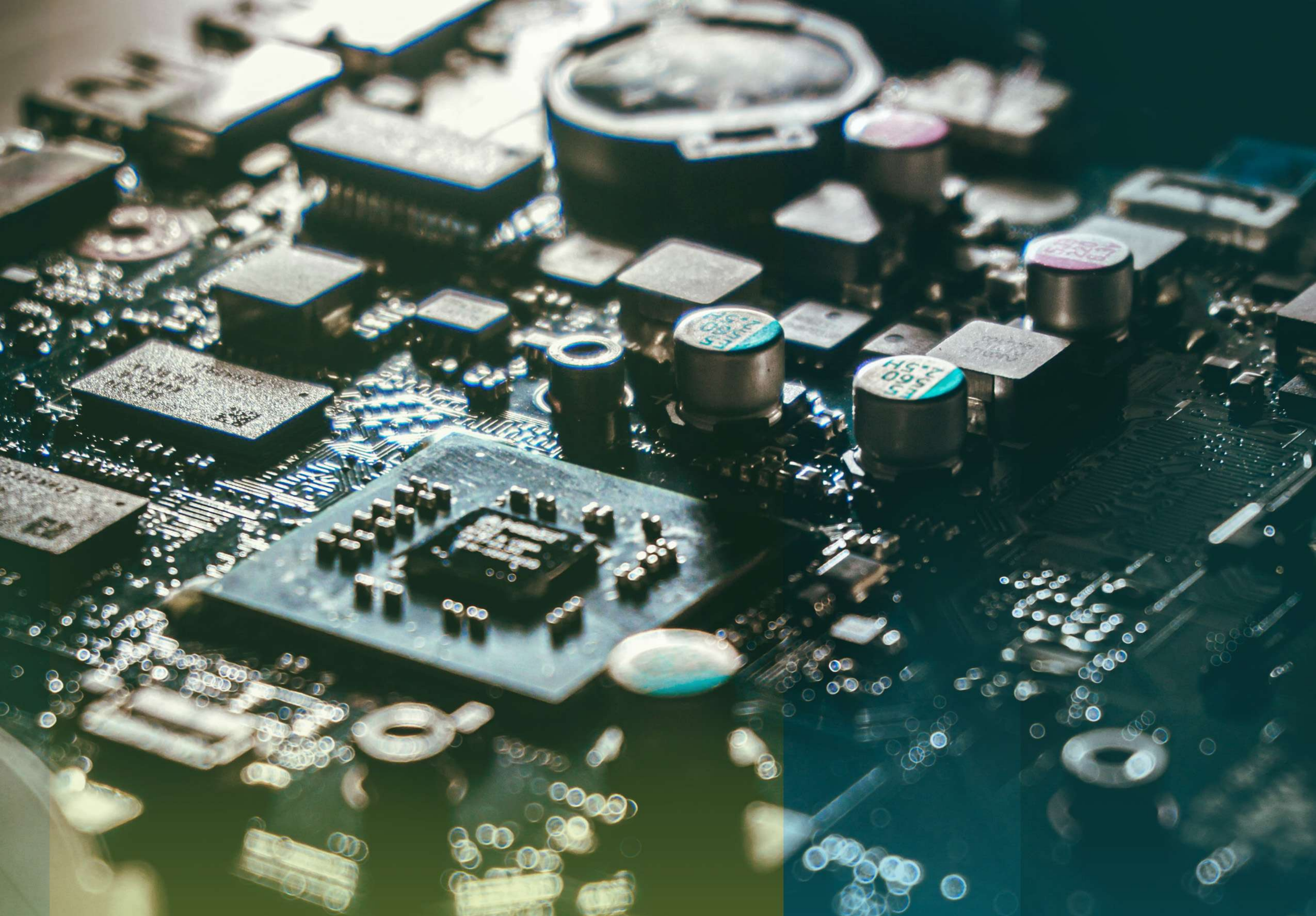

Semiconductor Value Chain:

Structure and Prospects for the New Global Scenario

Agustín Filippo
Carlos Guaipatín
Lucas Navarro
Federico Wyss

March 2022

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Inter-American Development Bank

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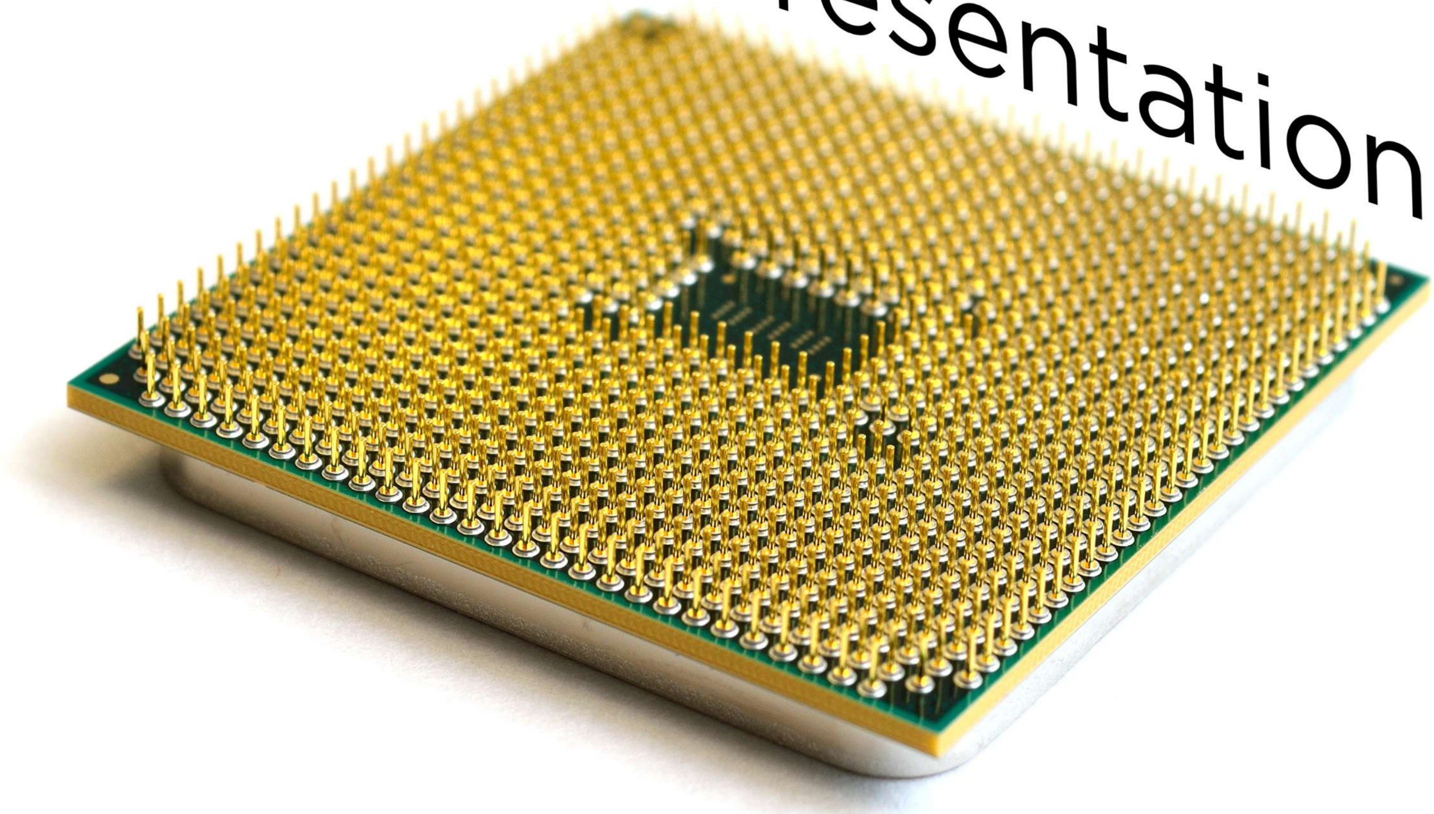


Study Presentation

External factors are causing disruptions in the global semiconductor supply chain, compromising the competitiveness of technology-intensive sectors, some of which, such as the automotive sector, are strategic for the economies of Mexico and the United States. In response, companies in the sector are analyzing the relocation of their links to safeguard their competitiveness, and the governments of the main countries involved in the chain have been announcing substantial incentive mechanisms to attract investment in the sector, treating the issue as one of national security.

The semiconductor chain is composed of segments that demand different levels of availability and investment in capital, R&D and talent. Therefore, supporting its development through public policy implies different strategies depending on the country's position in the chain and its conditions.

Mexico has opportunities to better insert itself into the global semiconductor value chain: geographic proximity to the United States, significant demand from competitive sectors (electronics, automobiles, and medical equipment, among others) and the presence of companies that occupy some strategic segments of the chain. It is a complex, high-stakes game that requires sophisticated coordination at different levels (private-private, public-private and within the public sector), and where, given the growing importance of technology in economies, the discussion is not whether to play or not, but how to do it.[1]

As the first stage of an agenda that will focus on Mexico, this document presents a description of the global semiconductor value chain, the supply problems it currently faces and the policy responses of the main countries in the chain, in order to contribute to understanding its complexity and to provide background information on the links where there is an opportunity for Mexican companies to develop.

The paper is structured in two parts: the first part maps the global semiconductor value chain, while the second presents the current challenges faced by the chain, given the current supply crisis, and the policy responses of the main countries that make up the chain.

[1] Such coordination within the public sector is complex. In the particular case of Mexico, it should take place at the level of the Economy and Finance Secretariats, of INAOE and other offices of CONACYT, the agencies in charge of job training, the federal level and the states interested in receiving investments.

Executive Summary

Executive Summary

PART 1. SEMICONDUCTOR VALUE CHAIN

What is a semiconductor? Definitions, Taxonomy and Target Markets

• Chips or semiconductors refer to small platelets of semiconductor materials (such as silicon) in which circuits are embedded that ultimately end up providing different types of functions for a wide range of electronic devices.

• Semiconductors play a key role both for their influence on recent and future economic growth, enabling technological change, and on the national security of countries, which explains why certain countries want to take significant part in the chain.

• Within semiconductors, integrated circuits (ICs) are the main segment in terms of impact and economic relevance; these circuits are the focus of analysis in this study.

• Although there are several ways of classifying semiconductors, three main groups can be considered:

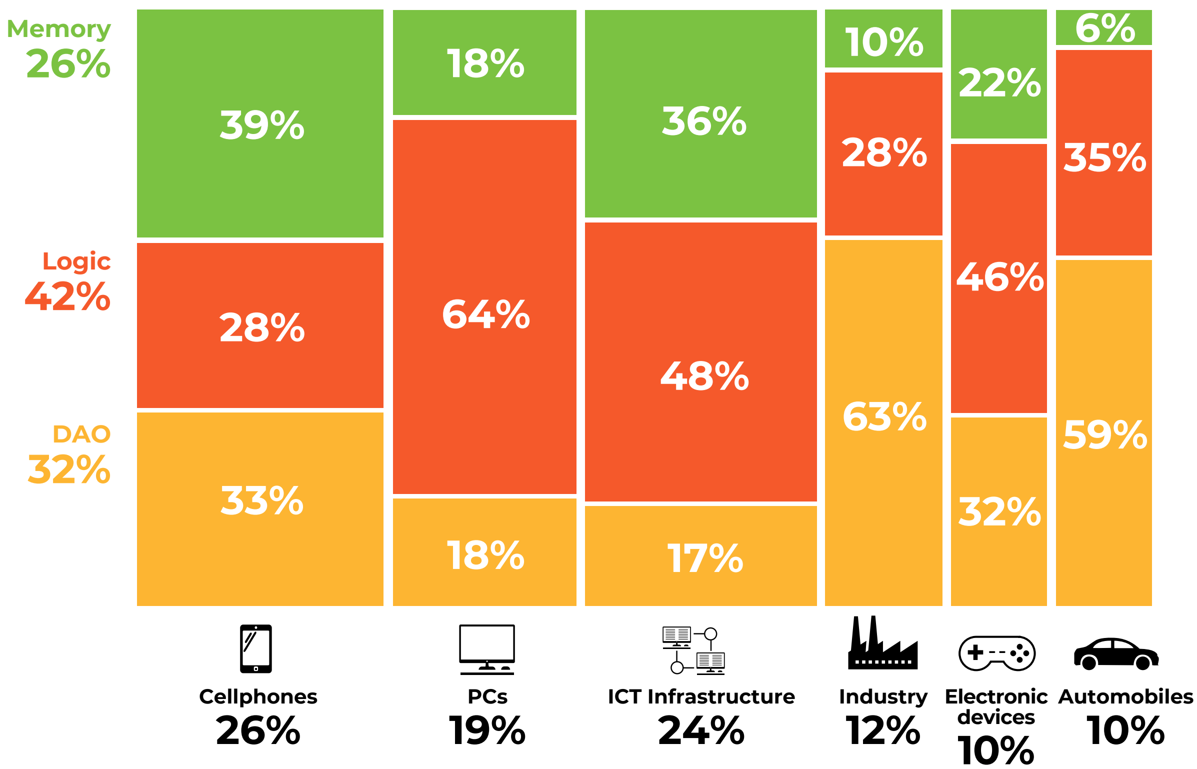
- **Memory devices.** They are digital integrated circuits that store information necessary to perform any computational task. It mainly includes DRAM (short-term memory) and NAND (long-term storage disk).

- **Logic devices.** This group of digital integrated circuits is understood as the "brain" of computers and other devices, they are the processing units of computers and cellphones.

- **Discrete, Analog and Other (DAO).** It groups the remaining semiconductors, associated with less complex technologies than those of digital devices and, therefore, much lower investment levels. They include analog integrated circuits, discrete devices (transistors, diodes), and others such as optoelectronics and sensors, etc.

• The Figure below shows the composition of global semiconductor sales according to the three main types of technologies and target markets, based on figures for 2019, when global sales were USD 412 billion. Logic devices represent 42% of the market, memory devices 26% and DAO have the remaining 32% of the market.

Composition of Semiconductor Sales by Technology and Target Market (2019)



Note: DAO refers to “Discrete, Analog and Other”
Source: Prepared by the authors based on Varas, et al. (2021)

• When considering the market by application, 26% of the chips are destined for cellphones, 19% are in computers, 10% in electronic devices, 10% in automobiles, and the rest of the demand goes to ICT infrastructure, servers and data centers. As seen in the graph, all the applications listed above use, to varying degrees, the three types of semiconductors considered.

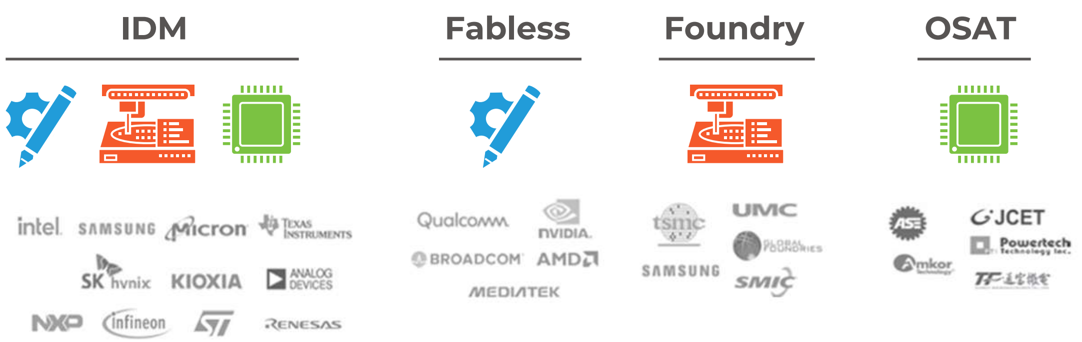
Value Chain and Business Models

• As shown in the Figure below, the semiconductor production process can be summarized in three main parts: Design, Manufacturing (known as Frontend) and Assembly-Testing (known as Backend).

Stages of the Semiconductor Production Process and Business Models

Value Chain Stages

Business Models according to Specialization Activities



Note: The companies listed are for illustrative purposes only, not as an exhaustive list.
Source: Prepared by the authors based on Kleinhans and Baisakova (2020)

• The way these stages are approached defines the business model of the companies, which can carry out the entire process in an integrated manner or specialize in only one of the links.

• Currently, although there are few fully integrated companies left (IDMs, Integrated Device Manufacturers), they are large and together account for approximately two-thirds of global production capacity, with operations distributed in different geographical locations, and more than 70% of sales.

• On the other hand, younger companies have tended to specialize in only one of the links. The Figure above presents examples of IDM companies and in each of the three business models of specialization, which are as follows:

- ***Fabless***, are companies specialized in the design link (knowledge-intensive, with high investment in R&D), which delegate physical production to *Foundries*.

- ***Foundry***, are companies specialized in the manufacturing stage, frontend (capital-intensive, with high physical investment). These companies take designs from *Fabless* or *IDMs* that outsource their manufacturing, so, since they do not have their own designs, they do not participate in the sale to integrators.

- ***OSATs*** (Outsourced Semiconductor Assembly and Test), are companies specialized in the assembly and testing stage, backend (labor-intensive, with lower margins). Like the previous model, they do not participate in the sales statistics. Because they are labor-intensive, they require a significantly lower level of investment, even though the share of capital costs in sales has recently increased.

• The Table below shows R&D and Capex expenditures as a proportion of sales for the different business models. The R&D intensity of the *Fabless* model can be appreciated, while the *Foundries* are more capital-intensive.

Financial Indicators by Business Model (percentage of annual revenues between 2016 and 2019)

Indicator	*IDMs*	*Fabless*	*Foundries*	*OSATs*
R&D	14%	20%	9%	4%
Capex	20%	4%	34%	16%

Source: Prepared by the authors based on Varas, et al. (2021)

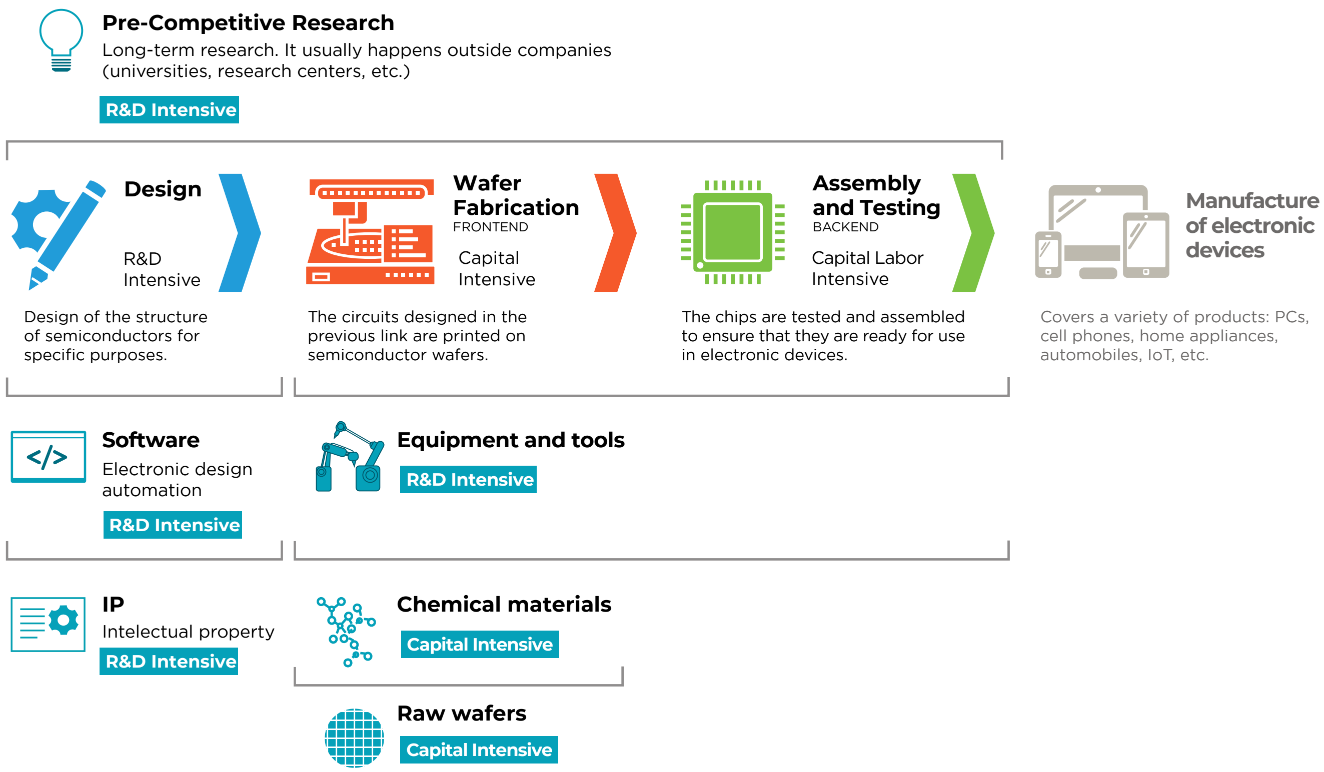
Chain Mapping: Links and Suppliers

• To the three aforementioned links in the semiconductor value chain (design, manufacturing and assembly), a transversal stage can be added, which is the **precompetitive research phase.**

• In turn, there are sectors that supply the links, often almost exclusively. Specifically, the Design link depends on the provision of **Software or Electronic Design Automation (EDA)** and **Intellectual Property (IP).**

• For their part, the fabrication and assembly links require specific **equipment** and **chemical materials**, while the fabrication link specifically demands the **semiconductor material "raw" wafers.**

Semiconductor Value Chain



Source: Prepared by the authors based on Varas, et al. (2021), Kleinhans and Baisakova (2020), and other sources

• The Table below shows what proportion of the industry's R&D and Capex expenditures at the aggregate level is made by each of the segments of the chain.

• The chain has the particularity of investing, on a global basis, almost as much in R&D as in physical capital.

• In line with the data on financial indicators according to the business model already presented, R&D expenditure is mostly in the Design link (with a strong presence of *Fabless*) and the highest expenditure in physical capital is at the Frontend level (where *Foundries* are located).

Estimated R&D and Capital Expenditures by Segment of the Global Semiconductor Value Chain (2019) - in billions of dollars

Indicator	Pre-competitive Research	Design	EDA + IP	Manufacturing (*Frontend*)	Assembling (*Backend*)	Equipment	Materials	Total
R&D	USD **17** *18%*	USD **49** *53%*	USD **3** *3%*	USD **12** *13%*	USD **3** *3%*	USD **8** *9%*	USD **1** *1%*	USD **92** *100%*
Capex		USD **14** *13%*	USD **1** *1%*	USD **69** *64%*	USD **14** *13%*	USD **3** *3%*	USD **6** *6%*	USD **108** *100%*
Value added		USD **145** *50%*	USD **12** *4%*	USD **70** *24%*	USD **17** *6%*	USD **32** *11%*	USD **15** *5%*	USD **290** *100%*

Source: Prepared by the authors based on Varas, et al. (2021)

The Chain from a Geographical Perspective: Specialization and Dependency

• The value chain is highly concentrated in the most sophisticated segments, although it is quite geographically dispersed, with each zone specializing in certain links of the chain according to its comparative advantages.

• Although the most developed countries dominate production, some emerging countries also participate in the chain.

