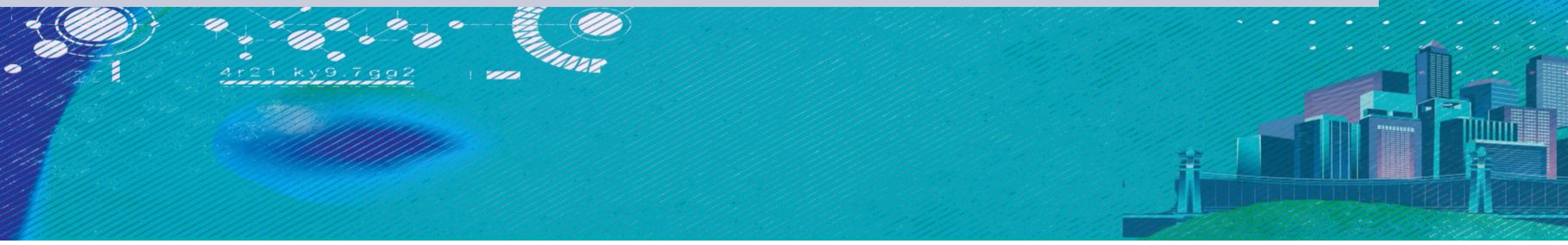
Council of the European Union
General Secretariat

The semiconductor ecosystem

Global features and Europe's position

12 July 2022



EXECUTIVE SUMMARY

Semiconductors (also called chips or microchips) are the building blocks of modern technology and a critical part of any advanced economy. The semiconductor shortage which accompanied the Covid-19 pandemic exposed the ***fragility of global supply chains*** in this sector, while the tech sanctions imposed on Russia as a result of its invasion of Ukraine have highlighted the key role of semiconductors not only for the economy but also for national security and the conduct of modern warfare.

The semiconductor industry, with its projected value of over $640 billion in 2022, is characterised by a highly globalised and interconnected value chain ***relying on large-scale capital investments, costly and lengthy R&D, a high degree of specialization and the need for large economies of scale*** in order to be financially viable. Much of the industry follows a ***'fabless-foundry model'***, whereby so-called 'fabless' firms focus only on the design of microchips but have no manufacturing capacity, while other firms called 'foundries' are responsible for manufacturing the microchips.

Looking at the semiconductor value chain as a whole, the ***EU ranks as a second-rate player*** with marginal capabilities in both the design and manufacture of microchips. ***However, besides being a leader in the field of automotive chips, the EU controls some crucial chokepoints in the global supply chain***. For example, the EU is the sole producer of some manufacturing equipment required for the production of leading-edge microchips, and a major supplier of other specialized equipment, materials and IP. The EU is also home to world-leading institutions in semiconductor R&D. ***While the EU is dependent on foreign actors for its supply of microchips, it is also itself a source of dependencies for other actors in the global value chain.***

Ultimately, the vulnerabilities and interdependencies built into the semiconductor supply chain stem directly from the same globalised and interconnected business model which has fostered decades of fast-paced innovation in this field. ***As no one country or region can possibly become fully independent or 'sovereign' in its semiconductor supply, it may be useful to view the semiconductor ecosystem as a global commons*** best served through international cooperation.

INTRODUCTION

Semiconductors are a staple of modern economies and an essential input of the digital transition. They are indispensable components not only of computers and smartphones, but even of everyday objects such as fridges, washing machines and LED lights. Key elements of tomorrow's economy – such as green energy, the Internet of Things, or artificial intelligence – all rely on the availability of leading-edge semiconductors. In the midst of the ***Covid-19 pandemic***, shiftings patterns of supply and demand caused a global chip shortage which highlighted the key role of semiconductors for manufacturing – most notably in the automotive industry, as a consequence of mistaken market forecasts by carmakers. The ***war in Ukraine***, on the other hand, has shone a spotlight the importance of semiconductors to national security and to the conduct of modern warfare: as a result of Western sanctions and export restrictions, Russia has reportedly been forced to use lower-grade microchips from household appliances in its military equipment[1], while experts expect that the Russian armed forces may soon have to resort to Soviet-era technology[2].

In response to these challenges, China, the United States and the European Union have all announced large spending plans to boost their production of semiconductors and reduce their reliance on global supply chains. On 8 February 2022, the European Commission unveiled its proposal for a ***'European Chips Act'*** entailing €45 billion of investments in the European semiconductor sector until 2030, with the goal of accounting for 20 percent of the global market share of chips production by that year, as 'a precondition for [Europe's] future competitiveness, and a matter of technological sovereignty and security'[3].

Without entering into the merits of that proposal, which is currently under negotiation, this paper aims to:

1. provide ***an understanding of the global semiconductor value chain***, its key features, main actors, as well as crucial chokepoints and vulnerabilities; and

2. assess the ***EU's position in the global semiconductor ecosystem***.

What is a semiconductor?

Technically, a semiconductor is simply any material which has an electrical conductivity between that of an insulator and that of a conductor. By extension, the term is used to refer to ***semiconductor devices***, in particular ***microchips*** (also called chips, computer chips, integrated circuits or IC). A microchip is a set of of electronic circuits on a small flat piece of semiconductor material, most commonly silicon.

