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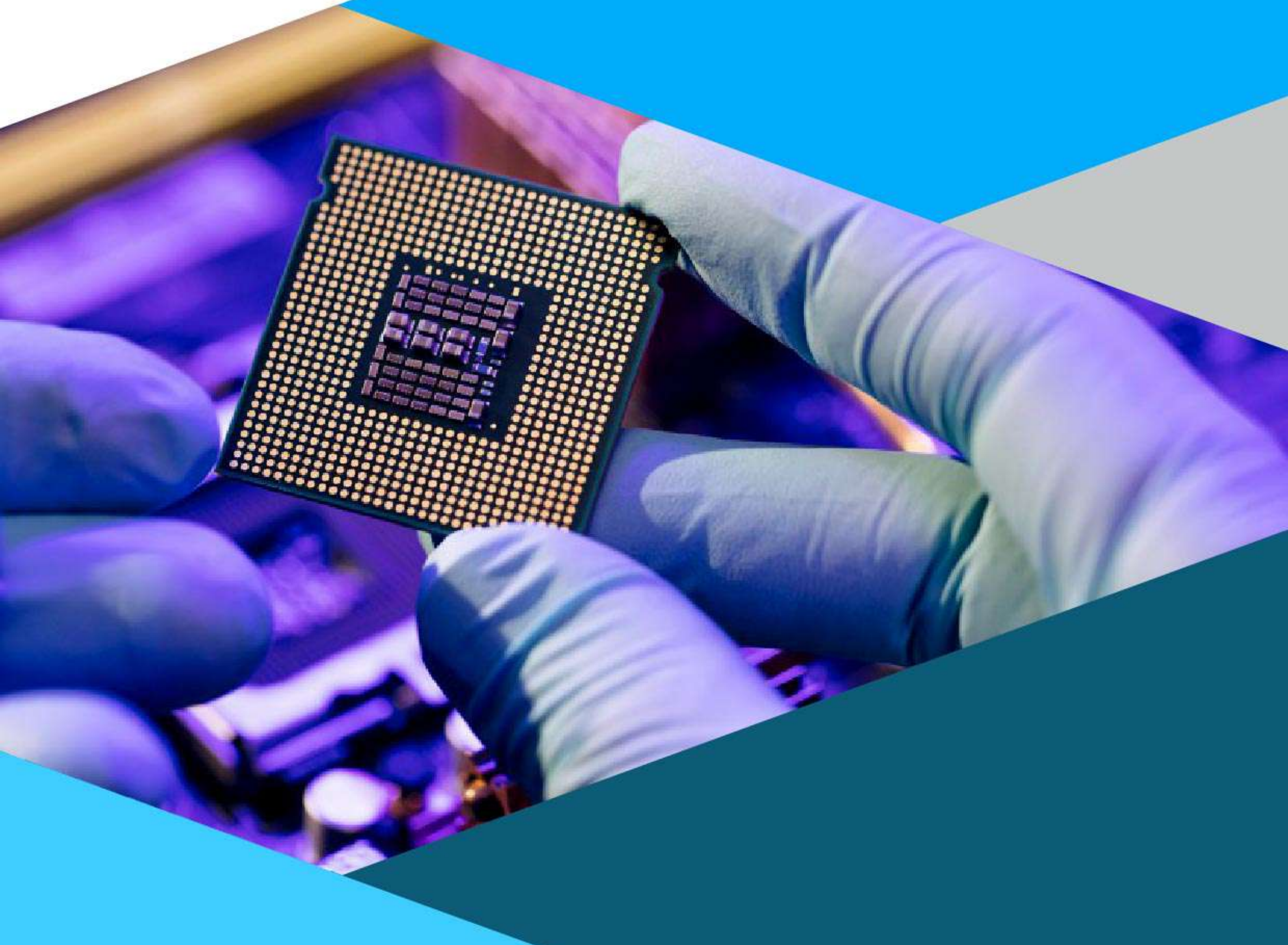
THE BEGINNING OF INDIA'S SEMICONDUCTOR AGE



Author Note

BlueKraft Digital Foundation

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Correspondence concerning this article should be addressed to

BlueKraft Digital Foundation
9, Hanuman Rd, Hanuman Road Area,
Connaught Place, New Delhi, India, 110085.
Email: contact@bluekraft.in

Abstract

India has really started to increase its level of focus and government level of support for the chip industry because it sees that semiconductors are important for the continuity of supply for its economy and the security of its critical infrastructure. The motives behind the Indian government's significant push for self-sufficiency in chip manufacturing extend to supply chain resilience to national security and technological sovereignty. The motives behind the Indian government's significant push for self-sufficiency in chip manufacturing extend from supply chain resilience for its expanding economic needs and green initiatives to national security and technological sovereignty. It is putting billions into its semiconductor push and following a three-fold strategy to achieve the mission. The first is to achieve self-sufficiency in semiconductor chips used in critical infrastructure across power, communications, space and defence sectors as a national security insurance policy in the digital age. The second aspect of the Indian government's strategy is the Collaborative Approach, where, unlike China, India is focused on establishing its domestic channels to strengthen its position in the global supply chain through investment and partnerships with the industry's biggest companies. The third aspect of the strategy focuses on building a global semiconductor industry by empowering local MSMEs and creating job opportunities. India's MSME sector can play a vital role in semiconductor manufacturing equipment, consumables and materials while significantly contributing to the country's GDP.

