The COVID-19 Pandemic and Supply Chain Disruption: An Analysis of the Semiconductor Industry's Resilience

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Abstract: *The semiconductor industry plays a huge role in producing end-user products like electronics, autos, computers, and mobile phones by manufacturing companies across various sectors. The industry is growing tremendously year after year. According to the Semiconductor industry association, the global semiconductor industry saw a 26% increase in revenue with sales totaling $555.9 billion in 2021, this is the highest-ever annual total.In recent years, the semiconductor industry has suffered setbacks in producing enough semiconductors to meet the industry demand. This is due to the COVID-19 long shutdown, this anomaly had a significant impact on global businesses that led to the vast demand for more advanced chips from consumers in various sectors.The demand for consumer electronics and computer components increased exponentially due to the enforcement of people working remotely by employers during the COVID-19 era. During this time, businesses were stuck with billions of dollars in unsold goods, causing inventory-to-sales ratios to surge briefly before businesses liquidated these inventories. But, as the economy recovered and demand increased, businesses have not yet been able to bring inventories fully back to pre-pandemic levels, causing inventory-to-sales ratios to fall. Inadequacy in demand forecast by chip manufacturing companies has led to longer lead times due to a surge in demand for the chips. The average lead time between 2018 and late 2020 was 13 weeks but shortly after 2021, there was a spike in the average lead time. However, depending on the nature of the business, the lead time could be longer. Some of the major issues affecting production that we have identified include the insufficient capacity of semiconductor fabs, expense, and complexity of the semiconductor production process. The top two biggest semiconductor companies by market shares TSMC (54%) and Samsung (17%) were hit by disasters in 2021 that halted the production of chips. TSMC uses 60,000 tons of water a day in manufacturing semiconductors and the droughts in Taiwan's TSMC production rate. In February 2021, Samsung was forced to shut down its microprocessors IC plant in Austin Texas due to a heavy storm that rendered 200,000 homes without power.*

***Keywords**: Semiconductor industry, research & development, COVID-19,capacity utilization, Just-in-Time*

I. Introduction

This research study was conducted based on the analysis of the semiconductor industry. Asemiconductor is a material product usually comprised of silicon, which conducts electricity. Also known as semis, or chips, semiconductors can be found in thousands of products such as computers, smartphones, appliances, gaming hardware, and medical equipment. The use of conductors is widespread across industries and the companies that manufacture and test them are excellent indicators of the health of the overall economy. Success in the semiconductor industry depends on creating smaller, faster, and cheaper products. The benefit of being tiny is that more power can be placed on the same chip. The more transistors on a chip, the faster it can do its work. This creates fierce competition in the industry, and new technologies lower the cost of production per chip so that within a matter of months, the price of a new chip might fall 50%.Semiconductors are indispensable. They are the brain of modern electronics, banking, healthcare, military systems, transportation, and countless other applications. Anything electric has a semiconductor inside it. The importance of semiconductors is synchronous with the importance of electricity and modern gadgets in our lives. The U.S Semiconductor Industry invests about 1/5th of its revenue into R&D each year. $44 billion were invested in 2020. Such a substantial investment in R&D for an industry speaks volumes about the future of semiconductors.TSMC is one of the major market players in the industry. They own 54% of the global market share in the semiconductor industry. They are also the 6th most valuable company in the world. Samsung is second to TSMC with a 17% market share.

II. Problem Statement

One of the major problems confronting the semiconductor industry is the continuous increase in average lead time. In recent years, this was mainly due to the COVID-19-long shutdown. This anomaly had a significant impact on businesses globally that led to stronger demand for more advanced chips from the consumer electronics and computer industry.The average lead time between 2018 and late 2020 was 13 weeks but shortly after 2021, there was a spike in the average lead time as seen in Exhibit 1. However, depending on the nature of the business, the lead time has been getting longer since then.

Industry Business Model

The main business model being practiced by chip manufacturing companies in the semiconductor industry is the "foundry model". This is an engineering and manufacturing business model consisting of a semiconductor fabrication plant (foundry) and integrated circuit design operation.Companies that practice both design and manufacturing of integrated circuits are referred to as Integrated device manufacturers (IDMs), examples of IDMs are Intel and Samsung. There are some companies known as "fables semiconductor companies" such as AMD, Nvidia, and Qualcomm. These companies only design devices. Lastly, some companies do practice a "pure-play foundry business model", these companies only focus on manufacturing devices for other companies without designing them. Examples of pure-play foundries are TSMC and UMC.TSMC pioneered the pure-play foundry business model with an exclusive focus on manufacturing customers' products. Based on this founding principle, TSMC's foundry business model has enabled them to be the world's leading semiconductor foundry. In 2021, the Company manufactured 12,302 different products using 291 distinct technologies for 535 different customers. (TSMC 2021 financials)