A microchip of the size of a fingernail can contain billions of transistors, which is why chip components are measured in the scale of nanometers (one nanometer equals one billionth of a meter: by way of reference, the smallest viruses are about 20 nanometers in diameter). The smaller the size of a transistor, the more can be fit on a microchip, thereby increasing the chip's capabilities.

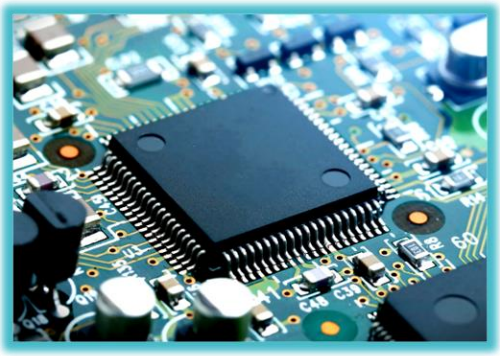
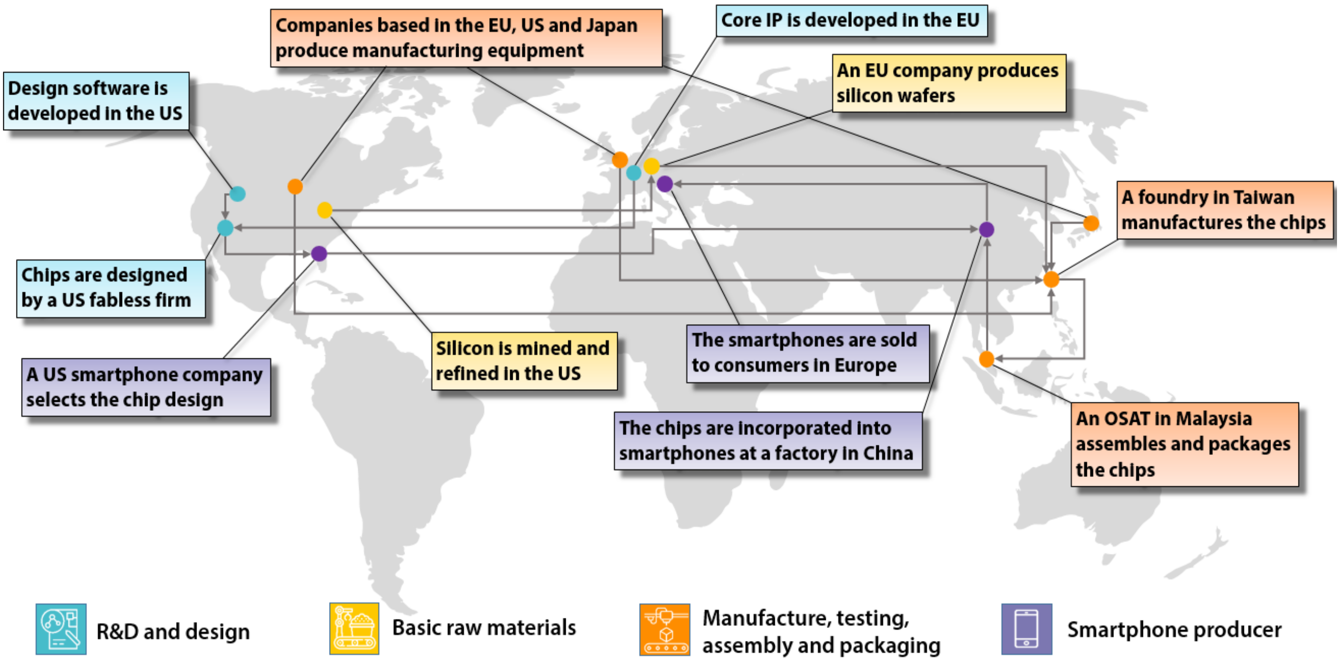


Photo credit: xb100 on Freepik.com.

Microchips are not fungible or interchangeable: different microchips have different functions, and are used by different industries in different devices. There are three main categories of chips: ***logic*** chips, ***memory*** chips and ***DAO*** (discrete, analog and other). Logic chips process information and act as the 'brains' of electronic devices (for example a laptop's CPU, a graphic processor, or an AI's neural processing unit). They made up 30% of the semiconductor industry's added value in 2019. Memory chips, like those contained in a USB flash drive on a laptop's RAM chips, are designed to store information. In 2019 they accounted for 9% of the industry's value. DAO semiconductors include optoelectronics and sensors, designed to turn analog environmental input (such as sound or images) into digital information. These chips are widely used in the automotive industry, and in 2019 they made up 17% of the semiconductor industry's added value.