Key words: U.S.-China tech rivalry, Chip self-sufficiency, India's Green energy initiatives, India's digital economy, India's semiconductor profile

The Beginning of India's Semiconductor Age

The 21st century is the era of the digital revolution, and semiconductor chips are the key enablers of almost every initiative of national importance. India needs a semiconductor chips industry for a number of reasons. The increased use of mobile phones and computers requires a robust supply of semiconductor chips. The manufacturing sector contributes very significantly to India's economy, and it also requires semiconductors. Semiconductor chips are used in critical infrastructures like power transmission and communication, which have implications for India's national security. Additionally, India faces climate change, domestic terrorism, cyber-attacks and disinformation threats. Digital technologies are pivotal in strategizing and addressing these challenges. Since semiconductors are the physical substrate that undergirds these technologies, they are crucial to India's national security. It is, therefore, becoming increasingly important for India to build Indigenous, competitive semiconductor-chip manufacturing capabilities. Chip self-sufficiency, therefore, is an existential imperative for India to survive and thrive.

The semiconductor value chain is increasingly concentrated in China, while it was traditionally concentrated in the U.S. and its East Asian allies (Kleinhans & Baisakova, 2020). However, amid pandemic-related disruptions, rising labour costs, geopolitical tensions in the South China Sea, and Beijing weaponizing semiconductor chips, New Delhi is strategizing to mitigate risks associated with over-reliance on a single supply source/region of semiconductor chips.

India has a large pool of talent for chip design. The country is known for its semiconductor design expertise since the 1980s (Dahad, 2024). Although India excels in creating chip designs for the rest of the world, little is created as IP for products designed in India specifically for the Indian market. Moreover, manufacturing capability and capacity have been limited despite building a fab in 1983 at Semiconductor Complex Limited (SCL) Dahad (2024).

India is rapidly positioning itself to become a global leader in electronic manufacturing, setting the stage for a future where the country handles the entire production cycle—from creating semiconductor chips to assembling finished electronic goods. This plan aligns with the government's 'Make in India' initiative to transform India into a manufacturing powerhouse. Since semiconductor chips are the backbone of modern electronics and are used in a wide range of industries, developing the semiconductor chips ecosystem will have a multiplier effect across different sectors of the Indian economy. The Indian government's plans to jump-start the semiconductor industry by offering PLIs and design-linked incentives (DLIs) through the Indian Semiconductor Mission (ISM) are applause-worthy. Experts have argued that New Delhi's big start in chip manufacturing in India shows the country's urgency to make the most of the supply chains shifting away from China and Taiwan, which Beijing threatens to annexe.

This paper investigates the motives behind the Indian government's significant push for self-sufficiency in chip manufacturing and the factors contributing to the semiconductor market's growth. Additionally, it analyses the Indian government's three-fold strategy for India's semiconductor ambition.

The next section briefly discusses the semiconductor chip development stages, which will be followed by a section on factors contributing to the growth of the semiconductor market in India. The fourth section will discuss the drivers of India's chip's ambition for self-sufficiency. In the penultimate section, India's semiconductor profile will be traced, and an analysis of India's semiconductor strategy will be discussed. The paper will conclude with a discussion of India's achievements.

Semiconductor Chip Development Stages

Semiconductor chip development is extraordinarily complex, capital-intensive, and highly segmented. However, it can be broadly divided into three distinct stages: Research and design, manufacturing or wafer fabrication, and assembly, testing, marketing and packaging (ATP/ATMP) (Figure 1).

Figure 1: Semiconductor Chip Production Steps

Each of the three stages is dominated by specialized companies and countries, supplemented by several specialized service providers such as chip design software/electronic design automation (EDA) tool makers, semiconductor manufacturing equipment (SME) suppliers, and raw material suppliers. Intellectual Property (I.P.) companies provide layout designs to build advanced chips. (Figure 2).

Figure 2

Based on the global value chain of semiconductors, the industry has seven different activities. Varas et al. (2021) at the Boston Consulting Group and Semiconductor Industry Association argue that the industry value chain involved in creating and producing any semiconductor is extraordinarily complex and globalized. However, at a high level, it consists of four broad steps: pre-competitive research, design, front-end manufacturing, assembly, testing, and packaging at the back end. Moreover, a specialized ecosystem of materials, equipment, software design tools, and core I.P. suppliers supports these steps. Further, pre-competitive research comprises 15-20% of the total industry R&D, while the design comprises 50% of the value addition. Front-end (manufacturing) adds 24% value. The rest of the value is added through the back-end (ATP, EDA, I.P., equipment & tools, and raw materials) (Table 1).

Activity	% Contribution
Pre-competitive Research	15-20
Design	50
Front-End (Wafer Manufacturing)	24
Back End (ATP, EDA, I.P., equipment & tools, and raw materials)	6-11

Table 1. *Data Source: BCG & SIA Report*

The semiconductor chip development process begins in design, where a blueprint of a chip architecture is sketched out to optimize for certain parameters, including cost, power consumption, and capacity, based on the needs of the chip in question. The design segment includes pre-competitive research, design automation software known as electronic design automation (EDA), and core I.P. Originally, chip designs were hand-drawn on individual sheets of paper. However, as the number of transistors on a single semiconductor grew to hundreds of thousands and eventually hundreds of billions, it became highly specialized. Software became necessary to manage the resulting set of complex interactions and layers. Chip design software is highly concentrated and critical in the value chain. Without the latest software, designing leading-edge chips is impossible. Certain portions of a chip's design are built using reusable pieces of intellectual property (IP), called core IP, that firms license to lessen the burden of the design process. Also, firms that opt not to build fully customizable chip designs from scratch rely on reusable design blocks built by others (Thadani & Allen, 2023).

