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Original Article

Semiconductor in Flux: Past Disruptions and Emerging Trends in Chip Industry

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Abstract *- Semiconductors or chips are the backbone of the digital economy, enabling advancements across industries such as consumer electronics, industrial automation, telecommunications, and healthcare. In 2024, global semiconductor sales exceeded $600 billion, and projecting growth beyond $1 trillion by 2030. This growth is driven by artificial intelligence (AI). Despite their ubiquity, semiconductor production involves intricate processes requiring advanced manufacturing techniques and globally distributed supply chains. The 2020–2023 chip shortage highlighted systemic vulnerabilities, underscoring the need for resilient supply chains and strategic investments in manufacturing capabilities. This review examines the semiconductor ecosystem, addressing its design, fabrication, packaging, and distribution stages while exploring emerging trends across the globe. By contextualizing these developments, this work emphasizes the pivotal role of semiconductors as critical technological and strategic assets shaping our today's world.*

Keywords *- Chip, Integrated circuit (IC), Chip shortage, Advanced Packaging, Semiconductor, CHIPS Act, Semiconductor Ecosystem.*

1. Introduction

Semiconductors are now considered the components of the digital economy in this era of technology advancement. These intricate and compact gadgets drive a range of devices such as mobile phones and computers to industrial automation tools and medical imaging machinery [1]. They also play a role in telecommunications infrastructure and cutting edge driver assistance systems found in contemporary vehicles. Serving as the intelligence behind gadgets semiconductors manage logic operations, memory storage, sensory functions and communication capabilities making them vital across various industries, in today's world. The worldwide semiconductor industry had its successful year ever in 2024 with sales surpassing $600 billion annually [2] for the first time. Several reports suggest a double digit market growth in 2025. Anticipate a rise above $1 trillion [3], by the end of the decade. This growth is attributed to the rapid expansion of artificial intelligence (AI) the Internet of Things (IoT) 5G networks electric vehicles (EVs) and edge computing technologies.

The paced advancements in technology have changed the direction of chip development towards specialized solutions that are high performing and energy efficient in nature. Semiconductor innovation is now seen as more than a supportive function; it has evolved into a competitive advantage, with significant national strategic implications. Although semiconductors are everywhere nowadays and essential in technologies and industries; their production process is intricate and delicate requiring advanced nanomanufacturing techniques and multi layered design processes. The global supply chain for these semiconductors involves companies scattered across Asia North America and Europe. Due, to the capital investment and specialized skills needed at every phase.

From designing to lithography to wafer fabrication packaging and testing ; the manufacturing centers are highly concentrated which streamlines efficiency but also raises significant systemic risks. The vulnerability of the system was exposed during the chip shortage from 2020 to 2023 caused by a mix of reasons such as supply chain disruptions due to the pandemic and trade limitations alongside natural calamities and increased demands, for electronic gadgets and cloud services. What started as a setback escalated into a significant global issue that stopped car manufacturing operations and postponed the release of smartphones while also affecting the distribution of essential medical devices.

1.1 What is a Chip?

A microchip (also known as a computer chip or an integrated circuit) consists of circuits placed on a small flat piece of silicon material. Figure 1 shows a simple type of chip where pinouts are dark circles around the IC. Within the chip are transistors that function as small scale electrical switches capable of controlling the flow of current [4]. The arrangement of these switches is crafted on the silicon wafer by altering materials to shape complex interconnected structures with multiple layers.

