable semiconductor and display manufacturing ecosystem in India. All these initiatives are over and above the firm-specific investment by the industry's top three players every year during the 2021-2023 period: Samsung ($36-40 billion), TSMC ($30-36 billion), and Intel ($20-27 billion).

In 2023, the global semiconductor industry has clearly reached a new critical juncture, where resilience, national security, and competition for technology leadership are challenging the highly popular and efficient fabless model of chip design and fabrication. The rise of this new techno-nationalism is transforming the highly internationalized semiconductor industry into the age of "real nation-states should have fabs". But as noted in this chapter's opening quote by CC Wei, TSMC's CEO, this techno-nationalist goal of "Everyone wants to build their own semiconductor factories" does not seem to be realistic.

The chapter is divided into six main sections before some concluding remarks. Section one describes current semiconductor GVCs and value distribution along a series of necessary tasks, including pre-competitive R&D; design of integrated circuits (IC); wafer fabrication; assembly, packaging and testing (APT); electronic design automation (EDA) and core intellectual property; semiconductor manufacturing equipment (SME); and materials and chemicals.

Section two reviews participation in semiconductor GVCs by economy. Massive innovations in semiconductor technologies have resulted in extremely high costs of cutting-edge chip design and manufacturing since 2010. Only a few market leaders dominate in the different segments of semiconductor global value chains, from design software and intellectual property to materials and equipment suppliers. American firms play a nearly monopolistic role in IC design software, while a small group of highly specialized firms dominate equipment manufacturers. At the same time, the ever-more sophisticated processes of chip design and production and their concomitant ecosystems of highly specialized firms today mean that no single economy can be self-sufficient in the entire semiconductor value chain.

Section three reviews briefly the evolution of the semiconductor industry from an IDM model to a fabless one. Market shifts in industrial applications towards computers/data storage and wireless communications since the 2010s are crucial in explaining the rapid growth of leading fabless firms, foundry producers, and IDM firms in microprocessors and memory chips. We emphasize that firm-specific competitive advantage, financial market pressures for economic efficiency, and changing market dynamics are the key drivers for this "fabless revolution" in the American semiconductor industry and, subsequently, the high concentration of semiconductor manufacturing facilities in East Asia. This history underlines the importance of vertical disintegration in driving the globalization of the semiconductor industry. These key factors also explain the continual hybrid co-existence of IDMs and fabless firms in different product segments (e.g. logic vs. memory chips) and industrial applications (e.g. computer/storage vs. automotive) through to the early 2020s.

In section four, we examine the role of the government in developing and, in some cases, steering its national semiconductor industry. While government expenditure in research and development (R&D) and defence procurement was significant in the industry's early development in the US and Western Europe, industrial development in East Asia benefited substantially from direct government subsidies and favorable industrial policies, particularly at the early stage. To address this importance of the "visible hand" in nurturing the semiconductor industry, we briefly discuss the historical experiences of Japan, Republic of Korea, Chinese Taipei, and Singapore up to the 1990s and the PRC since the 2010s. Section five continues with this discussion and makes the case that the dominance of East Asia in chip manufacturing since the 2010s has less to do with government-led initiatives of industrial catching-up and much more to do with firm-specific investment in capabilities and changing market dynamics. By pursuing specialization in foundry production and memory chips, East Asian firms have deepened their trust relationships with key fabless/OEM firms and their integration with global production networks in different and yet high growth industrial markets (e.g. ICT, automotive, artificial intelligence, robotics, industrial electronics).

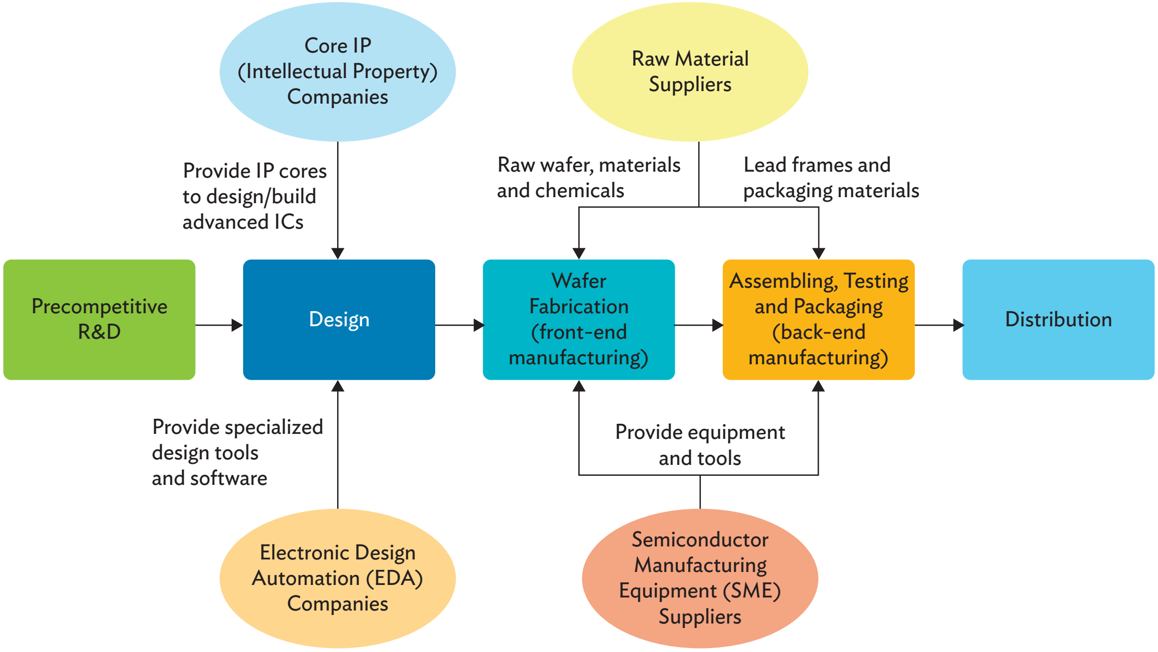
Section six focuses on the most recent years when the global semiconductor industry is increasingly shaped by techno-nationalist initiatives, as more national economies want to have own fabs for national security and risk mitigation reasons. We document policies and subsidies offered by major economies for strengthening the resilience of semiconductor supply chains and enhancing national capacity in semiconductor manufacturing and research. The pursuit of "fabs everywhere" through technological sovereignty is unlikely to be realistic because of the complex organization of existing semiconductor GVCs and the extreme demand for technological capabilities and capital investment in cutting-edge chipmaking. The race in building fabs everywhere will likely result in a fragmented rather than integrated global semiconductor market, which would inevitably undermine the sector's economies of scale and trust relationships and, even worse, lead to excess supply in semiconductor manufacturing capacity worldwide. In the concluding section, we summarize the key findings and outline some possible scenarios for the future of semiconductor global value chains.

4.2 Semiconductor Global Value Chains: Segments and Value Added Structure

There are four major segments in semiconductor global value chains, supported by a highly specialized ecosystem of three main upstream inputs, such that the entire semiconductor value chain consists of seven distinct types of activities illustrated in Figure 4.1. Together, they make up the enormous global semiconductor market of $485 billion sales in 2018, $570 billion in 2022, and a projected over $1 trillion by 2030. The following will discuss each of these seven distinctive activities (see also Suleman and Yagci, 2022a).

(i) Pre-competitive R&D. This activity aims at understanding fundamental processes that lay the foundation for chip design and manufacturing technology. It exhibits significant positive externalities and is clearly distinct from, and yet complementary with, proprietary and competitive industrial R&D. Governments often play an important role in advancing basic semiconductor research. In the US, for example, a number of major breakthroughs have emerged from federally funded research programs. The foundation for the extreme ultraviolet (EUV) photolithography technology, which currently is indispensable in manufacturing leading-edge semiconductors at 10 nm (nanometer) or

Figure 4.1: The Basic Structure of Semiconductor Value Chains



Sources: Adapted from SIA (2016: Figures 1 and 2); Capri (2020: Graph IV); and BCG and SIA (2021: Exhibit 4).

lower process nodes, was laid by the National Extreme Ultraviolet Lithography Program (NEUVLP) funded by the US Department of Energy in the 1990s. The gallium arsenide (GaAs) transistor, one of the critical technologies underlying smartphone chips, was developed in the Microwave and Millimeter Wave Integrated Circuit (MIMIC) program of the Department of Defense in the late 1980s.

(ii) Integrated circuits design. Designing semiconductors is highly knowledge- and skill-intensive, accounting for some 53% of total R&D expenditure and contributing to over 50% of the industry's total value-added in 2019 (BCG and SIA, 2021). Firms involved in chip design range from IDM firms to fabless design houses, and other new players. Section three will explain in depth the rise of these fabless firms and the changing fortunes in the global semiconductor industry since the late 1980s. Suffice it to say here that chip design takes place in IDM firms (e.g. Intel and Samsung), fabless firms (investing 10 to 20% of revenue in R&D), new players such as systems or platform companies (e.g. Apple, Alibaba, Alphabet, Amazon, Facebook, and so on) and industrial firms (e.g. Tesla). Designing cutting-edge chips, such as state-of-the-art processors or systems-on-chips, requires years of concerted effort by hundreds of engineers and is extremely costly. For example, in 2020 the cost of designing a 5 nm node chip exceeded $540 million. To amortize high design costs and to achieve economies of scale, most firms focus on designing cutting-edge general-purpose chips critical in end-market ICT devices, such as PCs and smartphones, and AI servers.

The US is by far the global leader in chip design, with a commanding 68% market share in the fabless segment in 2021 (IC Insights, 2022). With a 21% market share, Chinese Taipei also plays a prominent role in chip design. The PRC had a 15% fabless market share in 2020, but it plummeted to 9% in 2021 as a result of US sanctions on Huawei and its design subsidiary HiSilicon (Clarke, 2022). Republic of Korea, Europe, and Japan are relatively weak in the fabless IC design market, with inconsequential shares of about 1% each.

(iii) Wafer fabrication. Front-end chip manufacturing is one of the most critical segments in the semiconductor value chain, and is currently the focus of much national policy and security attention. Varying across many chip types, wafer fabrication involves 400 to 1,400 steps and takes an average of 12 weeks. Using hundreds of different inputs – including raw silicon wafers, commodity/specialty chemicals, bulk gas, and so on – as well as dozens of very expensive and proprietary processing and testing equipment/tools, the wafer fabrication process spans several stages, which, depending on the complexity of the circuit design, are often repeated hundreds of times. In 2023, a completed 12-inch wafer can contain several hundred of the most advanced chip cores in thumb-nail size, each holding ten or more billion transistors separated by a width of 3 nanometer!

Wafer fabrication, especially at the bleeding-edge nodes (5 nm in 2020, 3 nm in 2023, and an anticipated 2nm by 2025), is extremely capital-intensive and requires enormous upfront investments of tens of billions of US dollars to build highly specialized fabs. Capital expenditure of a pureplay foundry typically amounts to 30 to 40% of its annual revenue, and a state-of-the-art fab of standard capacity currently requires a capital expenditure of approximately $5 billion (for analogue fabs) to $20 billion or more (for logic/memory fabs). Wafer fabrication is also highly knowledge-intensive. Operating a fab at advanced nodes requires deep knowledge of complex processes spanning multiple scientific and engineering disciplines and necessitates the amassing of extensive technological resources and human expertise. Even Intel, the long-established top-tier wafer producer and the inventor of microprocessors in 1971, has encountered repeated setbacks in developing advanced process nodes below 10 nm since the late 2010s, and is still struggling to catch up with leading chipmakers such as Chinese Taipei's TSMC and the Republic of Korea's Samsung.

(iv) Assembly, packaging, and testing (APT). Commonly known as "back-end manufacturing", APT entails transforming silicon wafers produced by front-end fabs into finished chips ready to be fitted into electronic modules and final devices. APT activities are often outsourced to specialist firms that slice finished silicon wafers into individual chips, package them into protective shells, and test for defects before shipping them to electronics manufacturers. Back-end manufacturing is less capital-intensive and employs vastly more labor than front-end manufacturing. The total APT market size is around $30 billion (Kleinhans and Baisakova, 2020). Despite significant industry consolidation over the last decade, the APT market remains a less concentrated segment due to lower entry barriers. Most APT activities take place in Chinese Taipei (53% in 2019) and the PRC (more than 20%). Even Amkor, the only large APT firm headquartered in the US (in Arizona), is of South Korean origin, and 19 of its 20 manufacturing operations are located in East and Southeast Asia.

(v) Electronic design automation (EDA) and core IP. Fabless design houses rely heavily on access to EDA software and core intellectual property. EDA software, widely used in the design of almost all types of chips, becomes particularly complex and technology- and knowledge-intensive for the most advanced nodes. To keep up with the industry's extremely short innovation cycles, EDA software vendors have the highest R&D spending (on average, over 35% of revenue) in the entire semiconductor value chain (Nenni and McLellan, 2019). Although the EDA sector accounts for only around 3% of the semiconductor market, EDA software vendors have been instrumental in the continuous development of novel processes, playing a disproportionately large role in the industry and its ecosystem. These features have led to an oligopolistic market structure, where three US-based firms – Cadence, Synopsys, and Mentor (acquired by Siemens in 2017) – dominate the entire EDA market, taking a total of 75% of the market share in 2021 (TrendForce, 2022). Given this extreme market concentration and heavy reliance on vendors from a single country, the EDA segment has clearly become a supply chain dependency or "chokepoint" that is highly vulnerable to geopolitical conflicts.

In Figure 4.1, "core IP" refers to proprietary and reusable design of functional components/modules of ICs. With given interfaces and functionalities (IP blocks), these designs such as circuit diagrams are licensed by core IP suppliers to chip designers, who then integrate them into their chip layout as needed. Somewhat overlapping with the EDA segment, core IP is also highly R&D intensive and heavily concentrated in the hands of a few British and American firms, with UK-based ARM topping the list with a 40% market share in 2020, along with American EDA providers Synopsys (20%) and Cadence (6%) (Clarke, 2022).

(vi) Semiconductor manufacturing equipment (SME). Semiconductor manufacturing involves more than 50 types of highly sophisticated equipment supplied by various producers, each specializing in particular steps/types of the complex chip manufacturing process. Developing and fabricating these advanced, high-precision manufacturing equipment necessitates large investments in R&D. SME firms typically invest 10 to 15% of their revenue in R&D. In 2019, the segment accounted for 9% of the entire industry's R&D, 3% of total capital expenditure, and 12% of value added (BCG and SIA, 2021). The size of the global SME industry is estimated to be $103 billion in 2021, up from $71 billion in 2020 (SEMI, 2022a) and $64 billion in 2019. Given its high R&D intensity, it is not surprising that the segment is also dominated by five top SME suppliers that account for more than 70% of the market share. With revenue ranging from $5 to $15 billion in 2019, these five SME suppliers are Applied Materials (largest), Lam Research, and KLA (smallest) from the US, ASML from the Netherlands (see Box 4.1), and Tokyo Electron from Japan.

Box 4.1: ASML and the Dominant Supplier of Semiconductor Lithography Equipment

ASML was founded in 1984 as a joint venture among three Dutch entities – electronics giant Philips, semiconductor equipment manufacturer ASMI (Advanced Semiconductor Materials International), and state-owned private equity fund MIP. Specializing in the development and manufacturing of lithography machines for the past four decades, ASML has established itself as the largest supplier for the semiconductor industry. With $23 billion revenue in 2022, ASML holds more than 90% of the lithography market and is the world's sole supplier of extreme ultraviolet (EUV) lithography machines. Building on Philips' R&D, ASML's first lithography machine (PAS 2000 stepper) was launched in its founding year. In 1991, ASML launched its highly successful PAS 5500 system, bringing on board key customers (such as IBM and Micron from the US) to turn a profit, laying the foundation for its ultimate dominance. The development of immersion lithography and EUV lithography were the next two critical steps in ASML's rise to its current global dominance. In 2003, ASML rolled out the world's first prototype immersion machine (Twinscan AT. 1150i), well ahead of Nikon's launch of both its dry 157 and 193 immersion lithography. In 2004, TSMC became the first manufacturer to produce 90 nm-node chips using ASML's immersion lithography. By 2006, ASML had replaced Nikon as the No.1 lithography vendor.

The second critical step for ASML was the invention of revolutionary EUV lithography that enables chip manufacturing at bleeding-edge process nodes. ASML kicked off its EUV program in 1997. In 1999, ASML was allowed by the US government to participate in the more powerful US-based EUV lithography R&D consortium "EUV LLC", consisting of a few key US-based semiconductor manufacturers (e.g. Intel, AMD, and Motorola) and researchers from three national labs (Lawrence Livermore, Sandia, and Lawrence Berkeley) that aimed to bring EUV lithography to the market by 2006 or earlier. In 2010, ASML delivered the first pre-production EUV system (TWINSCAN NXE:3100) to Samsung, marking the beginning of a new era of lithography. The development became so costly and complicated that ASML invited its three most important customers – Intel, Samsung, and TSMC – to join its Customer Co-Investment Program. In 2012, the three agreed to fund ASML's EUV R&D in exchange for stakes in ASML. Having acquired the American lithography light sources manufacturer, Cymer, in 2013, ASML's development of EUV accelerated. In the same year, ASML shipped the first EUV production system – the TWINSCAN NXE:3300 (second generation EUV), with the third-generation EUV system (NXE:3350) following in 2015.

At the beginning of 2020, ASML shipped its 100th EUV system as EUV entered high volume manufacturing. In early 2021, the most advanced EUV photolithography systems from ASML cost 200 million euros. Still, these EUV systems were well oversubscribed. TSMC's most advanced 3 nm Fab 18 in Tainan alone required more than 50 EUV sets, but ASML could produce only about 31 sets in 2020, 42 sets in 2021, 55 sets in 2022, and estimated 60 sets in 2023 due to its own supply chain constraints.

