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The global semiconductor value chain

A technology primer for policy makers

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Executive Summary

Semiconductors such as memory chips or processors are a foundational technology and the backbone of modern society. Not only are they a prerequisite for any endeavors into emerging technologies, such as artificial intelligence, quantum computing or autonomous vehicles. But every industry relies on access to those chips. As a result, they are at the heart of the intensifying US-China technology rivalry. China is highly dependent on US-origin semiconductor technologies and the US government uses its export control regime to curb the technological advancements of several Chinese companies. These export control measures work especially well in this value chain because of strong interdependencies due to high divisions of labor.

The semiconductor value chain is defined by a few key countries – United States, Taiwan, South Korea, Japan, Europe and, increasingly, China. No region has the entire production stack in its own territory since companies often specialize on particular process steps (design, fabrication, assembly) or technologies (memory chips, processors, etc.) in pursuit of economic efficiency. Ultimately, no region has achieved “strategic autonomy”, “technological sovereignty” or “self-sufficiency” in semiconductors. In fact, this value chain is characterized by deep interdependencies, high divisions of labor and close collaboration throughout the entire production process: US fabless companies rely on Taiwanese foundries to manufacture their chips. The foundries themselves rely on equipment, chemicals and silicon wafers from the US, Europe and Japan. The semiconductor value chain is thus highly innovative and efficient but not resilient against external shocks.

Such a complex and interdependent value chain creates three challenges for policy makers: First, how to ensure access to foreign technology providers? Since any of the above-mentioned countries could disrupt the value chain through export control measures, foreign and trade policy plays a key role to ensure continued access to foreign technology providers. Second, how to build leverage by strengthening domestic companies through strategic industrial policy? Since no region will be able to have the entire production stack within their own territory, governments should support their domestic semiconductor industry to maintain key positions within the value chain. Third, how to foster a more resilient value chain? In certain parts, such as contract chip manufacturing, the value chain is highly concentrated and needs to be diversified to lower geographical and geopolitical risks.

This paper provides a first analytical basis for policy makers. It gives an overview of the global semiconductor value chain, its interdependencies, market concentrations and choke points.

Table of Contents

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Introduction

Semiconductors, such as memory chips and processors, are the backbone of modern society. Without these chips, we would not be able to run any software anywhere. Modern cars rely on hundreds of semiconductors, as do our energy grid, traffic management systems, hospitals, stock markets and insurance companies. Semiconductors are a foundational technology[1] and prerequisite for many emerging technologies, such as artificial intelligence (AI), quantum computing and autonomous vehicles.

The industry's enormous relevance for all aspects of technology is also reflected by its geopolitical role. Semiconductors are now at the heart of the intensifying US–China technology rivalry.[2] Both countries see semiconductors as a strategic asset.[3] China imports the most semiconductors (US$ 301 billion in 2019), more than crude oil (US$ 238 billion in 2019), and is highly dependent on US-origin semiconductor technology.[4] The Chinese government's goal is to be "self-reliant" in semiconductors as soon as possible. These ambitions have only been strengthened by the U.S. government's broadening application of export control measures to curb the technological advancements of various Chinese companies by cutting them off from critical US-origin technology.[5] Industrial policy to strategically strengthen the domestic semiconductor industry plays a key role in the US–China technology rivalry. The U.S. government proposed legislation in summer 2020 to invest $ 22 billion in its domestic semiconductor industry.[6] For the past several decades, China has invested heavily in its own semiconductor industry, with limited success.[7] Most recently, European policy makers also identified semiconductors as a necessity for digital sovereignty.[8]

What does self-reliance, digital sovereignty and strategic autonomy in semiconductors mean? To answer that question, a basic understanding of today's semiconductor value chain, market dynamics and interdependencies is necessary. To provide policy makers with the necessary context, this paper will give an overview of the semiconductor value chain.

The first section of this paper discusses different semiconductor technologies, such as memory chips and processors, to identify dependencies and market concentrations at the technology level. The second section then explains the semiconductor production process from chip design to fabrication and assembly, including the necessary supplies, and discusses important regions, companies and the existing interdependencies. Based on that analysis, the paper argues that the semiconductor value chain is defined by strong divisions of labor, deep interdependencies and "choke points" at many different levels that make it difficult for any country to proclaim self-reliance or autonomy.

Overview: Semiconductor Technologies

There are numerous types of semiconductors, and this section does not attempt to provide an exhaustive overview. Instead, the aim is to explain the most common business models and how they relate to different types of semiconductors. There are seven broad categories: memory, logic, micro, analog, optoelectronics, discrete and sensors. (*Figure 1*) The first four – memory, logic, micro and analog semiconductors – are the so-called **integrated circuits (ICs)**, and this paper mainly focuses on these ICs or "chips". In 2019, semiconductor sales totaled US$ 412 billion, and 80% of that (US$ 333 billion) were IC sales. Sensors, optoelectronics (such as LEDs) and discrete semiconductors (single transistors) together made up the remaining 20%.[9]

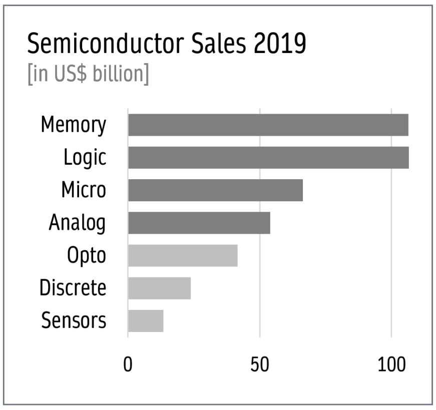


Figure 1

The production process for semiconductors, and in particular ICs, consists of three distinct steps: design, fabrication and assembly and test. (*Figure 2*) Whether a company provides all three production steps or focuses solely on a single production step for the sake of economic efficiency depends on the firm's business model.

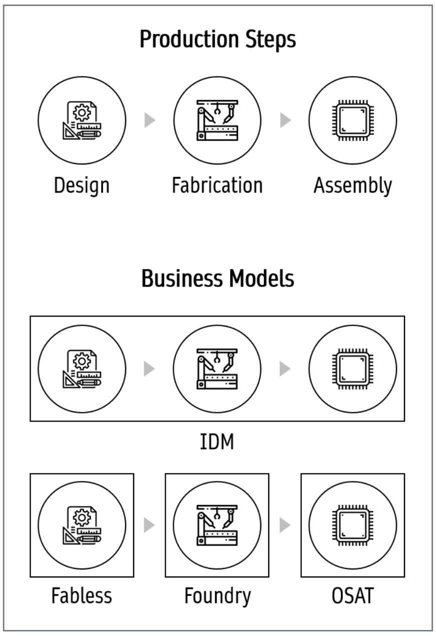


Figure 2

Integrated device manufacturers (IDMs), such as *Intel* or *Samsung*, perform all three steps in-house. Historically, this has been the dominant business model of the semiconductor industry. But with the increasing complexity and costs associated with design and fabrication of leading-edge ICs, many companies now specialize in single production steps. Companies that only design chips and rely on contract chip makers for fabrication are called **fabless**. These companies lack a fabrication plant. Fabless companies, such as *Qualcomm* (US), *Nvidia* (US) and *HiSilicon* (China), therefore, closely collaborate with **foundries** that manufacture chips in their fabrication plants (fabs). After the IC has been fabricated by the foundry, the chip must be tested, assembled and packaged to protect it from damage. This last step is done either by the foundry itself or by **outsourced semiconductor assembly and test (OSAT)** companies.