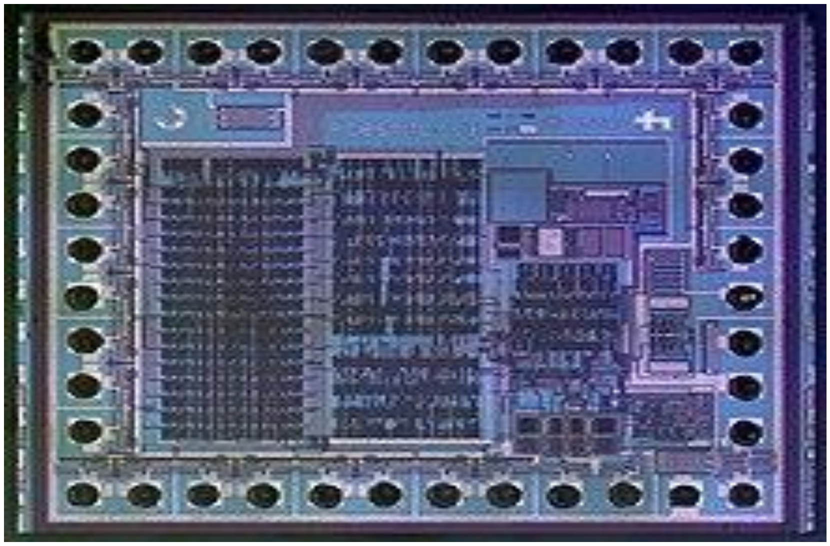

Figure 1. A microscope image of an IC die used to control LCDs [5]

Microchips can be categorized in two ways. Based either functional or the type of integrated circuitry they have inside them. They can. Be analog chips that process continuous signals with a range of values using traditional circuit elements, like resistors and capacitors or digital chips that deal with binary signals. When it comes to how they work there are four groups to consider ; Logic chips, Memory chips, application specific integrated chips (ASIC s) and system on a chip devices (SoCs). The top two types of chips. Chips and Memory chips. Are digital in nature ; they handle and save bits and bytes by utilizing transistors. ASIC s and SoCs mostly blend analog, with components.

The chip shortage went beyond a supply chain problem; it served as a wakeup call on a strategic level. It revealed how heavily the world relies on a small number of suppliers and shed light on the lack of backup capabilities in advanced manufacturing processes. Additionally it underscore the importance of being ready on fronts and having well trained workforces. In light of this situation nations have been rushing to implement programs to encourage production growth and ensure lasting access, to semiconductor technologies. This review aims to place these events in the larger context of the semiconductor industry's development with mainly three objectives. Firstly, delving into the root reasons, behind upheavals and the implications and vulnerabilities exposed by them particularly in the context of the worldwide chip scarcity. Secondly, exploring the network and worldwide connections, within the semiconductor industry involves studying everything from design and materials to production and packaging processes.

Lastly, In order to pinpoint the upcoming developments such as technological progressions (like chiplet design and AI chips) sustainability objectives and crucial policy changes (such as the CHIPS Act) that are influencing the trajectory of semiconductor industry, in the future. In the age marked by the rapid advancement of AI technology and the growing importance of digital independence and climate concerns; semiconductors have evolved from mere components to critical strategic resources with geopolitical significance. This piece provides a look ahead at an industry in transition where advancements in technology, alongside political dynamics and adaptability will shape the future course of global development.

2. Semiconductor Ecosystem

The semiconductor industry is a vast, intricate, and highly interdependent ecosystem. Unlike many industries that can function through vertical integration, the production of semiconductors is spread across a complex, globally distributed value chain. Each participant whether in design, manufacturing, equipment, or distribution, plays a critical role in transforming raw silicon into advanced integrated circuits that power today's technologies. This section unpacks the core stages of the ecosystem, key industry players, and the strategic implications of regional specialization

2.1 Core Stages

2.1.1 Chip Desing

Designing integrated circuits. Also known as semiconductor design or chip design. Is a part of electronics engineering that focuses on creating logic structures and circuit layouts for building integrated circuits (ICs). These ICs are made up of electronic components connected within an electrical network on a single semiconductor substrate usually made of silicon and are crafted onto a silicon wafer using the intricate process of photolithography which plays a crucial role in determining the functionality and performance of contemporary electronics. Designing integrated circuits can generally be categorized as either digital or analog in nature.

