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Vulnerabilities in the semiconductor supply chain

Antton Haramboure (OECD), Guy Lalanne (OECD), Cyrille Schwellnus (OECD), Joaquim Guilhoto (IMF)[1]

Semiconductors are a critical input into a wide range of downstream industries, including the wider information communications technology (ICT) industry, electronics, and motor vehicles. Semiconductor shortages can have large adverse effects on output in these industries, with ripple effects on the broader economy, as highlighted by recent supply chain disruptions. This paper maps cross-country and cross-sectoral dependencies in the semiconductor value chain based on new OECD Inter-Country Input-Output data that allow to analyse the semiconductor industry separately from the wider ICT value chain. It further discusses policy options to reduce the economic consequences of shocks to the semiconductor value chain while preserving the benefits of global sourcing.

Keywords: Global Value Chains, International trade, Resilience, Semiconductors

JEL codes: F14, F68, L52

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[1] Joaquim Guilhoto contributed to this paper while working at the OECD.

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Executive summary

Recent semiconductor shortages have highlighted the importance of semiconductors as critical inputs into a wide range of industries, including information and communications technology (ICT), electronics and motor vehicles. These shortages partly reflect unprecedented demand and supply shocks but also a number of structural features of the semiconductor value chain, such as high fixed production costs and high concentration.

This paper uses new Inter-Country Input-Output (ICIO) data that separates the semiconductor industry from the rest of the computer and electronics industry to identify key linkages and vulnerabilities. The new data cover the three core semiconductor manufacturing stages (chip design, wafer foundry, and assembly, test and packaging – ATP) and allows uncovering three key facts:

- **The semiconductor industry is among the most upstream industries:**
    - On average across countries, "ICT and electronics (excluding semiconductors)" stands out as the industry that is most highly dependent on semiconductors, with semiconductor value added accounting for 8% of final demand.
    - In another six industries (including machinery, motor vehicles, and other transport equipment), semiconductors are about as important as primary energy as an input into production.
- **The semiconductor industry is geographically highly concentrated, with the top-5 semiconductor-producing economies accounting for around three-quarters of global value added**:
    - Over the period 1995-2018, the centre of gravity of semiconductor production shifted from Japan and the United States to a few Asian producers, namely the People's Republic of China (hereafter "China"), Korea and Chinese Taipei.
    - In 2018, China, Korea and Chinese Taipei accounted for around 60% of global semiconductor value added.
    - Most semiconductor-using economies heavily depend on the leading Asian producers, with only limited differences in dependencies across purchasing economies.
    - Complementary analysis using highly disaggregated trade data reveals that geographic concentration of production is even more pronounced for some specific semiconductors (e.g. memory chips) and certain capital goods used in semiconductor production (e.g., specialised machinery and equipment).
- **Across economies, dependencies on semiconductors are driven by different industries:**
    - In most Asian economies, dependencies are mainly explained by the "ICT and electronics (excluding semiconductors)" industry.
    - In the United States and most European economies, dependencies reflect to a much larger extent the "transport equipment", "machinery" and "other manufacturing" industries.
    - In a small number of economies, including Canada and Hong Kong (China), the telecommunications industry accounts for a large part of dependencies.

Overall, these results are consistent with the view that the semiconductor value chain can be a significant source of vulnerability, with a disruption of semiconductor production in a single Asian economy potentially triggering shortages in a broad range of downstream economies and industries.

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FIGURES

1 Introduction

Recent semiconductor shortages have highlighted the critical importance of semiconductors for a range of downstream industries, including information and communications technology (ICT), electronics and motor vehicles.[1] For instance, a modern car may contain 3 000 semiconductor chips, which control anything from battery management, fuel injection to infotainment systems. These shortages can have sizeable effects on aggregate output and price developments (Leibovici and Dunn, 2021[1]), with some estimates suggesting that in the first nine months of 2021 the reduction in motor vehicle production related to semiconductor shortages lowered GDP by 1½ percent in Germany and between ½ - 1% in the Czech Republic, Japan and Mexico (OECD, 2021[2]).

To some extent, recent semiconductor shortages – that were particularly pronounced for legacy logic chips, analogue chips and optoelectronics chips (U.S. Department of Commerce, 2022[3]) – reflect the exceptional confluence of positive demand shocks and adverse supply shocks. Even before the COVID-19 crisis, demand for semiconductors had been exceptionally strong, partly due to stockpiling by Chinese tech players in anticipation of US export bans.[2] During the initial stages of the COVID-19 crisis, manufacturing companies in a range of industries, including motor vehicles, anticipated large drops in demand and cancelled most of their semiconductor orders. But demand for semiconductors quickly started to surge, as lockdowns and remote work triggered an increase in demand for electronic devices, and motor vehicle demand recovered faster than expected when mobility restrictions were eased. Surging demand for semiconductors was accompanied by a number of exceptional supply disruptions, such as fires at Japanese production sites, adverse climate events in the United States and Chinese Taipei, as well as shipping delays.

The impact of these exceptional shocks has been amplified by a number of structural features of the semiconductor value chain. First, large upfront investments, long lead times and access to a highly-specialised talent pool are required to increase manufacturing capacity, implying slow supply adjustment to surges in demand. Building a manufacturing plant for leading-edge semiconductors requires an upfront investment of USD 10-20 billion (Shih, 2021[4]). Second, the digital transformation may structurally raise the demand for semiconductors, as a growing number of products incorporate chips. Third, the bulk of semiconductor production is concentrated in a small number of key companies and economies, with each actor typically specialising in one specific stage of the value chain. For instance, many US semiconductor companies have adopted "fabless" business models, specialising on chip design and outsourcing manufacturing to East Asia, where about 80% of global chip exports originate.

More generally, these structural characteristics imply that the semiconductor supply chain may be vulnerable to short-term demand surges and supply disruptions, as capacity cannot easily be ramped up in the short term, demand is on an increasing trend and local supply disruptions may stress the entire value chain.

These vulnerabilities have given rise to policy initiatives aiming to onshore parts of the semiconductor manufacturing value chain, including the European and US CHIPS Acts. Given high levels of geographical concentration, segmentation of production into multiple stages and the wide variety of differentiated products, semiconductor users have only limited scope for diversifying their supply chains. Consequently, a number of key economies (including China, the European Union and the United States) aim to increasingly source semiconductors from close allies or onshore parts of the semiconductor value chain, with a view to achieving “strategic autonomy”.

Onshoring (or nearshoring) does not come without costs, both in terms of efficiency (higher production costs) and in terms of transitional costs (upfront investments into domestic production capacities),[3] and typically involves industrial policy measures, such as subsidies. Onshoring efforts can target both increased production capacities for existing technologies, or the domestic development of leading-edge chips. The key policy challenge when trying to achieve “strategic autonomy” is to promote the security of supply while simultaneously minimising adverse side-effects on economic efficiency and ensuring the efficiency of public support.

This paper provides a number of results on dependencies in the semiconductor value chain and lays the ground for future work. Despite the significant attention devoted to the causes of semiconductor shortages and their possible remedies, quantitative analyses of vulnerabilities in the semiconductor supply chain have been scarce, partly due to the lack of harmonised cross-country data.[4] This paper contributes to the debate by constructing new Inter-Country Input-Output (ICIO) tables that allow analysing the semiconductor industry separately from the rest of the computer and electronics value chain. In standard ICIO tables, semiconductors are reported jointly with the broader computer and electronics industry, precluding the disaggregate analysis carried out in this paper.

The remainder of this paper is structured as follows. Section 2 provides a primer on the semiconductor supply chain. Section 3 briefly describes the methodology used to separately identify the semiconductor industry in the system of ICIO tables, with the detail provided in Annex A. Section 4 analyses dependencies in the semiconductor value chain across countries, industries and time, and Section 5 concludes.

2 Setting the scene: The semiconductor value chain

The production of semiconductors consists of a multitude of stages, with the three core stages of chip design, fabrication and assembly depending on critical upstream inputs, such as a number of critical raw materials (European Commission, 2020[5]) and specialised software and machinery. Semiconductors are in turn a critical input into a large number of downstream industries, with different industries typically requiring a different range of specialised chips, for instance for artificial intelligence development and applications. This intricate landscape, marked by a high degree of fragmentation and specialisation, may contribute to potential vulnerabilities and risks in the supply chain.

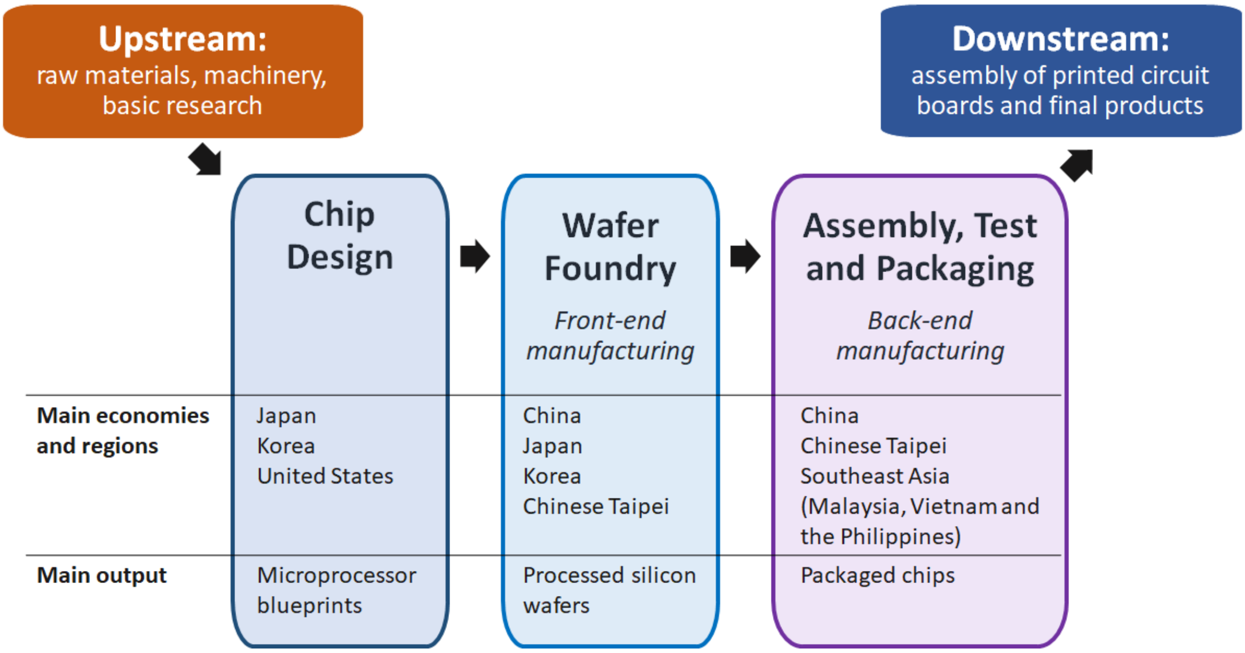
The value chain is highly fragmented

The semiconductor value chain consists of three core stages (BCG and SIA, 2021[6]; The White House, 2021[7]; McKinsey and Company, 2022[8]):