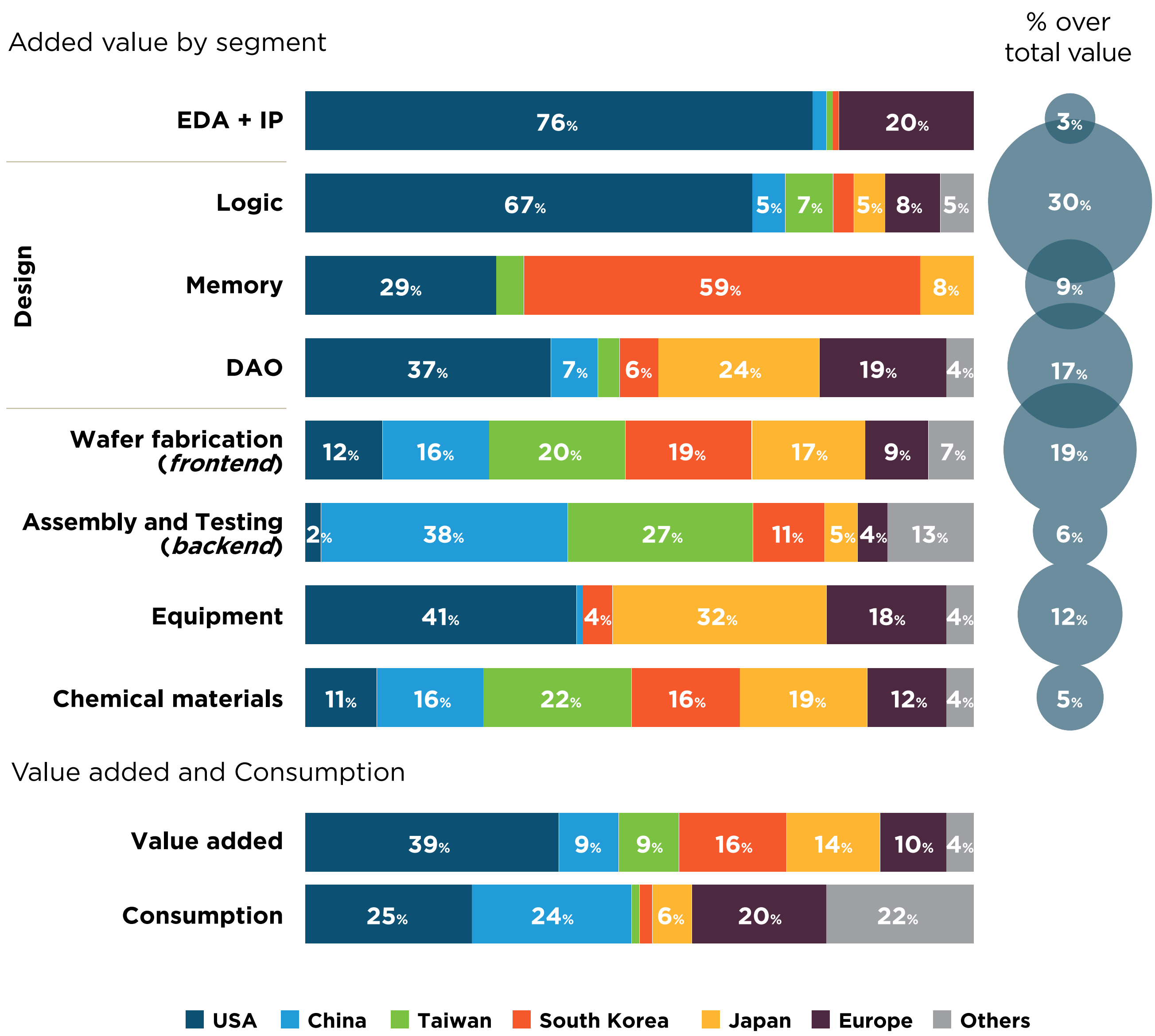
• Given the high geographic specialization by links, no country currently has the capacity for self-sufficiency.

• This feature makes the chain highly collaborative, but also highly exposed to disruptions caused by trade and diplomatic tensions between countries and various exogenous factors, as has been the case since the beginning of the pandemic.

• The Figure below shows the geographic distribution of the industry's global value added, according to the different links that comprise it.

• The United States is clearly dominant, contributing almost 40% of the industry's global value added. This leadership is due to a compositional effect; as can be appreciated in the graph, almost half of the value added in the entire chain is generated in the design stages, where U.S. companies have the largest market share.

Geographic Specialization of the Chain, by Value Added (2019)



Source: Prepared by the authors based on Varas, et al. (2021)

PART 2. CURRENT CHALLENGES AND POLICY RESPONSES

Technologies and Production Strategies in a Complex Sector

• Producing a semiconductor wafer involves repeating five generic steps hundreds of thousands of times. This can take, depending on the complexity of the circuit, between 3 and 5 months of work to have the wafer ready to be cut and sent to the backend link. This complexity defines the "manufacturing standard", also known as "technology node" or "process node".

• The technology node refers to the density of transistors that fit on a chip, which also involves certain design architectures and circuit generations: the smaller the node, the smaller the transistors, but the higher the speed and energy efficiency. This standard is measured in nanometers (one thousandth of a meter) and refers to the minimum size of the chip components.

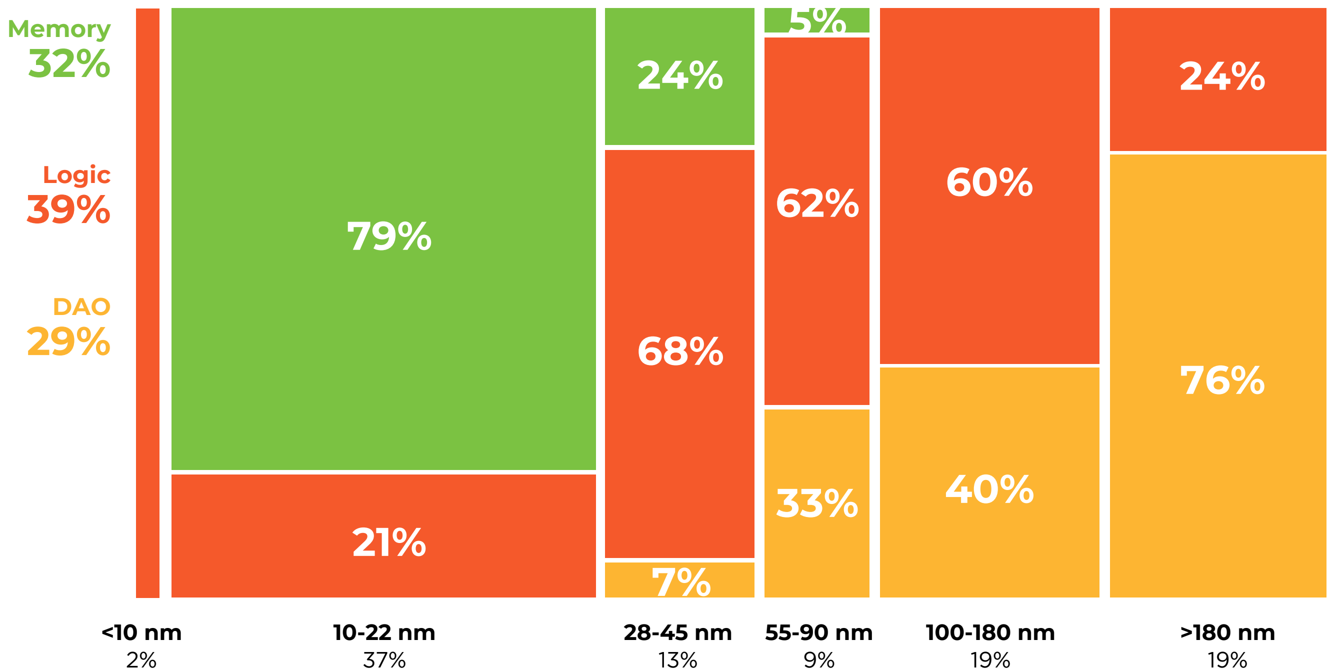
• Moore's Law predicts that the number of transistors on logic chips should double every 2 years or so. This empirical pattern has been fulfilled over time, leading to the fact that the most advanced technology at present is the 3 nm node technology, a standard achieved so far only by the Taiwanese TSMC, but which has not yet been launched on the market.

• This rate of technological advancement means that state-of-the-art production equipment has a useful life of approximately 5 years, in some applications dominated by device performance, before becoming obsolete in the face of the new, more advanced industry standard. On the other hand, there are applications where stability predominates, where technological solutions are more durable.

• In general, equipment designed for frontier production may be technically capable of producing chips of previous standards, but "old" equipment cannot produce frontier chips. This does not imply, however, that it is economically profitable at current prices to produce chips on equipment that is optimized for this purpose.

• The Figure below shows that in 2019 only 2% of the industry's installed capacity is for sub-10nm chips, and that technology is used only in logic devices. Most memory chips, meanwhile, are between 10 and 22 nm. Discrete, Analog and Other (DAO) devices, being less complex, comprise most of the installed capacity for nodes larger than 180 nm.

Installed Production Capacity, by Technology Node and Type of Semiconductor (2019)



Source: Prepared by the authors based on Varas, et al. (2021)

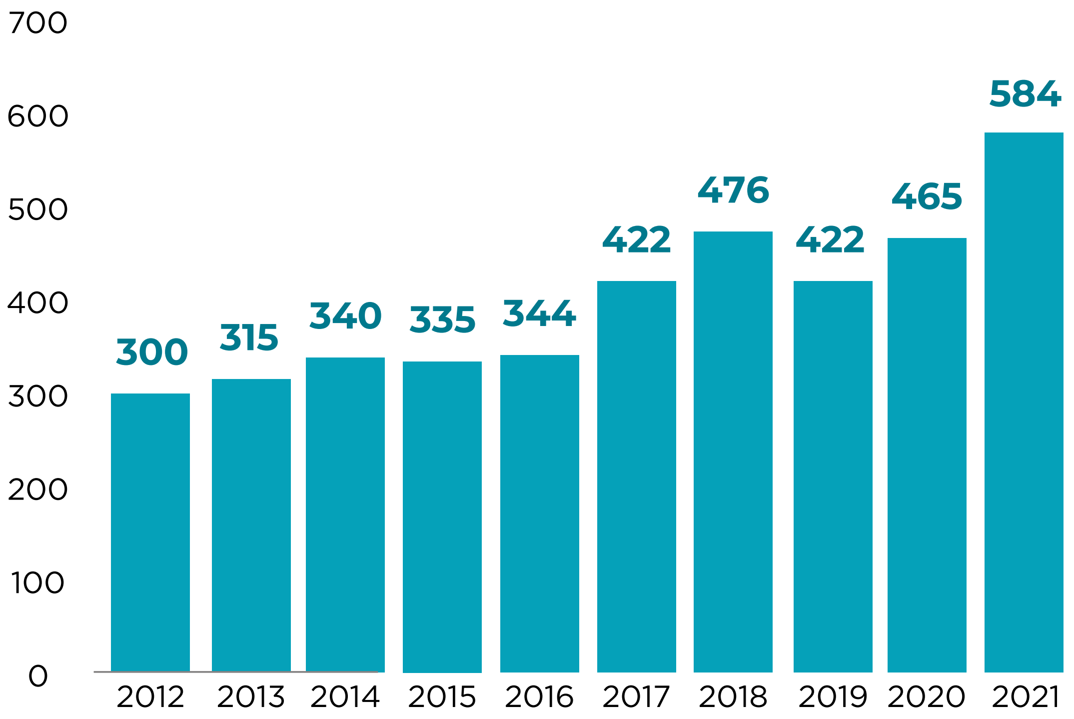
• According to various sources consulted, the current supply crisis appears to be mainly in the 180nm+ nodes, particularly in DAOs, which may indicate that industry production was directed towards other chips, such as logic, which compete with DAOs in the use of capacity for 180nm+ nodes.

Recent Developments and Crisis in a Key Sector

• Along with the massive expansion in the population's access to new technologies, the growth of the semiconductor sector has been remarkable during the last three decades, increasing its relevance to the global economy.

• Between 2012 and 2020, global semiconductor sales increased from USD 300 billion to more than USD 465 billion and had an annual growth of more than 25% in 2021, exceeding USD 583 billion. According to WSTS (2021), the global semiconductor market will grow by 8.8% in 2022.

Global Semiconductor Sales (in billions of dollars)



Source: Prepared by the authors based on Gartner (2022)

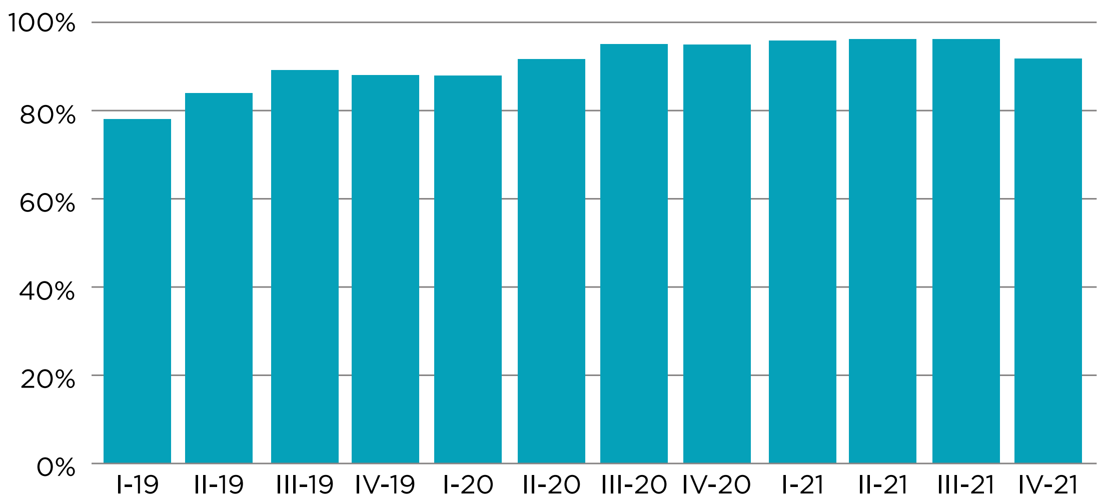
• In the first few months after the onset of the COVID-19 pandemic, the semiconductor sector was affected in supply, as were most sectors of the economy.

• However, solutions that emerged naturally in the face of the confinement caused by the pandemic, such as teleworking and tele-education, boosted global demand for electronic devices, especially personal computers. Contrary to projections, demand for automobiles remained solid.

• Thus, a situation was reached in which demand quickly exceeded the supply response capacity, where the bottleneck was the frontend manufacturing link, which requires large investments with a lead time of no less than two years.

• The sector's **immediate response** was to take its use of installed capacity from values around 80% to values very close to 100%. We see this in the Figure below.

Evolution of Industry Capacity Utilization (2019-2021)



Source: Extracted from SIA (2021)

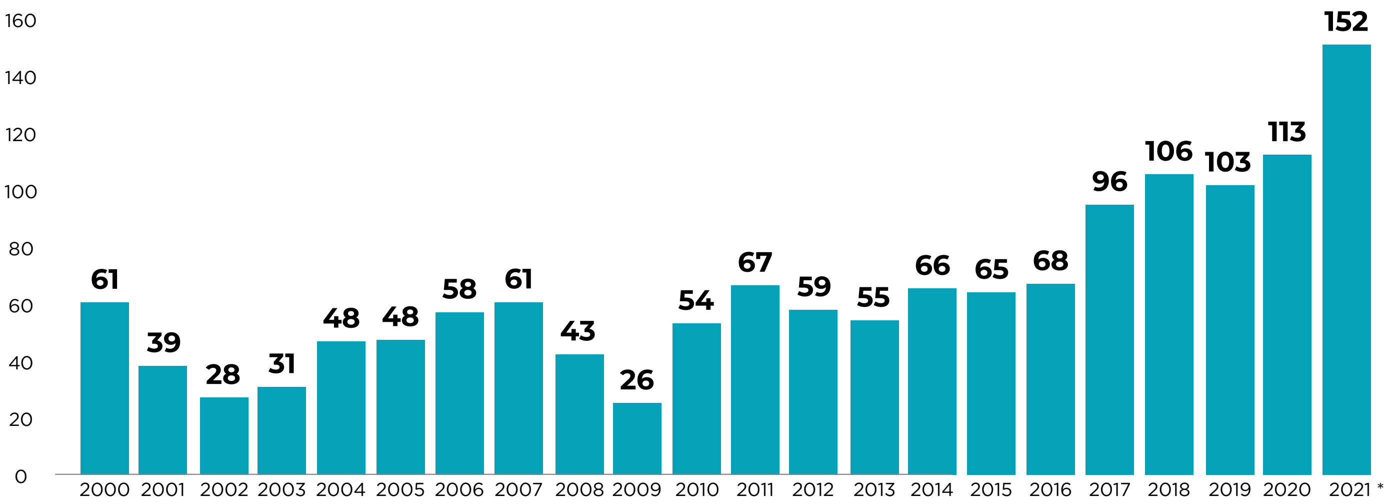
• This increase in installed capacity utilization occurred in parallel with a scenario of contract redefinitions by customers.

• In the early months of the pandemic, automotive companies incorrectly predicted a sharp drop in demand that led them to suspend semiconductor orders. But then, with demand remaining steady, when these companies wanted to recover their quota, it turned out that it had already been reallocated to the IT sectors, which faced a huge growth in demand.

• As a result, the average semiconductor delivery time doubled from 13 weeks before the pandemic to an average of 26 weeks by December 2021.

• In the medium term, the response was to increase investment. As shown in the Figure below, with a 34% increase over the previous year, capital spending by 2021 would have reached USD 152 billion (SIA, 2021), and is projected to be even higher in 2022.

Capital Spending in the Global Semiconductor Industry (in billions of dollars)



*Estimated.
Source: Gartner (2021)

• One aspect that is striking is that, while the shortage appears more marked in semiconductors of larger nodes, the investment announcements by companies and governments are directed towards more advanced standards.

• This suggests a pattern of investment that responds not only to the shortage, but to the break in the structure of demand (towards more technologically advanced components) that has been brought forward by the pandemic.

• In the face of this, the shortage in nodes larger than 180 nm would be solved by a combination of (1) increased supply from existing factories, which today do not deal with these semiconductors but are located nearby, (2) new factories for "large" chips, (3) changes in demand that achieve an adaptation towards generic, less specific and more flexible chips, with greater future supply.

• For governments, semiconductors are not only a key development tool, but also -today more than ever- a matter of national security.

Public Policy Incentives for the Sector

• In recent times, and in reaction to the crisis and geopolitical tensions, all countries or regions relevant to the chain announced fiscal stimulus packages for the manufacturing link.

• With packages of different sizes (see Table below), countries have agreed to provide fiscal incentives (either subsidies and/or tax incentives) to reduce the cost of investments in physical capital in the manufacturing link, but also to try to cover R&D expenditures.

Summary of Announced Policy Responses to the Supply Crisis

Country	Announced Amount (billions)	Horizon	Confirmed Policies	Prioritized Links
China	USD 150	2030	- Equity Participation - Tax Incentives - Land Grants - Subsidized Loans - R&D Subsidies	Frontend and Design
United States	USD 52	2026	The package is not defined at the time of this writing but is defined as a system of "tax credits for investment in semiconductor production equipment and facilities."	Frontend and Design
European Union	~ USD 30	2030	The package is not defined at the time of writing this report, but it is intended to subsidize investments and generate spaces for coordination.	Frontend and Design
South Korea	USD 400*	2030	- Tax deductions for R&D - Subsidized credit - Infrastructure	Frontend and Design
India	USD 10		Investment co-financing	Frontend

* This amount includes private investments by Samsung and SK Hynix in which the government´s participation is only partial.
Source: Prepared by the authors based on various sources

• However, the approach differs considerably from country to country. Thus, while Europe aims at a still integrated and resilient vision of the global value chain, China and the United States have proposals that are strongly conditioned by the prevailing geopolitical tensions, which neglects the aggregate objective of efficiency and the overall health of the chain.

• Finally, some authors are skeptical about the firepower of these packages, especially when compared to the private investments projected by major companies in the coming years, which reach much higher aggregate amounts.

• Additionally, the ability of governments to *direct* investments in the sector in a context of imminent technological disruption is not obvious either, considering the bureaucratic delays in responding to a crisis that has already found its situation privately.

• In short, the policy response to the crisis must be more than a mere reaction to the current situation but must involve an analysis of said situation and future prospects, in order to improve the resilience of the chain and the position of each country in it.

PART 1
Semiconductor Value Chain

Introduction

The semiconductor industry originated in the mid-1950s in the United States (Power and Beyond, 2020), and has become what many authors today call the "backbone" of the global economy (Kleinhans and Baisakova, 2020). Semiconductors are currently the fourth most traded commodity globally and it is expected that, by 2035, the global semiconductor trade volume will be 2.5 times higher than in 2020 (ASE, 2021).

Semiconductors are present in almost any of the devices that shape our daily lives (household appliances, vehicles, computers, cell phones), as well as being indispensable for the implementation of technologies that will lead the growth path of the immediate future (artificial intelligence, Internet of Things, quantum computing, smart cars, etc.).

This relevance has led several countries to treat semiconductors as a strategic product, aiming at the development of production capacity in their territories for some time now. Thus, according to comparative advantages and policy strategies, the semiconductor value chain is one of the most globalized in existence, with the product being able to pass through three continents before being integrated into the electronic device that will be delivered to consumers. This is possible, logically, because of the inherent characteristic of semiconductors to have a high added value per unit size; a circuit of a few square millimeters can sell for thousands of dollars (Varas et al., 2021).

As will be seen below, this globalization was accompanied by an intense process of specialization in the companies' business models, which was combined with a growing concentration in each of the links and supply sectors of the chain.

These three aspects (globalization, specialization and concentration) make the chain vulnerable to climatic or other events, as has been the case since the beginning of the pandemic. The chain is also exposed to political tensions between governments or geographic areas.

These vulnerabilities together with the vertiginous growth in demand for semiconductors globally (for private use, blockchain technology, etc.), led to a strong production shortfall, which is complicating the competitiveness of related industries. Because factory assemblies of this nature can take years to be fully operational, this shortfall is expected to remain at least until the end of 2023.

Faced with events such as those currently affecting the sector, both companies and governments have had to rethink the need to provide the chain with greater adaptability, flexibility and resilience, and even aim to reduce its geographic dispersion.

With a strong automotive and electronics industry, Mexico has been affected by the shortage of semiconductors; according to INEGI the monthly production of cars had in December 2021 a drop of 16.5% compared to December of the previous year and the accumulated production in 2021 had an annual decrease of 2%. Part of this drop is due to the aforementioned supply problems (Banxico, 2021).

In a context marked by the redefinition of the global semiconductor value chain, by a competitive domestic industry in some segments, which coexists with significant local demand from competitive sectors, and by prospects for growth in demand for semiconductors in the medium and long term in the Americas, Mexico could play a stronger role in the chain in the future.

The purpose of this document is to describe the chain and the technologies involved, in order to provide a first overview of the opportunities that Mexico may have to insert itself solidly into the global chain.

This first part of the paper is organized as follows. First, semiconductors are defined and technological variants are explained, together with how they reach the electronic devices that make up modern everyday life. This is followed by an analysis of the business models in force along the chain, and then by a link-by-link mapping of the chain at the global level. The analysis is completed with a geographical overview of the chain and a brief review of the role of the main countries involved.

What Is a Semiconductor?

Chips or semiconductors refer to small platelets of semiconductor materials (such as silicon) in which circuits are embedded that ultimately end up providing different types of functions for a wide range of electronic devices. For this reason, there are several types of semiconductors, which differ according to the function they perform, and the technology used.

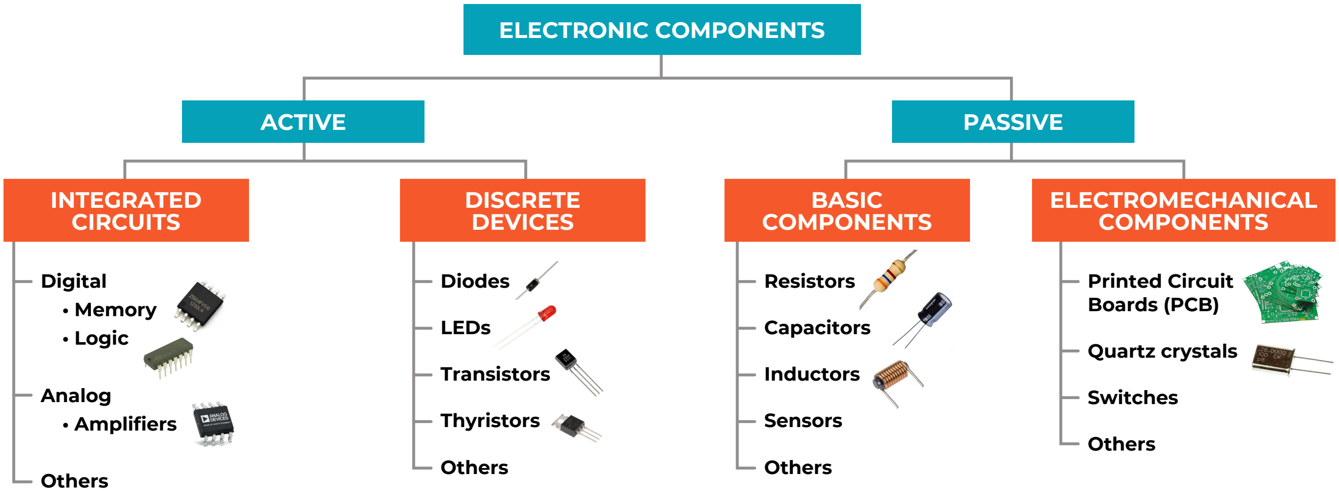
Figure 1 presents a classification of electronic components, according to their capacity to handle electrical energy, into Active and Passive.[2] Passive devices have the characteristic of dissipating or storing energy (strictly speaking, they have no semiconductor capacity, but belong to the chain as components), and are simple products of low relative value, in relation to the segments of the active components.