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Similar to SME supply, the demand for SME is also highly concentrated in the hands of only a few cutting-edge semiconductor manufacturers, an indication of their very close trust relationships embedded in mutually supportive ecosystems. Currently, only three giants – TSMC, Samsung, and Intel – are building bleeding-edge fabs and investing in the necessary advanced SME. The customer base for cutting-edge SME is thus relatively small and highly dependent on trade relations among customers from Chinese Taipei, Republic of Korea, the US, and increasingly the PRC (catching up in advanced chips manufacturing for self-reliance). In 2019, ASML's sales in Chinese Taipei and the Republic of Korea accounted for 64% of its global sales; Tokyo Electron generated 57% of its sales from the PRC, Republic of Korea, and Chinese Taipei; and Applied Materials' sales to TSMC alone accounted for 14% of its annual sales (Kleinhans and Baisakova, 2020). In short, while the US, Europe, and Japan are the leading locations for the production/supply of SME, they depend heavily on trusted customers in East Asia, i.e. leading-edge fabs in Chinese Taipei, Republic of Korea, and the PRC. This in turn indicates how interdependent the semiconductor global value chain is.

(vii) Materials and chemicals. Semiconductor manufacturers necessarily rely on specialized suppliers of materials and chemicals, the majority of which are large firms serving multiple industries. Semiconductor manufacturing uses more than 300 different inputs (materials, chemicals, and gases) for various process steps such as circuit patterning, deposition, etching, polishing, and cleaning, many of which are produced with cutting-edge technologies. For example, polysilicon, used to make silicon ingots that are then sliced into silicon wafers, has extremely stringent purity requirements. There are only four technologically capable major suppliers that account for over 90% of the global market share (BCG and SIA, 2021).

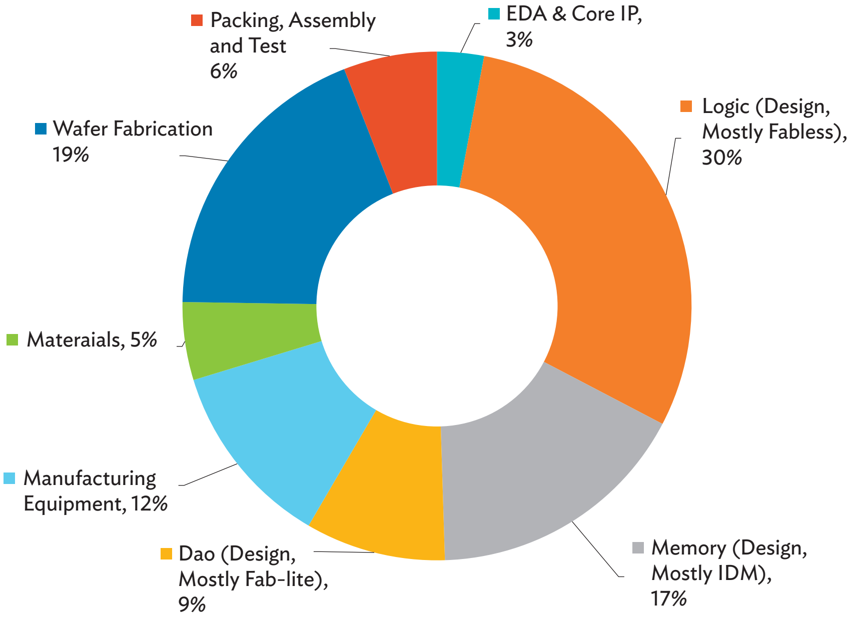
In 2019, the global market for semiconductor manufacturing materials used in front-end and back-end activities was estimated to be $52 billion. Many of the highly specialized materials are produced in mega-plants that require massive investments and exhibit strong economies of scale/scope. For the world's leading suppliers of silicon wafers, photoresists, and gases, capital expenditure typically accounts for 13% to 20% of their annual revenue. With many Japanese companies (e.g. Shin-Etsu, Sumitomo Chemicals, and Mitsui Chemicals) dominating in some sub-segments of this market, Japan is the most significant country supplier of semiconductor materials and chemicals, taking a 24% market share in the global market, followed by the US at 19%. European firms, such as BASF, Linde, and Merck KGaA, are also important chemicals suppliers (Khan et al., 2021).

These seven categories demonstrate the highly specialized semiconductor industry structure. In addition, there are three types of chips (i.e. logic, memory, and DAO – discrete, analog, and optoelectronics and sensors) that can be further differentiated at the design stage. Leaving aside pre-competitive R&D, which is largely a government function, the share of value-added in semiconductors can be broken down into eight categories illustrated in Figure 4.2. The design stage is by far the most important, divided between the design of logic chips (30% of semiconductor value added), memory chips (17%), and DAO chips (9%). This is followed, in terms of share in value-added, by wafer fabrication (19%) and manufacturing equipment (12%). The value-added of APT (6%), materials (5%), and EDA and core IP (3%) is much smaller.

4.3 Semiconductor Global Value Chains: Major Economy Participants

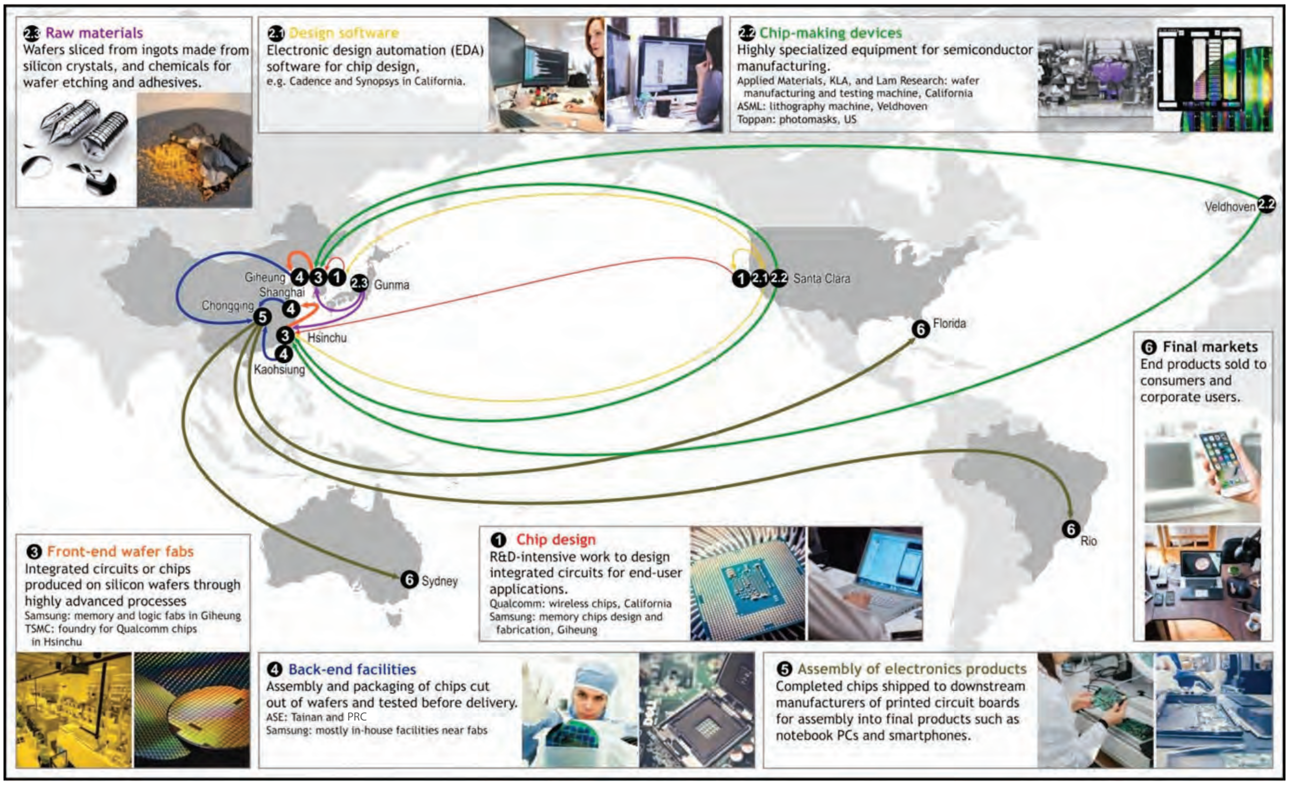
Over the past two decades, the semiconductor value chain has evolved into one of the most "global" value chains. Illustrated in a simple and stylized way in Figure 4.3, these rather complex semiconductor GVCs connect different world regions and continents and serve as crucial intermediate goods for the production of ICT and other end products for

Figure 4.2: Semiconductor Value Added by Activity, 2019 (in percent)



Source: SIA (2021).

Figure 4.3: Semiconductor Global Value Chains and the Production Networks of ICT End Products



2.3 Raw materials
Wafers sliced from ingots made from silicon crystals, and chemicals for wafer etching and adhesives.

2.1 Design software
Electronic design automation (EDA) software for chip design,
e.g. Cadence and Synopsys in California.

2.2 Chip-making devices
Highly specialized equipment for semiconductor manufacturing.
Applied Materials, KLA, and Lam Research: wafer manufacturing and testing machine, California
ASML: lithography machine, Veldhoven
Toppan: photomasks, US

❻ Final markets
End products sold to consumers and corporate users.

❸ Front-end wafer fabs
Integrated circuits or chips produced on silicon wafers through highly advanced processes
Samsung: memory and logic fabs in Giheung
TSMC: foundry for Qualcomm chips in Hsinchu

❶ Chip design
R&D-intensive work to design integrated circuits for end-user applications.
Qualcomm: wireless chips, California
Samsung: memory chips design and fabrication, Giheung

❹ Back-end facilities
Assembly and packaging of chips cut out of wafers and tested before delivery.
ASE: Tainan and PRC
Samsung: mostly in-house facilities near fabs

❺ Assembly of electronics products
Completed chips shipped to downstream manufacturers of printed circuit boards for assembly into final products such as notebook PCs and smartphones.

Source: Yeung (2022a: Figure 4.2; p.141). Copyright©2022, Stanford University Press, reproduced with permission.

diverse global markets. In 2019, in terms of value-adding operations, there were six major economies/regions (the US, Europe, the PRC, Republic of Korea, Japan, Chinese Taipei, and the rest of the World) engaging in semiconductor GVCs, each contributing 8% or more of the industry's total value added (BCG and SIA, 2021; Suleman and Yagci, 2022a). As companies in different regions specialize in distinct value-adding segments, a typical semiconductor production process involves most, if not all, of the major economies and the products may cross borders 70 times (Table 4.1 further illustrates the distribution of the eight categories of value-added activities in 2021).

The US is the global leader in the most knowledge/R&D-intensive activities, including EDA and core IP (72%), logic chip design (67%), and SME (42%), where its share is higher than its overall share in the semiconductor value added (35%). Indeed, as mentioned earlier, US firms have a commanding presence in the fabless logic chip design segment, which adds the most value among the eight activities in Figure 4.2. Of the world's top 10 fabless design companies in 2021, six are American firms (Qualcomm, Nvidia, Broadcom, AMD, Marvell, and Xilinx) (IC Insights, 2022).

Table 4.1: Domestic/Regional Value Added in the Semiconductor Value Chain by Activity, 2021 (in percent)

	US	Europe	PRC	S. Korea	Japan	Chinese Taipei	Others[1]
EDA & core IP	72%	20%	3%	-	-	-	-
Design (logic), mostly fabless	67%	8%	6%	4%	4%	9%	3%
Design (memory), mostly IDM	28%	-	-	58%	8%	4%	-
Design (Dao), fab-lite	37%	18%	9%	6%	21%	4%	6%
Design subtotal	49%	8%	5%	20%	9%	6%	3%
Equipment	42%	21%	-	3%	27%	-	5%
Materials	10%	6%	19%	17%	14%	23%	12%
Wafer fabrication	11%	9%	21%	17%	16%	19%	7%
Assembly, packaging & testing (APT)	5%	4%	38%	9%	6%	19%	19%
Overall	35%	10%	11%	16%	13%	10%	5%

[1] Others includes Israel, Singapore, and the rest of the world.

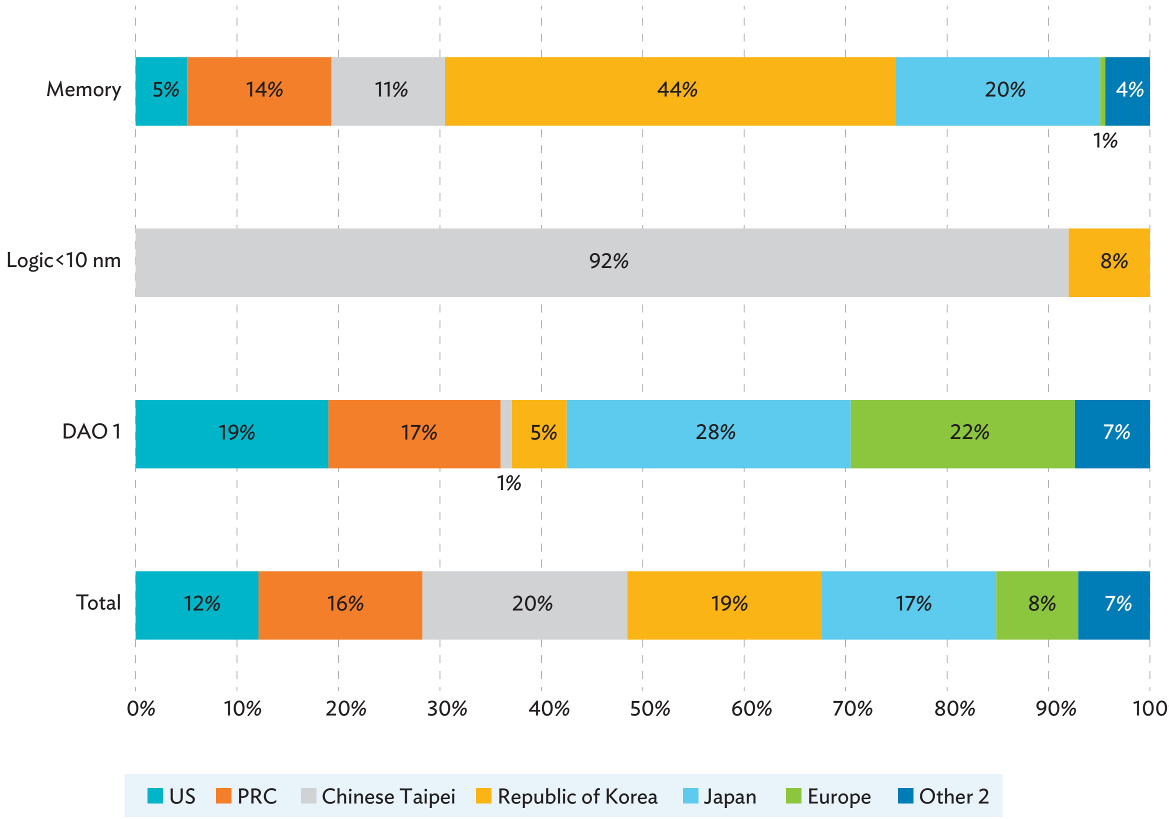
Note: Regional breakdown on EDA, design, manufacturing equipment, and raw materials is based on company revenue and company headquarters location. Wafer fabrication and assembly, packaging, and testing are based on installed capacity and geographic location of facilities.

Source: SIA (2023).

Those more capital- and labor-intensive activities, such as semiconductor front-end (wafer fabrication) and back-end (APT) manufacturing and semiconductor materials, are largely concentrated in East Asia, including the PRC, Chinese Taipei, Republic of Korea, Singapore, and Japan. The most labor-intensive activity of APT is carried out mainly in the PRC (38%), Chinese Taipei (27%), and so on (e.g. Malaysia). About 75% of the capacity for wafer fabrication is concentrated in East Asia – respectively 19% in Chinese Taipei, 17% in the Republic of Korea, 16% in Japan, and 21% in the PRC. The same four locations also account for more than 70% of the shares in the capital-intensive segment of the semiconductor materials. In addition, Japan has a sizable share both in the segment of SME (27%) and in DAO products (21%), whereas Republic of Korea has an overwhelming share (58%) in the increasingly commoditized memory products, where the production has been particularly capital-intensive and is dominated by IDM firms (98%).

In contrast, the US share in the labor-intensive APT segment is much smaller (5%), and its share in capital-intensive wafer manufacturing (11%) or semiconductor materials (10%) is considerably lower than its overall share of value-added in the semiconductor industry (Table 4.1). With a mere 10% share in total value-added, European firms play a relatively minor role in logic and memory chip supply. However, they show considerable strength in SME (21%), EDA and IP core (20%), DAO products (18%), and especially in automotive ICs (Kleinhans and Baisakova, 2020), but they have fallen behind in the two activities that add the most value, namely logic chip design (8%) and wafer fabrication (9%). The regional distribution of wafer capacity, particularly the high concentration of leading-edge capacity in East Asia, has been the focus of much attention in recent years and merits a more in-depth discussion (see also later in section five). In Figure 4.4, all the leading-edge logic chip capacity in 2019 was located either in Chinese Taipei (92%) or in the

Figure 4.4: Breakdown of the Global Wafer Fabrication Capacity by Region, 2019 (in percent)



[1] Discrete, analogue, and optoelectronics and sensors; [2] Others includes Israel, Singapore, and the rest of the world.

Note: The breakdown is based on location of facilities regardless of the location of company headquarter. For example, if Samsung sets up a fab in the U.S., the capacity is counted as North American capacity, not capacity in the Republic of Korea.

Source: BCG and SIA (2021).

Republic of Korea (8%). And yet this capacity for high-end chips below 10 nm represented only 2% of global semiconductor manufacturing capacity, whereas logic chips as a whole accounted for some 41% of global capacity. Moreover, Republic of Korea dominated in memory chip capacity (44%). Lastly, Japan's DAO chip capacity (28%) is the highest among all regions, followed by Europe (22%), despite US dominance in DAO design.

Given this current high geographical concentration of wafer capacity in general and leading-edge capacity in East Asia, it is obvious that natural disasters and geopolitical conflicts can pose significant threats to the configurations and stability of semiconductor GVCs, which are now widely perceived as critical matters of economic growth and national security. Before considering such chokepoints and risks in today's highly interdependent semiconductor GVCs in section six on techno-nationalism, we analyze in the next three sections (i) the changing organization of the semiconductor industry associated with the "fabless revolution", (ii) the role of the government in industry development, and (iii) the rise of East Asia in semiconductor GVCs.

4.4 Changing Fortunes in the Global Semiconductor Industry: From Integrated Fabs to the "Fabless Revolution"

The modern era of semiconductors began in the US with the almost simultaneous invention of the silicon-based bipolar integrated circuit by Jack Kilby from Texas Instruments in February 1959 and, four months later, Robert Noyce from Fairchild Semiconductor (Braun and MacDonald, 1982). By the end of 1961, some 150 to 200 semiconductor operations were spun off from a handful of these firms that had existed in the mid-1950s.