The path of a smartphone microchip: an illustrative example of semiconductor supply chains

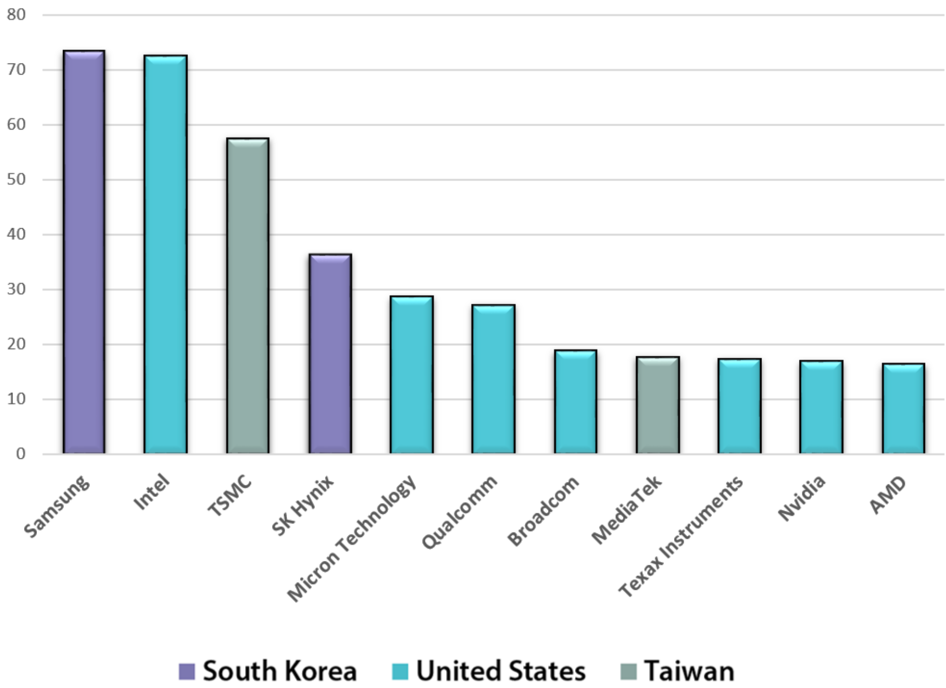


Source: ART, based on Semiconductor Industry Association[4]

KEY FEATURES OF THE GLOBAL SEMICONDUCTOR ECOSYSTEM

The global semiconductor market was worth $556 billion in 2021, and its value is projected to increase to over $640 billion in 2022, driven especially by growth in logic chips[5]. Market value is concentrated among a few key firms, in particular the US-based Intel (computer processors), the South Korean Samsung (memory chips) and the Taiwanese TSMC (smartphone processors), which together generated almost as much revenue in 2020 as the next 12 largest chipmakers combined[6]. In the market for semiconductors, companies whose products and services are slightly better than those of their competitors are able to capture an outsized portion of industry revenue[7].

Top semiconductor companies by revenue, 2021 (billion USD)



Data: Gartner[8] and Fortune[9]

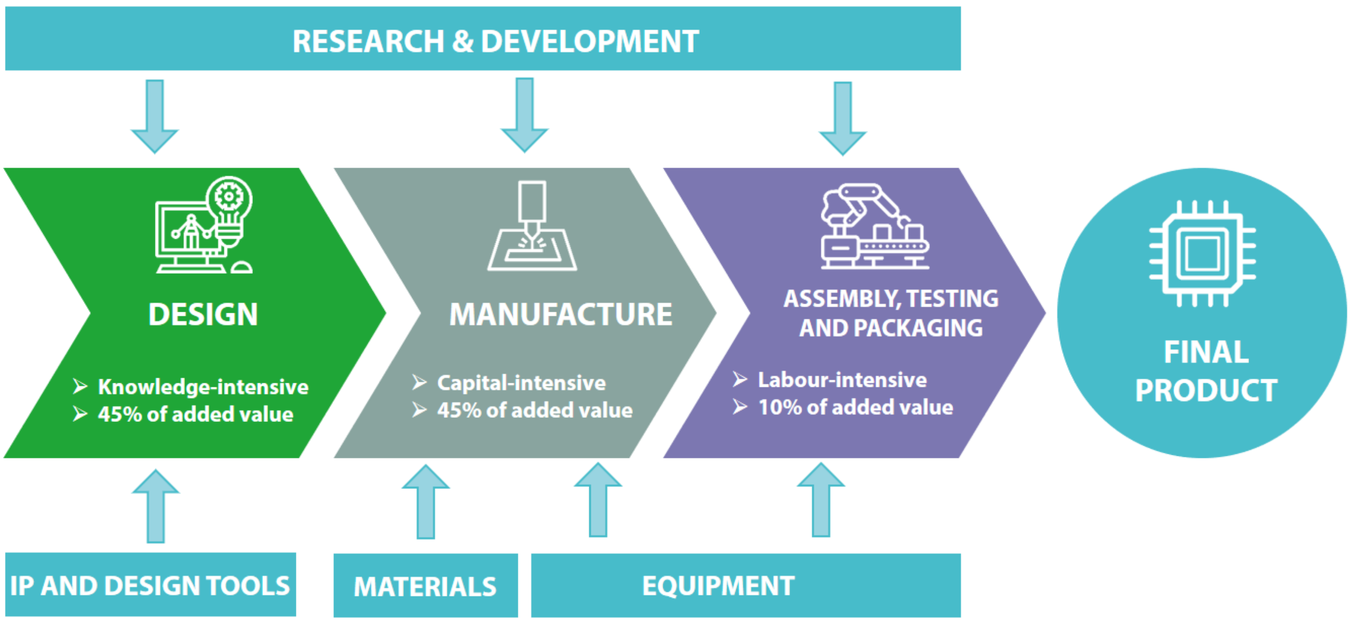
However, these figures hide the fact that ***the global semiconductor ecosystem is highly interconnected***[10]. Only a few companies are vertically integrated (Integrated Device Manufacturers, or IDMs, such as Intel, Samsung, SK Hynix and Micron Technologies), performing all production steps in-house, and even those companies may be vertically integrated only for the production of some specific chips: for example, Samsung might produce its memory chips entirely in-house, while it may outsource the manufacture of non-memory chips to other companies. In fact, much of the industry follows a ***'fabless-foundry model'*** whereby 'fabless' firms focus on chips design but have no manufacturing capabilities, foundries focus on manufacturing, and outsourced semiconductor assembly and testing companies (OSATs) focus on testing and assembling semiconductor components into devices. The US Semiconductor Industry Association (SIA) estimates that 90 percent of the value of a microchip is split evenly between design and manufacturing, while 10 percent of value added comes from the final assembly, testing and packaging (ATP)[11]. The SIA provides also an estimate of the economic advantages of geographic specialisation, compared to a model of fully localised 'self-sufficient' supply chains: according to their calculations, the globalisation of semiconductors allowed the industry to save $0.9 trillion to $1.2 trillion in upfront investment, to realise $45 billion to $125 billion in annual cost efficiencies, and to reduce semiconductor prices by 35 to 65 percent[12].

