# THE FIFTH WAVE

## BRIE-ETLA Collection of Articles

Timo Seppälä | Tomasz Mucha | Juri Mattila (eds.)

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# ARTICLE 8

# Supranationalism, Sino-American Technology Separation, and Semiconductors:

## First Observations

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## Abstract

Global forces have shaped the world since the industrial and digital ages. A recent perspective on globalization acknowledges the growth of three supranational economic, social, and manufacturing blocs, namely the USA, the EU, and most recently, China. In this larger picture China contends with the US to become the largest economy in the world. Recent developments in the US–China trade conflict have centered on digital technology and have set the two countries on a path towards a technology separation. This technology separation will disrupt the unique and strategically important global value chains of digital technologies. We define digital technologies as the stack of integrated hardware and software systems that enable various end applications to emerge from computation.

The technology separation will happen in the lower hardware levels of the technology stack, that is, in knowledge- and capital-intensive semiconductor technology, design and manufacturing. A separation within semiconductor technology could have serious implications for Europe, but especially for smaller open economies such as that of Finland. The key to designing Europe's semiconductor technology strategy is understanding the history, technologies, and dynamics of the semiconductor industry as well as understanding industrial policies regarding semiconductors in the USA and China. What are the different options for Europe if the technological separation continues?

### Keywords

Semiconductors, Semiconductor industry, Digital technology, Technology stack, Sino-American technology separation, Industrial policy

# 1 Tectonic shifts in the global world order

Different forces of globalization have shaped the world since the industrial and digital ages.[1] Additionally, globalization has made nations more integrated and interdependent through diverse networks of cross-border relationships (Baldwin, 2006). Most large multinational corporations (MNCs) trade regionally based on nationally located assets, and financial flows have been concentrated to North America, Europe, and East Asia (Seppälä, Kenney, & Ali-Yrkkö, 2014).

The contemporary view of globalization is based on recent events and acknowledges the progress of supranational economic, social and manufacturing blocks, namely the USA, the EU, and most recently, China (Seppälä, Kenney, & Ali-Yrkkö, 2014; Hirst, Thompson, & Bromley, 2015). The relationships between these economic, social and manufacturing blocs, and their overlapping interests govern global trade, industry, digitization, and technologies. Additionally, differing ideologies and modi operandi undermine multilateral endeavors. From this perspective, it has become evident that China is contending with the US to become the largest economy in the world (*The Economist*, 2020a; Frankel, 2020).

The Chinese state has assumed a large role in providing support for industrialization (Nolan, 2001; Harrison, 2014). Wade (1990) posited that late industrializers typically go through a distinct phase of state intervention and protectionism in order to develop domestic industries. It is also widely known that industrial policy and government intervention aimed at building technological competence have served as the driving forces behind late industrialization in advanced electronics industries, for instance, in Japan and South Korea (Amsden, 1989; Wade, 1990).

China initially entered labor-intensive parts of electronics value chains in the 1990s and later, those of semiconductor value chains in the 2000s, mainly through Taiwanese and American foreign direct investment (FDI) (Brown & Linden, 2005). This FDI made China the largest exporter of computers around 2004 (Yang, 2006). In the beginning of China's upgrading journey, as much as 90% of value adding components had to be imported from other nations (Assche & Gangnes, 2010).[2] It has later been documented that China has captured a larger share of value creation in the electronics supply chains (Larsen, Seppälä & Ali-Yrkkö, 2018). Furthermore, the Chinese state continues to provide strong support for its domestic technology industries (see the Made in China 2025 initiative [Zenglein & Holzmann, 2019]).

Recent developments in the US–China trade conflict have centered on digital technology and have set the two countries on a path towards technological separation (*The Economist*, 2020b). The US invokes national security concerns over 5G networks and it has targeted Huawei, the Chinese exporter of telecom network equipment and smartphones. To concretize, Huawei was first added to the Department of Commerce entity list in May 2019, requiring export licenses for American firms to continue supplying Huawei (Department of Commerce, 2019). Further Huawei export restrictions on integrated circuits (ICs) produced using American equipment were announced in May 2020 (Department of Commerce, 2020). The latest trade restrictions in the semiconductor value chain are particularly interesting as they affect China indirectly through Taiwan Semiconductor Manufacturing Company (TSMC).[3]

When it comes to the hardware (HW) and software (SW) digital technology stack, China has demonstrated its competitiveness in digital platforms (e.g., TikTok, WeChat and Alibaba) and digital systems (e.g., Huawei, Xiaomi, Oppo). Yet the country lacks self-sufficiency in semiconductors—the lower hardware layers of the technology stack. Discussions, policies, and actions relating to digital platforms and systems will accordingly have significance but arguably not be as important and decisive as those regarding semiconductors.

Semiconductors are essential to modern life. New digital technologies—such as edge computing, industry 4.0, general artificial intelligence (AI), and quantum computing—rely heavily on semiconductor progress in delivering their promise of massive benefits to the global economy. Leading-edge semiconductors are also seen as "critical to defense systems and US military strength" (PCAST, 2017). Additionally, the global and distributed nature of IC value chains pose hardware security risks, and ensuring the integrity of ubiquitous semiconductor devices is hence important in order to mitigate future cybersecurity threats (Rostami, Koushanfar, & Karri, 2014).

Computation with semiconductors has become a cornerstone of scientific research and the human ability to solve increasingly complex problems relies on digital technologies, that is, on "the synergy of advanced algorithms, data and hardware" (PRACE, 2018). It is quite trivial, then, to see that quicker and more pervasive computation with greater power efficiency can benefit the public and equally provide a strategic edge in national security and business.