Throughout the 1960s, many smaller American firms entered into the semiconductor market as IDM producers with their own chip fabrication facilities (fabs), including two famous Fairchild "spin offs" – Intel in 1968 and AMD in 1969. Two important technological breakthroughs occurred soon at the newly founded Intel. In October 1970, Intel introduced the world's first 1KB DRAM memory chip Intel 1103. One year later, the 4-bit microprocessor Intel 4004 was born. These would have very lasting effects on Intel and the global semiconductor industry even 50 years later. In 1972, Intel's first mass-produced 1KB DRAM became the world's best-selling memory chip, contributing to 90% of its $23.4 million revenue. Half a century later in 2021, Intel remained the world's top semiconductor firm in microprocessors and achieved a record revenue of $79 billion (see Box 4.2). But by now, other semiconductor firms – many without their own integrated fabs or "fabless" – have also come to the forefront of this much more globalized industry.

Box 4.2: Intel and the American Dominance in Integrated Device Manufacturing

As the classic case of IDM firms in semiconductors, Intel remains faithful to its vertical integration strategy implemented ever since its founding in 1968 and epitomizes this close integration of R&D and manufacturing. This strategy of co-locating development and manufacturing was envisioned by Robert Noyce and Gordon Moore at their co-founding of Intel in Mountain View, California, on 18 July 1968 (Moore and Davis, 2004). Intel exited the memory business in 1986 even though its very first invention was the world's first 1KB DRAM memory chip – the Intel 1103. During the peak of its memory business as the world's largest producer in 1979, Intel's profit was $78 million. But in 1983, Intel suffered a massive loss of $114 million in the third quarter alone due to intense competition from Japanese memory producers. As lamented by its former CEO Andrew Grove (1990: 159), "Intel is a sizable and strong company, but we are located in the wrong country. All of the action in our industry is moving to Japan".

Meanwhile, Intel has enjoyed an almost monopoly position in the personal computers (PC) market for central processing unit (CPU) chips, having invented the world's first microprocessor Intel 4004 in 1971. Under Grove's leadership, Intel eventually exited the DRAM market and focused on higher margin microprocessors that remained as its overwhelming core business and accounted for over 75% of its $70 billion revenue in 2018 and $78 billion in 2021. In micro-component products for computers and other numerical control devices, the market was dominated by the founder-giant Intel that still commanded 66% of market share in 2018. Today, and if Grove's (1996) notion that "Only the paranoid survive" is applied to another strategic inflection point in the global semiconductor industry, only IDM and foundry firms with the best fabs could survive in a highly volatile environment of global competition and geopolitical tensions in the 2020s (Yeung, 2022).

Back in 2000, then industry leader Intel was operating at the cutting-edge node of 130 nm. Foundry leader TSMC's process nodes at 150 nm and 180 nm were lagging behind most top IDM firms (at 130 nm). By the late 2010s, Intel was clearly the most vertically integrated, a strategic practice enshrined as its founding principle. All of its fabs were used for making "Intel Inside" microprocessors for PCs and tablets. In 2015, TSMC's leading fab F12 at 16 nm still trailed behind Intel's 14 nm D1X fab in the US. Still, intense competition among the big three of TSMC, Samsung, and Intel in entering mass production at the most advanced nodes of 5 nm in late 2020 and then 3 nm in late 2022 seemed to favour TSMC (see Box 4.6 later) and Samsung (see Box 4.5 later), with Intel trailing due to persistent delays in its transition to 7 nm (2021) and 5 nm (2023) in its new Fab 42 in Chandler, Arizona. This implementation delay occurred due to then sluggish demand for advanced technology in its microprocessors and logic chips for PCs and servers. Moving away from its specialization as an IDM firm fabricating only its own-designed chips, Intel announced in May 2021 its new strategy of launching internal foundry operations for third-party chip-design firms through a new division known as Intel Foundry Services (IFS).

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Yeung, Henry Wai-chung (2022), *Interconnected Worlds: Global Electronics and Production Networks in East Asia,* Innovation and Technology in the World Economy Series, Stanford, CA: Stanford University Press.

Table 4.2 summarizes the key trends and drivers of these changing fortunes in the global semiconductor industry from 1959 to 2022. By the late 1970s, the incredible success of these highly innovative American IDM firms, such as Texas Instruments, Motorola, and Fairchild, and the enormous strength of IBM Microelectronics division as a captive producer for its in-house mainframe computer systems meant that the US had virtually dominated the entire semiconductor industry. By the early 1980s, IBM was also the world's largest producer of integrated circuits for in-house "captive" use and a major innovator in semiconductor process and product technologies. American IDM firms had developed enormous economies of scale and scope through their vertical integration of the design, manufacturing, and marketing of their specialized semiconductor products, such as microprocessor chipsets and memory devices.

The 1980s and the 1990s witnessed major upheavals, as newcomers captured a growing share of the fabrication of memory chips, while major US firms exited. American and European firms faced incredible challenges in the DRAM market from Japanese firms and, later, South Korean firms (Brown and Linden, 2011). The top 5 market leader Intel exited the DRAM market in 1986 to focus on higher margin microprocessors and yielded its number one position in the entire semiconductor industry by 1995. By the late 1980s, nine of the 11 US-based DRAM producers exited the memory market. During the 1990s, two latecomers from the Republic of Korea – Samsung and Hyundai (today's SK Hynix) – became serious challengers in memory devices. As Japanese and, later, South Korean IDM firms became top memory producers since the mid-1980s and American IDM firms remained dominant in microprocessors, two transformative changes to the industrial organization of the global semiconductor industry started

Table 4.2: Changing Fortunes in the Global Semiconductor Industry: Key Trends and Drivers, 1959-2022

Evolution	Semiconductors
Emergence	**1959-late 1970s**
Nature	"Microelectronics revolution": invention of integrated circuits and microprocessors
Industrial organization	Vertical integration through integrated device manufacturing
Leading economies	US, Europe, and Japan
Lead firms	Fairchild, Texas Instruments, Intel, Motorola, National Semiconductor, AMD; Philips, STMicroelectronics, Siemens; Toshiba, NEC, Hitachi
Key shifts	**Mid-1980s-2010s**
Processes of transition	"Fabless revolution": the rise of the fabless-foundry model of outsourcing chip production Changing leadership in memory chips
Drivers of change	Strong command of process and manufacturing technologies Decoupling of chip design-fabrication with design automation software and intellectual property for design cores High and risky capital investment in new fabs New demand from personal computers, wireless communications, and data centers
Leading economies	Japan, Republic of Korea, Chinese Taipei, US, and Europe
Lead IDM firms	Toshiba & NEC, Samsung & Hynix, Texas Instruments, STMicroelectronics, NXP (Philips & Motorola-Freescale), and Infineon (Siemens)
Lead fabless firms	Broadcom, Qualcomm, Nvidia, Apple, AMD, MediaTek
Key manufacturing partners (East Asia)	TSMC, Samsung, UMC, GlobalFoundries (AMD), SMIC
Current status	**2020-2022**
Nature	Co-dominance of IDM and fabless/foundry firms High concentration in top 10 Cutting-edge process technology in foundry (3-5nm) Very high cost of new fabs ($20-30 billion) Dominance of end markets in computer & data storage, wireless communications Continual significance of "old guards" in automotive and other chips
Leading economies	US, Chinese Taipei, Republic of Korea, Japan, Europe, PRC, Singapore
Lead IDM firms	Intel, Micron & Texas Instruments, Samsung & Hynix, Kioxia (Toshiba) and Renesas (NEC), STMicroelectronics, NXP, and Infineon
Lead fabless firms	Broadcom, Qualcomm, Nvidia, Apple, AMD, MediaTek
Key manufacturing partners (East Asia)	TSMC, Samsung, UMC, GlobalFoundries, SMIC

Source: Yeung (2022a: Table 2.1).

to take place – the “fabless revolution” in logic or processor chip design and the rise of pureplay foundry in logic chip manufacturing (see Table 4.2). As noted earlier, chip design contributed to about half of the total value-added in the semiconductor industry by 2019. Here, we shed some empirical light on the vertical disintegration of global semiconductor production through the rise of “fabless” firms and their foundry suppliers.

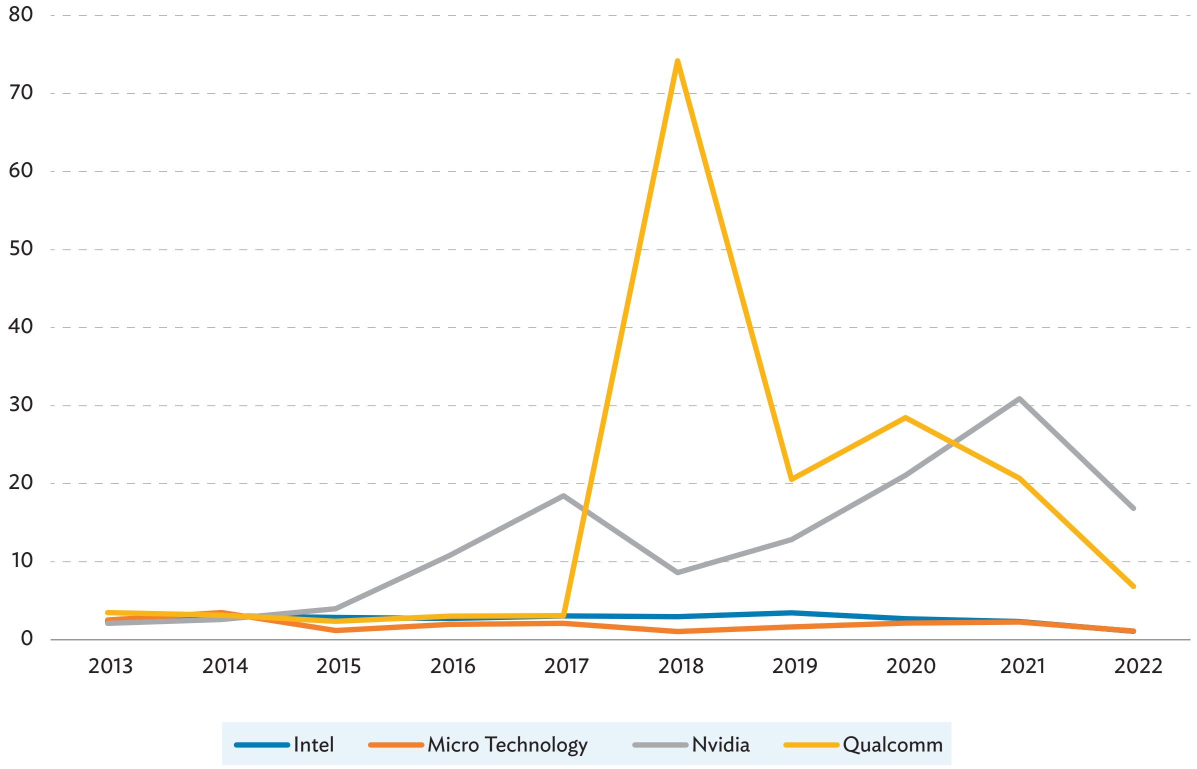
The Rise of the Fabless Firms

The American firm Xilinx, established in 1984, pioneered the fabless model of semiconductor production. Xilinx started its fabless business using Japan’s Seiko Epson as its foundry service provider in 1985, but later engaged American IDM firm AMD as its second source. Meanwhile, Cyrix was established in 1988 as a fabless firm in microprocessors and relied on the fabs of Texas Instruments and European IDM firm SGS-Thomson Microelectronics. Between 1985 and 1994, some 250 fabless semiconductor start-ups had emerged in Silicon Valley. By 2002, the US hosted 475 of the 640 fabless firms worldwide. During this turbulent period of the “fabless revolution” that led to what Langlois (2003) termed the “vanishing hand” of vertically integrated American firms, most fabless firms were relatively small and had to rely on the “spare” capacity of the existing fabs owned by IDM firms (e.g. Texas Instruments, Motorola, Fujitsu, and Seiko Epson) or OEM firms’ captive producers (e.g. IBM Microelectronics division). They became beholden to the capacity allocation of these IDM or captive firms.

Fabless firms grew rapidly from 2000 to 2020 (Table 4.3). The total revenue of all fabless firms reached $16.7 billion in 2000, or only 7.6% of the $221 billion global semiconductor market. The top fabless firm, Xilinx with $1.7 billion in revenue, was dwarfed by leader Intel’s $30 billion or 14% share. By 2020, however, fabless firms’ revenue had grown to $153 billion, or about a third of the entire market. The revenue of the top five fabless firms (as of 2020) increased exponentially from very modest levels in 2000 (except AMD when it was still a second-source IDM making microprocessors for IBM-compatible PCs), in part reflecting consolidation in the market and a concentration of revenue among the top 10 fabless firms. For example, the revenues of Broadcom and Qualcomm, today’s two clear market leaders in wireless modem and mobile application processor chips, rose from just over $1 billion in 2000 (when Intel’s revenue was already $30 billion and Toshiba was $10 billion) to $15.8 billion and $17.6 billion, respectively, in 2020, to become the fifth and sixth largest semiconductor firms worldwide. Two other market leaders in graphics processors, (Nvidia) and system-on-a-chip solutions (MediaTek), also achieved rapid growth during this period. These top fabless firms are mostly specialized in logic chips, including AMD.

This unforeseen development in the separation of semiconductor chip design and chip manufacturing was explained primarily by the rising costs of building fabs and financial market preferences in the US (Nenni and McLellan, 2019). In 1983, a bleeding-edge fab at 1.2 micron would cost $200 million – a price tag well beyond the affordability of many of these small fabless firms in Silicon Valley. By 1990, the cost doubled to $400 million for a 0.80-micron leading fab. By 2001, a 0.13-micron (or 130 nm) fab would need $3 billion. Even Xilinx, then the fabless market leader in 2000, had revenue of "only" $1.7 billion. Moreover, the investment preference of American venture capitalists for "cheaper" and faster-return chip design work since the late 1980s has meant that few fabless firms could secure sufficient funding to build their own fabs. With very few exceptions (i.e. Intel and Micron), capital markets in the US do not favor IDM firms that incur high capital expenditure in building fabs and take far longer to return good profits (3-5 years). In Silicon Valley, venture capital prefers to invest in high value and potentially high return chip design work by American semiconductor firms that remain fabless or fab-lite and yet strong in proprietary technology and intellectual property (Kenney, 2011). Throughout the 2010s, the preferred model for Silicon Valley-based semiconductor firms was to focus on software and custom chip designs and to outsource wafer manufacturing to foundry providers and their backend service partners in chip assembly, packaging, and testing based primarily in East Asia (see section five later on this rise of East Asian partners).

Figure 4.5: Price to Book Ratios of Leading American Semiconductor Firms, 2013-2022



Source: Bloomberg, March 2023.

Table 4.3: World's Top Semiconductor Lead Firms by Type, Revenue, and Share, 2000-2020
(in US$ billions and Percent of Semiconductor Market)

	HQ[2]	2000		2005		2010		2015		2018		2020	
Lead Firm[1]		$b	%	$b	%	$b	%	$b	%	$b	%	$b	%
IDM firm													
Intel	US	30.2	13.7	35.5	14.8	40.4	13.0	51.4	14.9	69.9	14.4	72.8	15.6
Samsung Electronics	KOR	8.9	4.0	17.7	8.9	28.4	9.1	38.7	11.2	74.6	15.4	57.7	12.4
SK Hynix	KOR	5.1	2.3	5.6	2.3	10.4	3.3	16.5	4.8	36.3	7.5	25.8	5.5
Micron	US	6.3	2.9	4.8	2.0	8.9	2.9	14.1	4.1	29.7	6.1	22.0	4.7
Texas Instruments	US	9.2	4.2	10.8	4.5	13.0	4.2	12.3	3.6	15.4	3.2	13.6	2.9
Kioxia (Toshiba)[3]	JP	10.4	4.7	9.1	3.8	13.0	4.2	8.8	2.5	11.4	2.4	10.4	2.2
STMicroelectronics	IT/ FR	7.9	3.6	8.9	3.7	10.3	3.3	6.9	2.0	9.7	2.0	10.2	2.2
Infineon	GE	4.6	2.1	8.3	3.5	6.3	2.0	6.8	2.0	9.1	1.9	9.6	2.1
NXP (Philips)[4]	NE	6.3	2.9	5.6	2.3	4.0	1.3	9.6	2.8	9.0	1.9	8.6	1.8
Renesas Electronics (NEC)[5]	JP	8.2	3.7	8.1	3.3	11.9	3.8	5.7	1.7	6.7	1.4	6.5	1.4
Freescale (Motorola)[4]	US	5.0	2.3	5.6	-	4.4	1.4	-	-	-	-	-	-
Fujitsu	JP	5.0	2.3	2.6	1.1	3.1	1.0	1.1	0.3	-	-	-	-
Fabless firm													
Qualcomm[6]	US	1.2	0.5	3.5	1.5	7.2	2.3	16.5	4.8	16.6	3.4	17.6	3.8
Broadcom[7]	US	1.1	0.5	2.7	1.1	6.7	2.2	8.4	2.4	17.5	3.6	15.8	3.4
MediaTek	TAP	0.4	0.2	1.4	0.6	3.5	1.1	6.7	1.9	7.9	1.6	11.0	2.4
Nvidia	US	0.7	0.3	2.1	0.9	3.1	1.0	4.4	1.3	10.4	2.1	10.6	2.3
Apple	US	-	-	-	-	-	-	6.1	1.8	6.2	1.3	10.0	2.1
AMD[8]	US	3.8	1.7	3.9	1.6	6.4	2.1	3.9	1.1	6.0	1.2	9.8	2.1
HiSilicon	CN	-	-	-	-	0.3	0.1	3.1	0.9	5.5	1.1	5.2	1.1
Total fabless firm revenue		16.7	7.6	39.8	16.6	65.4	21.0	87.5	25.3	97.4	20.1	153	32.8
Total Top 10 firm revenue		98.9	44.8	115	48.1	150	48.1	183	52.9	292	60.2	257	55.2
Total semiconductor market		**221**	**100.0**	**240**	**100.0**	**312**	**100.0**	**346**	**100.0**	**485**	**100.0**	**466**	**100.0**
Foundry firm[9]													
TSMC	TAP	5.1	38.1	8.2	37.6	12.9	39.3	26.5	53.1	31.1	50.6	46.0	54.1
Samsung (foundry)	SK	-	-	0.2	0.9	0.8	2.4	3.9	7.8	3.4	5.5	14.5	17.0
UMC	TAP	3.1	23.1	2.8	12.8	3.8	11.6	4.4	8.8	5.0	8.1	6.0	7.1
GlobalFoundries[10]	AB/ US	0.5	3.7	1.1	5.0	3.5	10.7	4.8	9.6	6.2	10.1	5.7	6.7
SMIC	CN	-	-	1.2	5.5	1.6	4.9	2.1	4.2	3.0	4.9	4.2	4.9
Total foundry market		**13.4**	**100.0**	**21.8**	**100.0**	**32.8**	**100.0**	**50.2**	**100.0**	**61.5**	**100.0**	**85.1**	**100.0**

[1] Lead firms in *italics* are those interviewed by one of the authors in 2017 and 2018. Multiple senior or top executives were interviewed in some of these lead firms (Samsung, STMicroelectronics, NXP, and AMD) and in different locations in Asia.

