University of Economics, Prague

Faculty of International Relations

Title of the master's thesis:

The global semiconductor shortage crisis – Why the high demand isn’t met by supply, a sign of a bigger crisis or a standalone issue?

April 2022

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Declaration:

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree, except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

Date:

Signature:

Acknowledgment

I would first like to thank my thesis supervisor Mgr. Ing. Jakub Jedlinský, Ph.D., for guiding me through the entire process and answering quickly whenever I had any questions about my research or my writing. I also want to express my extreme gratitude to my family for providing me with continuous support and encouragement throughout my years of study and through the process of researching and writing this thesis.

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Introduction

The global semiconductor shortage became the most prominent part of the worldwide supply chain crisis that has shaken the world together with the COVID-19 pandemic. This crisis has shown the vulnerability of today's complex global value chains and the interdependence of the Western and Eastern hemispheres regarding the production cycles of many products. At the same time, the importance of semiconductors has never been greater as new cars, phones, graphic cards, processing units, and other common-end products of the 21st century require an ever-increasing number of semiconductors to work correctly. The lack of these intermediary products has left the global market filled with unfinished products that may not be finished for months or even years due to this shortage. Although the COVID-19 pandemic affected the crisis in many ways by the closings of the factories, shipyards, and mining centers on the supply side and by the stay at home mandates on the demand side, many big names in the industry like Cristiano Amon have spoken publicly about the inevitability of the current shortage even without the pandemic. (Cristiano Amon 2022)

This thesis explores the other possible causes of the shortage, such as the U.S. – China trade wars, complex manufacturing of the semiconductors, cryptocurrency mining, and more, to judge the real impact of the pandemic on the shortage. Furthermore, this thesis covers many topics related either directly or indirectly to the current global semiconductor shortage of today to the necessary depth for reaching the secondary goals of the thesis.

This thesis has several goals. The main goal is to identify the possible causes of the current semiconductor crisis and determine if the crisis would have occurred sooner or later without the COVID-19 pandemic. The secondary objectives rising from this are to identify whether the semiconductor supply crisis is a standalone issue or if other industries could suffer through a similar crisis for the same reasons as the semiconductor industry, and to assess the global reaction to the crisis, provide recommendations for the industry with a prediction for the development of the semiconductor crisis after Q1 of 2022

According to a Goldman Sachs report, the spillover effect of the semiconductor shortage affected 169 global industries. (Goldman Sachs 2022) I find it extremely important that the real causes of this shortage are explored and resolved and not just mistakenly blamed at COVID-19 and forgotten, allowing for a repeat of the crisis in the future.

The thesis is split into a theoretical and a practical part, which both have two chapters. This distribution aims to create a logical, investigation-like structure of going through the possible causes of the crisis in the theoretical part and finishing with results and future prospects.

The first chapter serves as an introduction to semiconductors. What types are there, what is their market share and in which industries they are used. The chapter explores the level of importance of semiconductors for the modern economy. The methodology used in this chapter is literature research of primary sources.

The second chapter focuses on the possible causes of the semiconductor shortage crisis. It is divided into seven subchapters, each dedicated to one of the explored potential causes of the Semiconductor shortage. The methodology for this chapter is the same as for the first chapter, but the literature research is much more massive and combines many well-acknowledged primary sources with secondary sources that relate to the central issue of each subchapter. The ratio of primary and secondary literature differs in every subchapter as some of the causes have been more explored than others in previous research.

The third chapter compares the findings from the second chapter with the semiconductor industry trends before the pandemic and with the historical Semiconductor shortages to answer the question if the semiconductor shortage would have occurred without COVID-19 or not. Due to the ongoing and global nature of the subject and the fact that scientific debate still hasn't settled, the methodology used to conclude the answer is comparative work synthesizing shattered and evolving secondary literature on the ongoing crisis with the primary sources of other relevant research and topics that when combined can provide an educated guess. At the end of the third chapter, there is a summary table, which should provide the reader with the most essential information summary of the causes, their effects on the industry, and the impact of COVID-19 in increasing or not affecting that effect.

The last chapter establishes the most significant solvable causes of the current crisis, based on chapters two and three, and investigates their best plausible solutions. Furthermore, the chapter compiles reactions of private and public sectors of North America, the EU, China and East Asia to the semiconductor crisis and, based on that, predicts the industry's future prospects. The methodology is once again a synthesis of the most up to date primary and secondary literature available as of Q1 of 2022.

1. The importance of semiconductors in today's economy

Although semiconductors had been the subject of study since the mid-19th century and perhaps even before that, it wasn't until 1947, when the point-contact transistor was invented and licensed by Bardeen and Brattain at Bell Laboratories in the US, that the semiconductor industry was truly born (Holbrook et al. 2000). The Industry grew rapidly since that point, and the creators of the first transistor were awarded the Nobel prize in physics just nine years later (The Nobel Prize in Physics 1956 - NobelPrize.org). The industry was already valued at over 100 million dollars in 1957, which would be equal to roughly one billion dollars in today's dollar worth. (History of semiconductors : Hitachi High-Tech GLOBAL). Semiconductors quickly became essential in developing new technologies and were quickly improved upon. Within 60 years, humanity moved from transistor radio and simple silicon transistors to smartphones and bipolar integrated circuits (ICs). Today ICs are highly integrated and miniaturized to roughly one fifty-fifth thousand of the size and three billionths of the area of the original transistor radio (*Integrated circuit (IC) : Hitachi High-Tech* GLOBAL). Diodes, transistors, photoresistors, digital integrated circuits, and more essential building blocks of modern electronics require semiconductors' regulable resistivity. This unique feature results in their today's wide application in electronics, robotics, and automation systems. (Pehlivan, Keskin, Öztürk 2018)

Today's importance of the semiconductor industry can also be seen in the political landscape. For example, Taiwan and its sovereign status remain a constant source of tensions in U.S.-China relations, with Taiwan's independence relying heavily on support from the U.S. (Kastner 2015). Even though Taiwan is a small country, it has become an important hub of the global semiconductor industry and an incredibly crucial supplier for the U.S. consumer electronics corporations like Apple, making Taiwan a precious ally for the U.S. (Apple Inc. 2021). Another example of the strategic importance of semiconductors in high politics could be seen in the sanctions against Russia in the Russo-Ukrainian war, where the first sanctions against Russia by the U.S. and E.U. were also aimed at the export ban of semiconductors and other modern technologies into Russia. (www.consilium.europa.eu 2022), (Industry and Security Bureau 2022)

The following Figure 1 shows the size and segments of the semiconductor market in 2019, with a prediction for 2024. The figure shows that the largest segment in terms of capitalization is the smartphone industry, followed by personal computing and server-providing services. All the segments are expected to grow in market size by 2024, increasing around 50% in just five years. It is estimated that semiconductor "content" in electronic systems has reached 33.2% of the total value of electronic systems market in 2021 and is estimated to keep growing. (IC insights 2022)

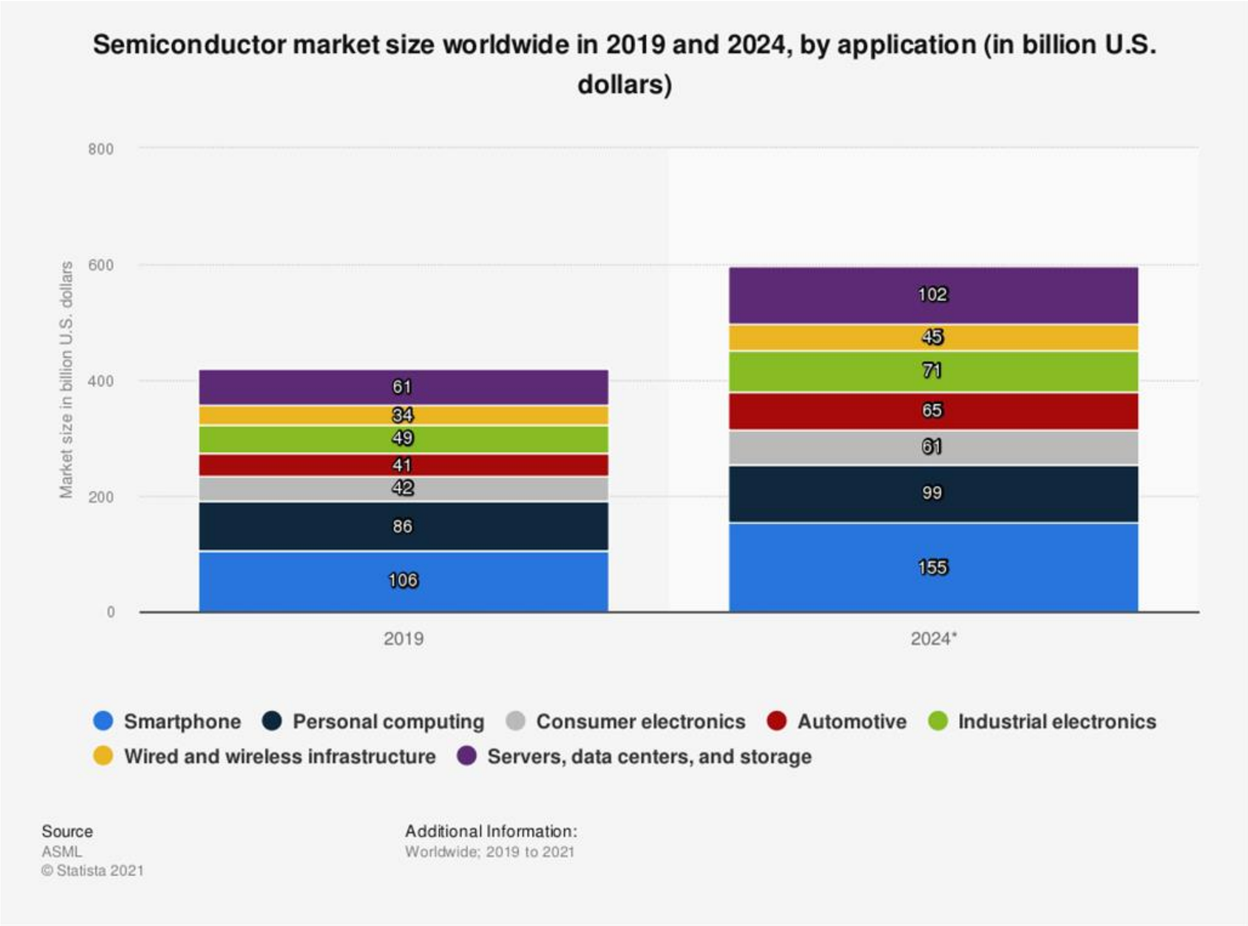


Figure 1 - Semiconductor market size worldwide 2019,2024, by application (in billion U.S. dollars) Source: Statista

Depending on the segment and on the specific product, a combination of different semiconductor components is needed during the manufacturing process of the end product.

Figure 2 shows the estimated distribution of the different semiconductor units on the market. The process of creation and the purpose of each of these units is very different. While the semiconductor industry can typically describe more than 30 product categories, the semiconductors can be either divided into two or three major groups with a few important subgroups.

The first standard categorization of semiconductor intermediary products splits the industry based on technology into so-called O-S-D devices, representing the more common and less technologically expensive semiconductor units with 67% of all total shipments for 2021 and the ICs - usually more expensive and complex but representing only 33% of total shipment volume for the year 2021. (IC Insights 2021) Products like microprocessors and logic ICs are essential for the more expensive end-products like smartphones or processing units of computers. The 2021 McClean Report expects that the intermediary products that target network and cloud computing systems, contactless systems, car electronics including autonomous systems, and devices connected to the adaptation of 5G technology applications will grow the most in future years. (IC Insights 2021)

- **O-S-D devices (Opto, Sensor, Discrete) 67% of all semiconductor units produced and shipped**
  - Sensors/actuators: (pressure sensors, accelerometers, gyroscopes, etc.)
  - Discrete (transistor products, diodes, rectifiers, and thyristors, etc.)
  - Optoelectronics (image sensors, laser transmitters, light sensors, etc.)
- **ICs (Integrated circuits) 33% of all semiconductor units produced and shipped**
  - Std Logic (all the different programmable Logic ICs)
  - Memory (static RAM, dynamic RAM, Ferro Electric RAM, etc.
  - Micro components (microprocessors, microcontrollers, etc.)
  - Analog (operational amplifiers, power management circuits, and sensors)

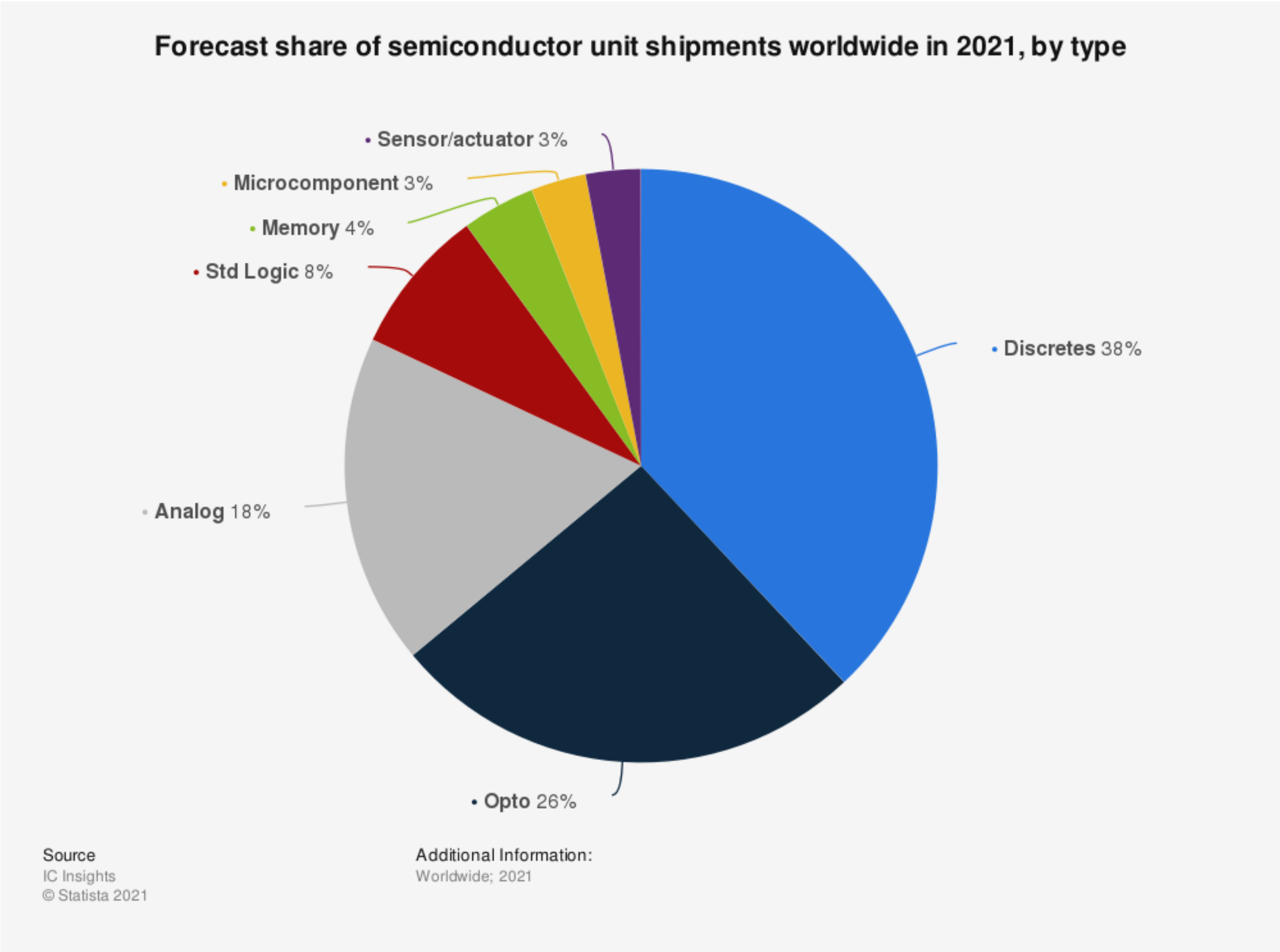


Figure 2 - Share of semiconductor units by type, source: The 2021 McClean Report

The second common categorization done by SIA reports (Semiconductor Industry Association) divides the semiconductor products by their broader purpose into three groups with subgroups that are almost the same as in the previous categorization. (Antonio Varas et al. 2021a)

- Logic (42% of industry revenues)
  - Microprocessors
  - General-purpose logic (Field Programmable Gate Arrays (FPGAs etc.)
  - Microcontrollers
  - Connectivity (WiFi or Bluetooth chips or Ethernet controllers)
- Memory (26% of industry revenues)
  - Dynamic RAM
  - NAND (solid-state drives etc.)
- DAO (32% of the industry revenues)
  - Discrete
  - Analog
  - Other (optoelectronics mostly)

In the report from 2021 by SIA, the following distribution of revenue for the whole industry was given. When we compare it with the previous MCclean report, we can see that more technologically advanced ICs like microchips and Std Logic products generate the majority of the revenue in the industry even though the number of units made is fractional to the OSD devices. One way of tracking the technological level of the semiconductor is via the size of nodes. Node is a term that describes in nanometers the size of transistor gates in the semiconductor architecture. In plain English, the smaller the node, the more expensive and technologically impressive the resulting semiconducting unit is (Antonio Varas et al. 2021a).

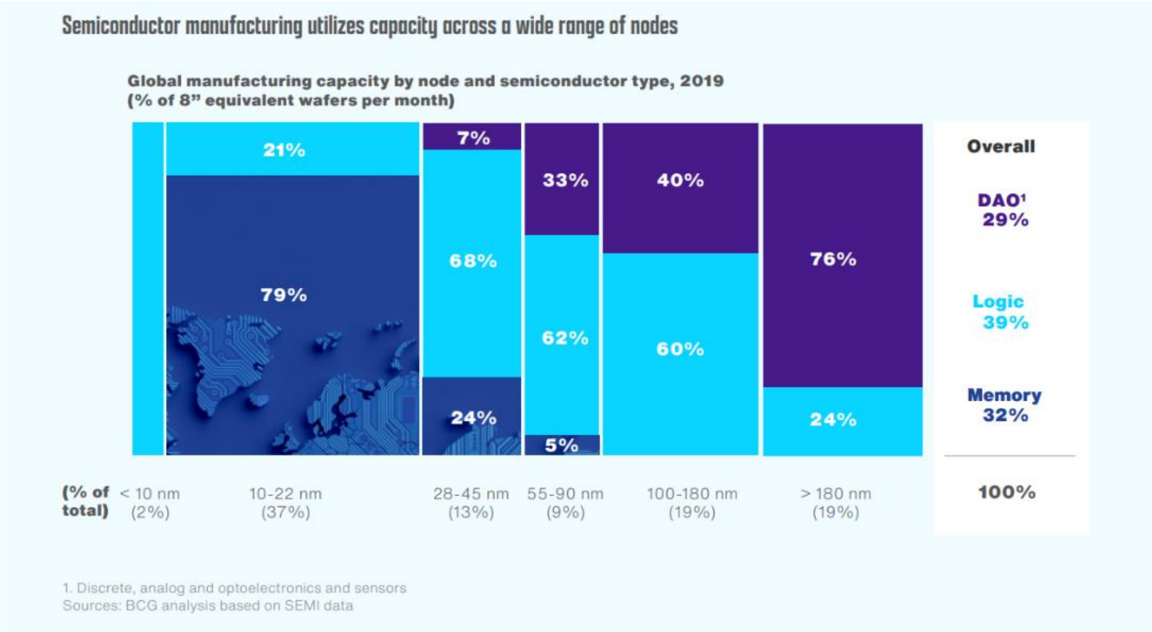


Figure 3 - Semiconductor nodes size and usage by purpose (source: BCG analysis based on SEMI data)

As the last figure shows, the logic and memory-purposed semiconducting units use the smaller, more expensive nodes when compared to the DAO units. DAO products like light-based sensors do not require or even benefit from fitting more computing power into smaller nodes like logic and memory-based units do. In other words, there is no reason for DAO units to migrate to smaller nodes. This clearly shows that most of the technological advances in the semiconductor industry are made for the logic and memory units. (Antonio Varas et al. 2021a)

Figure 1 shows the expected increase in the market capitalization of the semiconductor industry pushed by the growing innovation of the 21st century and new use cases for semiconductor intermediary products. The increase in the volume of semiconductors needed to satisfy the global demand Is staggeringly high. The best showcase of this is modern cars. All the new inventions and “unnecessities” have pushed the cost of electronic components in the average new car by more than 20%, up to 40% of the total average car cost in just 20 years. According to Rolan Berger’s report, semiconductor demand in the automotive industry increases by about 17% per annum.(Michael Alexander et al. 2021a) As one Bloomberg article puts it, and as the following figure shows, we have moved from horsepower to chip power. (King, Wu, Pogkas 2021)

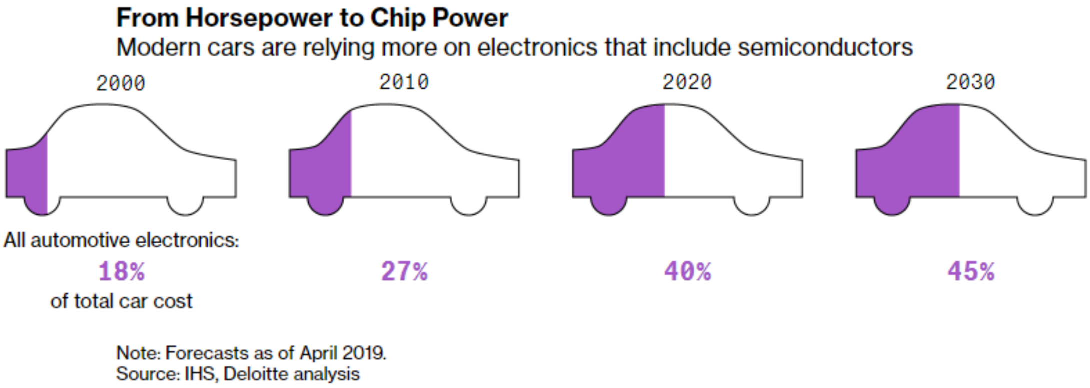


Figure 4 - Electronics as a major part of the total cost of modern cars, source: Deloitte analysis

A similar story for different reasons is happening in all the major end product segments mentioned in figure 1. This has led to almost quadrupling of total unit shipments of semiconductor units in the past 20 years, as shown in figure 5. The figure also shows the trend of the total volume of semiconductor units produced increasing almost every year since the year 1978 and only slowing during the years of economic recessions of the early 2000s, the great recession of 2008, and again during the COVID-19 pandemic as is highlighted by the red circles in figure 5. Altogether the compound annual growth rate for the past 43 years was estimated to be 8.6%. (IC Insights 2021)

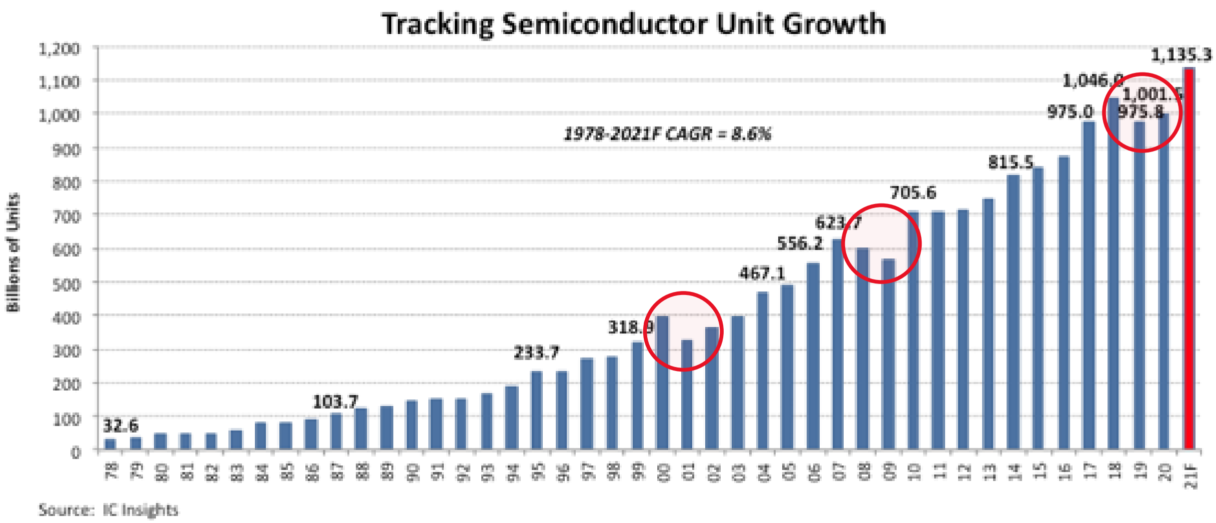


Figure 5 - Semiconductor unit shipments worldwide from 1978 - 2021 (in billions) Source: IC Insights

The semiconductor supply crisis the world has been experiencing since the COVID-19 pandemic has finally brought media attention to this crucial industry during the peak of the Covid19 crisis in Q1 of 2021 as major car-makers, and other key electronic industries worldwide were unable to deliver their end products due to the lack of semiconducting components like microchips. (Google Trends)

The semiconductor industry holds on its back the entirety of modern products, and any disruption can easily cause a domino effect throughout many industries, severely damaging the global economy. Semiconductors are the ultimate intermediate product of today. This is why all the possible causes of the crisis need to be explored in detail to prevent a future repeat of this supply shortage with correct precautions.