A good example of how the different business models work together are processors from Intel and *AMD*. Intel is an IDM. Therefore, it designs, produces and assembles its processors (mostly) by itself. In contrast, *AMD* processors are designed by *AMD* (fabless), produced in *TSMC's* fabs in Taiwan (foundry) and then packaged by *SPIL* (OSAT).[10] *AMD* and Intel produce general-purpose processors (x86), but their business models, and thus, value chains, differ.

Roughly speaking, chip design is skill intensive with high research and development costs. Fabless companies typically spend 25% of their revenue on R&D. Chip fabrication is capital intensive because of expensive facility and equipment costs. Building a modern fab easily exceeds $ 15 billion. Assembly is labor intensive with lower profit margins. But it is not just that each production step is governed by varying business dynamics. Different semiconductor technologies are also often produced by companies with certain business models. The following examples illustrate this relationship among the business model, certain types of semiconductor technologies and market concentrations.

DRAM: "short-term" memory for computing devices

DRAM chips are needed in all computing devices to temporarily store data that is being processed. The iPhone 11, for example, has 4GB of DRAM, while the fastest supercomputer today has 4,866,048GB.[11] In addition to traditional information and communication technology, everything from modern vehicles to energy grids and airplanes relies on access to DRAM chips. However, the DRAM market has consolidated significantly over the past 15 years.

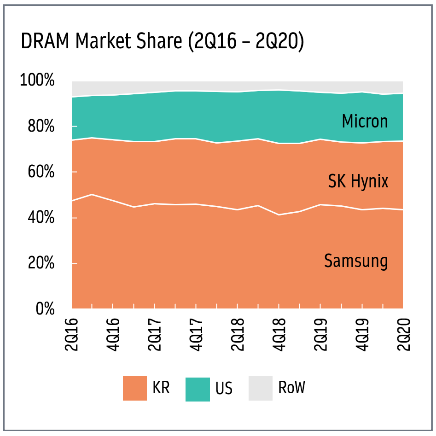


Figure 3

In 2005, the DRAM market had a volume of $ 25 billion, and the *eight* largest DRAM vendors had a combined market share of 97%.[12] In 2019, the DRAM market had a volume of $ 62.5 billion, and the *three* leading DRAM vendors had a combined market share of 95%: *Samsung* and *SK Hynix* in South Korea (KR) and *Micron* in the United States (US). (*Figure 3*) Because DRAM is a commodity with fluctuating prices and high capital investments for fabs, this oligopoly is not surprising. The DRAM market has seen several mergers and acquisitions over the past 15 years.[13] DRAM technology nodes (the production line in a fab) have very short lifetimes, and profitability requires maintaining pace with the technology leader *Samsung*. Therefore, all DRAM vendors operate as IDMs. Already before the market consolidated substantially, there were several price-fixing and anti-monopoly investigations of DRAM vendors in the US, Europe and China.[14] China is trying to enter this highly concentrated market and reduce its reliance on foreign memory chips. The *Fujian Jinhua Integrated Circuit Company (JHICC)* was established in China in 2016. However, the U.S. Department of Commerce banned exports to *JHICC* in 2018, and the U.S. Department of Justice filed indictments against the Chinese DRAM vendor alleging corporate espionage and intellectual property (IP) theft from *Micron*.[15] The indictments pretty much curbed *JHICC's* technological advancements. *ChangXin Memory*

Technologies (CXMT) is the other Chinese DRAM vendor. In contrast to *JHICC*, *CXMT* avoided U.S. patents and based its DRAM technology on patents from *Qimonda*, a former German DRAM manufacturer that went bankrupt in 2009.[16] Although *CXMT* cannot yet compete with the "big three" internationally due to a technology gap of several generations, the company still serves China's long-term goal of increased self-reliance in semiconductors.[17]

NAND: "long-term" memory for computing devices

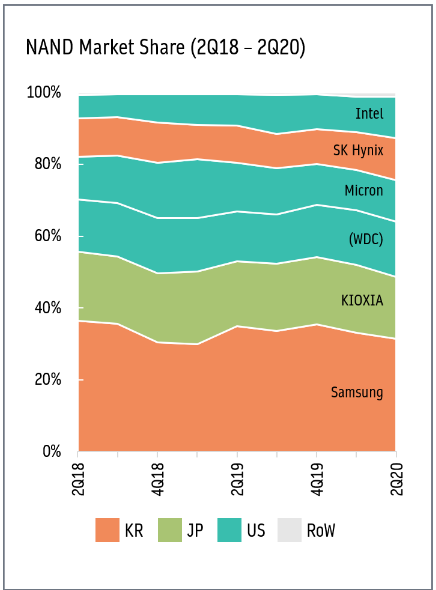


Figure 4

NAND flash memory chips are the "long-term" memory for most of today's computing devices – the modern version of hard disk drives. In 2019, the NAND market had a volume of $ 46 billion and was less concentrated than the DRAM market. The NAND market is essentially under the control of six vendors: *Samsung* and *SK Hynix* in South Korea, *KIOXIA* in Japan (*WDC* uses *KIOXIA* fabs) and *Micron* and *Intel* in the United States. (*Figure 4)* Similar to DRAM, NAND is a commodity where production volume and economies of scale are key. This is why DRAM vendors and NAND vendors typically operate as IDMs: The vendors take care of design, fabrication and assembly in-house. China is also trying to enter the NAND market. *Yangtze Memory Technologies (YMTC)* was founded in 2016. The Chinese company is producing NAND chips, and some analysts estimate that YMTC might reach 8% market share in 2021.[18]

Analog ICs: the connection to the physical world

Digital ICs (dark grey in *Figure 1*) operate only with 0s and 1s, but analog ICs interact with the physical world by generating or transforming signals, from electricity to radio waves or light. Without analog ICs, it would be impossible to charge a battery, drive an electric motor, make phone calls (access radio waves) or listen to Spotify. Thus, most devices that need electricity also depend on analog ICs. For performance gains, digital ICs depend on constantly improving production processes to fit more transistors on a square millimeter of silicon.[19] In contrast, analog IC vendors do not depend on shrinking production processes (nodes). These vendors are under much less pressure to invest in expensive cutting-edge manufacturing equipment than digital IC companies. Analog IC vendors depend on domain expertise because their products are designed for specific tasks in specific markets and various physical domains. Producing an analog chip that drives the motor of an electric vehicle requires very different domain knowledge compared to designing a digital-analog converter, which is necessary to listen to music on a smartphone or computer.