III. Challenges

The Increased Demand from Consumers

The current chip shortage is due to strong demand and no supply. This stems from COVID-19 lockdowns in the second quarter (Q2) of 2020 when demand for work-from-home technology increased exponentially. As demand grew, automakers found themselves competing for the semiconductor capacity located in Asian foundries (Leswing 2021).As a result, semiconductor retailers shifted their focus to the production of PCs and mobile workstations to support workers who had to stay at home and enable remote healthcare. Companies in charge of producing those electronics increased their requests to suppliers for more semiconductor chips to meet their needs. Some plants were closed due to restrictions, and the production of some parts was halted. This surge in demand suffocated foundries and manufacturers (Pizzemento 2021).

Supply Limitations

- Heavy dependency on natural resources: Semiconductor manufacturing requires a lot of water. TSMC used 63,000 tons of water a day. In 2021, Taiwan experienced one of its worst droughts in more than half a century. That was one of the prominent reasons for the global shortage in recent years
- Unpreparedness for natural calamities: The South Korean electronics giant (Samsung) was forced to shut down its Austin plant — which produces microprocessors like radio frequency integrated circuits and solid-state drive controllers — back in February 2021, after a storm left some 200,000 Austin homes without power. The shutdown lasted a month in total, the longest Samsung has ever had to halt production at a factory (www.theverge.com)
- The complexity of the semiconductor production process: For a business that is already established in the manufacturing line, the typical lead time can exceed four months and could even be longer for a new business that has not been established in a manufacturing line.
- Insufficient capacity of semiconductor fabs.

IV. Analysis

Increase in Lead time

Our team focused on some of the major indicators to analyze the increase in lead time which also gave us information on the demand, shortage, and supply of semiconductors. The semiconductor industry limped into 2020 with only modest growth prospects. Morales noted that demand for semiconductors had surged in 2018 as enterprises and cloud services ramped up their hardware purchases. That created oversupply in 2019, which drove a 12% decline in the overall semiconductor market. Consequently, analysts expected year-of-year growth of about 2% (4). Analyzing the indicators,wetried to find the exact time when the lead time of the semiconductors started increasing exponentially. Wewere able to localize this exponential increase in lead time from January to April 2021. The data found on the internet showed that the four major subgroupings of semiconductors saw an increase of more than 175% in the lead time. (Fig..).On average, the lead time across all semiconductors increased by 75%. This increase in the lead time of semiconductors has hampered recovery from COVID-19 for many industries. One of the worst-hit industries is the automotive industry whichhas lostmore than $200 billion in 2021. (Exhibit 1).

Numerous factors played a role in straining the semiconductor ecosystem, all the way from foundry to backend OSAT capacity. Some of the most notable include:

- Increase in consumer purchases of digital devices during the COVID-19 shutdown to enhance connection and productivity
- Accelerated buildouts of data centers
- 5G handset and infrastructure investments
- Exponential demand for cyber currency mining hardware

These factors all drove increased overall demand for a wide range of semiconductors, from microprocessors and power management ICs to memory controllers and various logic ICs. In addition, factory disruptions and US-China trade tensions exacerbated an already tight supply situation. Semiconductor prices are also increasing, with the average sticker price for processors and other chips jumping 15% or more in a year. Most end-customers experience increases to 52 weeks.All Vishay diode lead times had stretched by an added 10 weeks and were over 40 weeks.Some Infineon MOSFET lead times were being quoted at more than 52 weeks, the company said. Lead times for polymer-tantalum capacitors had grown to 45 weeks for Kemet and 34 weeks for Panasonic.To avoid cutting production, manufacturers are now trying to increase chip inventories, which has further increased demand. In September 2021 alone, more than 100 billion chips were being produced. The industry has seen a growth of over 27% in the 3rd quarter of 2021. All these points can indicate that there was an increase in production and supply, however, if this was due to an increase in demand or shortage due to backorderis speculative.