Semiconductor supply chains are extremely capital-intensive, and characterised by large economies of scale and market distortions as a result of high levels of government support[13]. By way of reference, building an entry-level factory costs about $15 billion, whereas the more advanced factories established by Intel, Samsung and TSMC cost over $20 billion each. TSMC reportedly planned on spending $28 billion on new plants and equipment in 2021 alone. Once built, these cutting-edge facilities become obsolete in five years or less, and chipmakers need to generate $3 billion in profit from each plant in order for them to be financially viable[14]. This means also that the 'yield' from each factory – the percentage of chips that are not discarded – must be no lower than 90 percent. Reaching that level requires considerable experience, which results in further market concentration and enormous obstacles for other players hoping to break into the market.

At the same time, the industry is also subject to short production life cycles driven by a high level of innovation, leading to frequent boom-and-bust cycles with sales declining in about every third year[15]. Due to the long time required to build new production facilities, to adapt production lines, or simply to manufacture a finished chip for a customer (with lead times of up to 26 weeks[16]), production cannot be adjusted rapidly to match variations in demand, and long-term industrial planning can be challenging. Nor can there be any significant planned overcapacity, as semiconductor factories need to operate at a capacity utilisation of more than 85% in order to be economicaly viable[17]. As both governments and the industry put in place measures to address the current semiconductor shortage, analysts have warned about the risk of creating a possible semiconductor glut by 2024[18].

The semiconductor supply chain comprises several distinct and interrelated steps. The actual production stage (with its three phases of design, manufacture, and assembly, testing and packaging) is preceded by a number of preliminary activities, such as pre-competitive and competitive research, development of specific IP and design tools, sourcing of raw materials, and investment in manufacturing equipment. After production, the microchips then enter a distribution phase and need to be incorporated into the final products sold to consumers. The figure below provides a simplified and schematic view of this process, which is discussed in more detail in the rest of this section.

A simplified overview of the semiconductor supply chain



Source: ART graph

Step 1: raw materials sourcing

Silicon has long been the key raw material for the semiconductor industry, but there is a growing consensus that companies are reaching the limit of their ability to fit a growing number of transistors onto a given length of silicon. The industry is therefore considering gallium nitride as a possible alternative which would allow for better electrical conductivity and higher temperature tolerance, and could cut power use by 10 to 25 percent[19].

According to US Geological Survey estimates, in 2021 China accounted for 71% of global silicon production[20] (while Russia accounted for 7%, Brazil for 5%, the US and Norway for 4% each) and 98% of global gallium production[21]. Quantitative estimates of silicon and gallium reserves are not available, but at least silicon reserves are thought to be ample in relation to demand in most major producing countries. According to the Europen Commission's 2020 survey of critical raw materials, the EU imports 11% of its silicon and 27% of its gallium from China, while the majority of the EU's supply is sourced within Europe[22].