The motivation for writing this working paper is a concern that Europe, including Finland, will fall behind China and the US in the development of the digital technologies that will drive economic growth in the future as the technology separation continues. Furthermore, Europe and Finland need to reconsider their technology strategies if the separation affects the semiconductor layers of the digital technology stack (see Figure 1 on the next page). What options does Europe have to secure technological sovereignty[4] if the Sino-American technology separation continues? Does Europe need to achieve technological sovereignty in semiconductors?[5]

The current European-wide technology strategy envisions developing a high-quality digital infrastructure by increasing EU, member state, and industry technology investments[6] to €20 billion annually in order to keep up with the US and Asia (European Commission, 2020). The goal is to secure "technological sovereignty in key enabling technologies and infrastructure" (European Commission, 2020). While there has been widespread discussion on American platform giants' market power in Europe, we want to bring semiconductor technology into European policy discussions.

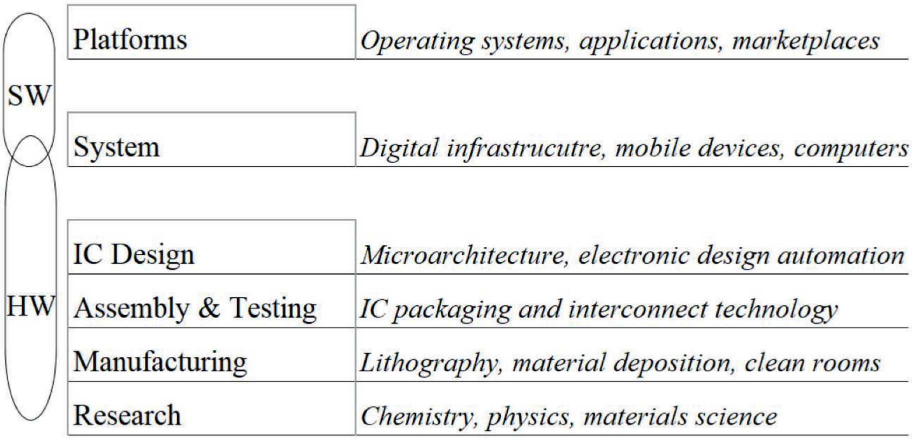
The European Commission's AI white paper is an attempt to steer technology industry development in Europe. However, Europe's strategy with regard to semiconductors remains unclear. The commission states that initiatives such as the European Processor Initiative (EPI) might reduce the dominance of non-EU players in the semiconductor markets (European Commission, 2020). However, meaningful achievements in upgrading the European semiconductor industry remain unlikely with the current strategy and current levels of investment.

This working paper continues as follows: First, we provide a definition of the semiconductor technology stack. Second, we write about the historical context of global value chains in the semiconductor industry. Third, we describe the current state of semiconductor manufacturing and how value is captured and created geographically. Fourth, we present how globally significant supranational blocs have acted in support and the policies of their semiconductor industries. We conclude that political action on European technology sovereignty might pose a threat to Finnish technology neutrality and respective exports in the future.

## 2 Defining the semiconductor technology stack

We define *digital technologies* as the integrated hardware and software systems that enable (and have enabled) various end applications to emerge from computation. The technology stack has been used to describe strategies and dynamics in the electronics industry and mobile internet (see, e.g., Kenney & Pon, 2012). We adopt a deeper view of the stack in order to capture how semiconductors affect the global technology competition. The hardware and software layers are depicted in Figure 1 below.

**Figure 1** The hardware and software stack of digital technologies



The top layer of the technology stack is *platforms*, an umbrella term that we use for operating systems, applications, marketplaces, and social networks. The platform layer remains largely unaffected by the trade war because only 3% of US software industry revenue was generated in China in 2019 (*The Economist*, 2020b) and vice versa. Furthermore, it can be noted that the open source standards, application programing interfaces, and easy reproducibility of software reduce the significance of software in the conflict. American platform companies that allegedly have large market power have been scrutinized, especially in Europe, while China has managed to cultivate its own breed of domestic technology giants. European consumers are currently free to choose between American and Chinese platforms.

In our view, the system layer bridges the hardware and software domains. It provides a category for a diverse range of companies providing telecommunications infrastructure, mobile devices, and computers. In this layer the functionality, performance, connectivity, and security (among other attributes) of digital technologies are defined. Without systems companies, there would not be any smartphones or computers, nor any wireless networks for platforms to provide their offerings. As opposed to the US, China and Europe are self-sufficient in telecommunications networks (Huawei, Nokia, & Ericsson). Global value chains in the electronics industry are heavily reliant on China, with China being the largest exporter of electronics.

The lower hardware layers have become a flashpoint in the Sino-American trade conflict. Semiconductor ICs are the foundation for computation in data centers, smartphones, PCs, aerospace, business, national defense, and healthcare. They underpin the estimated revenue of $2 trillion in global e-commerce (*The Economist*, 2018), and national leadership in semiconductors is strategic. The semiconductor industry enables both the system and platform levels of the digital technology stack. The US is trying to maintain its technology leadership by restricting Chinese access to leading-edge ICs while simultaneously accelerating innovation efforts at home. It is interesting to note that platform companies have begun moving down the stack by investing in proprietary chip designs to accelerate workloads in their computing environments (e.g., Google TPU [Cherney, 2020], Alibaba Hanguang [Kharpal, 2019]). There is however a clear distinction between the design and manufacturing of ICs—Apple is for instance making its own semiconductor designs but relies on TSMC for manufacturing.

The current positions of the supranational economic and social blocs in the semiconductor technology stack are indicated in Table 1 on the next page.