[2] KOR= Republic of Korea; US=United States; JP=Japan; IT/FR = Italy/France; GE = Germany; NE = Netherlands; TAP = Chinese Taipei; and CN = PRC.

[3] Toshiba's memory business was sold to a consortium led by Bain Capital in June 2018 and renamed to KIOXIA in October 2019.

[4] Philips semiconductor division was sold to private equity and renamed to NXP in 2006. Freescale was spun off from Motorola's semiconductor division in 2004 and NXP acquired Freescale in 2015.

[5] Renesas Electronics' data before 2010 refer to NEC that merged with Renesas Technology in April 2010 to create Renesas Electronics (a merged entity comprising Mitsubishi and Hitachi Semiconductors in November 2002).

[6] Qualcomm revenue only includes its chip-making services (i.e. not including its quite substantial licensing revenue).

[7] Singapore-incorporated Avago acquired LSI in 2014 and Broadcom Corp for $37 billion in 2015 to become Broadcom Inc. Its 2015 revenue is incorporated into Broadcom.

[8] AMD became fabless after spinning off its wafer fabrication facilities to form GlobalFoundries in 2009.

[9] Revenues by foundry firms are typically attributed as cost of revenue to fabless firms (40-45% of total revenue) and fab-lite IDM customers and therefore do not add to the total semiconductor market revenue.

[10] GlobalFoundries' revenue in 2005 refers to Chartered Semiconductor from Singapore that it acquired in September 2009. It was fully acquired by Abu Dhabi's state-owned Advanced Technology Investment Company in 2012. In 2015, GlobalFoundries acquired three fabs in Burlington (Vermont) and East Fishkill (New York) from IBM Microelectronics.

Sources: Data from IHS Markit/Informa Tech Custom Research, July-October 2016 and 2019, authors' interviews, and corporate reports and websites.

Throughout this unprecedented period of growth in American fabless firms, capital market influence remained very strong through institutional investment by venture capital firms, private equities, and hedge funds. Figure 4.5 illustrates Wall Street's continual preferences for such fabless firms throughout the 2010s as their price-to-book ratios have been persistently far higher than that of the leading IDM firm Intel (hovering around 1.1 to 3.1 between 2013 and 2022). In his 2020 year-end letter to Intel's then chairman Omar Ishrak, New York-based activist hedge fund Third Point's CEO Daniel Loeb even pushed the world's leading and largest IDM firm to reconsider its strategic alternatives, including focusing on in-house processor chip design and spinning off its fabs as new solutions to retain its customers such as Apple, Microsoft, and Amazon. Having amassed nearly $1 billion stake in Intel, Loeb argued that "Without immediate change at Intel, we fear that America's access to leading-edge semiconductor supply will erode, forcing the U.S. to rely more heavily on a geopolitically unstable East Asia to power everything from PCs to data centers to critical infrastructure and more" (Herbst-Bayliss and Nellis, 2020). As noted in Box 4.2, Intel responded positively by May 2021 when it launched Intel Foundry Services (IFS), an internal foundry operation for serving third-party chip-design firms.

The Rise of the Dedicated Foundry

The pureplay model of dedicated foundry has emerged as an innovative way of organizing semiconductor production and supporting fabless chip design firms since the mid-1980s. This pureplay foundry concept started with Orbit Semiconductor, a small and dedicated foundry established by Gary Kennedy in California in 1985 to manufacture semiconductor devices for defence, aerospace, and industrial customers (Saxenian, 1994). But the model's major adopters were located in East Asia, in particular Chinese Taipei. Founded respectively in 1980 and 1987 as spin-offs of Chinese Taipei government-sponsored Industrial Technology Research Institute, United Microelectronics Company (UMC) and TSMC have been the top three foundry firms since the early 1990s. UMC started as an IDM firm in logic and memory chips throughout the 1980s, but its strategic switch to pureplay foundry occurred only in the mid-1990s, partly in response to Intel's increasing legal action against microprocessor firms from Chinese Taipei (Mathews and Cho, 2000). By 2000, the dominance of TSMC and UMC in the foundry market was established. With respective revenue of $5.1 billion and $3.1 billion in Table 4.3, they accounted for 38% and 23% of the total foundry market revenue of $13.4 billion. Taking over the reign from IDM's foundry services, the top five pureplay foundry firms contributed $9.4 billion or 70% of this market.

The importance of the foundry market is underscored by its six-fold growth from $13.4 billion in 2000 to $85.1 billion in 2020, as compared to the doubling of the overall market revenue from $221 billion in 2000 to $466 billion in 2020 (and about $600 billion in 2021-2022).

The rise of fabless firms and dedicated foundry firms has therefore revolutionized the industrial organization of semiconductor production networks. This tightly coupled fabless-foundry model has shaken up the entire industry previously dominated by American IDM firms (e.g. Intel and Texas Instruments) and captive producers (e.g. IBM Microelectronics division), and enabled the massive growth of mobile devices, such as notebooks, smartphones, tablets, and IoT products, and data and networking centres since the late 2000s (Yeung, 2022a). In this new model of semiconductor production, a fabless firm does not need to have manufacturing facilities and thus its moniker "fabless". Instead, it specializes in developing proprietary technology and designing logic and processor chipsets for information and communications technology (ICT) products, such as mobile devices, digital TVs, cloud-based servers, and automotive digital display clusters. A fabless firm normally enters into long-term contracts with dedicated or "pureplay" semiconductor foundry providers, mostly from Chinese Taipei and a few from the Republic of Korea, the PRC and the US, to produce cutting-edge chipsets and other semiconductor devices.

The arrival of this innovative "pureplay" foundry model, defined as foundry fabs dedicated to serving external customers only, means that these providers do not develop their own chip designs and/or products – the very idea of "pureplay" foundry. They are thus viewed by fabless or fab-lite customers as trusted suppliers of chip manufacturing. This trust relationship is particularly critical in cutting-edge logic chips when design costs are enormous and proprietary knowledge are embedded in circuitry blueprints necessary in foundry production. With strong inter-firm trust relationships, large capital-intensive foundry providers can meet the cutting-edge wafer fabrication needs based on proprietary designs supplied by their customers, such as fabless chip design firms.

Some IDM firms also outsource a portion of their fabrication needs to dedicated foundry firms. Some of these "fab-lite" IDM firms are unwilling to invest in cutting-edge fabs. They can also hedge the high risk of building new expensive fabs by using foundry capacity during upswings in demand or for chips with shorter product life cycles or smaller volumes, and by benchmarking in-house fabs against these pureplay foundry providers. Adopting this "fab-lite" strategy, most established IDM firms did not develop new process technology and capability to compete in the most demanding categories of integrated circuits, i.e. logic chips. Only very few IDM firms, such as Intel, Samsung, SK Hynix, and Micron, were able to invest continuously in cutting-edge fabs through to the early 2020s.

A group of five "old guard" IDM firms have gone fab-lite and remained competitive in specific product segments (e.g. analogue chips, microcontrollers, and discretes) that can be fabricated without replacing their existing equipment using mature process technologies in legacy fabs. These products also have far longer product cycles for industrial applications (e.g. 20-year qualified supply contracts in automotive chips). Lacking more advanced process technologies (<28 nm), these IDM firms typically outsource most, if not all, of their logic chips to pureplay foundry providers. For example, in 2007 Texas Instruments was still the world's third largest IDM firm after Intel and Samsung and yet surprised the industry by announcing that it would not develop new in-house process technology after the 0.045-micron (μm) or 45 nm generation. Instead, it would rely on Chinese Taipei's TSMC and UMC for process development beginning with 32 nm node. By the time it acquired National Semiconductor in 2011, Texas Instruments had a total revenue of $14.3 billion and outsourced about 20% of its wafers (75% in advanced logic chips) to leading foundry providers.

By the late 1990s, this fabless-foundry model had enabled the internationalization of semiconductor production to newly industrialized economies in East Asia (see section five), well beyond simply the assembly, packaging, and testing of chips previously fabricated only in the US, Europe, or Japan (Henderson, 1989).

Overall Specialization in the Semiconductor Market

Thus, since the mid-2000s, the global semiconductor industry has been characterized by the hybrid co-existence of three forms of "verticality" or vertical specialization in organizing chip production networks: (i) IDM firms with advanced fabs in different locations; (ii) fabless firms partnered with trusted pureplay foundry providers; and (iii) fab-lite IDM firms with both in-house trailing-edge fabs worldwide and outsourced foundry support:

- Some IDM firms grew rapidly over the past two decades to become the largest semiconductor firms. They are mostly associated with market cycle-specific memory devices, e.g. Samsung, SK Hynix, Micron, and Toshiba. Intel's revenue more than doubled during this period, but its market share remained the same at 14-15%.
- The top fabless firms also expanded rapidly, as described above.
- Four of the five "old guard" fab-lite IDM firms, including Texas Instruments, STMicroelectronics, Infineon, and NXP (including former Motorola and Philips) achieved some growth, whereas Renesas's revenue decreased substantially between 2005 and 2020. Still, their individual ranking declined significantly among the top 15 semiconductor firms during this period because of the rising ranks of two top-3 memory IDM firms and all top-6 logic fabless firms (Table 4.3; Suleman and Yagci, 2022a).

Overall, the semiconductor industry has become much more concentrated since the mid-2000s. The share of the top 10 firms in total revenue increased from 48% in 2005 to over 60% in 2018. Most significantly, the top 5 firms in 2018 accounted for 47% of total revenue, with top-2 Samsung and Intel's combined share reaching almost 30%. Within the list of top 10 firms in different years, none was fabless in 2005 or earlier, but six were significant in 2020 – Qualcomm (see Box 4.3), Broadcom, MediaTek, Nvidia, Apple, and AMD. This changing pecking order indicates the tremendous success of the “fabless revolution” since the mid-1980s. But what does this rise of the fabless-foundry model of semiconductor production mean in relation to AMD Jerry Sanders’ proclamation that “Now hear me and hear me well. Real men have fabs!”? Must “real” semiconductor firms or even nation-states, as discussed in section six later, have fabs to stay in the game and remain competitive in this extremely technology- and capital-intensive industry by the early 2020s?

Box 4.3: Qualcomm and the “Double Revolution” of Fabless and Smartphones in the US

American fabless firm Qualcomm’s massive growth from 2000 and 2020 is underpinned by its central role in two revolutions – the fabless revolution and the smartphone revolution. Qualcomm’s success owes much to its dominance in the proprietary CDMA baseband processor chips (e.g. its Snapdragon series) for smartphones since the late 2000s. In particular, its close strategic relationship with Samsung, which became the early adopter of Qualcomm’s CDMA-based technologies and chipsets MSM6250 in 2003, has been instrumental in its success as the dominant technology leader for wireless chipsets in mobile communications. Prior to that, Texas Instruments used to be the dominant digital baseband chip supplier accounting for more than half of the global market share in all feature phones (also known as “cell phones”), including most of those in Nokia- and Ericsson-branded phones (Glimstedt et al. 2010).

The dominance of two leading fabless firms, Qualcomm and Broadcom, in the 2010s shows that this organizational separation of the design and fabrication of semiconductor chips has offered both fabless firms and their foundries a very significant joint window of opportunity in the rapidly growing global production networks of mobile telecommunications devices (Nenni and McLellan, 2019). The enormous success of these American fabless design houses is illustrated by their massive growth between 2000 and 2020. As shown in Table 4.3, Qualcomm had revenue of just over US$1 billion in 2000. In 2010, it became a top ten semiconductor firm in the world, achieving US$10 billion sales for the first time and overtaking such IDM firms in memory chips as Hynix and Micron. In 2020, Qualcomm remained as the top fabless firm with a chip-related revenue of $17.6 billion. This would more than double two years later to $37 billion in 2022 (or $44 billion if its licensing revenue is included) and earn it the distinction as the third largest semiconductor firm worldwide (after Intel and Samsung)!

In such rapidly moving industries as mobile communications, leading fabless firms, such as Qualcomm since its inception in 1985, have eschewed the vertically integrated model of global production networks pursued by IDM firms such as Intel, and developed a horizontally organized global production network leveraging on the core competencies of and trust relationships with its foundry partners (e.g. TSMC) and downstream customers (e.g. mobile handset makers).

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These dramatic shifts in the semiconductor market point to immense challenges for innovation-based development in both existing producer economies (e.g. the US, Europe, and Japan) and other “late” latecomers (e.g. PRC, Brazil, India, and Malaysia; see Yap and Rasiah, 2017; Grimes and Du, 2022). Part of the explanation for these changing industrial-organization dynamics since the late 1980s lies in the role of the government. The next section discusses the role of the government in supporting the growth of semiconductor industry, initially in the US and Europe and later in Japan, then three East Asian “tiger” economies, and most recently the PRC.

4.5 The Role of the Government in the Development of the Semiconductor Industry

The longstanding debate over the effectiveness of industrial policy has recently come to the fore due to efforts by the US, the EU and Japan to provide incentives for domestic semiconductor production. This section sheds some light on the potential impact of government support for semiconductor production by reviewing industrial policies for the sector in advanced economies and in East Asia. In the latter case, governments indeed played an effective role in funding research, training engineers, facilitating technology transfer, and easing financial constraints.

Support in Advanced Economies for Semiconductor Production

From the 1960s to the late 1980s, techno-nationalism was the dominant development pathway in semiconductor production embedded in national innovation systems and protective regulatory regimes. In this context and as noted earlier in section one on semiconductor R&D, national governments in advanced industrialized economies competed fiercely against each other in the race to technological advancement and market dominance (Langlois et al., 1988). Governments in the US, Japan, and Western European countries funded and supported national ecosystems of innovation in semiconductors comprising universities and research institutes, private firms, and industry alliances. Many of the early innovations in large-scale computer systems and semiconductors were also related to national defense and other critical military missions (O'Mara, 2019).

When their leading domestic firms were challenged by foreign competitors, national governments engaged in techno-nationalism to regulate foreign competition through legal and bureaucratic mechanisms during the 1980s (Reich, 1987). By the early 1980s, the US deployed measures to address the growing import competition from Japanese firms to American firms in semiconductors due to the former's better process technology and fab yield (Tyson, 1993). Voluntary Import Expansions, such as the US-Japan Semiconductor Trade Agreement of 1986, were imposed on Japanese producers in order to restrict their exports of DRAM memory chips to the US for computers and other consumer electronics products (e.g. at the time, video cassette recorders). This restriction would also allow American semiconductor firms, such as Intel and National Semiconductor, to retool their production facilities to compete better in this market segment. The Agreement also guaranteed that the Japanese government would ensure at least 20% share of these American firms in the Japanese semiconductor market.

In 1987, the US government led a consortium of 14 American semiconductor firms, such as Hewlett-Packard, AT&T, IBM, and DEC, to form SEMATECH (Semiconductor Manufacturing Technology) in order to fend off Japanese competition and to regain industrial competitiveness. This consortium was funded over five years for $1 billion, half of which came from the Defense Advanced Research Projects Agency (DARPA) of the Department of Defense. DARPA and, more broadly, the US Department of Defense, played a central role in promoting technological innovations and their commercialization all the way up to the 2010s (Weiss, 2014). In Europe, the European Strategic Programme for Research and Development in Information Technology (ESPRIT) was launched in 1983 as a ten-year effort to stimulate R&D cooperation in basic technology in semiconductors, data and knowledge processing, and office and factory automation. Its first five-year phase was funded to the tune of $1.3 billion, half from the European Economic Community (EEC) and the rest from other stakeholders (Borrus, 1988). Philips and Siemens, then two of Western Europe's largest semiconductor firms, also received some $400 million in subsidies after the 1985-1987 recession to enter the 1MB and 4MB DRAM markets.

The rise of Japan's semiconductor industry was well supported by home government in the late 1970s and up to the late 1980s. For instance, the VLSI Technology Research Association was initiated in 1976 as a four-year programme of public-private partnership and was supported by Japan's Ministry of Trade and Industry with ¥29 billion. It brought together the five largest Japanese semiconductor firms – Fujitsu, NEC, Hitachi, Mitsubishi Electric, and Toshiba – to develop 256K DRAM chips by 1980, two years ahead of the US. At its peak in 1986, Japan's share of world semiconductor market increased to 46% and surpassed the 43% share held by American firms; some 75% of world's DRAM products and 95% of the latest generation DRAM devices came from Japanese firms. As noted in Box 4.2, this dominance of Japanese memory chip makers led to Intel's reluctant exit of the very memory business it invented.

By the late 1980s, the US share had dropped further to 37%, and Japanese firms had replaced American firms as the dominant market player with almost 50% of the entire semiconductor market. As argued by Angel (1994), while Japanese government-sponsored cooperative research program in the late 1970s, such as the VLSI consortium, was instrumental in the catching up of Japanese firms in semiconductor process and manufacturing technologies, "[t]he subsequent competitive success of Japanese firms, however, had less to do with this much publicized form of government intervention than with the internal development efforts of individual firms and the superior manufacturing performance achieved by Japanese semiconductor producers throughout much of the 1980s".