Industry Dependence on East Asian Countries

The supply chain issues of this industry can, however, be narrowed down to a few reasons. One of which is the complete dependence on the manufacturing of chips inthe Asia Pacific.Most of the pre-production and manufacturing of these chips takes place in East Asian countries. Only 8% of global semiconductor production capacity lies in Europe. China is the leading producer of semiconductors in the world. China exports more than $300 billionin integrated Circuits and Semiconductors. South Korea ranks second in this with close to $150 billionin exports, closely followed by Singapore and Malaysia. However, when it comes to the consumption of these semiconductor chips, both USA and China sit at the top with 25% of consumption each.Though Taiwan and South Korea have significant manufacturing capacities, other East Asian countries play an important role in assemblies, testing, and packaging. (Exhibit 2)

The US leads in R&D-intensive activities, supported by its "talent magnet", and Asia leads in capital-intensive activities, supported by government incentives. While proximity to customers is a significant driver of the global, interdependent structure of the semiconductor supply chain, there are three additional key factors:

- Global R&D networks. International collaboration has allowed multinational companies, universities, and institutions to collaborate and pool resources. Together, they undertake pre-commercial research to pursue scientific breakthroughs that lead to major leaps in semiconductor technology.
- Geographic specialization. Regions are focused primarily on different activities within the semiconductor supply chain. This regional division of tasks has been driven by the comparative advantage developed over the last decades of the industry's history.
- Trade liberalization. Global trade policies enable participants in the semiconductor industry to move goods, equipment, capital, IP, and talent across borders, effectively supporting the geographic specialization across the semiconductor supply chain. (6)

This amount of globalization has left the supply chain of the semiconductor industry vulnerable to any form of an event that would interfere with its transportation and thereby putting the entire process on hold. COVID-19 was one major event that impacted the supply chain across all industries. However, there have been several such events that happened on a relatively small scale that have disrupted the semiconductor industry supply chain in the past. A few examples of such events are:

- In 2019, geopolitical tensions between Japan and South Korea rose sharply. Japan imposed export controls on semiconductor materials to Korea, impacting approximately $7 billion in semiconductor exports per month.
- In December 2020, a power outage affected a memory fab located in Taiwan for just one hour, impacting 10% of the global DRAM supply.
- Two fires at a package substrate plant in Taiwan in October 2020 and February 2021 aggravated the global capacity shortage for assembly, packaging, and testing services, which was already experiencing difficulties to meet the surge in semiconductor demand in the last few months of 2020.
- Widespread power failures following a polar vortex in Texas, and a fire in a Renesas fab in Japan in early 2021 further exacerbated the global chip supply shortage, especially for the automotive market.

COVID-19 has just highlighted an already existing problem of how the globalization of the semiconductor industry has left it in an extremely vulnerable situation. As you can see, this increase in the lead time of semiconductor chips due to the major disruption because of COVID-19 could be pointed toward the industry's dependence on East Asian companies.

Capacity Utilization

Since the COVID-19 pandemic, the global chip shortage has caused a huge blow to the economy, mainly in the form of capacity utilization being near-saturated. This project report will analyze the upstream and downstream of the semiconductor industry supply chain and the different statuses of new and old technologies from the trend of capacity utilization rate and expansion investment in research and development. First, the development of the modern semiconductor industry has shown two relatively mainstream and obvious supply and demand relationships. After understanding the semiconductor basic manufacturing materials distribution, three key points are obtained:

- Wafers smaller than 200mm.The old-generation mature chip supply chain dominated by 200mm (8 inches) wafers is mainly used in the automotive, medical, and aerospace chip markets where stability is the main requirement. Among them, TSMC is represented, accounting for 10% of the market share in this category.
- Wafers larger than 300mm. The new generation of advanced chip supply chain based on 300mm (12 inches) wafers, mainly used for computing chips, memory, high-tech, etc. require the latest process to achieve a better energy consumption ratio. Among them, Samsung and TSMC are occupying 21% and 15% of the market share respectively.
- The main difference between 300mm and 200mm wafers is that the waste rate of 300mm new generation wafers has dropped to 12.6%, compared to 18% of the old generation; In addition, the number of chips produced by a single wafer of 300mm is 305% higher than that of 200mm (Exhibit 1).

In summary, the new generation of 300mm wafers will have a huge leap in improving the capacity utilization rate of the semiconductor industry. The semiconductor industry is investing more capacity and investment in new-generation technologies.An analysis of the capacity utilization rate of the semiconductor industry in the past 20 years shows that the total production capacity of the industry has increased by 179%, which can reach an average capacity utilization rate of 88% (Exhibit 2), which is a normal level. Manufacturers usually expand their production capacity when capacity utilization reaches 80%. Next, we analyzed how the semiconductor supply chain deals with the shortage of different generation chips.