Active components, on the other hand, do not store energy, but have the characteristic of being able to control the electrical flow. These are subdivided into discrete components, which allow energy input and regulation to a circuit, and integrated circuits, which are the highest value-added semiconductor segment. This category includes digital circuits (including memory and logic/processor devices, which are the industry's main products in terms of added value and economic impact) and analog circuits. Appendix 1 provides more detail on these two segments, which will ultimately be the focus of the analysis in this paper.[3]

[2] It should be noted that this is a simplified and referential classification that serves the purpose of the analysis presented throughout the document. A more technical and detailed classification is beyond the scope of this paper.

[3] In this document, the terms "semiconductor", "chip" or "circuit" will be used interchangeably, even though they are technically different in their definition.

Figure 1. Classification of Electronic Components



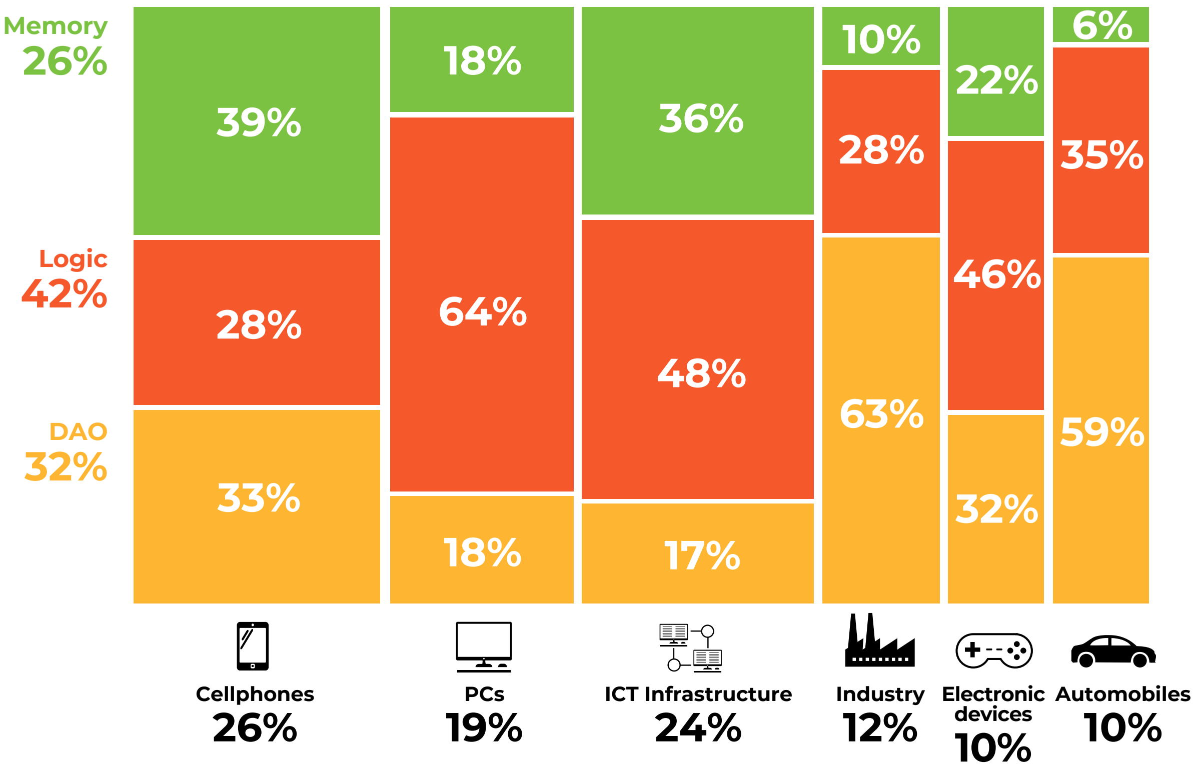
Source: Prepared by the authors based on Varas, et al. (2021), https://blog.mide.com/how-electronic-components-work y http://www.electronicsandyou.com/blog/active-and-passive-electronic-components.html

Figure 2 shows the composition of global semiconductor sales according to the three main types of technologies and target markets, based on figures for 2019, when global sales were USD 412 billion.[4] In the image classification, the focus is on the two main digital technologies (memory and logic), and analog devices are grouped together with discrete devices in a single category (DAO).

Logic devices, with 42% of the market, are understood as the "brain" of a computer and other devices, responsible for executing complex computational actions through the binary processing of instructions stored in memory devices, which represent 26% of the market. With the remaining 32% of the market, discrete, analog and other (DAO) devices, on the other hand, are designed to interact with the physical world: these semiconductors enable a wide range of tasks such as picking up radio signals, charging a cell phone battery, driving an electric motor, and making calls, among many others.

[4] Because they are the most relevant, the analysis of the semiconductor industry concentrates on the active electronic components in Figure 1.

Figure 2. Composition of Semiconductor Sales by Technology and Target Market (2019)



Note: DAO refers to "Discrete, Analog and Other"
Source: Prepared by the authors based on Varas, et al. (2021)

When considering the semiconductor market by application, 26% of the chips are destined for cellphones, 19% are in computers, 10% in electronic devices, 10% in automobiles, and the rest of the demand goes to ICT infrastructure, servers and data centers. As can be appreciated in Figure 2, within each application, there is wide heterogeneity in the distribution of the market according to the three types of technologies. In the case of the automotive industry, for example, DAO are particularly important, representing 59% of the market.

As will be detailed below, in addition to being a complex value chain, the semiconductor industry is highly concentrated on both the supply and demand sides. Ten companies accounted for more than half of global blockchain sales in 2020, including Intel as the leader, followed by major players such as *Taiwan Semiconductor Manufacturing Co.* (TSMC) and *Samsung*, among others (Xignite, 2021). On the demand side, *Apple, Samsung, Huawei, Lenovo* and *Dell* concentrated global semiconductor purchasing in 2020 (Gartner, 2021).[5]

[5] As one of the main suppliers and also demanders, Samsung's case reflects the situation of companies that produce semiconductors for end-consumer devices.

BOX 1. Automotive Semiconductors

Chips for the automotive industry are one of the main examples of the "field experience" demanded by certain verticals of the semiconductor chain. It is a vertical that demands digital (mainly logic) and to a greater extent analog circuits, but adapted to the specific tasks demanded by modern vehicles (Figure 2).

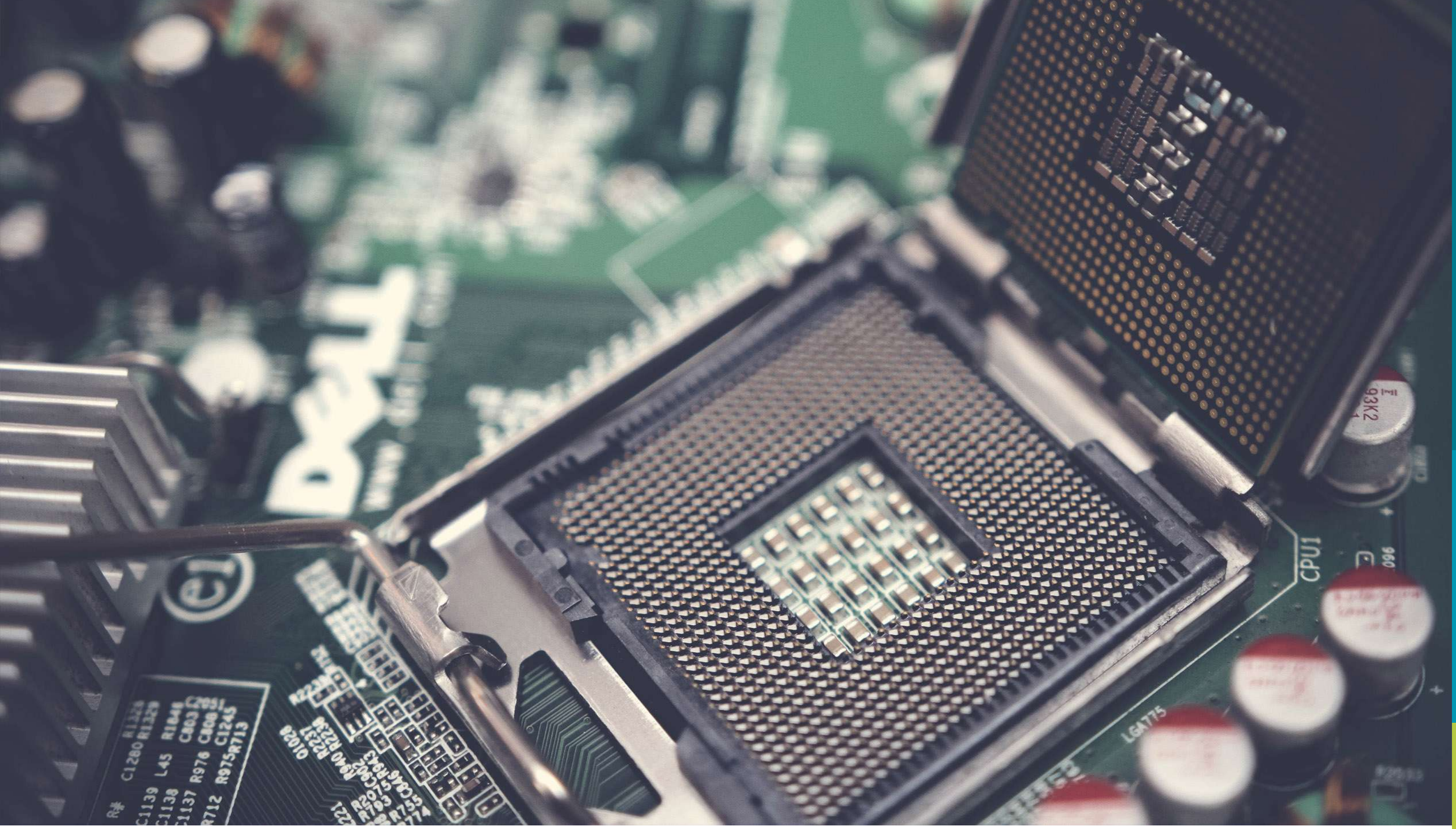
Depending on its complexity, an automobile can use between 500 and 1500 semiconductors, which control virtually every function of the units, from the airbags to the engine (ASE, 2021). According to McKinsey (2017) the global demand for semiconductors in automobiles is allocated to body (24%), safety (24%), driving information (22%), engine (21%) and chassis (10%).

The case of motor vehicles demands specificities such as resistance to a wide range of temperatures and physical conditions of the environment. At the same time, this is a sector that is somewhat reluctant to change, both in terms of technology and suppliers.

Five companies (*Infineon*, *NXP*, and *ST Micro* from Europe, *Renesas* from Japan, and *Texas Instruments* from the United States) supply half of the world market demand, with *Infineon* leading with more than 13% of the global market share in 2019 and 2020 (Infineon, 2021). The global market volume in 2020 was about USD 35 billion.

The use of electronic components in automobiles grew exponentially over time; in 1970 they represented only 5% of the value of an automobile, while in 2020 they rose to 35%. On the other hand, this also increases the need for repair capabilities and qualifications; returns to factories of cars due to electronic component failures increased from 5% to half of the cases between 2011 and 2019 (Infineon, 2021).[a]

[a] The average value of the semiconductor content varies according to the type of car; according to Infineon (2016) such value amounts to USD 352 in units with internal combustion engines, while in hybrid and electric cars it is USD 712 and 704, respectively.



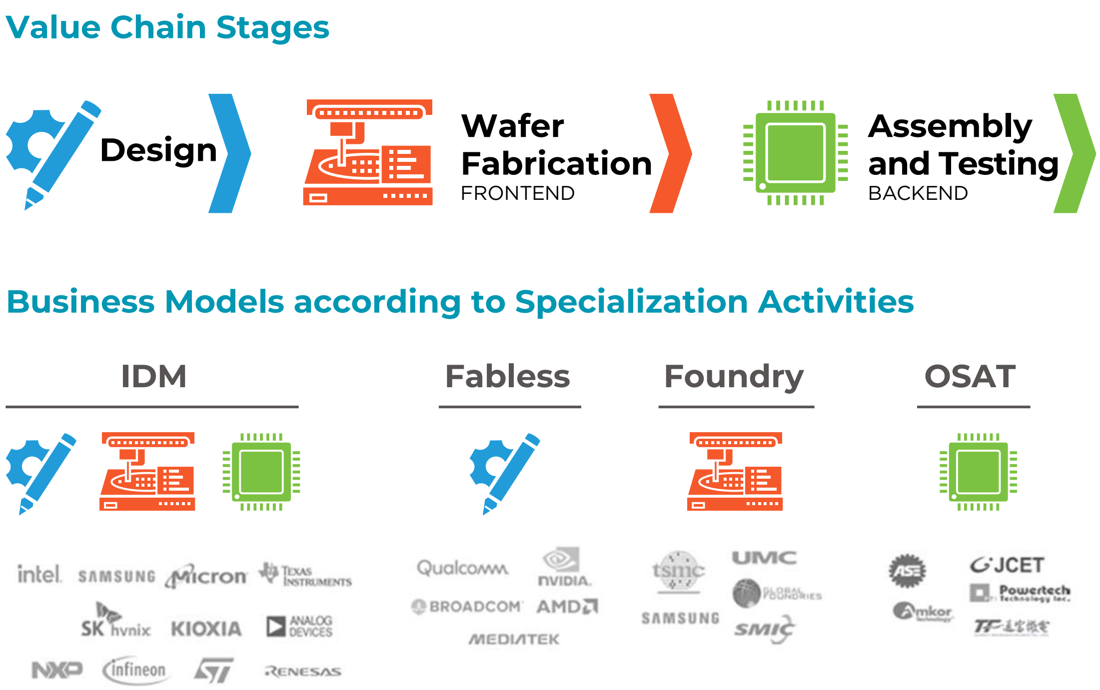
Value Chain and Business Models

Although the production of a chip can involve a large number of specialized companies in more than 1,000 stages and 70 border crossings,[6] the production process of a semiconductor can be summarized in three main parts: design, manufacturing and assembly (Figure 3).

The way these stages are approached defines the business model of the companies, which can carry out the entire process in an integrated manner or specialize in only one of the links. The growth in the technological complexity of the process led the chain to advance from an almost completely integrated model at the beginning in the 1960s to one of specialization at present. Faced with this, integrated firms began to adopt a hybrid model whereby they delegate part of their production process to specialized companies.

[6] See https://expansion.mx/empresas/2021/04/15/mexico-produccion-semiconductores-autos

Figure 3. Stages of the Semiconductor Production Process and Business Models



Note: The companies listed are for illustrative purposes only, not as an exhaustive list.
Source: Prepared by the authors based on Kleinhans and Baisakova (2020)

Currently, although there are few fully integrated companies left (*IDMs, Integrated Device Manufacturers*), they are large and together account for approximately two-thirds of global production capacity, with operations distributed in different geographical locations. Indeed, the global semiconductor chain is geographically distributed according to the comparative advantages of the territories.[7]

On the other hand, younger companies have tended to specialize in only one of the links. Figure 3 above presents examples of IDM companies and in each of the three business models of specialization, which are as follows:

- **Fabless**, are companies specialized in the design link (knowledge-intensive, with high investment in R&D), which delegate physical production to *Foundries*.
- **Foundry**, are companies specialized in the manufacturing stage, frontend (capital-intensive, with high physical investment). These companies take designs from *Fabless*

[7] As it will be discussed in Part 2 of the document, this high geographic dispersion of the chain generated supply difficulties in the face of the increase in demand that occurred from the beginning of the pandemic.

or *IDMs* that outsource their manufacturing, so, since they do not have their own designs, they do not participate in the sale to integrators.

- **OSAT** (*Outsourced Semiconductor Assembly and Test*), are companies specialized in the assembly and testing stage, backend (labor-intensive, with lower margins). Like the previous model, they do not participate in the sales statistics. Because they are labor-intensive, they require a significantly lower level of investment, despite the fact that the share of capital costs in sales has recently increased.

Table 1 shows R&D and physical capital expenditures as a percentage of sales for each business model. The knowledge intensity of the *Fabless* model, which devotes 20% of its revenues to research and development, can be appreciated, in contrast to the low capital expenditure in this model, which is in the order of 4% of revenues. R&D spending is also relevant for the integrated model (14%), which by its nature must also allocate a significant proportion of revenues to capital expenditures (20%).

Table 1. Financial Indicators by Business Model (percentage of annual revenues between 2016 and 2019)

Indicator	*IDMs*	*Fabless*	*Foundries*	*OSATs*
R&D	14%	20%	9%	4%
Capex	20%	4%	34%	16%

Source: Prepared by the authors based on Varas, et al. (2021)

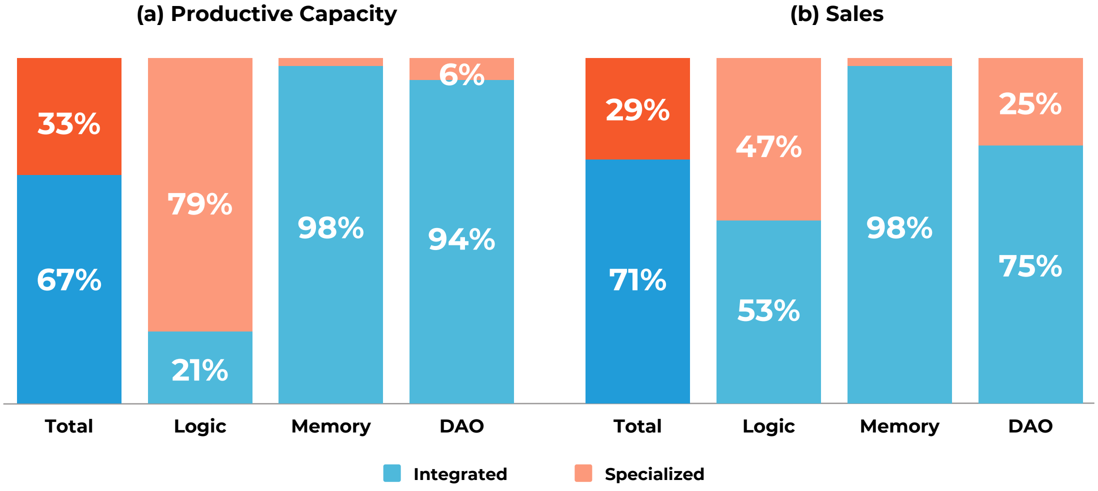
Meanwhile, for companies dedicated entirely to chip manufacturing (*Foundries*), capital expenditure amounts to 34% of revenues, with 9% of revenues also devoted to R&D for process improvement at the cutting edge. Finally, companies dedicated to the final link (*OSATs*), where labor acquires a greater relative importance with respect to the rest, have a relatively low expenditure on R&D (4% of revenues) although a higher expenditure on capital (16% of revenues).

As mentioned above, IDM firms are few, but they have a strong presence in the market since, in general, they have the longest history in semiconductor manufacturing. Thus, Figure 4 shows that IDMs account for 67% of the industry's productive capacity and 71% of sales. This means that not only is their market position dominant, but they also play a fundamental role in the production of semiconductors, which places them in a central position considering the current situation of excess demand (and insufficient response capacity on the supply side) that the chain is going through, as discussed in Part 2 of this document.

When considering the three main types of technologies described in the previous section, Figure 5 shows that integrated companies dominate mainly in the memory circuit segment (*Samsung, Micron, SK Hynix, Intel, Kioxia* are the main ones) with 98% of installed capacity and sales, as well as in discrete and analog devices (this is a relatively less relevant segment, dominated by integrated companies such as *Texas Instruments, Analog Devices, Infineon*, with 94% of production capacity and 75% of sales.

In turn, specialized models are gaining presence in the segment of logic devices or processing units in general, a direct consequence of the evolution of the business model of some IDMs, which first divested their manufacturing units and then strengthened their supply of these components through offshoring operations which, in turn, led to the growth of specialized companies - mainly in Asia. Figure 4 shows that specialized companies have almost 80% of production capacity, but 47% of sales. This difference between share in sales and production capacity can be explained precisely by the outsourcing of production by integrated companies, such as *Intel*, which is one of the main players in this segment (with products such as units for computers and servers) and still retains production capacity, with ambitious expansion plans, and which competes strongly in sales with the specialized AMD (*Fabless*), once an integrated company but which has completely divested its production units (taken over by *GlobalFoundries*).

Figure 4. Share of Business Models by Technology Segment, percentages of total industry (2019)

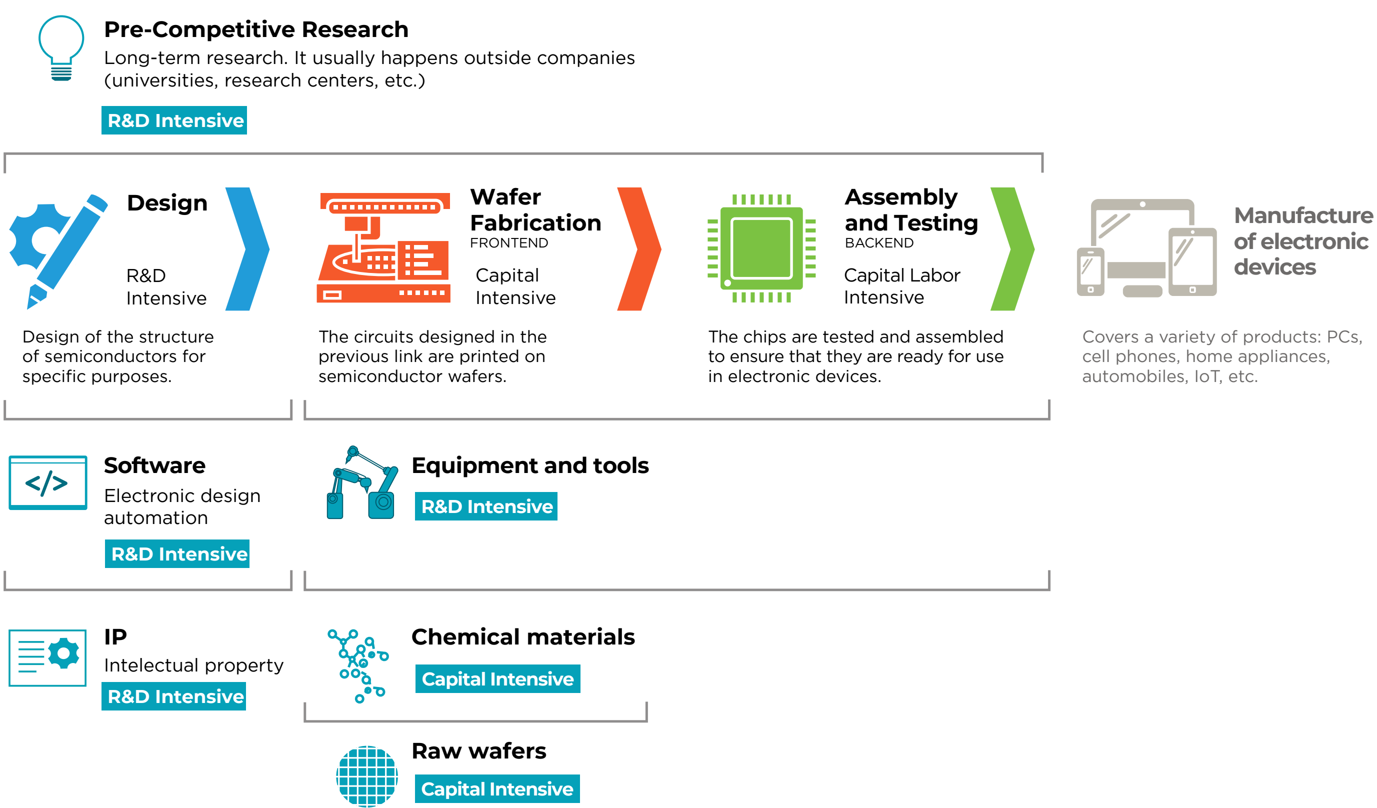


Note: DAO refers to “Discrete, Analog and Other”.
Source: Adapted from Varas, et al. (2021)

Chain Mapping: Links and Suppliers

To the three aforementioned links in the semiconductor value chain (design, manufacturing and assembly), a transversal stage can be added, which is the pre-competitive research phase. In turn, there are sectors that supply the links, often almost exclusively. Specifically, as shown in Figure 5, the Design link depends on the provision of Software or Electronic Design Automation (EDA) and Intellectual Property (IP). For their part, the fabrication and assembly links require specific equipment and chemical materials, while the fabrication link specifically demands the semiconductor material "raw" wafers.