The next stage in the chip development process is manufacturing, also known as the front end. At the front end, fabrication facilities (fabs) print integrated circuits by layering transistor elements onto raw silicon wafers. However, not all fabs are created equal; only a few have the capabilities and infrastructure to manufacture the most advanced semiconductors. Legacy chips (made using established manufacturing processes) are sufficient and, due to cost and complexity, preferred for some applications in the automotive industry, certain types of defence technology, aircraft, and consumer electronics. However, for advanced applications in artificial intelligence, quantum and high-performance computing, and other critical and compute-heavy technologies, advanced-node chips (16 nm or smaller) are essential.

Layering transistor elements requires extensive control over the process with highly specialized and sensitive equipment; the degree of precision required by semiconductor fabs is the most demanding of any manufacturing industry worldwide. Semiconductor manufacturing equipment (SME) facilitates the precision, scale, speed, purity, and dependability required to produce semiconductors sustainably, but they are expensive and extremely difficult to make.

Raw and manufactured materials, such as silicon wafers, photomasks, photoresists, and certain chemicals, are necessary for semiconductor manufacturing. Silicon wafers are the most common type of semiconductor wafer and are produced in various sizes.

Once the fab has completed its process on a wafer, individual chips get cut, separated, tested, and assembled for integration into final products at the back end. This portion of the supply chain is referred to as ATP. It is conducted by companies called Outsourced Semiconductor Assembly and Test (OSAT) vendors. It generally involves fewer complex processes and tools than the other two semiconductor manufacturing stages but is more labour-intensive. However, ATP has quickly become more complex with each successive transistor size and density shrinking.

There are two production models for semiconductor chips. The first one is the Integrated Device Manufacturing (IDM) model. It is done by companies such as Intel or Samsung (Kleinhans & Baisakova, 2020), in which all three 'verticals' of research & design, manufacturing and ATP are within the same firm. The companies perform in-house ATP services.

The other and dominant one is the Fabless Foundry Model (FFM), where different firms are involved in the three stages of chip production. Companies that only design chips and rely on contract chip makers for fabrication are called fabless. The fabless firms such as Qualcomm (U.S.), Nvidia (U.S.) and HiSilicon (China) research and design sophisticated chips for specialized purposes and sell them. On the other hand, the wafer foundries focus on making the physical chips based on the designs of the fabless firms. The primary purpose of a foundry is to create economies of scale and chips with ever-decreasing gate or node sizes. The fabless firms share the structure of the chip, and the wafer foundry executes the design in physical form, using highly specialized machinery and processes. Fabless firms buy assembly, test, and packaging services from OSAT firms.

A good example of how the different business models work together is the Intel and Advanced Micro Devices (AMD) processors. Intel is an IDM company. Therefore, it designs, produces and assembles its processors mostly by itself. In contrast, AMD processors are designed by AMD (fabless), produced in TSMC's fabs in Taiwan (foundry) and then packaged by SPIL (OSAT).

Factors Contributing to the Growth of the Semiconductor Market in India

Multiple factors contribute to the growth of the Indian electronics and semiconductors market. These include the escalating demand for electronics products within the country, the government's emphasis on developing a strong semiconductor manufacturing ecosystem, and the rising requirement for semiconductors in automotive, medical, industrial, and consumer electronics verticals, all expected to grow rapidly in India.

Green Energy Transition. India is the world's third-largest consumer of energy. The country is moving towards a greener, sustainable energy landscape. Global climate obligations, lower dependency on fossil fuels, and the need to enhance energy security are the primary reasons for this shift. Dependence on conventional energy resources is unsuitable as India imports nearly 80% of its crude oil requirements. Decarbonization efforts will increase the usage of renewable energy and electric vehicles in India. The government of India has set a target for increasing renewables capacity to 500 GW, establishing 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources, reducing cumulative emissions by one billion tonnes and reducing by 45% the emissions intensity of India's gross domestic product (GDP) by 2030 (Ministry of New and Renewable Energy, 2022).

Semiconductors are essential to decarbonize the economy as chips play a fundamental role in developing green technologies. Semiconductor chips harness, convert, transfer and store renewable energy as electricity and subsequently move it onto the electric grid with minimal loss of power. The photovoltaic (PV) cells that make up solar panels rely on semiconductor materials to transfer light energy (photons) from the sun into usable electric energy, which can be transferred to the grid. Meanwhile, semiconductors' capacity for allowing electricity to pass through them at a modulated rate enables them to convert energy harnessed by other renewable energy technologies such as wind turbines and hydropower. In this application, they act as efficient rectifiers, smoothing the electric current harnessed from renewable sources to transfer it to the electric grid with minimal energy loss.