The study analyzed Samsungthe world's largest new-generation semiconductor manufacturer. Most of its products use new-generation technologies, which is the development trend in this industry. We found in Samsung's annual report: Samsung rapidly increased its chip production capacity from 711,023,000 per year to 123,287,000 per year between 2018 and 2020, a 73% increase in capacity in just three years (Exhibit 3). Although Samsung encountered a shortage of chips during the pandemic because the market demand for chips has increased rapidly, Samsung can continue to increase investment in new-generation semiconductor technology. The annual growth rate of Samsung's chip capacity has reached about 24%, which is much higher than the average 8% capacity growth rate of the semiconductor industry over the past 20 years. This growth can stabilize its capacity utilization at around 85%. The high growth rate of the new generation of technology allows its supply chain to be adjusted promptly and to increase capital investment without hesitation.

The automotive industry is reliant on the older generation. The annual growth rate of the 200mm supply chain I analyzed is only about 6%, which is a normal level, but far less than the 24% annual growth rate of the new generation. Differences in data do not represent a lag in older generation capacity. Due to decades of development, demand for products using older-generation technologies has stabilized. However, in recent years, the demand for chips in the automotive industry has fluctuated greatly. It suddenly increased by more than 17% between 2020 and 2021, the capacity utilization rate exceeded 100% and there was a shortage level (Exhibit 4). To find this, we analyzed the North American market's largest car manufacturer –Toyota, and read the financial report data from 2019 to 2021. Wefoundout that Toyota's North American sales in 2021 are reducedby 2% (Exhibit 5), but inventory costs increased by 13% (Exhibit 6).

It is well known that Toyota is the inventor and best practitioner of the JIT theory. The purpose of this theory is to minimize or even zero inventory. The theory can be applied to most industries, including the semiconductor manufacturing industry. In the past, due to the great success of the JIT theory in the automobile and chip manufacturing industries, the demand index for automobile chips was 6% before the market shortage from 2018 to 2020, but the capacity utilization rate of automobile chips was around 85%, maintaining the current growth rate, semiconductor manufacturers do not need to expand capacity to meet demand with higher capacity utilization. However, the shortage of chips made Toyota quickly make a strategy of increasing safety stocks based on risk management, which led to the disruption of the originally stable supply chain demand, and the demand and supply index of the automotive industry for chips rose sharply by 17%. Semiconductor makers appear unprepared to add more capacity to the semiconductor supply chain for older-generation technologies because more profits lie in new-generation chips (Exhibit 7). Semiconductor manufacturers are more willing to invest in a new generation of chips rather than an older generation if they have the budget and technology. TSMC is currently the largest manufacturer of old-generation technology semiconductors (Exhibit 8). I analyze TSMC's financial report data for the past three years and find that the manufacturer invests more in the research and development of new-generation chip technology (Exhibit 9).

Global Semiconductor Manufacturer Global R&D spending by semiconductor companies is expected to grow 5% year-on-year to a record $68.4 billion in 2020 and is expected to increase to $89.3 billion by 2025(Exhibit 10). The top 10 semiconductor companies in the world in terms of R&D spending increased their R&D spending by 11 percent to $43.5 billion, or 64 percent of the industry. Investment in R&D by semiconductor manufacturers continues to increase, but only for high-margin next-generation processes.To sum up, we have concluded that the capacity utilization rate of the old generation and the new generation is at a normal level, and maintaining the 6% growth rate of the old generation is a reasonable range for the semiconductor industry. In the financial report, we analyzed that the recent fluctuations in market demand are because most auto industry manufacturers have increased safety stocks based on supply chain risk management, increasing overall demand. However, from the analysis of the market sales volume of the automobile industry, this is an inflated increase. It is only the inventory strategy adjustment of the automobile industry supply chain, and the actual market segment has not increased. To avoid the bullwhip effect in the semiconductor industry, it is necessary to maintain a growth rate of 6% on the premise of meeting the current capacity utilization rate and promoting the transfer of the industry to a new generation. It is predicted that the future includes the automobile industry, which will need to move to next-generation semiconductor technologies, and the semiconductor industry should continue to increase R&D and investment in new-generation technologies.

Prioritization of Industries

Data suggested that a sudden surge in demandcaused top semiconductor companies to direct their supplies to “life-saving” industries such as HealthcareTechnology and Medical Technology.As per reports by MedTech Dive, “Medtech sounds alarmed on semiconductor shortages, and asks feds to prioritize chips for medical use.” Being a major supplier to tech giant Apple, TSMC took all measures to ensure that their manufacturing facility did not get contaminated, and due to contractual obligations, prioritized orders of Apple before it did other companies.This led to a severe supply shortage in some industries such as Automotive that rely heavily on chips. According to AlixPartners, the global chip shortage cost the automotive industry $210 billion in lost revenues.