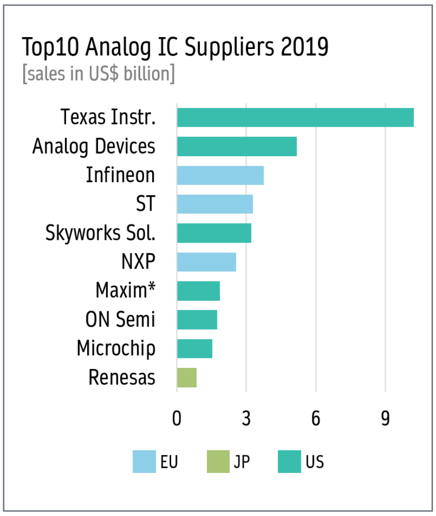


Figure 5

Both dynamics, the importance of domain expertise and the lack of pressure to invest in cutting-edge fabs, are why the analog IC market is far less concentrated than the memory chip or processor market. The 10 leading analog IC suppliers had a combined market share of only 62% in 2019.[20] The leading analog IC vendors are US American, European and Japanese IDMs. (*Figure 5*) Several of these IDMs follow a "fab-lite" business model. An IDM might rely on external foundries for the fabrication of certain chips, but not all. *NXP*, one of the leading European IDMs, just announced that *TSMC* in Taiwan, the largest foundry in the world, would manufacture *NXP's* new automotive platform.[21] *STMicroelectronics (ST)*, another European analog IC supplier that follows a fab-lite business model, expects to outsource 30% of their chip fabrication to external foundries.[22]

Automotive Semiconductors: the importance of domain expertise

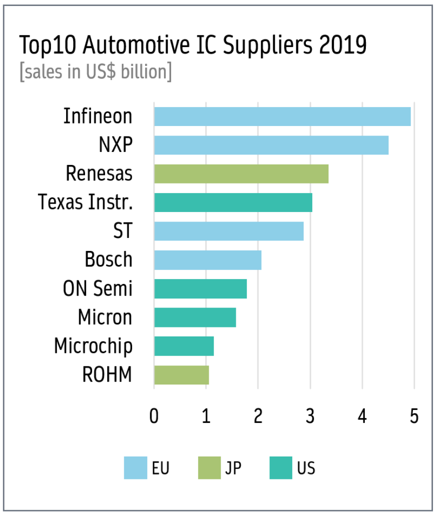


Figure 6

A great example of the importance of domain expertise is automotive ICs. This category encompasses digital and analog ICs, which are sold to the automotive industry. The requirements of this industry are very different from those for consumer electronics. The automotive industry requires operational specifications over a wide range of temperatures and other environmental conditions. In addition, the automotive industry does not like change. An automotive IC supplier (all are IDMs, often following a fab-lite approach) that is specified for an automotive application must be prepared to make these chips for up to 30 years without changes in their manufacturing processes.[23] European IDMs, such as *Infineon*, *NXP*, *STMicroelectronics (ST)* and *Bosch*, play a dominant role in the automotive industry (*Figure 6*) due to their strong domain expertise based on close connections to European car manufacturers and vertical integration. Among the leading automotive IC suppliers are European, Japanese and U.S. American companies.

Processor Architectures

Another semiconductor technology worth looking into are general-purpose processors – often called central processing units (CPUs) or application processing units (APUs). Processors fall under the "micro" category in *Figure 1*, and they are the "brain" of any computing device. But before developing a processor, engineers must decide which instruction set architecture (ISA) the processor is based on. The ISA defines the inner workings, the most basic instructions, of the processor. Interestingly, the most widely used ISAs are owned by only a few companies.

x86 in laptops, desktops and servers

If you read this paper on your laptop or desktop PC, you are almost certainly relying on a x86-based CPU that was built by either *Intel* or *AMD* in the United States. Only *Intel*, *AMD* and *VIA Technologies* (Taiwan) hold the patents to produce and further develop x86-based processors. *Microsoft Windows* was designed for x86-based processors, and *Microsoft* and *Intel* have relied on each other's success since the 1980s.[24] As software is compatible with only a certain processor architecture, x86 competitors must persuade software developers to invest significant resources to develop software for another architecture. This, essentially, creates strong vendor lock-in. As almost every personal computer is based on x86 processors, and the architecture is under full control of two U.S. companies, it is not surprising that China is looking for "homegrown" alternatives. *Zhaoxin* is a joint venture between Shanghai Municipal Government and *VIA Technologies* in Taiwan, the only company apart from *Intel* and *AMD* that holds x86 licenses.[25] The *Zhaoxin* CPUs are several years behind modern x86 processors from *AMD* and *Intel*[26] but play a key role in China's "3-5-2 program" (replacing all foreign PCs and software used by the government by 2023).[27] In 2020, *HP* started selling PCs with *Zhaoxin* CPUs in China.[28]

ARM for the mobile world

While x86 is the dominant architecture for personal computers and servers, ARM-based processors power smartphones, tablets and the Internet of Things (IoT). The ARM instruction set architecture was developed and then licensed by *ARM Limited* in the United Kingdom (UK) which was bought by Japanese *SoftBank* in 2016. *Intel* (IDM) and *AMD* (fabless) develop *and* sell CPUs, but *ARM Limited* develops "blueprints" (IP) that other chip designers, such as *Apple*, *Huawei* and *Samsung*, use to develop and sell their own processors based on *ARM's* IP. This also means that both mobile operating systems (*Google's* Android and *Apple's* iOS) are built for ARM-based processors. The mobile world depends on access to *ARM's* IP. As *ARM* is based in the UK (but has R&D in the US) and is owned by *SoftBank* in Japan, *ARM* came to the assessment that most of their IP is UK origin, and not US origin. Thus, Huawei still had access to (most of) *ARM's* IP even after the U.S. export ban.[29] This might change in the future if *Nvidia* (a US-based fabless company) is allowed[30] to buy *ARM* from *SoftBank*.[31] Last, the ARM instruction set has been hugely successful and goes beyond the mobile realm. *Apple* announced in

2020 that the company would develop ARM-based CPUs for its laptops and workstations.[32] In addition, the currently fastest super-computer, *Fugaku* in Japan, is based on ARM.[33] With *ARM Holding's* growing importance for the industry, this strategic asset might soon be under U.S. control.

