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***Abstract*—**In this work we evaluate the state of the semiconductor manufacturing industry and its challenges and trends. Future trends in the industry are analyzed from three perspectives: the evolution of Industry 4.0, the advances in semiconductor materials, and the impact of the Covid-19 Pandemic. The semiconductor manufacturing industry witnessed an acute decline in the United States and other regions in the two decades prior to the CoVid-19 pandemic. The decline was only uncovered after the chip shortage of 2021 that resulted from the severe supply chain disruption. Trends in the industry were analyzed from three perspectives: Industry 4.0, advances in materials, and the Post-pandemic era. As a result of the evolution of the fourth generation of industry (Industry 4.0), trends in semiconductor manufacturing include robotization, which caused the industry to become the largest market for industrial robotics since 2020, and an all-time peak globalization. The semiconductor industry is a very globalized industry with corporates from different parts of the world taking part in the production of the final product. Although some materials such as carbon and Gallium Nitride show promising trends to replace silicon as the material of choice. It will likely not be before two or three decades when a semiconductor material will be able to replace silicon. Challenges for the industry include the shortage of the trained-workforce, and the added inter-country restrictions that may hinder the globalization of the industry.

Keywords*—*Semiconductor industry, Manufacturing, Industry 4.0, semiconductors

I. Introduction

The chip shortage of 202 has put under the spotlight the semiconductor manufacturing industry again, which by that time has mostly relocated outside the United States. The U.S. accounted for 37% of the world production of semiconductors in the early 1990's and has steadily dropped to only 12 % in 2022 [1]. The migration of semiconductor manufacturing was very aggressive that the last time a major semiconductor fabrication plant opened in the U.S. before the chip shortage took place was over 20 years before that, and the industry was well-overshadowed by the mid 2010's.

Semiconductor production includes three major steps: Design, Manufacturing, and Assembly, Testing, and Packaging (ATP) [2]. The first two steps constitute the front-end of semiconductor production, in which photolithography and other processes are used to create electrical circuits on silicon wafers. The ATP stage constitutes the back-end processes, in which the electrical chips are cut, wired, and tested [3]. Of these three stages, the design and manufacturing stages require the most advanced technologies and highest levels of complexity, while the ATP stage requires a high level of manual labor. The complexity of the supply chain for the semiconductor industry is very sophisticated that to produce a computer chip, more than a thousand steps are needed during which international boundaries can be crossed over 70 times [2].

While the semiconductor industry grew exponentially over the last three decades (from an equivalent of $73 Billion in 1987 to over $481 Billion in 2018 using 2018 dollars) [4], in the U.S. the industry experienced the sharpest decline of all manufacturing industries (from 37 % to only 12 % of world production) compared to a drop from 30 % to 17 % of value-added manufacturing during the same period).

As a result of the migration of semiconductor manufacturing outside the U.S., the United States was the hardest hit country by the global chip shortage of 2021, exposing a severe shortage on all levels, and sounding loud alarms over national U.S. security as evidenced in Table 1.

TABLE I. PERCENTAGE OF WORLD PRODUCTION AND DEMAND BY COUNTRY IN 2021 [5].

Country/ Region	Percent of World Supply	Percent of World Demand	Net (+ / -)
United States	14 %	34 %	-20 % (High shortage)
China	21 %	29 %	- 8 % (Moderate shortage)
Europe/ Mideast/Africa	12 %	16 %	- 4 % (Moderate shortage)
Korea	7 %	10 %	- 3 % (Moderate shortage
Japan	16 %	8 %	+ 8 % No shortage
Taiwan	22 %	1 %	+21 % No shortage

The decline in semiconductor manufacturing was observed years ago; although there was a decline in the general manufacturing spectrum in the U.S. the semiconductor industry experienced the sharpest decline of all manufacturing industries. Furthermore, although the U.S. share in strategic industries like the aerospace industry is high (see table 2), that industry relies heavily on the semiconductor industry. Table 3. Lists the percentage share of the United States of value added manufacturing in five strategic industries.