Figure 6 - google trends search for Semiconductor shortage, 2018 -2022, source: trends.google.com, worldwide

2. Causes of the semiconductor shortage crisis

2.1. Lack of raw resources

The first logical assumption to have when investigating a lack of anything on the economy's supply side is that perhaps there aren't enough raw resources to produce the given thing in needed numbers. The semiconductor industry is limited to substances that are neither excellent conductors (like metals) nor insulators (like glass) but have just enough electrons at room temperature to be "semiconducting." (Rahman 2014)

The most used element with these properties in the semiconductor industry is silicon. Silicon has two advantages over the alternatives. Silicon is not particularly rare; in fact, the opposite is true. Silicon is the second most abundant element on earth and makes up 28.2% of the Earth's crust. (William M. Haynes 2017) The second advantage of silicon is that it is the most versatile semiconducting material out of all alternatives, thanks to its chemical properties and specific silicon structure that result in high stability in most cases. (Greenwood, Earnshaw 1997). Other semiconducting materials aren't used nearly as much as silicon. Germanium is often mentioned as number two. However, it was started to be replaced by silicon after the 1950s. The other semiconducting elements are usually used in niche cases where silicon properties aren't sufficient.

For example:

Gallium Arsidenide (GAs) is used for high frequencies – (ability to turn electricity into light - smartphones, etc.) (Nguyen 1999)

Indium Phosphide (InP) is used for very high frequencies (radiation detectors etc.) (Pekarek, Zdansky, Prochazkova 2008)

Gallium Nitride (GaN) has much higher voltages handling (military radios or Terahertz radiation devices etc.) (Ahi 2017)

Silicon Carbide (SiC) for dealing with very high temperatures (car engines etc.) (*Silicon Carbide breakthroughs to accelerate electric vehicle innovation* 2020)

According to the data from the mineral commodity report prepared by U.S. Geological Survey 7 871 000 metric tons of silicon were produced globally in 2020 around the world, with a majority of almost 69% of the world's production being allocated in China, as can be seen in the following figure. Silicon isn't the only REE (rare earth element) that is currently being mined and processed mainly in China, leaving China in a powerful political and economic situation where its capable of manipulating with prices of almost every REE, as can be seen in the following figure from 2019 US geological survey that shows just how much the entire world is currently dependent on the mining of REE happening in China. The figure is almost monocolored in the red color that represents China. (*Mineral Commodity Summaries 2019*, 2019)

China is well aware of its market position and has used it to pressure other countries. For example, in 2010, China cut off Japan completely from delivery of REEs due to a political dispute, leaving Japan without any delivery for two months till the dispute was resolved. (Mancheri et al. 2019)

So why is the mining of silicon and other REEs so heavily concentrated in China?

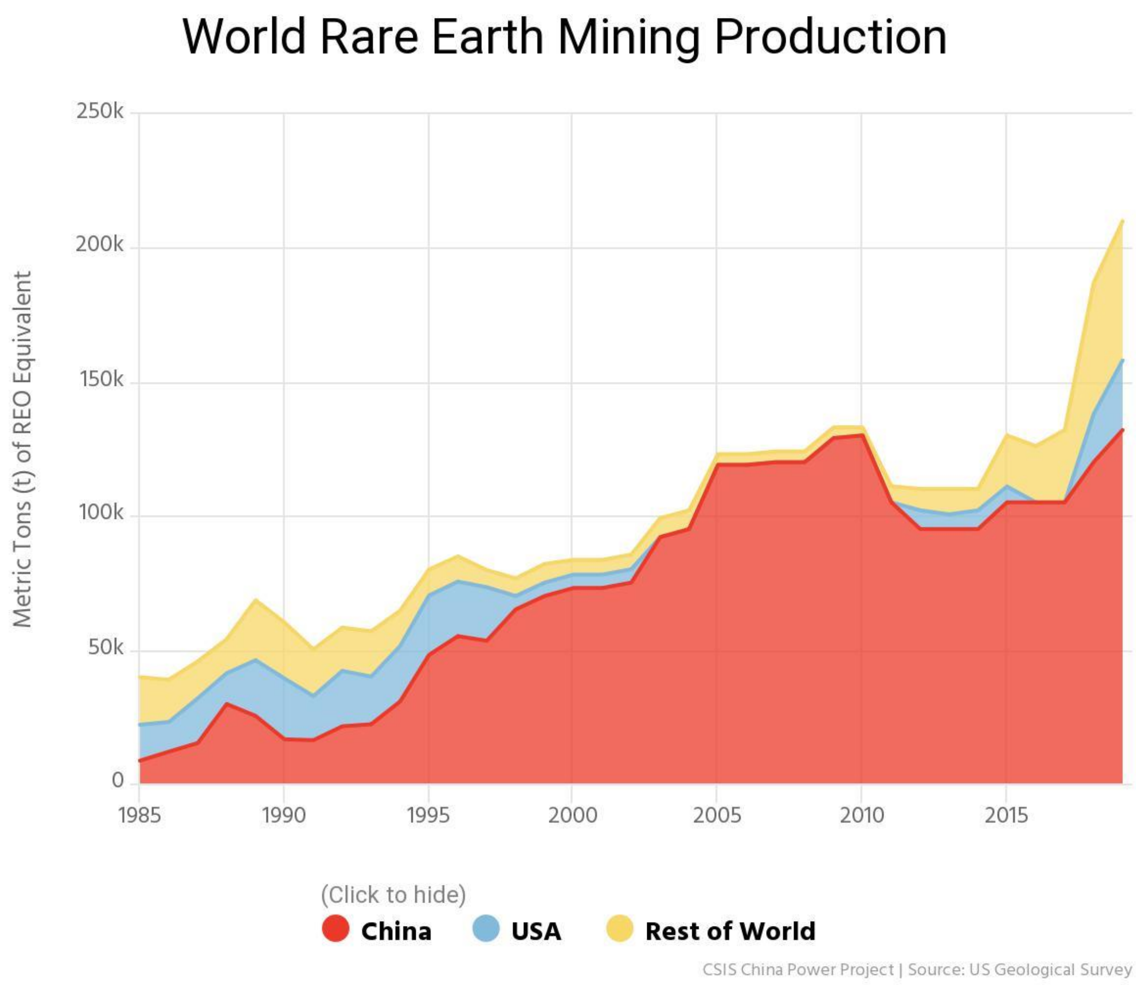


Figure 7 - World rare earth mining production, source: US Geological Survey

To mine and then to separate silicon and other rare materials from the minerals in which they are found is both challenging and costly. There are hundreds of such minerals, but silica sand containing quartz is the most commonly mined for silicon. In some cases, the purifying processes sometimes require thousands of phases to extract and prepare the finished material. (Kołodyńska et al. 2019). This has led to many companies not pursuing the extraction of rare elements. China, however, had focused on it since 1990, when the Chinese government declared REEs protected and rare and forbade any foreign companies to mine in China. The only option left for the foreign competition were joint ventures with Chinese firms. This allowed for only Chinese-approved companies to use their competitive advantages of cheap labor and almost no environmental regulations to push down prices. In just ten years, the mining production in China increased over 450 percent to 73,000 metric tons from about 16,000. (Mancheri et al. 2019) (Pui-Kwan Tse 2011)

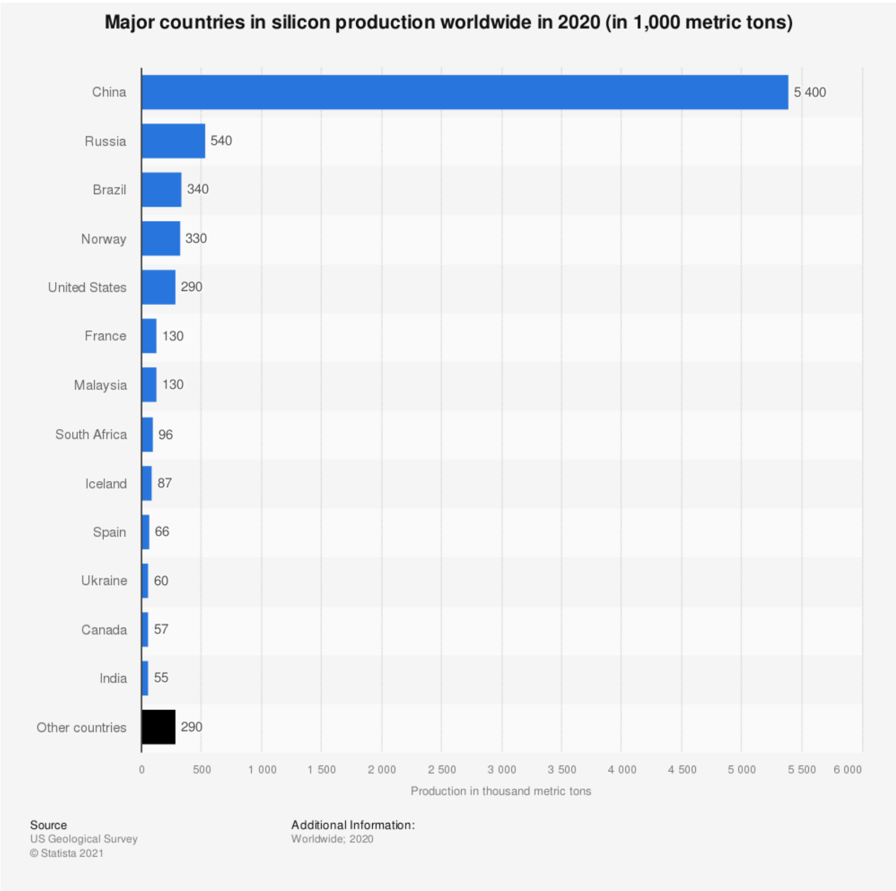


Figure 8 - Major countries in silicon production worldwide in 2020 (in 1000 metric tons), source: U.S. Geological Survey 2021

According to the data available to UN Comtrade Database from 2019, all the significant economic superpowers rely on imports of REEs, including silicon and other semiconducting material from China. The most reliant country on REEs imports from China before the COVID-19 pandemic was the US, with over 80%. Japan and South Korea are slightly less dependent, with roughly 60% in 2018. Although the dependence on Japan on Chinese REEs remains high, it used to be a lot higher. However, the dispute with China in 2010 forced Japan to seek alternatives, which they did by investing $250 million in Australian miner - Lynas Corporation. This investment slowly reduced the reliance on China by 30% and showed that the situation could be changed relatively quickly should the reliant countries be willing to invest. (*How rare earth shocks lifted an upstart Australian mining company* 2019) The purple line representing the EU is the most dynamic of the four lines. In 2015 the dependence on imports of REEs from China was only at 30%; however, since then, the reliance on imports from China started to increase again and reached almost 60% in 2018. (Chinapower.csis.org team 2020)

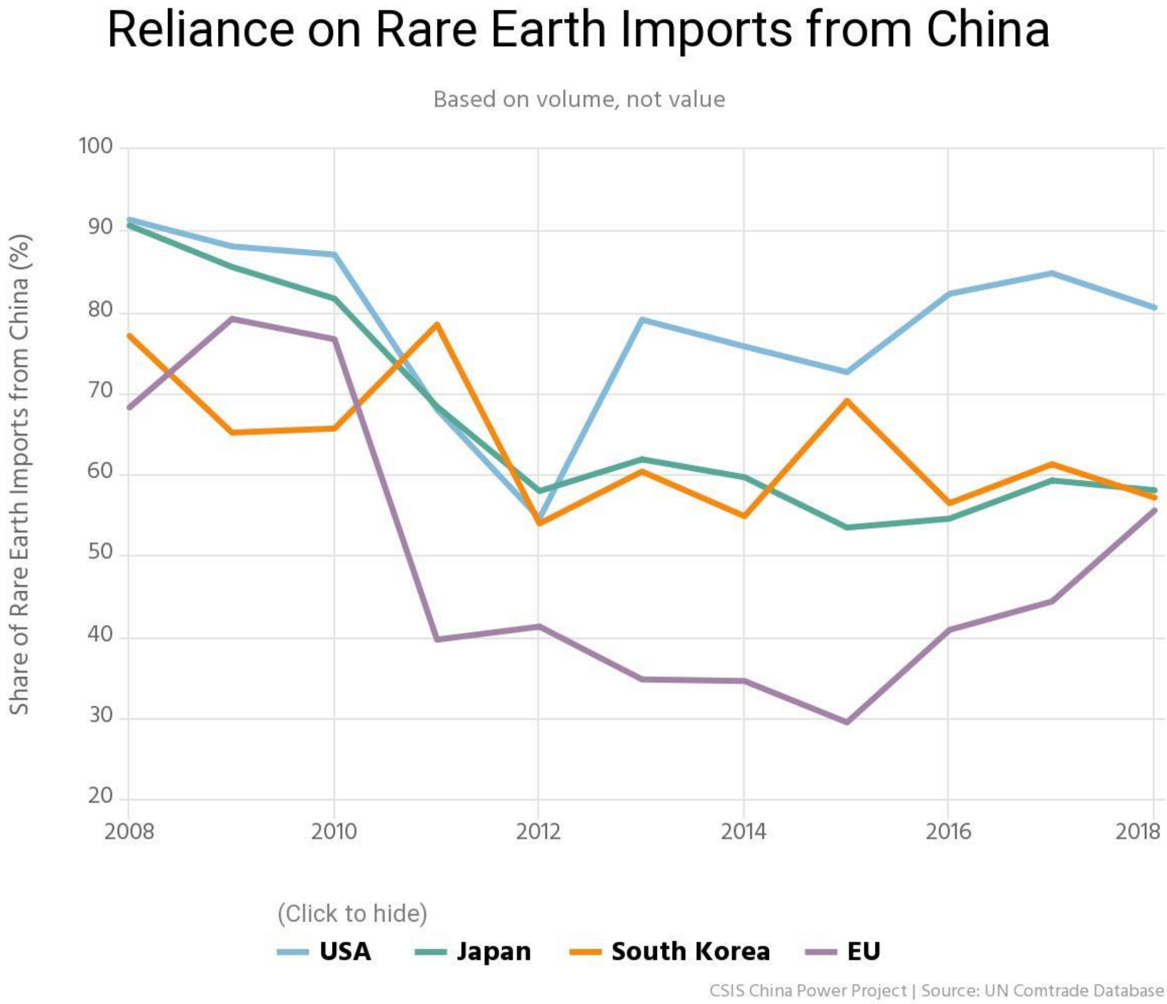


Figure 9 - Reliance on Rare Earth imports from China, source: UN Comtrade Database

From the last two figures, it is clear that the world's economy is in a deep reliance on mining and the export of REEs from China. This leaves many global supply chains, including the semiconductor industry, in a dangerous situation. China has already demonstrated that it isn't afraid to leverage its position to pursue its political objectives. Should any crisis like the covid 19 pandemic hit China and limit their mining capacities, it endangers most of the world's mining processes of REEs. China is also in an almost monopoly-like position, which allows it to manipulate with prices of REEs on the market. **However, there is no threat of Earth running out of semiconducting material in the foreseeable future as silicon is the most used semiconducting material and the second most common element in the Earth's crust.**

2.2. Complex manufacturing process of semiconductors

As difficult as it is to mine and extract silicon from raw materials, it gets even more complicated afterward. SIA divides the structure of the semiconductor supply chain into research, design, and actual manufacturing that has a front-end (manufacturing) and a back-end part. (assembly, packaging & testing) (Antonio Varas et al. 2021a)

Front-end manufacturing

The previous subchapter 2.1. already suggested how difficult and expensive the mining and follow-up purifying of silicon and other rare earth materials can be. The purification processes have the goal of creating polysilicon of certain purity. First, the extracted silicon is refined into so-called Metallurgical grade silicon that is roughly 98% pure. In this form, silicon is used extensively in the metallurgical industry. However, for the semiconductor industry, a much more refined form of silicon is needed – so-called electronic-grade silicon with "nine nines" of purity (99.9999999%) needs to be created by another chemical purification process done on the metallurgical grade silicon. Electronic grade pure silicon gained from this is finally used in semiconductor wafer manufacturing for electronic devices and ICs. The term wafer started to be used in the 1950s in the industry to describe a thin round slice of semiconductor material, typically germanium, at that time as the process reminded slicing of bread. (Voelkel, 2012) (Antonio Varas et al. 2021a) (polarismarketresearch 2019)

According to the research done by Bernreuter research in 2020 majority of the metallurgical grade silicon is purified in China, with five out of six biggest companies being Chinese and operating in China, which makes sense as most of the mining is happening there as well as was described in the previous chapter. Out of the following six companies shown in the figure, only Wacker isn't a Chinese company, it's a German one. Together these six companies reached a production capacity of 470,000 metric tons of m. polysilicon which was almost the total worldwide production in 2015. (Johannes Bernreuter 2020) The following figure shows the exact capacity for each of the six companies in 2020.

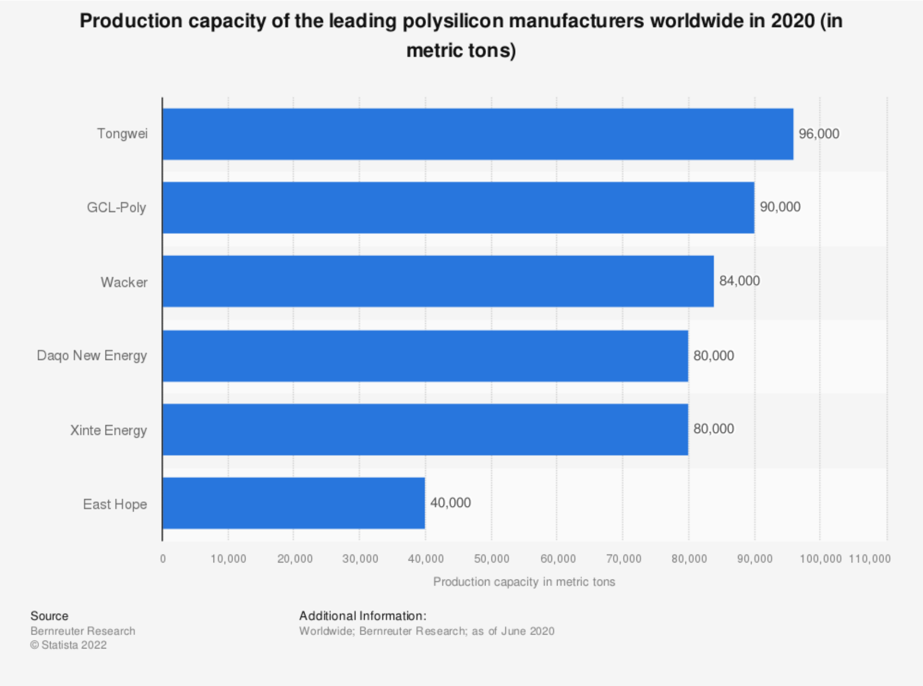


Figure 10 - Production capacity of the leading metallurgical grade silicon worldwide in 2020, source: Bernreuter research

The number of companies that dominate the market is even smaller for the electronic grade silicon. According to the report prepared by 360Research reports, most of the world's market is being supplied by just five companies (Shin-Etsu Chemical (JP), Sumco (JP), Global Wafers (Taiwan), Siltronic (GER), SK siltron (ROK). These five companies have a global market share of above 90%. (360ResearchReports 2020). None of these five companies are based in China, where metallurgical grade silicon is prepared, but four are based in East Asia, allowing for relatively short supply chains.

The front-end manufacturing requires additional materials aside from the main component of silicon for the wafer fabrication process. In fact, silicon only makes up 36% of the total market of the materials needed for the front-end fabrication. The following figure shows the compiled list of the most important ones with the total market value of these materials. Sometimes a combination of more than 300 different materials like special gases or photomasks is needed for the front-end fabrication process. According to SIA, the frond-end semiconductor materials had a market size estimated at 33 billion USD in 2019. (Antonio Varas et al. 2021a) This leads to very geographically dispersed value chains with many specialized suppliers that firms in the semiconductor industry need to rely on.

One of these specialized suppliers are, for example, the Neon gas mining facilities of Ingas and Cryoin, operating in Ukraine. Approximately half of the global supply of Neon comes from Ukraine, with the second-largest producer being China. China has used this fact to increase the price of their Neon gas by as much as 500 percent during the Russo-Ukrainian war as the Ukrainian factories needed to halt production, resulting in 35 000 cubic meters of neon being "unmined" every month. (Alper 2022)

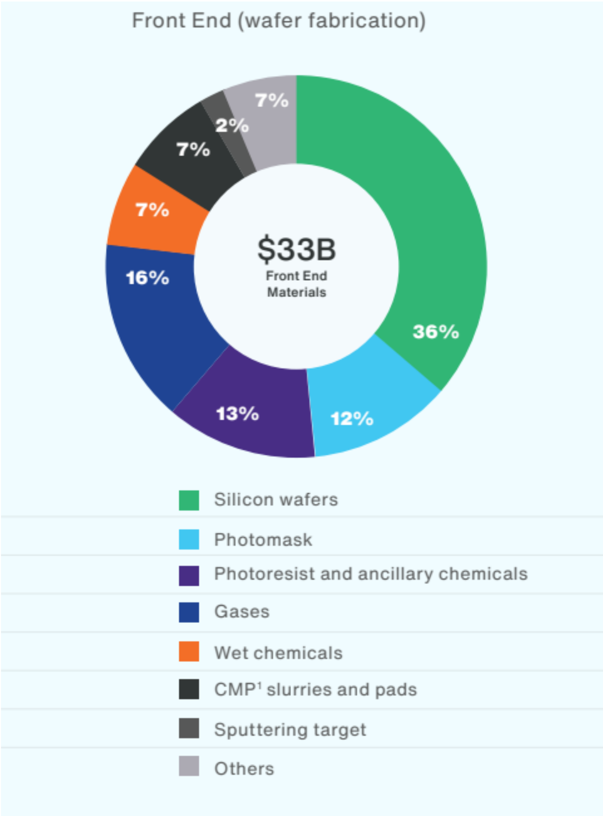


Figure 11 - Front-end semiconductor manufacturing materials market, in billions USD,2019 source: SIA report

The wafer fabrication process can begin once all the necessary materials are prepared. According to the SIA, it can be divided into five major steps, out of which the first four are repeated hundreds of times before the desired result is reached. Depending on the specific product, there can be between 400 and 1400 steps in the overall manufacturing process of semiconductor wafers. The process usually lasts between twelve to twenty weeks. The major steps in wafer fabrication are as follows: (Antonio Varas et al. 2021a)

1. **Oxidation and coating**
2. **Lithography**
3. **Etching**
4. **Doping**
5. **Metal deposition & etching**

The steps as mentioned above must be done with specialized expensive equipment in completely sterile conditions. The manufacturing is happening in specially built cleanrooms, as the slightest imperfection can affect the quality of the product. According to ISO standard 14644 that most cleanrooms have to fulfill, cleanrooms are defined as "*room within which the number concentration of airborne particles is controlled and classified, and which is designed, constructed and operated in a manner to control the introduction, generation, and retention of particles inside the room*." (international organization for standardization 2015) Cleanrooms are enormously expensive to build and maintain due to the advanced digital fume hoods and other sterilization equipment required to fulfill these standards. Depending on the system and level of sterility needed, the cost of these rooms ranges from $100 to more than $1,000 per square foot. The requirements for the wafer fabrication zone are on the higher end of this spectrum. (https://cleanroomtechnology.com 2018) The specialized equipment used in the wafer fabrication, such as lithography and metrology tools, operates on hundreds of technology subsystems. For example, EUV (extreme ultraviolet) scanner used in lithography has over 100,000 parts and costs roughly $150 million. A typical wafer fabrication has several hundreds of specialized machines like this. (CNBC 2021) Typically it takes between two to four years on average to build a fully operational fabrication plant. It can also be challenging to hire and train the needed workforce. Depending on the plant, between 3,000 to 6,000 people are required to operate such a building. This workforce needs to be highly skilled and consists mainly of skilled engineers. (Antonio Varas et al. 2021a)

These requirements make front-end manufacturing staggeringly capital intensive. According to SIA, a modern semiconductor analog fabrication plant of standard capacity requires roughly 5 billion USD investment to be built. A fabrication plant for more complex semiconductors (advanced logic and memory) can climb up to 20 billion USD in price. (Antonio Varas et al. 2021a) This makes it unthinkable for any company to enter the front-end market without access to substantial sums of capital. Building an advanced normal-size analog fabrication plant is roughly four times cheaper, with the estimated price being around 5 billion USD but is just as demanding on the human capital. (Raj Varadarajan et. al. 2020)

The following figure by SIA shows the global wafer fabrication capacity for each of the three big categories. From the figure, we can see the largest total volume of 20% is being produced in Taiwan. Taiwan also specializes in fabricating the most modern under 10nm logic nodes. The other big players, except for Europe are relatively even in the total volume produced. East Asia, combined with China, concentrates about 75% of global wafer fabrication, making the region of eastern Asia key for the front-end fabrication. Still, this part of the global value chain of the semiconductor industry is much more resilient and diversified when compared to the

Chinese silicon mining monopoly explored in the previous chapter. (Antonio Varas et al. 2021a)

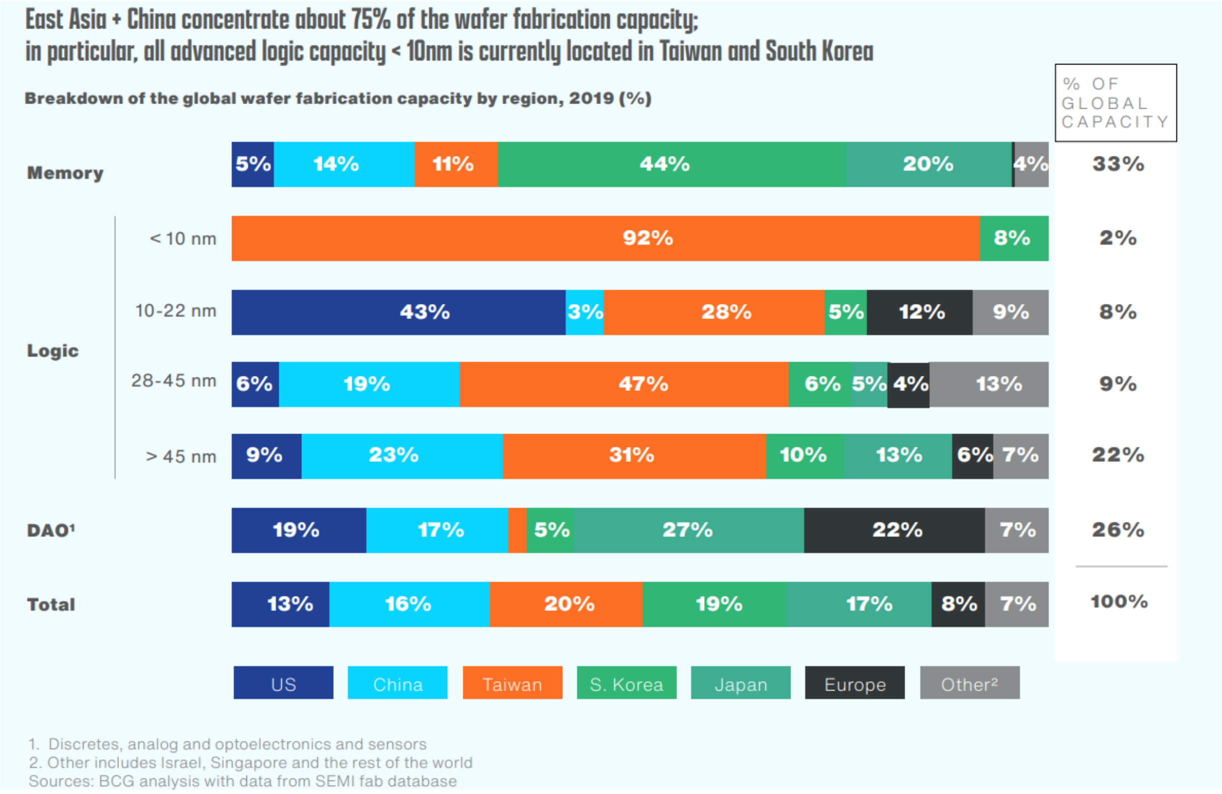


Figure 12 - Wafer fabrication capacity by type and region, 2019, source: BCG analysis with data from SEMI fab database

The following figure shows the most known companies in this layer of the semiconductor supply chain. TSMC, the largest company supplying the likes of Apple or AMD and other U.S. design behemoths, is based in Taiwan. It owns and operates 17 front-end facilities of different sizes, covering almost the entire market except for DAO. Only three of these 17 facilities were built outside Taiwan (one in the USA and two in China) (TSMC 2022). TSMC has over half of the total worldwide revenue of front-end fabrication. TSMC also accounts for about 15% of Taiwanese GDP, according to the Taiwanese government. (Cheng Ting-Fang and Lauly Li 2021) The second-largest company by revenue, with around 17%, is the South Korean Samsung which focuses much more on memory products foundries with DRAM and other DDR memory semiconductor products. Samsung is also not a strictly "pure-play" (only manufactures) company or "fabless" company (only designs), only producing foreign designs and end products like TSMC. (Samsung Global 2021) The following companies are quite small in revenue when compared to these two giants. They are primarily east Asia-based or owned companies with some more negligible exceptions.

