The Semiconductor Industry

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

The last half a century has seen a technological shift like no other. With the rise of semiconductors and integrated circuits, consumer technology has improved greatly in many different aspects such as size and computing power. Colloquially called chips, these transistor-based integrated circuits have changed the world's economy and geopolitical landscape rapidly and at a scale that has never been seen before. World War II was a conflict won with industrial might: steel, artillery, and ammunition (Miller, 2022), but the Cold War and the latest conflicts with China have been and will be defined by semiconductors. The personal laptops of today have much more computing power than the computers that put humanity on the moon for the first time (Fisher, n.d.). Technology developed at an incredible rate with the rise of transistors as a replacement for vacuum tubes (Kopyto, 2019). Computers chips were able to get smaller and smaller and computing power to get larger and larger.

The growth of the semiconductor industry is not just the result of one person or group of people, but a collective effort of engineers, project managers, marketing, and globalization (Miller, 2022). The semiconductor industry has grown from small startups in the US to an industry highly dependent on globalization. There are many companies involved with different specializations at each point in the chip making process, and if just one of those links fails, the whole system can feel its effects. The Covid-19 pandemic showed just how important each link in the chain of design to manufacturing is (Gadgets Now Bureau, 2022). Many industries nowadays rely on chips to make their products, like the automobile industry (Wu et al., 2021). When fabs, fabrication plants for chips, shut down, the chip shortage was felt all over the globe. The semiconductor industry has many ties in many places with a complex history with many

different motivations for growth. In this paper, I use actor-network theory to analyze different aspects of the industry as well as dive deeper into current US public policy with China and how past and present economic ties effect modern day policy decisions. A history of the semiconductor industry in the US and main global players including China, Taiwan, Japan, and the Netherlands is needed to analysis different players in the semiconductor industry as well as how different US companies and organizations plan to use money from "The Chip Act".

Industry Overview

The semiconductor industry is fundamentally built on one technology: the transistor. The term 'transistor' generally encompasses multiple types of devices. These devices can act like amplifiers or on and off switches. Both use cases are important for different systems to have. In the digital world, most transistors are used as switches. Computers and their Central Processing Units (CPUs) use transistors to accomplish computations and store data in memory. There are many different types of chips that all have specific purposes, and their design is fine tuned for that purpose. In the realm of designing chips, there are different design 'knobs' that engineers have at their disposal. These 'knobs', like transistor type or transistor size, can greatly affect how the design operates. A design engineer must be good at knowing which 'knobs' to optimize for a chip's specific function.

In the world of silicon and microchips, there are many different types of chips with different applications, and some may have different design flows as well. One of the beauties of the transistor is that when you put multiple transistors on one chip, then you can build large, complex circuits that have specific purposes. This is called the integrated circuit. The integrated circuit along with a manufacturing technique called photolithography were vital developments in the semiconductor industry because those inventions enabled companies to begin mass-

manufacturing chips. Integrated circuits provided a way for the industry to grow and gain capital and support from the US government and start broadening their horizons to the consumer market.

Another main part of designing a chip is the verification stage. Verification, compared to other parts of the design process, takes a large amount of time and is critical for development. It is very expensive to manufacture chips, and it is critical to catch design errors in the design stage rather than after production. Electronic Design Automation (EDA) tools are also used for verification. Many steps are taken to ensure that the design is correct and after the design is finished, the instructions given to the fab are correct. With today's highly complex designs of millions of transistors or more on a chip, this process is often done with help from tools that uses algorithms or different techniques to automate testing or layout.

Once the chip's design has been finalized and has gone through numerous testing, it can be sent over to be fabricated. Some chips are fabricated here in the US, but most high quality chips are made by one company, TSMC (Taiwan Semiconductor Manufacturing Company) (Johnny Harris, 2023). The cost of maintaining a fab is very expensive, as it can cost billions of dollars to make sure that the fab stays in production and that they are at the cutting edge of the latest technology node.