TABLE II. U.S. SHARE OF THE WORLD'S VALUE-ADDED MANUFACTURING IN DIFFERENT STRATEGIC INDUSTRIES, 2019 DATA [6].

Industry	U.S. share of the world
Aerospace	49 %
Medical Equipment	25 %
Pharmaceuticals	23 %
Petrochemicals	19 %
Semiconductors	12 %

The importance of revitalizing the semiconductor industry was pointed out in the 2018 National Defense Strategy which included the priority areas of electronics, 5G, quantum science, Artificial Intelligence, Cybersecurity, and advanced imaging [6].

II. CHALLENGES FACING THE INDUSTRY

Despite the significant efforts made to counter the chip shortages over the last year, such as the $280 Billion Chips and Science Act of 2022, another crisis is looming in the horizon, the shortage of workforce.

In addition to the shortage of a steadily available skilled workforce pool, another major reason for the migration of the semiconductor industry was to be at proximity to the backend of the chip industry: the Assembly, Testing, and Packaging (ATP) industry. Almost 90% of the world ATP industry is located in four countries (China, Taiwan, Japan, and Korea) [7]. This estimate is in agreement with a study by the Center for Security and Emerging Technology which found that the U.S. share of ATP tools is about 23 %.

Without a proper local ATP industry, that includes both a trained workforce and proper infrastructure, any efforts to revitalize the semiconductor manufacturing industry will be short-lived, as manufacturers will again need to ship products overseas to be assembled and processed.

The ATP infrastructure in the United States can be assessed as under-developed, with both North and South Americas together accounting for only 13% (65 facilities in total) of the 500 assembly and test facilities in the world [7].

TABLE III. STATUS OF THE SEMICONDUCTOR FABRICATION INDUSTRY IN THE U.S. BY STATE [8]:

Top five states in 2022	Number of Semiconductor establishments	Semiconductor exports
California	643	$ 11.2 billion
Texas	211	$ 19.3 billion
Florida	110	$ 2.6 billion
Arizona	93	$ 4.2 billion
Oregon	79	$ 13.2 billion
New York	72	$ 2.0 billion

III. Trends in the Semiconductor Industry

In this section, the trends in the industry will be considered from three perspectives:

- The impact of the advancements of the fourth generation of the manufacturing industry known as "Industry 4.0".
- Advances in material replacements for silicon
- The long-term impact of the Covid-19 pandemic on the industry.

A. The Semiconductor Industry in the age of Industry 4.0

With the arrival of the fourth generation of industry (Industry 4.0) in the 2010's [9] [10] [11] two trends can be seen in the semiconductor industry:

- A continued aggressive globalization trend that climaxed just shortly before the Covid-19 pandemic era.
- Robotization.

Globalization of the industry started in the 1980's, and ever since, semiconductor manufacturing has increasingly become one of the most globalized industries. This is due to the complexity in the manufacturing process that involves highly specialized companies in each stage of the process. For example, raw silicon may be produced in the U.S. then shipped to China in which it is processed into single-crystalline wafers, while chip architecture and design may be produced by a company in Canada and machinery for microchip production plants are manufactured in Germany, the microchip foundries may be located in Taiwan, and microchip testing and packaging companies in Malaysia, and finally, installation taking place in China or Japan [12].

The semiconductor industry is expected to exceed $726 Billion in 2027 at a growth rate of 8.4% pushed by the network and communication devices sector [13], which constituted about a third of the industry's market in 2019 [14].

The statistics released by Statistica for the leading semiconductor companies by market capitalization as of January 2024 are shown in Table IV. Companies from North America and the Asia-Pacific regions dominated the industry, with Nvidia taking the world lead. The European-based ASML remans the only company that produces extreme ultra-violet (EUV)) machines in the world.