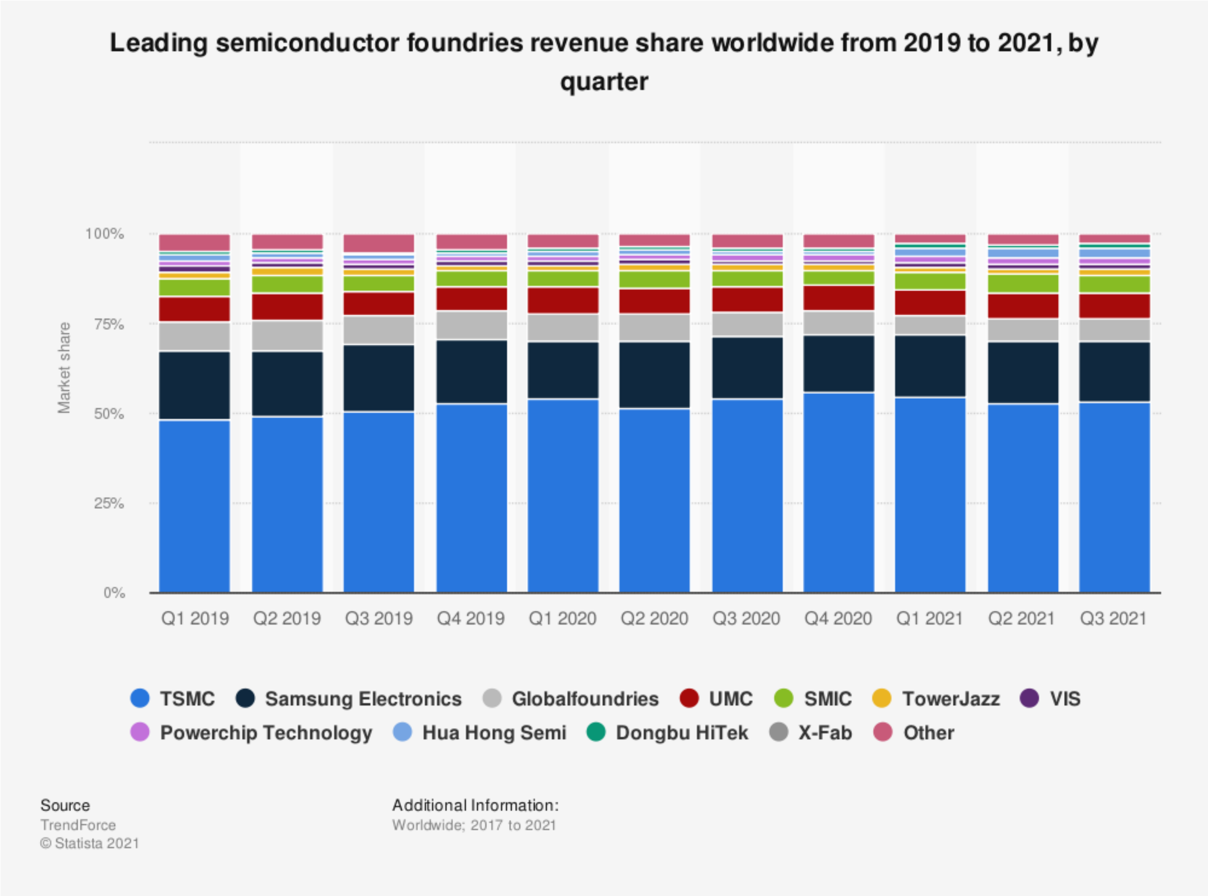


Figure 13 - Leading semiconductor foundries' revenue share worldwide from 2019 to 2021, by quarter, 2017-2021, source: TrendForce

Back-end manufacturing

Once the front-end process prepares the silicon wafers, they must be sliced and turned into their designated chips (assembly), tested multiple times (testing), and finally packaged and sent to the manufacturer of the final product (packaging). These processes are done by specialized companies and require the use of specific materials like leadgrames and ceramic packages, as the following figure shows. The back-end material market is half the size of the front-end manufacturing one. The suppliers of these materials don't need to overcome technical barriers like the suppliers in front-end manufacturing. (Antonio Varas et al. 2021a)

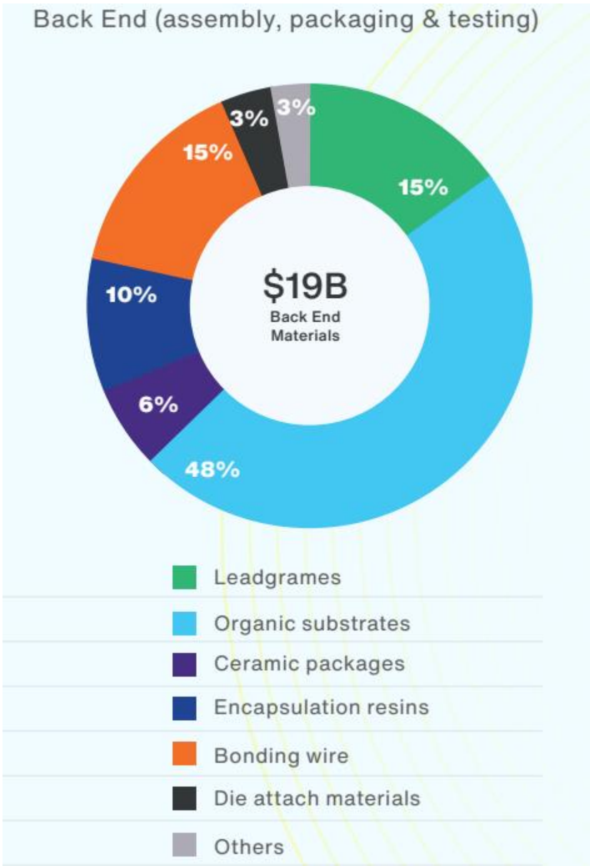


Figure 14 - Back-end semiconductor manufacturing materials market, in billions USD,2019 source: SIA report

According to SIA, east Asia countries and China control over 80% of the back-end manufacturing market. With its 38% share, China is the market leader in terms of countries and has been expanding aggressively in the past years. Back-end manufacturing is not as labor or capital intensive as front-end manufacturing, making cheap labor an essential factor for specialized companies. The value added by the back-end manufacturing into the whole value chain is also relatively small, with only six percent, according to the SIA report from 2019. In comparison, the front-end manufacturing value was 4x timed larger at 24% of the total value added by the SIA. (Antonio Varas et al. 2021a)

The most important part of the production cycle of semiconducting units was not yet mentioned. Semiconducting units are not only tricky products to manufacture but also to design. It is a very knowledge-intensive work that often requires hundreds of engineers with design support services behind them. Unsurprisingly, design is where half of the entire value of the semiconductor unit is added. A new microchip design for a new smartphone can easily cost over a billion USD to produce. (Antonio Varas et al. 2021a)

U.S. companies dominate this part of the value chain, focusing on advanced chip design. According to the SIA report from 2019, 10 of the top 20 semiconductor design companies with four of the top five companies by 2019 revenue are based in the U.S. The following figure shows the average number of citations per semiconductor patent. Europe and U.S. are the leading regions with the highest conversion into Triadic patents. (high-value inventions) (Antonio Varas et al. 2021a) China has been investing in semiconductor research and currently files the largest total number of semiconductor academic research papers and patents annually. Still, the U.S. today dominates research and design in the semiconductor industry, which is the most lucrative part of the entire value chain. (Antonio Varas et al. 2021a)

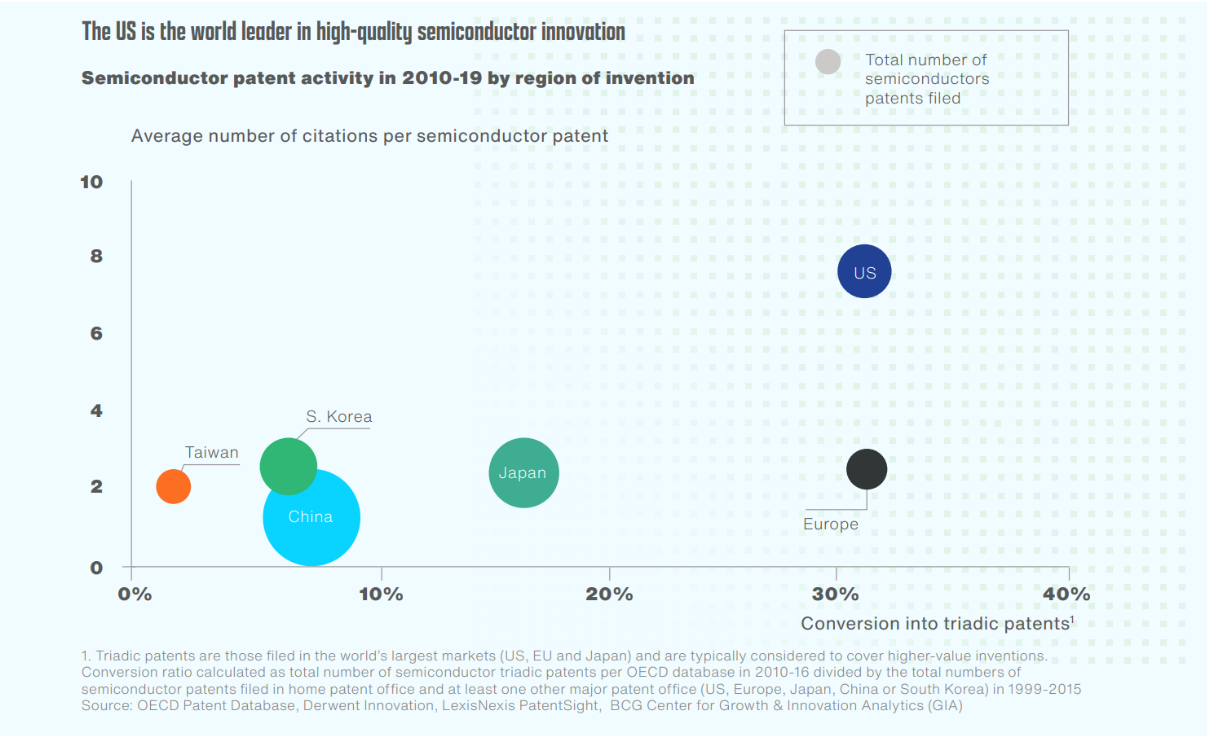


Figure 15 - Semiconductor patent activity in 2010-19 by region of invention, source: OECD Patent Database, Derwent Innovation, LexisNexis PatentSight, BCG Center for Growth & Innovation Analytics (GIA)

The following figure shows the largest IC design companies in the world by revenue. The top three companies by revenue (Qualcomm, Nvidia, Broadcom) are all American. The range of designs in their portfolio is extensive. Qualcomm has mainly focused on satisfying robust demand for 5G mobile phones from major mobile phone manufacturers worldwide. NVidias' most significant gains come from high-end graphics cards and data-centric products. Broadcom is mainly focused on designing network microchips, broadband communication chips, and storage and bridge chip designs. (Galen Tseng 2022) As the figure also shows, we can see a rapid increase in revenues of these giants since the pandemic started.

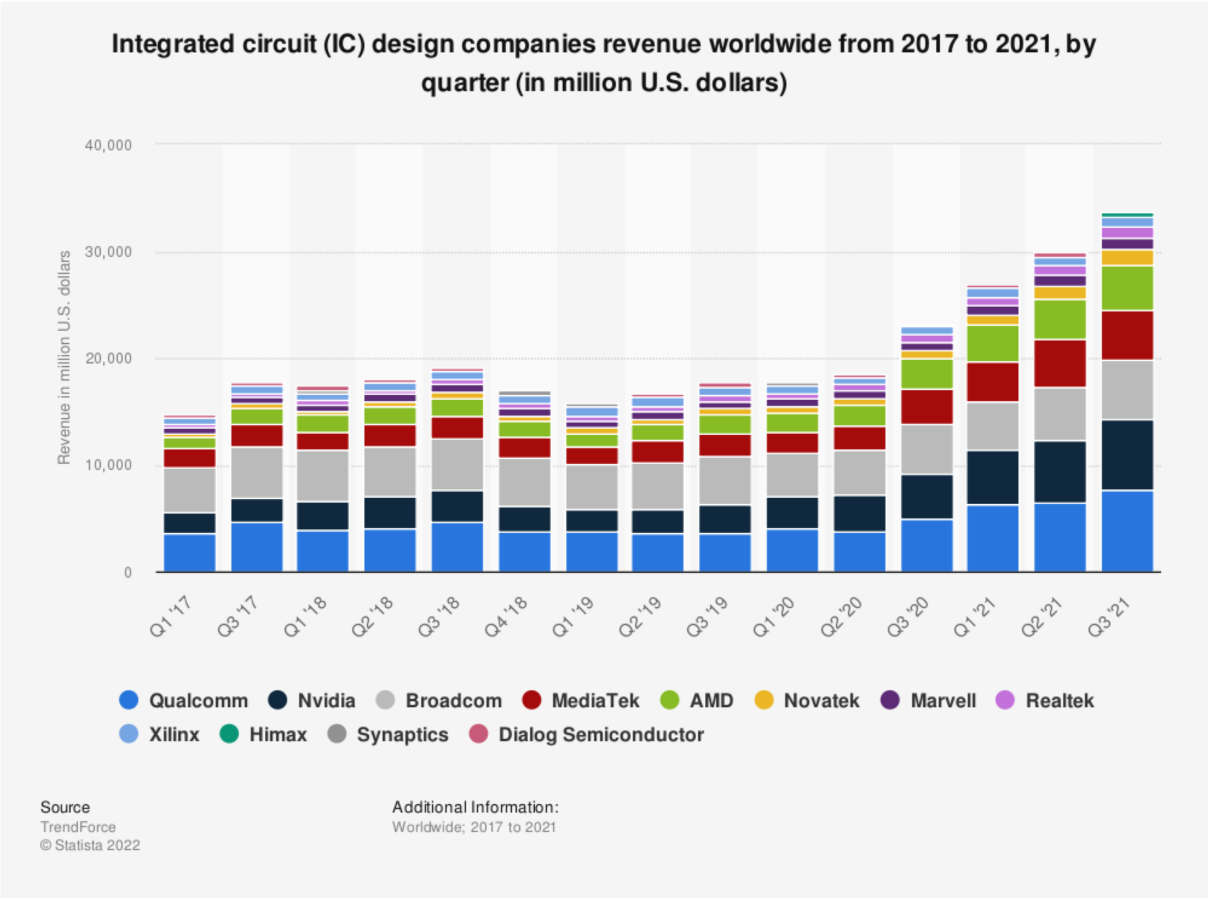


Figure 16 - IC design companies' revenue worldwide from 2017 to 2021 by quarter, in million USD, source: Trendforce

The following table with data from the SIA report shows the summary of the value chain of the semiconductor industry. Out of the six differentiated steps, the front-end manufacturing and design add the highest value percentages to the whole value chain while also being the most intensive on capital expenditures and research and development costs. Capital expenditure of companies focusing on front-end manufacturing typically amounts to 30 to 40% of their annual revenues. This results in front-end manufacturing being 65% of the total industry capital expenditures. In comparison, the design of semiconductor units is almost five times less capital intensive while adding much more value. On the other hand, design is unsurprisingly the largest portion of the research & development of the semiconductor industry. While the U.S. and Europe dominate the design sector of the market, Front-end and back-end manufacturing became the regional specialty of East Asia, hosting over 75% of the total production. The industry value chain of the semiconductor industry is one of the most complex and globalized, with a worldwide specialized ecosystem of specific material, equipment, and software design tools suppliers and core IP suppliers. This ecosystem was estimated at 490 billion USD in 2019, which is even higher than the value of the global sales of the semiconductor end products that year. (412 billion USD)

Table 1- Global value chains of semiconductor Industry according to SIA, 2019, source: BCG analysis using data from Capital IQ (company financial reports) and Gartner (total market sizes)

<table>
<tr><th>Process</th><th>Value-added</th><th>Research &Development total cost</th><th>Total capital expenditures</th></tr>
<tr><td>materials</td><td>5%</td><td>1%</td><td>6%</td></tr>
<tr><td>front-end manufacturing</td><td>24%</td><td>13%</td><td>64%</td></tr>
<tr><td>back-end manufacturing</td><td>6%</td><td>3%</td><td>13%</td></tr>
<tr><td>EDA & Core IP</td><td>4%</td><td>3%</td><td><1%</td></tr>
<tr><td>Equipment and tools</td><td>11%</td><td>9%</td><td>3%</td></tr>
<tr><td>Design</td><td>50%</td><td>53%</td><td>13%</td></tr>
<tr><td>Pre-competitive research</td><td colspan="3">-
15-20%
-</td></tr>
<tr><td>Total cost</td><td>$290 billion</td><td>$92 billion</td><td>$108 billion</td></tr>
</table>

disclaimer: "Pre-competitive research is aimed at identifying the fundamental materials and chemical processes to seed the innovations in design architectures and manufacturing technology that will enable the next commercial leaps in computing power and efficiency" (Antonio Varas et al. 2021a) 15-20% of R&D incorporates all the six major value chains parts of semiconductor industry highlighted in bold in the table (materials, design, etc.)

The semiconductor industry cannot quickly expand its production capacity due to the complexity of the entire supply chain. **Even though some of the six major steps in the production cycle, like back-end manufacturing, could have their capacities increased relatively easily and quickly, the critical process of front-end manufacturing, on which the rest of the chain depends the most, takes years to expand.** A single new manufacturing plant can take up to four years to be built and requires tens of billions of USD in investment and numerous qualified personnel before the wafer fabrication process can even start. This makes the semiconductor industry unable to react quickly to unexpected demand shocks as it can only increase its output with years long lag. Furthermore, the entire industry depends on many heavily specialized suppliers of material and machinery, making the industry very susceptible to supply crunches, like the one with Neon gas happening right now.

2.3. Impact of COVID-19 on the semiconductor sector

The COVID-19 pandemic disrupted and affected the semiconductor industry in multiple ways. The market's supply side was affected by the lockdowns and closed factories around the world that eventually led to bottlenecks being formed in the different parts of the production cycle.

It is almost impossible to gather the data for all the relevant closings of semiconductor-related factories during the pandemic around the world. Some information can be provided by the COVID-19 government response tracker developed by Oxford. A so-called stringency index indicates the toughness of the government response, including forced workplace closings (C2 indicator on the Oxford tracker). The following figure shows some of the most important countries for the semiconductor industry and how their Stringency index developed across time. Almost all of them had some limitations in place during the pandemic. (Oxford, Blavatnik school of government 2021)

Japan, Taiwan, and South Korea or the United States never forced any closure in the semiconductor sector, preventing a much larger semiconductor crisis as most governments listened to global semiconductor stakeholders' call to maintain semiconductor production at all costs. (SIA 2020) However, the pandemic could have negatively affected the production and distribution in these countries in lesser ways. (Oxford, Blavatnik school of goverment 2021) For example, in a survey by Ernst & Young LLP, 47% of all companies reported that they had their workforce impacted by the pandemic in 2020. (Ernst & Young LLP 2020)

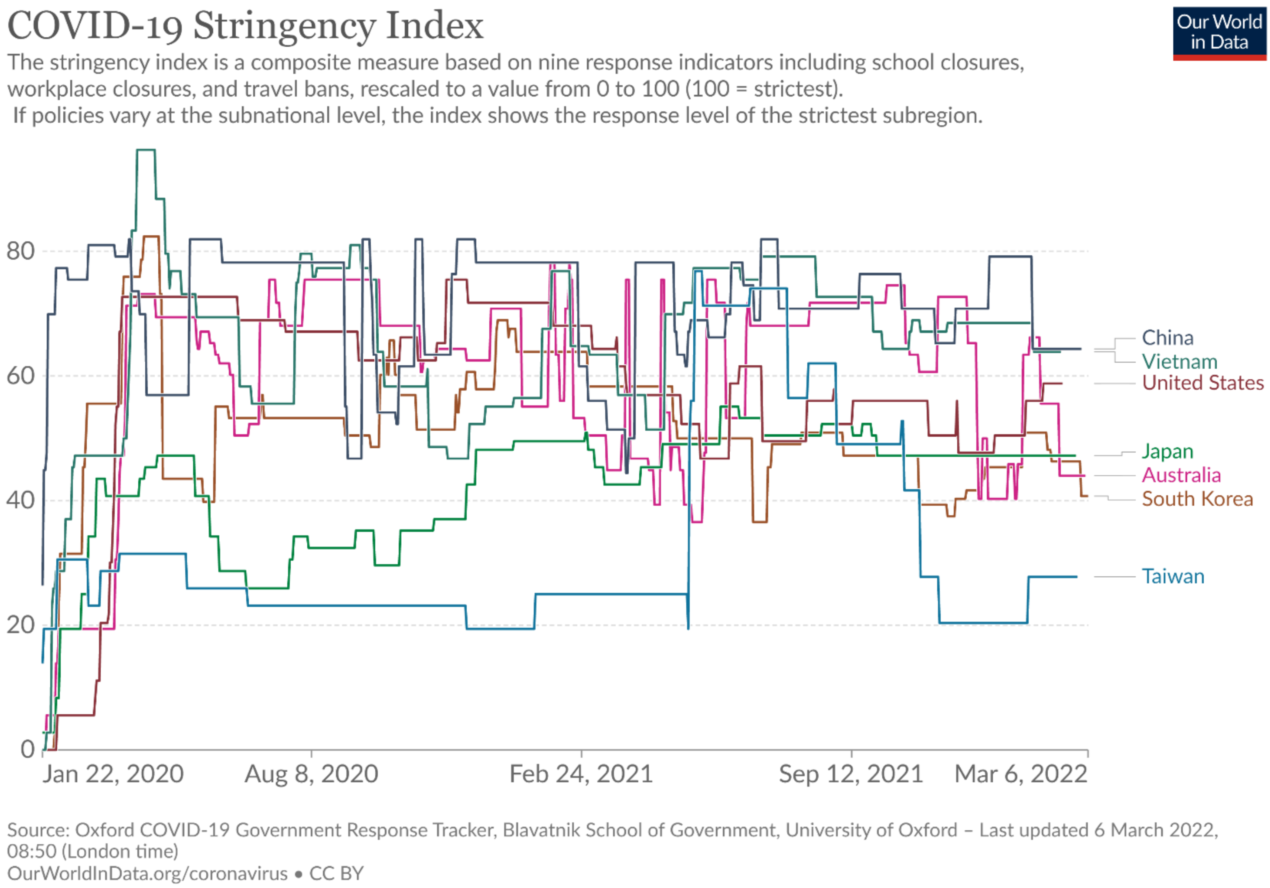


Figure 17- COVID-19 Stringency index for selected countries, 2020-2022 source: Oxford

Some of the harshest lockdowns in East Asia were in Thailand, Vietnam, and Malaysia, as the Delta variant cases hurt consumption and factory production just as much as in the first wave. Although these countries aren't the most important in the semiconductor value chain, they are important hubs for back-end manufacturing. (Reuters 2021a)

However, probably the most significant blow to many global supply chains, including the semiconductor industry, was caused by the lockdowns and zero Covid policy in China that resulted in weeks of closed mining facilities (Bala 2022). This resulted in a stunning price increase of silicon by 300% in just two months, as the following figure shows. This price increase had a significant impact on many smaller companies in the industry. (Bloomberg 2021a). While the Chinese fabrication plants managed to sustain the first wave of Covid in 2020, the second wave in 2021, and the third ongoing wave of 2022 have resulted in partial shutdowns in some key semiconductor industrial hubs like Suzhou or Xian (Lee, Saini 2021), (Pao 2022). During the pandemic, some of the Chinese companies ended in bankruptcy. Most of these bankrupted companies like Wuhan Hongxin Semiconductor or Tacoma Semiconductor Technology Co. were young projects funded by the Chinese government with the goal of

Chinese technological self-reliance. Covid wasn't the only blow dealt to these companies since they entered the market, but it was the last. (Sophia Yang 2020)

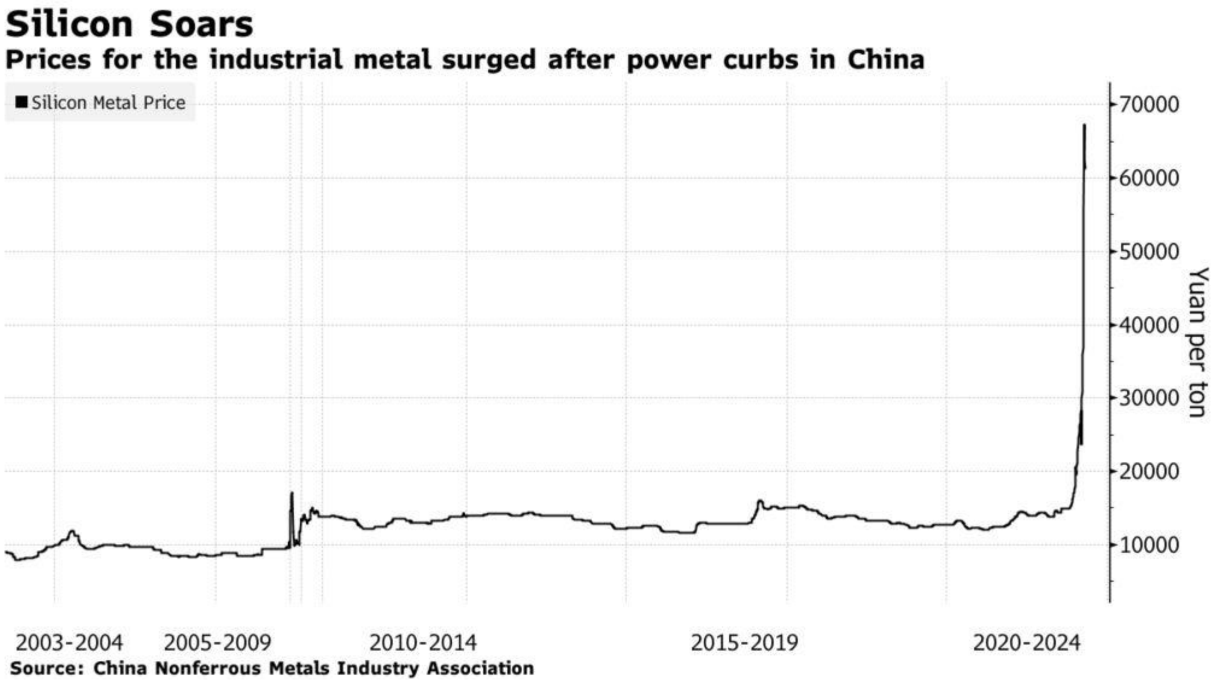


Figure 18 - Silicon Metal price since 2003, Yuan per Ton, source: China nonferrous metals industry association

Some of the most significant supply shocks of the industry that happened during the pandemic years of 2020 and 2021 weren't caused by Covid but were still thrown into the "Covid caused it bag." by many.