Actors in the Supply Chain

The semiconductor industry is globally connected and relies on very specific technology. The industry has changed dramatically over time. As Moore's Law has pushed innovation, engineers have found new ways to overcome manufacturing obstacles, companies have marketed themselves to different markets and driven profit. Moore's Law is not a scientific law, it is an

observation about how the semiconductor industry has seen exponential growth in technology nodes.

Even though this industry would not exist without many feats of engineering, the success of the industry cannot be solely attributed to engineers. Managers and marketing teams make a significant impact when marketing to the public as well as other companies. Government intervention can also make or break a company's success. Company leadership has many factors to consider when choosing to invest in or cut back in Research and Development (R&D) efforts. Market share is quite an important metric as well when determining what company is in the lead or what country has the most influence in the industry. Market share is the percentage of one item being produced by one group. Having experience in the industry and having the guts to pursue new technology while also knowing when to cut one's losses is critically important for growth and sustainability.

Even looking at only ASML's lithography products, every one of the parts needed to construct one of those machines is sourced from a global network of the highest quality of materials (Miller, 2022). The industry is dynamic and there are many moving parts. List 1 summarizes the most important actors in the network. There are many more, but these cover the main players Figure 1 shows a summary of the semiconductor actor network in a bubble graph. The solid lines represent main connections between categories and actors, while dotted lines represent connections between actors and actors.

List 1: Actors in the Semiconductor Industry

1. Semiconductor Chips
2. US Government
3. Taiwanese Government

4. Chinese Government
5. Other Countries semiconductor industries (Netherlands, Japan, South Korea)
6. Design Engineers + Design Companies
7. Equipment Companies + Equipment
8. Lithography Companies + Lithography Equipment
9. Manufacturing Companies
10. EDA Companies + EDA
11. Intellectual Property (IP)
12. Managers + Marketing Teams
13. Natural Resource Providers

The Biden Administration has been more aggressive than administrations past on relations with China when it comes to semiconductors. A spike in Intellectual Property theft from China, along with the realization that China has historically had the ability to simply purchase all the high-end chips and technology it needed to update its own military and civilian products. There have been cases from ASML and Samsung in which ex-employees of their respective companies have leaked information to China about their company's trade secrets ("ASML Says Ex-Employee in China Stole Chip Data," 2023; Sohn, 2023).

Intellectual Property is very important to the chip industry, as many chip developers do not want their designs leaked to their competitors. This fear of being stolen from was heightened before the dominance of TSMC in which sending a design to another fab to get fabricated could result in a case of reverse engineering and profit for that other company. When TSMC was founded, Chang promised his customers that TSMC would only fabricate chips, never design

chips. Chang and TSMC allowed for a boom in “fabless” chip firms, in that the firm only designs chips and does not manufacture them (Miller, 2022).