- ***Digital IC:*** This design primarily deals with logic driven structures like microprocessors and FPGAs well as memory components such as RAM and ROM or flash memory and digital Application Specific Integrated Circuits (ASIC). In these designs logical accuracy holds significance along, with circuitry and meticulous timing regulation.
- ***Analog IC:*** Analog design involves developing power management chips and radio frequency (RF) circuits along with analog signal processing parts like operational amplifiers (op amps) phase locked loops (PLLs) oscillators and regulators. Designers of analog circuits must take into account properties such as gain, resistance and power consumption – aspects which can be disregarded in circuit design. Additionally analog circuits typically require space within the die and are less densely packed due, to their susceptibility to noise and variations.

In the few years alone the intricacy of design has significantly increase with developments for small nodes which also increases design cost. As we approach towards node size < 10 nm the cost goes exponentially high as seen in the Fig. 2. Chip Design Cost in $ million [6]

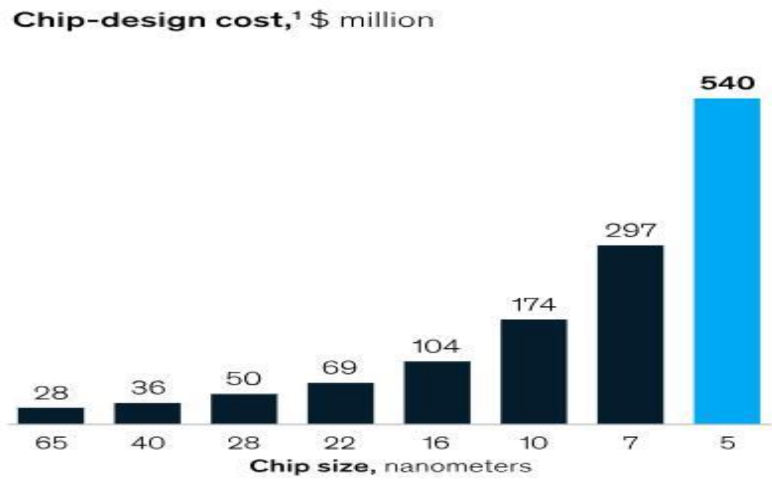

Figure 2. Semiconduct Ecosystem [7]

A contemporary processor may house billions of transistors. Follow thousands of fabrication guidelines. Many of which are statistical in nature rather than strictly deterministic. These intricate details highlight the role of Electronic Design Automation (EDA) tools. Engineers rely heavily upon EDA software to execute logic synthesis tasks like place and route operations timing assessments and design rule validations. In essence this software bridges the gap, between a high level design and the practical creation of silicon products. Artificial intelligence is currently being incorporated into EDA processes to automate the creation of layouts and enhance chip floor planning efficiency in areas such as cells and macro blocks design optimization strategies. These AI assisted design approaches are attracting interest, for speeding up product launches in intensifying settings.

2.1.2 Fabrication (Fab/Foundry)

Creating goods especially in the field of semiconductor foundries. After a chip has been designed and confirmed to be accurate, in its specifications and functionality it moves on to the manufacturing phase where the design is replicated onto silicon wafers through a sequence of processes conducted in cleanroom environments. These processes involve photolithography etching, ion implantation, chemical vapor deposition and metallization. A few companies have the expertise to produce chips using cutting edge technology like 5nm and below nodes. TSMC from Taiwan and Samsung Foundry from South Korea are among the players in this field along with Intel Foundry Services from the USA who are heavily investing in advanced equipment, like extreme ultraviolet (EUV) and innovative process technologies.

Fig. 3 gives a high level view of semiconductor ecosystem with each sector highlighting major players. Establishments like these not facilitate the manufacturing of chips for companies without fabrication facilities but are also crucial for staying ahead in the competitive global tech landscape. Building a fabrication facility nowadays requires investment and time; according to a report from BCG (Boston Consulting Group) a fab scheduled for completion in 2026 would entail a total cost of ownership (TCO) ranging from $35 billion to $43 billion, over a ten year period marking an increase of 33% 66% compared to current expenses [8]

2.1.3 Packing and Testing

After the manufacturing process is completed wafers are cut into chips which undergo tests to ensure they work properly and perform well. Following that the chips are enclosed in casings that help with temperature control and electrical connections. In cases this step is delegated to external companies known as OSAT (Outsourced Semiconductor Assembly and Test) like ASE Group and Amkor Technology as well as JCET. The testing process involves assessments such as parametric tests and burn in tests alongside final system level evaluations.