Renewable power generation costs have also decreased significantly over the past decade. The decade 2010 to 2020 saw renewable power generation becoming the default economic choice for new capacity. The International Renewable Energy Agency (IRENA) report (2021) shows that 62% of total renewable power generation added in 2020 had lower costs than the cheapest new fossil fuel option. In 2023, the global weighted average levelised (LCOE) cost of electricity from newly commissioned utility-scale solar photovoltaic (P.V.), onshore wind, offshore wind and hydropower fell further. Between 2022 and 2023, utility-scale solar PV projects showed the most significant decrease (by 12%). For newly commissioned onshore wind projects, the global weighted average LCOE fell by 3% year-on-year, while for offshore wind, the cost of electricity of new projects decreased by 7% compared to 2022. Battery storage project costs have dropped by 89% between 2010 and 2023 (IRENA, 2024). Such achievement was partly due to the steady improvement of energy-saving technologies that semiconductor devices empower.

India is on track to become the largest electric vehicle (EV) market by 2030 (Agarwal, 2024). As part of the global EV30@30 campaign, India's EV policy aims to ensure annual sales of 1 crore units by 2030 (Mukherjee, 2024). NITI Aayog aims to achieve 70% penetration of E.V.s in all types by 2030, indenting to attain net zero carbon emissions by 2070.

The EV market is projected to grow from $23.38 billion in 2024 to $117.78 billion by 2032 at a CAGR of 22.4% over the forecast period (Fortune Business Insights, 2024). Semiconductors are necessary for producing EVs and charging stations. On average, electric cars have about 2,000 chips, roughly double the number of chips in a non-electric car (Favino, 2022). Additionally, there is an opportunity to establish 13.2 Lakh charging stations across the country by 2030, requiring 400,000 installations annually.

For E.V. charging, semiconductors play a pivotal role in developing high-speed and efficient chargers, making the adoption of E.V.s more convenient for consumers. These chips are instrumental in managing lithium-ion batteries, extending their lifespan, improving energy efficiency, and reducing waste, which is crucial for sustainable mobility. Therefore, given their huge role in the country's E.V. drive, the semiconductor consumption in the automotive sector is estimated to increase to $22 billion in 2030 from the 2022 demand of $6.6 billion (Srivastava & Bhaisora, 2018).

Growing Demand. On the demand side, semiconductor technology is on the upswing. The Indian electronics manufacturing industry is experiencing a significant boom, given its huge role in the country's digitization drive and surge in the Work-from-Home trend, India's electronics production, valued at $101 billion in FY2023, is poised for further growth as companies adopt the "China + 1" strategy to diversify their manufacturing base, and India emerges as a viable alternative. Therefore, Indian electronic manufacturing is projected to triple to $300 billion by 2026 and to 5x to $500 billion by 2030 (Srivastava & Bhaisora, 2024). The mobile phone sector is a major contributor to this growth, where production is expected to increase from $44 billion in 2023 to $110 billion by 2026. India has already become the world's second-largest mobile phone manufacturer, doubling its share of global smartphone production to 19% over the past five years.

Moreover, as India is positioning itself for 100 % electronic manufacturing, from chips to finished goods (Haitong International Research, 2024), and semiconductor manufacturing being a key part of the electronics industry, India's semiconductor consumption is set to increase from $22 billion in 2019 to $64 billion by 2026, a CAGR of 16%. It is also estimated that India's consumption of semiconductors will cross $80 billion by 2026 and $110 billion by 2030, positioning India to account for approximately 10% of global semiconductor demand (International Trade Administration, 2023), while semiconductors are projected to become a trillion-dollar global industry by 2030 (Burkacky et al., 2022).

The demand for semiconductors has been estimated to be driven by five key market segments: wireless ($26.5 billion) and wireline communications ($8.2 billion), computer hardware ($16.1 billion), automotive electronics ($22 billion), and consumer goods ($26

Figure 3: Semiconductors Consumption Breakdown (Estimates in Billion Doillars), 2023

billion) (Figure 3).

The consumption of mobile devices and computers has sharply increased in India. It is increasing because of the rising domestic demand of Indian customers. Moreover, the Indian government's Digital India Program (DIP) has led to concentrating on going digital and making rural India adopt digital methods of education and transactions. With DIP and all the innovative ideas to come to reality, more and more electronic gadgets are being used.

However, India currently depends on imports to fulfil its semiconductor device needs. India imports 95% of its semiconductors from countries like China, Taiwan, South Korea, and Singapore (International Trade Administration, 2023). The major reason behind this highly dependent behaviour is the absence of semiconductor fabrication facilities in the country (IBEF, 2024). This dependence exposes India to external factors and hinders its ability to harness the full potential of its growing technological sector. Semiconductor manufacturing, a critical and strategic technology, increasingly drives innovation and modernization within India's manufacturing and technological sectors. Developing a robust domestic semiconductor manufacturing ecosystem is crucial for long-term success.

Drivers of India's Chip Self-Sufficiency Ambition

The motives behind the Indian government's significant push for self-sufficiency in chip manufacturing extend to supply chain resilience to national security and technological sovereignty.

While spelling benefits, the world's interconnectedness has also created its own issues. The last few years have seen a pressing shortage of semiconductors, which matters greatly since the future industries will heavily rely on chips. Although the shortage can be ascribed to various reasons, a primary cause of vulnerability in the semiconductor supply chain is the high concentration of production facilities in specific regions, notably East Asia.

According to Thadani & Allen (2023), while the semiconductor industry is truly global, East Asia and the transatlantic region are its critical regions, with firms headquartered in the United States, South Korea, Europe, Japan, Taiwan, and China that control the global semiconductor value chain. Countries like Taiwan, South Korea, and China account for a significant portion of global semiconductor manufacturing, with Taiwan's TSMC (Taiwan Semiconductor Manufacturing Company) alone producing around 90% of advanced chips. Collectively, Taiwans companies hold a 68 percent market share of all global chip production (Hilton, 2024).