- *Design.* This stage includes setting the requirements of the chip, designing its architecture, and validating its design on a test bench. The design stage represents about half of semiconductor value added but only 10-15% of physical capital expenditure.
- *Fabrication / Foundry.* This stage consists in printing (or “etching”) the integrated circuit designed in the previous stage on a silicon wafer. Fabrication/foundry relies on a large number of complex advanced manufacturing processes, representing about one-quarter of semiconductor value added but almost two-thirds of physical capital expenditure.
- *Assembly, Test and Packaging.* This stage involves slicing the wafers into individual chips, packaging the chips into frames or resin shells, and testing them. Assembly, test and packaging is less skill- and knowledge-intensive than the core upstream stages, representing only about 5% of semiconductor value added, but 10-15% of physical capital expenditure.[5]

Integrated Device Manufacturers (IDMs) integrate the three core production stages while others are specialised in a single stage. “Fabless” firms, for instance, focus on the design stage and outsource the core downstream stages to specialised manufacturing companies. In 2019, IDMs accounted for about 70% of global semiconductor sales (BCG and SIA, 2021[6]).

Figure 1. Semiconductor production



	Chip Design	Wafer Foundry	Assembly, Test and Packaging
Main economies and regions	Japan Korea United States	China Japan Korea Chinese Taipei	China Chinese Taipei Southeast Asia (Malaysia, Vietnam and the Philippines)
Main output	Microprocessor blueprints	Processed silicon wafers	Packaged chips

Source: Adapted from McKinsey and Company (2022[8]) and BCG and SIA (2021[6]).

The core semiconductor value chain relies on critical upstream inputs, including basic research to improve the design and performance of chips and specialised software (e.g., Electronic-Design Automation EDA), raw materials (e.g., silicon, rare earth elements, platinum group metals, gallium, germanium) and capital equipment (e.g. lithography tools, metrology and inspection equipment). Downstream stages include the assembly of chips onto printed circuit boards and their integration into high-tech products (e.g., computer and electronic products, transport equipment – such as cars, and military equipment).

Semiconductors consist of a vast number of specialised products

Semiconductors can be grouped into three categories (BCG and SIA, 2021[6]):

- *Logic chips,* which process binary information (i.e., 0s and 1s). They include microprocessors (e.g., central and graphics processing units, including for artificial intelligence applications), microcontrollers and connectivity chips (e.g., modems, Wi-Fi or Bluetooth chips).
- *Memory chips,* which store data (e.g., Dynamic Random-Access Memory chips and flash memory).
- *DAO chips* (for 'Discrete, Analog and Others'), which process non-binary information, typically continuous parameters (e.g., diodes, transistors, voltage regulators, radio frequency chips, optical sensors).

In general, high-tech goods rely on all three categories of semiconductor chips but electronic products tend to use a higher share of logic chips, whereas machines and transport equipment incorporate a higher share of DAO chips. "Fabless" business models are common in the production of logic chips, whereas IDMs dominate the production of memory and DAO chips.

Chips differ by node size (a proxy for the characteristic length of the electronic circuit components), which ranges from around 3 to more than 180 nanometres. Smaller node sizes require more complex and costly manufacturing processes, with nodes of DAO chips typically being large, memory chips being in the intermediate range (between 10 and 50 nanometres), and logic chips ranging from small to large node sizes depending on the final use.[6]

High fragmentation and specialisation of production can contribute to vulnerabilities

The international fragmentation and specialisation of semiconductor production is a highly cost-efficient business model. Companies designing semiconductors in economies with high R&D and technological capacities can shift the manufacturing stages to the economies with the lowest production costs. This enables them to harness the benefits of economies of scale by specialising in producing large quantities of highly differentiated semiconductors.

The flipside of high-cost efficiency is that fragmentation and product variety may lead to increased vulnerability to shocks, as the supply chain is exposed to various local risks. For instance, natural disasters affecting foundries in a key producer, such as Chinese Taipei, can have large ripple effects for both upstream suppliers and downstream users of semiconductors. Even industries and economies that do not directly export intermediate inputs to or import semiconductors from Chinese Taipei may be strongly affected through indirect value chain linkages. Moreover, given high degrees of geographical concentration of production and horizontal differentiation, semiconductors produced in a given economy or company may not be easily substitutable with other semiconductors, creating the potential for shortages even when shocks are circumscribed to few economies or companies.

ICIO tables can account for both fragmentation of semiconductor production and, to some extent, specialisation, making it an ideal tool for analysing implied vulnerabilities.

- ICIO tables allow tracing production along the entire value chain, enabling the identification of both direct and indirect exposures to disruptions. For instance, low direct imports of semiconductors from Chinese Taipei do not necessarily imply low exposure to disruptions in Chinese Taipei. Indirect exposure could be high if imports from other source economies incorporate high shares of Chinese Taipei semiconductors.
- Moreover, ICIO data allow identifying the origin of semiconductors for each purchasing industry and economy (and, conversely, the destination by industry and economy for each producing economy). For instance, they allow assessing whether the US automotive industry depends more heavily on semiconductors from a specific source economy than the US computer and electronics industry.

A limitation of ICIO data for the analysis of vulnerabilities in the semiconductor value chain is that ICIO data cannot account for disruptions in the production of specialised machinery that is critical for semiconductor production. According to national account conventions, machinery purchases are not considered intermediate input purchases but investments.[7] Moreover, ICIO data do not account for the role of substitutability of inputs or inventories in buffering global value chain shocks. Incorporating these two phenomena in the analysis would require behavioural assumptions, i.e., designing an economic model based on ICIO tables.

3 Data and methodology: Identifying semiconductors in the ICIO system

Standard ICIO tables are too aggregated to provide granular insights into the semiconductor value chain. In standard ICIO tables, semiconductor production is included in the "Computer, electronic and optical equipment" industry, which also contains products such as personal computers or smartphones that are largely used as final goods.[8] Therefore, standard inter-country and inter-industry flows of "Computer, electronic and optical equipment" provide little information on semiconductor flows.

This paper estimates semiconductor-augmented ICIO tables, where the "Computer, electronic and optical equipment" industry is split into two sub-industries ("Semiconductors" and "ICT and electronics (excluding semiconductors)"). The estimation proceeds in two main steps: (1) extracting relevant information from bilateral trade data and five domestic input-output tables that are sufficiently granular to identify semiconductors; and (2) constructing an estimated semiconductor-augmented set of technical input-output coefficients. Gross output, flows of intermediate inputs and value-added in the semiconductor industry follow directly from the estimated technical input-output coefficients. The details of the estimation procedure are described in Annex A.

Trade and input-output data used in the first step are obtained from the following sources. Bilateral trade flows of semiconductors over the period 1995-2018 are obtained from the "Bilateral Trade in Goods by Industry and End-use Category" database.[9] Information on inputs used in the semiconductor industry and the use of semiconductors as an input in other industries comes from five domestic input-output tables that are sufficiently granular to identify semiconductors (Korea, Japan, Malaysia, Chinese Taipei and the United States). These five economies represent 75% of the world semiconductor value added in 2018.

The technical input-output coefficients in the second step are constructed by combining the information in the bilateral trade data and national input-output data as follows. For the five economies with disaggregated domestic input-output tables, domestic technical coefficients are directly available. For the other economies, technical coefficients of an economy with a similar semiconductor industry are used, where the matching between economies is based on expert judgement.[10] Technical coefficients for international flows of semiconductors are estimated to match, firstly, bilateral trade flows of semiconductors and, secondly, the use of semiconductors across industries as reported in the five disaggregated input-output tables.

The semiconductor-augmented ICIO data have a number of limitations. First, primary information on the use of semiconductors is not available for all economies. Hence, data for the other economies need to be imputed. Second, the disaggregated national input-output tables are only available for one year. Even though the use of trade data over the whole period (1995-2018) ensures that the semiconductor-augmented ICIO tables accurately reflect the growth in semiconductor trade, it does not necessarily capture domestic trends. These limitations notwithstanding, imputations are informed by the best available trade and input-output data; balancing constraints ensure the overall consistency of the international input-output system; and the ICIO tables cover the three core manufacturing stages (chip design, foundry, ATP), as well as its upstream (e.g. raw materials) and downstream (e.g. the remainder of the ICT & electronics industry) linkages. Linkages with the industries providing specialised machinery cannot be analysed using ICIO data since capital goods purchases are not recorded as intermediate input purchases.