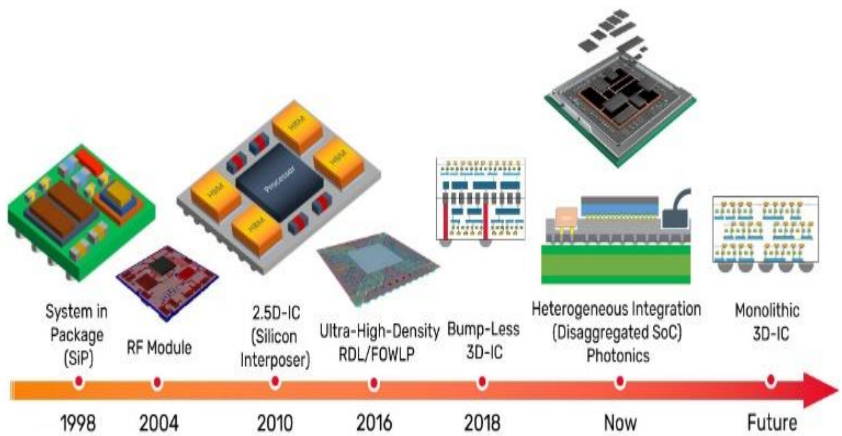

Figure 3. Evolution of packing [9]

Additionally packaging methods have progressed as shown in Fig. 3 from wire bonding to new technologies like 3D stacking, flip chip assembly and fan out wafer level packaging (FOWLP) and various other packaging style.

2.1.4 Equipment and Materials

Enabling Precision requires a network of equipment manufacturers and materials suppliers to support each stage mentioned above. Tools used for photolithography (such as ASML) etching and deposition (like Applied Materials and Lam Research) and metrology (such as KLA Corporation) are essential in the semiconductor industry. These machines come at a cost; for example ASML's latest chip machine has the capability to imprint semiconductors with lines as thin as 8 nanometers which is 1.7 times smaller than previous generations [10]. This represents an advancement over the previous generation. Each of these cutting edge machines is priced at 350 million euros (to US $378 million approximately) with a weight comparable, to two Airbus A320 aircraft.

The supplies needed include top quality silicon wafers from leading manufacturers like Shin Etsiu and Sumco and specific materials such as photoresists and dielectrics obtained from companies, like Entegris. In the realm of chip manufacturing precision is crucial as the components are frequently tinier than a virus necessitating atomic level management; consequently making it one of the most sophisticated sectors, in the worldwide production domain.

2.1.5 Distribution and Integration:

After packaging, chips are distributed to original equipment manufacturers (OEM's) and Tier-1 suppliers, who integrate them into final products. Following are some examples of the end users:

- Consumer electronics (e.g., Apple, Samsung),
- Automotive systems (e.g., Bosch, Continental),
- Networking and telecom (e.g., Cisco, Ericsson),
- Cloud computing and data centers (e.g., Meta, AWS, Google Cloud).

This final stage completes the transformation of raw silicon into advanced systems that support global communication, computing, healthcare, and automation.