TABLE IV. Top 10 Semiconductor Companies by Market Capitalization [15]:

Company	**Base Country**	**Market Cap**
Nvidia	USA	$ 1,341 billion
TSMC	Taiwan	$ 521.95 billion
Broadcom	USA	$ 443.09 billion
Samsung	Korea	$ 370.70 billion
ASML	Netherlands	$ 281.09 billion
AMD	USA	$ 238.35 billion
Intel	USA	$ 199.36 billion
Qualcomm	USA	$ 153.86 billion
Texas Instruments	USA	$ 151.02 billion
Applied Materials	USA	$ 123.92 billion

Another trend in the Industry 4.0 era is observed in the incorporation of industrial robotics in the industry. This is evidenced in the annual reports of the International Federation of Robotics, which show a breakthrough taking place in 2020 in the history of industrial robotics, with the Electronics industry, for the first time, becoming the biggest market of industrial robots [16], a position that has always been firmly held by the automotive industry [17] [18]. As a result of the booming growth of applications of Artificial Intelligence (AI)-based technologies, the increased deployment of robots in both industrial and service applications, as well as the deployment of 5G/6G, crypto mining, and the Internet of Things (IoT); and with the current production rates, which are already at maximum capacity, the semiconductor industry will have to double its production to keep up with the demand [5] [19] [20].

B. Trends in Materials

The semiconductor industry was initiated with the first Germanium-based solid state transistor that was fabricated by Bell Labs in 1956. Soon afterwards, Germanium was replaced by silicon, which offered significant advantages over Germanium ranging from the ease of use to fabricate CMOS technology components due to the simple process of forming the insulative SiO_2 layer, and its higher immunity to noise due to the higher potential between its conduction and valence bands, as well as the lower leakage current and higher peak reverse voltage in silicon PN-junctions and the considerably lower production cost of silicon [14];

In addition to that, silicon (when in porous form) has distinctive optical properties that can be controlled by varying porosity and pore morphology of the material [21] [22] [23], such as the ability to change refractive index with depth, and its photoluminescence properties, which allowed it to be used for *in-vivo* drug delivery [24] [25] [26]. Its intrinsic theranostic capability allows for in-situ assessment of therapy [27]. The unique properties of the semiconductor also open avenues for the futuristic biodegradable electronics [27], in which an electronic device is implanted to perform a certain task for a certain period of time, then degrades to a non -toxic material. That is in addition to its biocompatibility, thus not being rejected by the body's immune system, and its biodegradability to a nontoxic material (orthosilicic acid Si(OH)4) [28]. Finally, silicon has a low production cost and has the ability to change electric conductivity as desired [29] [30]. All these factors contributed to the wide use of silicon, and giving rise to the designation "Silicon Valley" for regions where high-tech industries proliferate.

Although silicon remains the dominant material in semiconductor manufacturing, researchers are increasingly facing challenges in increasing Field- Effect Transistor scaling for silicon, with research suggesting that it has reached its limit in Moore's law [31]. Other materials that have been researched to potentially replace silicon include wide bandgap materials such as Gallium Nitride and silicon carbide [32] [33], Carbon, Antimonide, Bismuthide, and Pyrite.

Among these materials, carbon nanotubes (CNTs) offer superior electron mobility and thermal conductivity, making them ideal for high-performance computing applications. Researchers have successfully fabricated microprocessors using carbon nanotube field-effect transistors (CNFETs), which demonstrate energy efficiency improvements by an order of magnitude compared to traditional silicon-based transistors [31] [34] [14].

Gallium Nitride (GaN), on the other hand, is much faster and more efficient than silicon in conduction, with a wide bandgap that is over three times that of silicon (3.3 eV compared to 1.1 eV) it found use in high frequency applications such as in optoelectronics. However, its limitation to depletion-type for devices made of this material is a major challenge that hindered its applications, this is due to its low active p-type doping and low hole mobility [35]. To offset this major limitation in the material, scientists relied on integrating GaN with silicon, such as by epitaxially growing GaN on Silicon [36], or by Metal Organic Chemical Vapor Deposition (MOCVD) on substrates formed by oxide bonding [37], or by monolithic 3-D layer transfer [35]. GaN possesses a wide bandgap, high electron velocity, and excellent thermal stability, making it suitable for high-frequency applications as stated earlier. However, GaN's widespread adoption is hindered by challenges in p-type doping and lack of a standardized process for integration with silicon substrates [36] [35] [38].