"AI chips" are ASICs

Chips that are specifically designed to work on machine learning models are so-called "AI chips", a type of application-specific integrated circuit (ASIC).[34] Many modern system-on-a-chip (SoC) – processor cores, memory and interfaces (mobile, Wifi, etc.) all in a single chip – in smartphones have integrated "AI accelerators". These are small parts of a chip that are used only for machine learning tasks, such as facial recognition.[35] As machine learning is a new field, there is no dominant architecture yet for these types of chips. Currently, more than 100 companies design AI chips or accelerators.[36] The architectures of these AI chips differ substantially and are often optimized for specific machine learning platforms.[37]

Looking at various semiconductor technologies, the interdependencies between different regions become obvious. Today's ICT systems depend on DRAM from South Korea, NAND from Japan, analog chips from the United States and IP from Europe. No region has access to all important types of semiconductors within its own borders. Collaboration and close cooperation, combined with competitive pressure to innovate, led to today's globally distributed, highly efficient and innovative semiconductor value chain. The necessary specialization and high division of labor also led to consolidated markets, oligopolies and even monopolies. This means that for several types of semiconductors there are only a few, sometimes just one, supplier. Losing access to these suppliers, due to natural disasters, pandemics or restrictive trade policies, quickly disrupts the value chain.[38] In addition, untangling these interdependent value chains comes at significant costs, and a loss of innovation and efficiency. One example is China's effort to become self-sufficient by building fabs for memory chips (DRAM, NAND) and developing their own x86 processor.

Although regions rely on each other for different types of semiconductor technologies, these interdependencies are even stronger when the value chain that produces integrated circuits is analyzed. This analysis is the focus of the next section.

Overview: Semiconductor Value Chain

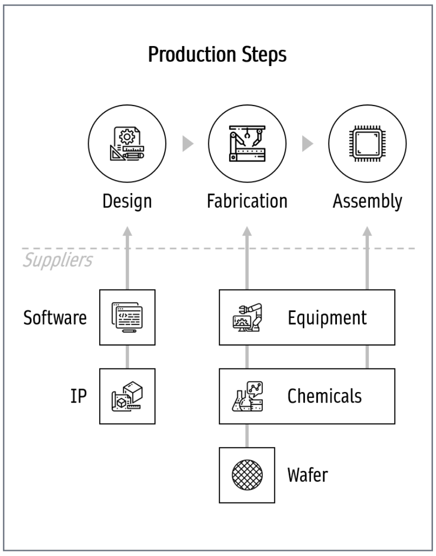


Figure 7

Each step in the semiconductor production process – design, fabrication and assembly – relies on specific inputs from suppliers. This section provides an overview of this semiconductor value chain by identifying important suppliers, market concentrations, dominant regions and interdependencies. *Figure 7* provides a schematic overview of the semiconductor value chain: **Chip designers** (in IDMs or fabless companies) rely on design software and intellectual property (IP blocks). The **fabrication** process (either by IDMs or foundries) depends on manufacturing equipment, chemicals and silicon wafers to produce chips. The **assembly** phase (either by IDMs or OSAT) requires equipment and chemicals. This section illustrates that the semiconductor value chain is defined by high divisions of labor, highly concentrated niche markets and pressure to constantly innovate and invest. No country currently has the entire production stack in its own territory. Instead, the semiconductor value chain relies on collaboration and trade between the United States, Taiwan, South Korea, Japan, Europe and China. Thus, the semiconductor value chain is highly innovative and efficient but not resilient.

Chip Design

Designing a leading-edge processor or SoC is expensive: In 2016, designing a chip for 10nm nodes cost around $ 170 million; in 2020, designing one for 5nm nodes costs more than $ 540 million.[39] Yet an increasing number of companies are designing their own chips. In addition to the traditional fabless companies, many new players have entered the market: *Alibaba*, *Alphabet* (*Google*), *Amazon*, *Facebook* and *Tesla* are all designing their own chips. One reason is the need for application-specific chips (ASIC) that do one task very well, such as AI accelerators for training or inference. The general-purpose processor simply does not scale enough anymore for these applications.[40] The United States is, by far, the leader in chip design. (*Figure 8*) Taiwan is another important region with companies such as *MediaTek*, *Novatek* and *Realtek*. Just behind Taiwan are Chinese fabless companies with a market share of 15% in 2019, placing China significantly ahead of Europe, South Korea and Japan.[41] If *Huawei's* chip design subsidiary *HiSilicon* were a publicly traded fabless company, it would be among the top five globally.[42]

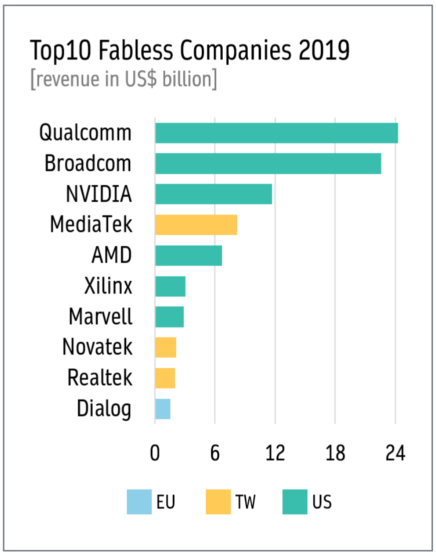


Figure 8

Fabless companies must work very closely together with contract foundries, such as *TSMC* in Taiwan or *Samsung* in South Korea, because a chip design has to fit a particular production process within a fab. Additionally, as chip design for cutting-edge SoCs is so expensive, much of the activity is focused on consumer electronics, such as smartphones, to achieve economies of scale. U.S. fabless company *Qualcomm* relies on *Samsung's* foundry business to produce *Qualcomm's* latest mobile SoC. The order volume is almost $ 1 billion.[43]

Software: Electronic Design Automation

Although fabless companies are on the rise, especially in China, and countless companies are developing special-purpose chips,[44] they all depend on access to design software. The market for these electronic design automation (EDA) tools is highly concentrated and dominated by three US-based companies: *Cadence Design Systems*, *Synopsys* and *Mentor*. The last was acquired by *Siemens* in 2017 but is still based in the United States. Leading-edge chip design depends on these software tools. *Synopsys* states that its EDA software is used for almost every design from 12nm nodes and below.[45] EDA vendors also have the highest R&D margins in the entire semiconductor value chain – spending more than 35% of their revenue on R&D.[46] Even more than fabless companies, EDA vendors have very close relationships with fabs (run either by foundries or IDMs) and equipment manufacturers. The vendors help fabs and equipment manufacturers research new process nodes and continuously improve them.[47] Thus, EDA vendors need to keep pace with the industry's extremely short innovation cycles, based on deep knowledge of the fabrication process and close ties to fabs and equipment manufacturers. This explains why over the years the EDA market has seen a significant number of acquisitions. Since 2010, *Synopsys* alone has acquired more than 46 companies or technologies.[48]

These dynamics have led to a highly concentrated market, where an entire industry depends on access to three vendors in one country. In such an environment, export bans can be highly disruptive. Since 2019, the U.S. government has put in place three export control measures against *Huawei* to curb *Huawei's* (*HiSilicon's*) chip design capabilities.[49] One of these bans focused on cutting off *HiSilicon's* access to US-origin EDA software, making it almost impossible for the fabless company to design modern ICs.