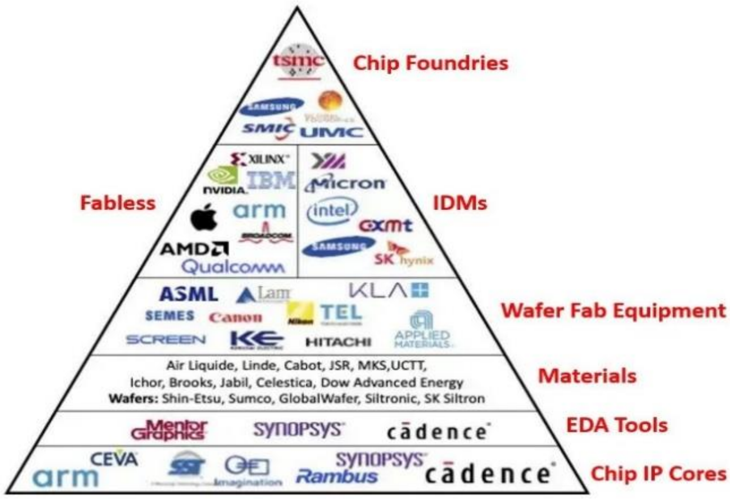

Figure 4. Original equipment manufacturers (OEM's)

2.2 Mapping the Value Chain

The interconnected nature of the world. The focus, on specialized regions. The semiconductor sector showcases a level of globalization in its advanced state of operation. It thrives on a network of interconnected suppliers spread across various locations with unique expertise. This worldwide reliance has facilitated advancements and cost efficiencies by tapping into top notch technologies worldwide. Nevertheless it has also brought about vulnerability by making the industry susceptible, to disruptions related to politics, the environment and logistics.

No one country possesses all the expertise needed to create and produce semiconductor products entirely on its own; it takes a collaborative effort involving multiple countries in various stages of the process. For instance a top notch processor may be conceptualized in the United States constructed with machinery from the Netherlands and materials from Japan manufactured in Taiwan packaged in Malaysia and finally put together into a product, in either China or Mexico as shown in table 1 below.

Table 1. Regional Expertise

Region	Specialization
United States	Chip design, EDA tools, equipment manufacturing, R&D
Taiwan	Advanced-node foundry manufacturing (TSMC) with sub 5nm node
South Korea	Memory chips, logic manufacturing (Samsung, SK Hynix)
Japan	Materials, specialty chemicals, precision equipment
Europe	Lithography equipment (ASML), automotive chips
China	Packaging, mature-node manufacturing, consumer electronics

The advantages of this distributed system are evident in the ability to tap into talent worldwide and access skills while also saving costs; however this interconnectedness leaves the entire system susceptible to disruptions at any point. For example the backend OSAT facilities in Malaysia and the Philippines faced shutdown during the COVID 19 pandemic resultant in bottlenecks in chip deliveries. Additionally the 2021 drought in Taiwan and the severe winter storm in Texas led to the closure of fabs whereas the conflict, between Russia and Ukraine interfered with the supply of crucial neon gas required for lithography processes. In every situation where there are delays at one point, in the process it has a ripple effect that impacts the entire worldwide supply network.

Lately semiconductors have become more than a technology tool. They now play a crucial role in national strategic importance. The trade tensions between the United States and China the restrictions placed on companies the limitations on EUV technology exports and the government subsidies all underline how vital the semiconductor industry is for economic security and technological advancement. This shift has given rise, to the concept of " sovereignty". Highlighting the necessity for countries to safeguard key elements of the semiconductor supply chain to maintain their geopolitical and economic positions.

Authorities worldwide have taken action, in response.

- The U.S.s CHIPS and Science Act provides than $52 billion, in subsidies and tax benefits to support local manufacturing and research efforts.
- The Chips act of the European Union sets a goal to increase its semiconductor market share to 20% doubling it by 2030 with an investment of €43 billion.
- China is investing funds in domestic EDA tools development as part of their Five Year Plans and National IC Fund initiatives to enhance capabilities, in lithography technology and memory and logic chip production.
- India well as Vietnam and Singapore are becoming popular choices, for carrying out assembly work and testing processes or even manufacturing tasks nowadays.

As competition becomes fiercer in the semiconductor industry landscape is shifting from a focus on efficiency to an emphasis, on resilience and redundancy. Supply chains of the future are expected to embody these qualities:

- Fabs and OSAT facilities are spread across locations such as Arizona and Texas in the United States as well as Dresden, in Germany and India.
- Storing resources strategically such as neon and gallium along, with rare earth elements.
- Collaborative efforts, among allied countries, known as "friendshoring," to ensure the security of semiconductor infrastructure.
- Allocating resources towards tools for managing the supply chain effectively while enhancing traceability and utilizing predictive models to assess potential risks, in advance.