Inventory Management in the face of COVID-19

The inventory levels of major semiconductor suppliers such as TSMC and Samsung increased significantly in the face of COVID-19.Quantitatively stating, the inventory value as gathered from annual financials for TSMC increased from T$85.79m to T$170.44m in a year after COVID-19, marking a rise of approximately 100%. Additionally, Stock Turn increased from 55 days to 85 days during the same period. From a logical point of view, an increase in demand and a resultant increase in backorders should lead to reduced inventory. In this case, an increase in inventory levels of the companyoccurs as the demand still outnumbered production in the company. The production capacity of semiconductor giants TSMC and Samsung could not handle a meteoric and sudden rise in the demand for chips. This led to lost sales for the companies and TSMC shares losing 8% in the year 2021.

Procurement of Raw Materials

The semiconductor materials industry faced a sudden surge in the demand for raw materials used for semiconductor manufacturing, leading to a shortage of supply in the industry.The materials that faced the most shortage were as follows: -

1. ABF (Ajinomoto Build-Up Film) and Glass Substrate used in computing parts manufacturing
2. PCB (Printed Circuit Board) Materialswhich are used heavily in the auto sector
3. 8-Inch Wafer Shortage used in Integrated Chips and 5G Network Deployment

Growth rates for materials Silicon Carbide and Gallium Nitride are also expected to rise as per McKinsey reports by more than 200% in 2026, due to increasing demand for semiconductors by industries [Exhibit 9]. This puts the Semiconductor materials industry under increased pressure to maintain a steady and improved supply chain due to both increasing demands and to account for unprecedented events such as floods or pandemics.

V. Recommendations

A foray of factors led to a supply chain disruption in the semiconductor industry in the face of COVID-19. Uncontrollable factors such as natural calamities, trade wars, and lockdowns in countries played a huge role but so did factors that the industry giants could have controlled. High knowledge and capital intensitiesof the industry have caused the industry to have high market entry barriers. Due to this, duringsupply shortages, it becomes difficult for a new company to enter the market and abate shortages. Semiconductor companies severely failed during the pandemic due to a localized supply chain of the industry where the procurement, manufacturing, and assembling are all dependent on Asia-Pacific countries. Moreover, before the pandemic hit, semiconductor companies adopted a Just-in-Time inventory system wherein they stocked up as orders came in. This way, they could not cope with the sudden change in demand. Unpreparedness in terms of expanding production and stocking inventory also led to supply chain failure for the industry. We have the followingrecommendations that make the industry better prepared for sudden demand surges and may make them more immune and less affected by unprecedented future events.

1. Geography:Chip manufacturing companies should build new production fabs in other areas outside of Asia
2. Inventory management: Rethinking the currently adopted Just-in-Time inventory model and stockpiling or adopting a hybrid model
3. Synchronized planning:Adopt collaborative planning across all players of the supply chain
4. Keeping a close eye on trends:Forward-thinking strategies to prioritize R&D investments for products with high forecasted demand
5. Postponement: Due diligence to exploring postponement strategies for better immunity towards changing market conditions and reducing lead times

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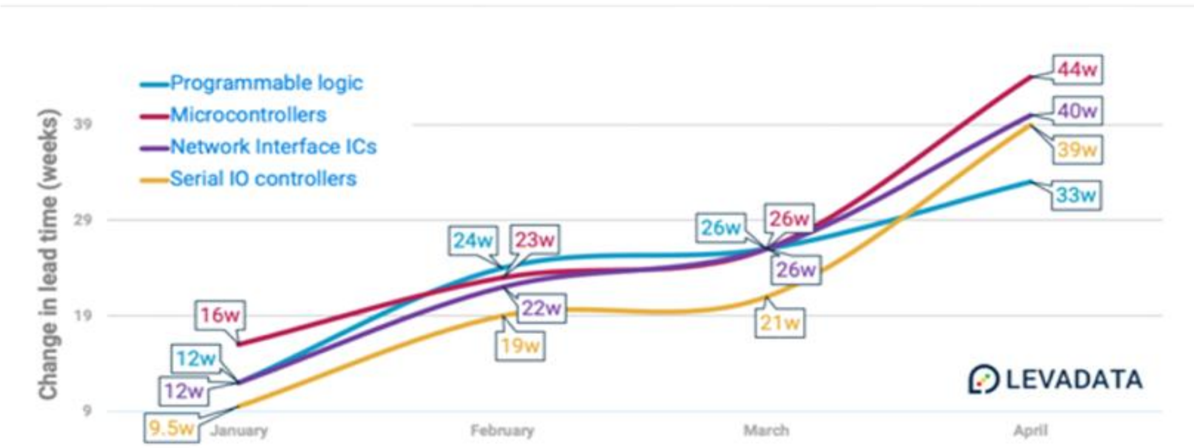