Intellectual Property (IP)

IP plays an important role throughout the semiconductor production process but especially during chip design. Apart from EDA vendors, several companies develop and then license semiconductor IP. One is the previously mentioned *ARM Holdings*. These IP blocks can be entire processor cores or smaller IP blocks for “standard” functionality, such as USB or networking interfaces, to name just a few. Semiconductor IP is one of the areas in which China is struggling.[50] The reason a Chinese state-owned investment company acquired *Imagination Technologies*, a UK-based IP provider for graphic cores, was at least in part to secure access to *Imagination Technologies*’ IP.[51] Another example is *ARM China*, a company that is 49% owned by *ARM Holdings* in the UK and 51% by Chinese investors. The long-term goal is that *ARM China* develops IP for the Chinese market.[52]

Last, it is important to understand the close relationship between chip design and fabs. Fabless companies, EDA vendors and IP providers all work closely together with foundries to match a design to a particular process node in a fab.[53] Very early during development, fabless companies must decide on which process node from which fab they want to build their chip. For example, switching a chip design from *Samsung’s* 7nm node to *TSMC’s* 7nm node means almost a complete redesign and thus, years of work for cutting-edge chips.

Fabrication

The finished chip design is then sent to the wafer fabrication plant (fab) for production. The fab is owned by either an IDM or a foundry and uses manufacturing equipment and chemicals to fabricate a chip design on a silicon wafer. Over the past two decades, this process became increasingly complex and expensive.[54] It is increasingly complex because of Moore’s Law: the observation that the number of transistors in an IC doubles roughly every two years. A self-fulfilling prophecy the semiconductor industry followed for the past 50 years. The smaller the transistor, the more can be squeezed on a single chip, making the chip more complex and powerful. A rough measure for the technological advancement of a fab is the minimum feature size of transistors the fab’s production nodes can produce, measured in nanometers (nm): A 7nm fab can produce smaller transistors and thus, denser chips than a 28nm fab.[55] Today, cutting-edge chips consist of tens of billions of transistors. Because of this race to fabricate smaller transistors for more powerful chips, the manufacturing equipment required becomes increasingly expensive and makes up most of the costs of modern fabs.[56] *TSMC* estimated that its next 3nm fab would cost around $ 19.5 billion.[57] However, the fab business is not just capital intensive. Operating a fab successfully requires deep knowledge of the complex process. Wafer fabrication involves hundreds of process steps spread over dozens of different types of equipment. Even IDMs and foundries with a lot of experience regularly struggle when introducing new process nodes.[58]

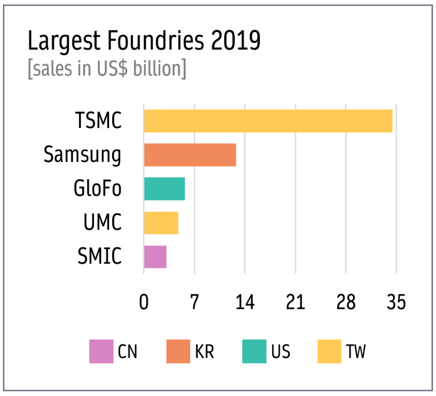


Figure 9

Because wafer fabrication is highly capital intensive and depends on deep process knowledge, it is not surprising that today the foundry market is concentrated in a few players worldwide. (*Figure 9*) *TSMC* in Taiwan is by far the leading foundry with a market share of more than 50%.[59] In 2019, *Samsung* in South Korea was the second largest foundry by revenue, and the company announced it would invest $ 116 billion in its foundry business until 2030.[60] Interestingly, Samsung is also the only IDM with a substantial foundry business. Together, *TSMC* and *Samsung* are the only foundries with 7nm nodes (and smaller), which are necessary to fabricate cutting-edge chips. *Intel* is also introducing 7nm fabs, but as an IDM, the company is not offering its fabs for contract chip making.[61] *GlobalFoundries*, headquartered in the United States but owned by an investment company owned by the government of Abu Dhabi, is no longer competing in the “More Moore race” and stopped developing a 7nm node in 2018.[62] *SMIC*, the largest foundry in China, started producing chips on 14nm nodes in 2019 (more than 4 years after *TSMC*), but 90% of *SMIC’s* revenue in 2019 is based on mature nodes of 40–250nm.[63] In contrast, 70% of *TSMC’s* revenue in 2Q20 came from 28nm to 7nm nodes.[64] How far *SMIC* will be able to upgrade its current process nodes to 7nm and smaller largely depends on the U.S. government’s decision whether to put *SMIC* on its black list as a part of the U.S. export control regime.[65] If that happens, *SMIC* will lose access to critical US-origin semiconductor manufacturing equipment, as analyzed in the next section.

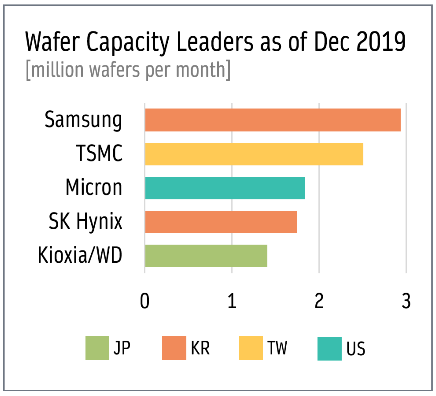


Figure 10

Looking at the overall wafer capacity of foundries and IDMs, *Samsung*, *TSMC*, *Micron*, *SK Hynix* and *Kioxia* fabricate the most wafers per month. (*Figure 10*) It is not surprising that the leading memory chip (DRAM and NAND) manufacturers also fabricate the most wafers per month. Memory chips are a high-volume business that depends on economies of scale. As of December 2019, *Samsung* (South Korea) produced almost 3 million wafers per month. That *TSMC* (Taiwan) fabricated almost as many wafers per month as *Samsung* (*TSMC* makes logic chips, not memory) illustrates how dominant *TSMC’s* foundry business is. In 2019, these five companies had 53% of the worldwide wafer capacity, while 10 years ago, in 2009, the five leading companies had only 36% of the world's wafer capacity.[66] This is another indicator how much the market has consolidated over the past 10 years.