Rise of the East Asian Tigers

Government support also has been crucial in the initial development of memory chip producers and foundry fabs in the East Asian economies that became major players in the semiconductor market. By the end of the 1990s, Japanese memory makers faced intense competition from a totally new cohort of chipmakers from other East Asian "tiger" economies. As indicated in section three and Table 4.3, the fortunes of Japanese makers began to dwindle during the 2000-2015 period.

In East Asia since the late 1990s, the rise of foundry wafer producers from Chinese Taipei and Singapore and memory chipmakers from the Republic of Korea (and Chinese Taipei) presaged the arrival of semiconductor manufacturing in these economies and their dominance in the subsequent two decades until today. In their early developmental periods, many of these firms required substantial investment to achieve scale economies and cost efficiency in order to catch up with pioneering first movers in advanced economies that had possessed superior technological and organizational capabilities. This longer time-horizon in initial investment prompted the governments in the three East Asian "tiger" economies to involve directly in the early founding of the semiconductor industry as an integral part of their industrialization programmes (Mathews and Cho, 2000). Table 4.4 summarizes the changing national and institutional contexts for this firm-specific capability building and industrial transformation in these three East Asian economies and the PRC that have come to play a very significant role in the global semiconductor industry since the 2000s. In general, these economies pursued target-specific industrial policies utilizing broadly a mix of the following instruments throughout the 1970s and the 1980s (Yeung, 2016; Suleman and Yagci, 2022b):

(i) Financial incentives through guaranteed loans or "policy loans", subsidies through grants, and tax rebates;
(ii) "Picking the winners" or targeting at chosen firms to be national champions;
(iii) Regulatory interventions in imports and restrictions on foreign firms to create domestic markets;
(iv) Initiating industry and technology consortiums to develop cooperative partnerships among domestic firms;
(v) Investment in research institutes to subsidize R&D costs, to initiate technology transfers, and to stimulate firm spinoffs and start-ups;
(vi) Imposition of performance requirements on recipients of incentives as a carrot-and-stick approach;
(vii) Broader development of industrial ecosystems and clusters, including linkages with foreign firms; and
(viii) Sanctioned programmes to repatriate citizen techno-entrepreneurs to helm public and private ventures, known as reverse "brain drain" or the "new argonauts" (Saxenian, 2006).

In a nutshell, the government in the Republic of Korea and Chinese Taipei actively pursued such sectoral or target-specific industrial policy during the 1970s and the 1980s but became less interventionist since the late 1990s due to the growing capabilities of domestic firms and their strategic coupling with global lead firms (e.g. fabless firms) and their production networks. The elite bureaucracy, such as Republic of Korea's Economic Planning Board and Chinese Taipei's Council for Economic Planning and Development, was either dismantled or weakened during the 1990s. Meanwhile, the Singaporean government has long been engaging in functional or horizontal industrial policy that promotes trade and investment openness. Since joining the WTO in 2001, the PRC's domestic political economy has been characterized by dual-tracks – state promotion of national firms (mostly state-owned) through sectoral industrial policy and continual support for foreign investment through trade liberalization.

In the first group of semiconductor foundry providers, the divergent cases of Chinese Taipei and Singapore involve a unique and dynamic combination of initial government interventions and the subsequent firm-specific process of industry market specialization through continuous innovations. Prior to the mid-1990s, government-led initiatives in both Chinese Taipei and Singapore laid important foundations for these leading foundry firms. In Chinese Taipei, the government steered the industry during the 1970s and the 1980s mainly through technology transfer led by Industrial Technology Research Institute (ITRI, established in 1973), Electronics Research and Service Organization (ERSO, established in 1974), and their subsequent spin-offs, rather than through direct allocation of credits to the industry. These research institutes obtained the initial, and often obsolete, technologies in chip fabrication (7-micron LSI) from the US firm RCA in 1976 and 2-micron VLSI technologies from Philips a decade later in 1987. These technologies were transferred to UMC and TSMC at the time of their spin-offs respectively in 1980 and 1987.

Looking back, the continual firm-specific technological innovations and organizational change through specialization in foundry services have proved to be vital in the unprecedented growth of these foundries in the 2000s. The massive growth of TSMC since 1995 came about after ERSO and ITRI had withdrawn from their earlier active role as the leading actor steering the development of Chinese Taipei's semiconductor industry. It tapped well into the enormous growth of fabless design houses, particularly in wireless and mobile communications devices and digital multimedia solutions discussed in the earlier section three. As the trusted foundry house for chipsets designed by Qualcomm, Nvidia, Apple, and MediaTek for mobile devices and computers, TSMC has attained high-capacity utilization and thus gained enormously from its specialization in semiconductor manufacturing.

While some of these organizational innovations specific to TSMC can also be observed in the case of Singapore's government-funded Chartered Semiconductor Manufacturing (CSM), a well-developed domestic ecosystem in the semiconductor industry can make a critical difference. This ecosystem refers to both upstream equipment suppliers and testing and assembly services, and downstream fabless customers and their end users comprising global lead firms and their manufacturing service providers. The failure of CSM in the foundry segment points to the necessary, but insufficient condition, of government support in developing semiconductor manufacturing (see Box 4.4).

The second and much larger segment of semiconductor manufacturing refers to domestic IDM firms in Chinese Taipei and the Republic of Korea producing memory chips. As evident in Table 4.3, some of these domestic IDM firms have become the world's largest semiconductor firms. But their pathways in these two East Asian

Table 4.4: Evolving Domestic and Institutional Contexts of Industry Development in Selected East Asian Economies, 1980-2022

Historical contexts	Republic of Korea	Chinese Taipei	Singapore	PRC
1980-2000				
Development strategy	National champions and export firms	Domestic firms for exports and global economy	Foreign firms with limited domestic firms for exports and global economy	State-owned enterprises, fiscal decentralization, and foreign firms for processing exports
Policy support	Sectoral industrial policy and high selectivity	Sectoral industrial policy but low selectivity	Horizontal industrial policy and high state ownership	Horizontal industrial policy and high state ownership
Capital formation	State and domestic banks; low reliance on FDI before 1997 Asian financial crisis	Banks; medium reliance on FDI	State financial holdings; high reliance on FDI	State banks; high reliance on FDI
Business structure	Dominance of chaebol or conglomerates; high family control	Significant business groups; high family control	High state and foreign ownership; limited family control	High state and foreign ownership
Semiconductor industry	From weak to emerging domestic IDM firms	From weak to emerging foundry firms	From weak to emerging domestic foundry firm and reliance on foreign firms	Weak and limited domestic development
2001-2022				
Development strategy	Corporate restructuring, market liberalization, and financial deregulation	More market liberalization and internationalization of domestic firms	Privatization and promoting domestic firms and their internationalization	Dual tracks of promoting national (state) firms and foreign investment Towards internal circulation/domestic market
Policy support	Less interventionist industrial policy and lower selectivity More active free trade arrangements	Horizontal industrial policy promoting firm upgrading More active free trade arrangements	Horizontal industrial policy promoting firm upgrading Highly active free trade arrangements	Sectoral industrial policy, upgrading, and restructuring of state ownership WTO entry and export promotion, 2001- US-PRC trade war and sanctions, 2018-
Capital formation	Restructuring of domestic banks; more FDI and reliance on capital markets	Restructuring of domestic banks; more reliance on capital markets	Continual state financial holdings; high reliance on FDI and capital markets	Large state financial holdings; medium reliance on FDI and capital markets
Business structure	Dominance of fewer chaebol; high family control	Family business groups and rise of technology firms	Dominance of government-linked and foreign firms	High state control and medium foreign and family control
Semiconductor industry	From emerging domestic IDM firms to dominant global lead firms	From emerging to dominant foundry firms	From emerging to significant presence of foreign firms	From emerging to crippled domestic foundry and memory firms due to US sanctions

Sources: Based on analysis in Yeung (2016) and Hamilton-Hart and Yeung (2021), with further information from Ning (2009), Fuller (2016), Lee (2019), and Xing (2021).

economies have sharply diverged. Unlike their highly successful "cousins" specializing in foundry services (i.e. TSMC and UMC), most IDM firms from Chinese Taipei were lagging behind in terms of new technological and organizational innovations by the 2000s. In retrospect, Chinese Taipei's semiconductor IDM firms started off on a solid ground laid and led by government-funded ITRI in the mid-1980s. But the segment did not take off in the same manner as pureplay foundries. Between 1983 and 1998, a steady number of IDM firms specializing in DRAM and flash memory chips were

Box 4.4: Singapore's Chartered Semiconductor Manufacturing and Failed State-Led Catching Up

Established in 1987 (the same year as TSMC) and with technology transfer from two American firms – National Semiconductor (IDM) and Sierra Semiconductor (fabless), Chartered Semiconductor Manufacturing (CSM) began as a division in the state-owned Singapore Technologies group. Singapore Technologies was fully owned by the state investment vehicle Temasek Holdings until the end of 1999. By the late 1990s, Singapore Technologies had developed a vertically integrated semiconductor foundry manufacturing value chain, encompassing chip design (TriTech), wafer fabrication (CSM) and test and assembly (STATS) (Mathews and Cho, 2000).

The case of Singapore's CSM might appear to be a perfect textbook case of state-led catching up in a highly capital-intensive industry – semiconductor foundry services. It was established at the time when the developmental state's industrial policy was switching towards promoting high value-added manufacturing industries such as semiconductors. It had the technological backing of industry leaders, such as Sierra Semiconductor and Toshiba, and the full financial support of the state-owned Singapore Technologies group. By the late 1990s, CSM had been blessed with a vertically integrated foundry value chain and Singapore's semiconductor industry had been quite firmly established. By the late 2000s, the output of Singapore's semiconductor industry was valued at US$26 billion. CSM was seemingly well positioned to take on major competitors in foundry services, such as TSMC and UMC. Throughout the 2000s, it counted on Microsoft, Broadcom, and Qualcomm as its largest lead firm customers (Yeung, 2016).

But something is missing in this story because CSM did not perform well starting in the late 1990s because of the lack of a critical mass of fabless design firms and the decreasing presence of their downstream "consumers", such as contract manufacturers in electronics and computer products, in Singapore. In fact, Singapore's semiconductor industry was, and still is, dominated by foreign-owned IDMs, most of which did not engage third-party foundry services such as those offered by CSM. Consequently, CSM suffered from major losses between 1998 and 2008. In September 2009, Temasek Holdings divested and sold its entire stake in CSM to Abu Dhabi-backed GlobalFoundries that has since merged CSM's fabs in Singapore with fabrication facilities spun off from loss-making American IDM firm AMD. GlobalFoundries paid US$1.8 billion for CSM and assumed its outstanding debts of US$2.2 billion.

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established in Chinese Taipei (Mathews and Cho, 2000). From such early entrants as Mosel-Vitelic, Winbond (ERSO's "unofficial" spin-off taken over by the Walsin Lihwa group), and Macronix (a specialist maker of volatile memories) to family-owned Nanya Technology in the Formosa group (and Inotera Memories, its joint venture with Infineon) and independents, such as Powerchip Technology and Elite Semiconductor, these IDM firms had leveraged on technologies licensed from global leaders, and developed into significant producers of memory devices for different computing and telecommunications equipment and consumer electronics by the early 2000s.

In their first decade of development, these IDM firms from Chinese Taipei successfully exploited the technologies licensed, via ITRI, from leading memory chip producers from Japan, the US, and Germany. By specializing in memory devices, these Chinese Taipei's IDM firms could improve on these technologies and develop cutting-edge memory products for a rapidly growing global market in the 2000s. Intense industrial competition in the global market for memory devices occurred during the 2000s when the technologies of these devices became standardized fairly quickly, and product life cycles were compressed sharply. Many Chinese Taipei's IDM firms specializing in memory devices became victims of industrial lock-in and could not resist the inevitable trend towards declining prices and profitability. Despite government support, their overemphasis on up-scaling to lower production costs did not lead to new technological or organizational innovations (Fuller, 2007). Most Chinese Taipei's DRAM producers became captive suppliers to their foreign partners and had to pay licensing fees and assume most of the investment risks. In the early 2000s, several top Japanese memory IDM firms also exited the market.

On the other hand, two South Korean *chaebol* giants – Samsung and SK Hynix – have been continuously developing technological innovations and achieving scale economies in memory chip production. In particular, Samsung (Box 4.5) has successfully integrated its logic chips and memory devices into a wide range of electronics products manufactured by its intra-*chaebol* divisions and other electronics giants, such as Apple's iPhones (till 2016). Arguably, the role of state-led initiatives has been important mostly at the initial stage of achieving second-mover advantages by these IDM firms from the Republic of Korea. To take advantage of President Park Chung Hee's Promulgation of Law for Electronics Industry Promotion (1969–1976) in the Republic of Korea, National Semiconductor from the US entered into a joint venture with Goldstar Electronics (the predecessor of LG Electronics) to manufacture transistors in 1969. In the same year, Samsung made its first foray into electronics through its joint ventures with Japan's Sanyo and NEC. These joint ventures laid the early foundation of these two *chaebol* giants in today's global electronics industry.

But once these leading Korean semiconductor firms have articulated into different global production networks since the 2000s, new and firm-specific technological and organizational innovations are necessary to stay ahead of their competitors and to sustain their continual growth and profitability. The Republic of Korea state implemented more liberal trade and investment policies to create a conducive environment for domestic firms to import intermediate goods crucial for their strategic partnership with global production networks and for foreign firms to invest in domestic firms in order to improve their production capacity and technological capabilities. Still, this functional industrial policy for promoting domestic R&D capacity in the semiconductor industry was superseded by private firm initiatives, as these firms found new conduits for developing such capabilities through their expanding global production networks. In the 1990s, Samsung, LG, and other chaebol began to disembed from state-sponsored R&D consortiums and accelerated their own in-house R&D activity and technological advancement to catch up with global lead firms. By the early 2000s, they had effectively taken over the control of both R&D and production activity in the domestic semiconductor industry and become the leader in steering the industry's high growth during the ensuring decade. The emergence of Samsung and SK Hynix (renamed from Hyundai after acquiring LG Semiconductor in 1999) in the global market for memory devices by the 2000s indicates that second-mover advantages, such as industrial market specialization and scale economies, can be a potent competitive advantage in favor of these South Korean chaebol IDM firms. These supply-side factors of favourable government support and firm-specific innovations are necessary elements of any explanation of the rise of East Asia in the global semiconductor industry.

Box 4.5: Republic of Korea's Samsung as a Successful Product of the Developmental State?

Samsung Electronics did not venture into semiconductors until the mid-1970s. President Park Chung Hee's fourth Five-Year Plan of 1977-1981 set the pace of development of the electronics industry as one of Republic of Korea's key sectors. In this historical context, the developmental state was imperative in the initial inducement of such chaebol as Samsung to diversify into electronics. On 1 December 1983, Samsung shocked Republic of Korea, if not the world, with a good working version of a 64K DRAM based on design technology licensed from then fledgling American DRAM producer Micron and process technology from Japan's Sharp. But state funding was no longer crucial to its massive growth by the mid-1980s. Between 1983 and 1989, Samsung, LG, and Hyundai invested some US$4 billion in VSI semiconductors. Only US$350 million of this came from state-initiated low-interest credit under the terms of the Promulgation of Basic Long Term Plan for the Semiconductor Industry (1982-1986) announced in 1981. In fact, the state-funded Electronics and Telecommunications Research Institute (ETRI)'s national R&D consortium for 4MB DRAMs between 1986 and 1989 failed to induce cooperation and sharing of technologies among its participants, such as Samsung, Hyundai, and LG, despite spending $110 million over the three years. Instead, each of them went ahead to develop their own 4MB designs through in-house R&D efforts (Dedrick and Kraemer, 1998).

Into the 1990s, Samsung closed the technology gap with its major competitors from the US and Japan (who are much weaker now, as respectively shown by Intel's exit of the memory chips market in 1986 and the bursting of the Japanese "bubble economy" in 1992). The number of Samsung's DRAM patents registered with the USPTO in the 1990-1994 period was close to those of NEC, Toshiba, and Hitachi, its three top Japanese competitors. By the mid-1990s, Samsung was able to transfer its 16MB synchronous DRAMs (SDRAMs) technology to Japan's Oki. This represents the first known case of Republic of Korea-Japan technology transfer in semiconductors. In 2001, Samsung became the first company in the world to use 300-nanometer wafer (12-inch) technology (Mathews and Cho, 2000). It would be misguided, however, to attribute the competitive success of Samsung in the 2010s exclusively to its earlier scale economies founded on the state-induced investment drive. Just like TSMC, continuous technological and organizational innovations were the more critical platforms through which Samsung could outcompete IDM firms from not just Japan and Chinese Taipei, but also the US and Western Europe. Unlike IDM firms from Chinese Taipei, Samsung has chosen a distinct developmental trajectory through path-breaking catching up in its semiconductor technologies and internationalization.

Samsung achieved rapid catching up through various technology agreements in the semiconductor industry between 1983 and 1997 (Shin, 2017). As early as in 1991, Samsung already invested 9% of its total sales in R&D, comparable to leading Japanese competitors. It became much less dependent on state-sponsored research institutes for their technological innovation. Instead, it turned to in-house R&D labs, friendly global lead firms, and international industrial associations. The success of Samsung in semiconductors was clear by the mid-1990s when it was ranked amongst the world's top ten semiconductor IDM firms. Since the late 1990s, Samsung's heavy investments in R&D and production facilities have been strategic in order to achieve further economies of scale and pose formidable barriers to entry to latecomers and other competitors from Chinese Taipei and the PRC. During the 2000s, it created a greater gap from its competitors in memory chips such as Micron (US) and Toshiba (Japan). Samsung had more DRAM patents in the 2000-2004 period than all of its Japanese competitors, except Hitachi. In the 2005-2009 period, Samsung's 61 DRAM patents were the most among all South Korean and Japanese DRAM producers. Its critical success factors were related to timely investments, speedy ramping up of production scale, and process innovations.

By the late 2010s, Samsung's competitive advantage rested well beyond its scale economies, sophisticated applied design, and process yield. Apart from its enormous lead in semiconductor technologies through continuous investments in R&D activity, Samsung had also benefited from unique organizational synergies embedded in Samsung's firm-specific business model of organizing its IDM business to supply both in-house own brand products (e.g. mobile phones and televisions) and third-party vendors, such as global lead firms in computers, telecommunications devices, and other consumer electronics (Yeung, 2022).