For example, two Japanese factories were partially destroyed by fires in 2020 and 2021. One of these factories owned by Renesas Electronics supplied roughly 30% of the global market for microcontroller units used in cars. Production was only restored after 100 days. Covid had nothing to do with one of the most damaging effects on the automotive industry, which arguably suffered the most in the semiconductor crisis. Another weather-based disaster happened to the U.S. plants when winter storms damaged two plants in Austin, Texas, owned by Samsung and NXP Semiconductors, causing a months-long delay in their products. (Reuters 2021b) TSMC almost had to limit its production due to the most severe drought the country experienced in recent memory, as TSMC facilities use more than 63,000 tons of water a day. It was by sheer luck that rains returned in June of 2021 and that production of TSMC was not affected. (EAMON BARRETT 2021)

So, were these disasters just a run of bad luck, or can we expect them with increasing frequency? According to data assembled by Jeff Masters, the world has seen a dramatic increase in weather disasters in the past two decades. The economic toll caused by these extreme events has been escalating with them. The following figure shows the number of inflation-adjusted disasters that caused damage measured over 1 billion USD. The uptrend from the figure is clear. (Masters 2020)

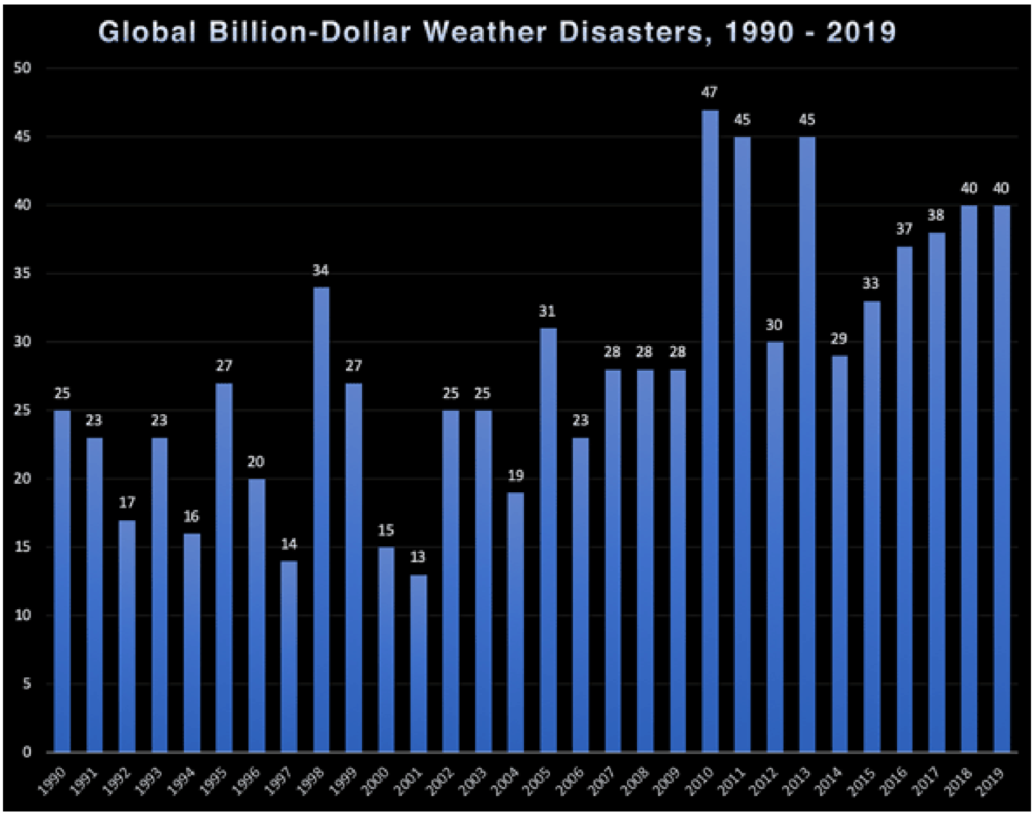


Figure 19 - Global Billion-dollar weather disasters, 1990-2019, source: Jeff Masters

Transportation is another critical aspect of the market that was disrupted by the COVID-19 pandemic. Ocean freight, land freight, and air freight were all affected in a greater or lesser way by the virus as various events connected to the pandemic, such as port closures, port congestions, and labor shortages have made the global logistic rather difficult. 20% of professionals working in the logistics industry reported that their supply chains were interrupted by the pandemic in 2020. (Agility - Transport Intelligence 2021)

Maritime transport is the backbone of international trade as over 80% of the volume of international trade in goods is happening on the sea. (United Nations 2021) The following figure shows the global container freight rate index from 2019 till 2022. As the suppliers worldwide struggled to secure limited ships for transport, prominent container shipping companies increased their profit margins by over 44% throughout the pandemic.

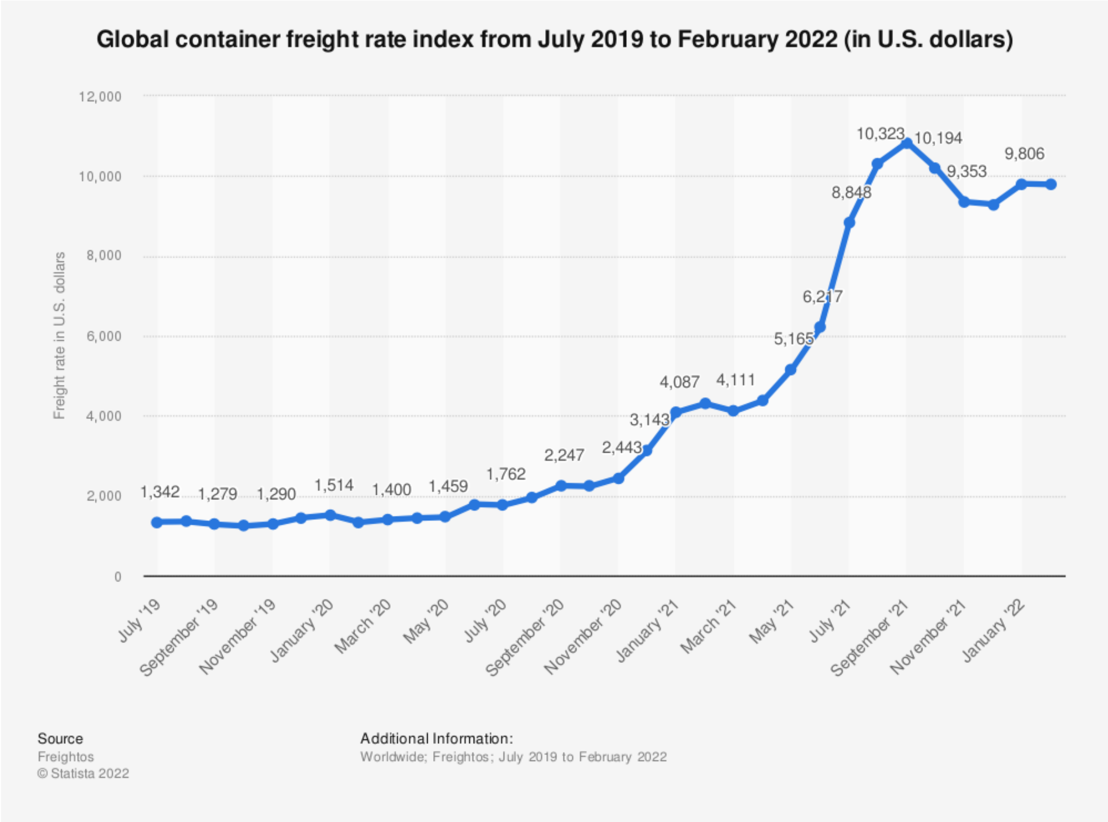


Figure 20 - Global container freight rate index from July 2019 to February 2022 (in U.S. dollars), source: Freightos

But similarly to the issues with the manufacturing, pandemic also was not responsible for all the issues in the transportation. In March of 2021, a 20,000 TEU container ship Ever Given has blocked the Suez Canal, a major trade route, for several days. At least 369 ships were queuing to pass through the canal and could not. This resulted in roughly 9.6 billion USD worth of trade being blocked, including many semiconductors products exported from Asia. (BBC News 2021) According to maritime experts, the domino effect from these few days was felt months after the Suez was reopened. (Stevens 2021)

The demand side was firstly influenced by a spike of orders for different home electronics like computers, consoles, etc., as the world was experiencing lockdowns and many people were forced to work, study and communicate and enjoy their free time from home. (Harald Bauer et. al. 2021)

This spike can be seen in the global increase of consumer electronics sold in 2020 when the COVID-19 pandemic became global. According to Gartner worldwide, PC Shipments Grew by 10.7% in the fourth quarter of 2020 and 4.8% for the entire year. This was the highest annual growth for the global PC market since 2010. (Gartner, Inc. 2021) The even more considerable increase in units sold experienced game consoles like Nintendo. Nintendo Co., Ltd. revealed that the sales in the last nine months of 2020 saw a 35.8% increase compared to the previous nine months in 2019. (Nintendo Co., Ltd. 2021) These devices include a ton of logic and memory chips controlling the display, power source, internet connection, etc.

However, the biggest demand shift was caused by the companies and not by households. According to the survey done by McKinsey, responses to companies have speeded the adoption of digital technologies and the use of advanced technologies by several years due to the pandemic. These technological advances will undoubtedly cause a lasting surge in demand for semiconductors as well. The following figure shows how executives of companies worldwide believe in the lasting effects of changes they made during the pandemic. 37% of companies increased the use of advanced technologies in operations, and 50% of respondents believe the changes will stay in their companies. 21% of companies increased their use of advanced technologies in business decision-making, and 49% of respondents believe the changes will stick. 34% of executives also experienced increase in migration to cloud servers in their companies, and 54% think that these changes will stick. (Laura LaBerge et al. 2020)

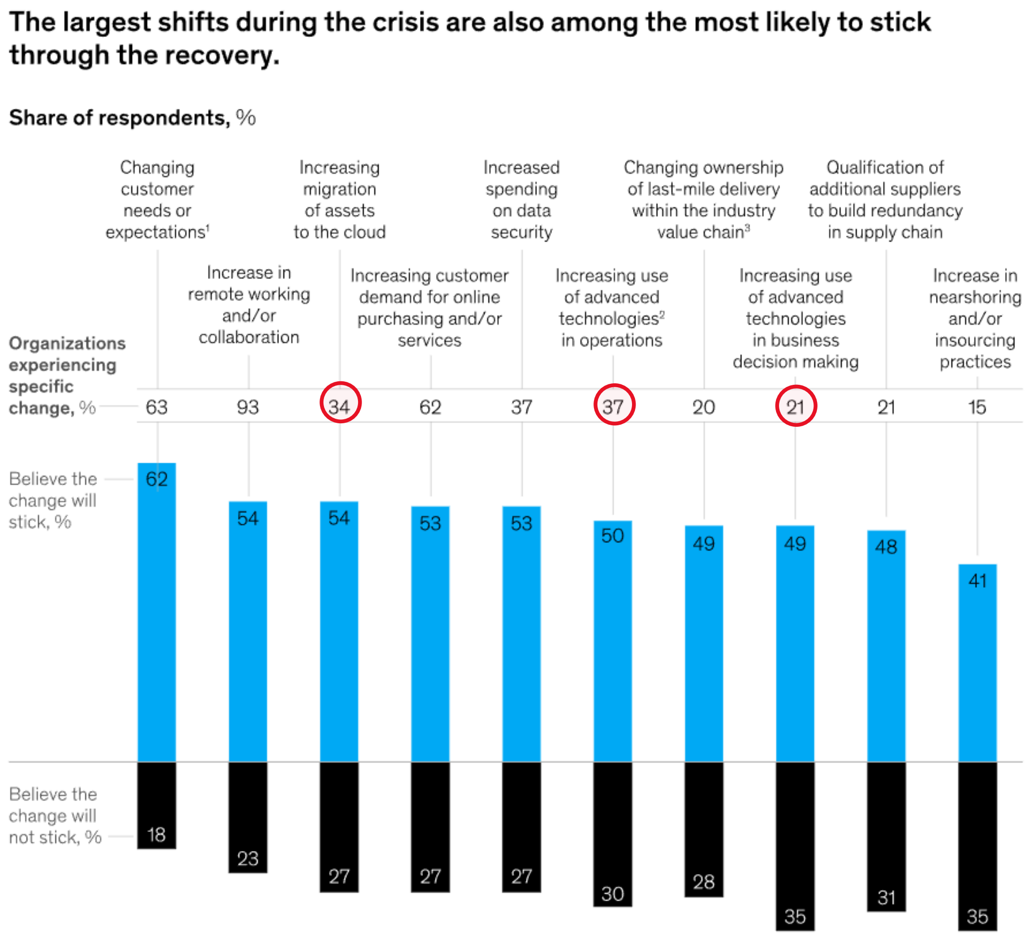


Figure 21- largest shifts during the crisis are also among the most likely to stick through the recovery, source: McKinsey company, 2020

The COVID-19 pandemic influenced the semiconductor industry by affecting both the demand and supply side of the market. However, the effects of the pandemic on the supply side weren't as significant as they might seem. During the two pandemic years of 2020 and 2021, the industry suffered many Covid unrelated calamities like the fires in the Japanese plants, energy shortages in the Texas manufactories, or the Suez Canal blockage. According to the SIA, global production never operated under 80% of its capacity during the pandemic as only a few vital manufactories were forced to shut down during the lockdowns or limit their production, as the following figure by SIA shows, the industry-wide utilization level was nearing 90 percent since late 2019. (SIA 2021) The COVID-19 pandemic did affect the prices of raw materials as well as the costs of transport, leading to additional pressure on many smaller semiconductor companies.

COVID-19 also forced households and companies into faster and greater digitalization. Increasing short-term but also long-term demand for semiconductor products. This surge in demand would never happen so unnaturally quickly without the pandemic.

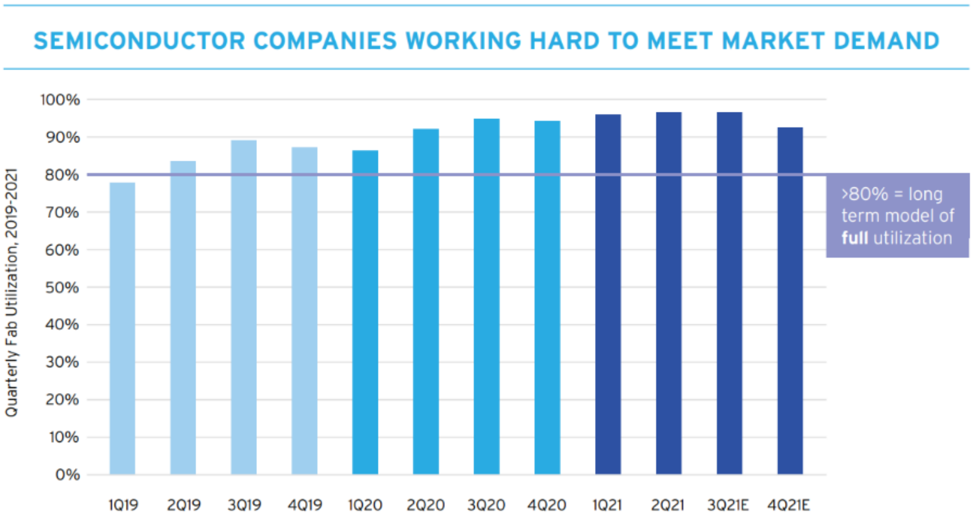


Figure 22 - Semiconductor companies working hard to meet market demand, source. SIA 2021

As of March 2022, when this paper is being finalized, the COVID-19 pandemic is still not over. Most notable, China is still facing the Omicron wave of COVID-19 and is still following its zero Covid policy (The Guardian 2022). It is very likely that more potential shocks for the semiconductor industry will arise from the lockdowns in China and the rest of the world.

2.4. Unprecedented stimulus of the economy and demand that can’t be met

“*Shutting down the economy, and more importantly turning it back on again, is not like shutting down and turning on a light bulb. It's more like shutting down and restarting a nuclear reactor. You need to do it carefully, and make sure the parts survive the shutdown intact.”* - (Cochrane 2020)

The COVID-19 pandemic is an entirely new crisis likes of which the newly globalized world has not yet experienced. Governments were forced to shut down some parts of the economy to enforce the health mandate, and that wasn’t easy. To relieve the crisis, governments worldwide initiated massive fiscal support programs, as the following figure with data from May 2021 shows. Economical giants like the United States or Germany spent over a quarter of their GDP. Still, even single-digit percentages like China committed can substantially impact the demand side of the market. The measures used differed from country to country, but they all had the same goal of continued liquidity support from the state. From cash relieves to households and companies, to be spent freely, to cheap loan offers and tax relief schemes. (Deb et al. 2022)

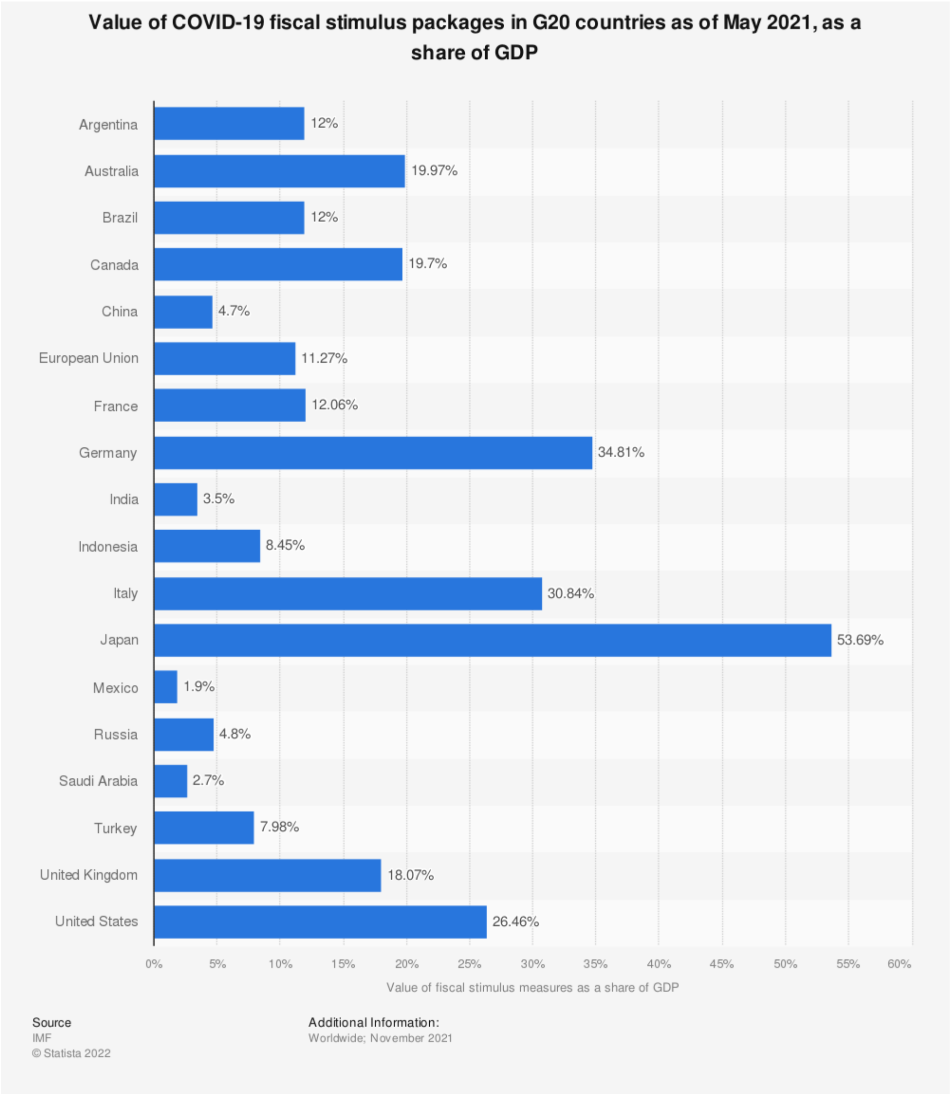


Figure 23- Value of Covid-19 stimulus packages in G20 countries as of May 2021, as a share of GDP, source: IMF

According to research by VoxEU, these Keynesian-inspired responses to the crisis did succeed in increasing standard indicators of economic activity like stock price indices, unemployment rates, the OECD's Composite Leading Indicator (CLI) for confidence, etc. and were overall successful at boosting consumption (Deb et al. 2022)

At the same time, research by Jesse LaBelle, as illustrated below, has shown that due to restrictions imposed and the nature of COVID-19 (changes in human behavior, etc.) the consumption of goods and services behaved very differently when compared to previous economic recessions. While consumption of services in advanced economies fell rapidly and only slowly recovered, the consumption of the goods on the other hand almost didn't fall and had a quick, strong recovery after that. Such was also the case with many semiconductor end-products. As the previous chapter described, lockdowns have led to an increase in demand after products that can be used at home, as people hunker up at home were spending their vacation money on a new gaming console etc. However, due to the COVID-19 restrictions, industrial production was very slow to adjust (in the case of semiconductors it was impossible to adjust as was explained in chapter 2.2), which has led to a large discrepancy between supply and demand. (LaBelle, Santacreu 2022)

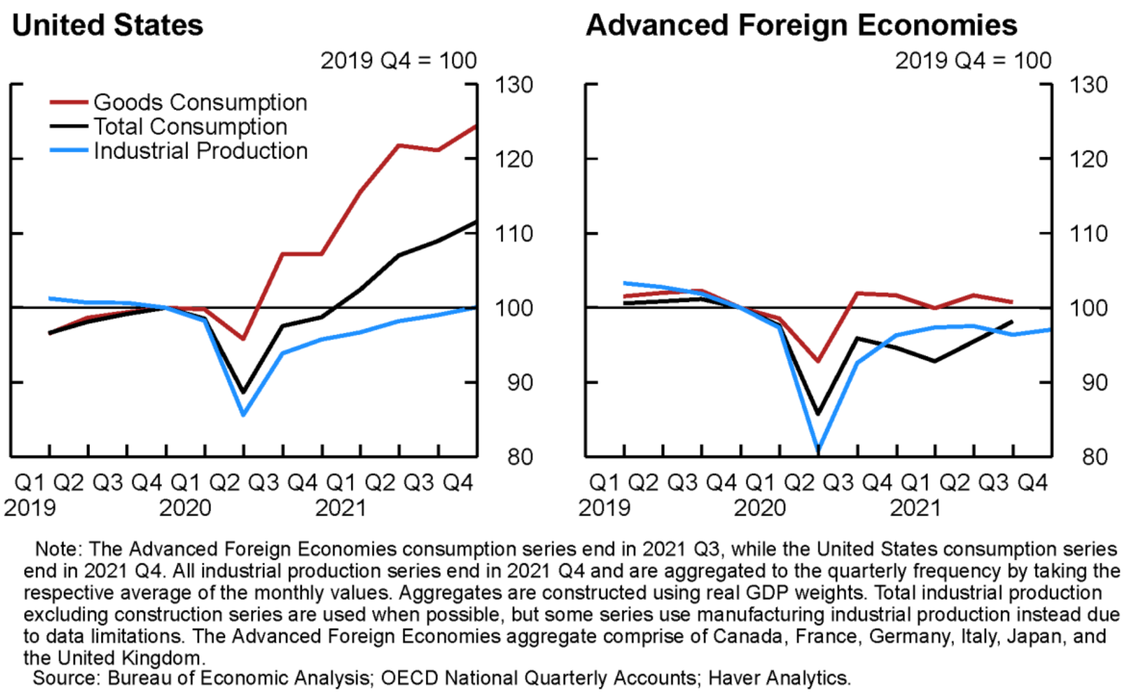


Figure 24 - Real consumption and industrial production during the pandemic, source : (Soyres, Santacreu, Young 2022), figure 2

Later research by VoxEU concluded that the **combination of government Keynesian tactics stimulating demand on the one side and the industrial production being limited by COVID-19 restrictions on the other helped to create large supply-demand imbalances across industries.** (Soyres, Santacreu, Young 2022)

The previous chapter described the sudden surge in orders of semiconductor end-products due to the nature of the pandemic. The much quicker surge in goods consumption compared to industrial production would not be happening without the continued liquidity support from the governments. Governments being able to "fix" just the demand side of the market, in the end, resulted in a more significant semiconductor shortage crisis by enabling more orders that simply could not be met. This unnatural imbalance between supply and demand has also led to high inflation across many industries, including the semiconductor industry. (Soyres, Santacreu, Young 2022)

2.5. Trade war between China and the USA

The semiconductor industry was already once a primary reason for the U.S. to start a trade war. In the 1970s, during the rapid economic rise of Japan, Japanese semiconductor producers started to penetrate the U.S. and by early 1980s, U.S. semiconductor imports from Japan almost doubled every year. The ongoing cold war made the U.S. military the largest importer of semiconductors in the world as advanced missile systems were dependent on them. Strike, the 1980s, and it was tough for the U.S. companies to compete with the Japanese imports due to the appreciation of the U.S. dollar, high-interest rates, higher R&D spending in Japan due to cheaper credit options, etc. On March 27, 1987, President Ronald Reagan decided that the United States would use prohibitive (100%) tariffs against an ally country for the first time. (Douglas A. Irwin 1996) (Bown 2020)

The trade conflict between U.S. and Japan lasted for several years, and it created multiple issues for the industry. With Japanese supply-constrained and the U.S. semiconductor industry shifting its product focus, a lack of memory-based semiconductor products like DRAM allowed new countries like Taiwan or South Korea to enter the market. Come the 1990 and the trade conflict petered out as import markets of the U.S., Japan, and the EU became less important. The US share of world semiconductor imports dropped from 27% in 1995 to just five percent in 2019. The EU dropped to just six percent and Japan to only three. China and the rest of the quicky developing Asia became the largest consumers of semiconductor goods and the primary market for all the bigger companies. In 2012, over half of all semiconductor exports were aimed at China. (PwC 2012) (Bown 2020)

During this time, China has also become an increasingly important supplier of semiconductors and material for them, as was described in the previous chapters. The following graph shows the development of significant exporters since the end of the trade war between Japan and the U.S. Taiwan, South Korea, and China, with the rest of Asia completely outshining the former giants of Japan and the U.S. in value of semiconductor exports.