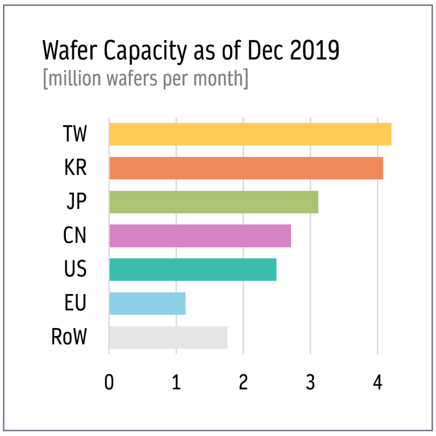


Figure 11

In summary, cutting-edge wafer fabrication is an increasingly concentrated market. Short- to mid-term, *Samsung* in South Korea and *TSMC* in Taiwan will continue to be the only contract foundries capable of producing cutting-edge chips smaller than 7nm. Even if new players could invest upwards of $ 15 billion to build a leading-edge fab, operating such a fab successfully requires highly specialized process knowledge, close cooperation with a variety of suppliers and the commitment of fabless companies to base their chip designs on this specific process node. Thus, it is highly unlikely that the foundry landscape will change significantly over the next 5 to 10 years. This also means that Taiwan and South Korea will continue to be critically important regions for chip production. (*Figure 11*) Although China might soon have a higher monthly wafer capacity than Japan, most of this comes from foreign companies such as *TSMC*, *SK Hynix* and *Micron* operating trailing-edge fabs (few generations behind the cutting-edge) in China.[67] Last, although Europe's wafer capacity is dwindling, the question is whether the United States will be able to re-shore wafer fabrication to the US with the recently proposed CHIPS for America Act.[68]

Equipment

Fabs rely on a variety of different semiconductor manufacturing equipment (SME) from many different vendors. Because SME vendors often specialize in particular steps of the fabrication process, fabs have to combine equipment from several different vendors for a process node. Different types of equipment are needed to fabricate the integrated circuits on a silicon wafer: *"Deposition is about putting the material on the wafer, lithography is about deciding where you want to leave the material or where you want to take it away, and etching is about removing the material that you don't want."*[69] The largest SME vendors are *Applied Materials* (*AMAT*), *Lam Research* (*LAM*) and *KLA* in the United States, *ASML* in Europe and *Tokyo Electron* (*TEL*) in Japan. (*Figure 12*) Even the largest companies with the broadest range of equipment focus on specific areas. *KLA* is very strong in metrology equipment for quality control,[70] while *Applied Materials* has a dominant position in plasma etching.[71] Dutch *ASML* does not compete

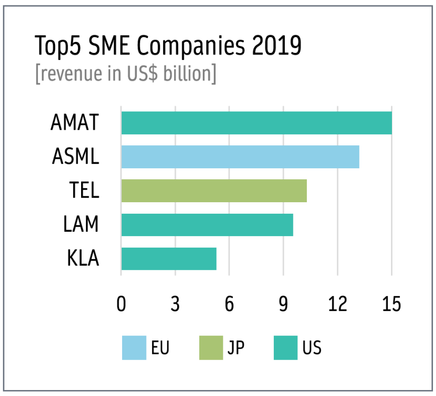


Figure 12

with any of the other large vendors as it produces photolithography equipment, necessary to transfer a circuit pattern onto a silicon wafer. *Nikon* and *Canon* in Japan are *ASML's* competitors, but the Dutch company has a monopoly on the latest generation of this equipment: extreme ultraviolet (EUV) lithography.[72] EUV equipment is essential to produce chips smaller than 7nm but highly complex to configure and maintain properly. For that reason, *ASML* just recently opened a training center for "EUV engineers" right next to *TSMC* in Taiwan.[73]

SME vendors themselves rely, perhaps more than any other supplier throughout the semiconductor value chain, on a broad network of highly specialized suppliers. *ASML* has 5,000 suppliers[74] across Europe, United States and Asia. However, for certain components, especially regarding EUV lithography equipment, there is often only one supplier in the world.[75] This creates an efficient and highly innovative value chain, but at the same time, one that is easily disrupted by trade measures such as export bans or a pandemic.[76] As fabs depend on equipment from U.S. SME vendors, such as *Applied Materials*, the U.S. government forbid fabs to use US-origin manufacturing equipment to produce any chips for Huawei.[77] The U.S. government identified manufacturing equipment and EDA software (see the previous section) as choke points in the semiconductor value chain due to the dominant position of U.S. companies. Exploiting those choke points through export bans can be highly disruptive for fabs and chip design companies.

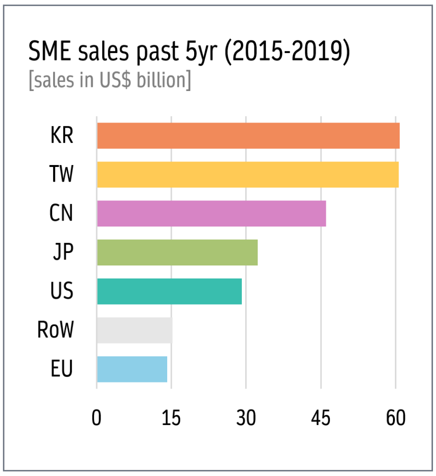


Figure 13

Another important aspect is the concentration of cutting-edge fabs. Currently, only *Samsung* in South Korea, *TSMC* in Taiwan and *Intel* in the United States are building cutting-edge fabs and buying the necessary fab equipment. The customer base for fab equipment is small and highly depends on trade relations with Taiwan, South Korea and increasingly, China. Roughly 57% of *Tokyo Electron's* sales in 2019 were in China, South Korea and Taiwan.[78] South Korea and Taiwan made up almost 64% of *ASML's* sales in 2019.[79] *TSMC* was responsible for 14% of Applied Materials' sales in 2019.[80] Thus, as South Korea and Taiwan are the most important regions for semiconductor fabs, they are also home to the most important customers of equipment vendors. (*Figure 13*) In summary, the United States, Japan, and Europe are the leading regions for semiconductor manufacturing equipment, but they rely on leading-edge fabs in Taiwan, South Korea and increasingly, China to buy and utilize that equipment. This example illustrates how interdependent the semiconductor value chain is.

Chemicals

Chemicals Suppliers
[alphabet. order]

- BASF
- Air Liquide
- Air Products
- DuPont de Nemours
- Fujifilm Holdings
- JSR Corporation
- LG Chem
- Linde
- Merck KGaA
- Mitsui Chemicals
- Shin-Etsu Chemical
- Sumitomo Chemical
- Taiwan Spec. Chem.
- Taiyo Nippon Sanso
- Tokyo Ohka Kogyo

Figure 14

Semiconductor manufacturing relies on many different types of chemicals and gases for the different process steps, such as patterning, deposition, etching, polishing and cleaning. These chemicals and gases are most often supplied by large companies that also supply other industries. Very few companies supply only the electronics industry. The competition is fierce, which is why the market has experienced several mergers and acquisitions and is mostly dominated by Japanese companies, such as *Shin-Etsu*, *Sumitomo Chemicals* and *Mitsui Chemicals*. (*Figure 14*) European companies such as *BASF*, *Linde* and *Merck KGaA* are also important chemicals suppliers. The total market for electronics chemicals is around $ 40 billion.[81] A key performance indicator for semiconductor chemicals is their purity, with impurity requirements of 1 part per billion (ppb) or below.[82]

Like other suppliers, such as SME vendors and EDA software providers, chemicals suppliers work closely together with fabs and equipment manufacturers. For example, *TSMC* asked *Taiwan Specialty Chemicals Corp*. to set up facilities in the United States, to support *TSMC* in their plan to build a 5nm fab in Arizona.[83]