Overall the worldwide reach of the semiconductor industry presents both its advantage and its significant vulnerability. Though international connectivity has driven advancements it also requires a heightened focus on strategic planning, collaboration and anticipation, in a time marked by political instability and swift technological evolution.

One notable aspect of the semiconductor industry is the teamwork, among different companies and fields as exemplified by following: Smartphone chips are often created in California before being manufactured with EUV machines from the Netherlands and then produced in Taiwan and packaged in Malaysia for final assembly taking place in China. Cloud service providers collaborate closely with semiconductor manufacturers to develop accelerators, for artificial intelligence and data analysis purposes. Car manufacturers are currently collaborating with semiconductor companies to jointly develop chips that prioritize safety and energy efficiency. The blending of hardware and software fields with systems engineering has led to a fusion of boundaries. This collaboration within ecosystems now plays a role, in driving technological advancements.

3. Chip Shortage: Cause And Impact

From 2020 to 2023 the worldwide semiconductor industry faced a supply chain disruption that was one of the worst in its history. A temporary slowdown in production turned into a shortage of chips highlighting how delicate the semiconductor ecosystem truly is. This scarcity caused disruptions, across industries including automotive sector consumer electronics telecommunications and healthcare. It also acted as a reminder for governments and semiconductor companies to reassess their supply chain strategies and potential risks.

3.1 Causes

The chip shortage had reasons behind it that created a complex situation referred to as a "perfect storm" of disruptions, by analysts. These reasons can be categorized into three groups:

3.1.1 Pandemic Disruption

During the start of the COVID 19 pandemic several sectors scaled back orders for chips in preparation for a slowdown. Automotive firms specifically cut down on their orders as a way to handle their cash flow issues. However the shift towards work and education unexpectedly led to a surge in the demand, for laptops, smartphones, data center chips and networking devices. With semiconductor production facilities operating at full capacity they struggled to quickly increase production due to strict health measures and shortage of workers. The visual representation demonstrates(Fig. 5) a situation where demand greatly exceeded supply from 2020 to 2022 and emphasized the peak of the worldwide chip scarcity at approximately 60 million units in 2022 [11, 12 & 13]. Although the supply situation started to improve by 2023,the crisis revealed weaknesses, in the semiconductor industry and spurred initiatives to enhance local production capabilities.

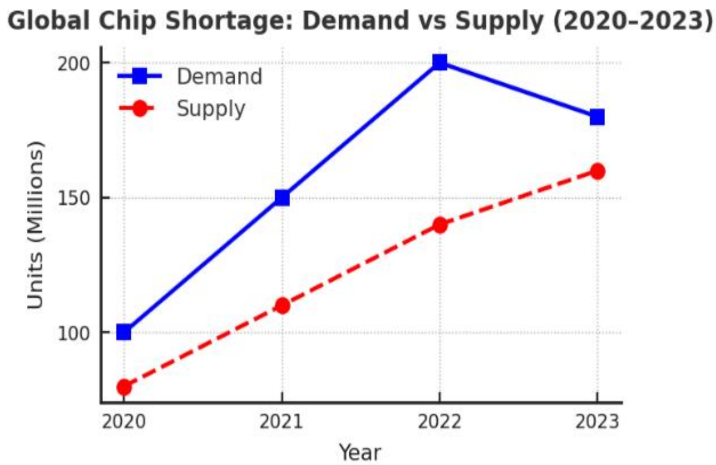

Figure 5. Chip Shortages Compiled Data [11,12 &13]

3.1.2 Geopolitical Trades

The escalation of tensions between the United States and China in the technology sector has had an impact on the worldwide flow of semiconductors. Export restrictions imposed by the U.S on Chinese tech companies such as Huawei and SMIC triggered a wave of panic purchases and stockpiling activities. In response to these actions from the U.S. China has increased its demand for semiconductors and altered its sourcing strategies. Simultaneously in 2019 trade disputes between Japan and South Korea affected the supply of high purity chemicals necessary, for chip manufacturing. These trade tensions have extended lead times globally. Added to the unpredictability surrounding supply chain management.