# 3 Semiconductors—a flashpoint in the US–China trade war

## 3.1 The US–Japan trade war in the 1980s

The innovation, competitiveness, and integrity of the US semiconductor industry is now facing challenges (PCAST, 2017). However, the prospect of a US deterioration in semiconductors because of foreign competition is nothing new. US semiconductor companies faced intense competition from Japanese dynamic random-access memory (DRAM) manufacturers in the 1980s (Brown & Linden, 2011). It took about 20 years for Japanese manufacturers to achieve technological parity with the US: in the 1960s, government agencies forced technology transfers from foreign companies (e.g., IBM) seeking access to the Japanese market (Prestowitz, 1988). The Japanese government furthermore actively subsidized research and promoted cooperation between its intensely competing business groups (Fransman, 1990).

By developing superior manufacturing capabilities, Japanese semiconductor divisions surpassed the US in both market share and R&D expenditure (Brown & Linden, 2011). Crashing demand for DRAM in 1985 and eager Japanese investments led to severe overcapacity and an acute crisis in US semiconductor manufacturing. US firms weathered the storm through consolidation and repositioning from DRAM toward custom logic processors. Industry collaboration simultaneously increased as the Semiconductor Industry Association (SIA) was formed to solicit support from the government amid calls for "fair trade" and the elimination of "dumping" in US and third markets, although the latter was never proven (Irwin, 1996).

Despite the rhetoric of semiconductors being strategic high technology, Irwin (1996) concluded that the 1980s DRAM dispute followed a similar pattern to that of other instances of trade friction. Namely, that the rapid entry of reasonably priced high-quality Japanese goods (e.g., cars and textiles) was a shock to isolated American manufacturers. The resolution of the US–Japan rivalry adopted numerical targets, so-called managed trade (see Flamm, 2010), for US access to the Japanese market (Irwin, 1996). In an interesting precedent to strategic high technology, US trade policy shifted away from setting trade "rules" and moved towards seeking a transaction-

**Table 1** The current position of each economic and social bloc in the semiconductor technology stack

|  | USA | China | Europe |
|---|---|---|---|
| Platforms | A leading role | Local platform firms since 2000s | A minor role |
| Systems | Equipotent status |  |  |
| Hardware | A leading role | On-going upgrading since 2000s | A minor role |

al "outcome" (Dick, 1996). The threat of US sanctions reduced the scope for direct government intervention in established industries (Brown & Linden, 2011). But, because Japanese manufacturers could sell to Europe and easily circumvent voluntary export restrictions, some argue that the extensive integration of semiconductor markets rendered the US unilateral approach inefficient in the short term (Dick, 1996).

Although a policy response might not work exactly as intended, history shows that industry leaders can collaborate and consolidate in order to lobby for support when facing an exogenous crisis. The current challenge to the US semiconductor industry however has a different nature. China plays a dual role in the ongoing conflict as it is developing its domestic semiconductor capabilities while simultaneously guarding the largest and fastest growing market for semiconductors globally. While the US sought to manage its trade deficit with Japan, the current goal of the US government is decoupling from China (Koskinen, 2020).

## 3.2 A brief history of TSMC

The nurturing and flourishing of Taiwan's semiconductor industry form one of the most successful cases of industrial establishment. The two main influences on Taiwan's success in the semiconductor industry are detailed in the related literature. The first was the institutional view of an innovative public-private partnership that enabled the diffusion of technologies and knowledge to private firms (Mathews, 1997). The second was highlighting the role of engineers and scientists with US educational and professional experience returning to Taiwan (so-called returnees; Saxenian, 2006), although these returnees mainly participated in later industry development (Kenney, Breznitz & Murphree, 2013). TSMC, for instance, benefited from returnees by recruiting many of them to senior management positions, which provided vital business connections in addition to managerial capabilities (Saxenian, 2006). Progressive integration into formal corporate production networks and informal knowledge networks helped Taiwan upgrade its technical capabilities and thus sustained its semiconductor industry's competitiveness (Ernst, 2010).

TSMC is the technology leader in semiconductor fabrication and can be seen as a bottleneck in the semiconductor value chains from the American perspective. At the height of the US–Japan DRAM crisis, TSMC was spun off from a pilot project within the Electronics Research Service Organization (ERSO) in 1985. ERSO had made several technology transfers from various actors in order to expand its technical semiconductor capabilities. Taiwan's first semiconductor fabricator, United Microelectronics Corporation (UMC), was created as an ERSO technology and staff spin-off with government financing in 1980. While taking over ERSO's manufacturing pilot, the new company, TSMC, was formed as a joint venture with Dutch multinational Philips. In return for an advantageous position in Taiwan's semiconductor industry, Philips transferred both its existing technology (which trailed the world leading-edge by 1–2 generations) and its cross-licensing agreements with other manufacturers to the new joint venture. The last detail effectively shielded TSMC from intellectual property (IP) rights disputes that plagued other East Asian manufacturers (Mathews, 1997).

By the mid-1990s, TSMC had retained its cost advantage while achieving technological parity with leading IDMs and foundries in the United States and Japan (Saxenian, 2006). All in all, the Taiwanese upgrade to the leading edge took 20 years (fundamental capabilities were being nurtured 10 years prior to TSMC's entry).

TSMC's success is founded in its reliability in regard to delivering timely manufacturing process advancements. The company pioneered the innovative pure-play foundry business model when it was conceived in the 1980s by TSMC's founder, Dr. Morris Chang. Chang had worked at Texas Instruments for 25 years and noticed a trend of top engineers founding their own semiconductor businesses. But these startups could not finance huge capital expenditure in semiconductor manufacturing, and Chang thus identified a new market opportunity (Nenni, 2020).