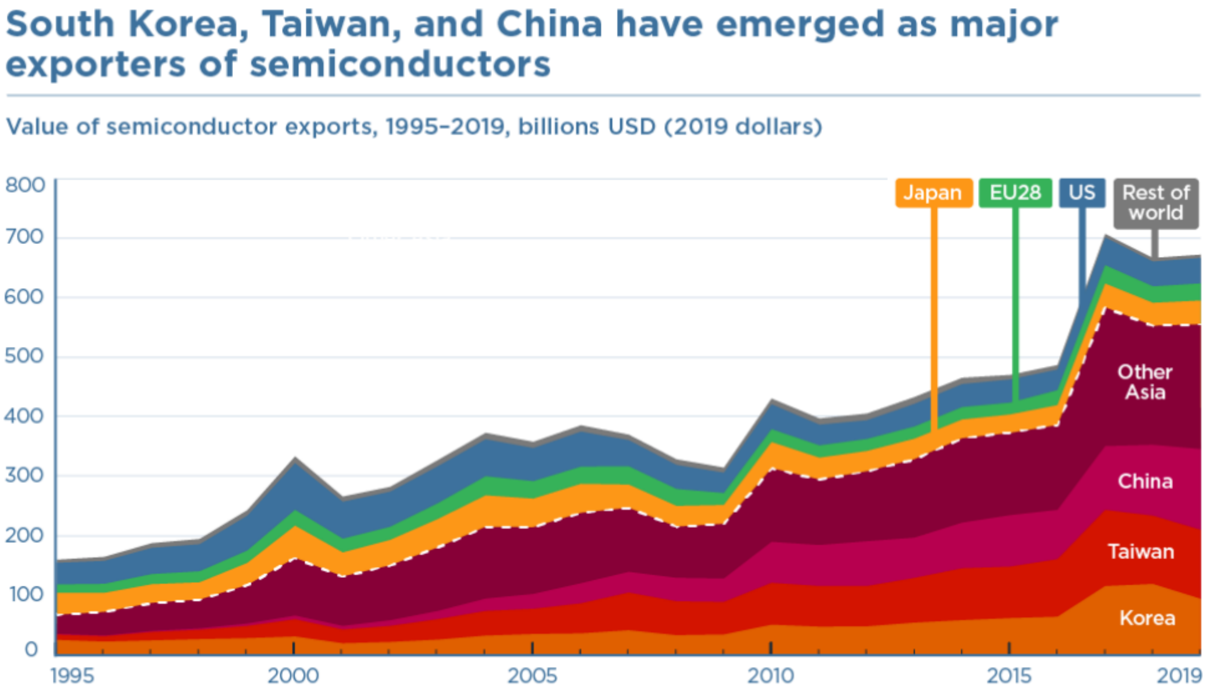


Figure 25- South Korea, Taiwan, and China have emerged as major exporters of semiconductors, source :(Bown 2020) figure 4

A combination of economic, policy and technological developments since the 1980s fundamentally shifted the semiconductor industry into much more complex value chains without any truly vertically integrated and self-reliant business, as was described in chapter 2.2.

In 2017 the U.S. started an investigation into China's unfair trade practices under Section 301, the same law that led to the U.S. – Japan trade war over 40 years ago. The U.S. made two major complaints. First was that China requires foreign firms to engage in joint ventures with local companies, which is a losing deal for US intellectual property–holders (reminder that design is the dominant added value part of the semiconductor production cycle and the leading U.S. product), and the second was industrial espionage and theft of intellectual property allegation aimed at Chinese company Huawei. (Bown 2020)

Soon after this report, the United States imposed 25 % tariffs on semiconductor imports from China. By 2019 U.S. Semiconductors tariffs covered more than 350 billion USD of imports from China. China retaliated by imposing tariffs of nearly 100 billion USD on US exports in 2018 and 2019, although it refrained from targeting ICs and manufacturing equipment. (Bown 2020)

Semiconductor Industry Association, that formed during the Japanese pressure nearly 40 years ago, was against similar protectionism measures in 2018 and 2019 and warned of the possible economic consequences. This suggests that unlike the trade war with Japan, Political motives were above the economic ones. (Bown 2020),(SIA 2018)

The trade war moved in 2020 when the United States and China implemented the Phase One agreement. The tariffs did not change, but the deal did cover 450 billion USD of bilateral trade, and China did commit to buying 200 billion USD worth of US goods and services over 2020 and 2021.

The U.S. also made a radical change with its attitude to Huawei, Chinese national champion, with 2019 global revenues about as large as Microsoft's. As Huawei was important source of demand for semiconductors created in the U.S. Government of the U.S. was worried that the Chinese government could abuse Huawei's telecommunications infrastructure equipment to spy on U.S. companies and citizens. Department of Justice also indicted Huawei for stealing US technology, laundering money, and helping Iran avoid sanctions. Department of Commerce added Huawei and its affiliates to the trade restriction list, making it illegal to trade with them without a specific license. The United States also increased the jurisdictional reach of its export controls through the foreign direct product rule (FDPR). (Bown 2020)

Finally, the US Department of Commerce imposed restrictions on China's largest chip manufacturer, Semiconductor Manufacturing International Corporation (SMIC), in late 2020 (Lyons 2020)

This trade war had a major impact on both the Chinese and the U.S. Semiconductor industries. Restricting such a large company with multitudes of products like Huawei will inevitably cause unwanted damage to both sides. Many Huawei products did not pose any risks to U.S. citizens. SIA also pointed out that the policy restrictions did not limit the Chinese manufacturing possibilities as they could get semiconductors from Taiwan or South Korea, which did not restrict their trade with China. In reaction to all of this, China began to stockpile semiconductors just before the Covid pandemic, further adding to the semiconductor crisis in the next year. (Bown 2020)

By the end of 2020, there was little evidence that the U.S. restrictions helped protect US technology or prevented China from subsidizing its semiconductor industry. The blacklisting of Huawei did damage the Chinese company, but it also disincentives U.S. based manufacturing as it could not trade with Huawei (Bown 2020)

The particular decision to also ban SMIC might prove to be the most damaging to the industry as it created a more pressure on companies to use other pure-play manufacturing plants like TSMC, which were already working at their maximum capacity. The Chinese trade war was also one of the many reasons that caused multiple young Chinese semiconductor companies to go bankrupt in China (Sophia Yang 2020)

The U.S.-Chinese trade conflict played itself differently than the U.S. - Japanese conflict. The U.S. is no longer such an important exporter of semiconductor goods; it, however, remains an important innovator and importer. The decisions made by the Trump administration against Huawei were, in my opinion, justified but ended up being too broad. The decision to cut off SMIC also seems to have mostly adverse effects on the industry as a whole. This opinion is also presented by Mr. Bown in his extensive paper on the topic. So far, the Biden administration did not remove any semiconductor tariffs and their stand remains very similar to the Trump administration. (Agence France-Presse 2022)

2.6. Overconcentration of the industry in Asia

As the previous chapters described, the majority of the production capacity of semiconductors, is located in East Asia. This wasn't always the case as was described in the previous section. Namely the U.S. and Europe used to be the biggest exporters just 25 years ago, although be it for a much smaller market.

This overconcentration of the production capacities in East Asia has left the Western hemisphere reliant on the countries of East Asia and without resilient supply chains. According to the report prepared by Boston Consulting Groups (BCG) in 2020 with the cooperation of SIA, the geographic diversification of the industry is imperative. (Raj Varadarajan et. al. 2020) So why do companies choose to build outside of the U.S. and the EU?

The following figure prepared by the BCG in 2020 represents the survey results of SIA members. The goal was to identify the most important factors when deciding, where to build a new semiconductor fabrication plant. (Raj Varadarajan et. al. 2020) On the X-axis of the figure, we can see U.S. competitiveness vs median, and on the Y-axis the importance of the factors measured, according to the SIA. **Synergies with ecosystem** (designing and manufacturing at the same place), **labor costs** and **access to talent** are seen as the most important factors, followed by **government incentives** and the **security of IP / assets**. Interestingly, **geopolitical considerations** were placed at the very bottom by the SIA members, although it might have been caused by the separation of the IP security as a standalone issue.

Even though the figure was built for the U.S., we can, with some assumptions, place the EU on the figure as well, given how similar both economies are. From figure 15, we know that the U.S. design companies dominate the market, and together with the EU, they are responsible for the majority of innovations. We can assume a high level of potential ecosystem synergy between design and production would also be measured in the EU. According to the United Nations research on the education index, both the United States and the EU averages were placed above 0.8 out of 1 on the scale, with EU being slightly worse on average than the U.S. (UNITED NATIONS DEVELOPMENT PROGRAMME 2022) When it comes to Labour costs the U.S. is somewhat more expensive on workforce when compared with the EU. (EUROSTAT, U.S. Bureau of Labor Statistics no date) The United States also placed better than most EU countries in the Doing Business report of 2020. (World Bank 2020). Both the EU and the U.S. are also some of the most stable geopolitical regions globally. (Angela Duca 2018) Since the COVID-19 pandemic escalated, there have been many new government incentives reported in both the EU and the U.S., suggesting a future move on the X-axis for both regions. Overall, both the EU and the United States possess enough qualified workforce, and secure environment and could offer high synergy for their design companies. The two main aspects that were holding these regions back were high labor costs and low government incentives, which are currently being increased by both the EU and the U.S. (Raj Varadarajan et. al. 2020) (The Economic Times 2022)

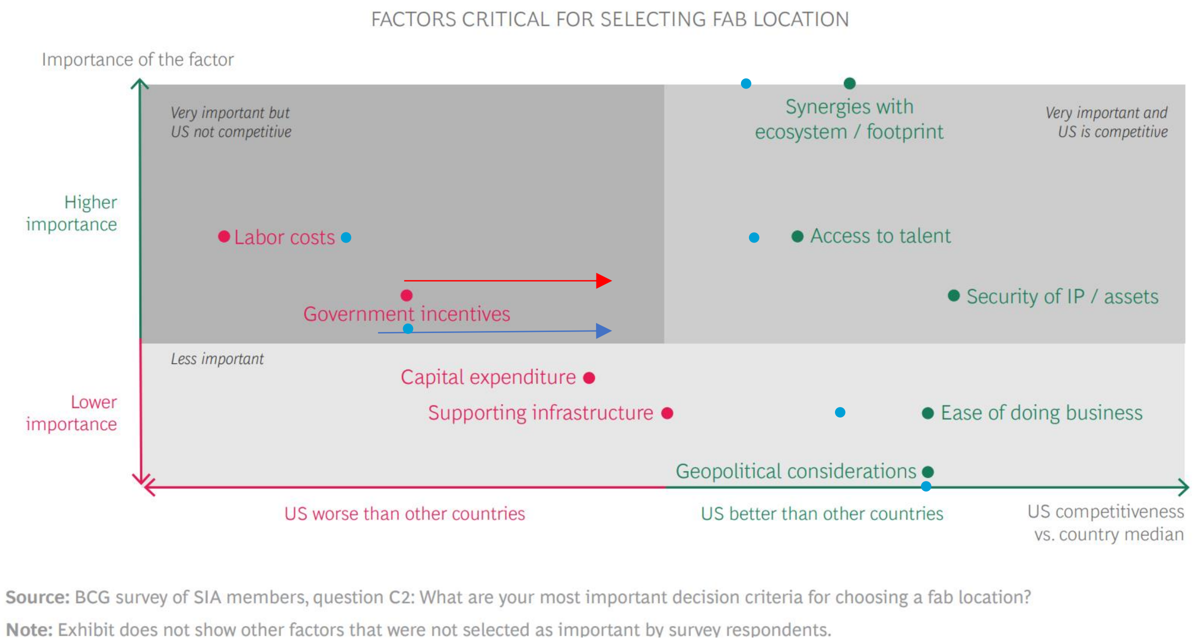


*Figure 26 - Factors critical for selecting Fabrication plant, 2020, source: BSG survey of SIA members, * edited by Martin Bok, EU represented by blue color.*

The lack of "synergy in the ecosystem", to use the term by SIA, could lead to a much larger issue for the entire industry. Erica Fuchs and Randolph Kirchain explored the impact of manufacturing offshore on technology competitiveness in the optoelectronics industry (Analog semiconductors - DAO) (Fuchs, Kirchain 2010a) Result of their research suggests that the geographical separation of design and fabrication will have a negative impact on any, technologically fast-evolving industries and will inevitable force companies into a dilemma situation of choosing single technology/location trajectory to reduce material, labor, and packaging costs. According to Fuchs and Kirchain, whenever a new design operating on a smaller node is introduced (which happens often in the semiconductor industry) it cannot cost compete with the prevailing design currently being manufactured in the foreign fabrication plants. This disincentivizes further research as it becomes uneconomical for the designer as he has to price under cost, to make the switch to new technology economically viable for the manufacturer. (Fuchs, Kirchain 2010a)

The semiconductor industry isn't the only intermediary industry which relocated in the past 25 years and is now heavily concentrated in Asia. the active pharmaceutical ingredients industry, an intermediary industry to the pharmaceutical industry, has a similar structure to the semiconductor industry. Like in the semiconductor industry, the products are extremely diversified and serve different purposes and require different specific ingredients, which leads to a complex supply chain. And just like electronic industries of today are reliant on the semiconductor industry, so is the pharmaceutical industry reliant on the active pharmaceutical ingredients industry (Patricia Van Arnum 2021)

According to revenue, the pharmaceutical industry is dominated by five western companies (Pfizer (US), Roche, Novartis (both Swiss), Merck (US), and GlaxoSmithKline (UK). These companies are responsible for the second of the two stages of pharmaceutical manufacturing, and that is a process known as formulations production. Formulation's production turns so-called active pharmaceutical ingredients (APIs) into the final consumable drug. Today majority of the APIs production, roughly 66%, is happening in the Asia Pacific, with Chinese manufacturing being responsible for over 40% of the total supply. (Patricia Van Arnum 2021; Horner 2020) The U.S., Europe, and Japan produced 90% of the world's APIs until the same shift as in the semiconductor industry happened in the mid-90s. (Horner 2020) Similarly to the different semiconductor types and sizes, the geographic distribution of APIs manufacturing is different for each drug. For example the EU is 100% reliant on imports of Paracetamol but is almost self-sustaining in Acetylsalicylic acid. (Patricia Van Arnum 2021)

Janet Woodcock, the director of the Centre for Drug Evaluation and Research at the US Food and Drug Administration (FDA) described the reasons for the massive movement of APIs manufacturing offshore to the U.S. Congress in 2019. According to Woodcock, labor costs, less stringent environmental regulations, and no government incentives, in general, are to blame for the industry relocation. (Woodcock 2019)

Low government incentives and high labor costs have led to East Asia dominating the majority of the production cycles of semiconductors, APIs, and other products. This leaves the countries outside of this region to be reliant on dangerously long supply chains they have no control over, as the current crisis has shown. Furthermore, the geographical division of design and production, which currently exist in the semiconductor sector, could disincentivize further research and progress in the semiconductor industry.

Both the EU and U.S. are committed to increasing government incentives for both of these industries, hopefully paving the wave for a more geographically balanced production capacity and a more resilient semiconductor and APIs supply chains. (EUROPEAN COMMISSION 2020a) (The White House 2021)

2.7. Cryptocurrency mining

Another aspect worth inspecting is cryptocurrency mining. Bitcoin, the original cryptocurrency, launched in 2009. (Davis 2011) However, the industry experienced its first real boom six years later, in 2017 when Bitcoin saw a 2,000% increase in value from January 1, 2017, to December 16, 2017 (CoinMarketCap 2022).

Some cryptocurrencies, like Bitcoin, operate on a proof-of-work concept (PoW). When the Bitcoin network users send each other digital tokens, a decentralized ledger gathers all the transactions into so-called blocks. However, someone still needs to confirm that the transaction happened and arrange the blocks. That someone in the Bitcoin network are the Bitcoin miners, who provide the network with their computational power via special nodes and are rewarded for it by some amount of bitcoin. (Tar 2018)

Total computational power being used by a PoW cryptocurrency network to process its transactions is called hash rate. The following figure shows the total hash rate of the Bitcoin network (the largest PoW network) in the last three years. We can see a clear uptrend on the graph. The Bitcoin network operates in such a way that mining difficulty increases when the hash rate goes up to keep the Bitcoin rewards to miners stable.

This leads to higher energy consumption and a need for better hardware. The second point is where cryptocurrencies really enter the semiconductor industry. In the early days of Bitcoin, mining was infinitely less demanding than today and could be done on almost any computer. As more and more people entered the Bitcoin mining industry, advanced mining equipment called field programmable gate arrays (FPGA) emerged. The first FPGA miner in China appeared already in 2011. Five years later, a company called Bitmain launched its capital ship Antminer S9 with 189 microchips built-in. (*The History and Future of Bitcoin Mining* 2021)

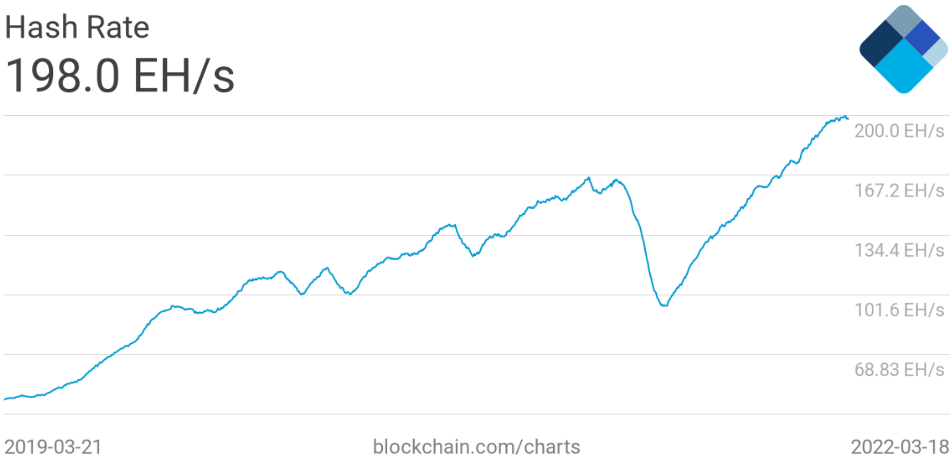


Figure 27- Total Hash Rate (terahashes per second) of the bitcoin network, march 2019- march 2022, source: www.blockchain.com/charts

Companies like Bitmain, providing specialized crypto-mining equipment, started to make deals with large pure-play foundries producers of semiconductors, including TSMC, to keep up with the demand that the new all-time highs of cryptocurrencies prices brought. (Rob Thubron 2021)

Matt Ranger has put together a qualified estimate that around 4-6% of TSMC's leading node production capacity of 2021 was spent on Bitmain's Antminer products. (Matt Ranger 2021) Another research done by Counterpoint estimates the production capacity of TSMC provided to "Crypto and others" in 2021 to eight percent as the following figure shows. (Counterpoint Research 2021) These products are made on 5nm wafers, or the best silicon chips humanity is currently capable of building, and they are competing with AMD, or Apple for production space.

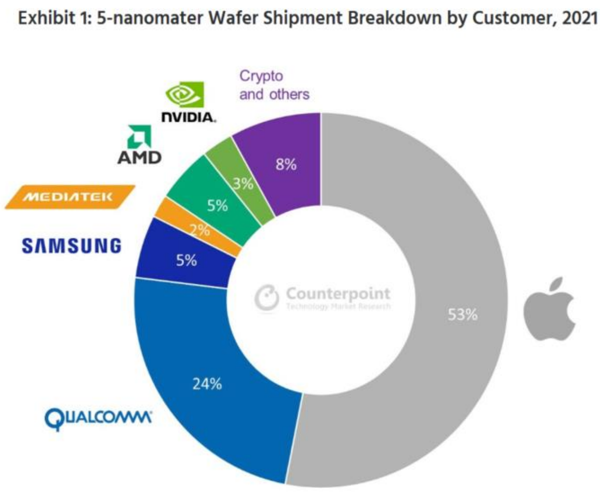


Figure 28 - Nanometer wafer shipment breakdown by TSMC Customer, 2021, source: Counterpoint Research

There is also a lot of evidence that the second largest cryptocurrency Ethereum was responsible for the demand increase for GPUs, as the modern PC GPUs (Graphical processing units) were still enough to mine Ethereum in recent years. One evidence is the high correlation between the price of Ethereum and GPUs on the market, as the following figure shows. (The Economist 2021) Nvidia, a company producing the most modern GPUs like RTX 3070 capable of producing 60MegaHash/s, had some of the capabilities of its GPUs deliberately stripped out in 2021 to discourage Ethereum miners from buying all the available supply, originally meant for gamers. (Bloomberg 2021b) Matt Ranger concluded that roughly 19% of all GPUs produced in 2020 went to the Ethereum miners. (Matt Ranger 2021)

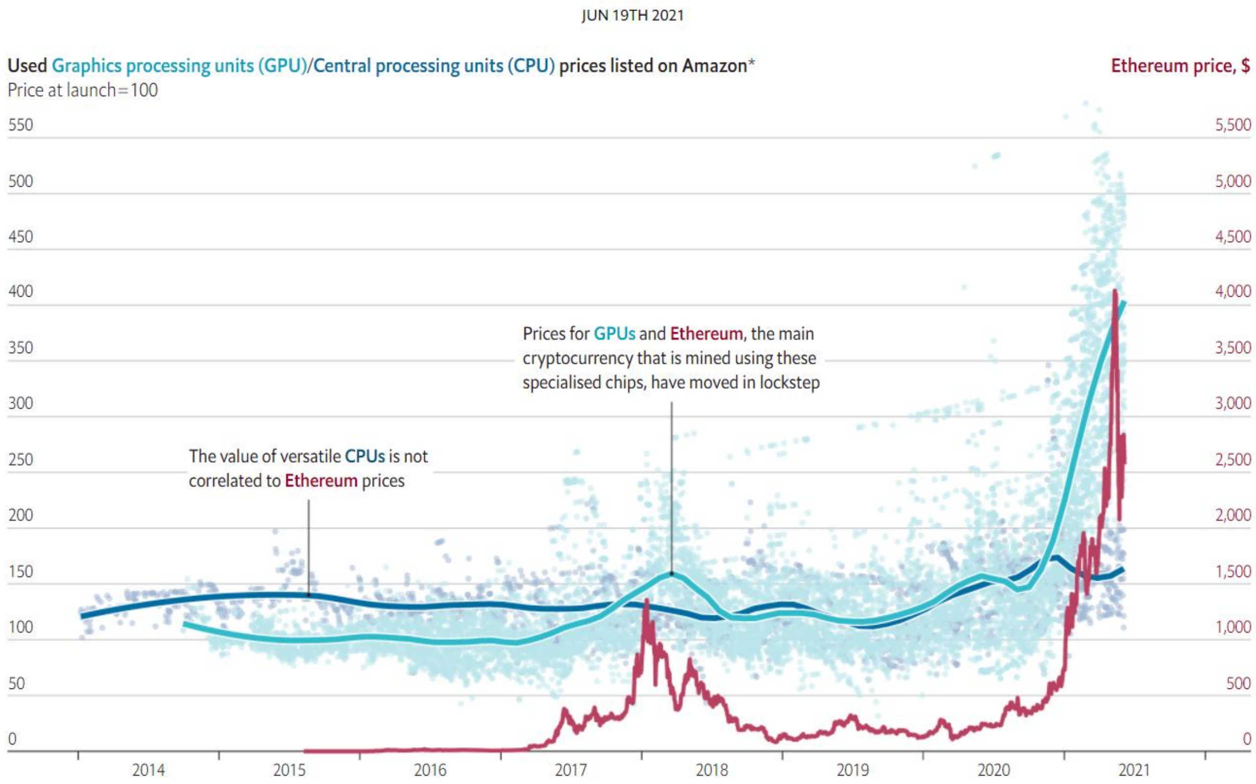


Figure 29 - Correlation between the price of Ethereum and GPUs, 2015-2021, source: economist.com

It is also not clear if the demand for these mining devices will stay at today’s level. Ethereum, the second-largest cryptocurrency by market cap, is shifting to the more popular newer consensus mechanisms of proof-of-stake this year. Proof-of-stake doesn't require miners to compete in solving complex equations. Instead, the validators stake their own cryptocurrency in the network for verifying transactions. This solution is not only more eco-friendly but also destroys the need for the specialized mining hardware equipment. (McCarthy 2022) Bitcoin, however is definitely not changing its consensus mechanism, and even though 90% of all

Bitcoin was already mined out, the mining of Bitcoin is estimated to continue until 2140. (George 2022)

Cryptocurrencies are a relatively new product that took the already overclocked semiconductor industry by storm. The Antminer products and other specialized crypto-mining devices require a large amount of computational power from state-of-the-art logic microchips, resulting in another unexpected demand surge for micro-processors, that the industry did not expect and without having production capacities to manage it.