Figure 5. Semiconductor Value Chain



Source: Prepared by the authors based on Varas, et al. (2021), Kleinhans and Baisakova (2020), and other sources

Table 2 shows the share of total R&D and physical capital (Capex) spending by each segment of the semiconductor value chain out of the total spent in 2019. Among the most noteworthy aspects of the table is that of the industry's total R&D expenditure, which in 2019 was USD 92 billion, 71% is made in the precompetitive research and design stages; in turn, of the chain's total value added of USD 290 billion in the reference year, half is generated in those stages. For its part, the most capital expenditure (Capex) intensive link is manufacturing frontend, representing 640 of the industry's total Capex of USD 108 billion in 2019. One of the main peculiarities of the chain emerges here, which is that, at the aggregate level, it has an investment in R&D that is almost as high as that demanded in physical capital (facilities and equipment).[8]

Table 2. Estimated R&D and Capital Expenditures by Segment of the Global Semiconductor Value Chain (2019) - in billions of dollars

Indicator	Pre-competitive Research	Design	EDA + IP	Manufacturing (*Frontend*)	Assembling (*Backend*)	Equipment	Materials	Total
R&D	USD 17 *18%*	USD 49 *53%*	USD 3 *3%*	USD 12 *13%*	USD 3 *3%*	USD 8 *9%*	USD 1 *1%*	USD 92 *100%*
Capex		USD 14 *13%*	USD 1 *1%*	USD 69 *64%*	USD 14 *13%*	USD 3 *3%*	USD 6 *6%*	USD 108 *100%*
Value added		USD 145 *50%*	USD 12 *4%*	USD 70 *24%*	USD 17 *6%*	USD 32 *11%*	USD 15 *5%*	USD 290 *100%*

Source: Prepared by the authors based on Varas, et al. (2021)

The following sections provide a brief detailed description of each of these segments.

Pre-Competitive Research

During precompetitive research, the fundamental materials and chemical processes that will lead to innovations in the design process are identified. This research usually culminates in auditable publications and most of the time takes place outside companies, in places such as research centers and universities. Therefore, this is one of the links where governments have greater policy interference, through various instruments that include direct funding of research or its development in public organizations, which will be analyzed in the second part of this document. Varas et al. (2021) indicate that R&D investment in this segment could account for 15%-20% of total R&D expenditure in the global R&D chain.

[8] It is worth mentioning that a large portion of R&D expenditures are made in the precompetitive research phase, where government disbursements play a central role (Varas, et al., 2021).

It is not a process that replaces or displaces the R&D processes that take place in the Design link, but rather it is a necessary complement that, by its nature, cannot occur within the product cycles of the aforementioned step. According to Varas et al. (2021), the average time for a precompetitive discovery to reach the productive phase of the chain is around ten to fifteen years, and in reality, it could be even longer, depending on the complexity of the proposal or innovation.

Design

In a context of strong technological growth, designing state-of-the-art semiconductors is expensive; Kleinhans and Baisakova (2020) note that designing a chip with 10-nanometer (nm) nodes cost approximately USD 170 million in 2016, and designing a more complex 5-nm node chip cost more than USD 540 million in 2020.[9] The increasing complexity of including more and more nodes in smaller and smaller surfaces is a trend consistent with Moore's Law.[10]

Due to the specialization trend in the industry, more and more companies are becoming involved in this link, designing chips for their own activities. Thus, companies such as *Alibaba, Alphabet (Google), Amazon, Apple, Facebook* and *Tesla* are designing their own chips to perform very specific tasks or activities, such as executing artificial intelligence algorithms.

The United States is the leader in the Design stage, followed by Taiwan and China. The ten leading global players in this segment had a turnover of USD 86 billion in 2020 (Trendforce, 2021a), 85% of which was generated by five companies (*Qualcomm, Broadcom, Nvidia, MediaTek* and *AMD*).

Fabless companies in the design link must work closely with their partners in the manufacturing link to optimize innovation and production processes. Very early in the development stage of a system, it is decided where and how a given chip will be produced. For this reason, companies in the Design link must work together with their key suppliers: Intellectual Property (IP) and Electronic Design Automation (EDA) companies.

[9] According to the industry standard, each generation of the semiconductor manufacturing process, also known as a technology node or process node, is designated by the minimum size of the process characteristic. Nodes are typically indicated by the size in nanometers (nm) of the gate length of the process transistor. The nanometers used to name process nodes has become a "marketing term" that has no relation to the actual feature size or transistor density (number of transistors per square millimeter). For more details, see https://hmong.es/wiki/Semiconductor_node.

[10] Moore's Law arises from an empirical assessment/prediction made by Intel co-founder Gordon Moore in 1965, which states that approximately every two years the number of transistors in an integrated circuit doubles, increasing the complexity of the production process in the semiconductor market. This prediction has been empirically supported up to the present day, but some references argue that it could come to an end, although not immediately, due to the physical impossibility of continuing to increase the number of transistors. This would lead to a change in the way of conceiving the expansion of this sector, based on new technologies.

As shown in Table 2, 53% of the industry's R&D expenditure is made in this design link and half of the value added is generated.

Software: Electronic Design Automation (EDA)

Electronic Design Automation, or EDA, is a market segment comprised of software, hardware and services with the collective goal of assisting in the definition, planning, design, implementation, verification and subsequent manufacturing of semiconductor devices or chips.[11]

The main activity of EDA companies consists mainly in the provision of highly complex software to the Design link.[12] This software is focused on three main types of objectives:[13]

- **Simulation:** These tools take a proposed circuit and predict its behavior before implementing it.
- **Design:** They take a description of a circuit function and assemble the collection of elements that implement that function. This is both a logical process (assembling and connecting the circuit elements) and a physical process (creating the interconnected geometric shapes that will implement the circuit during manufacturing). These tools are delivered as a combination of fully automated and interactively guided capabilities.
- **Verification:** They are tools that examine the logical or physical representation of the chip to determine if the resulting design is wired correctly and will deliver the required performance.

The EDA segment is highly concentrated and mostly dominated by U.S. companies. In fact, there are three that occupy almost the entire market: *Cadence Design Systems, Synopsys* and *Mentor* (Kleinhans and Baisakova, 2020). This link is the one with the highest relative investment in R&D (30%-40% of its revenues), which is required to sustain the pace of innovation, with increasingly specific needs demanded by the industry, in line with Moore's Law. This feeds back into the segment's concentration process; by way of illustration, in 2010 Synopsys alone acquired more than 46 companies or technologies (Kleinhans and Baisakova, 2020).

[11] See https://www.synopsys.com/glossary/what-is-electronic-design-automation.html

[12] While most EDA products are delivered as software, there are some cases where physical hardware is also used to provide capabilities. Dedicated hardware is typically used when extremely high performance is required. This dramatic increase in speed is usually necessary to complete several tasks in reasonable periods of time (hours or days versus weeks or months).

[13] See https://www.synopsys.com/glossary/what-is-electronic-design-automation.html

Intellectual Property (IP)

In addition to software design (EDA), several supplier companies develop and license intellectual property in semiconductors. These "blocks" or "cores" of intellectual property are essentially a piece of the final semiconductor design (which can mean anything from processor cores to standard processes) that has been previously verified and tested and is ready to be included in the design of a *Fabless* or IDM. These are, then, parts with generic functions that are essential to fulfill the product cycle of devices as complex as modern semiconductors: it is not possible for a single design company to be able to develop in a prudent time and cost all the necessary blocks for the final part.[14]

Typically, IP companies charge their customers a license fee for each product created that contains the component sold. This does not imply, however, that all patents in the industry come from companies specializing in IP. The research, and ultimately the formal control of patents can be vested in companies in various segments of the chain, and it is the bidding for control of these patents that gives rise to an active market where companies that were divisions of other companies, or business units that are transferred between different companies, are created.

Manufacturing (Frontend)

The final chip design is sent to the manufacturing plants (*Foundries*) to start production. Basically, these plants will "print" nanometer-scale circuits on wafers made of silicon or some other semiconductor material. The number of chips on a wafer can vary from one hundred to hundreds of thousands.

Thus, manufacturing will require semiconductor wafers, specific equipment and chemicals. The extremely complex process is carried out in “cleanrooms” that require specific equipment to avoid any contamination through microparticles in the air that may alter the properties of the materials. Depending on the type of technology, there are between 400 and 1,400 steps in the manufacturing process of these chips on wafers, which takes an average of 12 weeks, and can extend up to 20 weeks in more complex processes. Box 2 provides more details on the manufacturing process.

These highly complex processes require quite particular characteristics in the factories, which may imply lead times of at least two years for their full operational start-up, as well as large capital investments. A standard factory with advanced technology can cost between USD 5 billion (analog boards) and USD 20 billion (memory boards), including the value

[14] This characteristic of the production process in the Design link can interfere in the development of certain companies, and that is why it is one of the segments where China is betting heavily, in order to close technological gaps with its North American competitors (Varas et al., 2020).

of land, building and equipment (Varas et al., 2021). For all this, the Manufacturing segment is the most capital-intensive in the chain. The cost of capital[15] of the *Foundries* is around 30%-40% of their annual revenues, absorbing 64% of the chain's total capital expenditure (Table 2).

In turn, in the face of rapid technological change, investments may become "obsolete" (compared to frontier technologies) in 5 years or less from the time they are put into operation.[16] Cycles of technological change often result in differences in production capacities and costs between fabs: While a "frontier" machine can meet the production requirements of "old" products, it is not as common for an "old" machine to be able to cope with the requirements of "new" products. This can lead to differences in production routines, costs and yields, not only between firms, but within firms as well (Mönch, et al. 2017).[17]

Due to comparative advantages, in many cases stimulated by public policies,[18] the *Foundries* are mainly located in East Asia and mainland China. The high investment costs determine, once again, that this is a highly concentrated link, dominated by Taiwan's TSMC, with more than 50% of the market and specialized in 7nm and 5nm technologies, followed far behind by Samsung (Kleinhans and Baisakova, 2020). In the face of the strong increase in semiconductor demand, in 2021 projected sales of the *Foundries* grew 11% and would have reached USD 94.6 billion; 65% of the segment's global revenue was generated in Taiwan, 18% in South Korea and 5% in China (Trendforce, 2021b).

As it will be discussed in Part 2 of this document, given that it is in this link where the greatest bottlenecks to solving the supply crisis affecting the sector are to be found, the main players in the segment are investing heavily in semiconductor plants, supported by major government stimuli, mainly in the United States, China and the EU, which will eventually lead to changes in the geographical distribution of production in the future.

[15] It includes the annualized cost of buildings, land and production equipment.

[16] See https://www.bloomberg.com/graphics/2021-chip-production-why-hard-to-make-semiconductors/

[17] This can affect the final use of the resulting component: for example, in the testing process, it may happen that a microprocessor built for a 4 MHz speed may fail at that speed but work properly at 3 MHz. This particularity makes the material cost structure for a given electronic device well varied, as more advanced devices than required can supply the required functions anyway (Mönch, et al. 2017).

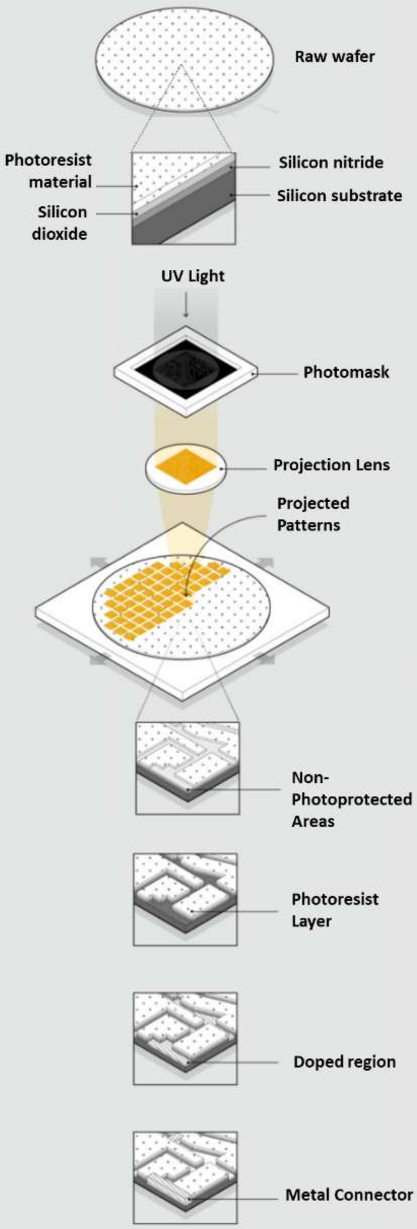
[18] Part 2 of this document provides details on the role of governments in the semiconductor GVC, and Appendix 2 presents guidelines on the main recommendations for an efficient intervention .

BOX 2. How a Semiconductor is Produced: A Complex Process at the Atomic Level

The most commonly used base semiconductor material is silicon. Silicon "ingots" are formed, which are solid cylinders of various diameters that are then "sliced" to obtain the "raw" wafers of approximately 75 mm thickness, on which, after being polished, this complex circuit printing process begins. Depending on the specific product, the manufacturing process of a semiconductor wafer can involve between 400 and 1400 steps that take between 3 and 5 months to complete (Varas, et al., 2021). This process, which we see schematized in the Figure attached in this Box, uses hundreds of different inputs, including basic and specialized chemicals for the process, equipment and tools in general also specific to the process. The chips consist of up to 100 layers of materials that are then partially removed to form complex three-dimensional structures connecting all the tiny transistors. Some of these layers are only one atom thick.

One of the most difficult parts of the process is lithography, which has only one supplier worldwide: *ASML Holding NV*. The company's team uses extreme ultraviolet light (which is generated naturally only in outer space) to burn patterns in materials deposited on silicon. These patterns eventually become transistors.

Semiconductor Wafer Manufacturing Assembly Process (frontend)



1. Oxidation and coating

Layers of insulating and conductive materials are applied to the surface of the silicon wafer. The wafer is then coated with a uniform layer of **photoresist material.**

2. Litography

The integrated circuit patterns specified in the designs are mapped onto a glass plate called a **photomask.**

Ultraviolet (UV) light shines through the mask to transfer the pattern to the photoresist layer on the silicon disk, passing through a **projection lens.**

The exposed portion can then be **chemically removed.**

3. Development and bake

The wafers are developed to remove the non-photoprotected areas and then baked to **remove the solvent chemicals.**

4. Etching

Areas of the silicon wafer unprotected by photoprotection are removed and cleaned with **gases or chemicals.**

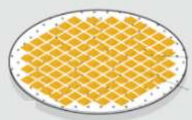
5. Doping

The wafer is showered with **ionic gases** that modify the conductive properties of the new layers by adding impurities, such as boron and arsenic.

6. Metal deposition and etching

A similar process is used to place the **metal bonds** between the transistors.

Steps 1 to 6 are repeated hundreds of times with different chemicals to create more layers, depending on the desired circuit features.



7. Completed wafer

Each complete wafer contains hundreds of identical integrated circuits. The wafers are shipped for assembly, packaging and testing, which includes cutting the wafer into individual chips.

Source: Extracted from https://www.bloomberg.com/graphics/2021-chip-production-why-hard-to-make-semiconductors/

Assembly (Backend)

At this stage, the silicon wafers manufactured in the frontend are converted into chips that are finally ready to be assembled into electronic devices. This stage also involves a rigorous testing process before finally reaching assembly into final devices.

In general, it is the most labor-intensive stage of the chain. However, the physical investment required in facilities, equipment and materials is in the order of 15% of the link's annual revenues (Varas et al., 2021). The technological changes and innovations involved in this investment are gradually making the link also capital-intensive. These changes have been accompanied by an increasing concentration of the sector: the top 20 companies in the link concentrated 70% of the market in 2009, and a decade later they concentrate 92% (Kleinhans and Baisakova, 2020). However, it is one of the least concentrated links in the semiconductor chain. The top four manufacturers globally (*ASE, Amkor, JCET* and *SPIL*) have a combined estimated *share* of global sales, which were USD 34.1 billion in 2021.[19] Other major players include *Powertech, TFME, TSHT, KYEC, ChipMOS* and *Chipbond* (Trendforce, 2021c). In terms of geographical distribution, two thirds of the value added in this Assembly segment is generated in China and Taiwan (Varas et al., 2021).

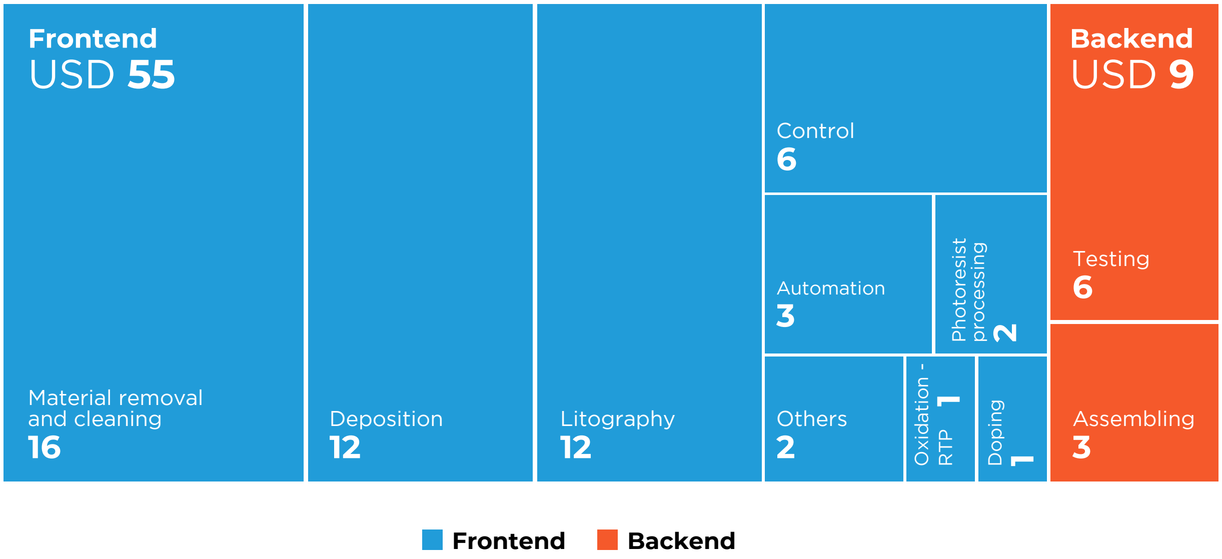
Wafer Production and Testing Equipment

Semiconductor production requires more than 50 types of specialized sophisticated equipment which are, in turn, particularly costly (Varas et al., 2021); by 2020 the global expenditure on equipment for the entire semiconductor industry was USD 71.18 billion (Gartner, 2021).

As mentioned above, the two final links in the chain (Manufacturing and Assembly) depend heavily on the provision of this specialized equipment, especially in the frontend stage, which requires many sub-processes (see Box 2). Figure 6, which presents data on the volume of the semiconductor equipment market according to different uses within the chain, shows this greater preponderance of the frontend link, which in 2019 absorbed more than 85% of the USD 64 billion equipment supply market.

[19] Data from Stratview Research, available at https://www.stratviewresearch.com/1653/outsourced-semiconductor-assembly-and-test-(OSAT)-market.html

Figure 6. Market Size for Semiconductor Chain Equipment, by Function (2019, in billions of dollars)



Source: Prepared by the authors based on Varas et al. (2021)

In turn, the equipment sector that supplies this link influences the health of the chain like no other supplier, due to its high degree of specialization. This specialization, as in other links, leads to a remarkable degree of concentration (there are certain critical equipment, such as EUV lithography, where there is only one supplier worldwide, the Dutch company *ASML*).[20]

The main equipment producers are in the United States, Japan and Europe, while the main consumers (where the frontend activity is located) are in Taiwan, South Korea and China (Gartner, 2021). In the case of equipment for wafers frontend, five companies (*ASML* from the Netherlands, *Applied Materials* from the United States, *Tokyo Electron* from Japan, *Lam Research* and *KLA*, both from the United States) covered 62.2% of the global market (The Information Network, 2020). This aspect has led the most important companies in the chain, such as *Samsung* in South Korea, *TSMC* in Taiwan or *Intel* in the United States, to allocate resources to investments in factories supplying equipment for their operations.

[20] *ASML* is the fourth-ranked company in the sector in terms of market capitalization, ahead of giants such as *INTEL* and *AMD*. https://companiesmarketcap.com/semiconductors/largest-semiconductor-companies-by-market-cap/

Materials

"Raw" Wafers

Manufacturers silicon wafers and other semiconductor materials are key suppliers to the frontend sector and are also highly concentrated.[21] From more than 20 suppliers in 1990, the sector grew to only 5 companies concentrating 90% of the market today (Kleinhans and Baisakova, 2020).

Chemicals

With a global market of over USD 50 billion in 2019 (Varas et al., 2021), chemical manufacturers supply both the frontend and backend, as well as a multiplicity of other industries. Although they are not specialized suppliers, this is also a highly concentrated sector, with the characteristic that the links in the chain that demand these products require a continuous flow of supplies that cannot be interrupted.[22]

Figure 7 presents 2019 data on the materials market for the semiconductor chain. This shows the relevance of each material segment according to whether they supply the frontend (USD 33 billion) or backend (USD 19 billion) link. In the case of frontend, we see that after **silicon raw wafers**, which are the main input in the sector (USD 12 billion), the **gases** used to protect these wafers from atmospheric exposure are the second most relevant input (USD 5.3 billion), followed by **photoresist material** (USD 4.3 billion).[23] In the case of Backend, **organic substrates** account for almost half of the supply market (USD 9.2 billion), accompanied by other materials that have much lower production barriers than the highly specialized chemicals that correspond to the supply of the preceding link.

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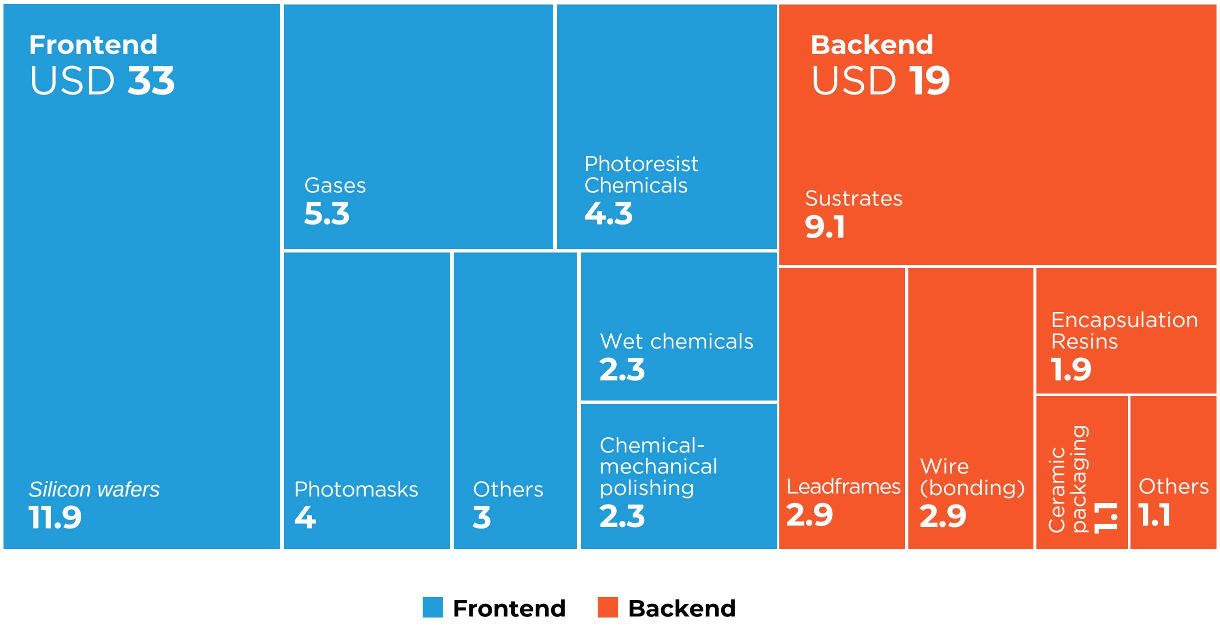
[21] Although silicon is the most widely used material, there are others used for specific applications, such as gallium arsenide (GaAs), gallium nitride (GaN) and silicon carbide (SiC).

[22] A large share of chemical suppliers is concentrated in Japan, and the Japanese government has tended to take advantage of this dependence by establishing export controls to block the development of links in the chain in South Korea et al., 2021).

[23] Box 2 briefly describes how different chemicals are involved in wafer manufacture.