This geographic concentration exposes the supply chain to regional political conflicts. For instance, rising tensions between Taiwan and China have raised concerns about supply disruptions that could cripple industries reliant on these chips. Taiwan's "Silicon Shield" TSMC might seem like a protective barrier, but it's a double-edged sword as Chip manufacturing prowess may increase the danger to Taiwan because China may covet it, and the U.S. may press Taiwan even harder for diversification.

In the U.S.-China geopolitical competition, rare earths, widely used in semiconductors, have emerged as a critical choke point due to their use in military applications and Beijing's willingness to use its dominance to restrict access to political and strategic gains (Seth, 2024). China accounts for 85-90% of global rare earth element mine-to-metal refining (Cohen, 2023). China's near-monopoly on rare earths gives it leverage that it has occasionally used as a strategic tool. For instance, in 2010, China put an embargo on rare earth elements sales to Japan during a territorial dispute in the contested waters of the East China Sea, demonstrating its capacity to use its supply dominance as economic leverage (Teufel Dreyer, 2020).

Given the intensifying U.S.-China tech rivalry, most obvious in the semiconductor industry, there are reasons to believe that China might weaponize and restrict exports of rare earths to the U.S. or other countries reliant on its materials to impact industries dependent on semiconductor technology (Hamdani & Belfencha, 2024). In 2020, China reportedly cut off exports of graphite to Sweden. In 2023, China implemented export restrictions on certain gallium and germanium products, two critical materials used in semiconductor production, retaliating against actions taken against China over the past few years by the U.S. and Europe, which has sparked concerns about further disruptions in the high-tech sector (John, 2023).

Given these risks, several countries, including India, are actively working to diversify their rare earth supply chains. The United States, Japan, and Australia invest domestically and through alliances in rare earth mining and processing facilities. For example, the U.S. Department of Defense has funded projects to develop domestic rare earth elements processing capacities as part of an initiative to reduce reliance on China (Lopez, 2024). Similarly, Japan has invested in rare earth mines in Australia and Vietnam to secure alternative supply sources (Nakano, 2021). With the world's fifth-largest reserves of rare earths, India could play a crucial role in reducing global overdependence on China and building a stable and diversified supply chain. In October 2023, the United States and India announced a major agreement in critical minerals supply chain cooperation to "expand and diversify" supply routes and leverage complementary strengths (Seth, 2024).

Supply chain disruptions stem from the industry's complex and highly specialized production process. This paper has discussed before that producing a semiconductor chip requires multiple stages, including design, fabrication, testing, and assembly. Any disruption at a single stage can delay the entire process. For instance, a shortage or delay in a key component or raw material like silicon or rare earth elements impacts the final product's timeline, causing bottlenecks across the entire supply chain.

The pandemic had an immediate impact on the semiconductor industry. Lockdowns and restrictions slowed or halted production in key semiconductor manufacturing hubs, including Taiwan, South Korea, and parts of China, while demand surged for electronics as remote work, online learning, and digital entertainment became essential. The widespread lockdowns, worker shortages and disruptions to shipping and logistics led to chip shortages and increased prices. The shift in demand patterns, with reduced production, led to a severe chip shortage. Automotive manufacturers, who had scaled back orders during early pandemic uncertainties, found themselves unable to meet demand as they attempted to ramp up production (Frieske & Stieler, 2022).

According to the World Bank, Ukraine makes more than 70% of the high-grade neon gas, an important input in the production of computer chips (Maur, 2023). At the same time, Russia provides a third of the palladium metal used in semiconductor components and sensor production (Hamblen, 2022). The disruption of these supplies due to the war in Ukraine has strained the chip-making process, adding delays and costs to semiconductor production. Global supply chains can lower production costs and improve efficiency. However, rising energy costs, triggered partly by sanctions and decreased gas flows from Russia to Europe, have impacted manufacturing costs for chipmakers, as energy-intensive chip-making operations face higher operational expenses (Athanasia & Arcuri, 2022).

The Red Sea shipping crisis, resulting from Houthi rebel attacks on cargo ships and tankers, is causing hundreds of vessels to avoid the Suez Canal, one of the world's most important waterways. Instead, these vessels are being forced to reroute around southern Africa, a lengthy detour that adds 4,000 miles to each journey, vastly increasing transport times and freight costs (JP Morgan, 2024). On the other side of the world, a severe drought at the Panama Canal has forced authorities to impose restrictions that have substantially reduced daily ship crossings since October 2023 (Kamali et al., 2024). The lengthening of supplier delivery times acts as an adverse supply shock. The Ever Given Suez Canal blockage in March 2021 is a stark reminder of how disruptions to key shipping routes can cascade through supply chains, particularly for semiconductor chip manufacturing industries that rely on just-in-time production and complex, globalized logistics networks (Area51Electronics, 2022).

These events have made it clear that the global semiconductor supply chain is quite vulnerable while demand for chips is growing rapidly. Therefore, India's aim to enhance its semiconductor manufacturing role could be crucial in building a stable and diversified supply chain.

Is Partnering With the U.S. A Solution? Considering this fragile geopolitical situation, while India is trying to be self-dependent, it seems reasonable if India strategically uses the power dynamics in its favour and makes alliances with powerful nations. Thus, it can be argued that making ties with the U.S. may be a fruitful decision.