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Since the mid-2010s, investment in new fabs has become very costly due to high capital spending, rapid depreciation, and frequent process technology upgrades. The cost of building new fabs easily exceeds $10-15 billion per fab and capital expenditure is often very large for leading semiconductor firms. In foundry services, this enormous pressure from financial discipline on the broader semiconductor industry has ironically favored only a few foundry providers from Chinese Taipei (TSMC), the Republic of Korea (Samsung foundry), and the PRC (SMIC) that invested aggressively in new fabs and capital equipment during the 2010s (Yeung, 2022a: 248-249). As a latecomer to foundry, the PRC's SMIC counts the state-backed China Integrated Circuit Industry Investment Fund – also known as the "National IC Fund" – among its major shareholders and is a major beneficiary of the "Made in China 2025" plan in 2015 to channel $150 billion over 10 years through the Fund to boost the PRC's domestic semiconductor production. Despite US sanctions on its import of American chip-making equipment and technology, SMIC remained committed to establishing new fabs to cater to applications in automotive and consumer electronics. On 18 March 2021, it announced a new $2.4 billion 28 nm fab to be built by 2022 in the southern city of Shenzhen, with 23% stake owned by the Shenzhen government. This channelling of state capital through investment funds to domestic semiconductor firms represents an institutional attempt to avoid charges of government subsidization. State ownership in SMIC increased from 15% in 2014 to 45% in 2018 – the National IC Fund (19%), state-owned Datang Telecom (19%) and Tsinghua Unigroup (7%).

While government support is useful in the initial stage of semiconductor industrial development, it is not a sufficient factor for continual success and dominance, as will be evident in the next section. The case of Wuhan Hongxin (HSMC) in Box 4.6 is highly instructive of the key difficulties of policy implementation. Despite its aggressive sectoral industrial policy since the 2000s (see Table 4.4), the PRC's position in different semiconductor product categories remains quite weak (Fuller, 2019; Yeung, 2022a: Table 4.1). As of 2018, its small number of fabs in analogue and discrete chips were all foreign-owned (e.g. Texas Instruments from the US and Rhom from Japan), and no micro-component IDM fab was located in the PRC. Despite its dominant role in the final assembly of ICT end products, the PRC's 26 domestic fabs in 2018 produced only about 6% of the domestic semiconductor market of $131 billion in 2019 and $143 billion in 2020. This share increases marginally to 16% even if large capacity foreign-owned fabs by SK Hynix, Samsung, Intel, TSMC, and UMC are included. At this pace, the PRC government's goal of 70% self-sufficiency for semiconductor production in the "Made in China 2025" initiative will not be achieved. As of 2020, the PRC's giant semiconductor market remained heavily reliant on imported chips manufactured elsewhere in East Asia (and some in the US and Europe). Since 2018, the PRC has been importing annually over $300 billion worth of chips – reaching $380 billion in 2020 and $163 billion in the first five months of 2021. About half of these imported chips went into ICT final products for domestic sales and exports.

Box 4.6: HSMC and the Problems of Industrial Policy Implementation

The PRC has made enormous efforts, both nationally and locally, to support the development of the semiconductor industry through various industrial policy instruments, such as capital injection and financial incentives, inter alias, but there are painful lessons to be learned along with successful experiences. The collapse of Wuhan Hongxin (弘芯 a.k.a. HSMC, Hongxin Semiconductor Manufacturing Co.) is probably the most dramatic case in this regard (Feng, 2021; Gan, 2021). In November 2017, three businessmen with no background in semiconductors (or anything tech-related) set up a company in Beijing, aiming to build a chip fab to challenge the PRC's national champion SMIC. Just four days later, HSMC was established in partnership with Wuhan's Dongxihu District government that provided RMB 200 million in start-up capital. Despite its lack of technology, experience, and talent, HSMC had strong backing from the local government in Wuhan. In 2018 and 2019, it was twice listed as a "Major Project of Hubei Province", with local government subsidies and extra investment following suit.

By January 2019, HSMC had received RMB 6.5 billion in investment from the local district government. In March 2019 alone, HSMC received another RMB 1.5 billion. HSMC's total planned investment was RMB 128 billion (US$18.5 billion), making it the largest single project under construction in Wuhan at the time (Caixin, 2021). But things quickly turned sour, as HSMC was soon rocked by a series of legal troubles. Due to a legal dispute with an engineering firm, a local court suspended HSMC's land tenure in November 2019 that in turn halted its fab construction on that land. In 2020, HSMC started experiencing liquidity crunches and failed to pay many of its suppliers. In July 2020, the local government acknowledged that HSMC faced a massive funding gap (RMB 112 billion out of the planned total investment of RMB 128 billion) and that the project could grind to a halt at any time as a result of its broken funding chain and legal troubles. HSMC's situation did not improve, and a total collapse of the cash-strapped project ensued. Having spent more than RMB 15 billion ($2.1 billion), HSMC failed ultimately without ever producing a single chip.

In the context of the PRC's rush to make breakthroughs in chip manufacturing, the case exposes serious loopholes in the implementation mechanism of the PRC's industrial policy. As acknowledged by a spokesman from the National Development and Reform Commission – PRC's central planning and regulating body (Qiu, 2020), HSMC manifests itself in the form of reckless entrants into the semiconductor industry "with no experience, no technology, and no experts," and in the form of blind investments by local governments that are clueless about the semiconductor industry. The lack of effective screening and accountability mechanisms – to mention a few, setting thresholds for the granting of subsidies, private matching funds requirement, performance-based phasing in/out of subsidies – means that the unfortune combination has resulted in a succession of problematic projects (Zhang, 2021).

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4.6 The Rise of East Asia in Semiconductor Global Value Chains

By the turn of the new millennium and with the exception of the PRC, the role of the government in the rise of the East Asian semiconductor industry was diminished, as their domestic foundry and IDM firms had become more integrated into global value chains in both semiconductors and downstream end products such as PCs, smartphones, and servers. This was the time when industrial market specialization had become the more critical factor for success (Yeung, 2022b). Through specialization in semiconductor industrial products and niche markets, these latecomer firms in Chinese Taipei and the Republic of Korea (and later the PRC) have developed new firm-specific capabilities that fit into the description of neither first-mover (new industries) nor second-mover advantages (up-scaling). These firm-specific capabilities are manifested in three critical dimensions: new semiconductor product or process technologies, flexible semiconductor production and product diversity, and organizational knowhow and proprietary access to market information (e.g. via fabless customers and their OEM end-users). This capability development at the firm level is also conditioned by a peculiar combination of new government roles and competitive industrial dynamics. As these new roles are less interventionist in nature, their direct influence on semiconductor firms and industrial development is also harder to trace.

Latecomer East Asian firms have developed their own and more sophisticated technologies over time on the basis of their production capability and manufacturing excellence, even after they have already achieved scale economies and out-competed first mover firms from advanced industrialized economies. These new technologies are crucial in sustaining their market leadership in the global semiconductor industry that has become more competitive over time and required greater firm-specific dynamic capabilities (e.g. continuous learning and upgrading of technologies). In some cases, East Asian semiconductor firms such as TSMC (Box 4.7) and Samsung (Box 4.5) have created dynamic capability through the non-incremental creation of complementary and integrative knowledge built on the existing incremental or under-utilized knowledge of first movers from the United States, Western Europe, and Japan.

Specialization in industrial market leadership enables East Asian semiconductor firms to develop greater economies of scope through flexible production and product diversification. While scale economies are important in their initial catching up with first movers (e.g. Samsung in memory devices), continual success in global production networks requires these East Asian semiconductor firms to engage in flexible specialization. In this capital-intensive industry, competing on the basis of lower per unit cost of each product or service is not as effective and sustainable as capturing higher value through product differentiation or service varieties. The competitive dynamics in the semiconductor industry tend to favor firms that provide both scale and scope economies in order to avoid lock-in to particular products or services (Hobday et al., 2004). Leading East Asian semiconductor firms such as TSMC tend to adopt a portfolio of strategies tailored to different products, markets, and business cycles (Dibiaggio, 2007).

As East Asian semiconductor firms deepen their integration with global production networks in different industries (e.g. ICT, automotive, artificial intelligence, robotics, industrial electronics), they develop new organizational routines and innovations that strengthen their trust relationships with key customers and suppliers, and enable them to exercise better control of market information and customer access. This unique condition of industrial dynamics increases substantially the costs of information asymmetry and market intelligence at the firm level (Epicoco, 2013). The more liberal and well-functioning trade regime in the 2000s and up to the late 2010s provided a favorable structural context for these East Asian semiconductor firms to consolidate their strategic relationships with lead firms in different global industries.

Box 4.7: TSMC and Technological Innovation in Chinese Taipei

Founded in 1987 as a spin-off of the government-sponsored Industrial Technology Research Institute (ITRI), TSMC has been a market leader in semiconductor foundry services since the early 1990s. In 1992, TSMC had sales of slightly over US$250 million. By 1997, its revenue almost doubled. In 2010, TSMC already dominated the semiconductor foundry market and accounted for almost 40% of its US$33 billion market (10% of the total sales of all semiconductor firms). Its US$13 billion revenue would place it next to only the top two IDM firms– Intel and Samsung (Table 4.3). Ten years later in 2020, its revenue more than tripled to $46 billion and its foundry market share increased further to 54%. Buoyed by demand for high-performance logic chips of its fabless customers such as Apple and Qualcomm, TSMC's revenue in 2022 grew further by 30% to exceed $70 billion for the first time.

The dominance of TSMC in the foundry market since the 2010s has benefitted all leading fabless firms. The symbiotic trust relationship between TSMC and its fabless customers goes well beyond conventional contract manufacturing found in the final assembly of electronics products (e.g. Sturgeon, 2002). In this mutually dependent relationship, TSMC not only manufactures with cutting-edge process technologies, but also provides highly process-specific design support and intellectual property (IP) library services for fabless and fab-lite IDM firms. Starting from its 65 nm process in 2005, TSMC established the Open Innovation Platform program to collaborate early on with leading vendors of design software (e.g. Synopsys and Cadence) and IP design cores (e.g. ARM). Together, TSMC and the design ecosystem operate as a virtual IDM firm that drives the development and test of the innovative technology of its fabless customers (Kapoor and McGrath, 2014). In 2018, Synopsys announced its Synopsys Cloud Solution to serve end customers developing SoCs for high performance cloud computing. This cloud-based design solution was a result of collaboration with TSMC and lead cloud providers, such as Amazon and Microsoft, and was certified for TSMC's cutting-edge processes to enable IC design and verification (Nenni and McLellan, 2019).

Aggregating the diverse demand for chip fabrication from leading fabless and fab-lite firms, TSMC can achieve better economies of scale and scope in its fab processes than IDM firms such as Intel. TSMC accumulates much greater experimental and institutional knowledge in managing complex requirements in different fab-specific process recipes, ranging from the initial qualification of a new chip device to its subsequent ramp-up and mass production. Over time, these in-house recipes of new product introduction and product life-cycle management processes would become TSMC's strongest proprietary advantage and create an enormous barrier to entry. The spokesperson from TSMC used to liken it to be the "central kitchen" making burgers and fried noodles for different semiconductor firms (Interviewed and quoted in Yeung, 2016: 142). Given its "pureplay" foundry model and high trust relationships with customers and equipment suppliers, TSMC has the organizational capability to serve more than 10 customers and fabricate more than 100 products in the same manufacturing facility.

After significant capital investment and collaborative ecosystem development during the second half of the 2010s, TSMC's cutting-edge process nodes at 3 and 5 nm in wafer fabrication was more advanced than Intel fabs in the US. Only Samsung's most advanced 3 and 5 nm fabs in the Republic of Korea were on par with TSMC's mega-fabs in Tainan, and this trend will likely persist in the mid- to late-2020s. This changing technological leadership in chip making pivoting towards top foundry fabs in East Asia has profound implications for the industrial organization of semiconductor global value chains. By the end of 2020, TSMC's 5 nm Fab 18 in Tainan had entered into mass production, initially for Apple's A14/A14X mobile application processor chips and Huawei's Kirin 1000 network processor chips. TSMC's corporate research office was also working on new 2D materials to overcome the nanometre constraints of bulk (3D) semiconductors (Li et al., 2019). By end 2022, TSMC's 3 nm Fab 18 in Tainan also entered into mass production at high yield, marking its continual technological leadership in semiconductor manufacturing.

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By the late 2010s, the global semiconductor market became co-dominated by both IDM firms and fabless firms from the US and East Asia, together with top foundry partners mostly based in East Asia. As illustrated in Figure 4.3 earlier, their main products are in memory, logic, and microprocessor chips that drive ICT devices (e.g. smartphones, personal computers, tablets, and servers) and other industrial applications (e.g. automotive and electrical machinery). Table 4.5 maps such changing geography of chip-making capacity during the 2000-2018 period, based on the fab-by-fab aggregation of micro data on over 300 fabs worldwide (Yeung, 2022b; see also earlier Figure 4.4). During this period, the total number of IDM and foundry fabs remained fairly stable – 325 fabs in 2000, increasing to 344 in 2010, and consolidating to 296 in 2018 (but expected to increase again to over 350 fabs when the current massive new fab construction worldwide is completed in the 2023-2025 period). However, the total capacity of these fabs worldwide increased very significantly, doubling between 2000 and 2010 and increasing further by 32% to reach almost 17 million wafers per month in 2018. This growth rate matches fairly well the semiconductor market's revenue growth during the same period – from $221 billion in 2000 to a peak at $485 billion in 2018 (and again at $590-$600 billion in 2021 and 2022).

Geographically, substantial growth in new fabs and capacity has shifted towards East Asia since the 2000s. While the two East Asian "tigers" of Republic of Korea and Chinese Taipei already had some capacity in 2000, they were still far behind Japan, the US, and, for Chinese Taipei, even Europe. Fab capacity in the PRC and Singapore was marginal. By 2018, Chinese Taipei became the world's largest producer of semiconductors at 4 million wafers per month, followed by the Republic of Korea (3.6 million), Japan (3.0 million), and the PRC (2.2 million). Even the city-state of Singapore's capacity of 1.04 million was slightly larger than the entire Europe's output of 1.02 million. The US fell to 5th place, with 1.8 million wafers per month from its 44 fabs. During the 2010s, there was a substantial consolidation of fabs in Japan, from 131 in 2010 to 87 in 2018. The US also witnessed the closure of almost a quarter of its fabs and a slight decline in total fab capacity. In terms of product applications, Chinese Taipei and the PRC were by far the largest foundry producers (mostly in logic chips), whereas the Republic of Korea and Japan led in memory chip-making, with Singapore and Chinese Taipei trailing behind. In both logic and memory chips, the US and Europe experienced declining fab numbers and capacity throughout the 2010s (see recent update in Huggins et al., 2023).

This enormous growth in global semiconductor manufacturing capacity and its pivot towards East Asia during the 2010s has been driven by the tremendous growth in intermediate market demand for logic and memory chips in several major product applications in ICT devices (PCs and smartphones), data center servers, and consumer electronics (e.g. TVs). Table 4.6 provides a firm-level perspective to the above macro-observations. In 2018, logic chips accounted for the vast majority of fab outputs by all top five foundry providers, led by TSMC (see Box 4.7). Contributing to Chinese Taipei's dominant role in foundry firms (Table 4.2), TSMC is ranked top in fabricating logic chips for smartphones, PCs, and industrial electronics, allocating some 54% of its 2018 fab capacity to making smartphone logic chips designed by Apple (24% share of TSMC's total revenue in 2019), HiSilicon (15%), Qualcomm (6%), and MediaTek (4.3%). Geographically, TSMC's enormous fab capacity of 2.3 million wafers per month is heavily concentrated in its 8 fabs in Chinese Taipei. While the US remains the dominant centre of logic chip design (i.e. fabless firms mostly based in Silicon Valley) and microprocessor design and manufacturing (i.e. Intel in Table 4.3), East Asian foundry providers are dominant in logic chip manufacturing.

Table 4.5: Geography of World Semiconductor Manufacturing by Fab Location, Product Applications, and Capacity, 2000-2018 (foreign owned in parentheses)

	2000	2000	2010	2010	2018	2018
Fab location	**Fab #**	**Capacity[1]**	**Fab #**	**Capacity[1]**	**Fab #**	**Capacity[1]**
US						
Logic	14 (2)	311 (85.5)	11 (3)	589 (309)	4 (3)	433 (370)
Memory	6 (3)	251 (134)	5 (1)	319 (36.0)	4 (0)	244 (0)
Foundry	4 (2)	90.6 (39.3)	5 (3)	125 (73.8)	8 (4)	285 (105)
Total	68 (18)	1,310 (407)	57 (14)	1,875 (529)	44 (12)	1,770 (547)
Japan						
Logic	43 (6)	509 (121)	47 (6)	696 (125)	25 (0)	481 (0)
Memory	14 (0)	359 (0)	13 (0)	1,035 (0)	14 (2)	1,658 (281)
Foundry	3 (1)	57.9 (38.3)	4 (1)	58.1 (25.7)	10 (3)	242 (76)
Total	132 (10)	1,724 (243)	131 (14)	2,667 (307)	87 (8)	2,965 (471)
Republic of Korea						
Logic	9 (0)	314 (0)	10 (0)	772 (0)	10 (0)	722 (0)
Memory	7 (0)	555 (0)	9 (0)	2,000 (0)	13 (0)	2,579 (0)
Foundry	1 (0)	28.6 (0)	2 (0)	92.3 (0)	3 (0)	211 (0)
Total	22 (3)	1,058 (107)	23 (2)	2,939 (74.4)	28 (2)	3,563 (50.8)
Chinese Taipei						
Logic	2 (0)	54.7 (0)	4 (0)	144 (0)	5 (0)	238 (0)
Memory	6 (0)	154 (0)	13 (0)	830 (0)	10 (3)	831 (393)
Foundry	17 (0)	514 (0)	24 (0)	1,630 (0)	27 (0)	2,947 (0)
Total	26 (1)	724 (1.7)	42 (1)	2,606 (1.7)	43 (4)	4,017 (395)
PRC						
Logic	1 (0)	7.2 (7.2)	1 (0)	8.1 (8.1)	1 (0)	12.9 (0)
Memory	0 (0)	0 (0)	3 (3)	189 (189)	5 (1)	728 (3.4)
Foundry	4 (0)	64.8 (0)	19 (2)	681 (92.2)	25 (4)	1,364 (264)
Total	8 (3)	84.3 (19.5)	27 (9)	913 (232)	37 (11)	2,189 (353)
Europe						
Logic	9 (3)	164 (58.0)	6 (1)	167 (36.0)	4 (0)	134 (0)
Memory	5 (2)	136 (59.6)	4 (2)	116 (55.0)	2 (0)	65.0 (0)
Foundry	3 (1)	47.3 (25.5)	7 (4)	150 (121)	8 (4)	259 (193)
Total	55 (30)	845 (437)	42 (25)	889 (441)	37 (19)	1,019 (559)
Singapore	8 (3)	167 (14.6)	14 (14)	702 (702)	12 (12)	1,042 (1,042)
Israel/Malaysia	6 (5)	77.8 (68.8)	8 (2)	290 (228)	8 (2)	431 (373)
Total	**325**	**5,991**	**344**	**12,879**	**296**	**16,997**

[1] Fab capacity in thousands of 8-inch (200 mm) equivalent wafer starts per month.