3. Would the crisis occur without COVID-19? Is it a standalone issue or the tip of the iceberg?

During the MWC (Mobile World Congress) Barcelona 2022 event, at the end of February 2022, the president and CEO of Qualcomm Cristiano Amon suggested that the semiconductor crisis would have occurred without the COVID-19 pandemic. And it would happen sooner rather than later because of the sudden demand increase for consumer electronics, automotive parts, and "*many other things that you wouldn't realize have semiconductors in them*" in the last few years. (Cristiano Amon 2022) He continued with a warning that, without large investments into semiconductor manufacturing, the world will face massive semiconductor supply shortages in the future. (Cristiano Amon 2022)

The first chapter of this thesis explained the importance of semiconductors for the modern economy. The second chapter covered all the major possible causes of the current Semiconductor shortage. The goal of this chapter is to assess the findings from the second chapter and conclude if the current crisis would have happened without the COVID-19 pandemic, like some major players in the industry suggest and if the main causes of this crisis could endanger other industries in a similar fashion, or if they are unique to the semiconductor industry.

Subchapter 2.1 explored the market of rare earth minerals with a greater focus on silicon. The chapter concluded that most REEs, including silicon, are being mined and processed in China, which leaves the world heavily reliant on exports of REEs from China. The European Commission has released a report in 2020 with a detailed description of the situation. One of the goals of the report was to identify critical REE materials for the EU economy. The 2020 EU list contains 30 materials as compared to 14 materials in 2011, suggesting growing importance of REE in multiple industries like electronics, renewable energy, mobility and automotive etc. (EUROPEAN COMMISSION 2020b). **Deep reliance on imports of REE materials from China is not an issue only specific to the semiconductor industry but is an issue that endangers many other large industries.** In fact, the semiconductor industry isn't the most threatened industry due to the availability of silicon as the chapter 2.1 describes. Other industries requiring other REE might not be as lucky. It is estimated that the world has 99 million tons of rare earth reserve deposits with China having 36 million tons of these reserves. (Anil Das 2011) This makes it likely that some rare materials have to be mined in China, as some of the largest deposits are there. When the global transport structures broke with the

COVID-19 pandemic, and limitations were put in place by China and other states, this reliance was highlighted.

The team and partners of McKinsey Global Institute put together a report on global value-chain resilience. In the report they measured different sectors´ resilience to seven different shocks. **The semiconductor industry was measured to have the highest exposure to the risk of trade dispute due to high levels of trade intensity and product complexity**, as figure 30 shows. In other words, the semiconductor industry breaks apart without logistics and trade due to highly specialized suppliers in a long value-chain and China with its REE monopoly is arguable the largest specialized supplier in the world. (Susan Lund et. al. 2020)

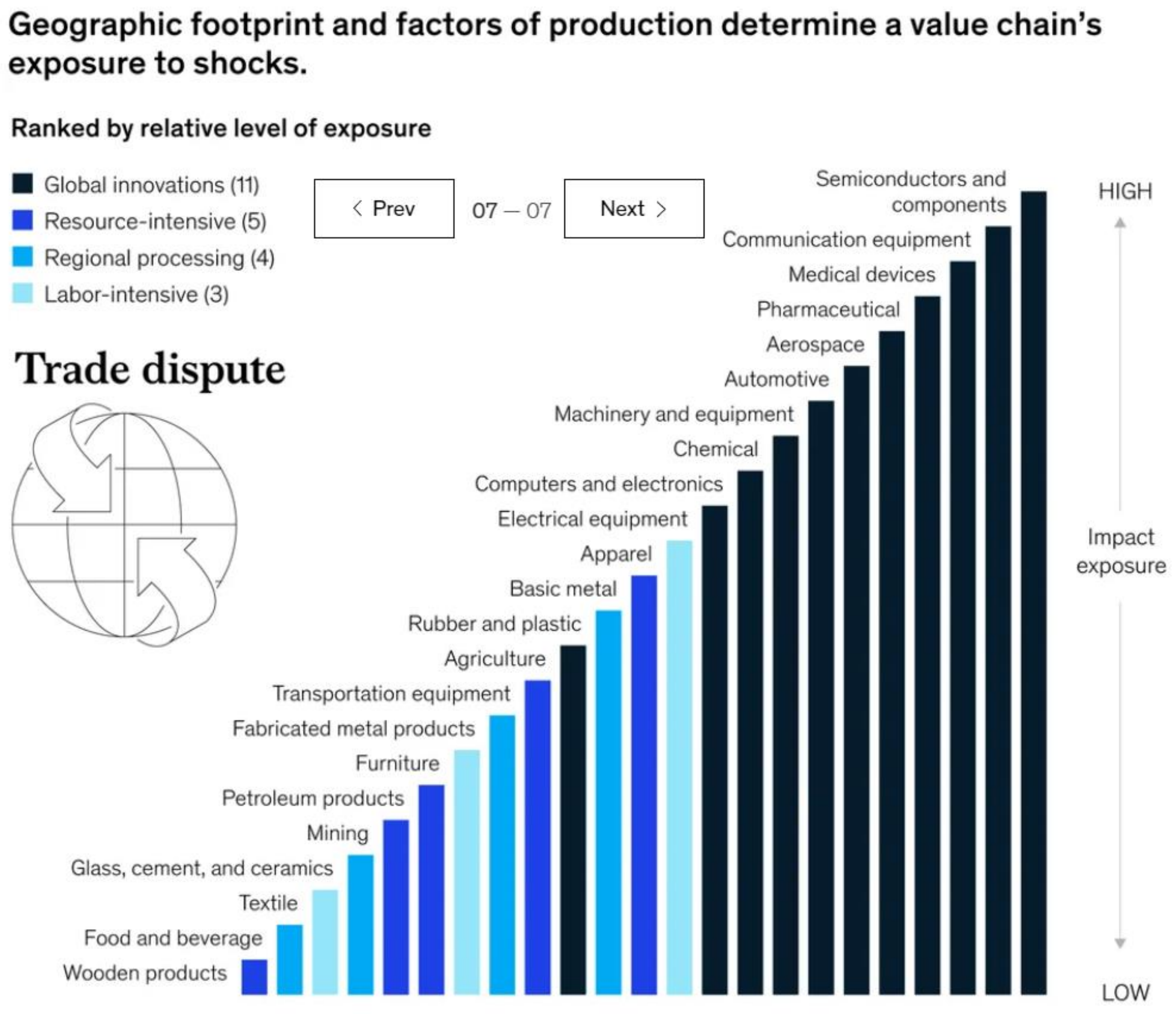


Figure 30 - Geographic footprint and factors of production determine a value chain´s exposure to shocks, source : Mckinsey and company, 2020

That alone wouldn't push semiconductors to the first place, as other industries, like automotive or chemical industries are just as dependent on REE suppliers as the semiconductor industry. However, the chain of highly specialized suppliers only grows from there. There are more than

50 points across the supply chain where one region and often a single company holds more than 65% of the total market share. The global nature of the semiconductor industry can also be seen in the distribution of the total value of the industry. US, South Korea, Japan, mainland China, Taiwan and Europe each contribute 8% or more to the total value and specialize in different production stages and products. (Antonio Varas et al. 2021a)

A perfect showcase of the importance of stable trade can be the Taiwanese giant TSMC, which is at the heart of the entire production cycle. According to the TSMC annual report from 2019, **TSMC alone has 1,226 tier one suppliers. ("Tier one supplier refers to a supplier trading with TSMC directly with more than two orders per year and selected mainly spending-based") and 110 critical suppliers ("a supplier which either (1) accounts for 85% of the purchasing expenses, or (2) is a single source of purchase")** (TSMC 2019) For comparison, recent research on industrial supply chains has shown that a car manufacturer has around 250 tier-one suppliers, aerospace manufacturers have on average 200 tier-one suppliers and technology companies, such as TSMC, average only 125 tier-one suppliers (total number of proliferates might be higher in these industries than for TSMC). (Thomas Baumgartner et. al. 2020) Should any trade restrictions limit just some of these critical suppliers, it will cause a major blow to the TSMC and by extension to the whole industry. Subchapter 2.5 described the trade war between China and the U.S. and its impact on the global semiconductor industry. This trade war wasn't on a massive scale, yet it proved damaging to both sides of the conflict, especially due to the delicate and global supply chain. **Trade wars will always be a threat to the majority of international industries but pose an extreme risk to industries with a high number of possible supply bottlenecks.** It's hard to find an industry with more of these than the semiconductor industry. **While COVID-19 didn't affect the international trade relations like a trade war can, it did negatively affect all forms of international transport as chapter 2.3 describes**, **which has a similar impact to a trade war**. Closed ports, increases in transportation costs, sick personnel all worsened the Semiconductor crisis as participants in the semiconductor industry must move goods, equipment, capital, IP and talent across borders.

Subchapter 2.2 described the complex manufacturing process of semiconductor products, which takes place in highly sanitized facilities with extremely expensive and unique equipment and hundreds of specialized suppliers as described in the paragraph above. Building a state of the art semiconductor fabrication plant takes between two to four years and is extremely demanding on capital. Once such a factory is built and well supplied by silicon, rare gases etc. it requires thousands of qualified workers to operate (Antonio Varas et al. 2021). All of these conditions make it extremely difficult and costly to quickly increase the global supply of semiconductors on the market as the current crisis has shown. The semiconductor industry has the highest capital expenditure intensity with 26% of annual sales of the industry. (Antonio Varas et al. 2021a)

What further differentiates the semiconductor industry from most other industries is the sheer scope of semiconductor products requiring different node (wafer) sizes (which serve completely different purposes) and the very fast innovation rate of the industry, where the number of transistors on a logic chips doubles every 18 to 24 months (ICs only, DAO products aren't innovating on such level). As a result, the semiconductor industry has the highest intensity of R&D out of all industries, where 22% of annual sales of the industry are reinvested into research. The pharmaceutical industry occupies the second place with 21%. (Antonio Varas et al. 2021) These facts were key in the forming of the unique ecosystem in today's semiconductor industry.

End-product industries are usually all manufacturing interchangeable products. Cars always serve the same purpose and are replaceable by any other car. On the other hand the semiconductor industry produces very specific irreplaceable products and not all fabrication plants can produce all designs on the market. When the front-end facility is built, the facility is designed for some largest wafer diameter it will be capable of processing, with a limitation of the smallest features that the facility is capable of etching onto the wafers. But if these criteria are met for several products, then a single fabrication plant can produce multiple designs and switch between their production. This has given rise to the trend of pure-play foundries companies like TSMC and fabless companies like Apple. This is, on paper, a logical step that allows for larger capital spending on both the design and manufacturing as fabless companies don't need to worry with manufacturing, and pure-play foundries with design. According to IC insights, 81.2% of foundry sales are done by pure-play companies like TSMC. (IC insights 2022b) That leaves the question, whether IDMs (integrated device manufacturers) like Samsung, which do both, can compete in the long run.

The research by Sarma from 2017 explored the financial data of publicly traded 49 IDMs and 75 fabless firms in North America from 1980 to 2013. The fabless companies quickly took control of majority of the market. (Sarma, Sun 2017) However according to other research from the same year, which analyzed the competition and cooperation relationships between these business models, the fabless and IDM models have a mutualistic relationship and should both keep existing. The research also estimated that the ultimate market share of IDMs would reach an equilibrium at approximately 55% and that of the fabless-foundry model at approximately 45%. (Hung, Chiu, Wu 2017) The rise of fabless companies was accompanied by the rise of the pure-play companies, which were predominately in Asia, due to the economic incentives described in subchapter 2.6 (Cheaper labor, low government incentives in the West compared to countries like Taiwan etc.)

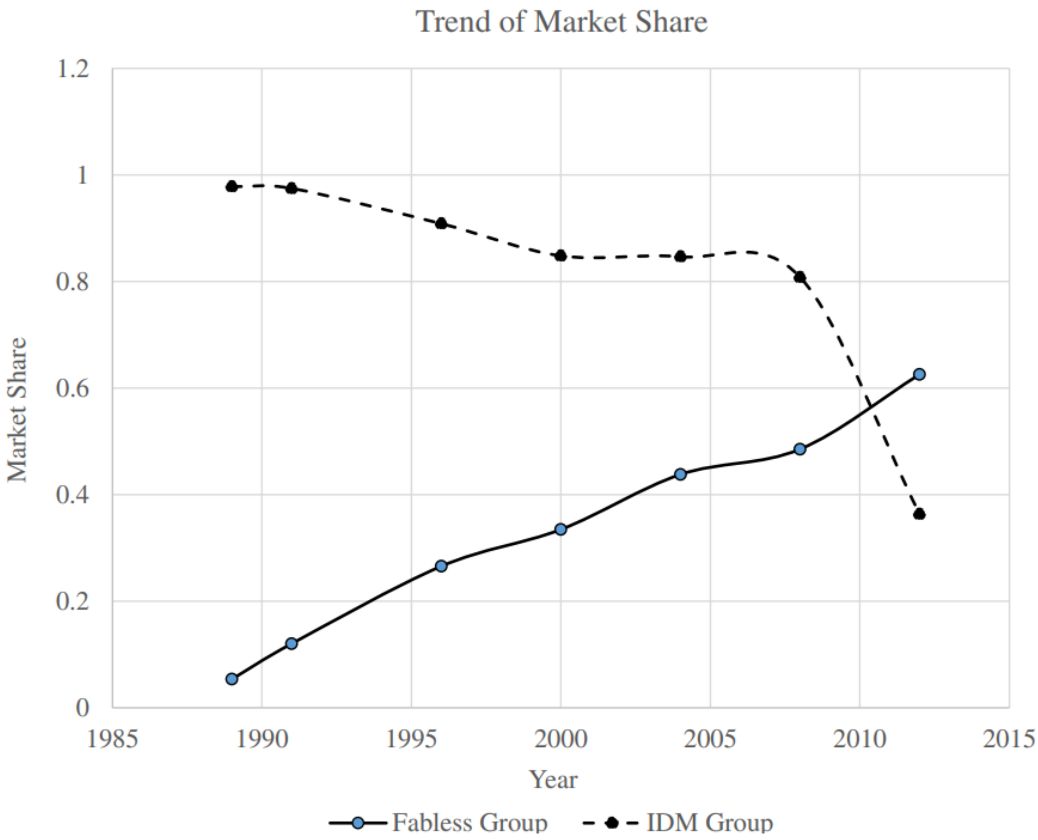


Figure 31- trend of market share in the North America, source: (Hung, Chiu, Wu 2017) figure 4

Although the fabless / pure-play model is certainly economically viable, and capable of competing with the IDMs, as shown by the mentioned research papers, the papers didn't focus on some of the risks the fabless model brings to the semiconductor industry and by extension to all the industries dependent on it. The risks are the following:

1. **geographic overconcentration of semiconductor manufacturing hubs**

From the chapter 2.2 we know that about 75% of semiconductor manufacturing capacity is located in East Asia and some most advanced semiconductor manufacturing capacity (logic nodes under 10nm) is only located in Taiwan (92%) and South Korea (8%) (see figure 12). This is primarily due to the fact that pure-play foundries companies like TSMC or UMC prefer building their new fabrication plants close to one another in order to achieve agglomeration and clustering effects, which increases the overall competitiveness of their factories. (Wang, Chiu 2014) For example, TSMC, has 14 out 17 plants located in relative proximity to each other on Taiwan. Such a concentration makes any potential local external shock extremely devasting. (TSMC 2022) This makes the manufacturing part of the semiconductor industry geographically very unbalanced when compared to some other industries. For example, the automotive industry manufacturing is much more balanced between East and West. According to 2020 data from ACEA (European Automobile Manufacturers' Association), East Asia (Japan + Korea + Greater China) produced roughly 48.5% of global units that year. Europe and the U.S. produced around 23% and 15% of the global car units. The remaining 13.5% were produced in South Asia, the Middle East and South America. (ACEA 2021a) Research from chapters 2.3 and 2.6 suggests that high **geographic concentration of manufacturing correlates with higher risk of supply chain disruptions as local external shocks become more damaging for the industry as a whole.** Although this should be true for most industries, geographical balance is even more important for the intermediary industries such as the semiconductor industry or the active pharmaceutical ingredients industry, on which other industries rely on for their production. The balance of the automotive industry manufacturing will be "meaningless" should it suffer from a semiconductor bottleneck like it did during the pandemic.

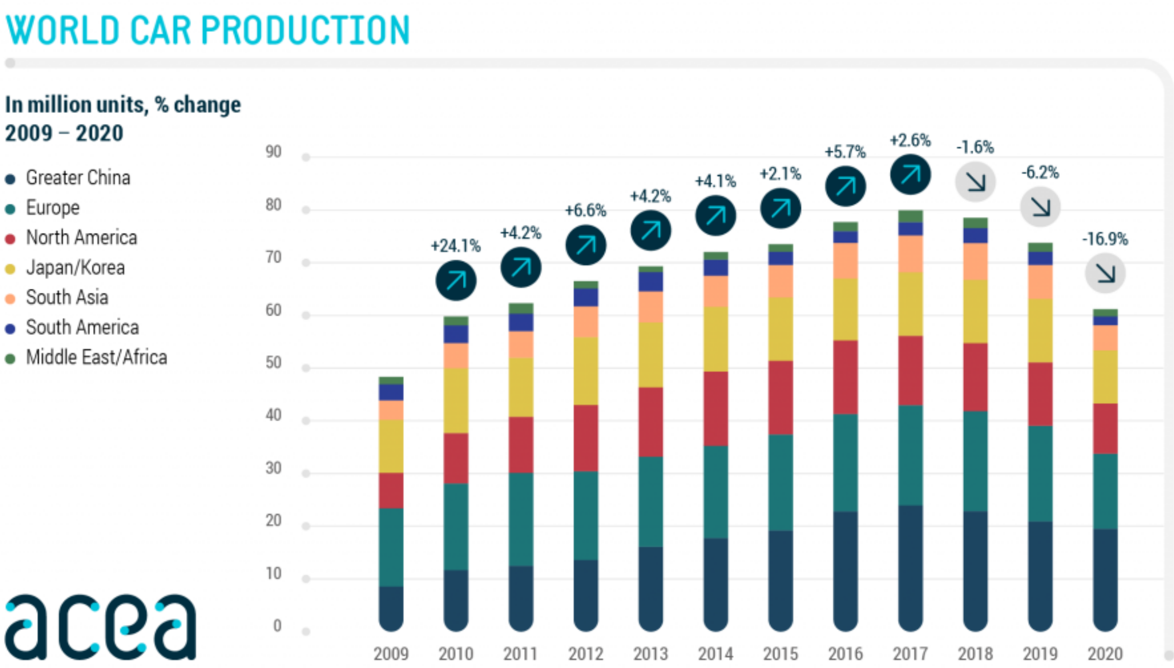


Figure 32 - World Car Production, source: ACEA, 2021

2. **separation of design and manufacturing leading to research deintensification**

- Chapter 2.6. referred to the research done by (Fuchs, Kirchain 2010a), which highlighted the disunity between the manufacturer and the designer on pushing new designs as the newer designs cannot compete on cost with the prevailing design currently being manufactured. This usually forces the designer to price the new product below manufacturing costs.

3. **fabless companies are more vulnerable to external shocks and poor management**

- External shocks and sudden markets changes might lead to unexpected demand increase that the fabless companies can't be able to provide, if they don't expect it beforehand. A perfect example of this was seen during the pandemic, when the car manufacturers temporarily halted their orders from suppliers (including pure-play fabs) and the "freed up" capacity, originally meant for car manufacturers , was sold to other buyers. When the car manufacturers resumed their production sooner than they expected, they found out they have no chips as the pure-play foundries were "fully booked". This is because many companies use Just in Time/Lean Purchasing Approach (JIT) which increases efficiency and decreases waste but leaves companies unable to react to potential disruptions in the supply chain. (Sahil 2017) Companies that realized the risk like Hyundai and companies producing their own semiconductor components, like Tesla, came out as winner in the industry. (Cohen 2021) (Joyce Lee 2021)

4. **Bidding wars**

- Further risk of this system are the potential bidding wars that can start for the production capacity as pure-play foundries have economic incentives to produce for whoever will be willing to pay the most for the silicon wafers. This is already happening with TSMC, which has its 3nm production booked until 2024 to the highest bidders. (Wickens 2021) This will translate to higher prices of the end-products and will be paid by the end-consumers.

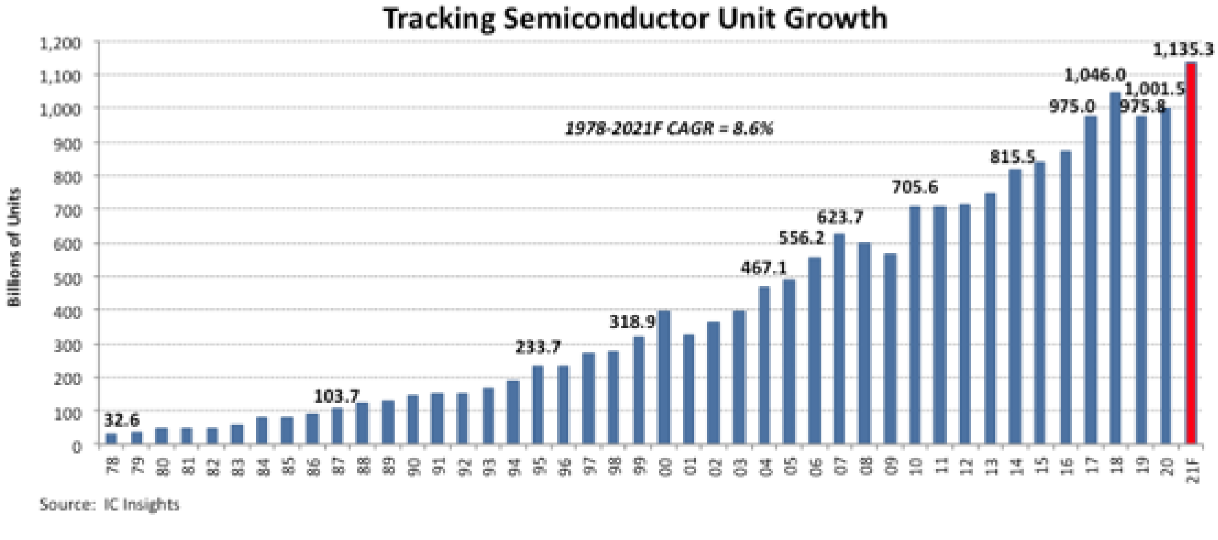
Separation of design and manufacturing is an ongoing trend in many industries, mostly with the goal of optimizing capital expenditures. The semiconductor industry has the highest intensity of research and capital reinvesting. This has led to a new trend of fabless designers, and pure-play foundries next to the IDMs, which do both. Although this separation of design and manufacturing is economically advantageous for both parties, it creates new risks and increases vulnerability to external shocks, like COVID-19 or natural disasters that were described in subchapter 2.3.

The subchapter 2.3 explored the impact of COVID-19 on both the supply and demand side of the market. Surprisingly enough, the COVID-19 pandemic had much smaller impacts on the Semiconductor supply side when compared to other external shocks that happened during the pandemic, like the fires in Japanese factories, snowstorms in Texas or the TEU container ship Ever Given accidently blocking the Suez Canal for several days.

The waves of lockdowns didn’t have a major impact on the semiconductor industry. This was achieved by the majority countries around the world marking the semiconductor industry as a vital one. This resulted in a very limited number of semiconductor front-end and back-end factories closed. The most damaging lockdowns happened in China, where silicon mining facilities were closed several times, which lead to a major increase in the cost of silicon and during the 2022 wave of COVID-19, some of the Front-end facilities were closed in China as well.