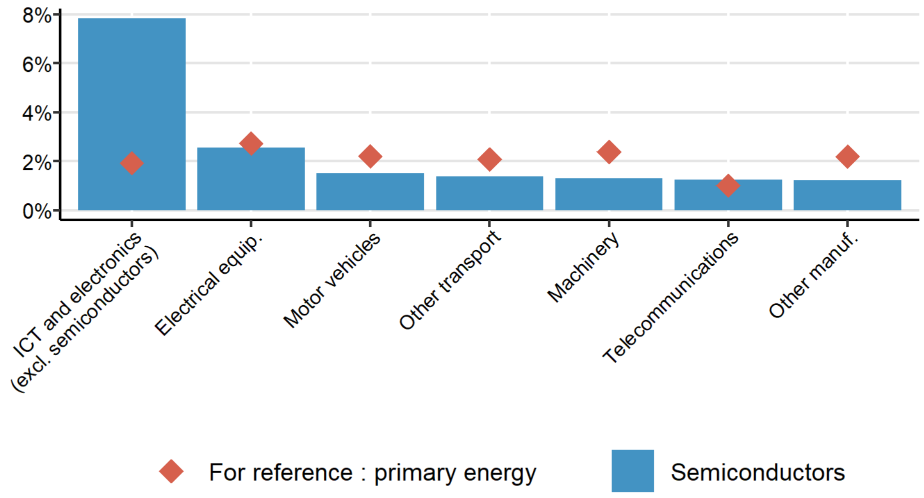
4

Dependencies in the semiconductor value chain across economies, industries, and time

Semiconductors are a crucial input into production in several industries (Figure 2). In the "ICT and electronics (excluding semiconductors)" industry, semiconductors account for around 8% of the value of the final product as compared to 2% for primary energy.[11] Given low substitutability of semiconductors, this suggests that a disruption in semiconductor supply could have significantly more negative effects on the "ICT and electronics industry (excluding semiconductors)" than a disruption in primary energy supply. In the other main purchasing industries, such as motor vehicles, other transport and machinery, and telecommunications, semiconductors are broadly on par with primary energy as input into production.

Figure 2. Semiconductors are a crucial input into a range of industries

Share of semiconductor and primary energy value added in final demand, 2018

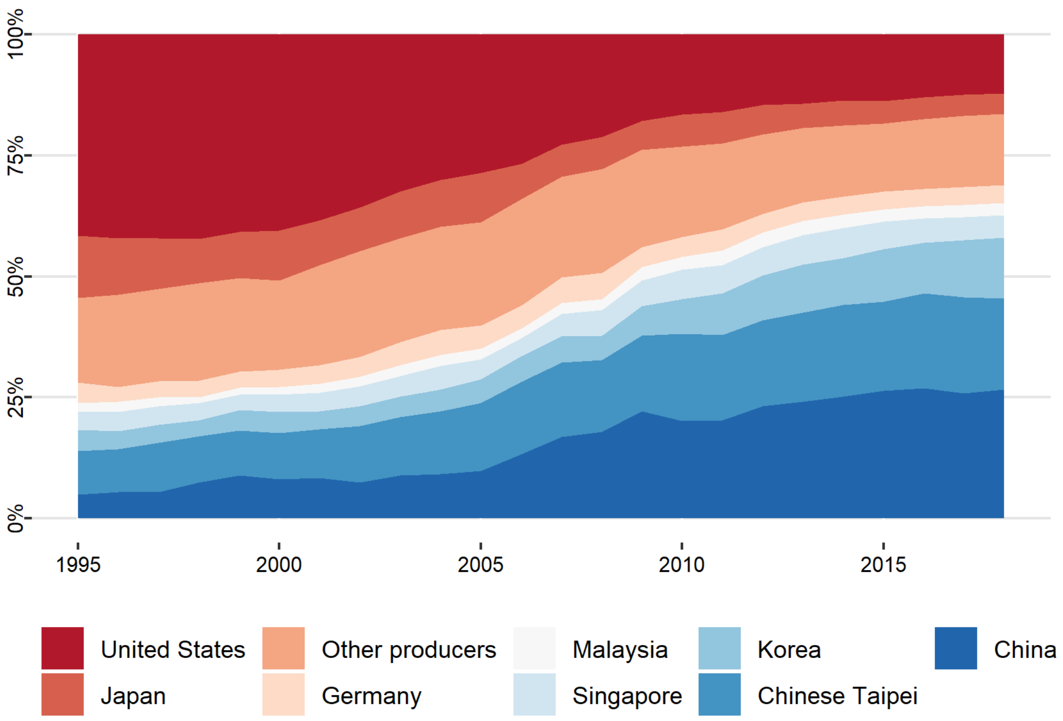


Note: The sample is restricted to the leading purchasing economies: Brazil, Canada, China, France, Germany, Hong Kong (China), Ireland, Italy, Japan, Korea, Malaysia, Mexico, the Netherlands, the Philippines, Singapore, Switzerland, Chinese Taipei, Thailand, the United Kingdom, the United States. Primary energy includes coal, oil and gas.
Source: OECD semiconductor-augmented ICIO tables

The centre of gravity of semiconductor production has gradually shifted from the United States and Japan to China, Korea and Chinese Taipei. In 1995, the United States and Japan accounted for more than 50% of global semiconductor value added while China, Korea and Chinese Taipei accounted for only about 20%. In 2018, market shares had shifted almost symmetrically, with China, Korea and Chinese Taipei now accounting for more than 50%, and the United States and Japan for about 20%. This was concomitant with the shift of some US semiconductor companies to a "fabless" production model, where foundry and packaging are outsourced and only chip design is retained in-house (Figure 1).[12] The shift of semiconductor manufacturing to Asia makes semiconductor producers and their clients vulnerable to production disruptions in Asia. At the same time, most Asian semiconductor manufacturing companies remain dependent on foreign chip designs and equipment and thus potentially vulnerable to bans on the sharing of intellectual property or export controls.

Figure 3. Semiconductor production has become increasingly concentrated in few Asian economies

Share of global semiconductor value added, %



Note: The main producers are defined as the economies with the highest average value added between 1995 and 2018.
Source: OECD semiconductor-augmented ICIO tables

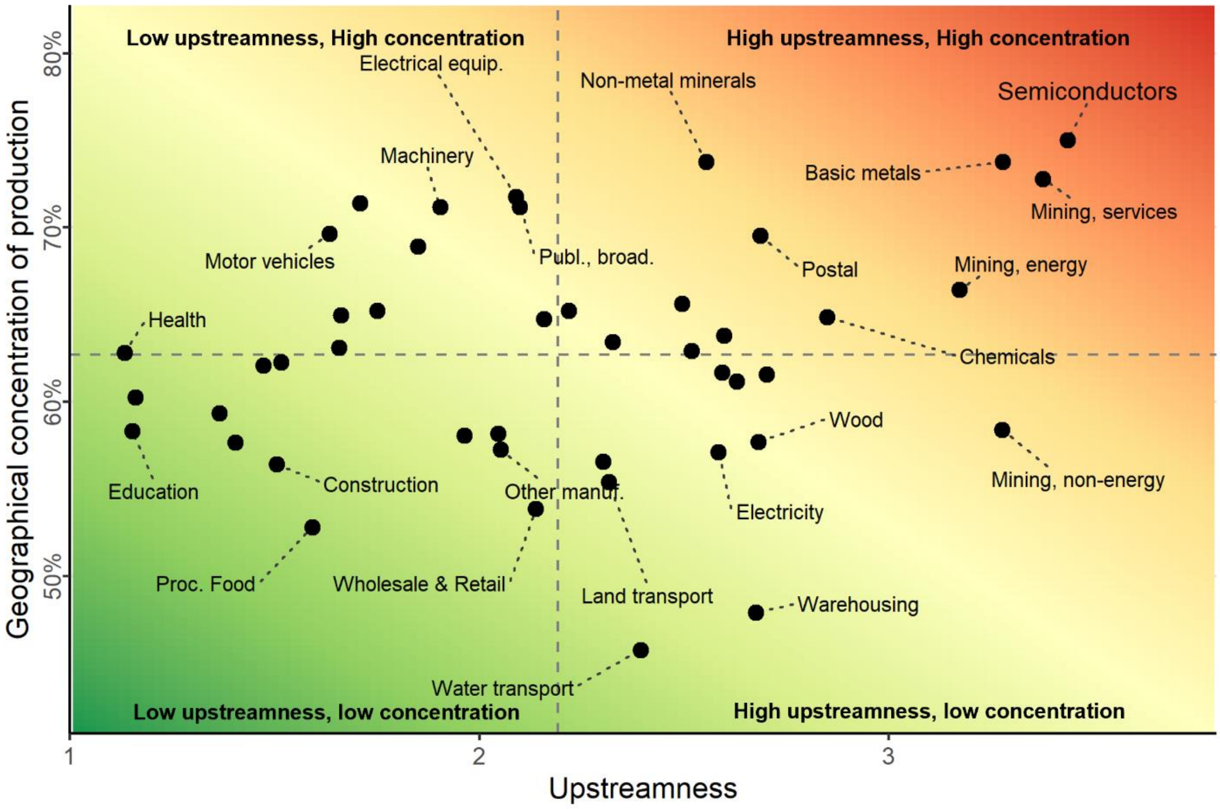
Supply disruptions in one economy can have large downstream effects, given that semiconductor production is among the most upstream and the most geographically concentrated industries (Figure 4).