Figure 7. Market Size for Semiconductor Chain Materials (2019, in billions of dollars)



Source: Prepared by the authors based on Varas et al. (2021)

The Chain from a Geographical Perspective: Specialization and Dependency

Given the high geographic specialization by links, no country currently has the capacity for self-sufficiency in terms of containing within its territory all the productive resources required to supply its domestic demand without having to depend on external purchases. This feature makes the chain highly collaborative, but also highly exposed to disruptions caused by trade and diplomatic tensions between countries and various exogenous factors, as has been the case since the beginning of the pandemic.[24]

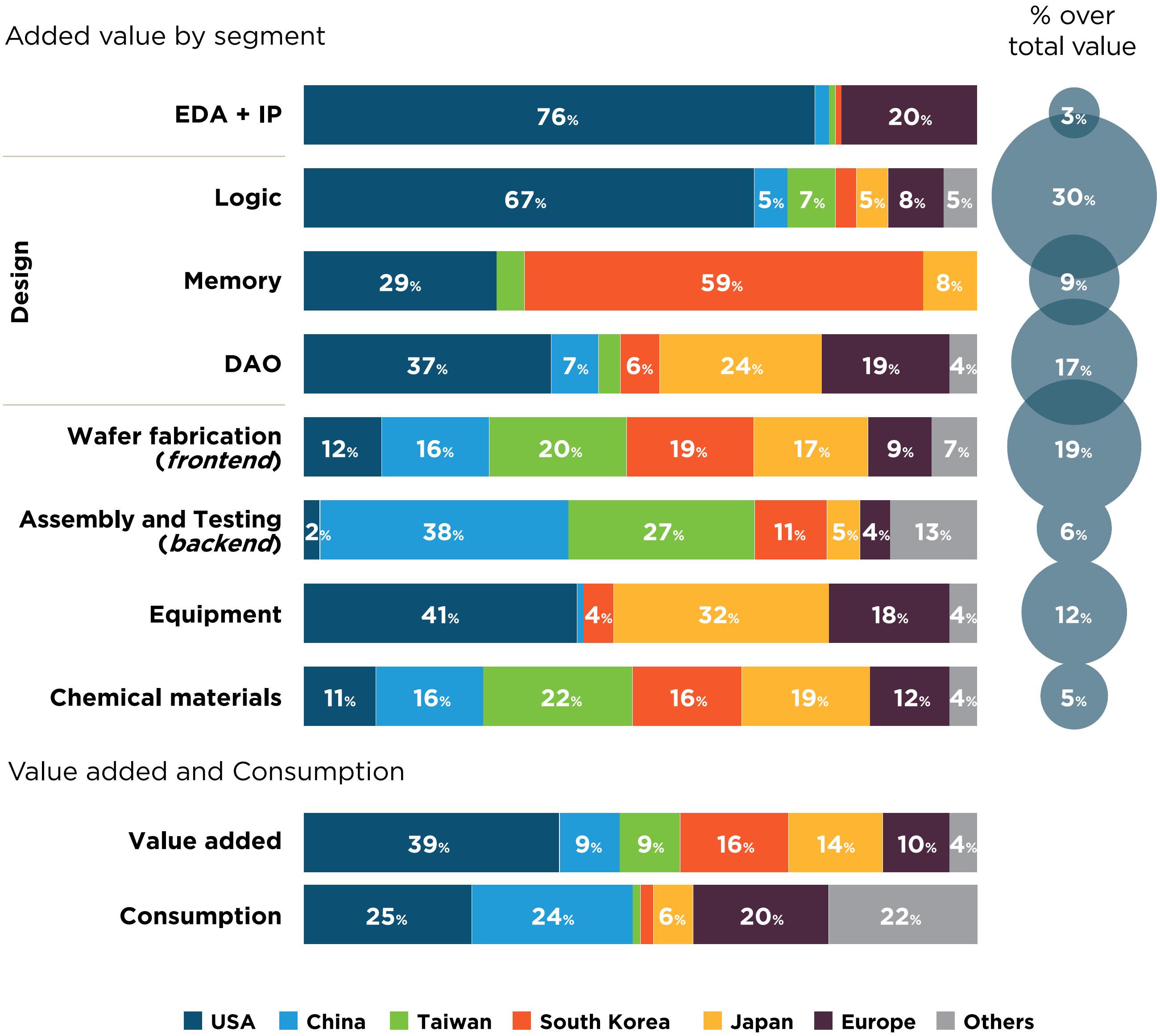
Figure 8 shows the geographic distribution of the industry's global value added, according to the different links that make up the chain.

In aggregate terms of the semiconductor sector, around 80% of global sales are concentrated in the United States, China, Europe and Asia Pacific. On the production side, the United States is clearly dominant, contributing almost 40% of the industry's global value added (Figure 9). This leadership is due to a compositional effect; as can be appreciated in the graph, almost half of the value added in the entire chain is generated in the design stages, where U.S. companies have the largest market share.

Below are summary profiles of the countries, according to their specialization in each link of the global semiconductor value chain.

[24] Faced with the supply crisis that the sector is currently going through, due to the acceleration of demand, the countries that belong to the chain have been faced with the dilemma between aiming for the possibly unfeasible and very costly objective of achieving national self-sufficiency (this is the case of China, to which must be added reasons that go beyond the crisis) or, on the other hand, taking the crisis as a warning of the importance of having a flexible and resilient chain. Part 2 of this document discusses this point in more detail.

Figure 8. Geographic Specialization of the Chain, by Value Added (2019)



Source: Prepared by the authors based on Varas, et al. (2021)

United States

U.S. companies have a dominant position along almost the entire supply chain. This is largely due to the high importance of the IDM model among U.S. companies in the sector. However, the United States is most dominant in the design link, with a very high market share in logic devices and in the software supplier sector (EDA + IP).

South Korea

South Korea is another major global player, also with important companies in the IDM model (*Samsung, SK Hynix*). Its largest market share is in the memory segment (DRAM, NAND), in the design link.

Together with Taiwan, China and Japan, they are in the group of countries with the largest production capacity of wafers (frontend). The companies are also the largest contributors to value added in terms of chemical materials for the semiconductor sector.

Europe

European firms play a much smaller role in the semiconductor chain, although they maintain an important weight in the design link supply sector (EDA + IP). In design, they have some relevance in specific technologies such as sensors, discrete semiconductors and, especially, integrated circuits for the automotive industry.

In turn, the main European companies (*Bosch, Infineon, NXP* and *STMicroelectronics*) follow the IDM business model, which gives Europe a certain positioning in the *Foundry* link (frontend).

Europe is also relevant in supplier sectors such as equipment (*ASML, ASM International, Aixtron*), chemicals (*BASF, Linde, Merck KGaA*) and wafers (*Siltronic*).

Taiwan

Nearly two-thirds of *foundries* global revenues are generated in Taiwan, with the majority of this market share being contributed by *TSMC* and to a much lesser extent by *UMC* (Trendforce, 2021b). Taiwan also has the largest market share in the supply of materials in the chain. In turn, with companies such as *ASE Group*, this country has an important presence in the backend (assembly and testing) market.

Japan

Japan plays a minor role in the chain, and its main relevance is in the supplying sectors, such as chemical materials, equipment and wafers production.

China

In general, China's presence in the chain is currently smaller than that of other central countries, but it has grown significantly in recent years and is expected to expand further in the future, given the chain development plans launched by the Chinese government, with a view to achieving self-sufficiency in the territory.

Today, China is the main player in the backend link, the lowest value-added link, and also plays an important role in the wafers segment and the supply of chemical products.

Latin America

Latin America's participation in the global chain is very low, with Mexico and, in second place, Brazil being the region's clear leaders. Mexico has several plants of various international companies, which cover several links in the chain, except for manufacturing: Design (*Intel*), Validation (in a public institute, the IANOE), and Assembly, Testing and assembly of electronic components for final devices (*Skyworks Solutions, Texas Instruments, Infineon*, among others). In Brazil, assembly and testing or sales services predominate (except for the design offices that *IBM* has in both countries). For its part, the Intel assembly plant that has recently been reactivated in Costa Rica had actually been a suspended project (relocated to Asia in 2014), until the current supply crisis led to its consideration.[25]

Despite its low participation, Mexico could benefit greatly from the changes that are occurring globally in the chain: the supply problems faced by the United States (which escalate to a national security level) can be addressed as a block from the whole of North America.[26] In addition, Mexico already has an ecosystem with at least 600 companies working in some part of the semiconductor chain. This, within the framework of the T-MEC agreement, may give rise to opportunities for joint projects that will allow Mexico to better insert itself into the global supply chain.

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[25] See https://www.investmentmonitor.ai/costa-rica/cinde-costa-rica-semiconductor-shortage

[26] As expected, the United States dominates the Americas market; sales in the continent were USD 94 billion in 2020, and USD 117 billion in 2021 (SIA, 2022).

PART 2

Current Challenges and Policy Responses

Introduction

From the analysis of the first part of this paper, the following salient aspects of the semiconductor value chain emerge:

- The value chain is highly concentrated in the most sophisticated segments, which can only be produced in more developed countries, although with a considerable geographic dispersion, where each zone has specialized in certain links of the chain, according to comparative advantages, including the participation of emerging countries.
- At the same time, no country has a certain potential to achieve "self-sufficiency".
- This geographic specialization goes hand in hand with the deepening of the *fables-foundries*, business model, where companies are dedicated to only one of the links. This does not detract from the fact that the main companies in the sector (including the oldest ones) operate in their integrated model (IDM), distributing their production across the globe.
- Specialization and the *fables-foundries* model are accompanied by increasing concentration in each link, through mergers and acquisitions.
- It is one of the value chains with the highest level of R&D expenditure, along with others such as pharmaceuticals and aerospace.
- Each link has certain particularities of resource intensity: the design link is knowledge-intensive, while manufacturing and assembly are more capital-intensive; the assembly stage is the most labor-intensive of the three.

- Semiconductors play a key role both for their influence on recent and future economic growth, enabling technological change, and on the national security of countries, which explains why certain countries want to take significant part in the chain.

- In turn, geographic specialization and concentration make the chain vulnerable to adverse events such as catastrophes (earthquakes or the pandemic itself, for example), as well as to geopolitical tensions.

This second part of the paper focuses on the last two points mentioned above. Based on the sector's recent dizzying growth, it analyzes the main challenges arising from the supply crisis affecting the sector and the policy responses that almost all countries involved in the chain have recently announced.

The text is organized as follows: first, the main figures outlining the recent evolution of the sector and associated trends are reviewed. The analysis then focuses on the supply crisis that has been taking place since the second half of 2020, attempting to draw some preliminary lessons on the current state of the chain in terms of its resilience. Finally, the last section reviews the policy responses of the main global players within a framework of considerations on the role of governments in the chain.

Technologies and Production Strategies in a Complex Sector

Before turning to the analysis of the semiconductor shortage crisis and the industry and public policy responses, it is useful to understand how production strategies work within the industry. In the first part of this document, reference was made to the fact that the semiconductor production process is very costly, as well as requiring long production lead times and joint work with the supplying sectors. This section reviews these aspects and their implications in more detail.

Producing a semiconductor wafer involves repeating the five generic steps described in Box 2 hundreds of thousands of times. This can take, depending on the complexity of the circuit, between 3 and 5 months of work to have the wafer ready to be cut and sent to the backend link.

This complexity defines the "manufacturing standard", also known as "technology node" or "process node". This standard is measured in nanometers (one thousandth of a meter) and refers to the minimum size of the chip components. Thus, the definition used to refer to the gate length of transistors, but this is no longer the case and process nodes are now a mere reference (not an exact measurement) of the degree of sophistication of the companies' production.[27] In a general sense, it can be said that the technology node refers to the density of transistors that fit on a chip, which also involves certain design architectures and circuit generations: the smaller the node, the smaller the transistors, but the higher the speed and energy efficiency.

The aforementioned Moore's Law predicts that the number of transistors on logic chips should double every 2 years or so. This empirical pattern has been fulfilled over time, leading to the fact that the most advanced technology at present is the 3 nm node technology, a standard achieved so far only by the Taiwanese TSMC, but which has not yet been launched on the market.

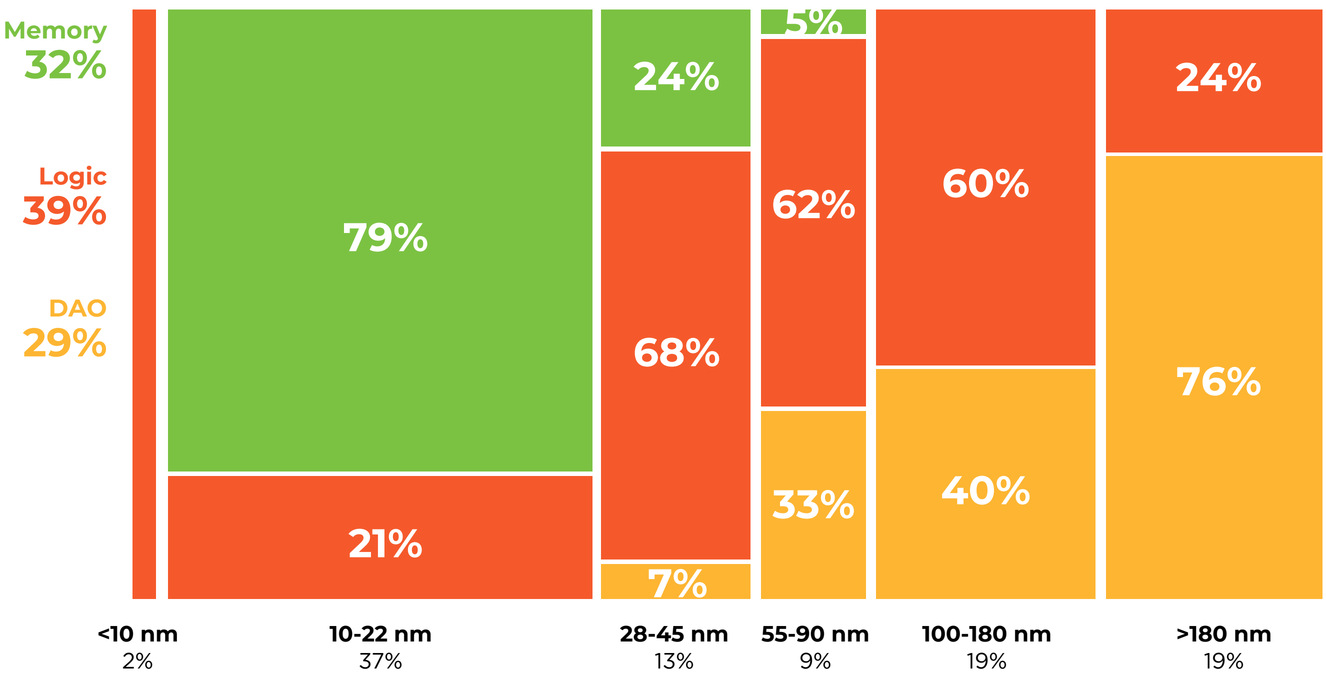
This rate of technological advancement means that state-of-the-art production equipment has a useful life of approximately 5 years before it becomes obsolete in the face of the new, more advanced industry standard. In general, equipment designed for frontier production may be capable of producing chips of previous standards, but "old" equipment cannot produce frontier chips (Mönch, et al. 2017).

This can lead to differences in production routines, costs and yields both between and within firms, which is a relevant point in understanding the industry's short-term response to the recent shortage. Another point worth noting is that these technological changes do not necessarily make the other nodes obsolete: less complex chips are still in demand in various sectors.

Figure 9 shows that in 2019 only 2% of the industry's installed capacity is for sub-10nm chips, and that technology is used only in logic devices. Most memory chips, meanwhile, are between 10 and 22 nm. Discrete, Analog and Other (DAO) devices, being less complex, comprise most of the installed capacity for nodes larger than 180 nm. According to various sources consulted, in the current shortage the largest undersupply appears to be in the 180+ nm nodes (IDB, 2022), particularly in DAOs, which may indicate that industry production was directed towards other chips, such as logic, that compete with DAOs in capacity for the 180+ nm nodes. Considering that, as it will be shown in what follows, private investments and country support plans are aimed at frontier technologies, the shortage in the less sophisticated segments would be solved by "capacity release" in already operating factories, since the equipment would have the potential to cover operations of previous technologies.

[27] The information presented is based on https://en.wikichip.org/wiki/technology_node

Figure 9. Installed Production Capacity, by Technology Node and Type of Semiconductor (2019)



Source: Prepared by the authors based on Varas, et al. (2021)

Finally, it is also worth considering the companies' delivery strategies. Following Mönch, et al. (2017), there are essentially two types of strategies in the industry: make to stock (MTS) and *make to order* (MTO).

The MTS strategy predominates in companies that produce on a large scale (RAMs, flash memories, etc.) and consists of maintaining inventories of already tested semiconductor "dies" (die-bank inventory).[28] This is possible since, with an off-the-shelf design, the initial manufacturing stages are the most important bottleneck in terms of lead times. This makes sense mostly for IDM firms that accumulate stock before the assembly and testing stages and consume inventory (or expand it) according to backend demand.

Companies with MTO strategies produce for several customers; this is a strategy that is increasingly used, given the technological specialization. For this type of company, an MTS strategy is not possible because the changes occur at the manufacturing stage. Thus, these companies choose to work with "modular" structures that allow to have critical parts of the wafers pre-assembled (wafer bank). It is even possible to combine capacity from

[28] The "dies" are the pieces that result after cutting the wafer already printed with circuits.

different factories (pool) if necessary, due to the inability to expand production capacity as fast as demand may change.

Many firms operate with mixed MTO-MTS strategies, making contractual agreements with certain clients that allow some stability and predictability in the medium term, and the remaining capacity is covered with an MTO strategy that is more "uncertain".

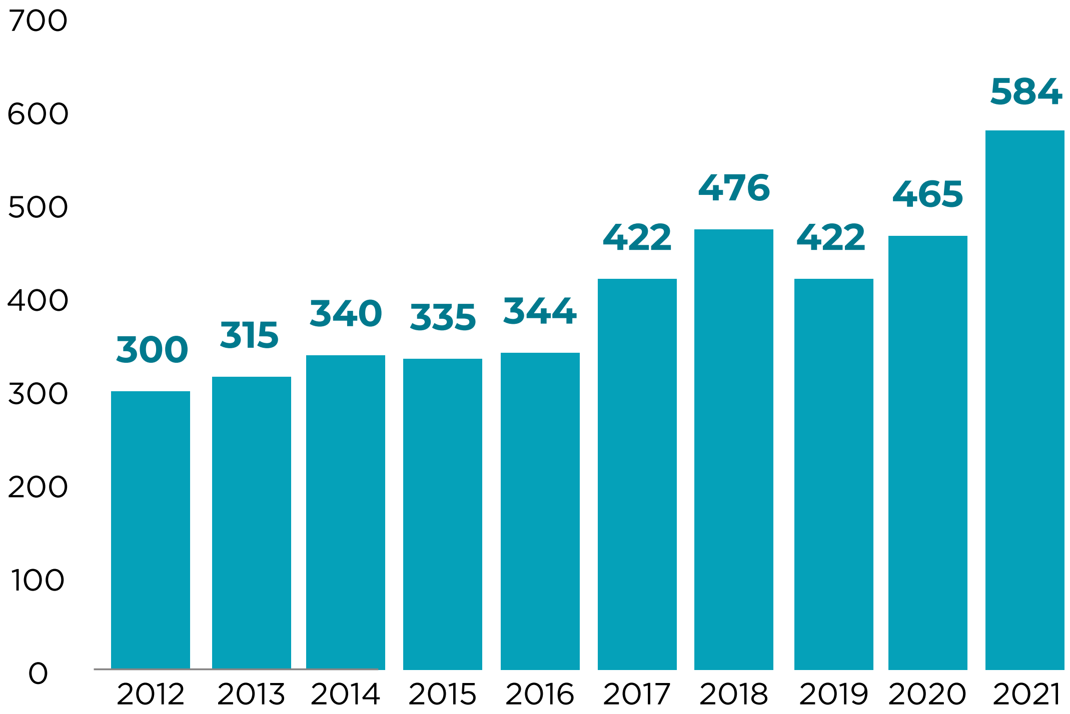
What happened in the current crisis is that the customers' forecasts (especially those of the automakers) were wrong, leading them to break contracts and redirect the companies' production capacity to other contracts and customers with growing demand. This process was accompanied by the emptying of stocks, given the discrete jump in the quantities demanded.

Recent Developments and Crisis in a Key Sector

Along with the massive expansion in the population's access to new technologies, the growth of the semiconductor sector has been remarkable during the last three decades, increasing its relevance to the economies. Thus, the increased efficiency of chips and their cheapness enabled the massive expansion of personal computers in the 1990s, web services in the 2000s, and the "smartphone revolution" that took place mainly in the last decade.

Between 2012 and 2020, global semiconductor sales increased from USD 300 billion to more than USD 465 billion and had an annual growth of more than 25% in 2021, exceeding USD 583 billion (Figure 10). According to WSTS (2021), the global semiconductor market will grow by 8.8% in 2022.

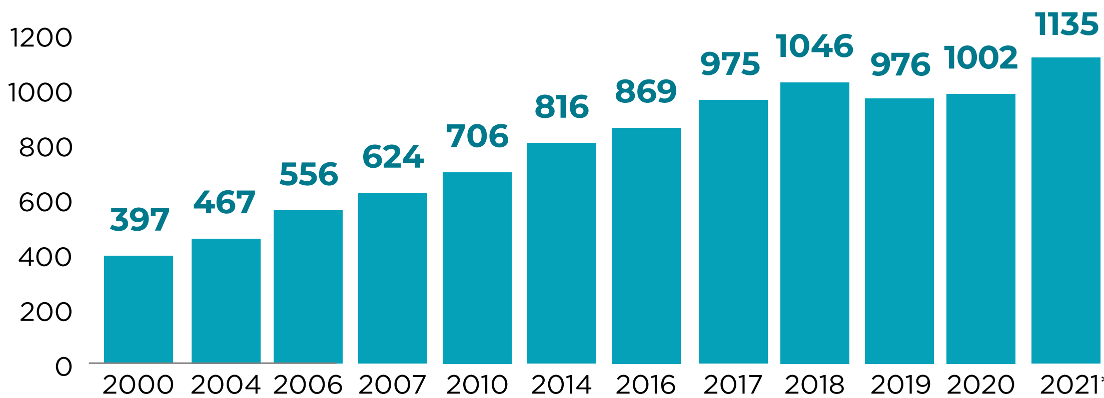
Figure 10. Global Semiconductor Sales (in billions of dollars)



Source: Prepared by the authors based on Gartner (2022)

Another indicator of the sector's remarkable expansion is the number of semiconductor shipments, which rose from 400 billion units in 2000 to an estimated 1.14 trillion units by 2021 (Figure 11). Dispatch growth in 2021 was 13%, less in relative terms than the 25% increase in sales mentioned in the previous paragraph, which may be an indication of strong price increases in the face of the supply crisis.

Figure 11. Global Semiconductor Shipments (in billions)



Source: Prepared by the authors based on IC Insights (2021)

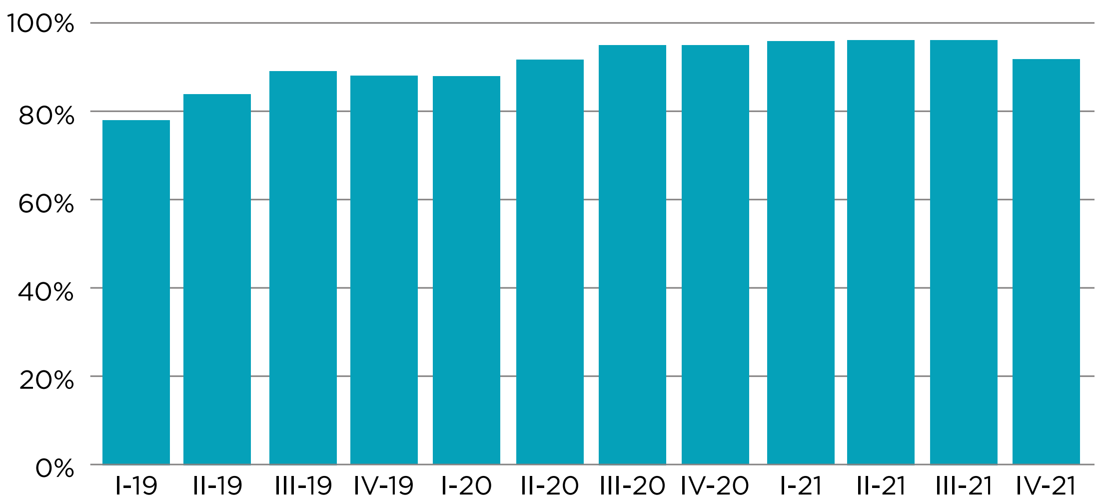
As mentioned in the first part of this document, the great development of the sector during the last decades was accompanied by changes in the market structure, with tendencies towards a greater concentration of production, within each of the links, in fewer companies, although more geographically dispersed.