Exhibit 1

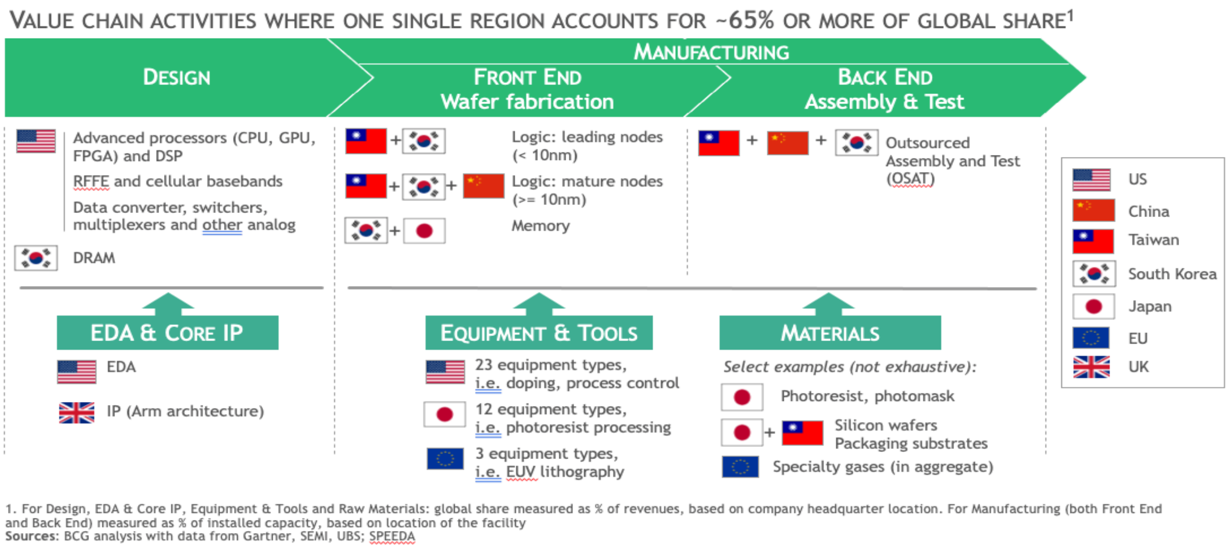

Exhibit 2

A. Production capacity, output, utilization rate

(Capacity)

(1,000 units)

Division	Item	Capacity 2020	Capacity 2019	Capacity 2018
CE	Image devices	51,538	51,418	60,699
IM	HHP	321,600	346,960	397,497
DS	Memory	1,230,287,000	988,104,000	711,023,000
	Display panel	7,274	8,236	9,167
Harman	Digital cockpit	9,362	7,921	5,238

Production capacity for major product categories on a consolidated basis.
CE data for 2019 and 2018 are restated to expand the range of products from TVs to image devices, including monitors.

Exhibit 3

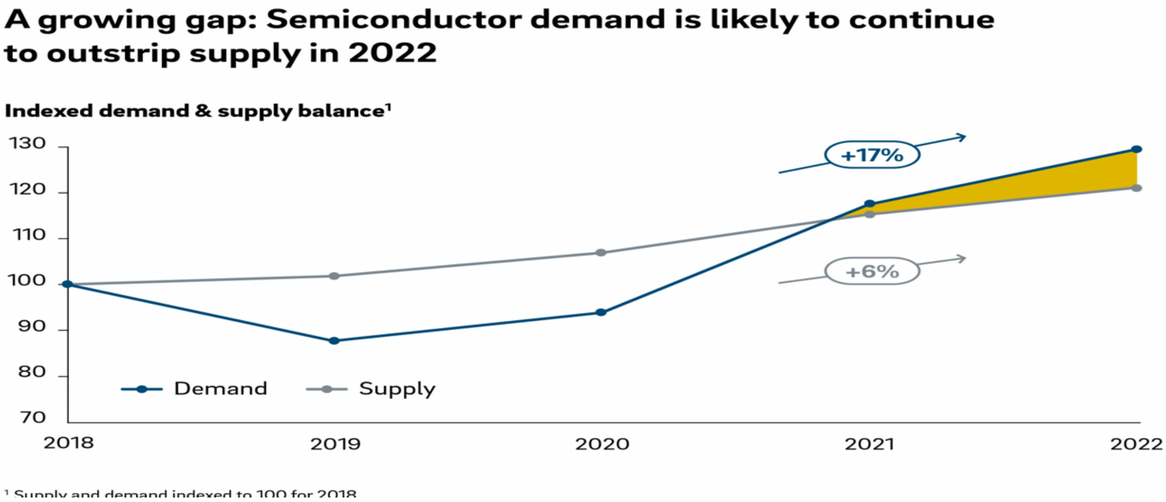

Exhibit 4

(2) Sales by product

Outside customer sales by product consist of the following.