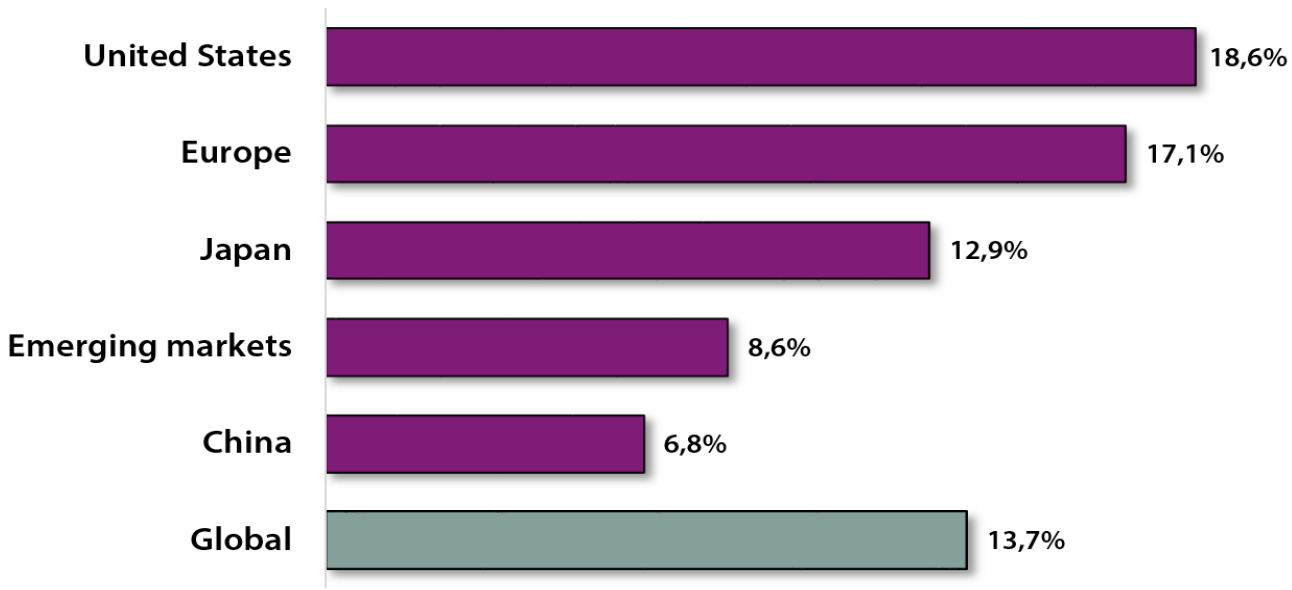
In addition to these basic materials, the production of semiconductors requires a large number of other material inputs, such as chemicals and gases which are employed at different stages of a lengthy and complex manufacturing process. The war in Ukraine, in particular, has raised concerns about the continued availability of inert gases such as neon, which are required in semiconductor lithography processes and of which Ukraine is a major source[23]. Technology analysts at Goldman Sachs[24], however, point out that neon is used only in the relatively older deep ultraviolet (DUV) lithography, and not in the leading-edge extreme ultraviolet (EUV) lithography machines. And while a protracted conflict may eventually endanger supplies, semiconductor producers have built up stocks and diversified their sources of neon in response to past supply shocks[25].

Step 2: research and development (R&D)

Research and development informs the design activities of fabless firms and IDMs. Key organisations in this sector are based in Europe (e.g. IMEC in Belgium, CEA-Leti in France and Fraunhofer in Germany) and the US (e.g. SEMATECH and the Semiconductor Research Corporation)[26]. Fraunhofer, in particular, is widely recognised as the world's best organisation in applied research relevant to the semiconductor industry[27]. IMEC, on the other hand, is a unique institution bringing together competing stakeholders from the entire global value chain to collaborate on pre-competitive research. Under the 'CHIPS for America' Act, the US is set to establish a new National Semiconductor Technology Center (NSTC) as a public-private consortium which – according to analysts – should take IMEC as a point of reference[28].

Top corporate R&D spenders include Intel, Samsung, Broadcom, Qualcomm, NVIDIA, TSMC, MediaTek, Micron, SK Hynix and AMD[29], and the sums invested in R&D have been growing steadily in recent years: in 2021, Intel spent over $15 billion in its efforts to launch new generations of logic chips and to establish itself as a major provider of advanced foundry services, while Samsung – one of the main players in the field of memory chips – spent $6.5 billion to boost its research on leading-edge (< 5nm) logic chips[30]. US companies are by far the largest investors in R&D, both in absolute terms and as a percentage of the value of semiconductor sales: the US private sector invests 23 times more than the federal government in direct semiconductor research[31]. In terms of R&D expenditure as a percentage of revenues, the global semiconductor industry is comparable only to the pharmaceuticals and biotechnology sector[32]. R&D cycles can also be very long, sometimes extending beyond ten years, and often without immediate returns on investments. For example, ASML spent 17 years (and about $7 billion) in the development of its technology for EUV lithography[33].

Semiconductor R&D expenditures as a percentage of sales



Data: Semiconductor Industry Association[34]

Step 3: production

As discussed above, microchip production comprises three separate stages, which can be either vertically integrated (in the case of IDMs) or performed by different companies in the fabless-foundry model.

1. Design – The ten top-ranking fabless design firms in 2021[35] were based almost exclusively in the US (e.g. Qualcomm, Broadcom, NVIDIA, AMD) and Taiwan (e.g. MediaTek, Realtek, Novatek). The British company Dialog Semiconductor had a spot in the top ten in 2020, but lost it to the Taiwanese Himax in 2021. Chinese fabless companies are just behind Taiwan, with a market share of 15% in 2019. Huawei's chip design subsidiary HiSilicon would be among the top five globally, if it were a publicly traded company[36]. Increasing demand for faster technology, such as 5G, is a major driver of fabless market growth.

2. Manufacturing – The ten top-ranking foundries in 2021[37] include companies based in Taiwan (TSMC, UMC), South Korea (Samsung), USA (GlobalFoundries), China (SMIC, Hua Hong, Nexchip), Israel (Tower, recently acquired by Intel in its effort to expand into the foundry business). But this is only part of the picture, because equipment producers also play a major role and can represent a critical chokepoint in the supply chain – particularly for China, whose access to state-of-the-art equipment has been severed by countries that are aligned with the US. For instance, the Dutch company ASML holds a monopoly in the production of extreme ultraviolet (EUV) lithography machines, which are sold to giants such as TSMC, Samsung and Intel for the manufacture of the most advanced chips (such as the ones that TSMC produces for the latest Apple iPhones[38]). Following pressure from the Trump administration in 2018, the Dutch government revoked ASML's licence for the export of its most advanced equipment to China[39]. In 2022, ASML reported a possible case of intellectual property infringement by a rival Chinese 'little giant'. A spokesperson for ASML clarified that the IP involved concerned optical proximity correction (OPC) software, and not the company's core lithography technology[40]. Nevertheless, access to this software could significantly expedite China's efforts to develop its own EUV lithography capacity[41]. The wafer-cutting industry, on the other hand, seems to be fairly segmented: while Japan and the US are clear industry leaders, other important players include, for example, the German company Logomatic[42].