Semiconductor manufacturing is notoriously difficult and expensive. Since India lacks fabrication capacity, catching up will not be easy or quick for India, given that making state-of-the-art chips requires billions of dollars of investment, pure raw materials, and solid infrastructure. Chip fabs are also very thirsty units requiring millions of litres of clean water, an extremely stable power supply, a lot of land and a highly skilled workforce (Singh & Vaid, 2024). The U.S. (with its allies and partners), on the other hand, controls significant capabilities. An industry that was invented and established in the U.S. and developed in the U.S. is dominated by the United States.

Moreover, the U.S. government's support also helps reduce geopolitical risks for American companies that invest in other countries in the world, including India.
In August 2022, the CHIPS and Science Act was passed by the U.S. Congress, which provides $280 billion for funding domestic research and manufacturing of semiconductors within the U.S. However, the U.S. went to the extent of semiconductor friend shoring in the Quad, where the leaders of Australia, Japan, India, and the U.S. planned to build "resilient, diverse, and secure supply chains of critical and emerging technologies" (Subramanian, 2023). India can collaborate in three archetypal stages (design, manufacturing, and outsourced assembly test (OSAT) for the semiconductor supply chain.

In fact, the connection between the U.S. and India is an important component of the global semiconductor design ecosystem, and India's strength lies in providing skilled engineers for chip designs. It currently contributes 20% of the global semiconductor design talent, with over 35,000 engineers engaged in chip design, with plans to train 85,000 professionals in semiconductor design, fabrication, and packaging (Srivastava & Bhaisora, 2024). Several American semiconductor firms and global development centres, including Intel, Qualcomm, and Texas Instruments, have design centres in India. And Indian engineers at these GDCs are heavily involved in R&D, contributing to cutting-edge innovation (Sharma, 2024). The top three American electronic design automation (EDA) companies, Cadence Design Systems, Synopsys, and Siemens EDA, which control about 70% of the global EDA market and are important for the design integration process, have their research and development centres are in India (Suraksha P, 2024).

However, given the critical requirement of semiconductors in India's national security domain, U.S. and Western semiconductor technology export controls targeting China's intention to modernize its economy and military have important lessons for India as it grows in stature and power.
In 2022, while President Joe Biden signed the CHIPS and Science Act

to boost U.S. manufacturing of advanced chips, the U.S. also took unprecedented steps to limit the sale of advanced computer chips to China, escalating efforts to contain Beijing's tech and military ambitions. The moves have been designed to cut off supplies of critical technology to restrict China's ability to buy or build the most sophisticated computer processors that may be used across sectors, including advanced computing and weapons manufacturing (Huang & Drexel, 2023). The crackdown marks the most significant action by the U.S. against Beijing on technology exports in decades, escalating a trade battle between the world's two most powerful economies. Further, in March 2023, the Netherlands joined the U.S. when its government put export restrictions on the country's most advanced microchip technology to China. The Dutch and Japanese governments also imposed these kinds of export restrictions. In fact, Japan and the Netherlands agreed to join the U.S. in restricting exports of equipment used to manufacture advanced semiconductor chips to China (Townsend et al., 2023).

The U.S. efforts to monopolize technical advancements worldwide paint a picture of the 21st century. Therefore, the U.S. has made preserving its technological edge a national imperative. As a result, the focus of the West in terms of technology continues to turn inwards. The concern over technology leakage, therefore, may lead to strong technology control regimes to prevent others from gaining an edge over it. In September 2022, it was announced by U.S. National Security Advisor Jake Sullivan to change the U.S. policy of being "only a couple of generations ahead" of China in key technologies to maintain "as large a lead as possible" (Scharre, 2023). Thus, it is a concern of national security for the U.S. to preserve the lead and deny it to competitors, and the U.S., its allies, and partners have committed to choke China's semiconductor industry and reduce its alliance with Asia.

India's geographical position and natural endowments enable it to project power and create political and military ties with various nations. There may come a time when India's national interests may not converge with those of the U.S. and its allies that control access to the latest technology (Upadhyay, 2023). In the past, the USA has used export controls as a method to prevent the proliferation of sensitive and strategic technologies to target India on several occasions (Chellaney, 2002; Sood, 2023). New Delhi would never want to be in a spot where another nation can control a valuable resource or a technological proscription, on which it depends.

Moreover, semiconductors are important in India's growing ambitions in the military domain of Indigenous production and modernization since they serve as the foundation for advanced defence systems, enabling capabilities like sophisticated radar, communication systems, precision weaponry, and sensor networks (Singh, 2024). India also looks at semiconductors from a national security perspective, as the issue of backdoors in chips imported from abroad is of concern (Upadhyay, 2023).

According to Bogost (2018), China has not been a designer or manufacturer of advanced semiconductor chips. It imports most of them. Some of those chips are used domestically, but many are used as parts for computers, embedded systems, and other computing tools, which are then exported globally. However, China has excelled in making large volumes of chips quickly and cheaply and assembling imported parts into new components or devices for export. As a result, more and more computing devices rely on Chinese manufacturers in one way or another, even if China still relies on imports to fulfil those demands (Bogost, 2018).