Source: Calculate from the fab-level data of each semiconductor manufacturer available from IHS Markit/Informa Tech Custom Research, July-October 2016 and 2019.

In memory devices – the largest chip application with $165 billion revenue or 34% of world market in 2018 (Table 4.6), the geography of chip manufacturing and fab locations is still based on the IDM-model of vertically integrated production networks highly concentrated in East Asia. As evident in Table 4.3, this market is controlled by four very large IDM firms – Samsung, SK Hynix, Micron, and Toshiba/Kioxia. Having emerged as the market leader in the late 1990s (Box 4.5), Samsung alone accounted for 40% of the memory market in 2018, the equivalent of the next two combined – SK Hynix (22%) and Micron (18%). Samsung and SK Hynix's memory fabs are mostly located in the Republic of Korea, whereas all of Toshiba/Kioxia's five fabs are in Japan

Table 4.6: World’s Top Semiconductor Manufacturers by Fab Capacity, Main Applications, Fab Locations, and Markets, 2010 and 2018

Lead firms	Sales ($b)		Fab capacity[1]	Applications (% of 2018 sales)	Location of HQs and fabs	Key end market segment (% of 2018 sales)
	2010	2018				
IDM *Samsung*	28.4	74.6	2,474	Memory 88%	Republic of Korea, US, PRC	Smartphones, PCs, consumer electronics
Intel	40.4	69.9	722	Microprocessors 76%	US, Ireland, Israel, PRC	PCs, servers, and data centers
SK Hynix	10.4	36.3	1,385	Memory 99%	Republic of Korea, PRC	Smartphones and PCs
Micron	8.9	29.7	1,038	Memory 100%	US, Singapore, Chinese Taipei, Japan	PCs, servers 37 %; storage 26%; smartphones 21%
Toshiba	13.0	11.4	1,310	Memory 100%	Japan	Smartphones, PCs, consumer electronics
Foundry TSMC	12.9	31.1	2,266	Logic 87%	Chinese Taipei, PRC, US	Smartphones 54%, PCs 15%, industrial electronics 17%
Global-Foundries	3.5	6.2	592	Logic 68%	US, Germany, Singapore	Smartphones 35%, PCs 23%, consumer electronics 23%
UMC	3.8	5.0	653	Logic 84%	Chinese Taipei, PRC, Singapore	Smartphones 42%, PCs 16%, consumer electronics 28%
Samsung	0.8	3.4	371	Logic 100%	Republic of Korea, US	Smartphones and PCs
SMIC	1.6	3.0	451	Logic 53%	PRC	Smartphones and wireless 41%, consumer electronics 38%
World market	312	485	16,997	Memory 34% Logic 22% Microprocessors 12%	-	Computer & data storage 37% Wireless and smartphones 30% Industrial electronics 11% Consumer electronics 8.6%

[1] Fab capacity in thousands of 8-inch (200 mm) equivalent wafer starts per month.

Sources: Authors’ interviews with IDM firms and foundry providers in *italics*, IHS Markit/Informa Tech Custom Research, July-October 2016 and 2019, and corporate reports and websites.

(Table 4.6). In comparison, American IDM Micron’s seven fabs are more diversified geographically, but its four fabs in Singapore, Chinese Taipei, and Japan account for 80% of its total capacity.

The massive building of new fabs or capacity expansion in East Asian locations during the 2010s cannot be adequately explained by favorable government policies and strong support from localized ecosystems. These necessary “East Asian” conditions would be insufficient if there were no corresponding market demand for memory and logic chips utilizing this new capacity in East Asia. Top semiconductor firms in East Asia would not have incurred massive capital expenditure in the 2010s to build new fabs without anticipating future demand and/or attaining strong commitment of orders from their top customers, e.g. Apple’s iPhone chips exclusively utilizing TSMC’s latest process nodes in dedicated home fabs since 2016 and OEM lead firms in PCs and servers as key customers for memory chips from Samsung and SK Hynix (see also Fontana and Malerba, 2010).

Without accounting for the demand-led market dynamics driving these firm-specific strategies within their global production networks, it will be difficult to explain why further capacity growth in Chinese Taipei and the Republic of Korea occurred in the 2010s when their respective government supports had already become weaker and less interventionist and their leading domestic semiconductor firms had depended less on government support and much more on their strategic coupling with lead firms in global production networks and value chains. But as global competition and geopolitical tensions have increased much further in the post-pandemic 2020s, more economies and macro-regions want to localize/reshore their own semiconductor value chains with “real fabs” in the spirit of AMD’s Jerry Sanders. The next, penultimate section will consider this ongoing techno-nationalist approach to the question of whether nation-states are indeed more “real” by having their own fabs in semiconductor manufacturing.

4.7 Techno-Nationalism: Must Real States Have Fabs?

Recently enacted national policies, such as the CHIPS and Science Act of the United States, the EU Chip Act, and the ¥2 trillion subsidy allocated by the Japanese government to the semiconductor industry, indicate a revival of industry policy in developed nations, which in the past preferred laissez-faire to government interventions and aggressively promoted the free-market doctrine, commonly known as the Washington Consensus, to developing nations. Free market believers often dismiss the need of industry policy and use information barriers and possible rent-seeking as powerful arguments against industry policy (Rodrik, 2008). A recent report by Cato Institute “Questioning Industrial Policy” (Lincicome and Zhu, 2021) argues strongly against the adoption of new industrial policy in the US for strengthening semiconductor manufacturing and other strategic industries. On the other hand, Nobel laureate Michael Spence (2023) argues that industry policy serves not only economic but also social objectives. Economic efficiency should not be the only yardstick for assessing the efficacy of industry policy. Given the recent geopolitical tension and national security concerns, Spence claims that implementing industry policy in the US is inevitable.

Since the 2020s, the renaissance of a new wave of techno-nationalism (Capri, 2019; Luo, 2022) can be associated with three main driving forces: (i) concerns over the resilience of semiconductor GVCs; (ii) semiconductors as the foundation of national security; and (iii) the interactive process between the great powers today, notably the Sino-US race for technology leadership. We summarize recent policies enacted by all major economies to domesticize semiconductor capacity and to improve semiconductor resilience and evaluate their likely short-term effects.

First, the COVID-19 pandemic and recent geopolitical conflicts have served as catalysts for policymakers around the world to recognize the importance of supply chain resilience, i.e. the ability to recover quickly from and adapt to an unexpected shock (Pettit et al., 2010), for such critical products as semiconductors. In particular, pandemic-related and environmental disruptions have revealed long-existing vulnerabilities in global supply chains, especially those associated with overdependency for the supply of some critical products on a single nation/region – a circumstance exacerbated by geopolitical concerns (White House, 2021). Since mid-2020 and driven mainly by the stay-at-home economy, the demand for chips has spiked, especially in the consumer electronics and automotive sectors. On the supply side, there have been bottlenecks in qualified chips manufacturing capacity (in particular, for use in the automotive industry; see Suleman and Yagci, 2022b), which are located mostly in East Asia and were adversely impacted by the COVID-19 lockdowns. Together, the two forces resulted in severe global supply shortages and rapid price increases of chips in 2021 and 2022 (LaPedus, 2021; J.P. Morgan, 2022), affecting automotive, industrial, and communications products, among others.

For several decades, GVCs have been organized and dominated by transnational corporations in the wider context of a liberal policy approach to domestic production in many nations, prioritizing efficiency, productivity, and low costs over security, sustainability, and resilience. In semiconductors, the pursuit of hyper-efficiency through the "fabless revolution" discussed in earlier sections has led to the heavy concentration of logic chip production in foundry providers based in Chinese Taipei and the Republic of Korea. Industrial policy success and market dynamics in East Asia have also created giant memory chipmakers in the Republic of Korea, Japan, and the PRC. Ironically, the same geographical concentration is evident in the supply of semiconductor manufacturing equipment and materials. According to BCG and SIA (2021), there are at least 50 chokepoints across virtually all major types of value-adding activities in semiconductor GVCs, where a single region, either in terms of physical location or ownership, accounts for 65% or more of the total global supply. All major economies are now waking up to the idea that they need to diversify their source of semiconductor imports and improve their supply chain resilience, possibly by reverting to domestic production, nearshoring, or friend-shoring to new locations (Lund et al., 2020; G7, 2023).

The fact that semiconductors are the foundation of national security would be a second reason for the rise of techno-nationalism. Indeed, more resilient and secured supply chains are deemed essential for a nation's economic security (in terms of steady employment and smooth operations of critical industries), national security, and technological leadership. More substantially, major economies around the world concur that semiconductors are the critical technological foundation of economic and national security.

In the US, policy makers believe that advances in science and technology are poised to define the geopolitical landscape of the 21st century. Together with biotech and clean tech, computing-related technologies, including microelectronics, quantum information systems, and artificial intelligence, are identified as truly "force multipliers" throughout the American tech ecosystem. Accordingly, a key element of its new National Security Strategy is to invest in the sources of its national strength, recharging the engine of American technological dynamism and innovation, especially in these foundational sectors. At the same time, the US would adopt a “small yard, high fence” strategy for such critical technologies as semiconductors, ensuring that “choke points for foundational technologies have to be inside that yard, and the fence has to be high because these competitors should not be able to exploit American and allied technologies to undermine American and allied security” (Sullivan, 2022).

Third, and unlike the mid-1980s discussed in section four, this new techno-nationalism rests on the premise that the world has entered into a new era of systemic geopolitical rivalry between competing powerhouses with radically divergent ideological values, political systems, and economic models; it indeed is posed as a political-economic response to such structural changes. By highlighting the importance of technological autonomy/self-sufficiency (Reich, 1987; Tyson, 1993), it justifies and advocates for proactive government interventions, seeking to get an upper hand over its rivals in technological fields of strategic importance in order to attain geopolitical gains. New techno-nationalism thus exhibits a tendency toward de-globalization, decoupling, and de-risking through the imposition of restrictions on technology flows and increasingly unilateral, aggressive, and extraterritorial measures to achieve national objectives.

To strengthen semiconductor supply chain resilience and address national security concerns, governments in major economies have recently pushed for the localization and/or reshoring of chip manufacturing capacity through techno-nationalistic industrial policies, mainly in the form of the provision of direct subsidies and tax credits:

(i) The US. The CHIPS and Science Act of 2022 is the most representative sample of this new wave of interventionalist industrial policy, reflecting a broader shift of stance in American economic policy-setting. Signed into law on 9 August 2022, the Act provides $52.7 billion in emergency supplemental appropriations to support authorized semiconductors programmes, together with a semiconductor investment tax credit estimated to be worth around $24 billion. This 25% investment tax credit (ITC) for investments in semiconductor manufacturing equipment and facilities is created by the Act, serving as an additional tool to close the cost gap between semiconductor investment in the US and other countries. The Act installs strong guardrails that exhibit a strong techno-nationalist overture, such as preventing funds/ITC recipients from expanding/building manufacturing facilities below some technology threshold in the PRC or other foreign countries of concern, and restricting them from engaging in any joint research or intellectual property transaction with a foreign entity of concern. Division B of the Act authorizes – rather than appropriates, as with the semiconductor funds in the Act – nearly $170 billion in funding over five years for R&D initiatives administered by multiple federal agencies. This amounts to a $82.5 billion boost over the baseline funding budget, representing the largest five-year investment in public R&D in US history.

(ii) PRC. Apart from the two major Chinese techno-nationalist initiatives of "Made in China 2025" and "National IC Plan" discussed earlier, the PRC has responded strongly to the American imposition of sweeping export controls toward the PRC in advanced semiconductor technology. In October 2022, Beijing reportedly planned to roll out a new 1 trillion yuan ($143 billion) fiscal incentive package for its semiconductor industry in 2023, representing a major step towards "self-reliance and strength (自立自强)" in semiconductors to counter American moves to slow its technological advancements. As such, Beijing is seemingly changing its strategy by moving away from catching up in leading-edge technology to the full-range domestication of mature-node technology. The incentive package will be allocated mainly as subsidies and tax credits to bolster the production and research activities of semiconductor and chipmaking tools at home, rather than as direct interventionist mega investments. The majority of the package will likely be used to subsidize a handful of the most successful semiconductor firms and the purchases of domestic semiconductor equipment (for up to 20% of the costs).

(iii) Europe. In February 2021, the European Parliament approved the EU's proposed €672.5 billion worth "Recovery and Resilience Facility" (RRF) in the form of grants and loans to be disbursed over the next few years. The co-legislators agreed that a minimum of 20% of the REF would be devoted to supporting the "digital transformation" of Europe, with the specific goal for the semiconductor industry. By 2030, the production of cutting-edge semiconductors in Europe should be at least 20% of the world total in value, and the manufacturing capacity below 5 nm is targeted at 2 nm and 10 times more energy efficient than today. Noting the EU's reliance on external suppliers and its diminished share in semiconductor GVCs, the European Commission decided, after the US had announced its CHIPS for America Act, in September 2021 that it too would enact a new "European Chips Act", aiming at creating a state-of-the-art European chipmaking ecosystem to keep the EU competitive and self-sufficient. In April 2023, the European parliament approved the European Chips Act. legislative proposal took shape in February 2022. It will mobilize more than €43 billion ($47 billion) worth of public and private investments by 2030 and leverage Europe's strength in world-leading R&D organizations and networks, as well as hosting pioneering equipment manufacturers.

(iv) Japan. As discussed in section four, Japanese semiconductor manufacturers held more than half of the global market share in the 1980s (see also Table 4.3). Since then, their market share has declined substantially, and, in the 2010s, Japanese chipmakers withdrew from competition in large-scale chip development. In the current context of semiconductor supply shortages and concerns for economic security and supply chain resilience, the Japanese government has been trying to establish a legal framework to subsidize the construction of new semiconductor production facilities (especially cutting-edge processes) in Japan. A legislative proposal was submitted to the parliament in December 2021, and was approved with a ¥774 billion ($6.8 billion) supplementary budget for fiscal 2021 that would fund the subsidies for semiconductor fabs. The TSMC-Sony plant in Kumamoto announced in October 2021 would be the first beneficiary. Producing at mature nodes, the plant began in 2022 and would start mass production in 2024 – the Japanese government would provide half of the overall ¥1 trillion ($8.82 billion) in capital investment. Other possible beneficiaries include memory chipmakers such as Micron from the US and Kioxia from Japan. Under an economic security promotion law enacted in 2022, Japan further dedicated ¥1.3 trillion supplementary budget for fiscal 2022 to fund new and expanded subsidies for up to one-third of capital investment related to a variety of semiconductors, chipmaking equipment and components, and up to half of investment in raw materials. Both domestic and foreign firms investing in Japan can qualify for such subsidies. Rapidus, a newly founded Japanese chipmaker aiming to produce 2nm chips, received ¥330 billion subsidy from the Japanese government. American company Micron would receive ¥200 billion subsidy for expanding its factory in Hiroshima.

(v) India. In December 2021, India approved the Semicon India Program (Program for Development of Semiconductors and Display Manufacturing Ecosystem in India) that comes with an outlay of $10 billion to an incentive scheme for the development of a sustainable semiconductor and display manufacturing ecosystem in India. The program aims to provide attractive incentives to bring in a total of $25 billion investment in semiconductors and display manufacturing. The aim is to increase India's semiconductor self-sufficiency and to make India a key player in semiconductor GVCs. More broadly, incentives worth $30 billions will be available to position India as a global hub for electronics manufacturing.

Taken together, the short-term effects of these techno-nationalist policies are rather obvious – the massive increase in fab capacity worldwide or "fabs everywhere". From 2021 to 2023, the global semiconductor industry is projected to invest more than $500 billion in 84 new high-volume front-end chipmaking facilities, with the number for the three years being 23, 33 (a record high), and 28 respectively (SEMI, 2022b). While East Asia still accounts for the majority of this new capacity, its global distribution is significantly more diverse than before. Not surprisingly, the US has become a top location for new capital spending around the world. From 2021 to 2023, 18 new facilities are forecasted to start construction in the US alone. The PRC is expected to outnumber all other locations in new chip manufacturing facilities, with 20 mature-node facilities planned. Propelled by the European Chips Act, European investment in new semiconductor facilities is expected to reach a historic high, with 17 new fabs planned between 2021 and 2023. In the same period, Chinese Taipei is expected to start construction of 14 new facilities, while Japan and Southeast Asia are each projected to begin building six new facilities, and the Republic of Korea is forecast to start construction of three large facilities.

But is this "fabs everywhere" phenomenon realistic for the coming decade? Before we offer some concluding remarks, we examine briefly this phenomenon in the context of the PRC-US race for technology leadership and the PRC's drive for semiconductor self-sufficiency. It has long been argued that policymakers with a techno-nationalist mindset would not hesitate to curtail or sever economic and technological ties with rivals if they believe that such ties benefit their rivals more (e.g. Nelson and Ostry, 1995). Indeed, this is what is happening among major competing geopolitical powers during the 2020s. The evolution of the new wave of techno-nationalism can be viewed as an interactive process between the great powers, notably the US and the PRC. This wave first emerged in the 2010s, when the PRC introduced a series of massive industrial policy initiatives. Inspired by the successful experiences of industrial policies in many East Asian economies, especially in the semiconductor industry discussed earlier in section four, the PRC launched multiple mega industrial policy initiatives in the 2010s, notably the "Made in China 2025" initiative in 2015 and the somewhat overlappingly "Guideline for the Promotion of the Development of the National Integrated Circuit Industry" (a.k.a. the "National IC Plan") that comes with the accompanying "National IC Industry Investment Fund" (a.k.a. the "Big Fund") in 2014 (VerWey, 2019; Capri, 2020).