3. Assembly, testing and packaging (ATP) – Top-ranking Outsourced Semiconductor Assembly and Testing firms (OSATs) in 2021[43] were based in Taiwan (e.g. ASE, Siliconware Precision Industries, Powertech), USA (Amkor) and China (JCET). This stage is the most labour-intensive and requires fewer technical skills, so factories are often based in low-wage markets including the Phillippines, Malaysia, Vietnam, China etc.

As discussed, IDMs integrate the entire process in-house, at least for some of their semiconductor production. Notable IDMs are based mainly in the US (e.g. Intel, Micron, and Texas Instruments), South Korea (Samsung and SK Hynix) and Japan (Toshiba). Smaller IDMs based in Europe include STMicroelectronics (France-Italy), Infineon (Germany) and NXP (Netherlands), but Europe accounts for only 7% of the IDM market[44].

Step 4: distribution

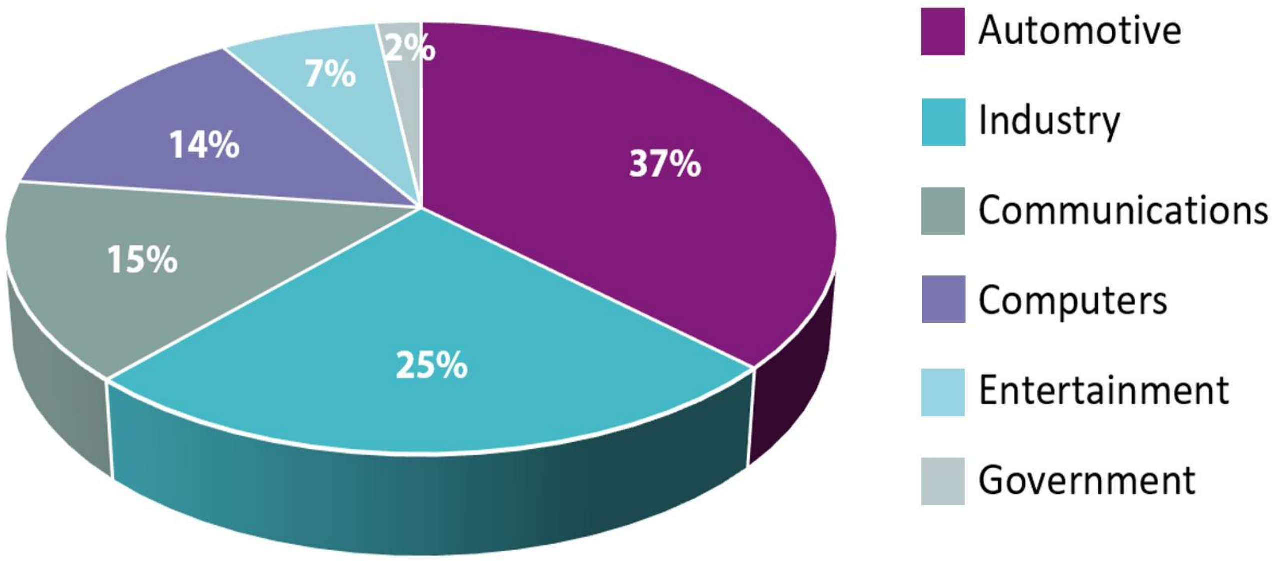
Electronic Manufacturing Services (EMS) companies test, manufacture, distribute, and provide return/repair services for electronic components for the original equipment manufacturers (OEMs). Seventy-five percent of the global EMS market is held by Taiwanese companies. North America holds the second highest market share at 35.3 percent. Foxconn (Taiwan) is the leading EMS provider in the world, accounting for more than 50 percent of revenue. Chip manufacturers sell their products either directly to consumers (e.g. Intel, Samsung, Apple) or to other companies (e.g. TSMC).

EUROPE'S POSITION IN THE SEMICONDUCTOR ECOSYSTEM

According to the European Semiconductor Industry Association (ESIA), the European semiconductor market reached a volume of $47.8 billion in 2021, marking a 27.3% increase compared to the previous year, and accounting for 8.6% of the global market. European demand for semiconductors is driven mostly by the automotive sector (37 percent of the market)[45], followed by industrial consumption at 25%. This is in contrast with the American and Chinese markets, where computers and communications are the main categories of end uses. European chipmakers such as Infineon and NXP are among the top suppliers of the 'mature nodes' used by the automotive industry, due to their high levels of domain expertise, close connections with European carmakers, and vertical integration[46]. These companies often follow a 'fab-lite' approach, meaning that they also rely on foreign foundries such as TSMC, Global Foundries and Samsung for part of their production lines.