Chinese spies have systematically infiltrated U.S. corporate and government computer systems by installing hardware exploits on the motherboards of servers destined for widespread use, from video-streaming services to the CIA. Beijing reportedly used a tiny chip to infiltrate U.S. Companies, allowing Chinese spies to reach almost 30 U.S. companies, including Amazon and Apple, by compromising America's technology supply chain (Robertson &

Riley, 2019). Chinese spies also implanted backdoors in motherboards used by high-profile customers, including the U.S. Department of Defense (Goldman, 2022). The Biden administration's move to ban approvals of new telecommunications equipment from China's Huawei Technologies and ZTE, citing "an unacceptable risk" to U.S. national security (Bartz & Alper, 2022), did not go unnoticed in New Delhi. With increased government scrutiny and more strict procurement regulations, ZTE Corporation and Huawei Technologies have been unable to acquire new businesses in India, including the supply of 5G technology (Outlook Business Team, 2022).

However, India's dependence on semiconductor imports for use in critical infrastructure continues to raise concerns. Chinese policymakers, aware of the dependence, are inclined to exploit the Indian conditions for strategic and political gains against New Delhi. For instance, in 2021, amidst the Galwan Valley crisis, Chinese solar equipment manufacturers threatened twice to pull out of existing contracts and stop polysilicon supplies to Indian power developers, resulting in completion delays and cost increment of solar power projects in India (Mohanty, 2021). According to Banerjee (2021), these instances are likely to happen again in future when bilateral disputes emerge between the two countries.

India's Semiconductor Profile

India's record in developing semiconductors was not very encouraging till very recently. India could have had its own semiconductor chip fabrication decades ago. However, it missed the opportunities several times. India's semiconductor-chip manufacturing dream was sabotaged by red-tapism, lack of infrastructure, bureaucratic lethargy, corruption, and, above all, a lack of visionary leadership by the governments in the past. In the late 1980s, India was just two years behind in the latest chip manufacturing technology (Ray, 2023).

When the silicon revolution started in the early 1960s, Fairchild Semiconductor, an American semiconductor company, announced that it would set up a factory in India. However, the bureaucratic fatigue helped them move to Malaysia (Rudra, 2023). A few months after the 1962 Indo-China war, Bharat Electronics Limited (BEL), a PSU under the Ministry of Defence, started a new factory producing semiconductor chip-based transistors. The demand for these transistors was so high that various global companies lined up to place orders (H.W., 2023). Without protection, BEL could not compete with the quality and price standards. Several fab units were forced to shut down. The cost-efficient semiconductor chips developed by plentiful, low-cost, and well-trained workforces from Taiwan, South Korea, and China dominated the Indian market (Reilly, 2022).

Semiconductor Complex Ltd (SCL) was set up in Mohali in 1978, with a project cost of 15 crore, and it started operations in 1984. Initially, the company started functioning with 5,000 nm node semiconductor chips and 800 nm cutting-edge technology, and that was the time when countries like Taiwan and China could not even think of competing with India in this sector (Kumar, 2022). However, to India's misfortune, in 1989, when a major fire incident broke out in the plant, the country suffered a massive setback. The mysterious fire ruined billions of dollars worth of imported equipment, and there was a colossal loss of Rs 60 crore (Rudra, 2023). India's dream of leading semiconductor manufacturing was shattered into pieces. The intelligence bureau carried out a detailed investigation, but no clear information about the cause of the fire was ever released.

In this rapidly changing industry (Zaman, 2023), the Indian bureaucracy took eight years to rebuild SCL, but SCL failed to commence its manufacturing facility fully. ISRO revived SCL and used it for its programs' low-volume manufacture of chips, but it was only a shadow of what it could have been (Kumar, 2022).

Business dynamics had altered all over the globe, and technology and equipment in this industry had changed. When the SCL was able to restart production in 1997, the plant was outdated and unable to compete with more efficient manufacturing plants in other countries. To make matters worse, the Congress governments did not make ample investments, and there was a lack of vision for such a critical and emerging economic and national security technology. These factors made it difficult for SCL to plan for the future, compete with foreign companies, and slow down its growth.

However, during technological proscription against India, reinforced by the U.S. when India became the principal opponent of the Nuclear Non-Proliferation Treaty after the Pokhran test in 1998 (Chellaney, 2002), the company started producing chips for strategic ventures in defence and aerospace. SCL continued doing R&D in microelectronics to address the country's strategic goals (Majumder, 2023).

In the mid-1980s, there was another golden opportunity. In partnership with BEL, IISc professor A.R. Vasudeva Murthy formed Metkem Silicon Limited to manufacture polysilicon wafers, thin slices of semiconductor used to fabricate integrated circuits and solar cells. However, without proper government policies, incentives, schemes, and a lack of subsidized power, Metkem failed to manufacture top-notch polysilicon wafers. Initially, the government had committed to providing electricity at a subsidized rate. However, it did not fulfil its promise (Majumder, 2023).

Manmohan Singh's government introduced semiconductor policies in 2007 and 2013. In 2007, the government introduced India's first Semiconductor Policy, intending to attract INR 24,000 crore in investments over three years and establish three fabrication units. AMD and Intel contemplated establishing fabrication units in India. However, these plans did not materialize due to delays in the passage of the Semiconductor Policy and the policy's stringent minimum investment requirements (Ray, 2023).

Then came the Manmohan Singh Government's final failed semiconductor policy in 2013-14, when the government made an effort to rejuvenate its semiconductor-chips initiatives by granting Letters of Intent (LOIs) to two consortia: Hindustan Semiconductor Manufacturing Corporation and Jaiprakash Associates Ltd (Press Information Bureau, 2014). The latter group withdrew its proposal in 2016, citing financial challenges. In 2019, the government had to revoke HSMC's permit due to prolonged paperwork delays on the company's part.