It is estimated that the Chinese government's overall funding commitment to these initiatives amounts to an almost unprecedented scale of $300 billion, with the ultimate goal of nurturing the next generation of "national champions" in key strategic areas such as semiconductors. While there have been painful lessons in policy implementation such as the Hongxin Semiconductor Manufacturing debacle (Box 4.6), the PRC has steadily closed the technology gap with global leaders and established itself as one of the leading players in many foundational and emerging technologies of the future (Manyika et al., 2019). In semiconductors, a well-known example is Huawei. Its rapid rise to the world's largest telecommunication equipment manufacturer and one the world's top semiconductor firms via its chip design subsidiary HiSilicon (see Table 4.3) has amplified the long-standing allegations about its connection to the state and the sources of its competitive edge (Berman et al., 2020).

By the late 2010s, many in America's political establishment had increasingly perceived the PRC as engaging in a broader campaign to challenge America's great power status. Consequently, technology transfer to and technological cooperation with the PRC was viewed not just on its commercial merits, but also as a potential national security risk. This heightened anxiety then prompted the US to initiate the process of trying to decouple from the PRC in certain technological sectors since 2020. In particular, the US has two significant issues with the PRC's industrial policy in semiconductors (Hodiak and Harold, 2020). First, the sheer scale of state-backed financial support of the PRC's semiconductor industry has raised concerns about the resulting market distortions. Second, worries over the PRC's relatively lax intellectual property protection have further heightened skepticism about how the PRC would achieve parity with leading-edge design and manufacturing in this sector without technology transfer from foreign firms. By around 2020, there was a growing conviction in Washington and among its allies that the

PRC's industrial initiatives were motivated by geopolitical ambitions beyond economic considerations.

Starting with the Trump Administration, the US has taken a flurry of techno-nationalist countermeasures, including the tightening of control over "dual use" technologies, the imposition of sanctions and restrictions on a few high-profile hi-tech Chinese firms, and the rolling out of fully-fledged semiconductor export controls toward the PRC. Suleman and Yagci (2022a: 12) argue that such moves represent a strategic orientation by the US to ensure its leading position in critical supply chains such as semiconductors. In part as a response to Beijing's mega industrial policy initiatives, the US congress passed the Export Control Reform Act (ECRA) in 2018. Focusing on "emerging" and "foundational" technologies, the act expands the scope of dual-use technologies on US Department of Commerce's Controlled Commodity List (CCL), placing all 10 categories of technologies targeted in "Made in China 2025" under the umbrella of "dual-use". This means most, if not all, US-PRC technology transfers are now susceptible to stricter export controls and license requirements. Moreover, the US has imposed sweeping sanctions and restrictions on Huawei and other hi-tech Chinese firms (see Box 4.8). Washington has singled out Huawei and other Chinese high-tech firms, such as ZTE and SMIC, in the context of US-PRC techno-nationalist innovation race, denied their access to US (telecommunications) market, and imposed stringent export controls against them.

Most recently in October 2022, the strong US reaction to the PRC's technological and geopolitical ambitions culminated in the Biden administration imposing the most stringent restrictions on technology exports to the PRC in decades. These sweeping restrictions, in essence, prohibit the PRC from access to the most advanced chips made with American software and/or equipment in design and manufacturing, as well as by fabs hiring Americans to work in them. The holistic nature of these highly targeted restrictions comprises interlocking elements targeting the different segments of semiconductor GVCs, each leveraging American dominance in a specific chokepoint while all working together to serve the overarching goals (Allen, 2022; Suleman and Yagci, 2022a). In March 2023, Japan and the Netherlands followed suit without explicitly referencing the PRC and announced new export controls on key semiconductor technology to prevent undesirable end use (e.g. military deployment) and unwanted long-term strategic dependencies, and to maintain their domestic technological leadership. These controls will take effect respectively in July and September 2023.

Not surprisingly, the PRC has also taken tit-for-tat countermeasures against these US-led sanctions. Two recent moves stand out. On 23 May 2023, in a first big move against an American semiconductor company Micron, the Cyberspace Administration of the PRC (2023) announced that it would ban the PRC's domestic operators of critical information infrastructure from purchasing Micron's product, citing national security reasons. Micron is the leading US memory chips manufacturer, with 25% of its global sale coming from the PRC and Hong Kong, China (Olcott and Sevastopulo 2023).

Box 4.8: The Impacts of US Sanctions on Huawei

Semiconductors have been at the heart of US-PRC trade war. The US strategy is to limit the PRC's access to critical technologies in an attempt to slow down its technological progress in the sector, whereas Huawei is the most affected ICT firm based in the PRC (Suleman and Yagci, 2022).

On 19 May and 19 August 2019, the US Department of Commerce added Huawei and its subsidiaries to the Export Administration Regulations (EAR) "Entity List". Prior to its addition to the list, Huawei was the world's largest telecoms equipment manufacturer and third-largest smartphone vendor, sourcing more than $10 billion worth of goods and components from the US annually. On 15 May and 17 August 2020, the US Department of Commerce further announced two more expansions of export controls on Huawei. Apart from adding 152 more associates of Huawei to the entity list, the most critical element of the new restrictions is to impose license requirements not only on US-made items, but on any foreign-made item that incorporates more than a de minimis amount of controlled US-origin items, or that is the direct product of a controlled software or technology. Under this new rule, US authority effectively prohibits Huawei's non-US suppliers that rely critically on US equipment or technology from supplying chips to Huawei and its affiliates.

As a result of the sanctions, HiSilicon, Huawei's chip design arm aiming to rival market leader Qualcomm, was cut off from access to updates and technical support for mainstream EDA software (Nikkei 2019), a segment dominated by three US-based firms. Even worse, subject to US restrictions, as of 15 September 2020, TSMC stopped providing foundry services to Huawei for advanced chips designed by HiSilicon (e.g. Kirin chipsets for smartphones). The combination of strikes has all but crippled Huawei's semiconductor design operations. Since the second half of 2020, HiSilicon's market position and sales revenue have plummeted dramatically (IC Insights, 2020; 2021). Moreover, the new restrictions have also blocked Huawei's access to advanced chips and other critical components. The impact of these restrictions on Huawei is most pronounced in its rapidly diminishing share in the global smartphone market. In 2019 Q1, Huawei shipped 59.1 million smartphones, giving it a 17% global share. In 2021 Q1, Huawei's global share fell sharply to only 4% (mostly in the domestic market), with the shipment being only 15 million units (Counterpoint, 2021). Due to the rapid loss of smartphone market share, Huawei's smartphone business literally collapsed by 2021 (Strumpf 2021).

Meanwhile, Huawei's telecoms carrier equipment business has also been suffering from the shortage of critical chips and components, albeit to a lesser extent. In 2021, Huawei's carrier business posted a revenue of 281.5 billion yuan, down around 7% year-on-year (Kharpal 2023). Overall, the negative impacts of US sanctions on Huawei were most deeply felt in 2021, when Huawei's revenue fell by 29% year-on-year to $99.9 billion (636.8 billion yuan), marking its first yearly decline. In 2022, Huawei's revenue stabilized at 642.3 billion yuan (a 0.9% year-on-year rise) as the company diversified into new areas such as cloud computing and automotive technology. However, its 2022 profit plunged 69% year-on-year to $5.18 billion (35.6 billion yuan), making a record-low net margin of 5.5% due to the continual pressure from U.S. sanctions and the PRC's pandemic controls (Kharpal 2023).

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The PRC's second countermeasure came on 3 July 2023, when the Chinese Ministry of Commerce (2023) imposed new export restrictions on gallium, germanium, and their compounds, again citing national security reasons and in an apparent retaliation for new US-led Western sanctions on its semiconductor industry. The two rare metal elements are critical to the manufacture of semiconductors, for which the PRC is the world's largest producer, accounting for more than 95% and 67% of their respective global outputs (Zhen 2023). Clearly, the prospect of a rapid escalation of US-PRC tension creates great uncertainty for the future of global semiconductor value chains.

Conclusions

The recent COVID-19 pandemic, global chip shortages, and the US export restrictions on semiconductor technologies have focused worldwide attention on this important high-tech sector. Many national governments in advanced economies have now placed far greater urgency on, and enacted specific industrial policies for, (re)building their domestic semiconductor manufacturing capacity or wafer fabrication (fabs). From the US and the EU to Japan, the Republic of Korea, India, and the PRC, these government-led initiatives are often couched in the name of supply chain resilience and national security considerations. In this global race to build "fabs everywhere", there is a common neglect of the fact that semiconductor global value chains (GVCs) are themselves in massive transition from previously fully integrated devices based on in-house design and manufacturing within the same semiconductor firm to – increasingly since the 1990s – the organizational and geographical separation of the design and fabrication of these devices. In this "fabless revolution" since the late 1980s, chip design and production can be completed in entirely different firms and geographical locations. Meanwhile, ingenious technological innovations in semiconductor design and manufacturing have continued unabated to push the frontiers of the so-called "Moore's Law" of shrinking chips with far greater computing power. Coupled with the incessant demand for such smaller and more powerful chips in new industrial applications such as personal computers, smartphones, and servers in the past two decades, semiconductor manufacturing has become far more sophisticated in technological terms and capital-intensive in financial commitments. By the late-2010s, only three semiconductor firms were able to invest continuously in new leading-edge fabs (defined as process technologies at the 10 nanometre or smaller nodes).

These industry-specific characteristics have posed fundamental challenges to the current national policy initiatives in building "fabs everywhere". As we opened the chapter with a quote from the CEO of TSMC – currently the world's leading chip manufacturer, these policy efforts must be viewed with some circumspection because it is neither realistic nor easy for every nation to build their own fabs. Indeed, this chapter has demonstrated with substantial evidence that semiconductor GVCs are far more complicated in both organizational and geographical terms than what most policy advocates of "own fabs" would have thought. The chapter has shown that the top semiconductor lead firms have increased their collective market share during the past ten years, particularly in two types of chips – logic and memory. While only a few market leaders dominate in the different segments of semiconductor GVCs, from design software and intellectual properties to materials and manufacturing equipment, each of these segments in turn depends on a wide range of trusted key suppliers and technology leaders worldwide. Even ASML from the Netherlands, as the sole provider of the most sophisticated lithography machines for chipmaking, is dependent on hundreds of specialized suppliers for its very limited annual production of the €200 million EUV lithography machine indispensable in any bleeding-edge fab.

To account for these transformative shifts in semiconductor GVCs up to the early 2020s, the chapter's third main section has examined the changing fortunes in the industry by focusing on the rise of fabless logic chip design firms and their manufacturing partners, known as pureplay foundry firms such as TSMC, since the 1990s. Our findings have pointed to the significant role of high costs in chip design and production, capital market preferences, necessary economies of scale, and changing market dynamics in driving this "fabless revolution". As logic chips become ever more sophisticated with higher computational power and energy efficiency, their design and production require even more costly human capital, electronic design automation software, intellectual property, and highly specialized manufacturing equipment that only a few can afford. In the US and Silicon Valley in particular, the preference of venture capital for asset-lite semiconductor firms has compelled more American start-ups to go fabless. But who gets to make the chips for these fabless firms? The clear answer lies in the rise of pureplay foundry fabs based in East Asia, such as Chinese Taipei, the Republic of Korea, Singapore, and, most recently, the PRC. Empirical evidence in this chapter supports our arguments outlined in Introduction, that such vertical disintegration in chip design and manufacturing has indeed driven the globalization of semiconductor production and the global reach of semiconductor GVCs.

But such "fabless revolution" has not happened in every product category of semiconductors: there have been different forms of "verticality" or vertical specialization in semiconductor GVCs since the 2010s. Our analysis has shown that the fabless-foundry model of semiconductor GVCs is particularly strong and efficient in application-specific logic chips. But in memory chips, another key product category in the currently $600 billion global semiconductor market, integrated device manufacturing (IDM) or vertical integration remains the dominant mode of organizing global production networks and global value chains. The same kind of IDM-led chip design and production is also prevalent in microcomponent, analogue, and discrete chips. In all these product categories, leading IDM firms (except Intel in microprocessors) take a hybrid approach to organizing their production networks characterized by in-house fabs for mature technology nodes and the complete outsourcing of advanced logic chips to leading foundry providers such as TSMC and GlobalFoundries. Through this fab-lite approach, these IDM firms are able to capitalize on their existing and well depreciated fabs and to avoid the tremendous costs of investing in new cutting-edge fabs. This dependency of fab-lite IDM firms on leading foundry providers in turn explains why their customers, many in the automotive sector, suffered from global chip shortages during the 2021-2023 period.

In terms of industrial concentration, East Asia has now played a dominant role in logic and memory chip production because of several top pureplay foundry providers (TSMC, Samsung Foundry, UMC, and SMIC) and IDM firms (Samsung, SK Hynix, and Kioxia/Toshiba). Empirical discussion in the fourth section has provided some evidence to support our argument that the government support in Japan, Republic of

Korea, Chinese Taipei, and Singapore was crucial in supporting the initial development of champions in foundry and memory chip production in the 1970s through to the early 1990s. Through a mix of government-sponsored industry consortia, favourable financial support through loans and grants, technology transfer facilitated by national research institutes, and policy preference for specific firms (i.e. "picking the winner"), these East Asian economies were able to achieve, in successive historical periods starting with Japan in the late 1970s, rapid catching-up in semiconductor process and manufacturing technologies. And yet it is critical to note that not all East Asian government-led initiatives have been successful. While Chinese Taipei's achievement in semiconductor foundries, as epitomized by TSMC and to a lesser extent UMC, is well known by now, its policy support for IDM producers in memory chips has been far less successful. Similarly and as evident in Box 4.4, Singapore's state-led push for a national champion in pureplay foundry has also not been effective in attracting foreign semiconductor firms, such as Micron in memory chips and UMC in foundry.

One key reason for such a checkered historical experience of government-led initiatives in semiconductor catching-up and/or building cutting-edge fabs is the often-overlooked "demand-side" explanation of semiconductor GVCs – the critical role of market dynamics.

The chapter's fifth section has provided empirical data on how market shifts in industrial applications towards computers/data storage and wireless communications since the 2010s have been crucial in explaining the rapid growth of leading fabless firms and foundry producers in logic chips and IDM firms in microprocessors and memory chips. While the role of East Asian governments remains supportive through a more horizontal kind of industrial policy (e.g. institutional support for R&D and industrial clusters and trade liberalization), their role in directly steering the development and transformation of domestic firms in the semiconductor industry has become much less visible and feasible, with the exception of the PRC – a late latecomer. Instead, East Asian lead firms in semiconductor manufacturing have capitalized on new market dynamics supported by the "fabless revolution" and massive demand from new industrial applications in computing, data centres, and wireless communications. Through firm-specific capability enhancement and industrial specialization, these East Asian firms have developed new semiconductor product or process technologies, flexible chip production and product diversity, and sophisticated organizational knowhow and proprietary access to market information (e.g. via fabless customers and their OEM end-users).

By the turn of the 2020s, semiconductor GVCs could no longer be contained within any specific firm nor national territory. The chapter's final two sections have provided further evidence to support the conclusion that even though more national governments want to be "real states" by having their "own fabs" for national security and risk mitigation reasons, the prospect for such a techno-nationalist drive towards technological sovereignty in semiconductor manufacturing in the post-pandemic era is neither easy nor credible. Without a realistic assessment of how both demand- and supply-side explanations have accounted for the transformative shifts in semiconductor GVCs over the past two decades, such a global race in building "fabs everywhere" will likely lead to excess capacity, underutilized fabs, market fragmentation, and technological bifurcation worldwide. Even though some of these "costs" are part and parcel of the techno-nationalist policy goals, their prospect in achieving technological sovereignty cannot be guaranteed.

Bearing in mind these potential costs of pursuing "fabs everywhere", it is useful to conclude with an outline of three possible scenarios for the future of semiconductor GVCs throughout the 2020s. The first and most likely scenario will be the muddling-through of the current organization and geographical distribution of semiconductor value chains. While more chip production capacity will be added in the US and the EU through recent techno-nationalist industrial policies, this extra capacity will remain relatively modest and not at the bleeding-edge and will not fundamentally reshape the competitive dynamics of semiconductor GVCs. But as discussed in the penultimate section, these policies may not be efficacious in every national economy and thus their impact on the existing centres of excellence, i.e. US in chip design; the US, the EU, and Japan in equipment and materials; and East Asia and the US in chip manufacturing, will be relatively modest. In this scenario, the PRC will remain as a major player only in the mature nodes of logic and memory chips.

The second and third scenarios will be far more radical and perhaps even revolutionary. In the less likely second scenario of major technological innovations, one or more national economies such as the PRC or the US develops new breakthrough platforms for producing integrated circuits beyond the use of semiconductors. Intensive R&D efforts and financial resources are clearly necessary for these radical innovations to take place. So is the end-market demand for such ICs based on new materials or process breakthroughs. This revolutionary scenario is based on the key assumption of no substantial worsening of the existing US-PRC relations, world trade regimes, and global neoliberal order that would hamper technological change. The existing semiconductor GVCs will then be challenged by these revolutionary platforms that may possibly lead to a major shift of gravity in the entire industry away from the existing dominant centres of excellence.

A third and most destructive scenario is the escalation of geopolitical rivalries, government interventions, and even military conflicts that will fundamentally disrupt or even destroy semiconductor GVCs. Here, the Cross-Strait relation between the PRC and Chinese Taipei can be a major force and inflection point in reshaping global semiconductor production and markets. An equally severe change is the further trade restrictions and technology sanctions imposed by the US on the PRC that might cover all semiconductor technology classes, key inputs, and major industrial applications. This escalation in government regulation or even hostility can turn the entire global semiconductor industry upside down precisely because of the vast diversity of end users of chips identified right at the beginning of this chapter. In either case of further escalations in military or trade/technology tensions, the interconnected world of semiconductor GVCs will likely end, and a new and perhaps worse world will emerge in its wake. What we know for sure is that “fabs everywhere” will remain a pipe dream in such a new era of global disintegration.

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