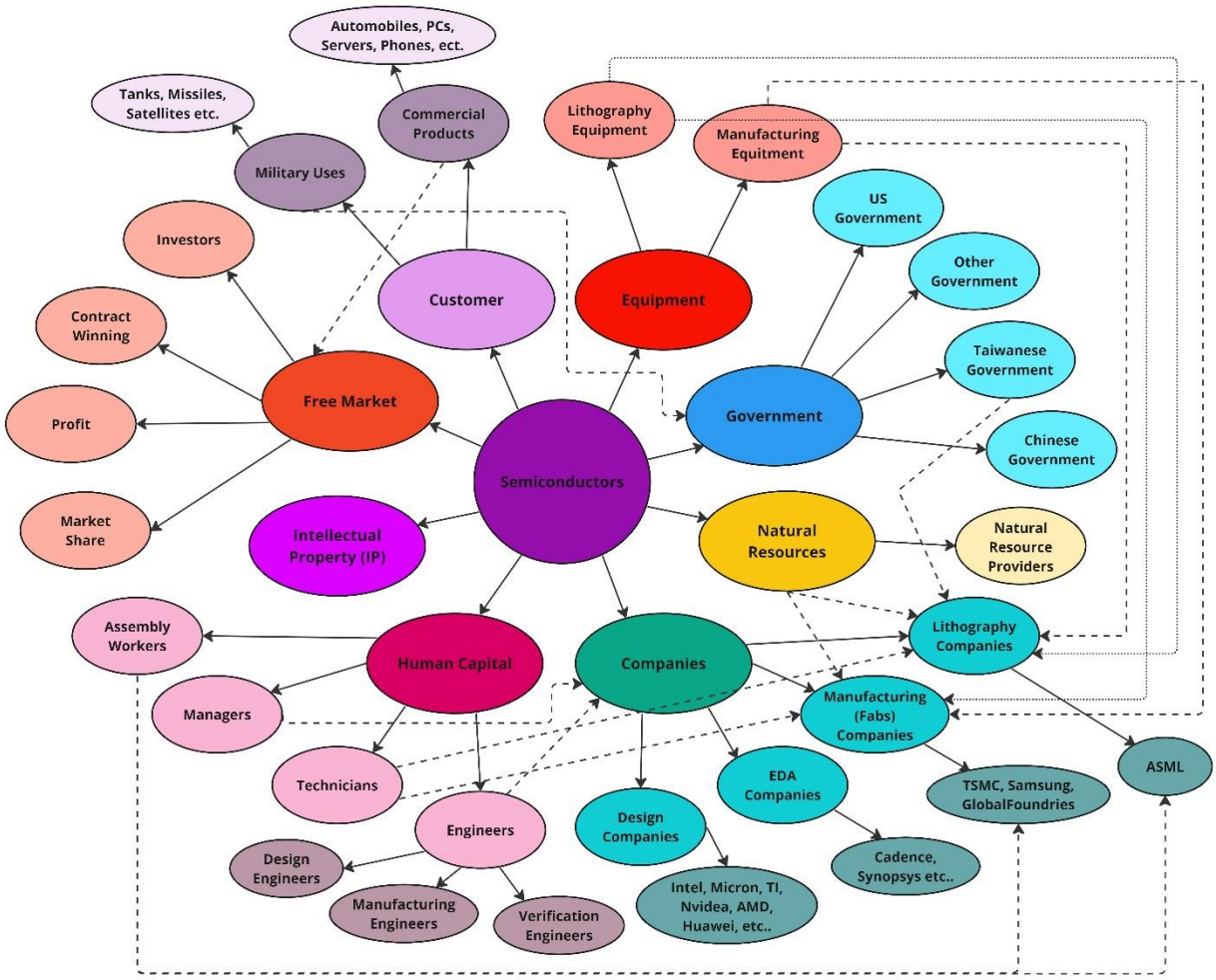

Figure 1: The Actor Network Map of the Semiconductor Industry

In late 2022, Biden passed multiple bans that would limit the amount of high-end chips and American chip technology, banning Huawei from having access to many American chip technologies (Bartz et al., 2022). As early as 2018, the US had banned ZTE, a Chinese telecommunications company, from purchasing key parts from the US. This was also in recent

light of Trump's other trade policies and tariffs on China ("U.S. Ban on Sales to China's ZTE Opens Fresh Front as Tensions Escalate," 2018).

The US, like China, has come to realize that the semiconductor industry relies very heavily on a select few companies and choke points. The dominant player has historically been the US, in that no other sector of the industry could survive without some of the US's technology and IP. Many in the US want to keep it this way. The US chip industry has had to pick and choose its battles at times, like the race for DRAM production or choosing to rely on TSMC and close many fabs, but the US still wants to maintain its high market share and ensure that it is at the center of the chip industry.

China is going into the chip industry as a potential disruption of the norm. China is a powerful player, and after coming to the realization that all its high-end chips and the technology to make those chips lie in the hands of its geopolitical adversaries, one of China's main goals is to be able to be self-sustainable in the realm of advanced chip making. This is not an easy task, but China seems determined to build its industry, by means of internal growth or through theft. For comparison, during the Cold War, the USSR did attempt to build its own semiconductor industry, but their main strategy was to "copy it" (Miller, 2022). This was inevitably unsuccessful due to the USSR always being behind US chips and the chip fabrication and design process was becoming more and more complex, so complex it was almost impossible to recreate without the correct equipment.