(Millions of yen)

	FY2020 (April 1, 2019 - March 31, 2020)	FY2021 (April 1, 2020 - March 31, 2021)
Automobile	613,886	591,673
Vehicle	89,943	88,393
Engine	138,532	139,975
Car air-conditioning compressor	328,274	301,621
Electronics parts and others	57,135	61,683
Materials Handling Equipment	1,436,396	1,431,455
Textile Machinery	61,756	40,850
Others	59,316	54,322
Total	2,171,355	2,118,302

Exhibit 5

8. Inventories

Inventories consist of the following.

(Millions of yen)

	FY2020 (As of March 31, 2020)	FY2021 (As of March 31, 2021)
Merchandise and finished goods	120,232	139,481
Work in process	59,411	72,370
Raw materials and supplies	76,094	80,609
Total	255,738	292,461

Exhibit 6

6.2.4 Recent Years Major Capital Expenditures and Impact on Financial and Business

Unit: NT$ thousands

Plan	Actual or Planned Source of Capital	Total Amount for 2020 and 2019	Actual Use of Capital	
			2020	2019
Production Facilities, R&D and Production Equipment	Cash flow generated from operations and issuance of corporate bonds	952,577,255	496,152,977	456,424,278
Others	Cash flow generated from operations	15,083,617	11,085,745	3,997,872
Total		967,660,872	507,238,722	460,422,150

Based on capital expenditures listed above, TSMC's annual production capacity increased by approximately 0.7 million 12-inch equivalent wafers in 2020.

Plan	Actual or Planned Source of Capital	Total Amount for 2021 and 2020	Actual Use of Capital	
			2021	2020
Production Facilities, R&D and Production Equipment	Cash flow generated from operations and issuance of corporate bonds	1,327,249,575	831,096,598	496,152,977
Others	Cash flow generated from operations	19,184,855	8,099,110	11,085,745
Total		1,346,434,430	839,195,708	507,238,722

Based on capital expenditures listed above, TSMC's annual production capacity increased by approximately 0.9 million 12-inch equivalent wafers in 2021.