The fragmentation of the semiconductor industry started in the 1970s when integrated device manufacturers (IDMs; such as Intel), along with independent equipment and materials producers, were founded in Silicon Valley. TSMC capitalized on the beginning fragmentation by focusing purely on the manufacturing process and catering to a newly established chip design industry. Through a design–manufacturing partnership, semiconductor foundries benefited from having access to developing (novel) end markets and the design firms gained access to leading-edge manufacturing without the huge capital commitments required for a fab. The availability of electronic design automation (EDA) tools and standardization through IP blocks facilitated the entry of design firms without manufacturing capabilities. IC manufacturing was further unbundled by third firms specializing in the final assembly and testing of ICs. Fragmentation has driven innovation and allowed specialized firms throughout the value chain to generate value with innovation in new products, materials, microarchitectures, manufacturing processes, and IC packaging (Saxenian, 2006).

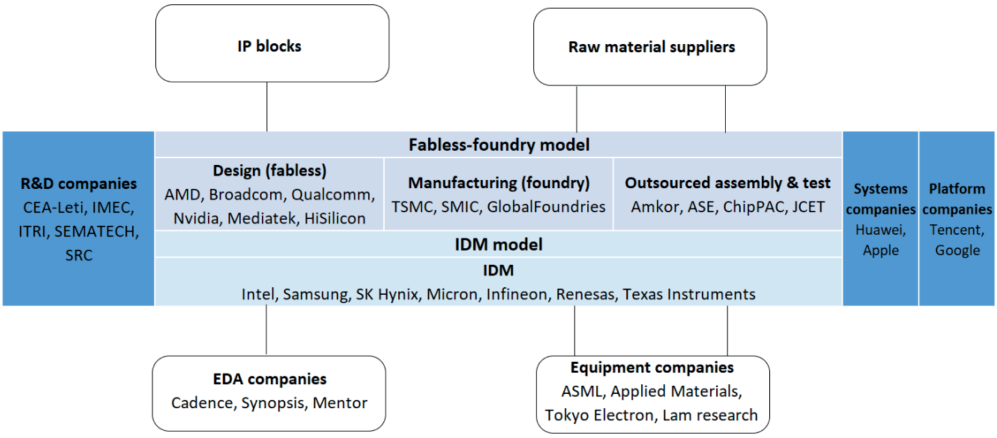
## 3.3 The current semiconductor value chain

Manufacturing ICs from silicon requires one of the most complex manufacturing processes on earth, and the semiconductor industry constitutes a great but idiosyncratic example of a global value chain (SIA, 2016). The industry is mature, with most segments dominated by a small number of firms located in the US, South Korea, Taiwan, Japan, Europe, and China. There are considerable entry barriers, most notably first mover technology advantages, intellectual property, and extremely high fixed costs (King, 2003). Competitive advantage in the semiconductor industry is dependent on the manufacturing process, which greatly influences performance, power consumption, time to market, and cost. Due to its complex nature, profitable semiconductor manufacturing requires large-scale operations and an imperative to fully utilize capacity.

To facilitate the commercialization of new digital technologies and the utilization of available capacity, the industry disintegrated into the specialist segments of design, fabrication, assembly, testing, and packaging, as described above. These distinct activities form a global value chain where both down- and upstream firms can generate value through innovation. The suppliers of materials, EDA software, IP blocks, and manufacturing equipment complement the core firms in the value chain to form the geographically distributed semiconductor ecosystem. There are still two parallel operational strategies in the semiconductor industry. The traditional mode of operation is being an IDM that vertically integrates design, manufacturing, test, and assembly. Within the newer fabless-foundry model that emerged with industry fragmentation, specialized firms cooperate in the ecosystem. The semiconductor value chain is presented in Figure 2 below.

Modularity in both product architecture and industrial organization provides strategic opportunities for entrants and incumbents in the electronics industry (Sturgeon & Kawakami, 2010). Additionally, offshoring to exploit lower labor costs and gain better access to growing Asian markets has contributed to semiconductor and electronics manufacturing shifting to Asia. To summarize, the semiconductor industry is characterized by rapid technological advances, global markets, and strategically designed industrial policies (Flamm, 2010).

**Figure 2** The semiconductor value chain



An adaptation from SIA (2016).

## 3.4 Industry challenges to meeting diverse computational demands

Taking a top-down perspective, the exponential growth of data and emerging technologies—such as autonomous vehicles, 5G, the internet of things, and scientific computing—promote the demand for faster and more energy-efficient computers. Ranging from data centers to IoT edge devices, each technology has different requirements for the underlying semiconductor ICs. As an example, we can contrast the systems on a chip (SoC) used in smartphones that integrate the central processing unit (CPU), graphics processing unit (GPU)—as well as network, video, and AI processing—on a single silicon die with the large monolithic CPU designs used in data centers (Waldrop, 2016).

There are myriad technical details about advancing semiconductor manufacturing, and progress is needed in materials, transistor design, manufacturing, packaging technologies, and microarchitectures. Extensive coordination between designers, materials suppliers, equipment makers, and manufacturers is needed in order to realize these goals (Waldrop, 2016). We briefly dive into the lowest layers of the stack to give an outlook on how the semiconductor industry plans to meet the insatiable demand for more computation.

At the heart of the microprocessors and memory devices in our computers is the transistor, billions of which have been integrated in modern ICs. Improving the performance and boosting the density of transistors has been the most straightforward way to speed up and cheapen all the digital devices we use today. Although the shape and materials of transistors have changed, the same basic structure of complementary metal oxide semiconductor (CMOS) technology (a gate controlling an electric channel between the transistor's source and drain), which was invented in the 1960s,[7] remains in place today. This is the premise of the empirical observation made by G. Moore in 1965 and has been sustained by the semiconductor industry for over 50 years (Ye, Ernst, & Khare, 2019). But the scaling of CMOS transistors has continually faced physical challenges and will eventually come to an end (Waldrop, 2016).