- The semiconductor industry is among the most distant from final demand, with a degree of "upstreamness" comparable to those of industries such as mining and basic metals. This implies that disruption of semiconductor production may affect a broad range of industries that use semiconductors directly or indirectly (as an input of another supplying industry).
- At the same time, semiconductor production is also highly geographically concentrated with the top five economies accounting for about three-quarters of global semiconductor value added. An analysis using more disaggregated data reveals that geographic concentration is even higher for certain types of semiconductors, especially memory chips (Box 1).
- Together, these facts imply that a disruption in a single country has the potential to disrupt production in a large number of downstream industries and economies.[13]

- Recent developments have brought about only small changes in the geographic allocation of the semiconductor industry. Figure A B.3 and Figure A B.4 show that the total value of traded semiconductors has surged by nearly 30% between 2018 and 2021. Despite this growth, the share of trade accruing to the leading economies has remained stable.

Figure 4. Semiconductor production is highly upstream and highly concentrated

Share of top five economies in global value added (concentration) and distance to final demand (upstreamness), 2018



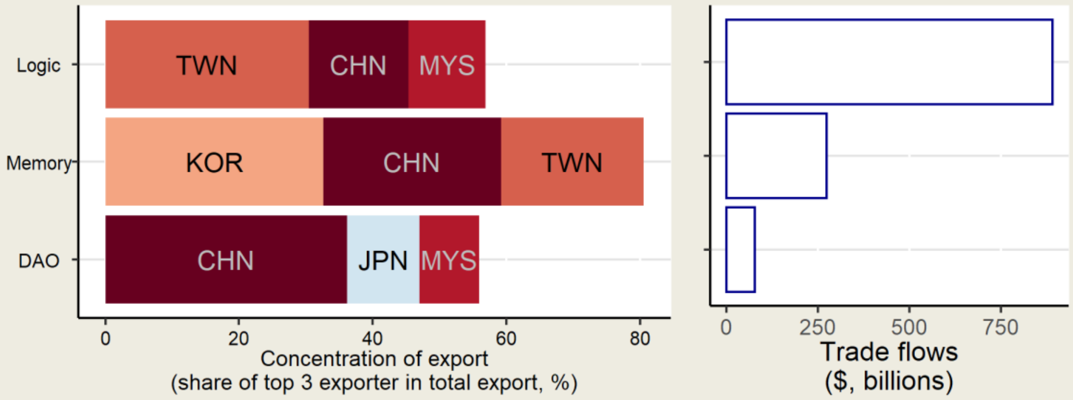
Note: Geographical concentration of production is measured as the share of the top five economies in global value added of an industry. Upstreamness of an industry is measured as the distance to final demand (Antràs et al., 2012[9]).
Source: OECD semiconductor-augmented ICIO tables

Box 1. The geographic concentration of semiconductors: a more granular approach

The separation of semiconductors from the rest of the ICT and electronics industry in the ICIO requires using a broad definition of semiconductors, obscuring that chips are very diverse. As described in section 2, logic, memory and DAO chips are produced using different manufacturing processes and serve different purposes. Using trade data for 2021, Figure 5 shows that they also differ in the location of their production and the resulting export origin. For each type of semiconductor, a different leading economy is responsible for exporting around one-third of the goods, while the top three exporters account for over 55% and the top five for over 70%. Memory chips appear particularly concentrated, with over 80% of exports accruing to the top three exporters.

Figure 5. China, Korea and Chinese Taipei lead different segments of the semiconductors industry

Concentration of export and trade flows, 2021



Note: Logic, memory and DAO semiconductor segment group goods under headings 8541 and 8542 of the Harmonised Systems. For a more granular presentation of the leading exporters for each product, please refer to Figure A B.1.
Source: COMTRADE, and OECD calculations.

The broad semiconductor segments used in Figure 5 may be understating the concentration for specific semiconductors by grouping together goods of different qualities. However, a more granular approach using product data (Figure A B.1) would not entirely solve the problem as there is substantial differentiation across chips within COMTRADE product categories. For example, semiconductors differ by node size, which ranges from more than 180 to around 3 nanometres for the most advanced logic semiconductors. As of early 2023, only TSMC in Chinese Taipei (TSMC, 2022[10]) and Samsung in Korea (Samsung, 2022[11]) have started producing advanced chips with the smallest node size (3nm) at scale.

The core semiconductor value chain is itself highly dependent on capital goods, such as specialised machinery, software and intellectual property necessary to design processor architecture. Even though ICIO data only provide a view on intermediate input purchases, and not on capital goods, highly disaggregated trade data allow highlighting the key inter-dependencies (Box 2).[14]

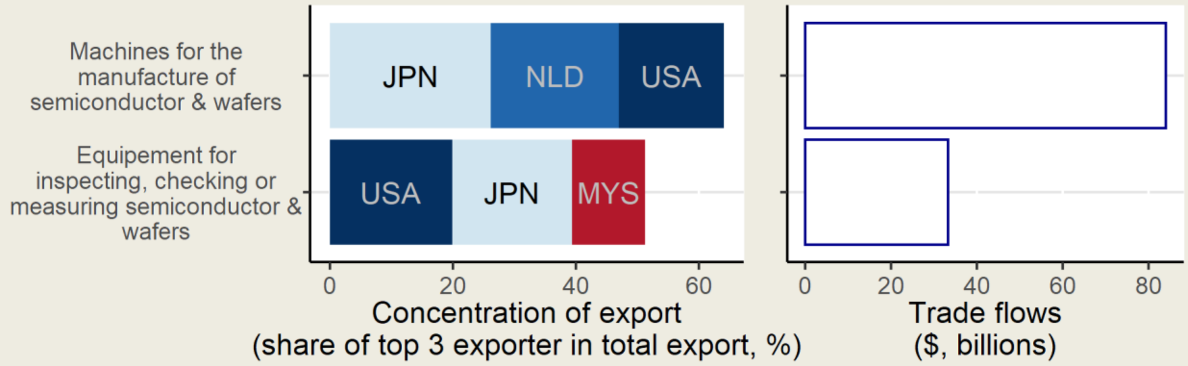
Box 2. The supply chain for specialised machinery

To provide a comprehensive picture of dependencies in the semiconductor value chain, it is essential to look beyond the ICIO data and examine the upstream suppliers of capital goods.

An analysis of highly-disaggregated trade data on specialised machinery and equipment shows that exports of "machines for the manufacture of semiconductors & wafers" are even more concentrated than the highly concentrated export of logic and DAO semiconductors (Figure 6). Even though sufficiently disaggregated trade data are not available, anecdotal evidence suggests that this is even more pronounced for the machines needed to manufacture leading-edge chips (<10 nm). These high-end lithography machines are almost entirely produced by one Dutch company, which in turn uses specialised optical instruments from one German company (BCG and SIA, 2021[6]).

Figure 6. Exports of semiconductor machinery are even more geographically concentrated than exports of semiconductors

Share of top three exporters in total exports, 2021, %



Note: The plot represents the share of top three exporters in total exports for several goods of the semiconductor value chain. For a more granular presentation of the leading exporters for each product, please refer to Figure A B.2.
Source: COMTRADE, and OECD calculations.

Electronic Design and Automation (EDA) tools and intellectual property (IP) necessary to design processor architecture are both critical inputs for the design of semiconductors.[1] As of 2021, the United States concentrated as much as 72% of the total revenue in the IP and EDA market, while Europe accounted for 20% of the revenue (McKinsey and Company, 2022[8]).

These results suggest large interdependencies in the semiconductor supply, as no country has control over the full production process.

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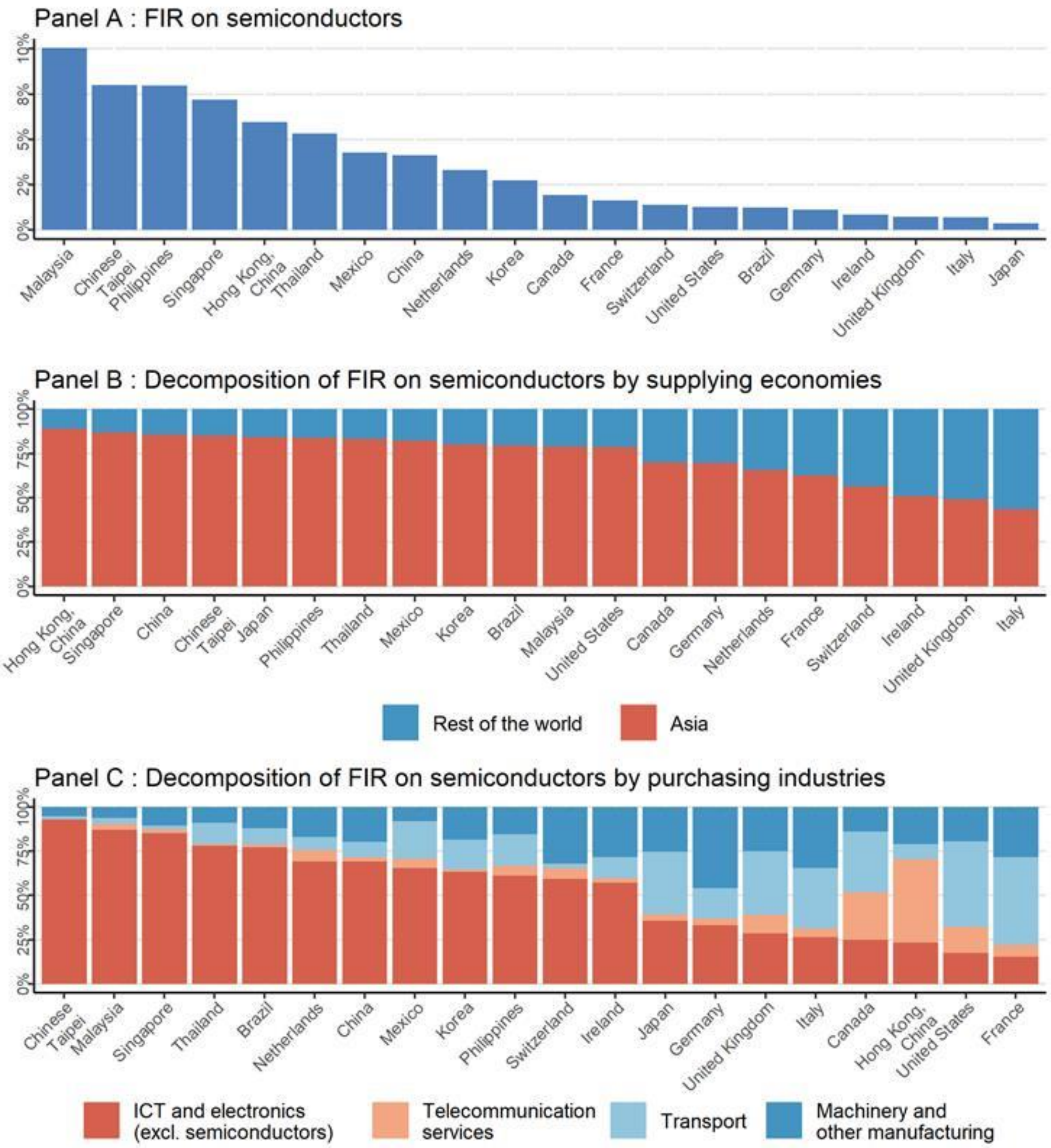
[1] IP refers to reusable design components that can be licensed and integrated into semiconductors, while EDA comprises software tools and methodologies used to automate and streamline the electronic design process.