There have also been changes in the structure of business models; starting from a situation at the beginning of the century in which sales were highly concentrated *in* integrated companies (IDM), over time companies specializing in design (*Fabless*) have been gaining share; indeed, based on data from Gartner (2021), it is observed that the ratio of sales of IDM over *Fabless* went from ten to less than three between 2000 and 2020.

It is against this backdrop that, in the first months after the onset of the COVID-19 pandemic, the semiconductor sector was affected in terms of supply, as were most sectors of the economy: paralysis due to uncertainty and disruption in the production chain (paralyzed demand). However, solutions that emerged naturally in the face of the confinement caused by the pandemic, such as teleworking and tele-education, boosted global demand for electronic devices, especially personal computers. Contrary to projections, demand for automobiles remained solid. The chain then became much more than an "essential activity", and demand quickly outstripped the supply response capacity.

The bottleneck was the frontend manufacturing link, which, as we have seen, requires large investments with a lead time of no less than two years. The immediate response of the sector was to take its use of installed capacity from values slightly around 80% to values very close to 100%, as shown in Figure 12.

Figure 12. Evolution of Industry Capacity Utilization (2019-2021)



Source: Extracted from SIA (2021)

This increase in installed capacity utilization occurred in parallel with a scenario of contract redefinitions by customers. Some sectors, such as the automotive industry, initially predicted a sharp drop in demand and suspended semiconductor orders. This forecast did not materialize in the end, and when companies tried to recover their quota, it turned out that it had already been reallocated to the IT sector, which faced a huge growth in demand. The shortage is, therefore, greater in semiconductors over 180 nm, mostly associated with the automotive segment.

This situation of contract breach and production reallocation resulted in a marked increase in delivery times for some of the chain's customers. According to *Susquehanna Financial Group*, the average time elapsed between purchase order and delivery was 25.8 weeks in December 2021; this is six days longer than in the previous month and represents the highest value in the series, which is compiled since 2017, when delivery time was less than 13 weeks.[29,30]

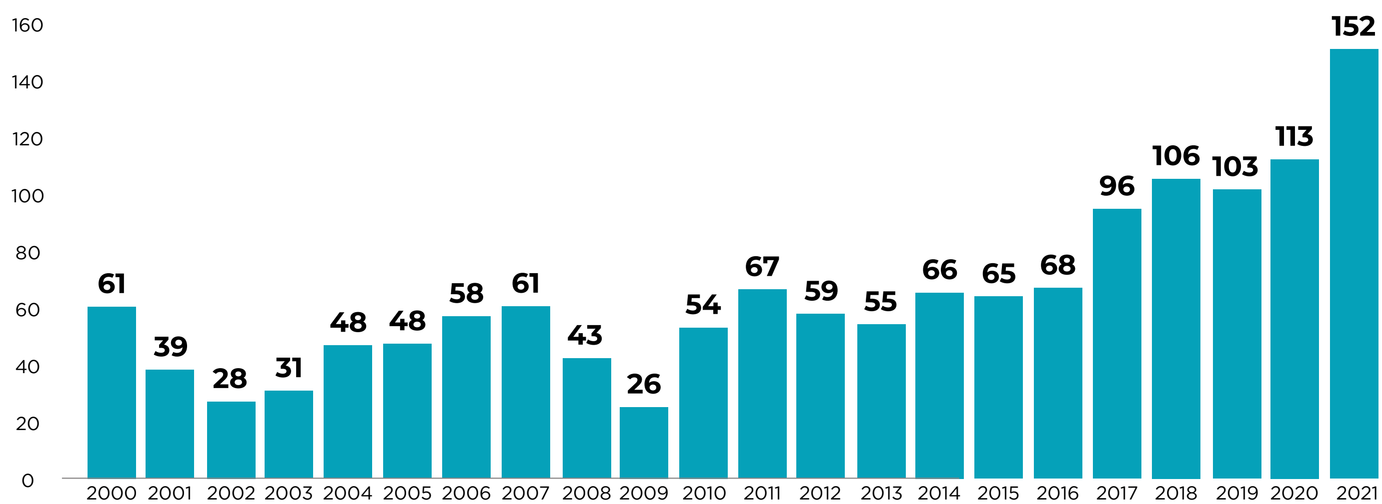
[29] For more information see https://www.zerohedge.com/technology/chip-delivery-times-hit-record-shortage-worsens
[30] According to sources consulted, one of the responses of consumer companies to this increase in delivery times was to resort to alternative supply channels, such as auctions, in which components are purchased without knowing the specific origin or manufacturer and involving payments of several times the regular value of the component.

Looking to the medium term, the answer had to do with more investment: with an increase of 34% over the previous year, capital investment by 2021 (Figure 13) would have reached USD 152 billion (SIA, 2021), and would be even higher in 2022. These are unprecedented numbers for the sector, which, according to some analysts, could lead to a problem of oversupply in the medium term (Global Times, 2022).

At the same time, one aspect that is striking is that, while the shortage is more marked in semiconductors for larger nodes, the investment announcements (as well as the direction in which most of the public programs that will be analyzed in the following section point) are directed towards the most advanced standards. This suggests a pattern of investment that responds not only to the shortage, but to the break in the structure of demand (towards more technologically advanced components) that has been brought forward by the pandemic.

In the face of this, the shortage in nodes larger than 180 nm would be solved by a combination of (1) increased supply from existing factories, which today do not deal with these semiconductors but are located nearby, (2) new factories for "large" chips, (3) changes in demand that achieve an adaptation towards generic chips, with greater future supply.

Figure 13. Capital Spending in the Global Semiconductor Industry (in billions of dollars)



*Estimated.
Source: Gartner (2021)

However, although projected private investment is at historic highs, it is also true that uncertainty is also high. This is because not only have companies reacted to the "wake-up call" that this sectoral crisis has turned out to be, but so have governments, as the chain's essential vulnerability to external disruptions has been exposed.

For governments, semiconductors are not only a key development tool, but also —today more than ever— a matter of national security. The current crisis has raised alarm bells, and the main countries involved in the chain have reacted with substantial fiscal packages of measures in an attempt to increase chip production capacity in their own territories. This, in a context where China already has plans in place to consolidate its relevance in the chain for the next decade.

Perhaps the most unexpected response (as will be seen below) is that of the United States, which is said to have made an unprecedented shift towards industrial policy. These attempts by Washington to disrupt the GVC, and the response of China who, together with Japan, South Korea and other Asia-Pacific countries, implemented the Regional Comprehensive Economic Partnership (RCEEP) in order to form a supply chain free from US interference, increase the degree of uncertainty regarding the new geographic configuration of the supply chain.[31]

In this context, while several key aspects affecting the market are being defined, producers are reportedly following a “wait and see” strategy that could even imply price increases in the short term (Global Times, 2022).

A study by KPMG (2021) shows the results of a survey of 156 executives in the semiconductor industry. The paper finds that the main concerns in the industry are geopolitical and territorial issues, particularly on the part of China and the United States, which could generate cost pressure and greater complexity in the chain. In addition, tariffs on exported or imported components increase costs, encouraging companies to seek mitigation strategies while creating logistical and compliance challenges.

Chain disruption is another area of major concern; increases in trade costs and tariffs are leading some manufacturers to take new measures to optimize the value chain through changes in the geographic origin of supply sources.

Finally, the human capital factor remains important, although to a lesser extent than in the years prior to the pandemic, mainly because remote work makes it possible to resolve some bottlenecks. In fact, 64% of those surveyed by KPMG recognize that remote work has allowed them to enlarge the search base for potential talent, making it easier to meet the talent requirements of companies.

[31] The RCEP, in force since January 2022, is the world's largest free trade agreement; the signatory countries, notably the absence of India, account for 30% of global GDP and 25% of international trade. The agreement includes significant tariff reductions (to be implemented gradually) and trade facilitation among the signatories to stimulate trade and investment within the bloc and strengthen regional supply chains.

BOX 3. Drivers of Semiconductor Demand Growth and Prospects

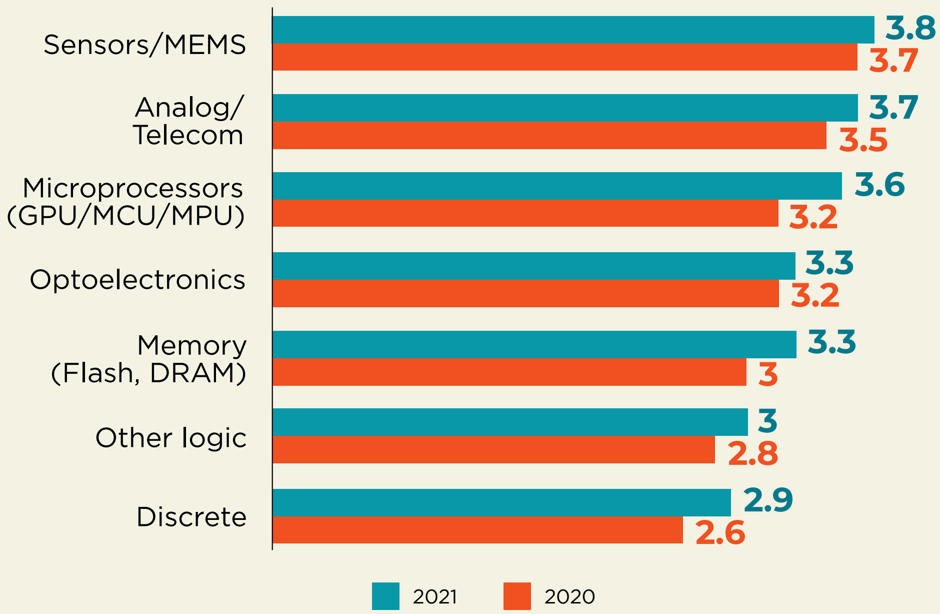
During the last two years, the semiconductor sector saw an alteration in the circumstances projected for its demand. The world's solutions to the coronavirus pandemic, such as teleworking or tele-education, led to strong growth in the consumption of semiconductors for personal devices, such as computers. Indeed, according to SIA (2021), demand for computer semiconductors increased by more than 21% in 2020. Also important was the 8% growth in demand for chips for industrial equipment, which is mainly linked to the response of industries in terms of digital acceleration.

Regarding expectations for the future, the KPMG study (2021) finds that 85% of respondents expected sales growth by 2021, and only 8% expected declines. These favorable prospects for the sector are even more pronounced among smaller companies (with annual revenues of less than US$100 million). There is also optimism regarding the sector's profits, which has to do not only with the large increase in demand, but also with the companies' adoption of a more efficient spending strategy.

The same study suggests that no major changes are expected in the technological niches that will boost the sector's growth compared to the pre-pandemic situation. The sensor and analog sectors have the greatest opportunity for growth, according to the more than 150 entrepreneurs interviewed. This may be in response to significant projected growth on the Internet of Things (IoT), which includes in part demand for innovations in the automotive sector. There are also good prospects for growth in demand for microprocessors, especially due to the boom in cryptocurrency mining.

BOX 3 (Continued)

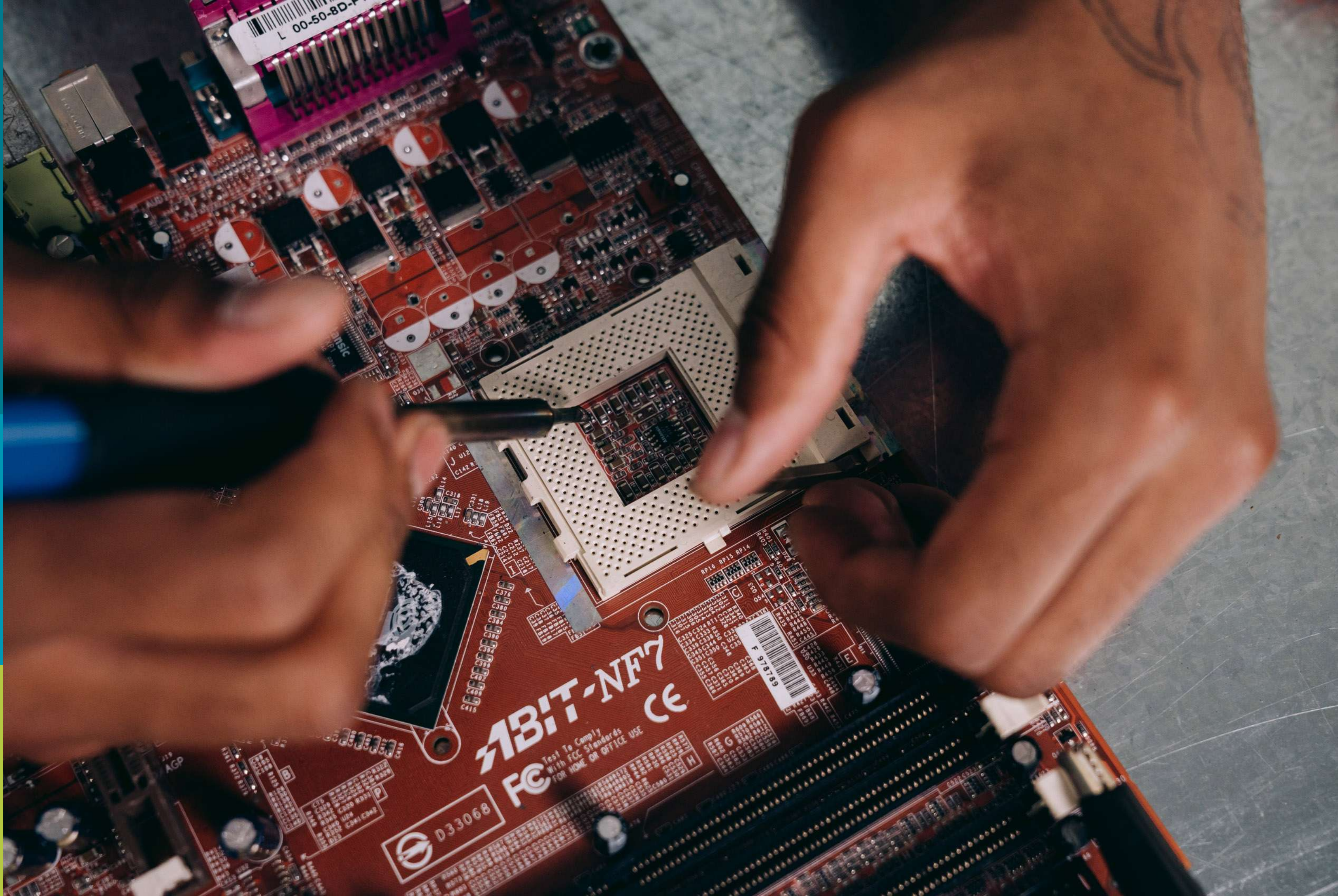
Technology Sectors according to Growth Opportunities
(1 = Low growth potential, 5 = High growth potential)



Source: KPMG (2021)

The applications that will mark the greatest demand for semiconductors are wireless and IoT communications, followed by 5G technology and the automotive sector.

Automakers are gaining importance as consumers of semiconductors; as the development of more connected, electric and autonomous cars continues, and as there is better infrastructure for autonomous vehicles with 5G, artificial intelligence and cloud developments, the automotive sector will become increasingly important as a buyer of semiconductors in the coming years.



Supply Crisis: What are the Alerts?

The crisis in the sector is presented as one of excess demand, due to rigidities in the manufacturing link. This disruption had an effect not only on the chain and direct consumers of microchips, but also spread to other chains, such as the automotive industry (see Box 4). A reference case is that of Michelin Spain, which in November 2021 had to suspend shifts in its tire production due to unforeseen drops in production at Ford and General Motors due to the lack of semiconductor components for their vehicles.[32]

[32] See https://as.com/meristation/2021/10/16/betech/1634352373_453529.html

The situation has raised warnings for both companies and governments about the resilience of the chain. As mentioned above, the current crisis in the chain is focused on the manufacturing link (frontend), due to the time and cost involved in expanding capacity in this segment.

Thus, while the companies seek to ensure their supply in the coming years, the central countries involved in the chain have announced various fiscal packages that seek, to a greater or lesser extent, to attract investments to their territories, mainly in the production link, which will be analyzed in the following section.

However, given the intentions of all those involved to attract investment, the question that arises is whether these incentives are sufficient in themselves or whether other factors are important for a company to decide to make investments of this magnitude. Varas, et al. (2020) analyze the factors that affect the participation of the United States in the productive capacity of the chain. Based on consultations with key industry players, the paper argues that there are five key points that determine a company's decision to set up a plant in a given country:

- Labor costs
- Government incentives,
- Access to talent,
- Security of intellectual property and assets, and
- Existence of an entrepreneurial ecosystem linked to the chain.

Other less important, but desirable and necessary, issues are of a more general or macro nature, such as ease of doing business, cost of capital, general support infrastructure, and geopolitical considerations. The relative position of the United States is favorable in three of these key areas (talent, security and ecosystem) and unfavorable in labor costs and government incentives.

BOX 4. Impact of the Supply Crisis on the Automotive Sector

Semiconductor shortages could cost the automotive sector USD 210 billion in 2021, which equates to a reduction in production of 7.7 million units.[b] In the United States, the chip shortage resulted in 1.28 million fewer cars that year. Mexico has also been affected, according to INEGI, light car production was 2.98 million units in 2021, evidencing an annual drop of 2%, partly explained by the supply crisis (Banxico, 2021), and with a very significant reduction in sales in February 2022.

Although new investments underway will expand production capacity, the problem may not begin to be resolved until 2023, and therefore long lead times, availability problems and price fluctuations will continue throughout the year.

For the automotive industry, the market expects an increase in component prices in the range of 10-20%, which would be explained by the shortage of materials, such as copper, gold, fuels and silicon wafers. Another factor that could put pressure on automakers' costs is the price of foundry service, which could also see a significant increase in 2022. TSMC, the largest manufacturer on the planet, would apply price increases of between 10 and 20% this year. These cost increases are likely to be passed on to automobile prices.[c]

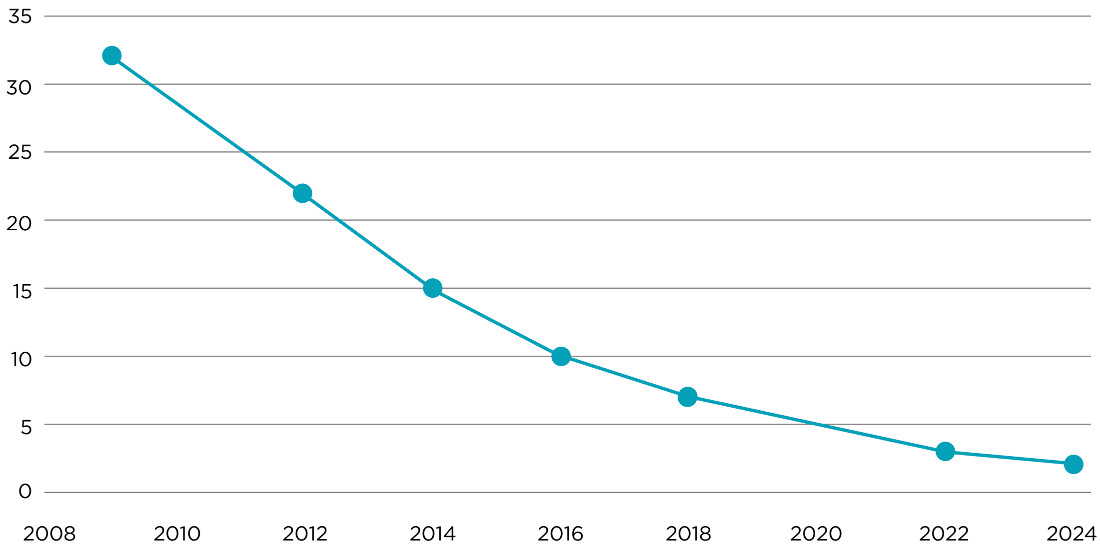
[b] See https://www.freep.com/story/money/cars/2021/06/15/car-chip-shortage-2021/7688773002/
[c] For details, see:
https://www.supplychain247.com/article/predictions_for_the_2022_global_semiconductor_sector

It can be seen from the above that government incentives are not everything, but that a favorable environment is needed in an integral manner. But at the same time, looking to the future, there is another condition related to the prediction by some experts that Moore's Law, which predicts the doubling of the number of transistors per chip every two years, will eventually reach a point of exhaustion (Calhoun, 2021).

The reasons for that depletion are based on physical issues: the most advanced chips currently contain 3 nm nodes (Figure 14), and while they may continue to advance, they will be at a slower and slower pace to the point that eventually there will be an asymptotic convergence to a lower nm limit. Faced with this, we could be at the gates of new paradigms with associated technologies (neuromorphic computing, quantum computing) less bounded by physical space where most of the investment in basic research is currently made by the public sector (McKinsey, 2021).

Thus, the question arises as to whether it is correct to strongly direct policies towards factories, or whether governments should broaden their policy approach to investments that will end up reshaping the chain on a global scale.

Figure 14. Industry Manufacturing Standards (Size in Nanometers of the Processing Nodes)



Source: Prepared by the authors based on Calhoun (2021)

[33] It should also be noted that, among other activities, Intel's Guadalajara Design Center conducts basic research in autonomous systems, neuromorphic systems and quantum computing (Intel, 2022).

BOX 5. The Distribution of Production Capacity over Time and Geopolitical Issues

The current semiconductor crisis has to do with bottlenecks in the production link. Almost all the countries involved reacted with fiscal stimulus packages aimed at strengthening the position of their territories in this link, in order to mitigate possible disruptions in the future.

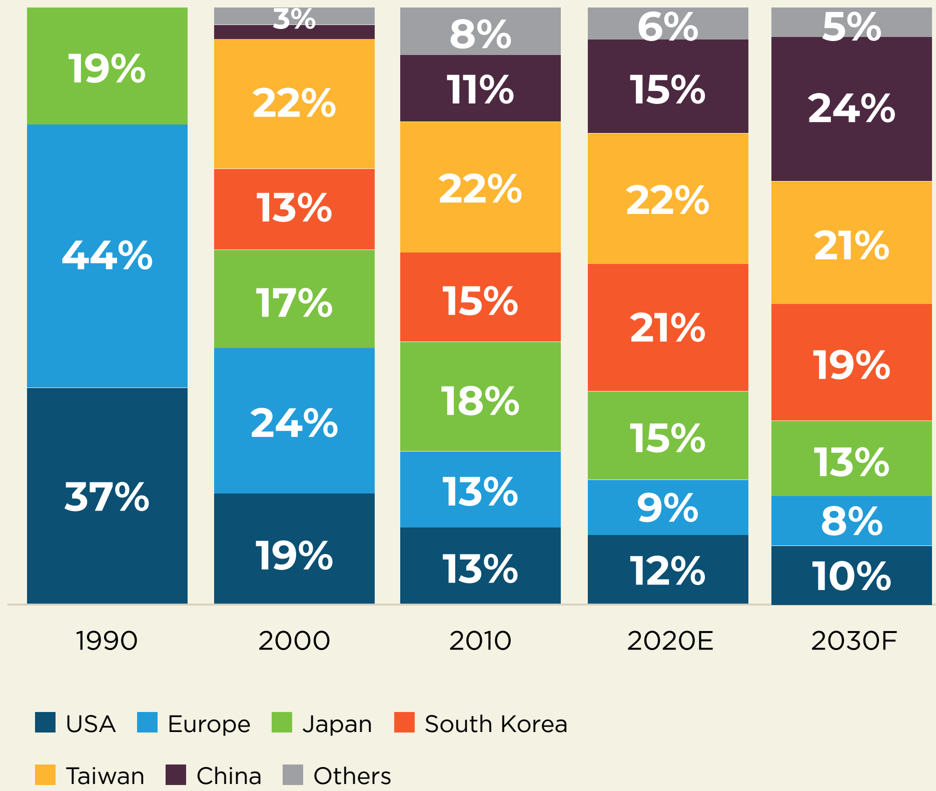
Today, such actions seem to make sense, as global production capacity is more diversified. In 1990, only three regions accounted for the total productive capacity: Europe (44%), the United States (37%) and Japan (19%). Thirty years later, production capacity expanded to other Asian countries (in addition to Japan), such as China, Taiwan and South Korea.