Exhibit 7

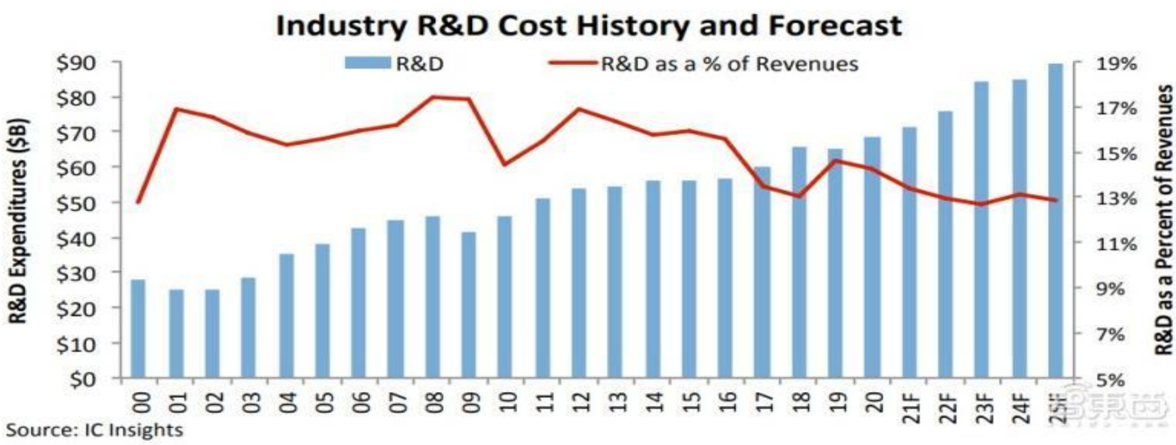

Exhibit 8

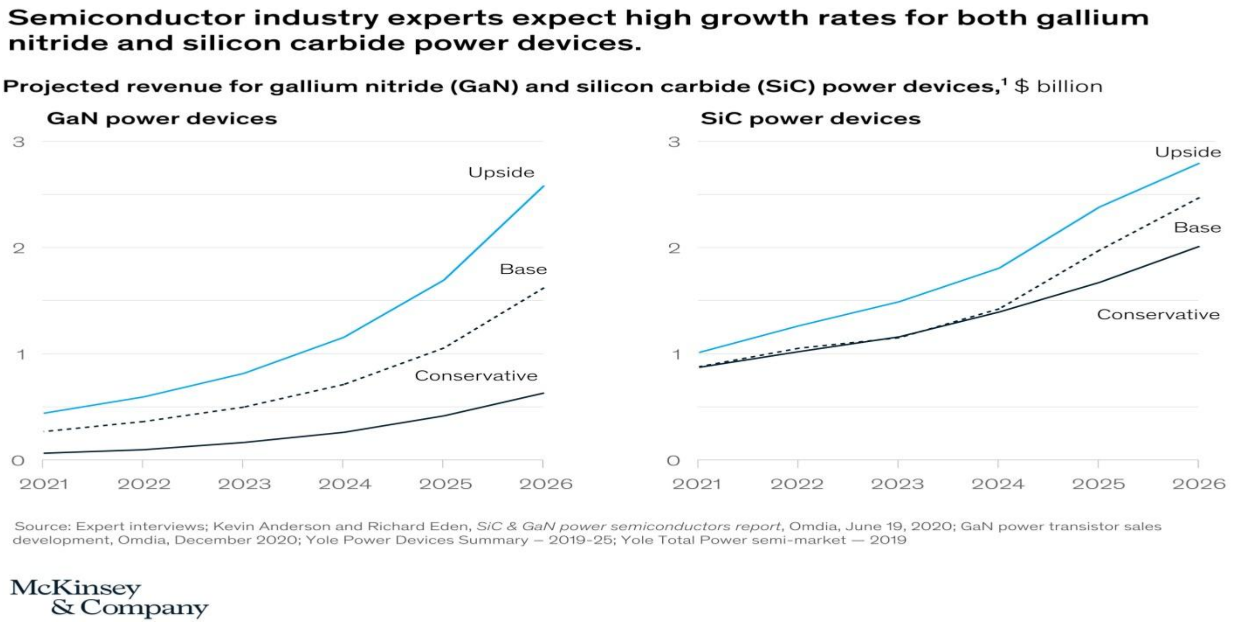

Exhibit 9

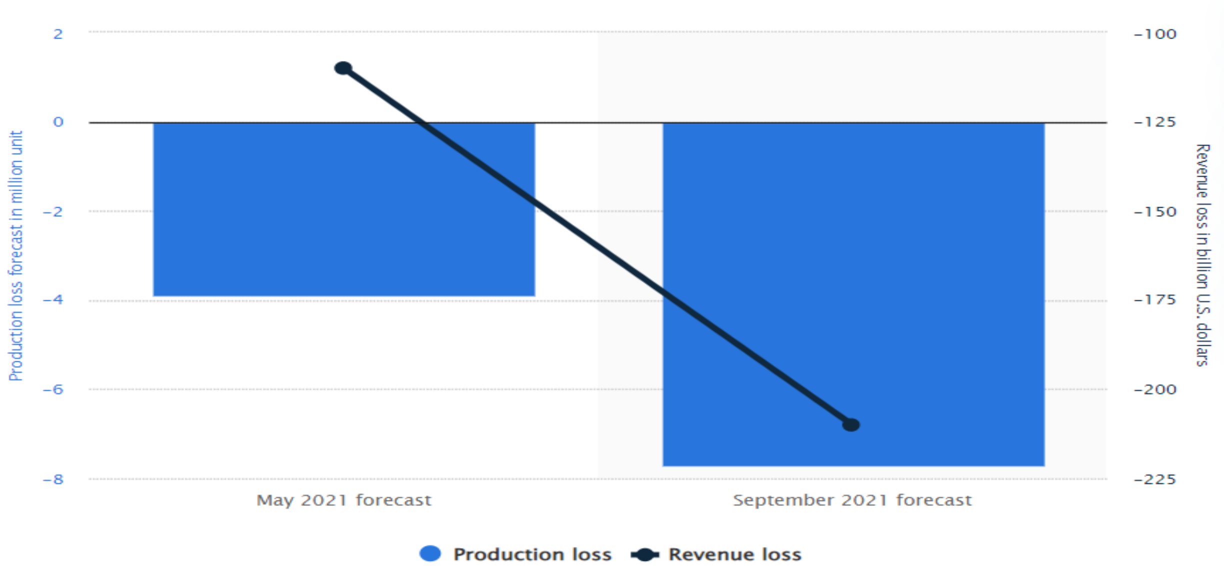

Exhibit 10

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