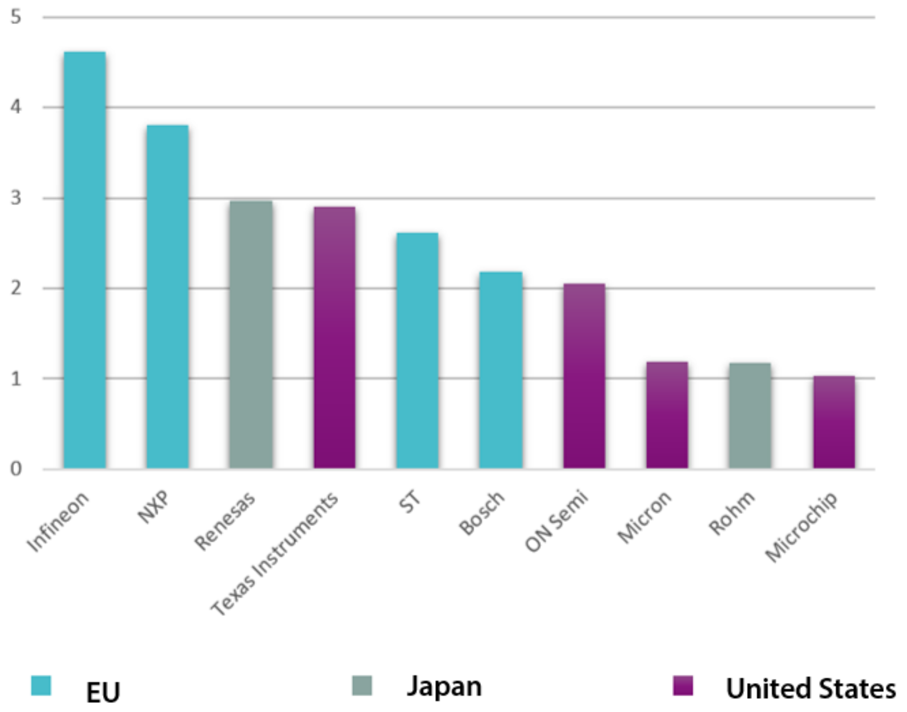
According to analysts' projections, the demand for leading-edge chips in Europe is expected to increase over the coming decade, and to account for the large majority of increased semiconductor consumption. However, Europe's share of global leading-edge chip consumption is actually projected to decrease from 15 to 14 percent[47].

Shares of EU semiconductor market by end use, 2019



Data: ZVEI[48]

Top ten automotive semiconductor suppliers, 2020



Data: Strategy Analytics[49]

Two decades ago Europe was a leading producer of semiconductors, accounting for nearly 25 percent of the world's manufacturing capacity, and 19 percent in particular for leading-edge technology. Today those percentages have dropped to 8 percent and zero percent respectively, according to a recent report by Kearney[50]. The reasons for Europe's decline are (1) a general decline of its original equipment manufacturers (OEMs) of consumer electronics, in particular mobile phones; and (2) the emergence of the fabless-foundry business model, driven by increasing costs and complexity of leading-edge semiconductor manufacturing and the incentives offered by certain Asian governments (e.g. Taiwan) to offset these costs.

On the other hand, the same analysts also emphasise that Europe could count on significant strengths to relaunch its semiconductor industry. In their line of argument, the key to Europe's success would lie in combining advanced engineering (research and design) with manufacturing (equipment and fabrication), by leveraging strategic assets which Europe already holds in the semiconductor value chain: leaders in semiconductor manufacturing equipment (SME), top R&D capabilities, a stable political environment, excellent infrastructure (for example, stable power grids) and the necessary financial capabilities.

Other analysts argue that Europe ought to focus its efforts on the fabless design sector, pointing out that the lack of leading-edge foundry capacity in Europe is mainly due to a lack of demand. Without strong chip design capabilities upstream, an EU foundry would not have sufficient domestic demand to operate at a sufficiently high rate to amortise equipment costs, especially when faced with increased manufacturing capacity in the US and Taiwan[51].

Weighing both sides of this argument points to the idea that ***the future of leading-edge semiconductor manufacturing in the EU hinges largely on Europe's capacity to develop the high-tech industrial sectors*** which can absorb this kind of chip supply. While the EU lacks major smartphone or computer producers, the European semiconductor industry could instead work ***in synergy with other industrial sectors in which Europe holds some competitive advantage***, such as the automotive industry, healthcare, aerospace or robotics[52]. In this light, the key question for the EU will be whether the creation of leading-edge manufacturing capacity in Europe can lead to the kind of positive externalities which would foster the emergence of a regional high-tech ecosystem comprising all the key stages of the value chain (from research and innovation to fabless design and back-end manufacturing), and such as to justify large-scale public investment in this sector.

A niche market: semiconductors in the defence industry

US Army soldier launching a Switchblade 300 drone

Semiconductors play a crucial role in modern warfare – not only in cutting-edge applications such as artificial intelligence, cybersecurity and hypersonic guidance systems, but also for more mundane applications such as sensors and communications. While the defence industry relies heavily on commercially available semiconductors, it also also has specific requirements for reliable high-performance chips with higher durability, heat tolerance, and even radiation tolerance. Such military-grade microchips are often based on gallium compounds (particularly gallium arsenide, or GaAs), rather than silicon. US firms Skywords and Qorvo account for over half of the GaAs semiconductor market, but over 90 percent of such chips are manufactured by Taiwanese foundries[53]. Many of the top suppliers of military and aerospace semiconductors in general, such as Infineon (Germany) or Xilinx (US), have outsourced their production to foundries based in Taiwan, for reasons of cost-effectiveness.