Thus, the crisis of insufficient supply occurs in a context where several territories are competing for world production leadership, or to regain their lost positions (Europe, United States) in the face of the threat of Chinese positioning. However, as Calhoun (2021) points out, this race is not only about quantitative capacity, but also qualitative capacity. Earlier, in Part 1 of the document, it was mentioned that countries have different levels of specialization according to the chip technologies produced. Thus, the challenge is not only to invest in capacity, but also to choose the right niche in which to specialize (if any). Within this technological division, there are different levels of sophistication (intrinsically linked to patents and the relevance of R&D investment in the chain).

As an example, Calhoun (2021) notes that China's current production capacity is associated with processors approximately 12 years behind the industry standard for the United States and related countries. Moreover, Varas, et al. (2020) point out that, even if China's investment aspirations for the next decade are realized, the Asian giant would still be one or two generations behind by 2030.

BOX 5 (Continued)

Percentage Distribution of Chip Production Capacity by Region



Source: Varas, et al. (2020)

Public Policy Incentives for the Sector

Prior to the supply crises, almost all countries with a significant presence in the global semiconductor chain have been implementing policies to diversify the chain activities carried out in their respective territories. Appendix 2 delves into the set of countries' main policy strategies and their possible implications, from a medium- and long-term conceptual perspective.

In general, from a public policy perspective, there is consensus that intervention as far upstream as possible in research and development processes is usually the least distortive and most desirable way to close investment gaps with respect to what is socially desirable. However, governments usually have a larger set of policies at their disposal, including subsidies and tax exemptions for capital investments and machinery. At the same time, in such a globalized chain, trade policies are of great importance and, although average tariffs on products linked to the chain have been falling, it is also true that this has occurred in parallel with an increase in non-tariff measures (NTMs) imposed in response to geopolitical tensions in the countries (OECD, 2019).

With the current supply crisis, policy responses were boosted with large stimulus packages to the sector, both in interventionist countries such as China and in others without a tradition of industrial policy such as the United States.

The following lines describe the main aspects of the measures taken in recent years and the most recent ones announced by China, the United States, Taiwan, Europe and South Korea, as well as by other countries of lesser importance, but with a consolidated ecosystem and high potential, such as India, Malaysia, Singapore and Israel. The section concludes with a comparative summary of the main findings and the implications for chain development.

China

China is structurally dependent on technologies from other countries, especially the United States. For the Chinese government this translates into a national security issue, which also hinders other purposes such as consolidating a relevant role in the international technology industry. Thus, over the last decade, China has devoted increasing resources to expanding its role in the global chain. China's productive capacity increased from 3% in 2000 to approximately 15% in 2020. This is considering the mainland portion of the country; if we include Taiwan capacity, the figure rises to 37%, and is expected to rise to about 50% by 2030, with mainland capacity expansion alone (Varas, et al. 2020). However, it is important to bear in mind that Chinese production at that time will still be one or two generations behind the technological frontier set by its competitors.

Currently, the main program for the development of the semiconductor chain in China is the *Made in China* 2025 Plan, based on which the Asian country aims to reach self-sufficiency by 2030. This plan covers ten technology sectors that China considers key and to which it will allocate USD 300 billion over a ten-year period. All these sectors are, of course, heavily dependent on the semiconductor chain.

Before *Made in China*, a significant list of actions aimed at developing the semiconductor chain was implemented; according to SIA (2020), since 2011, the Chinese government's announcements in support of the chain exceeded USD 100 billion, mostly oriented to the last two links in the chain: manufacturing and assembly. According to Capri (2020), the objective of the Chinese policy set is to (i) attract investment via FDI, and (ii) incorporate new technologies into its production matrix.

In 2014, the Chinese government released its Guideline for the Promotion of the National Integrated Circuit Industry, also known as the IC Plan or the “China Big Fund”. This included funds of USD 150 billion from the three levels of government (central, provincial and municipal).

The Chinese government has provided some funding to more than 70 SIA (2020) semiconductor fabs through various incentives, which are listed below:

- **Equity Interest.** China has two national funds totaling some USD 50 billion. Approximately two-thirds are allocated to manufacturing. According to OECD (2019), Chinese government contributions exceed 30% of the annual revenues of the country's major chipmakers.

- **Tax Incentives.**
    - Partial VAT refund for equipment purchases.
    - Import duty exemptions for equipment.
    - Corporate tax exemptions for chip producers according to product size.

- **Site.** Local governments have land available at no cost (or at very low cost) for the siting of factories.

- **Loans.** Preferential rates for equipment and investments.

- **Grants** stipulated in programs such as *Made in China*, which focus mainly on research and development, are usually subject to domestic production.

By the beginning of 2021, China's State Council updated its Guidance on semiconductors, extending the existing benefits. The renewed incentives include 10-year corporate tax exemption for investments in nodes 28 nm or less, 5-year exemption for node manufacturing lines from 28 to 65 nm, 2-year exemption for manufacturing lines up to 130 nm and import duty exemptions for the purchase of materials and equipment.

United States

The United States is facing a situation in which its share of global chip production capacity has fallen from 37% in 1990 to the current 12% (see Box 5). This is because, in recent years, Asian countries have consolidated their efforts to attract investment, while the United States has not, relying on *laissez faire* and its natural advantage over the initial stage of the production process (design). In the face of China's aggressive policy towards self-sufficiency by 2030, the dynamic scenario looks worrisome for U.S. leadership, against a backdrop of transnational tensions and national security concerns.

One response to this situation has been the CHIPS for America Act,[34] enacted in 2021, and awaiting regulation to develop into the largest subsidy plan in U.S. history, with a fund of approximately USD 50 billion.[35] In turn, the US Congress is also drafting the Fabs Act, which considers tax credits for the establishment of factories in the territory, but with the possibility of expanding this benefit also to the Design link, thus giving a more comprehensive contemplation to the local semiconductor ecosystem.

These rules, which represent an unusual U.S. foray into industrial policy, are not well defined at the time of this writing. CHIPS is defined as a system of "tax credits for investment in semiconductor production equipment and facilities through 2026."

At the same time, the Act exceeds the mere industrial policy character, acquiring a geopolitical aspect by establishing a clause that stipulates the total return of the benefits received by the companies if they initiate joint research or technological licensing with the governments of China, Russia, Iran or North Korea (Section 4, Article 4).[36]

Taiwan

Taiwan is the world leader in semiconductor production capacity, with 22% of the estimated 2020 capacity. As such, and because of its position between China and the United States, it occupies a central place in the current crisis in the sector and in the outlook for the next phase of the chain.

[34] CHIPS as an acronym for Creating Helpful Incentives to Produce Semiconductors.

[35] This is approximately 100 times the size that *SEMATECH* was between the 1980s and 1990s. The *SEMATECH* (Semiconductor Manufacturing Technology) is a consortium of chip manufacturers and their lithography equipment suppliers, established by the US government in 1987 to compete against Japanese firms in this segment.

[36] See https://www.congress.gov/bill/116th-congress/house-bill/7178/text

To reach its current relevance in the GVC, the influence of the Taiwanese government was of great importance. Like other East Asian countries, Taiwan was a major recipient of semiconductor companies around the 1960s, particularly in the third link of the semiconductor chain. However, the Taiwanese government's intentions were for the country to move from a country with low value-added operations to one with a presence of high-value activities. That is why, early in 1973, he founded the Industry Technology Research Institute (ITRI), which has played a key role in the innovation of the country's activities, beyond the semiconductor industry. In 1974, with a focus on research and development in the chain, the government also created the Electronics Research and Service Organization (ERSO).

In 1980, as an offshoot of these two institutions, United Microelectronics Corporation (UMC), the first semiconductor company of Taiwanese origin, was founded. That same year, the Hsinchu Science Industrial Park (HSIP) was also inaugurated, following the Silicon Valley design, with proximity to large centers of knowledge generation, and framed within a set of support policies for the installation of companies such as tax deductions for R&D expenses, loans at subsidized rates, exemptions for exports, among others. The HSIP played a decisive role in the "repatriation" of highly skilled workers who had emigrated to the United States (Rasiah, et al. 2016).

The sustaining of this policy line led Taiwan to move from being an "assembler" to a territory where all links in the chain have a presence, but with a focus on device design and wafer manufacture (SIA, 2016), the latter link for which the government offers subsidies and fiscal aid that can reach up to 30% of the total investment cost (see Appendix 2), which places it on the podium of countries with the most incentives for this link. In the current wave of announcements, Taiwan intends to maintain these benefits and, above all, to reinforce its talent attraction policies in order not to lose its leading position in the market.[37]

Europe (UE)

The strong commitment that the Chinese government appears to have achieving global leadership in the semiconductor chain has not only concerned the United States. The European Commission will have, by 2022, its own set of incentives to the chain through the European Chip Act.

Europe is the region that has been "left behind" the most in the race for chip production capacity. In 1990, the continent held 44% of global production capacity, while in 2020 its share fell to below 10%. This is partly explained by the fact that Europe has bet on becoming strong in the segment of supplying intellectual property modules for the Design link (which

[37] For more details see https://www.businesstimes.com.sg/government-economy/taiwan-dangles-incentives-to-boost-global-chipmaking-lead

is mostly concentrated in the United States), as well as in the manufacture of certain specific equipment for factories (mostly located in Asia). However, in view of the crisis caused by the shortage of semiconductors, the EU has shown interest in starting to regain weight in chip manufacturing capacity and aims with its new program to double its current share in ten years, reaching 20% of global capacity by 2030 (EU, 2022). Naturally, the aim is not only quantity, but also quality, so that investments are expected to be directed towards state-of-the-art chips. The specific fund is expected to reach €20-€30 billion by 2030, a significant figure but well below that announced by the United States, and far below that planned by China. However, it is expected that there will be complementary benefits from certain strong countries in the chain (Germany, France) and the European Investment Bank (EIB).

The Act will attempt to cover the entire chain, also seeking a European R&D strategy. It also notes the understanding of the global nature of the chain, so that the strategy would consider strengthening the weak points that the Commission believes exist in Europe, but always within a framework of international cooperation.

The details of the Act will be defined with the active participation of the recently created (July 2021) Semiconductor and Processor Technologies Industry Alliance. Representatives of the semiconductor and electronics industries, as well as the related academic sector, participate in the Alliance as a sectoral roundtable. The objective of the body is to strengthen the European electronics design ecosystem and establish industry capacity requirements.[38]

Within the European Union, Germany is the main country for the semiconductor GVC, although France's *SOITEC* (with an integrated structure) is the main European company in the chain. Outside these countries, little is left for the rest, which operate more as subsidiaries of the European semiconductor strategy. In this context, and in light of the current crisis, Eastern European countries have gained some notoriety as possible candidates for attracting investments in their territories (mainly for assembly and testing). The agreement signed by the EU countries in this area includes Belgium, Croatia, Estonia, Finland, Greece, Italy, Malta, the Netherlands, Portugal and Slovenia. Other countries (Slovakia, Czech Republic and Lithuania) are also in talks with Taiwan to establish a possible cooperative relationship.

[38] For more details see https://ec.europa.eu/growth/industry/strategy/industrial-alliances/industrial-alliance-processors-and-semiconductor-technologies_en

South Korea

Together with Taiwan, Korea is today one of the leaders in production capacity, with a global share of 21%. More specifically, the country is the absolute leader in the memory segment, with a market share of over 60%.[39] As in the other countries analyzed, the current crisis has also triggered concerns for the Korean government, which is looking ahead to 2030 with the intention of consolidating its position in the memory segment, but also aiming for a more diversified position in the chain.

- Tax deductions for R&D and capital expenditures/equipment.
- Loans at subsidized rates for investments.
- Infrastructure measures: plans have been announced to expand and ensure access to potable water and energy.

India

India has a powerful electronics industry that has led to a gradual development of the semiconductor chain in the country, mostly focused on the design of devices that will eventually be consumed by the local electronics industry. This strengthening of the design of electronic systems is a government objective that has been in place for more than a decade of consolidating incentives for foreign direct investment, export promotion, human capital development and the provision of infrastructure required for the production parks of electronic devices.[40]

This electronics design and manufacturing ecosystem was negatively affected by the current shortage crisis in the sector, as India is sourcing chips from the United States, Japan, Taiwan and China. Faced with this, the Indian government decided to redirect its policy efforts towards attracting investment in the manufacturing link. In this context, an incentive plan in the order of USD 10 billion was announced, which includes financing in excess of 50% of the capital cost of eligible projects, including the main firms in the industry.[41] The first major investment announced in this context was that of the Indian mining company *Vedanta Limited*, with a joint venture with Taiwan's Foxconn for the production of semiconductors in India. In addition, the local *Tata Group* has announced plans for USD 300 million for an assembly and testing plant.[42]

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[39] This concentration in this segment occurred because this was the niche that companies in Korea found it convenient to develop towards the end of the 1980s. Prior to this, the semiconductor industry in Korea operated as a U.S. subsidiary, mostly focused on the assembly (labor-intensive) link. Unlike other industries in Korea, the development of this segment was not coordinated by the state, but autonomously by the companies in the sector (Kim and Kim, 2006).

[40] See https://www.meity.gov.in/sites/upload_files/dit/files/Esdm_Policy.pdf

[41] See https://techwireasia.com/2022/01/india-ambitious-plans-to-be-a-global-semiconductor-hub/

[42] Tata Group is an Indian conglomerate of nearly 100 companies in seven economic sectors. The semiconductor and electronics sector, then, is just one among others such as energy, services, chemicals, and communications.

Malaysia

Malaysia is one of the countries with the longest history in the semiconductor value chain, with operations of companies such as *Intel, AMD, Texas Instruments, Hitachi, Motorola* and *Siemens* since the early 1970s. By the 1990s, new global players (*Infineon, STMicro*, among others) also set up operations in the country. In this process, the government understood early on the strategic nature of the semiconductor value chain, founding the *Malaysian Institute of Microelectronics Systems* (MIMOS) in 1985 to support the R&D activities of the companies in the chain, which in the 1990s began to form a productive part of the chain with the incubation of a semiconductor wafer manufacturing plant. At that time, the Malaysian government structured its chain development efforts in its Action Plan for Industrial Technology Development (APITD). Since then, the government has developed production parks and also implemented various facility and subsidy schemes for setting up businesses (Rasiah and Shan, 2016a). Thus, the Malaysian ecosystem encompasses the presence of firms in all links of the chain, despite the fact that their relative importance in the global market has been declining over time as other locations have become stronger. Currently, the country specializes in the assembly and testing link.

In the shortage crisis, the (temporary) closure of factories in Malaysia played no small role, particularly in the late 2021 wave linked to the Delta variant of Covid-19, which strongly affected Malaysia.[43] Nevertheless, the territory continues to be a strong attractor of investment in the current context: Intel has announced a new assembly and testing plant, and the country has open cooperation relations with the United States and Taiwan, increasing its strategic role.[44] The government has not announced plans along the lines of those of other countries, but it continues to play an active role in promoting the chain with the policy instruments already in place.

Singapore

Singapore, once named a “silicon island in the east” (Matthews, 1999), is a case similar to Malaysia, at least in its inception. With the flourishing of the semiconductor industry, by the 1970s Singapore was one of the countries chosen by multinationals to develop operations: *TSMC, Texas Instruments, American Microsystems, Motorola, National Semiconductor*, among others, installed production facilities in the country. Particularly hand in hand with Taiwanese companies, Singapore became the world's leading semiconductor exporter (Rasiah, R and Xiao Shan, 2016b).

Also as in Malaysia, the government sought to play an active role in promoting investment in the territory. In the case of Singapore, the body designated to spearhead this was the

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[43] See https://www.bloomberg.com/news/features/2021-12-06/how-the-global-chip-shortage-led-to-covid-tragedy-for-one-malaysian-town

[44] See https://asiatimes.com/2021/12/big-chip-and-tech-investment-pouring-into-malaysia/

Economic Development Board (EDB). Particularly since the 1980s, the EDB has undertaken a strategy of financing investments for the design and manufacture of chips in the local territory. We also supported the development of talent for the industry.

Currently, Singapore has operations in various links of the chain of all relevant companies in the global value chain, and some national ones. It is one of the countries with the most state support for chain manufacturing investments, including benefits such as the granting of land without costs, capital and operating cost financing, as well as tax deductions (see Appendix 2).

Israel

Although one of the intrinsic characteristics of the semiconductor GVC is its globalization, it is also an industry that requires the presence of a consolidated ecosystem in the territories where it performs its various tasks. In this sense, Israel, a world leader in R&D investment as a percentage of GDP, has established itself as a technological-scientific pole that plays a key role on the global stage, and the government has played a decisive role in this. Although not of the magnitude of the main players in the chain, the Israeli government provides extensive incentives for semiconductor manufacturing projects in its territory (see Table 3, Appendix 2). The country also has a large presence in the assembly and testing link and, above all, is very prolific in the design link and its associated activities. *Apple, Facebook, Google* and other companies are developing their designs in this country, where other industry giants, such as *Intel*, already have a long history of operation.[45]

The current crisis finds Israel in a complex situation, in light of the implications of the tensions between the United States and China. Israel's relations with the United States are strong, and the role of U.S. giants such as *Intel* is decisive in this. In turn, China has become Israel's second largest trading partner, and semiconductors are a crucial part of this relationship. In its race to achieve a quick catch up in the industry, China sees Israel as an opportunity to move up a few boxes, leveraging its deep innovation ecosystem. Of course, this has sparked tensions with the United States, which has openly expressed its concern about the relationship between China and Israel.[46]

Summary and Implications

It is relevant to note that, until the supply crisis, except for China, no country had policies vertically oriented to the semiconductor sector (OECD, 2019). In recent times, and in reaction to the crisis and geopolitical tensions, all countries or regions relevant to the chain

[45] For more details see, https://en.globes.co.il/en/article-israel-seen-as-major-player-as-global-chip-war-intensifies-1001366716

[46] See https://thediplomat.com/2020/11/israeli-semiconductors-and-the-us-china-tech-war/

announced fiscal stimulus packages for the manufacturing link, which is the bottleneck that led to the current crisis, but not necessarily the determinant of the future structure of the chain on a global scale.

With packages of different sizes (Table 3), the countries have coincided in providing fiscal incentives (either subsidies and/or tax incentives) to reduce the capital cost of investments in physical capital in the manufacturing link, but also trying to cover R&D expenditures.

Table 3. Summary of Announced Policy Responses to the Supply Crisis

Country	Announced Amount (billions)	Horizon	Confirmed Policies	Prioritized Links
China	USD 150	2030	- Equity Interest - Tax Incentives - Land Grants - Subsidized Loans - R&D Subsidies	Frontend and Design
United States	USD 52	2026	The package is not defined at the time of this writing but is defined as a system of "tax credits for investment in semiconductor production equipment and facilities."	Frontend and Design
European Union	~ USD 30	2030	The package is not defined at the time of writing this report, but it is intended to subsidize investments and generate spaces for coordination.	Frontend and Design
South Korea	USD 400*	2030	- Tax deductions for R&D - Subsidized Credit - Infrastructure	Frontend and Design
India	USD 10		- Investment Co-financing	Frontend

* This amount includes private investments by Samsung and SK Hynix in which the government´s participation is only partial.
Source: Prepared by the authors based on various sources

However, the approach differs considerably from country to country. Thus, while Europe aims at a still integrated and resilient vision of the global value chain, China and the United States have proposals that are strongly conditioned by the prevailing geopolitical tensions, which neglects the aggregate objective of efficiency and the overall health of the chain. Korea, on the other hand, has a nationalistic vision, but with a strong integration of its private sector, in which it coincides with Europe. In these cases, the resulting policy is intended to have a strong private sector involvement, unlike in the Chinese case, where the path is laid out by specific plans dictated by the government, even at the cost of sacrificing aggregate efficiency.

Finally, some authors such as Calhoun (2021) are skeptical about the firepower of these packages, especially when compared to the private investments projected by major companies in the coming years. Even in the face of huge plans such as that of China (USD 180 billion), or others without precedents such as that of the United States (USD 52 billion), the amounts seem insignificant along with the investment programs for the next few years of at least the following companies (Calhoun, 2021):

- *Intel*'s proposed investment in Europe over the next 10 years: USD 95 billion, in addition to the company's recently launched investments in the United States (Arizona and Ohio, totaling USD 40 billion).
- *Micron*'s spending plans over the next decade: USD 150 billion
- *Samsung*'s proposed investment for the next three years: USD 205 billion
- *SK Hynix* will spend USD 97 billion to expand its existing smelting facilities, in addition to the USD 106 billion previously pledged for four new plants.
- *TSMC* investment over the next three years: USD 100 billion

Additionally, the ability of governments to *direct* the sector's investments in a context of imminent technological disruption is also not obvious, considering the bureaucratic delays in responding to a crisis that "has already found its situation privately" (Calhoun, 2021).

Does this mean that governments should not interfere in the value chain? No. But, as noted in Appendix 2, interventions should always seek to address market failures. Thus, the response to the crisis must be more than a mere reaction to the current situation but must entail an analysis of the current situation and future prospects, in order to improve the resilience of the chain and the position of each country in it.

Conclusions

Conclusions

This paper presents a description of the global semiconductor value chain from the perspectives of the technological content of production, business models and geographic distribution, which serves as a background to contribute to the understanding of the global semiconductor supply crisis that has been present since the beginning of the pandemic, and the measures that have been taken in both the public and private sectors in response to it.

Part I of the paper presents a detailed analysis of the semiconductor value chain and its associated sectors. Considerations are also made on the nuances that the different chip technologies, of varying complexity but all necessary for the assembly of any of the electronic devices that make up our daily lives, add to the chain. The global value chain has several characteristics that make it unique, which must be taken into account when considering policy actions. Among the main characteristics, the following stand out:

- The value chain is increasingly geographically dispersed, with each zone specializing in certain links of the chain according to its comparative advantages. That said, there are very sophisticated and highly concentrated segments, with a few global suppliers, and relatively less sophisticated ones that have been able to expand geographically.
- At the same time, no country has a certain potential to achieve "self-sufficiency".
- Over time, the chain has evolved from a market structure of integrated companies (IDMs) to one of specialization (where different business models specialize in each of the three central links of the chain). This process occurred in parallel with another one of strong concentration (mostly through mergers and acquisitions) in most sectors.
- Each link has certain particularities of resource intensity: the design link is knowledge-intensive, while manufacturing and assembly are more capital-intensive; the assembly stage is the most labor-intensive of the three.
- At the aggregate level, the chain has the particularity of allocating a proportion of sales to R&D that is almost as high as that allocated to physical investments. In both cases, these amounts are higher than those of other chains.

These particularities of the chain attribute certain vulnerabilities to harmful external events (such as natural disasters or the current pandemic) or geopolitical tensions that threaten its resilience.

In light of the crisis of excess demand suffered by the sector, due to the unusual growth in demand that arose as a result of the pandemic and the rigidities in the expansion of supply in the production link, the second part of the document focuses on the analysis of the causes of the supply crisis affecting the sector and the policy responses of the countries to this situation.

Virtually all countries involved in the chain have announced significant fiscal packages to help with the crisis and redefine the role of their territories for the next decade. The coincidence is that they all point, to a greater or lesser extent, to the causal link of shortage, the manufacturing link.

This raises questions as to whether the focus and magnitude of these programs are consistent with the premise of correcting market failures, which should be the main motivation of public policy in the chain.

Progress remains to be made in an analysis to identify opportunities and limitations for greater export development and insertion of this industry in the Global Value Chains in which Mexico participates.

What are Mexico's resources to enter the semiconductor value chain? At what stages of the production process? Why? What are the future research challenges? How much is exported today? By whom? What supplies are imported? Which companies manufacture these inputs locally and could be suppliers? What kind of public policies, institutional capacities, and instruments to support R&D and human capital formation would be needed?

Answering these questions is not a simple task and will be part of the next stage. As a preliminary step, we were able to access administrative data processing to begin to address some of these questions.

Based on ad hoc processing of Panjiva data, in 2020 companies from 9 States (Baja California, Chihuahua, DF, Estado de México, Guanajuato, Jalisco, Nuevo León, Tamaulipas and Zacatecas) exported semiconductors, with 98.5% of these destined for the United States. Of these shipments to the neighboring country, 83% came from Chihuahua and Baja California.

When considering the intermediate goods imported by the main exporters, 76 relevant tariff headings were identified. As an initial step to identify the input production capacity in Mexico, two independent sources of information were used. On the one hand, according to data from the DENUE, for the 32 SCIAN branches that produce the identified inputs, it was found that there are 1,676 economic units that can provide inputs for semiconductor manufacturing in Mexico. More than two-thirds of these companies are located in seven states (Nuevo León, Mexico, Baja California, Mexico City, Jalisco, Guanajuato and Chihuahua). Another way was to identify with information from customs tapes companies that export, but do not necessarily produce, these inputs, from which 9,546 companies were detected in this condition.