Production in some Asian economies is particularly vulnerable to disruptions in the semiconductor supply chain (Figure 7, Panel A), which reflects both sectoral and trade specialisation patterns (Figure 7, Panels B and C). Many Asian economies, including China, Malaysia, and Chinese Taipei, are specialised in “ICT and electronics (excluding semiconductors)” manufacturing, which is highly dependent on semiconductors as an input (Figure 7,Panel C). At the same time, the Asian ICT and electronics value chain is highly interconnected, implying that a disruption in a single Asian country may have large ripple effects on its Asian value chain partners (Figure 7,Panel B).

Across economies, dependencies on semiconductors are driven by different industries, partly reflecting industrial specialisation (Figure 7,Panel C). In most Asian economies, dependencies are mainly explained by the “ICT and electronics (excluding semiconductors)” industry. In the United States and most European economies, however, dependencies reflect to a much larger extent the “transport equipment”, “machinery” and “other manufacturing” industries. Finally, in a small number of economies, including Canada and Hong Kong (China), the telecommunications industry accounts for a significant part of dependencies.

Figure 7. Foreign Input Reliance (FIR) on semiconductors by purchasing economies



Note: FIR on semiconductors (Panel A) is computed for each pair of purchasing economy and industry in the sample. FIR on semiconductors of purchasing industry j and purchasing economy c is defined as the foreign gross semiconductor output required to produce one unit of domestic gross output ($FIR_{c,j}^{semi} = \sum_{c'=1}^{N} Foreign\ output_{c,j}^{c',semi} / Gross\ output_{c,j}$). It is then averaged by purchasing economy across purchasing industries, weighting by the industries' gross output ($FIR_{c}^{semi} = \sum_{j=1}^{7}(FIR_{c,j}^{semi} * W_{cj}^{GO})\ where\ W_{cj}^{GO} = GO_{cj} / \sum_{j'=1}^{7} GO_{cj'}$). The share of FIR explained by a supplying economy (Panel B) is computed for each pair of purchasing economy and industry of the sample and then averaged by purchasing economy across industry, weighting by industry's gross output. ($ShareSupp_{c}^{c',semi} = \sum_{j=1}^{7}(FIR_{c,j}^{c',semi} / FIR_{c,j}^{semi}) * W_{cj}^{GO}$). The share of the FIR explained by a purchasing industry (Panel C) is computed for each country as follows $ShareUse_{ci}^{semi} = FIR_{c,i}^{semi} * W_{ci}^{GO} / FIR_{c}^{semi}$.The sample is restricted to the main purchasing economies: Brazil, Canada, China, France, Germany, Hong Kong (China), Ireland, Italy, Japan, Korea, Malaysia, Mexico, the Netherlands, the Philippines, Singapore, Switzerland, Chinese Taipei, Thailand, the United Kingdom, the United States and the seven purchasing industries that are most reliant on semiconductors as reported in Figure 2. “Transport” includes “Motor vehicles” and “Other transport equipment”; “Other manufacturing” includes “Electrical machinery”, “Machinery” and “Other manufacturing”.

Source: OECD semiconductor-augmented ICIO tables

The concentration of demand can exacerbate supply disruptions, as shown by the chips shortage that affected the motor vehicle sector during COVID-19 crisis (Box 3).

Box 3. The motor vehicles industry during the COVID-19 crisis as an example of a demand-induced supply shortage

At the onset of the COVID-19 crisis, the demand for ICT and electronic equipments surged due to widespread telework and the increase in personal use during lockdowns. This surge in demand outpaced the production of semiconductors, leading to widespread shortages. However, the impact of these shortages varied across different industries. Car makers were particularly affected by shortages while the impact was smaller for firms from the ICT and electronics sector (McKinsey, 2022[14]; OECD, 2021[2]).

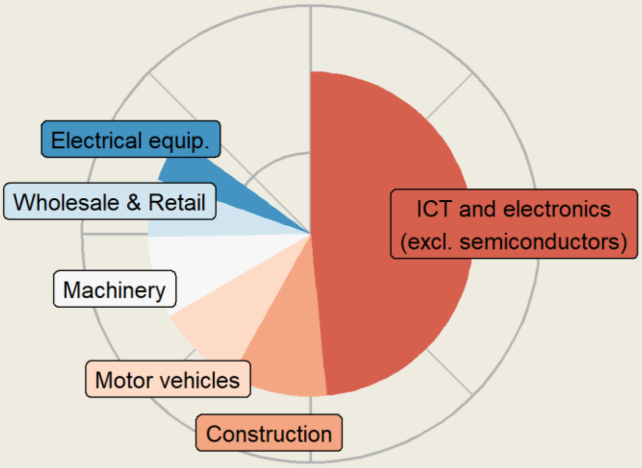
First, ICT and electronics accounts for a substantial share of semiconductor demand, potentially giving the industry some market power. Figure 8. shows that, as of 2018, most of the value added produced in the semiconductor industry is incorporated in the final goods of a handful of industries, with the ICT and electronics industry accounting for about half of the total value added.

Second, the ICT and electronics industry tends to directly source its inputs from the semiconductor industry, while suppliers from other industries often intermediate the trade relationship with car manufacturers. This indirect relationship prevented carmakers from anticipating supply disruptions (McKinsey, 2022[11]), which would have been crucial given their just-in-time manufacturing strategy.

Third, the chips needed for the car industry are on average less advanced and profitable than the ones used in the ICT sector, with semiconductor manufacturers tending to prioritise the most profitable production lines.

Figure 8. Demand for semiconductors is concentrated in the ICT and electronics industry

Share of top six industries in global semiconductor value added incorporated into final product, 2018



Note: The plot presents the share of semiconductor value added incorporated in the final product of the top six industries in the total semiconductor value added.
Source: OECD.

5 Conclusion

This paper constructs a novel dataset on direct and indirect dependencies in the semiconductor value chain. The data are built from ICIO tables, bilateral trade data and granular input-output tables from five key economies. They provide technical input-output coefficients, gross output, flows of intermediate inputs and value-added for the semiconductor industry, its suppliers and buyers from 1995 to 2018.

Building on this dataset, the paper documents dependencies on semiconductors across economies, industries and time. It reveals how semiconductor production has shifted away from Japan and the United States to China, Korea and Chinese Taipei over the past two decades, each country specialising in a specific segment of semiconductors (China in DAO, Chinese Taipei in logic and Korea in memory chips).

The key result is that the semiconductor industry is both the most upstream and the most concentrated industry in our data. As a result, disruptions in a few key economies could destabilise the supply of semiconductors and quickly propagate to numerous downstream sectors. Such disruptions could severely hit the ICT industry (excluding semiconductors), as well as several other large industries, like motor vehicles and electrical equipment. Asian economies, which are highly specialised in ICT and electronics, would be particularly vulnerable.

Many countries are exploring ways to increase the resilience of the semiconductor supply chain. For instance, the yet-to-be-enacted EU Chips Act, the US Chips and Science Act and several Korean laws have pledged significant budgets to an array of policies ranging from tax credits for semiconductor firms to the funding of training. This paper suggests that no economy controls the whole semiconductor value chain, and even large-scale national industrial policy initiatives are unlikely to change this.

Instead of attempting to individually onshore large parts of the semiconductor value chain, OECD economies need to coordinate policy initiatives in order to mitigate the risks of zero- or negative-sum outcomes. This includes reinforcing and broadening multilateral initiatives, such as the EU-US Trade and Technology Council or the Chip 4 Alliance.

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Endnotes

[1] A semiconductor chip (or a chip, or a semiconductor, or an integrated circuit) is an electric circuit consisting of many components, such as transistors, diodes, capacitors or resistors, and their interconnections formed on a semiconductor wafer.

[2] See The White House (2021[7]), Thorbecke (2021[31]) and Institut Montaigne (2022[15]).

[3] For instance, establishing fully domestic semiconductor manufacturing supply chains within the United States could require upfront investments of USD 1 trillion (Deloitte, 2022[19]).

[4] The literature on production networks, which studies the transmission of shocks at the sectoral level (Acemoglu et al., 2012[20]; Acemoglu, Akcigit and Kerr, 2016[21]; D'Aguanno et al., 2021[22]; Giammetti, Russo and Gallegati, 2020[23]), at the firm level (Carvalho et al., 2020[24]) or focus more on the structural evolution of GVCs and the increasing integration between countries (Criscuolo and Timmis, 2018[25]; Antràs et al., 2012[9]; Chen, Hu and Li, 2021[26]; Arriola et al., 2020[27]; Grassi and Sauvagnat, 2019[28]; Frohm and Gunnella, 2021[29]; Iliopoulos et al., 2020[30]) has not shed light on the peculiarities of the semiconductor supply chain. Previous studies of vulnerabilities in the semiconductor supply chain (The White House, 2021[7]; Institut Montaigne, 2022[15]) have remained largely qualitative.