History of the Semiconductor Industry

During the beginnings of the semiconductor industry, American engineers and scientists had to source everything they needed to produce integrated circuits, like silicon and

photosensitive materials, in house, but companies and managers soon realized that labor was cheaper overseas for mass production of chip assembly (Miller, 2022). Fabs soon became almost nonexistent in the US. Nowadays, 92% of the world's high-quality chips and 63% of all chips are manufactured in Taiwan (Johnny Harris, 2023) (Vox, 2023).

Semiconductors and chips have become a defining technology in everyday life. Their history starts with a similar yet quite different technology, vacuum tubes. Computers had their beginnings with a technology called vacuum tubes. Like transistors, these vacuum tubes acted like switches, yet they were clunky and not as reliable as desired (Kopyto, 2019). They attracted moths and engineers had get all the moths out witch was the birth of the term "debugging" (Miller, 2022).

The main consumer of high quality and cutting-edge chips at first was NASA and the US military. Due to the birth of transistors and integrated circuits being in the United States and that the US was in the middle of the Cold War with the USSR, NASA had the money to invest in this brand new transistor technology in their Apollo missions (Miller, 2022). By the 1970s, the semiconductor industry had become a large force on the stage of global economy. The percentage of chips bought by the US Military as compared to the chips made for commercial markets continued to decline as the commercial side of chip design and manufacturing took off. Engineers were able to find clever solutions to manufacturing problems and companies in the United States soon learned that to save costs, they should offshore the most expensive part of the process, manufacturing, overseas.

The semiconductor industry did really get its footing in the United States with companies and producers like Fairchild, Intel, IBM, Texas Instruments, and later on Micron (Miller, 2022). Intel was founded by Gordon Moore and Robert Noyce (Intel, n.d.) after they decided to leave

Fairchild due to gripes with Fairchild's management (Miller, 2022). Intel would be a key player in innovation of semiconductors as articulated by Moore himself in his article "Cramming more components onto integrated circuits" (Moore, 1965). This article was the basis for years and generations of innovation as it describes the observation that semiconductor technology capability was doubling about every two years. This observation later was dubbed as Moore's Law and the industry has pushed innovation through the years to follow this trend.

The semiconductor industry also would not be where it is today without the development of the tools needed to design high-end chips. Companies like Cadence and Synopsys today are the main developers of these Electronic Design Automation (EDA) tools that allow engineers to design circuits with increasing levels of abstraction which in turn makes it easier to design highly complex systems. When chips now a days have over a million transistors on a single chip, it is impossible to design at the transistor level. This is why tools and Hardware Description Languages (HDLs) are also such a critical component of chip design, and these tools were developed here in the United States.

With the COVID-19 pandemic, the world had to make many sacrifices. The supply chain of chips was drastically impacted, like other lines of work. Factories were shut down due to the inability to continue to be in production, which resulted in an increased demand for chips. People may think that the main reason for the chip shortage was a lack of chips, but in reality, chip production in 2021 was at an all-time high, 13% higher than 2020 (Miller, 2022). The shortages were mainly felt due to a supply and demand issue. The automotive industry is a large customer for the semiconductor industry in that many of today's cars are equipped with computer chips and complex embedded systems. As an industry, in preparation for a decreased demand of cars, the automotive industry did not purchase the normal amount of chips needed to make a car. In

2020, demand for PCs and chips for servers spiked as well, as much of the world's workforce moved to being completely online. These devices are dependent on the semiconductor industry for production. With these strains on the supply chain, prices have increased, shipping times and delivery times are often late, and many chips are out of stock. As for the automotive industry, when demand quickly rose again sooner than expected and they went to go and try to purchase chips needed, automotive companies soon came to find out that chip makers had relocated their production to other chips that were in demand (Miller, 2022).

China has realized that it has been relying on the US for the design of high-quality chips and other countries for the materials and equipment, so in order to catch up, China began pouring money into its own semiconductor industry and ensuring that they have the IP to back it (Vox, 2023). The US realized with different IP theft cases that China had started stealing IP from different US and US allied companies like ASML (Vox, 2023). When the US government realized how large of a problem having almost all production of these high demand chips be overseas, congress developed and signed a bill dubbed "The Chip Act" mainly for companies to start producing and making fabs again here in the US (Breuninger, 2022; The Chips and Science Act of 2022, 2022; *The CHIPS And Science Act Of 2022*, 2022).