3.1.3 Environment

The crisis worsened due to weather conditions impacting Taiwan's chip manufacturing hub in 2021 with a significant drought jeopardizing water dependent fabrication processes [source 1]. In Texas during the same period power outages from a winter storm halted production at Samsung, NXP and Infineon fabs [source 2]. These incidents highlighted the ramifications of local environmental disruptions in areas, with concentrated manufacturing facilities.

3.2 Impact

The lack of semiconductors caused delays in industries and unveiled their individual reliance, on this technology.

3.2.1 Automotive Industry

The automotive industry suffered the significant impact during the pandemic as car manufacturers shifted their focus away from chips early on and faced delays when demand suddenly rose high up on their priority list. This caused disruptions in production lines resulting in factory closures and a decrease of 11 million vehicles worldwide in 2021 due to semiconductor shortages. Key technologies, like driver assistance systems (ADAS) infotainment units and electric vehicle control modules were hit hard by these constraints leading to an estimated global revenue loss of $210 billion.

3.2.2 Home Electronics

Smartphone and computer manufacturers experienced setbacks particularly with advanced processors and memory components in short supply. Gaming consoles such as the PlayStation 5 and Xbox Series X were consistently unavailable for months due, to demand. The scarcity not postponed the release of products but also led to increased expenses putting pressure on profit margins and restricting availability during crucial retail periods.

3.2.3 Medical Equipment

The healthcare industry faced delays in receiving tools and imaging equipment along with ventilators and patient monitoring systems due to the prioritization of high margin advanced logic chips over mature node microcontrollers and analog chips by foundries. The discrepancy between the demand for these devices and the focus on profitability highlights the difficulties of aligning business goals, with public health needs.

3.3 Lessons

The worldwide chip scarcity taught us a crucial lesson, on the significance of understanding our supply chains better and diversifying risks while also planning strategically for the future.

Key points to remember from this experience are:

- Supply chain resilience is absolutely crucial now in the industry – we can't just depend anymore solely rely only on just in time logistics and single source suppliers are no longer enough. It's crucial to have strategies such as using sources, for supplies creating redundancy in different regions and enhancing inventory planning. These aspects are now seen as vital components.
- The importance of nodes is significant; the scarcity issue mainly arose not from cutting edge nodes like 3nm to 7nm but from established nodes such as 28nm and 65nm used in automotive and industrial chips. Foundries are currently enhancing capacity, for nodes to cater to a wider range of demands.
- Semiconductors play a role in our infrastructure as the current situation has shifted their importance from just being a commercial product to a key element in national security and economic stability with policymakers emphasizing the need for semiconductor independence, as a cornerstone of technological self-reliability [14]
- The need for a revamp in demand forecasting is evident due to the gap between customer demand signals and production forecasts in the semiconductor industry, which has led to discrepancies, in supply and demand alignment. Both original equipment manufacturers (OEM) and semiconductor foundries are now emphasizing the adoption of advanced demand sensing technologies and integrated planning tools to address this challenge.

4. Emerging Trends

The semiconductor industry is not merely recovering from past disruptions, it is being reshaped by them. Driven by demand from AI, IoT, electric vehicles, and data centers, chipmakers are investing in next-generation technologies while also navigating a complex global landscape. This section outlines the major trends likely to define the future of the semiconductor sector.