[5] These three core stages therefore account for about 80% of semiconductor value added. The rest comes from upstream production stages (raw materials, machinery…) in other industries.

[6] While smaller logic and memory chips are considered as more advanced, this is not necessarily the case for DAO semiconductors, whose performance is not affected to the same extent when migrating to smaller node sizes (Semiconductor Industry Association, 2021[10]).

[7] Machinery, in particular lithography machinery, is a key upstream industry in the semiconductor value chain and tends to be vulnerable to disruptions. For instance, ASML, a Dutch company, produces the vast majority of the Extreme Ultra-Violet lithography machines, which are essential to produce the most advanced chips (with a node size below 7 nanometres) (BCG and SIA, 2021[6]).

[8] See https://www.oecd.org/industry/ind/TiVA-2021-industries.pdf and Guilhoto, Webb and Yamano (2022[14]).

[9] http://oe.cd/btd

[10] The detail of the matching is described in 0.

[11] For the purposes of this note primary energy is defined as Divisions 05 and 06 in the ISIC (Rev. 4) industry classification (coal, oil and gas).

[12] Value added in the semiconductor industry includes chip design, suggesting that the decline in US chips manufacturing value added was larger than the increase in chips design value added..

[13] Given the variety of chips (see Section 2), geographic concentration measured at the product-level is probably higher than when measured at the industry-level, and is likely exacerbated by concentration at the individual supplier level (Handley, Kamal and Monarch, 2021[33]).

[14] Disruptions in the supply of capital goods are likely to take longer to impact downstream production than intermediate goods shortages.

Annex A. Methodology

This Annex describes how, starting from the ICIO data, a semiconductor-augmented ICIO table can be estimated. Additional data (granular input-output tables for five economies and bilateral trade flows in semiconductors) is used to obtain a semiconductor-augmented matrix of technical coefficients. From this matrix, it is possible to estimate the rest of the semiconductor augmented ICIO data (gross output, flows of intermediate inputs, value added). Guilhoto, Webb and Yamano (2022[14]) provide an overview of the main ICIO variables.

Pre-processing the additional data

Identifying bilateral trade flows in semiconductors

For each year and each economy pair, bilateral trade flows of semiconductors are obtained from the 'Bilateral Trade in Goods by Industry and End-use Category' database (http://oe.cd/btd). Flows of semiconductors are identified by Harmonised Systems headings 8541 and 8542.

Processing national IO tables for economies that provide sufficiently granular information to identify semiconductors

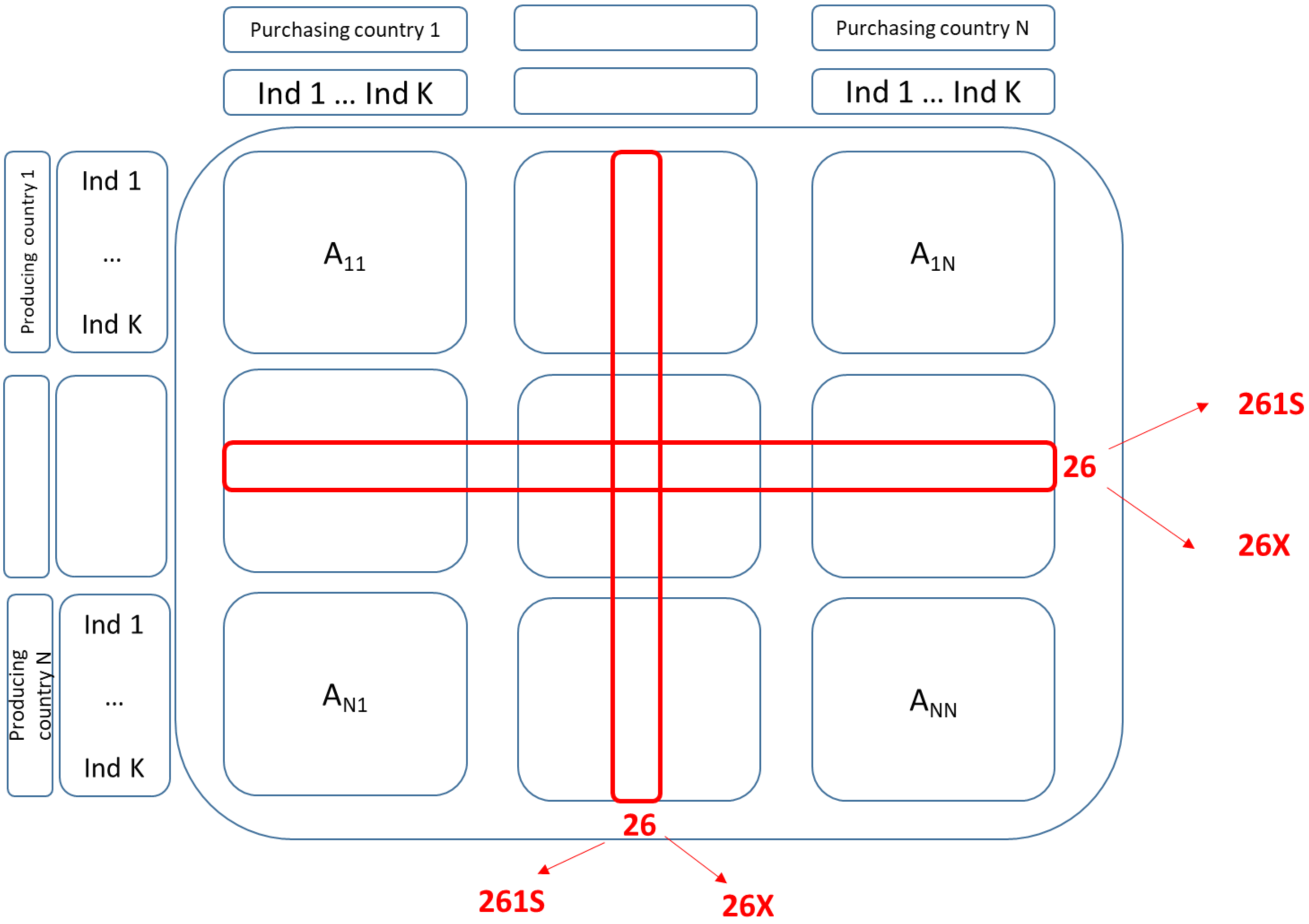
This step relies on granular input-output tables for Korea (2014), Japan (2011), Malaysia (2010), Chinese Taipei (2016) and the United States (2012). These granular tables are aggregated up to the industry classification used for ICIO, with the exception of the split between "Semiconductors" and "ICT and electronics (excluding semiconductors)".

Even though disaggregated national input-output tables are only available for one year, the use of trade data over the whole period (1995-2018) ensures that the semiconductor-augmented ICIO tables accurately reflect the growth in semiconductor trade. However, they do not necessarily capture domestic trends.

Estimating the matrix of technical coefficients

The split is first performed for the matrix of technical coefficients (the A matrix following the notation of Guilhoto, Webb and Yamano (2022[14])). For each producing economy, the coefficients for domestic and foreign uses of 'Computer, electronic and optical equipment' (ISIC rev. 4 division 26) have to be split between uses of semiconductors (261S) and ICT and electronics excluding semiconductors (26X) – rows in Figure A A.1. Similarly, for each purchasing economy, the coefficients for domestic and intermediate inputs used by the 'Computer, electronic and optical equipment' have to be split between intermediate inputs purchased by the semiconductor industry (261S) and those purchased by the ICT and electronics (excluding semiconductors) industry (26X) – columns in Figure A A.1.

Figure A A.1. Estimating a semiconductor-augmented matrix of technical coefficients



Source: OECD.

Diagonal blocks of the matrix

Estimation of the split for the diagonal blocks of the A matrix proceeds in two steps.

First, for economies for which granular input-output tables are available, diagonal blocks are directly available for a base year from the pre-processing step described above. For other years, it is assumed that the shares of the base year can be used to split the technical coefficients of 'Computer, electronic and optical equipment' (e.g. $a_{t}{}_{261S,j}^{r,r} = a_{t}{}_{26,j}^{r,r} * \frac{a_{t_0}{}_{261S,j}^{r,r}}{a_{t_0}{}_{26,j}^{r,r}}$ and . $a_{t}{}_{i,261S}^{r,r} = a_{t}{}_{i,26}^{r,r} * \frac{a_{t_0}{}_{i,261S}^{r,r}}{a_{t_0}{}_{i,26}^{r,r}}$ where t_0 is the base year).

Second, for the rest of the economies, domestic technical coefficients are obtained as a linear combination of domestic technical coefficients in these five economies. The following rules, based on a literature review of their role in the semiconductor value chain (BCG and SIA, 2021[6]; The White House, 2021[7]; Institut Montaigne, 2022[15]; Abad et al., 2015[16]; Kleinhans and Baisakova, 2020[17]), have been applied:

- China is assumed to have the same domestic technical coefficients as Malaysia.
- Singapore is assumed to have domestic technical coefficients calculated as the average between those of Korea and Chinese Taipei.
- European Union member states are assumed to have domestic technical coefficients calculated as the average between those of Japan and the United States.

- Other economies are assumed to have domestic technical coefficients calculated as the average between those of Japan, Korea, Malaysia and Chinese Taipei.