The subchapter concludes that the largest impact of the COVID-19 pandemic was on the demand side, as the pandemic also forced households and companies into faster and greater digitalization that was also enabled by continued liquidity support from the governments as subchapter 2.4 describes. However, Cristiano Amon and others argue, that the global demand for semiconductors would outpace the supply sooner or later, even without the pandemic.

Figure 5 shows the annual growth from 1978 to 2021. Since then, 32.6 billion semiconductor units were shipped. The compound annual growth rate during these 43 years amounts to a very impressive 8.6 %. The largest annual unit growth rate across the 43 years was 34% increase in 1984 and the second-highest growth rate was 25 % in 2010. In these 43 years, there were only two years with a consecutive years of unit shipment declines, those were 2008 and 2009 after the great recession.



As the figure 5 shows, there were lots of rapid spikes in demand during those 43 years but were there many shortages? The history of Semiconductor shortages goes as follows:

The first shortage happened in 1988, during the U.S. – Japanese trade war (described in subchapter 2.5). The demand during those years was pushed mostly by a growing computer industry. At that time, majority of the ICs manufacturing was happening in Japan. As a result of U.S. protectionism, a chip pact was enacted in 1986 was designed to help the U.S. compete with Japan on this front. The pact forced Japanese companies to stop dumping (selling under cost), which led to the Japanese companies producing and exporting fewer chips which in turn caused the crisis. (L.A. TIMES ARCHIVES 1988)

There was almost another shortage just five years later in 1993, when a Japanese factory producing 60% of the world's supply of resin exploded. Luckily the crisis was averted just in time and supplies lasted. (Mintz 1993)

There were several smaller shortages where the demand after specific chips was unexpectedly high, like the Intel shortage in the year 2000 or Qualcomm shortage of the snapdragon chip in 2012. It is safe to say, that most of the years the balance between demand and supply was very nil. (Robertson 2012), (Staff no date).

In 2011, the Fukushima nuclear disaster happened, and entire Japan was paralyzed by the earthquakes and tsunamis. Many semiconductor factories were shut completely, and it was estimated that 25% of world’s wafer production didn’t operate for quite some time. This has caused a relatively major shortage of NAND memory and displays in the following year and was named the largest semiconductor crisis so far, by Dale Ford, a senior vice president with IHS iSuppli. (Gaudin 2011)

Most of the historic Semiconductor shortages had a single specific root cause. Either an unexpected demand surge after a specific semiconductor product, geopolitics, logistical bottlenecks, or an environmental disaster. So, could just the recent rising demand cause the similar shortages we have experienced in the past two years on its own without Covid? The demand spikes in the historical shortages were almost always over a new logic or memory-based semiconductor products. However, in the past few years, the demand after older and cheaper products began to increase rapidly, which is a new trend for the industry. Generally speaking, the leading-edge silicon products of today are manufactured on 300mm or 450mm wafers. 300mm and 450mm wafers are in theory superior to the 200 mm wafers, because the larger wafer size leads to reduced waste and typically improves the foundry’s output in terms of chips manufactured per day. (Future Horizons 2012) Due to the fast technological advancement of the industry, the commercial foundries stopped building factories dedicated to 200mm and smaller fab lines. In 2008, there were ongoing talks about transitioning to even more effective 450mm fabs by TSMC, Samsung and Intel. (TSMC 2008) The following historic graph by GlobalFoundries shows how they imagined the market to evolve in the following decades. GlobalFoundries and other foundries expected majority of semiconductor products to be adapted for the 300mm in a similar speed that the transition from 150mm to 200mm happened in the early 2000s and that the future will belong to by that time theoretical 450mm fabrication plants. However, this did not happen. After 2015, 200mm demand began growing again and rapidly, while the 450mm wafers never even launched as the benefits would barely outweigh the costs for all parties involved (Ancker 2012).

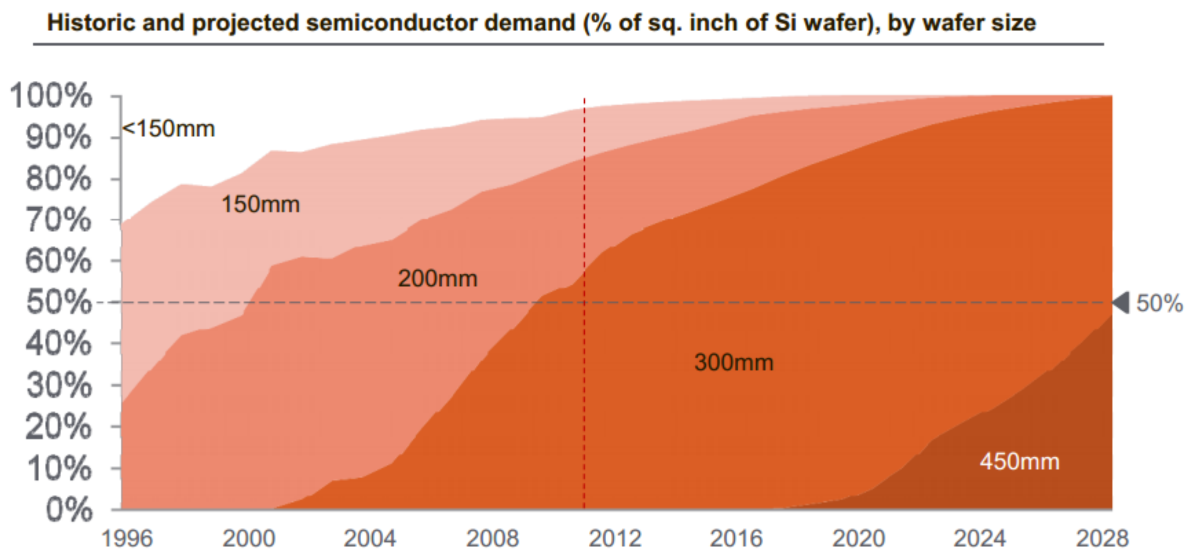


Figure 33 - Historic and projected semiconductor demand, 2011, source: Global foundries

The demand after the 200mm fabs is pushed by the fact that customers like building on 200mm lines because the manufacturing technologies are extremely mature by now and the costs are low and redesigning products for the 300mm line can be very costly. However, the industry didn't maintain its historical investments in 200mm fabs as a significant shift to 300mm was expected. According to the data from SEMI, the amount of global fabrication plants operating the 200mm lines was estimated to be 193 in 2007. Since then, there was a steady decline until the IoT (Internet of things) revolution arrival in 2015, where the global 200mm capacity was sold out and remained sold out until 2021 and operating close to 100% according to Woo Young Han, product marketing manager at Onto Innovation. (LaPedus Mark 2020a) Even though the industry reacted and more 200mm fabs were being build, yet still in some cases customers weren't able to meet the demand. The following figure shows the increase in 200mm capacity after the surge in demand since 2016. (SEMI 2018) (SEMI 2022)

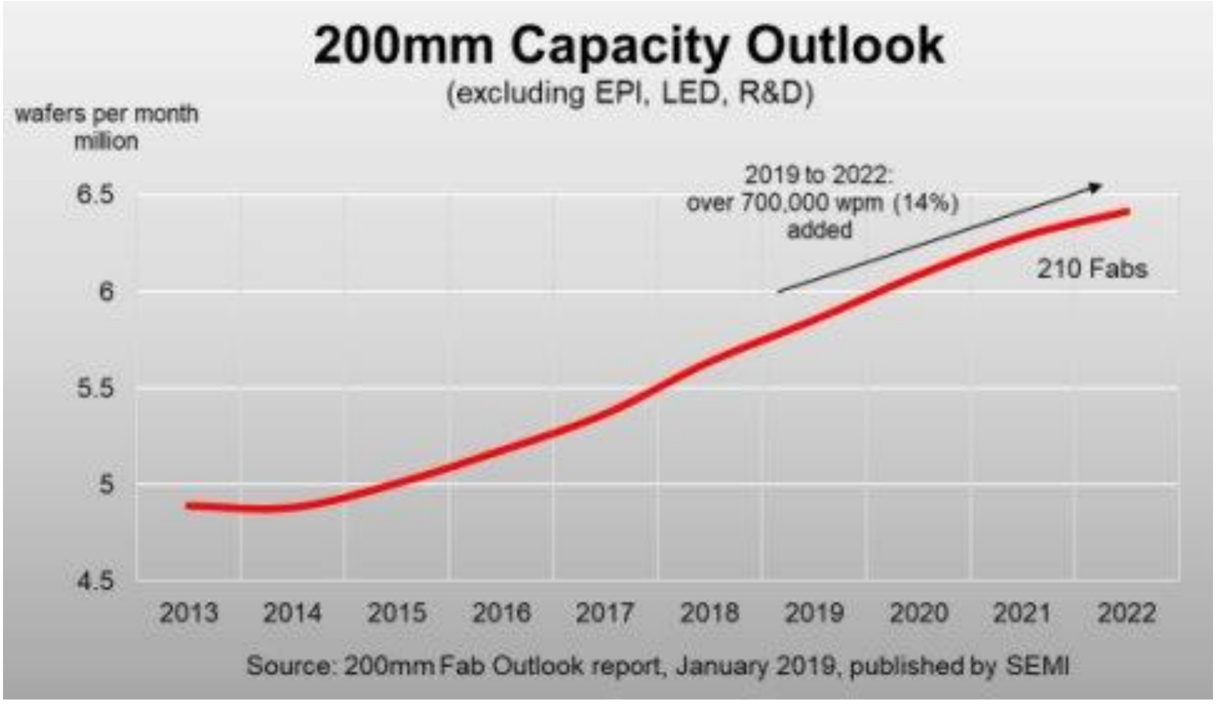


Figure 34 - 200mm capacity outlook 2019 (excluding EPI, LED, R&D), source: SEMI

In 2018, the amount of 200mm fabs once again reached 2006 levels of capacity but the structure of the 200mm fabs changed. Logic and memory product focused fabs shifted most of their production to 300mm, and at the same time a strong growth was brought by IoT revolution in the form discrete, analog, MEMS and foundry-produced devices at the 200mm manufacturing node. (Brown 2016)

Demand after these is being pushed mostly by the everyday smart electronics and especially by the automotive industry. (LaPedus Mark 2020b) Example of a such semiconductor device experiencing a massive demand surge since 2016 is a display controller unit priced at $1. For comparison, the modern chips made in the 300mm fabs by Qualcomm Inc. and Intel Corp. are ranging from $100 to more than $1,000 cost each. (*How a $1 chip shortage is causing a global crisis* 2021, p. 1) As one can imagine the profits and margins aren't as big in the 200m plants when compared to 300mm and so the market expects that the prices for once cheap OSD devices will be pushed by the foundries. (LaPedus Mark 2020b)

According to Samuel Wang, the analyst at Gartner, the situation isn't going to change for the better possibly until 2025. Currently, the global 200mm capacity is already fully sold out until second half of 2022.

"200mm capacity at the foundries is sold out for the first half of 2022. I would expect the tightness of 200mm foundry capacity will last a few years, possibly to 2025," – (Wang 2022)

The 300mm fabs on the other hand were managing before the COVID-19 pandemic and only came under greater stress with the switch to the "stay at home" economy powered by the stimulus of the economy as described in subchapters 2.3 and 2.4. in combination with general demand increase pushed by cases like cryptocurrency mining. Today there are no signs of the demand decreasing any time soon (semiengineering.com 2021)

Both the 200mm and 300mm lines are suffering from the same issues when it comes to expanding their production capacities. Out of all the complexities of expanding front-end fabrication described in the subchapter 2.3, it is the supply crunch of tools and equipment provided by specialized suppliers that is hurting the expansion the most. Tools for a single modern fabrication plant incorporate more than 50,000 parts from dozens of suppliers. Chambers, pumps, RF generators, seals and valves are among the key components in a tool. (semiengineering.com 2017) According to Bruce Kim, chief executive of SurplusGlobal (supplier of secondary equipment), the delivery times of brand-new equipment pieces for both 200 and 300mm are very long, and so in many cases fabs managers are forced to contact a used/refurbished equipment vendor. According to Bruce Kim, there are less than 250 200mm core tools from all entities in the worldwide market as of January 2022. 300mm equipment is easier to obtain as many suppliers started focusing on them before the sudden comeback of 200mm started. According to Bruce, it is becoming common practice to downgrade modern 300mm tools to 200mm systems. Covid has also made it difficult to install these devices due to travel restrictions. (Lapedus 2022), (Bruce 2022)

The semiconductor industry was ranked as the most fragile industry by McKinsey Global Institute when it comes to any trade disruptions due to the global and complex supply chains. The lockdowns luckily weren't as devasting as they could have been, and majority of the factories involved in the chain kept on operating. Still the lockdowns in China and in East Asia did cause some delays and price spikes of the raw resources and may continue to do so. The largest impact of the pandemic were the limitations in transportation which affected all the layers of the semiconductor industry. The semiconductor industry evolved much differently than was anticipated around the year 2010. The now considered old 200mm fabs have been experiencing renaissance due to IoT revolution. The demand for the 200mm lines outstripped supply years before COVID-19 pandemic started, as expanding capacity takes years and is difficult in the industry. The more modern 300mm lines were more robust and capable of expanding quicker as there are currently more specialized suppliers for the modern lines. However, during the COVID-19 pandemic dramatic shift to the “stay at home” economy proved too much for the available supply.

This chapter also explored the fabless/pure-play foundries trend and uncovered potential long-term issues with it, that could have added to the current crisis in different ways. **All the major historical Semiconductor shortages usually had a singular cause, however the current semiconductor shortage has had multiple of reasons, and some of them, like the renaissance of older technology, the industry never experienced.**

The semiconductor industry was already experiencing a supply shortage since the IoT revolution restarted the demand after the mature nodes. However, the situation was nowhere near the disastrous state it reached due to the COVID-19 pandemics many effects. The following table provides an overview of the causes of the semiconductor shortage and distinguishes between COVID-19 related and non-related issues and describes the effect they had on the shortage.

Table 2 - Causes of the Semiconductor crisis and the impact of COVID-19 with comparison to other industries. Own creation, source: Findings of this thesis, according to the sources mentioned

Possible cause	Contrib. to crisis?	**Affected by Covid?**	Effect	Semiconductor specific issue?
Lack of raw resources (REE)	No	**No**	There was no real lack of REEs during the crisis.	No, multiple industries are dependent on REEs.
Overconcentration of REE mining operations in China	Yes	**Yes**	The silicon prices skyrocketed when the mining operations in China stopped due to the COVID-19 pandemic.	No, most industries that use REEs are dependent on mining in China.
Very long and complex supply chains	Yes	**No**	The complex supply chains of the semiconductor industry create risks of bottlenecks at any stage of the production cycle as one specialized supplier relies on another, and vertically integrated, and fully self-reliant businesses don't exist in this industry.	No, Averaging across industries, companies can now expect supply chain disruptions lasting a month or longer to occur every 3.7 years, according to McKinsey Global Institute. (Susan Lund et. al. 2020)
complex manufacturing process	Yes	**No**	The semiconductor industry is only capable of expanding production on a yearly basis as the front-end fabrication plants take between two to four years to build.	Yes, but few other industries face similar limitations in expanding manufacturing capabilities.
Lockdowns	Marginally	**Yes**	The lockdowns had only a marginal effect on the industry as most of the countries marked the industry as vital and the operations continued	No, many industries were forced to shut down and lockdowns had much more devastating effect on them,
Separation of manufacturing and design	Yes	**No**	The ongoing trend of fabless companies ordering at pure-play foundries causes multiple of issues described in the thesis.	No, these issues could arise in any advanced industry, where design and manufacturing are separated
Stimulus of the economy	Yes	**Yes**	Economic stimulus of many economies led to people and companies spending more on semiconductor products that weren't really available.	No, stimulating demand on the one side and the industrial production being limited by COVID-19 restrictions on the other helped to create large supply-demand imbalances across industries

Possible cause	Contrib. to crisis?	**Affected by Covid?**	Effect	Semiconductor specific issue?
U.S. Chinese Trade war	Yes	**No**	This trade war had a major impact on both the Chinese and the U.S. Semiconductor industries.	No, multiple of U.S. and Chinese industries were damaged by the trade war.
Overconcentration of the manufacturing in East Asia	Yes	**No**	Yes, overconcentration of manufacturing in a single region makes any local external shocks more damaging to the entire industry.	No, currently there are many industries completely reliant on exports from East Asia, like for example the active pharmaceutical ingredients industry.
Other natural disasters and external shocks	Yes	**No**	There were multiple of natural disasters and other external shocks that damaged the industry during the crisis.	No, any industry can be damaged by an external shock.
Supply and demand trend change	Yes	**Partially**	Yes, the COVID-19 did increase the demand after semiconductor industry, but the IoT revolution was already happening before the pandemic.	No, but major unexpected shifts in industries like the IoT revolution brought are rare.
Transportation issues	Yes	**Yes**	Yes, the transportation limitations made the entire industry lag behind the schedule.	No, all the industries reliant on global transportation suffered during the pandemic.
Cryptocurrency mining	Yes	**No**	Yes, cryptocurrency mining took the already overclocked semiconductor industry by storm.	Yes, although GPU industry was also affected by this trend but in a different way.

4. Recommendations for the semiconductors industry and predictions for the future

4.1. Recommendations for the semiconductor industry

The current semiconductor shortage has been ongoing for several years now and it served as a wake-up call for many governments and private businesses alike. From new manufacturing plants being built to new laws being introduced, the semiconductor industry is set to experience some massive changes in the near future. However, what should be the goal of this industry metamorphosis? The goal of this chapter is to identify the best course of action for the industry as a whole and to answer, if the current steps that are being undertaken, are leading the industry to that desired outcome or not.

In the previous chapters the possible causes of the crisis were analyzed. Not all of these causes can be prevented in the future due to their nature. However, some can and should be resolved, to prevent a repeat of today's crisis. The following issues contributed the most to the current crisis and can also be in theory fixed.

1. **Large number of single points of failure in the supply chain**

- One of the most striking issues is the large amount of single point failures with majority of the world's market share which increases the risk of an external local event causing major disruption to the entire industry. (Antonio Varas et al. 2021b) Furthermore powerful monopolistic suppliers, on both private and state level, might lead to further trade wars, as countries will be able and willing to leverage their advantages. This was already demonstrated by China in the recent past. (Mancheri et al. 2019)

2. **Concentration of manufacturing in East Asia**

- In the past 25 years economic incentives have led to majority (3/4) of the world's Semiconductor manufacturing to be relocated to East Asia. This transition has led to the forming of fabless companies and pure-play foundries next to IDMs. This creates several issues. The most obvious is the fact, that any trade disruptions leave the Western hemisphere in a severe lack of semiconductor units, as the pandemic showed. It also increases the danger from local natural disasters, which are five times more common in the Asia-Pacific. (Lin et al. 2021) Even though the demand for semiconductors is the largest in Asia, it is important to diversify and balance out the semiconductor manufacturing in the world. Secondary issue is connected to the separation of manufacturing and design, which when operated by separate companies across large geographical distances often leads to both parties acting in their best economic self-interest, which however can go against their partner wishes. Furthermore, it makes for logistically complicated transitions to new technology. The most common results of this are price increases and research deintensification as reported by Fuchs. (Fuchs, Kirchain 2010b)

3. **IoT revolution without reliance on pure-play foundries**

- The resurgence of demand after 200mm fabrication lines came out of nowhere and left the semiconductor industry struggling for supply of mature nodes. The main issue here is that large industries experiencing IoT revolution, like the automotive industry, chose to rely on pure-play foundries for their semiconductor production which is not agile at all. With the expected 17% per annum semiconductor demand growth in the automotive industry, the situation has reached a boiling point, where it might become necessary for these large semiconductor consumers, to become semiconductor independent with their own semiconductor fabrication plants. (Michael Alexander et al. 2021b)

It might seem that the best solution for the first two issues would be for the regions to become semiconductor autarchies in order to secure their own supply chains and reduce the reliance on other regions to the extent that is possible.

The SIA already did research on this topic in 2021 in a form of cost-benefit analysis for the industry as whole, with an extensive focus on the USA. Figure 36 shows the incremental costs that would be needed in order to cover the 2019 pre-pandemic demand with fully sufficient localized supply chains. According to SIA, this would require an additional upfront investment of between 900-1225 billion of USD and between 45 to 125 billion of USDs annually to maintain. SIA didn't try to research theoretical feasibility of such regional autarchies, as it would require extensive research into every region. These extra costs would of course be paid by the end customers with an expected price increase of 35-65% for the end products. (Antonio Varas et al. 2021b) Such a drastic measure would make electronic devices less accessible around the world, which would most likely outweigh any benefits of avoided shortages.

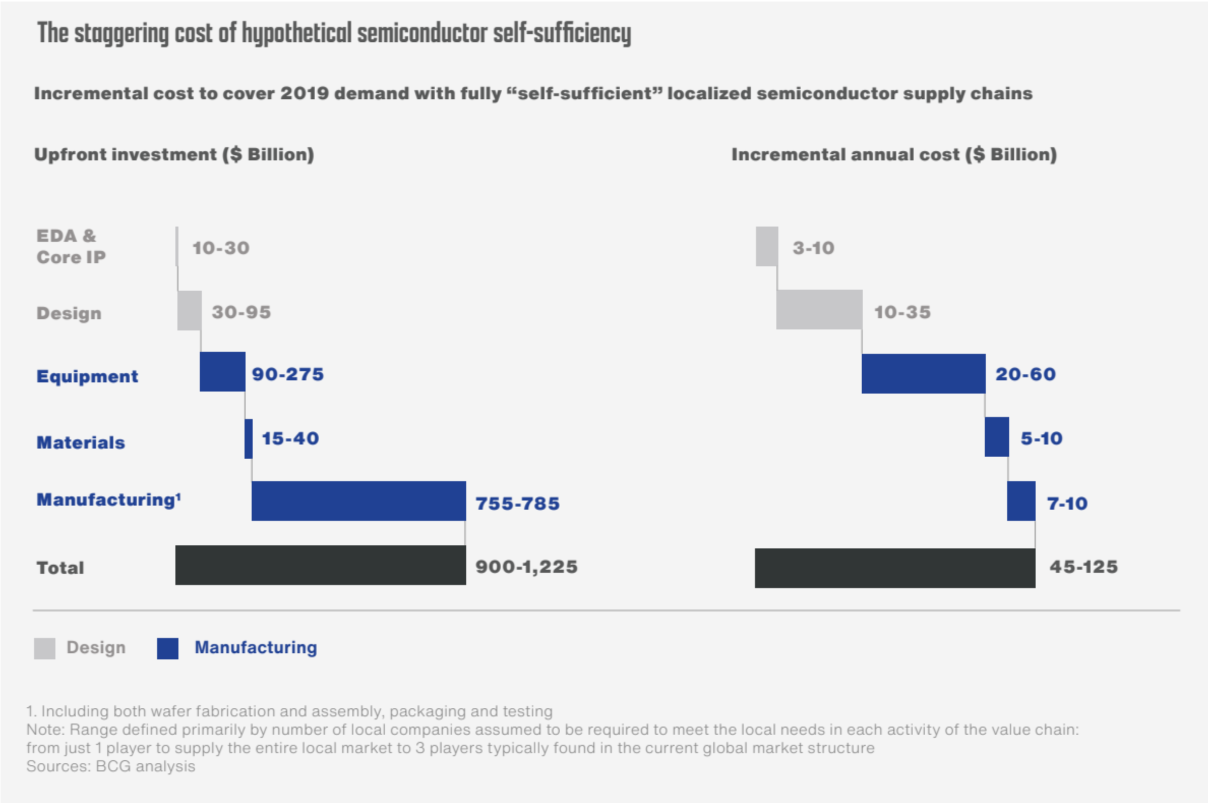


Figure 35- The staggering cost of hypothetical semiconductor self-sufficiency, 2021, source: SIA

So the semiconductor industry must be reinforced without breaking the global trade and the comparative advantages of the regions, if the global economy wants to sustain today's price levels. Debate between self-reliance and benefits of global trade was historically mostly discussed in the food industry, especially after the 2008/2009 food shortage crisis. (similar spark to the todays semiconductor debates) (Anuradha 2009) As achieving food self-sufficiency would be expensive and unpractical, as with semiconductors, it was generally agreed that the best approach is a more balanced approach, instead of either of the extremes. (Clapp 2015).

Singapore for example currently follows a 30 by 30 strategy, which stated the critical food-self-reliance percentage of the country at 30 %. (Wijkvliet 2021) Should all the regions create and follow a similar rule for the semiconductor industry (or at least for some key parts, like the manufacturing, raw resource mining, equipment manufacturing etc.) it would lead to a more diversified and robust global supply chain without a drastic cost increase like. Every region should preferably focus on the parts of the supply chain, it is weakest in and on the parts of the supply chain with the highest concentration of points of failure, as they are the most likely to cause a shortage due to an external shock.

The most important regions and countries of the semiconductor industry are the North America (U.S. + Canada), EU, China and the rest of East Asia (South Korea, Japan, Taiwan). The following paragraphs will examine situation of the semiconductor industry of these regions and countries before the shortage, as well as the impact the shortage had on them. The individual reactions will be examined too.

4.2. The European Union (EU)

Situation before the pandemic

EU had four companies in the top 20 semiconductor companies by revenue in 2020. (globaldata.com 2021) Those companies are: (ASML Holding – equipment manufacturer, STMicroelectronics - IDM, Infineon Technologies - IDM and NXP Semiconductors -IDM). Europe (mostly EU) accounts for only 9% of the world supply of Semiconductors. Majority of the EU factories are producing DAO semiconductor products and older logic semiconductor units (Embedded systems in cars, planes and semiconductor for healthcare products). EU completely lacks in the memory-based product department and in the 5nm logic department. Detailed situation for Europe (EU + others) can be seen in figure 12.