From a bottom-up perspective (e.g., considering what type of transistor is used), the industry has made multiple transitions throughout history (O'Reagan & Fleming, 2018). The most recent and relevant shift was the adoption of the fin field-effect transistor (FinFET), a new transistor type which was technically proven around 2001and first commercialized in 2011 by Intel. The transition required a concerted collaboration between major American semiconductor companies, leading-edge universities, and federally funded research programs. Interestingly, the FinFET was successful because it was not too radical a change. Because of immense investments by the international semiconductor industry in CMOS technologies, the FinFET needed to fit within the existing manufacturing paradigm (O'Reagan & Fleming, 2018).

The FinFET breakthrough has sustained Moore's law during the 2010s; however, TSMC and Samsung have announced that they will transition to nanosheet transistors at the leading edge in two to three years. FinFETs suffer from electrical leakage that becomes untenable at the upcoming 3 nm[8] node. Nanosheet transistors wrap the gate around the channel to provide better electrodynamic control over the transistor channel, a concept that researchers have tried to utilize since as early as 1990[9] (Ye, Ernst, & Khare., 2019). This highlights the long development cycle in the bottom layers of the technology stack: 30 years from conceptual idea to the start of mass production.

Extreme ultraviolet (EUV) lithography equipment, introduced at the 7 nm node and solely provided by Dutch company ASML,[10] has allowed single exposure patterning of critical chip structures in the advanced nodes. Single patterning provides cost, yield, and cycle-time benefits in manufacturing. But beyond the 5 nm node, multi-patterning EUV lithography becomes inevitable, which adds to the wafer costs. Lithography equipment therefore needs improving in order to shift back to the single exposure patterning of critical chip features at future (1 nm) nodes (Samavedam, 2020).

Further problems are caused by the fact that the amount of heat a microprocessor can dissipate (i.e., the power density) has not scaled in the past decade. Processor clock rates are being kept down to manage heat and the industry has thus shifted to multicore microarchitectures to utilize increasing transistor counts. Many workloads can be parallelized to take advantage of many processor cores and reach a solution as quickly as a faster single processor core. One solution for the heat issue is to introduce new materials in the channel region of the transistor, which has the potential to reduce heat and provide higher efficiency (Ye, Ernst, & Khare, 2019).[11] With nanosheet transistors, improvements in manufacturing equipment and new materials, transistor density can continue to scale for eight to ten years but performance increase at fixed power will be likely to slow down (Samavedam, 2020).

Despite the potential to increase performance through various innovations, the increasing complexity of sustaining Moore's law has led to rising costs in both fabrication and design. A leading-edge fabrication plant now costs over $15 billion (TSMC, 2018) and non-recurring engineering work on a 7 nm microarchitecture (the currently maturing manufacturing process) reportedly costs up to $300 million (Lapedus, 2018). The huge costs of regenerating manufacturing infrastructure for the technology successors will most likely constrain the future of the industry (Isaac, 1997). The industry is hence shifting towards heterogeneous integration with die-to-die connectivity as a cost-efficient way to improve system performance (Samavedam, 2020).

## 3.5 The US leads semiconductor value capture and creation

The US is a clear leader both in creating and capturing value in the semiconductor industry. We use sales revenue and R&D expenditure figures in support of this claim.

Global semiconductor sales were $481 billion in 2018 and annual sales growth is forecast at 4.6% through 2022.[12] The growth in demand is driven by high-performance computing, electric and autonomous vehicles, and the proliferation of AI applications, as well as by the implementation of 5G networks around the globe (PWC, 2019). On the other hand, declining PC and laptop sales, as well as stagnated smartphone sales, create a drag on semiconductor demand. Investment is generally driven by demand for technologically superior products with improved capabilities and reliability (SIA, 2016).

US headquartered firms account for 47% of revenue while firms headquartered in China only generated 7% of global revenues. Revenue generated in the semiconductor industry by region and across segments in 2019 is presented in Table 2 below. Fabless design firms and IDMs are included in the same category since they both have chip design capabilities. The IDM and design segment is by far the largest in semiconductor value chains and includes multiple companies with revenues exceeding $20 billion (e.g., the IDMs Intel, Samsung, SK Hynix, and Micron, as well as the fabless companies Qualcomm and Broadcom). The US has a particularly strong position in chip design, IDMs, manufacturing equipment, and EDA software. China, on the other hand, has a relatively large share of outsourced assembly and testing but still lags far behind the US and other advanced semiconductor countries in other segments.

**Table 2** Semiconductor industry sales by region and segment[13]

| Semiconductor industry sales, in billions | | | | |
|---|---|---|---|---|
| | Total | US | China | The rest of the world |
| IDM & design | $407.7 | 54% | 7% | 39% |
| Equipment | $71.6 | 47% | 2% | 52% |
| Foundry | $54.7 | 11% | 8% | 81% |
| OSAT | $28.3 | 14% | 21% | 64% |
| IP & EDA | $9.5 | 78¤ | 1% | 21% |

van Hezewijk (2020).