The Growth of Taiwan, TSMC, and Asia

TSMC is a global powerhouse for chip manufacturing, as many fabless chip design firms trust the company to make their cutting-edge chips. TSMC chip manufacturing began with Dr. Morris Chang and the Taiwanese government. Chang graduated from MIT with a doctorate in electrical engineering and then went on to work at Texas Instruments for a long time doing advanced semiconductor design and manufacturing. TSMC began at the non-profit research institution of ITRI (Industrial Technology Research Institute). Chang joined them in 1986 as

President and Chairman and was able to develop the first FAB of TSMC ("History and Milestones of TSMC," 2019).

One of the unique aspects of TSMC is that it was created hand in and with the government of Taiwan, resulting in a good foundation for growth due to monetary support. Dr. Chang pushed boundaries of the ages and was constantly investing in new technology nodes, and the world began to trust that TSMC would always have the new and best node at a high quality demanded for specific applications.

In the 1980s, Japan had come to center stage in the semiconductor industry as companies began to produce DRAM. DRAM, Dynamic Random Access Memory, is a type of memory that Intel had created for computers. Producing DRAM, or any other silicon chip, is a very expensive task. The cost of creating a new fab, a factory where chips are fabricated, can cost upwards of billions of dollars (Miller, 2022). Even before TSMC became a player in the game, American companies like Texas Instruments, where Dr. Chang was previously employed, had begun to move manufacturing process overseas. This was the best economic decision for companies like Texas instruments and other soon to be fabless design firms, because in order for the fab to be profitable, a high volume of chips needs to be manufactured. Many companies had to close their fabs due to them not making any profit, many losing money. Only highly specialized chips, like analog chips, can be profitable when quantity is low. The manufacturing equipment also needs to be running constantly to meet those quotas for profitability. Manufacturing jobs like assembly and manufacturing of chips tended to be cheaper in Asia. Other countries in Asia were looking to get into the chip industry. South Korea's Samsung and Japan's Sony were key players in the development of the chip industry. They all provided competition with the US, and eventually chose to partner with the US on a global scale.

China

Economics and geopolitics are heavily intertwined, and so the relationships between China, its allies, and its adversaries are complex. China also has become a global powerhouse after the cold war and knows that chips are a fundamental piece of technology for military applications. China realized that they were not their own producer of high-quality chips, and so they decided to deconstruct technology from the US to create their own version of the highest quality and latest technology node chips. When the US realized that their technology had been legally purchased by China to improve their military, the US knew that something had to be done to stop China from getting their hands on US IP (Intellectual Property). The US then instituted bans on China from purchasing different IP and chips from the US, which in turn hurt some US companies due to China being a huge market for US companies.

One of China's main problems with how the current industry is set up today is not that the semiconductor industry has reached a global scale, but more the fact that the industry has many choke points all lying with its adversaries. For example, the most advanced lithography equipment is made by ASML, a company based in the Netherlands. ASML sells lithography machines that cost upwards of millions of dollars. Without their machines, it is impossible to fabricate the most cutting-edge chips. This is due to how technology has progressed in the manufacturing of chips and lithography. There were a few lithography companies in the US, but they all went out of business. Back when the first transistors and integrated circuits were being made, everything was drawn out by hand and then made into a photomask in which light was shown through different lenses onto a piece of silicon. The light would react with different materials on the silicon, "etching" the design onto the chip. Following the trend of Moore's Law, transistor size needed to shrink compared to the size of the actual chip. There came a point where

visible light was no longer small enough to etch these patterns onto silicon. ASMLs solution was to create EUV machines which use Extreme Ultraviolet light to etch designs onto chips (*ASML EUV Lithography Systems*, n.d.). This decision to invest in EUV technology was, at the time, a huge gamble mainly funded by Intel. The top engineers at the time were not even sure if the technology was going to be able to be used.