As Japan is a major supplier of semiconductor chemicals, and South Korean fabs rely on an uninterrupted supply, the Japanese government exploited that dependency by introducing export restrictions on such products to Korea in July 2019. All chemicals that fell under export control measures represented the most important inputs for the Korean semiconductor industry. *"The targeting of specialized materials between two countries with highly integrated supply chains have been interpreted by the industry as a signal of a willingness to expose supply chain vulnerabilities for what industry representatives view to be unrelated bilateral political disputes."*[84] Not surprisingly, South Korea's industry responded by investing in domestic capacity for key semiconductor chemicals and gases.[8]

Wafers

Wafers are a key supply for fabs, and they are produced in several different sizes and types. Silicon wafers are the most common and most important, but there are also gallium arsenide (GaAs), gallium nitride (GaN) and silicon carbide (SiC) wafers for certain applications. Today, 300mm silicon wafers are the standard for advanced chips, such as processors, SoC and memory. The silicon wafer market, across all diameters, is highly concentrated. Al-

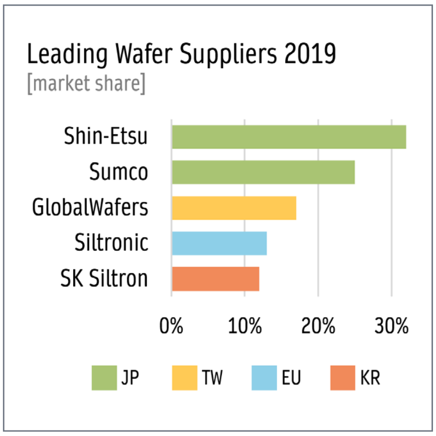
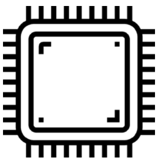


Figure 15

though there were more than 20 silicon wafer suppliers in the 1990, 30 years later 5 companies control 90% of the market.[86] *Shin-Etsu* and *Sumco* in Japan lead the market, followed by *GlobalWafers* (Taiwan), *Siltronic* (Europe) and *SK Siltron* (South Korea). (*Figure 15*) Highly pure and planar silicon wafers are of critical importance to fabs but account for 5–10% of the overall operational costs (300 mm).[87] Thus, wafers are a critical supply but have limited costs. Both circumstances make it unlikely that the silicon wafer supplier market will see significant changes in the near future.

In summary, for the semiconductor manufacturing process fabs rely on equipment, chemicals and (silicon) wafers to fabricate integrated circuits. While cutting-edge fabs are mainly located in Taiwan and South Korea, the necessary equipment, chemicals and wafers come from the US, the EU and Japan. The fabrication process relies on close collaboration between the different suppliers, the fab and chip designers. Over the years, all supplier markets (EDA, equipment, chemicals, wafers) consolidated, sometimes to the point that there is only one supplier for a particular technology, such as EUV scanners. This created a highly efficient and innovative semiconductor manufacturing value chain, but it relied heavily on free trade and close collaboration between the key countries. It also has become obvious that none of the countries can be considered “self-reliant” or “strategically autonomous” in the fabrication process.



Assembly

After the manufacturing process in the fab, the silicon wafer contains many small integrated circuits (die) that must be cut out, tested and packaged to protect them from damage. These process steps are called the “back-end,” while all previous steps at the fab are called the “front-end”. Wafer fabrication (front end) is highly capital intensive, but assembly and test is labor intensive with typically lower profit margins.[88] Companies specializing in the back-end of the semiconductor production process are so-called Outsourced Semiconductor Assembly & Test (OSAT) companies. The OSAT market grew from $ 17 billion in 2009 to more than $ 30 billion in 2019.[89] Just like fabs, OSAT companies rely on equipment suppliers and chemicals but on a much smaller scale: A new manufacturing line cost $ 100 to $ 200 million in 2018.[90] Similar to other areas within the semiconductor value chain, the OSAT market consolidated significantly, and the 20 largest OSAT companies held 92% of the market in 2019, up from 70% in 2009. (*Figure 16*) Taiwanese OSAT companies such as *ASE Group* (26% in 2019) have 53% of

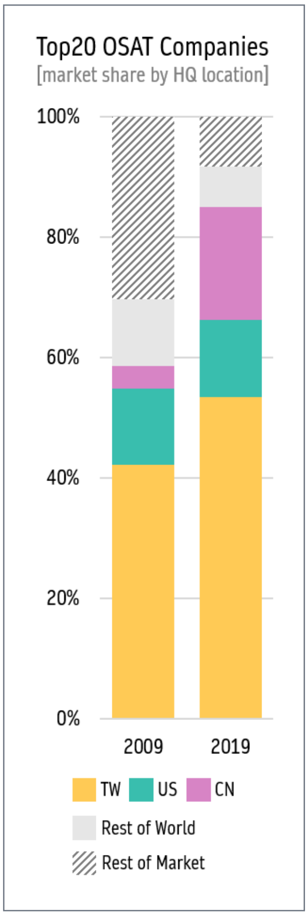


Figure 16

the global back-end market. *Amkor Technologies* (13%) is the only large OSAT company from the United States. Interestingly, since 2009 the market share of Chinese companies, such as *JCET*, grew significantly to higher than 19%. OSAT companies from other countries such as Singapore and Malaysia lost market share over the past 10 years. Overall, the OSAT market is certainly one of the lesser concentrated markets throughout the semiconductor value chain. It is also the only other market, next to chip design (fabless), in which Chinese companies have been able to gain significant market share. Of course, there is still a technology gap but much smaller than in wafer fabrication, EDA software and manufacturing equipment.[91] As an example, *Huawei* collaborates closely with *JCET*, the leading Chinese OSAT company, to improve *JCET's* processes in response to the U.S. export ban against *Huawei* in 2019.[92] However, whether *JCET*, even with significant public investment, will be able to provide leading-edge packaging to *Huawei* short- to mid-term is remains to be seen. Last, a general trend of the industry is that fabs also provide advanced (wafer-level) packaging.[93] For example, leading-edge mobile SoCs from *Qualcomm* and others are often packaged directly at the fab and not at an OSAT company, further increasing the importance of foundries within the semiconductor value chain.

Findings and outlook

The previous two sections about the various chip technologies and the value chain itself showed that different countries (regions) hold key positions within the semiconductor industry. This high division of labor allows continuous specialization[94] which is the reason, together with significant R&D margins, the semiconductor industry was able to keep pace with Moore's Law, although fulfilling Moore's Law costs 18 times more resources today than in 1970.[95] Following is a brief overview of the various countries and their position within the value chain based on the analysis in the previous sections.