To indicate the relative positions of the countries participating in semiconductor value chains, we present consolidated data on industry and government R&D expenditure in Table 3 on next page. R&D expenditure in the semiconductor industry has averaged 15% of sales (SIA, 2016) and we see it as a proxy for value creation. US-based semiconductor companies account for over half of this investment. China is the outlier with the government providing most of the R&D funding.[14] However, a large share of Chinese government investment is allocated to capacity installments and acquiring existing technology (van Hezewijk, 2019), which only upgrade local capabilities incrementally. Finally, honorable mentions go to South Korea and Taiwan, as well as to the Netherlands, whose research and investments have made the continuation of Moore's law possible.[15]

**Table 3** Geographical distribution of semiconductor R&D expenditure

| Semiconductor R&D expenditure, in billions | | | | | | |
|---|---|---|---|---|---|---|
| | US | China | The rest of the world | | | |
| | | | S. Korea | Taiwan | Japan | Netherlands |
| Revenue | $270.9 | $41.3 | $80.9 | $75.9 | $50 | $25.4 |
| Industry R&D | $37.8 | $2.6 | $8.4 | $6.8 | $5.2 | $3.6 |
| Government R&D | $1.5 | $5.5 | $1.7 | n/a | n/a | $0.1 |
| % of revenue | 15% | 20% | 12% | 9% | 10% | 15% |
| % of total | 54% | 11% | 14% | 9% | 7% | 5% |

van Hezewijk (2019).

# 4 An overview of Sino-American semiconductor policy

## 4.1 The USA—maintaining leadership

As seen above, the US holds dominant market positions in the EDA, equipment, and IDM/design segments of the semiconductor industry. But China is the largest IC market globally and US semiconductor firms generate 36% of their revenue in the mainland market (Fitch & Davis, 2020). The largest equipment firms and IDMs generate over twice as much revenue in China, as opposed to the US, highlighting the importance of the Chinese market (van Hezewijk, 2019). Any (US or Chinese) policy that diminishes American companies' revenue from China will hurt their competitiveness.

Adding to American woes, Intel, which was once the paragon of advanced chipmaking is now one process generation between behind TSMC and has announced delays in developing its most advanced 7 nm[16] manufacturing process (Salter, 2020). The US thus finds itself amid a technology war with China at a point when its domestic semiconductor mass manufacturing capabilities are beginning to trail behind the leading edge. Nevertheless, US industry, academia, and the US government are again collaborating to tackle cost, complexity, and competitive challenges with a similar model to the FinFET breakthrough discussed above (DARPA, 2020).

US lawmakers have realized that the domestic semiconductor industry's competitiveness and investment capacity may be diminished by the trade war and have proposed legislation that would provide over $20 billion in aid to support US semiconductor manufacturing (Nellis, 2020). The bill would provide investment tax credits, a federal "matching" fund to match state incentives, allocate federal funds for semiconductor R&D, and also focus on developing advanced IC packaging capabilities (Warner, 2020).

TSMC has been enticed to build a $12 billion semiconductor foundry in Arizona and has reportedly agreed on subsidies with the local government in order to offset higher production costs[17] in the US (Wu, 2020). However, the planned foundry capacity is small compared with TSMC's Taiwanese "giga fabs" and the manufacturing process would be one generation old upon completion. But TSMC's Arizona fab could be trusted for US defense applications with smaller production runs.

As witnessed in the recent trade war escalation, the US evidently has the technological clout to inflict damage on Chinese firms and thus restrict China's technological development. It is not the first time the US has restricted semiconductor exports to China. For instance, Intel was denied an export license to supply Xeon server-grade processors to a Chinese supercomputer in 2015, citing concerns over nuclear device development (BBC, 2015). Another example of protectionist measures by the US Commerce Department was the banning of all exports of components and software to the second-largest Chinese telecom equipment firm, ZTE, in 2018. Restrictions were imposed because ZTE failed to comply with economic sanctions against Iran and North Korea. A settlement requiring ZTE to pay a $1 billion fine was reached and the ban was subsequently removed. However, ZTE is said to remain under close scrutiny by US authorities (Ballentine, 2018).

US prosecutors have furthermore indicted Taiwanese foundry UMC, as well as newly established Chinese memory producer Fujian Jinhua, of stealing the trade secrets of Micron, a US DRAM manufacturer. A manager became part of Micron following an acquisition and then became a president of Micron's Taiwan subsidiary MMT. The manager resigned from MMT after two years, bringing with him some 900 proprietary files when he joined UMC in 2015. A partnership was then quickly established with Fujian Jinhua to transfer DRAM technology for mass production. Other engineers from MMT brought more intellectual property with them when they were recruited to UMC (Department of Justice, 2018).

## 4.2 China—catching up and securing access

China is extremely dependent on semiconductor imports. The import value was $312 billion in 2018, amounting to over 60% of global sales (*The Economist*, 2020c). Recent events in the trade war underscore China's predicament—it is subject to politically motivated decisions across the Pacific, and Huawei finds itself effectively cut off from the leading-edge chip supply. China is playing technological catch up in the semiconductor industry while it is trying to secure its supply.

China has launched *Guidelines to Promote a National Integrated Circuit Industry* in 2014 and Made in China 2025 in its latest efforts to achieve technological self-sufficiency (VerWey, 2019). The country has implemented industrial policies since the 1960s to support the strategic development of a domestic semiconductor industry.

Made in China 2025 outlines a vision to "develop the IC design industry, speed up the development of the IC manufacturing industry, upgrade the advanced packaging and testing industries, facilitate breakthrough in the key equipment and materials of integrated circuits." Furthermore, Made in China 2025 describes aiming to domestically produce 70% of chips by 2025. The above-mentioned guidelines called for $150 billion to be invested by 2025 and set out a two-pronged strategy that focuses on outbound investments in foreign technology companies and the facilitation of domestic greenfield investment and joint ventures (VerWey, 2019).

Between 2014 and 2017, Chinese investments in US semiconductor companies totaled a record $10 billion (Yue & Lu, 2017). But Chinese acquisitions of foreign technology firms have now become subject to scrutiny. The acquisition of US firm Lattice Semiconductor was blocked on national security grounds (Executive Order, Sep 13th, 2017). Furthermore, Germany has introduced new measures that allow the government to scrutinize and block deals in strategic economic areas (e.g., in AI, robotics, semiconductors, biotechnology, and quantum technology) (Chazan, 2019).