Among the most important companies in Mexico are Intel, with a design center with more than 1,200 engineers in Guadalajara and USD 100 million in annual investments, which began operations at the beginning of the century, and *Skyworks Solutions*, with almost 50 years of presence in Mexicali Baja California, which has an assembly, testing and packaging plant that employs more than 6,000 highly qualified employees and demanded an accumulated investment of USD 1.5 billion. Also in the backend link, Mexico has plants of *Texas Instruments* and *Infineon*, the world leader in semiconductor sales to the automotive sector.

Among the resources available to Mexico from the public sector, the National Institute of Astrophysics, Optics and Electronics (INAOE), which is part of CONACYT, has 147 researchers with PhDs, 22 technology developers and nearly 50 technicians to support R&D activities.

With proven capabilities in Design and *backend*, plus a privileged geographical location, Mexico can benefit from the recent wave of investment in semiconductor plants that is occurring in the United States. The challenge remains to identify the appropriate policy mix to enhance the country's capabilities in order to take full advantage of these opportunities.

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Appendix 1. Semiconductor Chain Technologies: Description and Markets

This Appendix, which closely follows the work of Kleinhans and Baisakova (2020), presents further details on the markets for the main segments within the **integrated circuits** (digital and analog) category that is ultimately the central focus of this paper.

Logic Devices: Processing Architectures

This group of semiconductors is understood as the "brain" of computers, since they constitute a processing architecture based on binary code capable of executing complex computational operations from the instructions stored in the memory devices (see below).

This includes central processing units (CPUs), graphics processing units (GPUs), and application processors (APs). There are also structures that do not require fixed instructions but can be programmed by the user (examples are Field Programmable Gate Arrays, FPGAs).

Before developing a logic processor, the instruction set architecture (ISA) on which it will be based must be decided. In this regard, an interesting feature is that the most widely used ISAs globally are owned by a few companies, depending on the different types of devices on the market.

X86: Computers and Servers

Almost all laptops and desktops have an ISA x86-based CPU. Patents for the production of such architectures for CPUs are held only by three companies, two American (*Intel* and *AMD*) and one Taiwanese (*VIA Technologies*). This has strong market implications, as the software is designed to run specifically on a particular architecture. Given that most computers on the planet are x86-based, it is difficult for competitors to convince software developers to invest resources in an uncertain market. Hence the strong interdependence between, for example, *Microsoft* and *Intel*, since the development of *Windows* in the 1980s.

Thus, the global market is basically captive to two U.S. companies, which has triggered a reaction from China to have its own alternatives, at least for its market. This led to the existence of a joint venture between the Shanghai Municipality and Taiwan's *Via Technologies*, which has a patent; *Zhaoxin* is producing processors that, although several generations behind those produced by Intel and *AMD*, are already marketed in *HP* computers in China since 2020.

ARM: Cellphones

The dominant architecture for mobile devices such as cell phones, tablets and IoT devices is generally ARM. This ISA was developed by UK-based *ARM Limited*, which was purchased by *SoftBank* (Japan) in 2016. The difference between *ARM Limited* in its market and *AMD* and *Intel* in the computer processor market, is that its product is not the manufactured processor, but the "recipe" with intellectual property (IP) so that other companies such as *Apple* or *Samsung* can design their own processors.

Despite this, the overall result ends up being quite similar to the computer market scenario: the main mobile softwares (*Android* and *iOS*) are developed on the basis of an *ISA* whose intellectual property belongs to a single company.

What is remarkable about this infrastructure is that it has potential outside the mobile market, and *Apple* has already announced that it will start developing *ARM* based CPUs for its laptops.

ASICs: Machine Learning and Artificial Intelligence

Application-specific integrated circuits (ASICs) are designed specifically for certain tasks. Today, one of the main areas of expansion are artificial intelligence tasks, such as facial recognition. These task-specific chips are then included in, for example, smartphones or other devices.

As artificial intelligence is in a strong expansion process, there is still no dominant technology for these circuits, and there are more than 100 companies performing design of this type of semiconductors.

Memory Devices

Memory store information necessary to perform any computational task. These are highly concentrated markets, due to their commodity nature with economies of scale in production. Companies that dominate production tend to operate in an integrated manner, covering almost all the links in the chain themselves. There are two dominant types of memory technologies.

DRAM: “Short term” Memory

Every computational device needs DRAM memory to temporarily store the information that is being processed at a given moment. Naturally, we associate these functions with personal computers, but they are also present in cellphones and most modern vehicles.

This is a segment that has become highly concentrated in recent times. In 2005, with a market of USD 25 billion, the eight leading companies accounted for 97% of the market. In 2019, the market volume grew to USD 63 billion, and 95% is dominated by three companies: *Samsung* and *SK Hynix*, both from South Korea, and *Micron* from the United States.

In market terms, *DRAM* behaves as a commodity. At the same time, their production requires high amounts of investment, which act as barriers to the entry of new competitors and led to the concentration described above, achieved through mergers and acquisitions over the last fifteen years. This is a sector that has been under the scrutiny of antitrust agencies at that time.[47]

China intends to enter this market to reduce its dependence on foreign chips. Thus, in 2016 appears *Fujian Jinha Integrated Circuit Company* (JHICC), which was affected by export restrictions by the U.S. Department of Commerce because of espionage activities at the U.S. *Micron*. The other Chinese company trying to compete (with German technology) is *CXMT*, but its products are several generations behind those of the leaders.

NAND: “Long-term” Memory

Unlike DRAMs, NAND memory does not require power to store data, so they are used for permanent storage (solid state drives *SSDs* or *SD cards* are examples).

In 2019, the NANDs market had a volume of USD 46 billion, and has a significantly lower degree of concentration than DRAMs. The market is essentially under the control of six companies: *Samsung* and *SK Hynix* (Korea), *KIOXIA* (Japan), and *WDC*, *Micron* and *Intel* (United States). However, China also intends to play strong here, through *YMTC*, founded in 2016.

As for the general structure, the same is repeated as in DRAM, the product behaves as a commodity with economies of scale in production, which generates barriers to entry.

Analog Components: The Link to the Physical World

These chips transmit, receive and transform information, not through zeros and ones like digital chips, but by interacting with the physical world.

The manufacture of this type of semiconductor requires much lower investments than that of digital circuits, such as logic and memory, due to their lower relative complexity. Here, what is relevant is not always being at the technological frontier, but the "field knowledge"

[47] In 2020, mergers and acquisitions in the global semiconductor industry were valued at a record USD 118 billion, surpassing the previous high of USD 107.7 billion reached in 2015 (Gartner, 2021).

of the customers they serve: analog circuits are designed for specific tasks in specific markets. Thus, the know-how required to produce a chip that drives an electric motor is quite different from that required for a semiconductor that can pick up radio waves.

It is, therefore, a much less concentrated market than that of digital circuits. However, the top 10 companies are dominated by U.S. and European companies.

Appendix 2. The Role of Public Policy in the Semiconductor Chain

When analyzing the role of public policy in the semiconductor value chain, the structure of the chain itself must be considered, as well as a basic distinction of policy objectives.

In general, government actions have tended to favor business investment in the national territory. This investment can be both in physical capital (mostly relevant for the intermediate manufacturing link) and in research and development (relevant throughout the chain, but especially in the design link). The specific tools to achieve these investments tend to coincide in both types of investments: subsidies and tax deductions. In turn, the attraction of both types of investments need not be dichotomous: the attraction of one may determine the attraction of the other. A less common alternative is that of state production or participation in companies, which is a fairly common practice in the case of China.

Regardless of these specific tools, investment attraction also depends on several other factors in which governments can play a role. Of course, macroeconomic and political stability, as well as access to competitive services (energy, water, etc.) and infrastructure are the minimum basic conditions to guarantee a flow of investment.

The ecosystem is also a crucial variable. Although this is a deeply globalized chain, it is important that the countries where the investments are located have a favorable ecosystem in terms of other companies or related activities, as well as the presence of a stock and flow of specialized human capital at a reasonable cost. In this aspect, the role of governments ranges from regulations to their participation in the promotion of certain professional profiles and the attraction of human capital from other locations.

Finally, such a globalized chain demands stability and clear rules of the game in terms of foreign trade policy; we will see that this is a weak point in the chain's resilience.

In summary, when establishing policy tools, governments must be clear about what type of investment they wish to promote and in which link of the chain they intend to do so, which requires a clear understanding not only of the structure of the chain, but also of the place that local companies occupy in the global chain. Attracting investment is not an end in itself, but an action that should seek to correct market failures. The aim is to answer how to correct situations that are far from the social optimum. In this sense, the identification of these market failures is what ultimately determines the appropriate set of tools to achieve convergence towards a socially optimal allocation of resources.

In what follows, a detailed analysis of these governance objectives and their policy tools will be made from a perspective that combines the normative with the experience of the countries in each case. The purpose of this Appendix is to complement the analysis presented on the response of governments to the current supply chain crisis, to provide a broad perspective on the policy actions planned for the short and medium term for the sector.

Investment Leverage

Promotion of Development Research

The promotion of research and development is one of the main objectives of the policies of the governments involved in the chain. This makes sense, particularly considering that the semiconductor value chain is one of the most R&D intensive globally. It is also worth remembering that this feature has the particularity of decreasing along the chain: the Design link is by far the most knowledge-intensive link, while in the Assembly link the relative expenditure on R&D is much less relevant.

Innovation activities are generally reinforced by some form of government intervention, since companies are considered to invest less in these developments than would be socially desirable. In general, beyond the specific case of the semiconductor chain, it is agreed that there are market failures that justify the need to intervene to stimulate innovation (Griffit, 2000; Lucking, Bloom and Van Reenen, 2018).[48] However, how to approach this intervention may be decisive in terms of not generating more distortions by trying to fix one.[49] In this regard, the evidence is inconclusive. Authors such as Dimos and Pugh (2016)[50] find that subsidies to R&D activities of private firms "are not wasted"; that is, they do not displace spending that firms would have executed anyway, but rather, thanks to these subsidies, R&D expenditures are generated that would not have been executed otherwise. However, the same study also finds that this strategy is not capable of DRIVING additional R&D expenditures by companies.

There is a relative consensus that interventions in this area should be directed as "upstream" as possible (OECD, 2019). In the case of semiconductors, the precompetitive research stage can take more than ten years to see its findings materialize in the production chain. This is a long-term research process, with much higher risks than R&D investments in the semiconductor production links. Thus, the investment gap with respect to what is socially desirable will be greater in the pre-competitive segment than in R&D, for example, at the

[48] Cited in OECD (2019).

[49] An example where intervention could have been distortive is cited in Peck (1985), where reference is made to the U.S. Very High Speed Integrated Circuits Program (VHSIC) in 1980. This microchip and process development program for the semiconductor industry may have contributed to a shortage of skilled human capital in the private sector by increasing their remuneration in the public sector.

[50] Cited in OECD (2019).

design or production link, where competition and fast production cycles generate sufficient incentives for investment. Put another way, encouraging precompetitive research can correct major distortions, as well as potentially generate greater spillovers throughout the chain, minimizing risks of distortions.

Promotion of Physical Investment

The promotion of physical investment is normally associated with the search for domestic chip production capacity. As shown in Box 5, this the objective was pursued (and achieved) by Asian countries. China and South Korea were able to consolidate increases in their production capacity over the last decade, while Taiwan and Japan managed to sustain their levels of participation in the global production capacity of the chain.

A relevant aspect is the high amount of investment required to start up a new chip plant. In this regard, Varas, et al. (2020) made a cost comparison between countries to cover three standard capacity model factories in three different technologies over a 10-year period: logic, memory and analog devices. The cost of setting up these plants in the United States would range from about USD 5 billion (analog) to about USD 20 billion (logic-memory) including the cost of land, buildings and equipment. In turn, operating costs (labor, energy, materials, taxes and others) would be in the order of USD 0.6 to 2 billion per year for plants with 3 to 6 thousand employees, depending on the technology.

Given the high amounts of investment required to build a chip factory, government incentives are critical in deciding where to make the investment. In general, these incentives are aimed at reducing the initial capital cost (land, construction, equipment), as well as the operating cost. Table 4 presents the comparison of government incentives by item resulting from the survey of the aforementioned study, measured in terms of the reduction in total cost of ownership before incentives.[51]

[51] Total cost of ownership (TCO) is calculated as the sum of capital expenditures (Capex) plus operating costs (Opex) over a 10-year period, minus incentives.

Table 4. Government Incentives in Different Locations (as % of total cost of ownership, first ten years of operation)

	USA (1)	Japan	South Korea	Taiwan	Singapore	Asia (2)	China (3)	Germany	Israel
Capital reductions (Capex)									
Land	50%	75%	400%	50%	100%	85%	100%	100%	75%
Construction	10%	10%	45%	45%	25%	33%	65%	35%	45%
Equipment	6%	10%	20%	25%	30%	20%	35%	5%	30%
Operating reductions (Opex)									
Work and benefits	5%	5%	5%	5%	15%	7%	33%	7%	5%
Tax Reductions									
Corporate Taxes	-	-	60%	-	35%	30%	75%	-	74%
State Taxes	100%	-	-	-	-	-	-	-	-
Property Taxes	100%	100%	100%	-	-	60%	-	-	-
General abatement	**10-15%**	**15%**	**25-30%**	**25-30%**	**25-30%**	**25%**	**30-40%**	**10-15%**	**30%**

(1) Based on a best-case scenario with current incentives and recent agreements. (2) Excludes China. (3) Mainland China

Source: Extracted from Varas, et al. (2020)

However, physical investment is normally directed to where the market sees "comparative advantages" in terms of costs, legislation, infrastructure, services and legal security. Thus, investment attraction policies should be aimed at correcting failures (both market and government) that result in the national territory being "uncompetitive" in the face of other options.

However, many governments have acted to *create* such comparative advantages by reducing the costs of implementing (and sometimes operationalizing) these investments through subsidies, tax exemptions and the provision of land at zero or subsidized cost. This type of policy tends to create distortions that can threaten the resilience of the chain.

Although the current crisis in the sector has to do with insufficient production capacity, it is still a crisis of excess demand that is cyclical, and it cannot be said that the crisis is due to insufficient investment in relation to the social optimum.

Policy Tools

We have seen that government actions in fiscal matters can take the form of subsidies or tax incentives and are used both to achieve physical capital investments and to bring R&D actions to socially desirable levels.

Following Crespi, et al. (2014), **subsidies** establish a type of direct support in which money is transferred to companies to execute an investment or innovation action. There are two usual ways of making these transfers: matching grants) and conditional loans (at below-market rates).

Tax incentives are usually the most widespread tool in the semiconductor chain and consist basically of a tax deduction for companies, conditional on the realization of the investment. The goal is to reduce the cost of capital.

In R&D promotion programs, these tax incentives are often combined with **collaboration** stimulus clauses with other players in the innovation system, such as research centers, technology institutes and other firms.

Crespi, et al. (2014) compare both types of fiscal instruments, which are summarized in Table 5.

Table 5. Tax Incentives: Subsidies vs. Tax Incentives

	Direct Subsidies	Tax Incentives
Mechanism	Project-based financing.	Based on R&D activities at the company level.
Impacts	Reduce marginal costs of R&D activities.	Reduce marginal costs of R&D activities.
Collaboration	Funding can be geared towards collaboration.	Deduction can also be oriented towards collaboration.
Externalities	Financing can be oriented towards projects with high externalities.	Mechanism totally favorable to the market. The company decides. It may be biased in favor of projects that are more appropriable by the private sector.
Liquidity Restrictions	Financing can provide partial cash advances (relaxing liquidity constraints). Financing can give “signals” to outside investors.	They operate entirely ex post and are less suitable for solving financial constraints. No signs
Focus	High (financing can be oriented towards companies with innovation problems, such as SMEs or innovative start-ups).	Low (efficiency depends on the overall tax context of the country, other tax exemptions and loopholes) with a bias in favor of larger companies.
Implementation Costs	High ex ante and ex post.	Low ex ante, but high ex post.
Institutional Capabilities	High capabilities in innovation agencies.	Lower capacities in innovation agencies, but higher capacities in the tax authority.
Business Capabilities	High (to develop a project).	High (to identify an innovation program)
Tax Costs	Controlled and transparent costs. The financing is oriented to marginal project.	Without control, tax costs depend on the decisions made by the company. When based on volumes, the subsidies are intended for intra-marginal projects as well. They make the tax system more complex
Moral Hazard	Financing can be targeted to companies that do not face market failures.	They create an incentive to artificially classify non-R&D expenses as R&D that will not be easily controlled by the tax authorities.
Good Design Practices	Implementation of a competitive allocation process (call for bids). The subsidy rate is proportional to the size of the externalities (higher for public goods, generic research or collaborative projects). Transparent allocation through a public-private board based on evaluations by external and independent peer reviewers. Capacity building in companies for project formulation and setting targets for financing. Inclusion of a sunset clause with a rigorous monitoring and evaluation system.	Base incentives on R&D growth rather than on volume or establish a project-based decision-making process similar to subsidies. Building monitoring and evaluation capacities in the tax authority. Include in the deduction a premium for externalities (e.g., collaboration or hiring of R&D personnel). Inclusion of deferral or cash conversion for new companies. Predicting the fiscal cost and including it in the budget, establishing a transparent mechanism to allocate credits when demand exceeds supply. Inclusion of a sunset clause with a rigorous monitoring and evaluation system.

Source: Extracted from Crespi, et al. (2014)

Another strategy to increase investments (physical and intellectual) is for the government itself to **participate in the productive process.** Countries such as China and Korea have tried and have agendas to achieve "national champions" (or world leaders) in this segment, but the truth is that it is difficult to catch up technologically with respect to the players already established on the global stage. However, **direct state production** is something that only China has incurred, under its policy framework for semiconductors with *Made in China* 2025.

The Importance of Trade Rules

In a chain as globalized as the semiconductor chain, countries' trade policies are a crucial element when talking about their resilience. Thus, an adjusted trade structure allows the normal development of the production flow, but a situation of geopolitical tensions or the quest of some countries to strengthen their position may end up compromising this flow of work.

Within the international framework provided by the International Trade Organization (WTO), there are currently 82 countries representing 97% of trade in technology products[52] grouped under the Plurilateral Information Technology Agreement (ITA). This agreement (which began in 1996) consists of the elimination of import tariffs on 201 products, 33 of which are directly linked to the semiconductor chain.

The OECD (2019) article finds a substantial reduction in the average tariff for the chain. In the case of China, the decrease is substantial, but it still has a high average tariff compared to the other countries surveyed.

Unfortunately, this reduction in tariff measures does not in itself mean an increase in the chain's trade facilities. In fact, this process occurred in parallel with an increase in non-tariff trade measures (NTMs), which include production standards, intellectual property regulations and particular public procurement requirements. The latter is particularly relevant when the focus is on national security; there may be restrictions on the composition of the company's board of directors or its legal residence and may also extend to investments in the country.

National security has also been the banner under which export restriction policies, which have a long history in the history of the semiconductor chain, have been raised. In this regard, the 1996 Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies has helped restrict exports of certain parts or components more closely linked to the military sector.

[52] It is worth mentioning that, although it is a "limited" multilateral agreement, the tariff eliminations associated with the agreement apply on a Most Favored Nation (MFN) tariff basis, also benefiting the remaining WTO members that do not explicitly participate in the agreement.

Human Capital Development

As previously mentioned, the establishment of investments (physical or knowledge) requires the pre-existence of a certain ecosystem that contributes to the return of these disbursements. A fundamental part of this ecosystem is the existence of qualified human capital at reasonable costs. As in all other sections, what is stated here has its nuances depending on the stage of the chain on which we focus, and even on the technological segment on which the focus is placed.

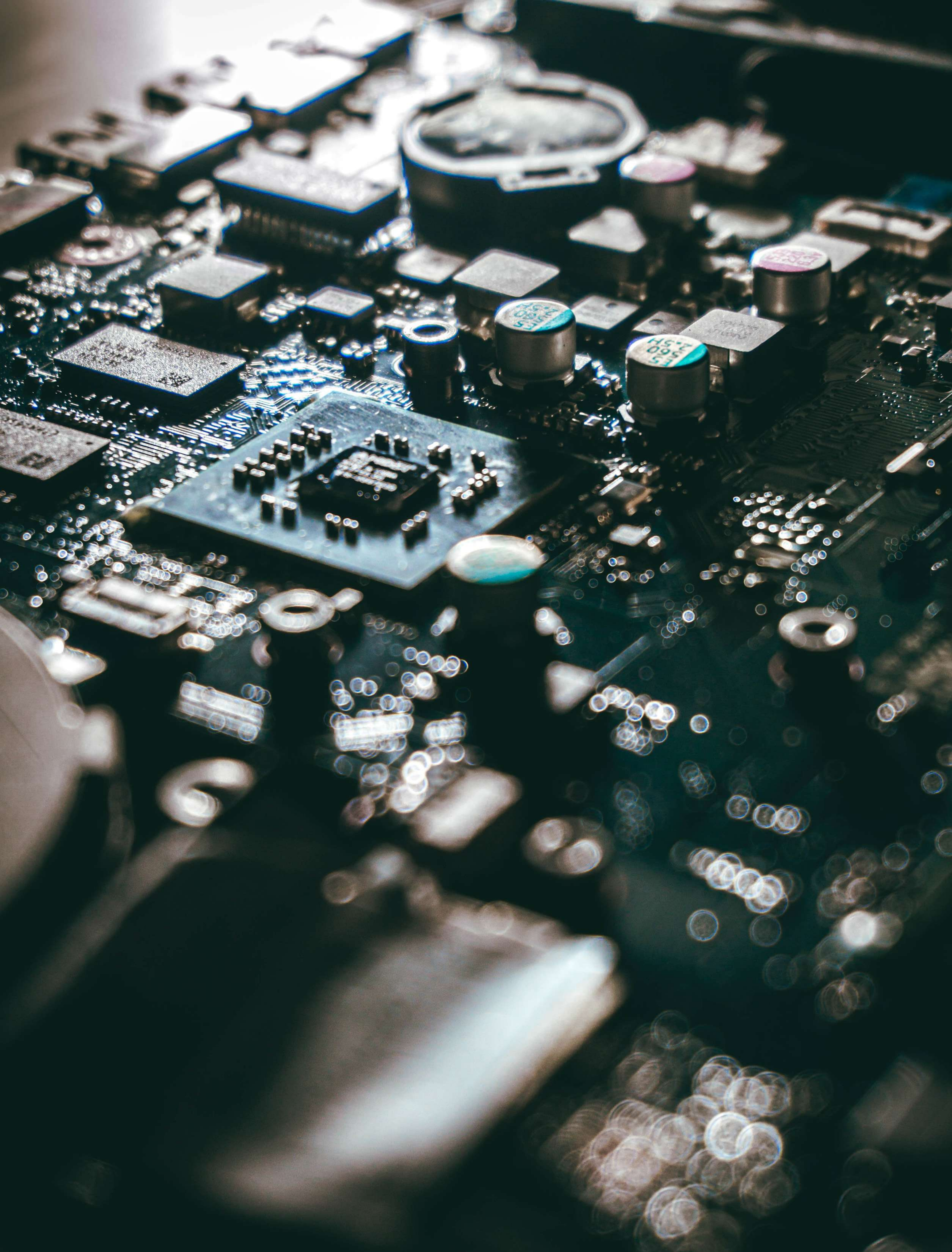
Nevertheless, it can be said that, in general terms, governments have three main tools to collaborate in the development of human capital:

- **Promotion of Related Careers.** Regardless of the prevailing university system, the government can contribute to the promotion of certain careers of interest to industry, and even influence the content of curricula. Although this type of action may include monetary transfers such as scholarships, it is worth noting that often in the educational segment the main shortcoming is not access to financing, but rather lack of information. Thus, the role of the government may have nuances, depending on the situation.

- **Flexible Legislation.** It is a horizontal action, in the sense that it is usually extensive to the entire economy and has to do with labor legislation. Flexible labor markets are often relevant to the operational phase of the investment and are linked to the following item.

- **Facilitating Mobility.** The movement of talent is a characteristic feature of R&D-intensive industries, so governments should seek to facilitate it. This is because this mobility is a natural way of transferring tacit knowledge which, in the semiconductor industry, is of relevance.[53]

[53] According to OECD (2019) there are numerous successful examples of talent mobility in the semiconductor value chain, highlighting for example the cases of Samsung (sending engineers to California to assimilate newly licensed technology from *Micron* and *Zytrex*) and Intel (early hiring of Israeli staff in top positions, who then led the company to establish R&D and foundry operations in their home country).



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