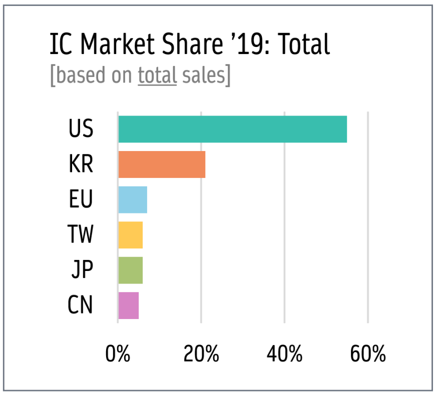


Figure 17

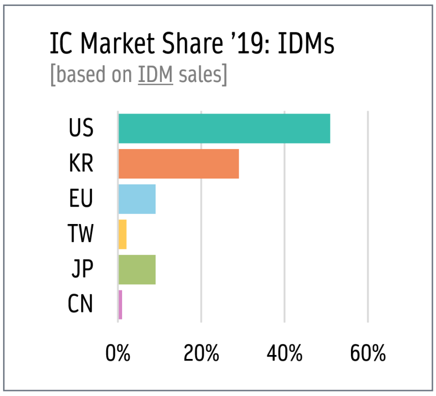


Figure 18

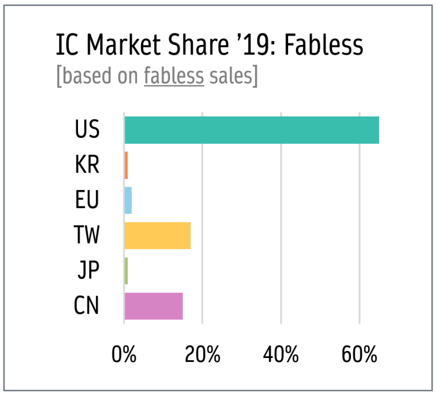


Figure 19

United States

U.S. companies hold dominant positions across the entire semiconductor value chain. (*Figure 17*) The huge share of U.S. **IDMs** comes from companies such as *Intel* (the largest semiconductor company by revenue), *Texas Instruments* and *ADI* (analog semiconductors) and *Micron* (memory chips). (*Figure 18*) The US also has a strong position in **fabless** companies focused on chip design. (*Figure 19*) Last, looking at specific production steps and suppliers, U.S. companies have a **quasi-monopoly in EDA** software and thus, also important IP vendors. Some of the largest **equipment** vendors (*Applied Materials*, *KLA*, *Lam Research*) are based in the US. U.S. companies such as *Amkor Technologies* are also active in **assembly and test** but not as dominant as other regions.

South Korea

South Korea is another important player in the semiconductor value chain. South Korean IDMs (*Figure 18*) such as *Samsung* and *SK Hynix* dominate the **memory chip** market (DRAM and NAND). *Samsung* alone is strong in many different areas, memory chips and chip design (mobile processors), and has the **second largest foundry** business, for example. Together with Taiwan, South

Korea has the highest production capabilities (**wafer capacity**) which also means it is one of the most important regions for equipment sales. Interestingly, South Korea has **no equipment vendors**, few chemicals (*LG Chem*) and wafers (*SK Siltron*) suppliers and no substantial fabless industry. (*Figure 19*)

Europe

Looking at overall volume, European companies play a minor role in most of the semiconductor value chain. (*Figure 17*) They are strong in sensors, discrete semiconductors and especially, **automotive ICs** due to existing domain expertise that allows vertical integration. European semiconductor companies such as *Bosch*, *Infineon*, *NXP* and *STMicroelectronics* are **IDMs**, often following a fab-lite approach. (*Figure 18*) Which means they also rely on foreign foundries such as *TSMC*, *GlobalFoundries* and *Samsung*. Apart from production, European companies play important roles as **suppliers**: *ASML*, *ASM International*, *Aixtron* (equipment); *BASF*, *Linde*, *Merck KGaA* (chemicals); and *Siltronic* (wafers). However, overall, Europe **has fallen behind** severely in wafer fabrication (high-volume, cutting-edge fabs) and chip design. (*Figure 19*)

Taiwan

With companies such as *Mediatek* and *Novatek*, Taiwan has a strong presence in the **fabless industry**. (*Figure 19*) Even though Taiwan does not have many IDMs, simply because of **TSMC's foundry business**, the importance of Taiwan for the semiconductor value chain cannot be overestimated. Almost the entire fabless industry for cutting-edge chips, globally, relies on TSMC – it is potentially the most critical **single point of failure** in the entire semiconductor value chain. Taiwan has also the **highest wafer fabrication capacity** and together with South Korea, is currently the **most important market for equipment vendors**. Due to companies such as *ASE Group*, Taiwan also dominates the back-end market (**OSAT**).

Japan

Japan's position in the semiconductor value chain is comparable to that of Europe. Japanese companies are dominant suppliers for fabs: They hold more than 50% of the **silicon wafer** market, they are critical for the supply of **chemicals and gases**, and they play an important role as **equipment** vendors (e.g., *Tokyo Electron*). With the IDM *KIOXIA*, Japan is also present in the NAND memory market. (*Figure 18*) Like Europe, Japanese companies play only a minor role in chip design. (*Figure 19*)

China

Overall, China has a relatively **small presence** in the semiconductor value chain. The two areas in which Chinese companies **gained significantly** over the past 10 years are **chip design** (*Figure 19*) and **assembly**. Chinese companies are trying to enter different supplier markets, such as silicon wafers, manufacturing equipment (*AMEC*, *Naura*, *SMEE*) and chemicals, with limited success.[96] As Chinese companies depend highly on foreign semiconductor suppliers, Beijing's push for "self-reliance" in semiconductors is understandable, and China will certainly play an increasingly important role not just as an importer of chips[97] but also as a producer. Additionally, China is increasingly important for wafer fabrication and is expected to spend more on manufacturing equipment in 2020 than Taiwan or South Korea.[98]

Conclusion

The previous sections analyzed different semiconductor technologies and their global value chain to identify dominant actors and regions, understand interdependencies and assess the resilience of this value chain. What is clear is that no country, including the United States, comes even close to being "self-reliant" or autonomous in the production of semiconductors. In pursuit of economic efficiency and under pressure to innovate, the semiconductor industry relies on high divisions of labor with companies focusing on particular technologies or production steps. These dynamics created a value chain that is riddled with several "choke points," a technology or process step for which there are only one or two suppliers in the world. Through export bans, governments are now exploiting these choke points to deny foreign companies access to certain technologies: The U.S. government identified EDA software as an effective choke point, as all major EDA vendors are US-based, and used export restrictions to block *Huawei* from accessing this critical technology. The Japanese government realized that their domestic chemicals suppliers play a critical role in the value chain of South Korean fabs and exploited this choke point as well.[99] It remains to be seen if these are singular incidences or part of a broader trend toward "weaponized interdependence".[100]

Looking at these long-term interdependencies within the semiconductor value chain, future government policies should address three different, but related, dimensions. First, how to ensure and secure access to foreign technology providers through trade and foreign policy. Second, how to build leverage by strengthening domestic companies through strategic industrial policy. Third, how to foster and support a more resilient supply chain.

These dimensions will be discussed in future publications as part of SNV's work on *Technology and Geopolitics*.

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