At this stage, the methodology gives the diagonal blocks of the A matrix. Omitting time indices, domestic purchases of ‘semiconductors’ and ‘ICT & electronics (excluding semiconductors)’ products ($a^{r,r}_{261S,j}$ and $a^{r,r}_{26X,j}$) are available for each purchasing industry j and economy r. In addition, domestic purchases of ‘semiconductors’ and ‘ICT & electronics (excluding semiconductors)’ industries ($a^{r,r}_{i,261S}$ and $a^{r,r}_{i,26X}$) are available for each input i and economy r.

Off-diagonal blocks of the A matrix

The next step of the methodology aims at imputing the off-diagonal blocks of the A matrix using trade data and the diagonal blocks obtained in the previous step. The step can be decomposed into dealing with two different questions: 1/ How to allocate imported inputs between the ‘semiconductors’ and ‘ICT and electronics (excluding semiconductors)’ industries? and 2/ How to allocate imported ‘semiconductors’ and ‘ICT and electronics (excluding semiconductors)’ goods across domestic industries?

How to allocate imported inputs between the ‘semiconductors’ and ‘ICT and electronics (excluding semiconductor)’ industries?

This first step corresponds to splitting the columns in Figure A A.1. It requires calculating the coefficients $a^{r,s}_{i,261S}$ and $a^{r,s}_{i,26X}$ for each producing industry i, economy of origin r and economy of destination s (with $r \neq s$).

To this end, imported intermediate inputs of product i in economy s are split between the two sub-industries using the shares observed for domestic inputs of product i in economy s:

$$a^{r,s}_{i,261S} = a^{r,s}_{i,26} * \frac{a^{s,s}_{i,261s}}{a^{s,s}_{i,26}} \text{ and } a^{r,s}_{i,26X} = a^{r,s}_{i,26X} * \frac{a^{s,s}_{i,26X}}{a^{s,s}_{i,26}}\ ,\ \forall\, i, r, s, r \neq s$$

How to allocate imported semiconductors across domestic industries?

This second step corresponds to splitting the rows in Figure A A.1. It requires calculating the coefficients $a^{r,s}_{261S,j}$ and $a^{r,s}_{26X,j}$ for each importing industry j, economy of origin r and economy of destination s (with $r \neq s$).

This estimation consists of three stages: 1/ estimating initial auxiliary values of intermediate flows in monetary terms (the Z matrix following the notations of Guilhoto, Webb and Yamano (2022[14]) – here $\tilde{Z}$ to indicate that it is an auxiliary matrix used in this step, whereas the final Z matrix will be calculated further down the line), 2/ balancing these auxiliary values to match trade data on semiconductors and 3/ calculating the technical coefficients, based on the auxiliary values.

Stage 1. To initialise imports of semiconductors in purchasing industry j, it is assumed that the share of semiconductors among computer and electronics inputs is the same for domestic and imported goods :

$$Z^{r,s}_{261S,j}{}^{(0)} = \frac{a^{s,s}_{261S,j}}{a^{s,s}_{26,j}} * Z^{r,s}_{26,j} \text{ and } Z^{r,s}_{26X,j}{}^{(0)} = Z^{r,s}_{26,j} - Z^{r,s}_{261S,j}{}^{(0)}$$

At this stage, there is no guarantee that the $Z^{(0)}$ matrix is consistent with trade flows. In particular, the following equality, where $M^{r,s}_{261S}$ denotes imports of semiconductors from economy r by economy s, does not hold.

$$\sum_j Z^{r,s}_{261S,j}{}^{(0)} = M^{r,s}_{261S}$$

Stage 2. Therefore, the $Z^{(0)}$ matrix has to undergo a balancing procedure. A balanced system verifies $\sum_j \tilde{Z}^{r,s}_{261S,j} = M^{r,s}_{261S}$ and, for each industry j, $\tilde{Z}^{r,s}_{261S,j} + \tilde{Z}^{r,s}_{26X,j} = Z^{r,s}_{26,j}$.

The RAS method, also called biproportional adjustment procedure, is used to balance the relevant rows and columns of the auxiliary $Z^{(0)}$ matrix.

While the system is not balanced, the RAS procedure consists in :

- Calculating the error in rows ${\varepsilon_{261S}^{r,s}}^{(i)} = M_{261S}^{r,s} - \sum_j {Z_{261S,j}^{r,s}}^{(i)}$, and allocating it proportionally to each cell: ${Z_{261S,j}^{r,s}}^{(i+1)} = {Z_{261S,j}^{r,s}}^{(i)} + \frac{{Z_{261S,j}^{r,s}}^{(i)}}{\sum_j {Z_{261S,j}^{r,s}}^{(i)}} {\varepsilon_{261S}^{r,s}}^{(i)}$. The same procedure is used to obtain ${Z_{26X,j}^{r,s}}^{(i+1)}$.
- Calculating the error in columns (zero at iteration $i = 0$, but they are introduced by the balancing procedure starting in iteration 1) $\varepsilon_j^{r,s(i+1)} = Z_{26,j}^{r,s} - {Z_{261S,j}^{r,s}}^{(i+1)} - {Z_{26X,j}^{r,s}}^{(i+1)}$, and allocating it proportionally to each cell: ${Z_{261S,j}^{r,s}}^{(i+2)} = {Z_{261S,j}^{r,s}}^{(i+1)} + \frac{{Z_{261S,j}^{r,s}}^{(i+1)}}{{Z_{261S,j}^{r,s}}^{(i+1)} + {Z_{26X,j}^{r,s}}^{(i+1)}} \varepsilon_j^{r,s(i+1)}$. The same procedure is used to obtain ${Z_{26X,j}^{r,s}}^{(i+2)}$.

Bacharach (1970[18]) shows that this procedure converges towards a balanced $\tilde{Z}$ matrix, as defined above.

<u>Stage 3.</u> The estimated input inflows are used to calculate the technical coefficients.

$$a_{261S,j}^{r,s} = \frac{\tilde{Z}_{261S,j}^{r,s}}{Z_{26,j}^{r,s}} * a_{26,j}^{r,s} \text{ and } a_{26X,j}^{r,s} = \frac{\tilde{Z}_{26X,j}^{r,s}}{Z_{26,j}^{r,s}} * a_{26,j}^{r,s}$$

Estimating gross output, value added and intermediate consumptions

The previous steps provide an A matrix where ‘semiconductors’ and ‘ICT and electronics (excluding semiconductors)’ are split.

In addition, a new vector of final demand is created, where it is assumed that final demand for semiconductors is null ($Y_{261s}^{r,s} = 0$ and $Y_{26X}^{r,s} = Y_{26}^{r,s}$), i.e. semiconductors are only used as intermediate inputs. This is a rather mild assumption, as semiconductors are rarely use for consumption or investment, but are rather incorporated into other goods.

From the technical coefficients and final demand, it is possible to recover gross output (X), intermediate consumption (Z) and value added as a share of gross output (V), where ‘semiconductors’ and ‘ICT & electronics (excluding semiconductors)’ are split, as follows:

$$X = (I - A)^{-1} Y$$

$$Z = A\hat{X}$$

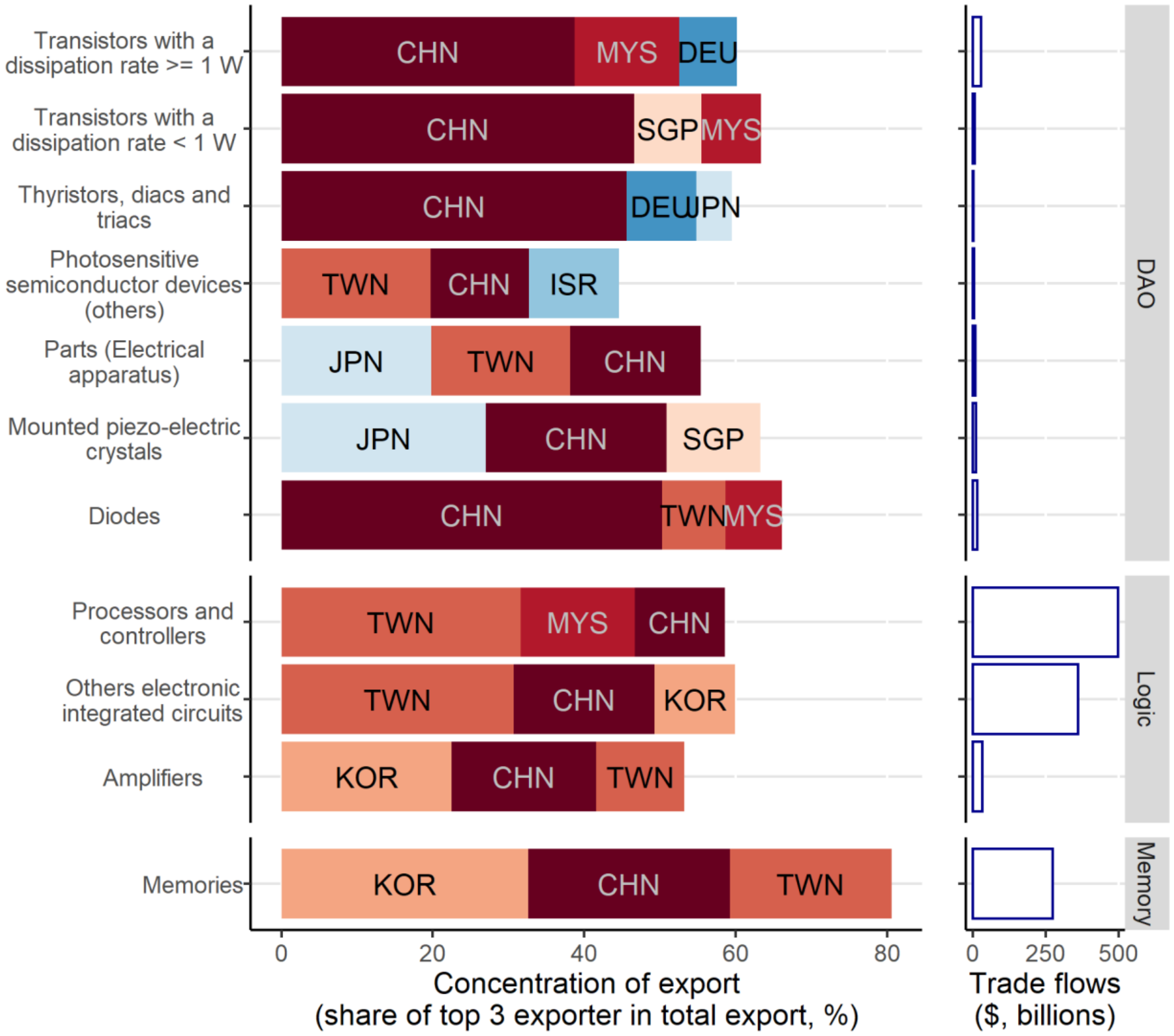
$$V = (I - A')\mathbf{1}$$

Where $\hat{X}$ is a matrix with the X_i^r on its diagonal and 0s for its other elements and $\mathbf{1}$ is a vector of 1s.