The current well-funded and clearly defined policy is part of a continued effort by the Chinese government to promote nationalism and achieve independence from foreign technology (Zenglein & Holzmann, 2020). The government has enacted the strategy by establishing the China Integrated Circuit Industry Fund, which raised $22 billion in 2014 and $29 billion in 2019 (van Hezewijk, 2019). This centrally established "big fund" guides provincial governments in their efforts to implement the industrial policy, and a United States Trade Representative section 301 report (2018, p. 94) cites an SIA estimate that provincial and municipal IC funds have raised an additional $80 billion since 2014.

China is championing SMIC to pursue the goals set out in Made in China 2025. The Shanghai-based foundry raised close to $10 billion in financing in the spring of 2020 in order to increase capacity and develop its manufacturing processes (Wei, 2020; Fang & Li, 2020). Higher up in the value chain, Chinese chip design companies, such as HiSilicon and Tsinghua Unigroup, are among the global top 10 IC design firms by revenue (*The Economist*, 2018). China continually tries to recruit engineers from Taiwan by offering better compensation (Ihara, 2019; Fang, 2020).

However, the country is set to fall far short of the targets set out in Made in China 2025, calling into question the efficiency of the centrally designed incentives in the Chinese approach. Hybrid firms (Chinese enterprises with foreign financing) have furthermore been the most innovative in developing Chinese technology when compared with local state-owned enterprises (Fuller, 2016). Looking at Chinese IC production, domestic fabricators (those with HQ in China) covered only 5% of DRAM, flash memory, and logic sales in China in 2018. Accounting for both domestic and foreign producers, ICs fabricated in China covered 15% of the demand (IC insights, 2019).

New tax subsidies for semiconductor companies were announced in August of 2020 (Kharpal, 2020). Chinese efforts have so far merely had incremental success because of the industry's highly globalized, competitive, and market-driven nature. Companies absolutely need more than cash to compete and Chinese policy looks likely to only have a marginal impact on Chinese semiconductor firm's ability move up value chains.

China leverages the size of its domestic market in its soft power retaliation. For instance, Qualcomm's merger with NXP fell through in 2018 as China's State Administration for Market Regulation (SAMR) was delaying approval of the deal (Martina & Nellis, 2018). Two thirds of Qualcomm's revenue are generated in China, and it thus needed Chinese approval of the acquisition. In the same year, SAMR started an investigation against Samsung, SK Hynix, and Micron for price-fixing in DRAM markets. The three firms collectively control a daunting 95% market share (Harris, Jung-a, & Song, 2018). China again used access to its domestic markets as leverage, but it is not the first to punish DRAM producers for price-fixing. Both Samsung and SK Hynix have paid hundreds of millions in fines for price-fixing to both the European Commission and the US Justice department in 2010 and 2005 respectively.

# 5 Discussion and policy implications

## 5.1 The next semiconductor crisis and technological separation

Brown and Linden (2011) argued that different interconnected and recurring "crises" shape the semiconductor industry. Sturgeon (2011) saw the economic crisis of 2008–2009 as an inflection point at which Asian firms assumed a leading role in developing the global electronics industry. Building on these commentaries, we see that the ongoing Sino-American technology separation marks an inflection point for global competition in the semiconductor industry—it forces change in value chains and innovation networks.

To recapitulate, the American semiconductor industry is faced with a crisis of increased competition and the loss of leading-edge manufacturing. On the other hand, China's semiconductor industry faces a limited supply of experienced engineers and risks being cut off from critical American and European manufacturing equipment by decades-long technology barriers. Moreover, Chinese technology products face a branding crisis in Western markets, and they are seen as being unsecure and under the malign influence of the Communist party. The crisis is compounded by a pandemic-induced recession.

The Sino-American technology separation might result in two separate industrial ecologies and two technological spheres of influence. Defensive American action will slow Huawei's progress. On the other hand, actions taken to limit the supply of leading-edge chips absolutely reinforces China's drive to technology self-sufficiency. We (i.e., all blocs) should also harbor no illusions about the costs of a technology separation at the lowest levels of the hardware stack. Many American and European semiconductor firms have their largest markets in China and might be greatly affected by further escalations in the conflict. In response to Chinese state-led upgrading, the US is drafting a bill that would provide tens of billions of dollars in support to the US semiconductor industry.

## 5.2 Technical challenges and national policies

Technical challenges to meeting increased demand for computational power affects the top layers of the technology stack as well. With the increasing cost and complexity to sustain Moore's law, semiconductor research institutes now explore other computational technologies—such as quantum, neuromorphic,[18] or photonic computing—that might provide solutions in the medium term (Lapedus, 2019). The ultimate question is how a balance can be struck between investments in current and future needs. Investing in mathematics, algorithms, and computer science is as important as developing new types of logic devices and manufacturing techniques (PRACE, 2018). Although the industry is vertically specialized, we observe that platform and system companies expand vertically into chip design for strategic reasons.[19]

The diffusion of technical semiconductor capabilities and expected changes in technology have led to the establishment of state-sponsored national champions that directly engage in fierce global competition, resulting in high-stakes political intervention (Flamm, 2010). It is simply not possible to completely stop the diffusion of technology, and protecting the leadership status of a strategically important industry such as semiconductors requires deep collaboration, a focus on IP protection, bringing new innovations to market, and setting standards. Competing in global semiconductor markets is not cheap or easy because products are founded on long scientific research projects and some segments of development are protected by national security priorities (PCAST, 2017). Additionally, industrial policy has frequently supported the establishment of local semiconductor businesses (PCAST, 2017). This has implications for trade and industrial policy, which needs to account for the reality of supranational blocs investing in new technology that disrupts industrial landscapes.