Military demand for semiconductors represents simply too small a portion of global demand to affect the business choices of the commercial sector. As a result, military contractors have to rely on commercial solutions which are driven exclusively by profitability and are not always in line with the requirements of the defence sector. For example, the US Trusted Foundry Program – launched by the US Department of Defense in 2003 to ensure a domestic production base for military chips – provides only about 2 percent of the semiconductor devices used in US military systems[54]. While there is insufficient data to gauge the full extent of US military reliance on Taiwanese foundries, it is thought to be an important factor behind US government pressures on TSMC to relocate part of its production to the United States[55].

Europe is also home to a large number of military electronics companies, but European defence contractors have often prioritised partnerships with Asian manufacturers such as TSMC and Samsung over firms based in the EU. According to Franz-Stefan Gady, an analyst at the London-based International Institute for Strategic Studies, 'European advanced semiconductor manufacturers produce low-volume niche products with limited military applicability'. According to Gady, it is unlikely that European chipmakers will supply Europe's defence industry over the next two decades, as the cost would be prohibitive, even with strong political backing: 'there is no real market and very little genuine demand from the European defence industry for indigenous European products en masse, despite paying lip service to the concept of strategic autonomy'[56].

With its marginal fabless and foundry capacity, Europe is currently in many ways a second-rate player in the global semiconductor value chain. Nevertheless, Europe plays an important role not only in terms of final consumption (20% in 2019, second only to the US with 25% and China with 24%)[57] but also as a provider of essential inputs. This is most evident in the field of manufacturing equipment. The US is the global leader in terms of equipment revenues, with companies such as Applied Materials (AMAT), Lam Research (LAM) and KLA, but different equipment vendors often specialise in different steps of the fabrication process, and a company such as the Dutch ASML can play a pivotal role by being the only world supplier of EUV lithography machines, as discussed above. However, focusing on ASML alone can be misleading, as it hides the fact that ASML itself relies on critical suppliers: for example, ASML's operations would be impossible without the laser technology provided exclusively by the German company TRUMPF[58]. Europe is also home to key suppliers of materials used by the industry, such as chemicals and wafers (the Munich-based Siltronic, for example, supplies silicon wafers to both Intel and TSMC)[59].

While Europe may not be in a position to capture a significant share of the global semiconductor market, ***the unique role played by some European actors may enable it to exercise forms of 'network power'*** by working both as a critical hub for the flow of information and as a potential chokepoint in the value chain[60].

CONCLUSION

Policy debates in recent years have focused on the vulnerabilities and resilience of global supply chains as a result of the supply shocks caused by the Covid-19 pandemic[61]. Current debates on semiconductor shortages and on the need to secure sufficient supply capacity in this critical market must be read in the same light. At the same time, semiconductor supply chains have specific features which make them unique, and must be addressed accordingly. The semiconductor ecosystem is necessarily globalised and highly interconnected, due to its reliance on massive capital investments, costly and lengthy R&D, the need for large economies of scale, and a high level of specialisation. ***No one country or region can be fully independent or 'sovereign' in its semiconductor supply***, not even those which currently dominate the market.

Approaching the global semiconductor ecosystem through the lens of supply chain dependencies may be misleading. As a net importer of semiconductors, the EU is indeed dependent on foreign players; but it also controls some crucial chokepoints in the supply chain: ASML's role as the sole provider of EUV lithography equipment is perhaps the most notable of these chokepoints, but Europe is also a major supplier of other specialised equipment, chemicals and IP. As such, Europe is a source of dependencies for other actors in the global value chain. This is particularly important insofar as semiconductors have become a key battlefield for US-China geopolitical competition[62], leaving the EU in the very delicate position of having to balance economic and political interests. Managing the supply chain effectively may require international recognition of the fact that ***the semiconductor ecosystem is best viewed as a global commons***, with interdependencies built into it almost by design.

These interdependencies need to be managed actively and intelligently, in cooperation with global partners, and with a sharp eye on shifting geopolitical dynamics in order to avoid interdependencies turning into vulnerabilities. Equally, diversifying the EU semiconductor ecosystem by branching out from the automotive sector into higher-end technology sectors could help the EU to leverage its research capabilities and further consolidate its position in the global supply chain. This is particularly important in sensitive sectors such as the defence industry, where dependence on foreign suppliers significantly undermines any ambitions to achieve 'strategic autonomy'. Even so, the nature of the semiconductor ecosystem is such that full independence remains unrealistic.

According to 'Moore's Law' – an empirical observation turned into a sort of self-fulfilling prophecy in the semiconductor industry – computing power is expected to double every two years, with increases in miniaturisation and circuit complexity at ever lower costs. Shifting away from the current interconnected and globalised model of the semiconductor ecosystem could stifle long-term innovation, and bring Moore's Law to a premature end. Balancing the needs of innovation with those of resilience will be the main challenge for the years to come.

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