Taiwan is also a point of contention for China. Taiwan was a part of the Chinese Empire during the 1700s and 1800s after being briefly colonized by the Dutch (Duzor & Graphics, 2022). Taiwan was also briefly ruled by Japan until Japan's defeat in World War 2. Modern Chinese history can be defined by the rise of the Chinese Communist party in 1920 after the Qing Dynasty fell due to the 1911 revolution. China's Civil war ended in 1949 when the People's Republic of China was established by Mao Zedong and the Communist party. The Nationalist Party and its leader, Chiang Kai-Shek, fled to Taiwan. Ever since then, Taiwan has been governing itself as a separate state from mainland China. China still sees Taiwan as apart of China and is willing to fight for Taiwan if Taiwan declares independence. As of 2021, most Taiwanese do not support immediate independence. Only 5.6% support independence as soon as possible, while 55.7% support the status quo (Duzor & Graphics, 2022). China's semiconductor industry efforts begin with Huawei, founded in 1987 (Miller, 2022).

Geopolitical tension has not to come to war just yet, as a war in the area would be extremely devastating (Miller, 2022). Though, war is not impossible. The US knows how reliant it is on Taiwan, specifically TSMC, for high end chips for its military systems and many other chips designed by the US. US chip makers like Intel has also begun to loose it's cutting edge advantage (Miller, 2022). Intel invested about $200 million into ASML's EUV technology, not knowing if it would be profitable yet. Though when the time came, Intel did not prioritize it's

processor manufacturing line, and it fell behind the leaders, TSMC and Samsung (Miller, 2022). For the US military to maintain its advantages over its adversaries, the US needs weapons systems that are more accurate.

Conclusion

Overall, the semiconductor industry is vastly complex as it has grown to a global scale over the past half century. Each component of the industry is important for the making of successful chips. From design to fabrication, the industry has created many standards to follow to ensure the different steps flow together seamlessly. The different companies that have grown to specialize in their craft, like ASML, TSMC, and others are critical choke points in the industry which have resulted in some geopolitical conflict especially between the current economic superpowers, the US and China. Investment from the government, venture capitalists, and shareholders is often critical for the birth of a company in this industry. Government regulations can greatly affect trade and profit, which in turn affects a company's priorities. With the case of ASML, now the only top lithography company, there were a few lithography companies in the US, but they all went out of business due to the inability to keep up with ASML technologically and earn a larger market share.

One of the main reasons that the US and Chinese government are so invested in the makeup of the semiconductor industry and how it is performing is that the government that holds the most accurate weapons and the latest technology weaponry has an advantage to those who do not. The playout of more accurate weapons can be seen when the first integrated circuits were used in self-guided bombs and how the newfound computing power increased accuracy tenfold. When the US cut off China from purchasing many of its technology, companies crumbled as

they were not able to continue production. Specifically, companies like Jinhua, one of China's most advanced DRAM manufacturers, went out of business after being cut off.

The US is though not currently at the top of the industry when in comes to manufacturing high end chips. The Biden administration in the summer of 2022 passed a bill dubbed "The Chip Act" that will provide funding for more fabs and more high quality fabs to be built here in the US. Also, for the US to recapitalize manufacturing, the technical knowledge must be behind it. Intel has plans to revitalize its manufacturing center by obtaining the latest ASML technology, building new foundries, close the technological node gap, and learn from TSMC (Miller, 2022). Samsung also has plans to build a new foundry in Texas with some of the Chip Act money.

The question now becomes, is it worth it to attempt to bring the US back up to speed on chip manufacturing? Or lithography techniques? The US government and top chip design firms believe it is time for the US to make a comeback in the realm of manufacturing. There can be many reasons for this. Profit might be one of them, but also national security is a huge part of the US's worries. Having high quality foundries would put more of the supply chain in the US, further enhancing the US's semiconductor industry. Overall, the US wants to maintain and reclaim its dominance in the semiconductor industry by rivaling China, Taiwan, Japan, and other nations to ensure the industry leaders are US companies in order to maintain geopolitical and economic power.

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