In their work Udabe et al show that Silicon carbide-based devices have seen significant improvements recently, with power MOSFETs and Schottky diodes showing superior performance to the silicon-based devices. On the other hand, they argue that the lack of standards for Gallium Nitride devices, which show better performance at high frequencies than silicon, limits their adoption by the industry; this is in addition to their limitation to low power applications due to the low breakdown voltage of Gallium Nitride [32].

Carbon stands out as a strong candidate material to replace silicon. In their work, Hills et. al. used carbon nanotubes to fabricate a microprocessor that is based on the Carbon-based Carbon Nanotube Field-Effect Transistor (CNFET) technology [31]. Energy efficiency can be improved by an order-of magnitude with the Carbon Nanotube technology [31] [34] [14].

Another candidate material for the semiconductor industry is two-dimensional antimony, which has a significantly higher charge mobility than silicon. Computational works demonstrate that 2D-antimony has a potential in increasing the scaling of electronics beyond that currently possible in silicon [39]. Bismuth-based semiconductors have also been investigated by researchers particularly for photovoltaic cells. These compounds such as Bi_2O_3 and Bi_2S_3 have band gaps less than 3 eV and have shown strong potential as photocatalysts [40].

In conclusion, despite advancements in materials, almost all the alternative materials have one or more of three major challenges: lack of an established infrastructure, lack of a standardized process, and the high cost. Consequently, it is expected that silicon will remain the dominant material in semiconductor manufacturing for the next two or three decades due to its established infrastructure and cost-effectiveness.

C. Long-Term Impact of the CoVid-19 Pandemic

The spread of the Corona Virus Disease of 2019 (CoVid-19) caused a turning point in the manufacturing industry and intensified the need for "intelligentization" and "networkization". The pandemic affected almost every aspect of the human civilization. By the end of April 2020, the pandemic resulted in a 52% decline in the automotive sales in the U.S. [41] and a paralyzed aviation industry that shrunk at an unprecedented level of 94% [42] [43]. Almost every manufacturing industry faced supply chain disruptions, however, the semiconductor industry experienced an acute shortage with the sudden increase in demand for electronics that facilitate remote work [11]. The chip shortage of 2021 that came as a result of the pandemic caused governments across the world to prioritize the semiconductor industry and consequently increase regulations that may hinder its globalization trend on the long term.

IV. CONCLUSION

An analysis is conducted on the state of the semiconductor manufacturing industry and its challenges and trends. In this work, trends in the industry are analyzed from three perspectives: the evolution of Industry 4.0, the advances in semiconductor materials, and the impact of the Covid-19 Pandemic. The semiconductor manufacturing industry witnessed an acute decline in the United States and other regions in the two decades prior to the CoVid-19 pandemic. The decline was only uncovered after the chip shortage of 2021 that resulted from the severe supply chain disruption.

The main challenge that face the industry include the shortage in the technical workforce, and the inter-country regulations that may impact the manufacturing process for this super-globalized industry.

Two primary trends in the industry from the perspective of the evolution of Industry 4.0 can be noticed: Robotization, which caused the industry to become the largest market for industrial robotics since 2020, and an all-time peak globalization. The semiconductor industry is a very globalized industry with companies from different parts of the world taking part in the production of the final product.

From the advances in materials perspective, some materials such as carbon and Gallium Nitride show promising trends to replace silicon as the material of choice. However, the drawbacks of these materials are very prominent that it will likely not be before two or three decades when a semiconductor material will be able to replace silicon as the material of choice.

In the United States, the manufacturing industry witnessed an acute decline in the two decades prior to the CoVid-19 pandemic, which caused the chip shortage of 2021 due to the severe supply chain disruption and brought attention to the industry. Although US-based companies dominate the global semiconductor market capitalization, several core elements of semiconductor manufacturing process such as Assembly, Testing, and Packaging (ATP) remain very poor in the US. This is in addition to the need for the skilled workforce pool.

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