## 5.3 Policy implications for Europe

Any public policy aiming for technology sovereignty should consider the limited talent pool, market development, innovative capabilities, national research priorities, and new competition (Ernst, 2010). Europe clearly needs deep external collaboration in order to keep abreast with semiconductor innovation abroad. Simultaneously looking inward to improve European cooperation is likely to be required in order to succeed.

Given the dichotomy of a technology separation, the options for Europe can be outlined as follows:

- **Choose American technology:** Continue participating in leading American innovation networks and be a fast adopter of US technology products in order to quickly reap the benefits of high-risk, low-return US investments. The main question with this strategy is if American interests curb European decision-making autonomy.
- **Choose Chinese technology:** Chinese hardware is not extensively used in Europe, but systems and platforms are, in principle, available to Europeans. Adopting Chinese technology might become necessary in order to access the main growth market for MNCs, but is all business good business?
- **Upgrade European technology:** In theory Europe has an option for ambitious industrial upgrading in semiconductor manufacturing with globally recognized research institutes Cea-Leti and Imec, and dominant lithography supplier ASML, as well as the IDMs NXP, STMicroelectronics, and Infineon. This strategy, however, requires a commitment of 20–30 years, as well as multi-billion-euro funding programs. A technology leadership strategy is extremely costly, and a more prudent option might be to diversify into multiple technology areas (see Ernst, 2010).

## 5.4 Concluding remarks

It is currently unclear what Europe's strategy is in regard to reacting to the changing competitive landscapes in the semiconductor industry. If a commitment to any option above is to be made on a European level, Finland's policy of technology neutrality and standards might become obsolete quickly. From the perspective of Finland's export-dependent economy, the risks of losing global sales opportunities needs to be considered when planning for the industrial and digital future of Europe. In the future businesses might be forced to become more flexible in terms of their product designs, for example that Chinese hardware and software must be used in products for the Chinese market. If the world is moving towards unilateralism, Europe should definitively consider how to keep in contact with regional innovation networks in Silicon Valley, Japan, South Korea, and Taiwan, but also China.

Today the semiconductor industry is facing a crisis that is likely to accelerate innovative efforts within supranational blocs. Current broad disagreements in international relations, alarming as they are, heighten the risk of uneven development in different parts of the world. Rapidly evolving technology and digitization will continue driving large shifts in the social and economic order. Therefore, it is hard to tell if there will be a winning side or standard in the current technology confrontation or if new rules for international technology competition and collaboration will emerge to accommodate multiple actors.

# Endnotes

[1] Globalization is commonly used to frame discussions in social sciences, politics, business management, and journalism.

[2] Mainly Taiwan, South Korea, & Japan.

[3] The TSMC is the technology leader in advanced semiconductor manufacturing and commands a majority share of the IC foundry market. Huawei and Apple generated 14% and 23% of the TSMC's revenues in 2019 respectively, highlighting American and Chinese dependence on TSMC's leading-edge manufacturing in order to deliver products with superior performance (TSMC, 2020). China is championing Semiconductor Manufacturing International Corporation, which is 1/10th the size of the TSMC, to spearhead efforts of semiconductor self-sufficiency. The Shanghai-based foundry raised close to $10 billion in financing in the spring of 2020 in order to increase capacity and develop its manufacturing processes (Wei, 2020; Fang & Li, 2020). Meanwhile leading-edge semiconductor manufacturing in the US is facing headwinds as Intel has announced delays in its upcoming 7-nm process node (Alcorn, 2020).

[4] *Sovereignty* in this context relates to either common European values, maintaining control over the technology used in member states, building competitiveness of European MNCs, or improving cybersecurity.

[5] This raises multiple other research questions, e.g., With Sino-American relations souring, can Europe remain neutral regarding the digital technology stack? Will Europe be forced to choose between American or Chinese technology? Should Europe invest more resources in developing hardware? What is the European position on semiconductors? And what are the European policy responses?

[6] Concrete examples include €80 million in EU seed funding for the European Processor Initiative, an industry consortium that will design a high-performance computing processor (Cordis Europa, 2020; EPI, 2020), and €3 billion in EU investments in high-performance computing resources (EuroHPC, 2020).

[7] State-funded academic research has been vital since the formative days of the semiconductor industry and defense spending was a catalyst for early growth (O'Reagan & Fleming, 2018).

[8] The naming convention is a heritage from planar transistors; however, the current node names do not have a direct relation to the size of physical features but rather only reflect the degree of transistor miniaturization.

[9] Additionally, nanosheets provide flexibility since the width the sheet can be varied to either boost performance or limit power consumption.

[10] See ASML's equipment in the work of Seeker (2019).

[11] Making transistors, e.g., from III–V semiconductors with higher electron mobility.

[12] Semiconductor sales statistics should be compared with care as they risk double counting.

[13] Consolidated data contains more (and smaller) companies from China but only the largest and most important companies for the US and the rest of the world. The materials segment is excluded.

[14] Chinese government spending is calculated from the first tranche of the national IC fund, spread out over a five-year investment period.

[15] South Korea, Taiwan, Japan, and the Netherlands together make up 90% of revenue generated in the rest of the world and are therefore included in the comparison on R&D expenditure.

[16] Intel’s 7 nm process is like TSMC’s 5 nm process in terms of transistor density.

[17] Technician salaries are 2 times higher in the US compared with Taiwan, and a lack of assembly, test, and other ancillary services raises costs (Patterson, 2020).

[18] In practice, neuromorphic computing has meant AI accelerators that parallelize the training task in hardware.

[19] In the US, this means a concentration of semiconductor talent in “tech giants.” The US hardware industry might face a shortage of skilled labor due to software engineering work having stronger “pull.”

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