4.1 Technological Advancements

4.1.1 Sub 5 nm Node Manufacturing and Beyond

Leading-edge semiconductors have shrunk to sub 5 nm nodes, with 3nm processes now entering mass production. These ultra-small geometries enable more transistors per chip, boosting performance and power efficiency. TSMC began 3nm commercial production in late 2022, and Intel aims to reach 1.8 nm by 2025 under its "Intel 18A" roadmap [15] However, these advancements come at a steep cost financial, technical, and environmental. EUV (Extreme Ultraviolet) lithography is essential for producing these nodes, with ASML's systems costing can range from $200 - 380 million per machine.

Figure 6. Intel Lunar Lake

4.1.2 Chiplet and Heterogeneous Architectures

Instead of designing a monolithic chip, manufacturers are increasingly adopting chiplet architectures, where smaller chips (chiplets) are combined into a single package. AMD's Ryzen CPUs and Apple's M-series SoCs exemplify this trend. It allows for modular design, better yield management, and faster time-to-market [16]. For example, Intel's Lunar lake[17] is built with advanced packaging as shown in Fig. 6.

4.1.3 AI-Specific and Domain-Specific Chips

The growth of artificial intelligence has led to domain-specific architectures. Companies like NVIDIA (with GPUs), Google (TPUs), and startups like Graphcore are designing chips optimized for machine learning workloads. These chips prioritize parallelism, memory bandwidth, and low-latency data paths [18]

4.1.4 Edge Computing and IoT

There is a growing need for low-power, high-performance chips that enable real-time processing at the edge on smart sensors, wearables, and industrial devices. This has led to increased focus on edge AI chips and energy-efficient microcontrollers, often manufactured using mature nodes (e.g., 28nm, 65nm)

4.2 Geopolitical Implications

4.2.1 Impact of U.S.–China Trade Policies

Export controls imposed by the United States such as restrictions on selling advanced chips and equipment to China are fundamentally reshaping global semiconductor trade. In October 2022, the U.S. expanded its restrictions to include AI processors and chipmaking tools. China has responded by doubling down on its indigenous chipmaking capabilities under initiatives like the Made in China 2025 strategy. Despite progress in memory and mature-node fabrication, it still relies heavily on foreign lithography and EDA tools.

4.2.2 Regional Diversification Efforts

The U.S. CHIPS and Science Act [19], signed into law in 2022, allocates over $52 billion in subsidies to boost domestic chip manufacturing. Intel and TSMC are building new fabs in Arizona and Ohio. Similarly, the EU Chips Act seeks to double Europe's global chip production share to 20% by 2030 [20] These policy moves signal a shift away from hyper-globalization toward techno-sovereignty a bid by nations to secure supply chains amid rising geopolitical tensions.

4.3 Sustainability Goals

Semiconductor manufacturing is resource-intensive. A single fab can consume millions of gallons of ultrapure water per day, and chipmaking is responsible for significant carbon emissions from energy-intensive cleanroom operations. Companies are now investing in closed-loop water recycling, clean energy adoption, and low-emission materials to meet environmental targets. Intel and TSMC have both pledged net-zero goals by 2040–2050 [21 & 22]. As data centers grow in size and energy consumption, chipmakers are designing energy-efficient processors. Innovations like ARM-based chips, near-threshold voltage design, and neuromorphic computing are gaining traction to reduce power usage at scale.

5. Conclusion

The semiconductor sector is currently undergoing a shift where advances in technology intersect with global challenges of a geopolitical nature. As semiconductors continue to pave the way for progress in intelligence (AI), Internet of Things (IoT) electric vehicles (EVs) and other fields the complexities of their production remain interconnected worldwide. The chip scarcity from 2020 to 2023 highlighted key weaknesses in supply chains and manufacturing procedures stressing the importance of diversification and resilience in the industry. In response to these challenges governments are acting through initiatives such as the CHIPS Act to strengthen production capacities and ensure reliable access to semiconductor technologies. New developments like chiplet designs and AI supported design methods along with manufacturing techniques are set to change the way industries operate in the future. To make these advancements a reality collaboration across regions, policy interventions, talent development are crucial. In today's world where semiconductors have transformed from parts to essential resources with global significance, their path will have a major impact on technological progress and economic stability worldwide.

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