Annex B. Additional figures

Figure A B.1. Export concentration of semiconductors by HS6 product

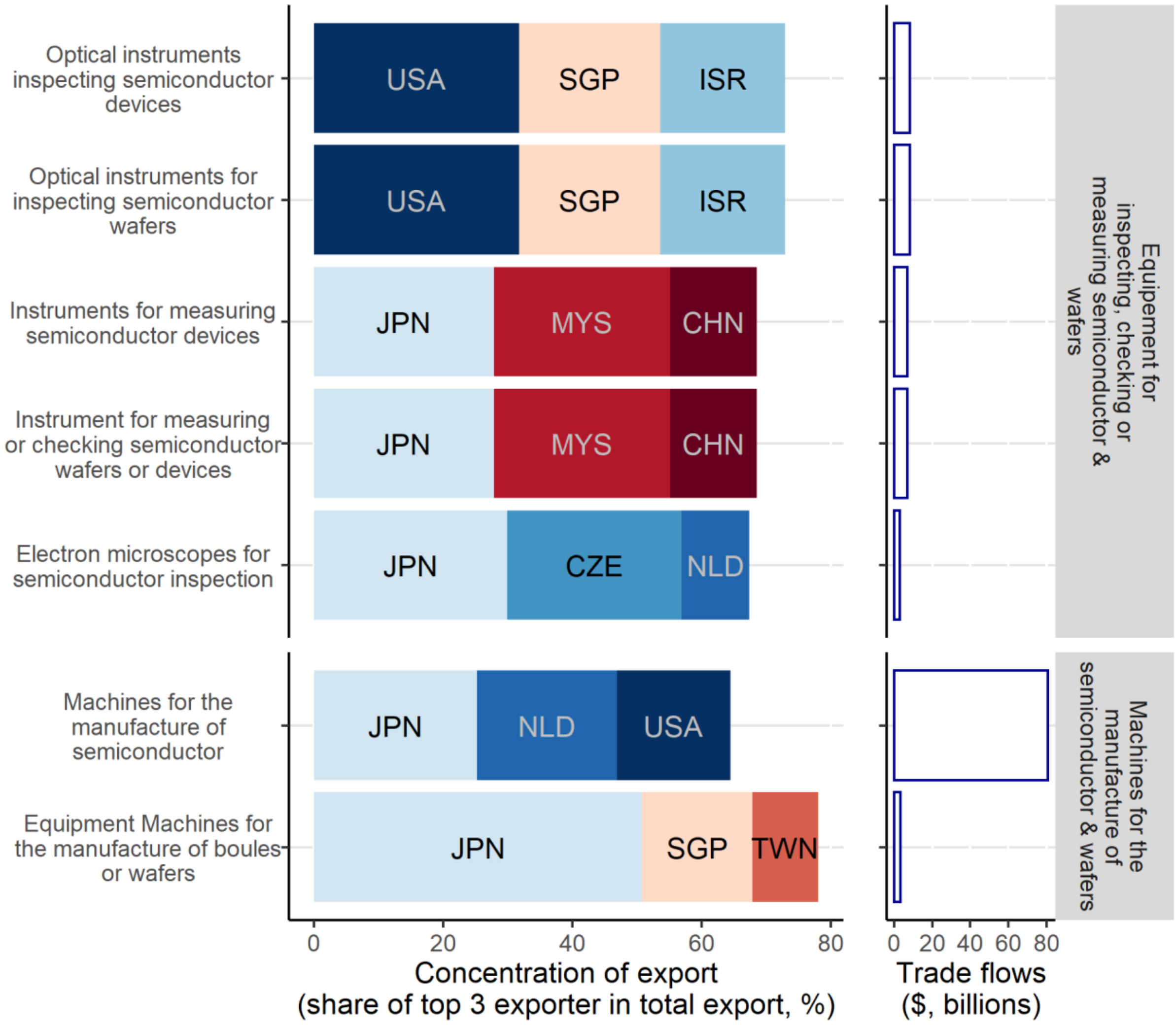
Concentration of export and trade flows, 2021



Note: The figure presents the concentration of exports for all the goods under headings 8541 and 8542 of the Harmonised Systems, except Photovoltaic cells & light-emitting diodes.
Source: COMTRADE, and OECD calculations.

Figure A B.2. Export concentration of machinery and specialised equipment by HS6 product

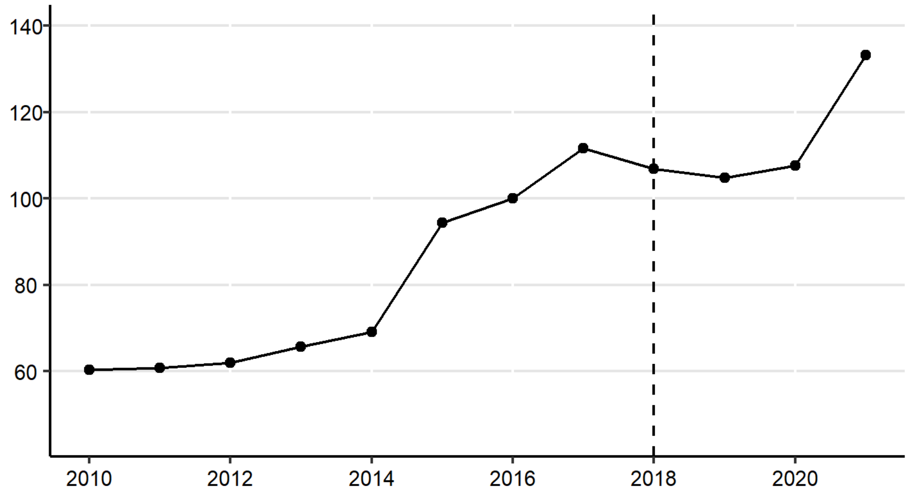
Concentration of export and trade flows, 2021



Note: The figure presents the concentration of exports for several specialised equipment and machinery for semiconductor production.
Source: COMTRADE, and OECD calculations.

Figure A B.3. Trade in semiconductor has increased since 2018…

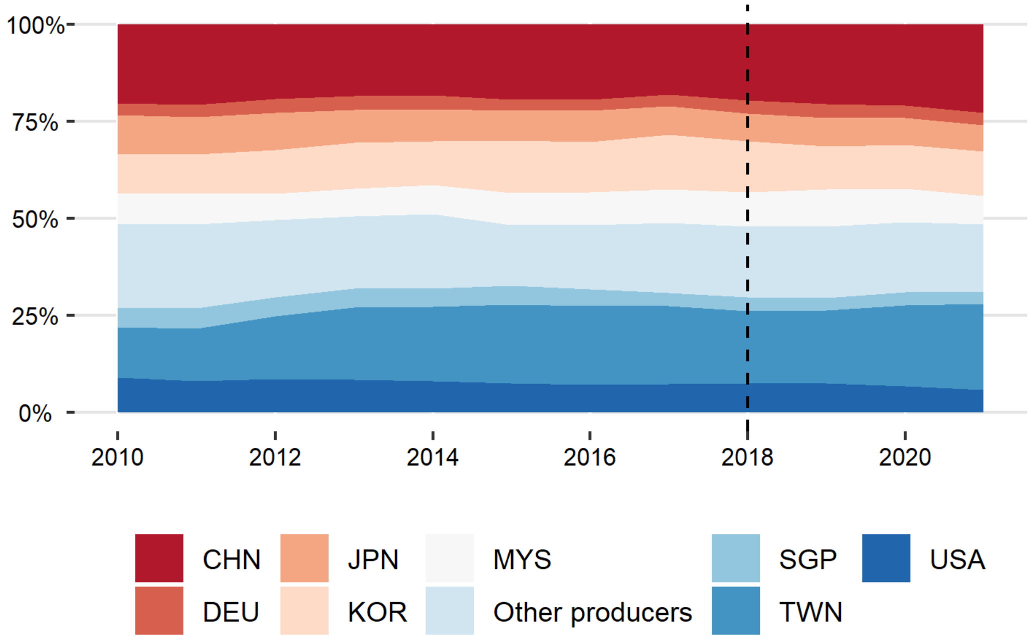
Semiconductor exports volume (Base year 2016), 2010-2021



Note: This plot represents the total value of semiconductor recorded in the COMTRADE data. The data is normalised to be equal to 100 in 2016. In that year, 1,99 trillion dollars worth of semiconductors were exchanged.
Source: COMTRADE, and OECD calculations.

Figure A B.4. …but the leading economies remain the same

Share in total semiconductor trade, 2010-2021



Source: COMTRADE, and OECD calculations.