Impact of the crisis:

For an uninterested European listener, the current semiconductor shortage was defined by its impact on the automotive industry in Europe, even though many other European industries suffered similarly. Europe is the second largest car manufacturing region after China and is very much defined by it. There were 298 automobile assembly and engine production plants operating in Europe (196 of which are in EU) in 2020, according to the data from ACEA. (ACEA 2020). In 2020, European production losses due to COVID-19 amounted to 22.9% of total European production in 2019. Not all of the 2020 losses can be attributed to the Semiconductor shortage, as there were, on average 29 days long lockdowns, across the industry in EU. (ACEA 2021b) However European passenger car production contracted further by 5.7% in 2021, failing to reach the pre-pandemic levels and according to the ACEA, the global semiconductor shortage was the main cause. (ACEA 2022)

Reaction:

The reaction from the EU came relatively quickly. In December 2020 a new initiative was signed, titled a *European Initiative on Processors and Semiconductor Technologies* with a simple goal of increasing investments. This was followed by a plan of producing the next generation leading edge chips by 2030. (*2030 Digital Compass: the European way for the Digital Decade* 2021), (European Commission. 2020). These goals were confirmed and expanded upon in February 2022 with the European Chips Act which reinstated the goal of Europe reaching 20 % of global semiconductor manufacturing capacity, promoting research, greater support for semiconductor startups and finding reliable partners. EU has already planned 15 billion EUR of public and private investments until 2030, which is on top of the 30 billion EUR of public investments already planned beforehand. There are also major private and national investments planned next to these investments. Overall, it is safe to say, that the EU realized the importance of the semiconductor industry and started to invest into it. However, is the investment into the cutting edge 5-2nm fabs the correct step for the region? (European Commission 2022)

According to the director of the "Technology and Geopolitics" project, Jan-Peter Kleinhans it is not. EU currently lacks chip design capabilities for advanced logic semiconductors of such size. So even if a modern EU foundry would be built, it would need to attract non-European customers, which is unlikely as the cost of operating in Europe is considerably higher than in Taiwan and South Korea, mostly because of electricity costs. In other words, Europe currently has no own business case for the cutting-edge logic and memory chips and would only be capable of building such a facility with the help (licensing) from TSMC, Samsung or Intel. (Kleinhans 2021)

Time proved Kleinhaus right. It was Intel that announced 80 billion EUR investment over the next decade into EU. The initial phase, which represents a 33 billion EUR investment, includes two advanced fabrication plants in Magdeburg, Germany and further investments across Europe. These factories, however, won't be of much use to the current automotive applications. But Intel also announced that it will assist anyone with designing chips in order to make the transition to more advanced (300mm) lines, the new factories will operate on. (McGregor, 2022) GlobalWafers were also attracted by the subsidies and will be building several 300mm and the much needed 200mm plants in Europe. (Nick 2022)

The EU seems to have succeeded in bringing in advanced chip manufactures, which will help to globally balance the advanced manufacturing. However, should the current crisis repeat, it wouldn't really help the key businesses of Europe, which currently use the more mature chips (7-14nm). EU also didn't make any real changes in their raw resource supply chains and as such is remaining very dependent on deliveries of REEs from China and others. Intel also offered help to the European companies with chip design and transition

to the modern 300mm lines. This could perhaps lead to a cooperation between the European carmakers and Intel, should they choose to follow Tesla or Ford, in their own chip creation. EU today still needs more 200mm lines fabrication plants and larger investments into building its own business cases for the modern chips, it plans to produce. Currently there are no recognizable European mobile phone or computer producers, which make the core audience for the advanced chips.

4.3. North America (USA + Canada)

Situation before the pandemic

The U.S. has 10 companies in the top 20 companies by revenue. Some of the most important and known are the following: (Intel - IDM, Micron - IDM, AMAT - equipment manufacturer, Broadcom - fabless, Qualcomm - fabless, Texas Instruments -IDM, Nvidia - fabless, AMD – fabless). (globaldata.com 2021) But the U.S. also has many smaller companies that are very important for the Semiconductor Industry like the AMAT or LAM research, which are one of the largest specialized equipment providers for the semiconductor fabrication plants in the world. The U.S. is still, on the country level, either the first, or second largest consumer of semiconductors, right on pair with China (taking into consideration only products bought by the Chinese and consumed in China and not reshipped). The U.S. is also the largest total value creator of the semiconductor industry with 38%, mostly due to high R&D intensity. (Antonio Varas et al. 2021b) However, The U.S. only accounted for 13% of total wafer fabrication capacity in 2019 as the figure 12 shows. Unlike the EU, USA has much more robust and diversified manufacturing plants, but the largest focus is given to logic and DAO products. The U.S. also produces most of the global manufacturing equipment for the front-end processes and was estimated to own 41% of the value added in this part of the supply chain. (Antonio Varas et al. 2021b) Canada on the other hand wasn't and still isn't big player when compared to the U.S. with mostly small companies or startups. The largest three Poet Technologies, Spectra7 Microsystems, and Ynvisible Interactive focus on niche specific semiconductors. (Liew 2022)

Impact of the crisis:

Similarly, to the EU, one of the most affected industries in the U.S. was the automotive industry. The number of cars made in the U.S. decreased by 2.07 million units to 8.82 million units from 2019 to 2020 and even though the industry slightly recovered in 2021 with 9.17 million units, it still hasn't managed to reach the pre-pandemic levels of production due to the missing semiconductor units, among other things. The U.S. hosts some of the largest companies in consumer electronics, like Apple, as well as provides manufacturing for many foreign companies. Apple reported, that it lost the equivalent of six billion USD in sales due to semiconductor shortages as it was unable to meet the increased demand during the pandemic. (Rosenbaum 2021) The data collected in the US showed that semiconductors had a lead time—the time from start to delivery of the product—of between 84 and 182 days before the pandemic. By late 2021, those numbers increased and the lead time had stretched to 103-365 days according to the U.S. Commerce Department. (Leary 2022)

Reaction:

The reaction to the current crisis came from both the U.S. and Canadian governments and from the American private sector as well. The two largest American-based carmakers Ford Motor Co. and General Motors Co. outlined a strategic agreement with U.S.-based semiconductor manufacturers like GlobalFoundries Inc. or Qualcomm Inc. to design and manufacture their semiconductor units in the U.S. According to the president of General Motors Mark Reuss, this step is necessary, as the company expects the semiconductor requirements to more than double over the next several years with the rise of electric cars. (Foldy 2021) While Apple has been focusing on developing its new chips inhouse, instead of outsourcing the development, Apple didn't show any intentions of trying to manufacture its semiconductor components as well. Instead Apple is focused on booking out majority of the 3nm production lines of TSMC. (Reuters 2020) (Mayo 2021) According to report by the White House, the semiconductor industry invested over 80 billion USD into new investments in the U.S. mostly focusing on building more manufacturing plants. (The White House 2022) The reaction from the government came in June 2021, when The U.S. Senate passed a broad competitiveness legislation called the U.S. Innovation and Competition Act which included includes $52 billion in federal investments into the U.S. semiconductor industry called the CHIPS for America Act. As of writing this, the chambers didn't yet finalize the final version for the signing of the president, however the investment size is estimated to remain the same. (Shepardson 2022) Congress also introduced the FABS act which would establish a semiconductor investment tax credit. Furthermore, the FABS act should also include additional expenditures for expanding the U.S. manufacturing and design of semiconductors. The FABS act was only introduced and must still pass both the chambers and the be signed by the president. (Wyden 2021) The U.S. government has recognized the REE dependency on China in 2017 and the government signed the executive Order 13817 to ensure secure and reliable supplies of critical minerals. As a result of this, a deal to open a $30 million processing plant by Australian company Lynas in Texas (The same company the Japanese are using). According to Simon Moore (managing director of Benchmark Mineral Intelligence), who spoke about the potential issue Infront of the U.S. Senate thinks, the U.S. is still sleeping on the issue. (Tegler 2021) Canada has put together a plan in May 2021 called "Roadmap to 2050: Canada's Semiconductor Action Plan" has a goal to foster a strong domestic semiconductor industry in the coming decades. (Canada's Semiconductor Council 2021) Canada has already invest 240 million USD into its domestic industry as the first step in this plan. (Brown 2022)

The United States seem to be on the right track of reducing their dependance on offshore front-end manufacturing, however the U.S. isn't making sufficient moves to reduce the dependency on the foreign REE imports, needed for these facilities, solving only half of the equation. The largest U.S. car manufacturers, unlike their EU counterparts, are also planning to secure and take more direct part in their semiconductor value chains. This model of in-house semiconductor creation already secured Tesla a strong output throughout the crisis. Apple, the largest consumer electronics company in the world, plans to remain purely fabless and dependent on TSMC for deliveries. This makes the tech giant extremely vulnerable to any external shocks in Taiwan. The current shortage has also motivated Canada to try and enter this large market. Canada has the means to truly become a powerful semiconductor hub by 2050, however in the next few years Canada won't play any important role in the industry.

4.4. China

Situation before the pandemic:

By the most basic matric, China became the largest semiconductor consumer in the world in the year 2005 when it overcame Japan during its rapid economic rise and modernization. Since then, Chinese consumption more than doubled and in 2019 it accounts for over 60 % of the total semiconductor consumption. (daxueconsulting.com 2020) These statistics however don't take into consideration if the devices are effectively sold to the local end users. The real Chinese consumption is estimated to be somewhere around 25 % and is expected to keep growing. (Antonio Varas et al. 2021b). Even though the Chinese government has made the semiconductor industry a major focus since 2014 with its "made in China policy", and established very ambitious goals in its latest 14th five year plan of reaching technology independence, China remains lacking in many key aspects of the semiconductor industry and remains very dependent on imports and global trade. (Council on foreign relations 2021) Before the pandemic, in 2019, China was responsible for 16 % of wafer fabrication according to the figure 12 with a focus on mature nodes. China is however extremely lacking in design, and equipment manufacturing. According to IHS iSuppli, less than 1% of electronic design software, semiconductor tools, and materials are made in China. This means that China would be completely unable to build and equip a manufacturing plant on its own. (Thomas 2021) It is no shock then, that China had no companies in the top 20 of the industry in the year 2020 as reported by Globaldata. (globaldata.com 2021) China also admitted that it is lacking the needed engineers for the industry growth. According to the Yu Xiekang, the vice president of the Chinese SIA, China was lacking some 300 000 engineers in the industry in 2019. (Suying 2019) China is strongest in the "least important and the most easily replaceable part of the production cycle" which is the back-end manufacturing with the estimated 36% share of the global back-end market in 2019 according to the SIA. (Antonio Varas et al. 2021b) Since the trade war with the U.S. started in 2016, as explained in the subchapter 2.5, the government made manufacturing subsidies contingent on a commitment to use local suppliers and pushed the industry further on the indigenization path.

Impact of the crisis:

The Chinese automotive industry was damaged in a similar fashion to the U.S. and the EU. According to estimations by experts, the Chinese car manufacturers faced a 10% to 20% shortfall of semiconductor units. (Qu Hui et. al. 2021). Disrupted supply chains have stopped many ongoing projects of building more fabrication plants as well as reduced production in some of these plants. (Che 2021) China is also the largest producent of worlds electronics with 36 %. There still isn't a clear picture about the damage, the lack of semiconductors caused in China. But from the increased demand after consumer electronics around the world, it is safe to assume, it will be billions of USD. Huawei, the Chinese giant, which was already the main target of the 2016 trade war, was further decimated by the Semiconductor shortage. According to the Counterpoint research, Huawei was selling 50 million units of smartphones quarterly before the trade war, and in 2021 it was just 7 million per quarter. Another prove for the company's horrible situation is the fact, it had to pull multiple of its models from production completely. (Consumer.huawei.com 2021) Xiaomi, another giant Chinse smartphone company has lost more than a third of its value in 2021, due to supply chain issues. (Bloomberg 2021c) Many Chinese semiconductor companies also declared bankruptcy during the shortage as was described in the subchapter 2.3.

Reaction:

The semiconductor shortage and the COVID-19 pandemic only encouraged Chinese government to further invest into the semiconductor industry, however the goal of self-reliance and large Chinese semiconductor industry was set out by the government long before the current crisis in 2014. Chinese government is planning to spent $150 billion by 2030 on the industry. (Erdemir 2022) In August 2020, as a reaction to the worsening situation, the Chinese government exempted advanced nodes semiconductor companies from paying taxes for 10 years. (Zhang 2020) Encouragement of the Chinese government has led to 15,700 new companies involved in everything from designing to manufacturing chips to be registered in just four months in 2021. (Ye 2021)

With the goal of achieving semiconductor self-reliance, the Chinese government has been investing heavily in its semiconductor industry since 2014. But even 8 years later, these goals are far from becoming reality. One obvious issue is the fact, that China cannot design majority own semiconductors, it is using or manufacture the equipment to produce them. This leaves Chinese companies completely reliant on imports, making them vulnerable to external shocks. More importantly, there is a major lack of qualified semiconductor engineers in China. It does not matter how many new semiconductor companies are set up if there aren't enough qualified workers on the domestic market.

4.5. East Asia (Japan, Taiwan, South Korea)

Situation before the pandemic:

Japan, Taiwan and South Korea are all giants in the fields of the semiconductor industry and large exporters, however together they only form roughly 7 % of the global demand. (Antonio Varas et al. 2021b). According to the figure 12, these three countries together possess 56% of the global wafer fabrication capacity, but they quite differ in strategies and products they produce. South Korea´s Samsung has a comfortable market lead in memory products, while Japan is the largest DAO creator, due to the large domestic automotive industry. Taiwan is the undisputed leader in advanced logic chips manufacturing. Taiwanese companies, unlike the Japanese and South Korean have chosen to become either a pure-play foundry or a fabless company. On the other hand, Japan and South Korea have some of the largest IDMs of the world like Samsung. Six out of top twenty semiconductor companies by revenue are from these three countries. (Samsung – IDM, SK Hynix – IDM, TSMC – pure-play, MediaTek – pure-play, Renesas Electronics – IDM, UMC – fabless) (globaldata.com 2021) But there are many more important large companies, similarly to the U.S. Japan was also the second largest equipment manufacturer in 2019 with 32%. (Antonio Varas et al. 2021b) South Korea and Taiwan both lack in this department. All these countries are also dependent on delivery of REEs as explored in the previous chapters.

Impact of the crisis:

Japan, which is the largest consumer of Semiconductors out of these three (6% of the global consumption in 2019 as reported by SIA) and has a large automobile sector was hurt the most out of these three countries. According to the data from Teikoku databank, 115 Japanese companies reported negative impact on their business by the Semiconductor shortage. 86 of these companies were Manufacturing companies, usually operating in the supply chain of the Japanese automotive industry. (nippon.com 2021) Japanese Renesas Electronics was the company to report the largest loss out of the semiconductor companies in the top 20, due to the fire that destroyed two-thirds of Renesas production in 2021. (www.ETAuto.com 2021) Consumer electronics companies of Japan were damaged by the shortage as well. For example, Sony was unable to meet the demand after its new gaming console PlayStation 5. Due to the Semiconductor shortages the company shipped till December 31 of 2021 only 17.3 million units of PlayStation 5, nearly three million units fewer than the 20.2 million units of the previous version shipped during the same period after launch. (CNBC 2022) On the other hand Taiwanese and Korean semiconductor companies experienced a ridiculous profit jump during the shortage. Samsung had YoY growth of 19.9% in 2020 and continued the growth in 2021. (globaldata.com 2021) In the last quarter of 2021, Samsung forecasted 53% jump in revenue. According to Samsung, this was due to the global transition to the “stay at home” economy. (BBC 2021) TSMC and other Taiwanese pure-play foundries companies experienced big double-digit growth. TSMC had a YoY net profit growth of 57.4% in 2020 and expected capex between 40-44 billion USD in 2022 vs 30 billion USD in 2021. Truly a staggering multi-year growth. That doesn’t mean that other industries of these countries also weren’t affected by the shortage. Even though the South Korea companies were more resilient at first during the shortage, in the second half of 2021, the shortage caught up to them as well and many South Korean carmakers like Kia and Hyundai, and others had to limit their production. (Ferrier 2021), (Reuters 2021c), (EUN-SOO 2021). For Taiwan, for which the semiconductor industry is the most important one in terms of GDP, the shortage brought more economic positives, then negatives.

Reaction:

South Korean private sector reacted in a massive way and was accompanied by the reaction from the government. Samsung decided to increase its range of semiconductor products and will be investing 151 billion USD in its non-memory chip foundries over the next ten years, an increase of 33.6 billion USD on previously announced plans. These new facilities will also be able to produce the most modern 5nm logic chips. SK Hynix also pledged 106 billion USD to build more facilities and is planning to invest an additional 97 billion USD to upgrade its existing fabs. Meanwhile, the South Korean government offered tax breaks for chip businesses and funded the training of 36,000 new staff, which will be required in these new facilities and will spend 1.3 billion USD on semiconductor R&D. Altogether, South Korea will be spending 451 billion USD in the next 10 years, which is over a quarter of the South Korea GDP in 2020. During the Japanese semiconductor trade show in Tokyo in December 2021, the prime minister Fumio said Japan is planning to invest over 1.4 trillion YEN (almost 11 billion USD) in the near future. 774 billion YEN of those 1.4 trillion were already spent in the year 2021. (Nippon 2021) The largest investment was 400 billion YEN subsidy for TSMC new foundry in Kumamoto prefecture, in Japan. (www.asiantechpress.com 2021) Ministry of Economy, Trade and Industry of Japan released a report in 2021 which underlined the importance of improving the technologies that are deployed in semiconductor material and production equipment. This is already a Japanese strongpoint and a potential block for worldwide expansion of fabrication capacity. (Togashi 2022) Taiwan and its companies have also reacted in a massive way and increased their capital expenditure for the coming years. TSMC has committed to investing 100 billion USD in the next three years to ramp up its production. TSMC is also planning on building fabrication plants outside of Taiwan in Europe, Japan and the U.S. which lowers the risk of the industry suffering that much from a local external shock in Taiwan. MediaTek and UMC are also increasing their spending and expanding aggressively, and not just in Taiwan. (Reuters 2022) (Sean 2021).

Out of the three East Asian giants, it was Japan that suffered the most during the shortage. South Korea proved resilient for the larger portion of the 2020 and 2021 but was affected later as well. Almost all the East Asian semiconductor companies experienced rapid growth and are reinvesting to resolve the shortage. South Korea has announced a staggering 451 billion USD investment over the next 10 years. Taiwanese companies are also investing heavily. TSMC and UMC are also becoming willing to build their foundries around the world, not just in Taiwan. Dismantling some of the fears about the pure-play

model overconcentration in Taiwan, described in the chapter 3. Japan understands that the ongoing expansion of foundries will require more of specialized equipment, which is now missing on the market, and it will be focusing on this part of the global supply chain. The East Asia countries investments are much more pushed by the private sector when compared to the EU and the U.S. and China. Furthermore, the private sector is being supported by the public sector in an effective way (focusing on training more qualified workers in Korea, quick tax relieves etc.). It seems that the East Asia will stay the most important player in the semiconductor industry in the near future.

4.6. Prediction for the future

Both the explored public sphere of the most critical regions and the private subjects within have reacted to the semiconductor shortage somehow. Still, are the three main issues described at the beginning of the chapter being addressed? The only country that pushes for the expensive path of semiconductor autarchy is China, however, the goals set by the government in the 14th five years plan cannot be realistically reached in time. The other countries have chosen the more cost-effective path of semi-independence, but some parts of the supply chain are given more attention than to others. Both the EU and the U.S. are committed to expanding front-end manufactories in the Western hemisphere, which could help solve the major issue of the geographical concentration of manufacturing in East Asia. However, neither EU nor the U.S. have reacted to possibly the biggest bottleneck risk of the Chinese monopoly on REE mining, although they acknowledged the problem. Even though new fabrication plants will be built in the West, it is unlikely that the % distribution between West and East will change much in the near future as East Asia is investing even more into the industry. Some of the fears about pure-play foundries are being addressed as well. Taiwanese companies are beginning to build more outside of Taiwan, reducing the concentration risk. After the current shortage, The U.S. carmakers are also leading the way in becoming semiconductor self-reliant. This would make the U.S. supply chains of these carmakers more robust and agile and would also ease the stress from the pure-play foundries, which want to build more modern lines for the logic and memory products for a higher return on investment. Another hope for a solution to the current lack of the older chips would be for the car manufacturers and other industries to invest in making larger portions of their semiconductors manufacturable on the 300mm line. Intel already offered help to the European carmakers, but it remains unaccepted so far. As of early 2022, some experts have ongoing fears that once the majority of these newly announced fabrication plants are finished, which should happen sometime in 2024, the semiconductor shortage will change into semiconductor oversupply. This has been historically the case with the industry's boom and bust cycles and is a very likely possibility should the industry grow at the speed that is being predicted today. Nonetheless, should there be any more events like COVID-19 or the rise of the cryptocurrencies that increased the demand rapidly, as described in previous chapters, today's predictions won't stand. (Dashveenjit, 2022) **It is very unlikely that the semiconductor shortage will be truly resolved before 2024, and it is pure guessing how dynamically the demand will evolve beyond that.**

Conclusion

The goal of this thesis was to find out whether the current semiconductor shortage would have also occurred without the COVID-19 pandemic, and whether the causes of this crisis will lead to similar global supply shocks for other industries. The thesis also aimed to give recommendations how to solve this crisis and assess if the global reaction to the crisis was sufficient and well-aimed.

After examining the possible causes of the semiconductor shortage, analyzing trends and inner workings of the semiconductor industry, and finally researching historical shortages, the findings suggest that the COVID-19 wasn't the primary cause of the semiconductor shortage. It was a catalyst for it. The core causes of the semiconductor shortage are intertwined with the complex nature of the semiconductor products.

The semiconductor industry was experiencing shortages for several years across several segments before the pandemic started, as the industry entered its largest demand boom in its history, pushed mostly by the IoT revolution as semiconductors are required for all the electronics used in daily live.

In 2019, the semiconductor industry had the highest investment level in both R&D and capital expenditure. (Antonio Varas et al. 2021a) In order to reduce these costs, the industry became globalized and very specialized on both the regional and the company level. The specialization has led to a large number of single points of failures and created the breeding ground for more bottlenecks than in any other industry during the pandemic. Furthermore, the industry is unable to react to the demand spikes due to the complex manufacturing front-end process. A single new manufacturing plant can take up to four years to be built and requires tens of billions of USD in investment and numerous qualified personnel before it can start to operate. The wafer fabrication process, which is at the core of the industry, takes months to complete.

Another specific issue of the industry is the incredible range of different semiconductor products that exist. Not all these products can be created in the same facility. The suppliers expected a large demand shift from the now mature nodes produced mostly in the 200mm manufacturing plants to the cutting-edge nodes produced in the 300mm manufacturing plants. The IoT revolution increased the demand mostly for the mature nodes. The suppliers didn't expect that. Since then, the industry has been in a catch-up mode, operating at maximum possible capacity. The entire situation was then worsened by additional issues and trends before and during the pandemic, such as the U.S.–China trade war, series of natural disasters, massive fiscal support of government programs or the unexpected demand increase from cryptocurrency mining.

Finally, the pandemic created large logistical and operational issues on the supply side, while the "stay at home" economy of the pandemic led to a further increased demand after semiconductors. Table 2 is a summary table providing an overview of all the explored causes for the semiconductor shortage. It distinguishes between COVID-19 related and non-related issues and describes the effect they had or didn't have on the semiconductor shortage. The table also classifies the issues as either semiconductor specific or as general, that could endanger other industries as well.

During the Covid-19 pandemic new, previously unexplored issues appeared with the fabless/pure-play model and were described in the thesis. These issues were:

- Fabless companies' vulnerability to external shocks and poor management.
- Bidding wars of big players over the capacities of pure-play foundries.
- Pure-play foundries are economically incentivized to cluster their fabrications plants close to one another.

SIA explored the plausibility of regional semiconductor autarchies as a solution to future crises in 2019. The research shows that such a solution, if even possible, would be highly economically inefficient and would resolve in price increases of 35-65% on the end products. (Antonio Varas et al. 2021b) This means that the industry needs to resolve its issues without reducing the economies of scale and specialization of the industry. From combining the recent primary and secondary sources, the thesis offered three major recommendations for the industry based on their potential beneficial impact and solvability level. The recommendations are the following:

- Reduce the large number of single points of failure in the supply chain.
- Reduce the overconcentration of manufacturing in East Asia.
- Push large industries that are reliant on semiconductors to get involved in the production process instead of relying on pure-play foundries.

The last chapter also explored the impact of the crisis on the USA, the EU, Canada, China, Taiwan, Japan, and finally South Korea as well as reactions of public and private sectors of these countries and of the EU. It evaluated their reactions as sufficient or not in terms of mending the crisis. Only China chose the economically inefficient path of the autarchy but is in no shape to reach it in the next decade. Both the EU and the U.S. with Canada are committed to expanding front-end manufactories in the Western hemisphere in order to reach certain given share of global semiconductor manufacturing, which could theoretically help solve one of the major issues. Other dangerous points of failure, like the Chinese monopoly on REEs, were identified by the countries but aren't being addressed enough. Taiwanese pure-play foundries have committed to building fabrication plants outside of Taiwan, reducing the potential damage a local external shock could pose on the industry. The U.S. carmakers are looking for ways of bringing semiconductor production inhouse, instead of relying on foreign production, which could bring some relief and future stability to the industry. Overall, the global reaction to the crisis has been mostly well targeted and in line with the primary literature on the issues and with the three recommendations made in this thesis.

The predictions for the end of the current semiconductor shortage differ drastically one each other. However, it is very unlikely that the semiconductor shortage will be resolved before 2024. Some analysts fear that the shortage could change into oversupply, should the demand trends stay the same as today after 2024, due to the overwhelming reaction during the pandemic. However, the history of the industry shows that predictions are rarely on point, and so any predictions remain just qualified guesses.

This thesis is large in scope and was written under the limitations of an evolving topic. It will take years before the global data is assembled and processed and before the impacts of the last two years will manifest itself on the semiconductor industry. This opens a lot of space for future research on the causes and effects of the current semiconductor shortage.

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