The 2007 and 2013 semiconductor policies failed because they were not lucrative enough. There were also delays in the implementation of the policies by the Singh government. Manmohan Singh's ministers created hype about the government being serious about semiconductor-chip manufacturing but only to make fab a "photo opportunity" (Gupta, 2005). All this meant India missed another opportunity to attract semiconductor manufacturers and investments. It led to the loss of job opportunities in neighbouring nations, especially in East Asia, that offered incentives to global semiconductor companies.

Three-Fold Strategy For India's Semiconductor Ambitions

India may have missed the semiconductor bus in the 1990s, but the Indian government today is determined not to repeat the mistakes committed by previous regimes. Therefore, choosing the right development model for the industry is essential for India's semiconductor future. India is executing a three-fold strategy to accelerate semiconductor manufacturing capability within the country and India's transition into a "Chip Maker" from a "Chip Taker."

Firstly, the strategy strives to achieve self-sufficiency in semiconductor chips used in critical infrastructure across power, communications, space and defence sectors.

India is equipped to design advanced chips and test and assemble them, but it lacks in its fabrication. The Indian Space Research Organisation (ISRO) and the Defence Research and Development Organisation (DRDO) have their respective fab foundries. However, these foundries were mainly for their own requirements. Therefore, to attain self-sufficiency in critical infrastructure across power, communications, space and defence sectors, the Indian government decided to invest in modernizing SCL. In May 2023, the Centre announced it would invest $2 billion in the SCL for research and prototyping. SCL Mohali has been handed over to the Ministry of Electronics and Information Technology (MeitY) from the Department of Space by the government.

However, along with modernization, commercialization is equally critical. While modernization is essential for the Indian industry to keep up with technological advancements and meet the growing demand for semiconductors, commercialization and the demand for faster and more efficient memory solutions drive the development of more complex semiconductors. Therefore, India has also decided to open SCL as a commercial fabrication facility for broader participation by Indian semiconductor design companies (MeitY, 2022).

Along with these steps, the Indian government's announcement of establishing an Indian Semiconductor research centre (ISRC) that will collaborate with top institutions like the IITs to develop cutting-edge semiconductor research is significant in indigenizing critical technology. It will safeguard India against a group of selected countries controlling the technologies. The U.S. is not the only game in town, and the European Union has its own chips act, striving to dominate the world by denying technology access to the world or making its accessibility conditional.

One may argue that completely isolating itself by developing and using only domestic products can be counterproductive because achieving complete self-reliance in a truly global semiconductor chip industry is neither possible nor desirable. Enhancing self-reliance through indigenous efforts and linkages with developed countries is imperative to ensure strategic autonomy. Yet, in an era of global uncertainty and geopolitical competition, self-reliance in semiconductor chip manufacturing for critical infrastructure is akin to a national security insurance policy in the digital age.

The second aspect of the Indian government's strategy is the Collaborative Approach. Unlike China, India is focused on establishing its domestic channels to strengthen its position in the global supply chain through investment and partnerships with the industry's biggest companies. With the global semiconductor market projected to reach USD 1 trillion by 2030, India would aim to achieve a 10% share in the global semiconductor market by 2030.

However, Moore's law dictates that the technology required to produce semiconductors changed every few years, thus making the technology obsolete by the time the factories came up. A semiconductor fabrication facility can cost multiple of a billion dollars to set up, even on a relatively small scale, and may still lag by a generation or two behind the latest in technology (Business India, 2023). Additionally, semiconductor fabs demand critical resources such as clean water, uninterrupted power, and specialized human expertise. Moreover, India faces tough competition from well-established global players in East Asia, who boast decades of experience and robust supply chains. Competing with these industry giants necessitates a long-term commitment rather than being a short-term challenge.

Therefore, the government is encouraging global semiconductor companies that dominate the industry to set up factories in the country (India Briefing, 2021). In fact, India's Semiconductor Mission aligns with a global trend wherein countries increasingly prioritize semiconductor autonomy to mitigate vulnerabilities in the supply chain. Many countries, including India, have started increasing their focus and support for semiconductor chip manufacturing companies. For companies, that means a variety of semiconductor subsidies. However, it also allows these companies to play off countries against each other (Iyengar, 2024). Therefore, New Delhi will cooperate, not compete like Beijing, with other countries to attract the companies and have a much stronger weight in the global semiconductor ecosystem(Ezell, 2024). Backing the large semiconductor companies that already control the lion's share of the sector will aid semiconductor manufacturing in India. The government's support of their manufacturing and granting them access to the Indian market creates twin incentives for the companies to invest in India.

The third aspect of the strategy focuses on building a global semiconductor industry by empowering local MSMEs and creating job opportunities on a massive scale. According to Manickam et al. (2024), "instead of subsidizing thousands of crores to established firms, the government can leverage the MSME sector, which, with capital investments in the range of '50 crore to `100 crore, can play a vital role in semiconductor manufacturing equipment, consumables and materials while making a significant contribution to the country's GDP." These experts have argued that "there are global players eager to partner with Indian companies, and this collaboration can drive significant job creation" (Manickam et al., 2024).

Since India possesses a unique depth of design talent and programs like Skill India and Startup India that no other country can match, adopting this strategy will ensure that Indian chip companies primarily benefit from government subsidies, encouraging local innovation and sustainable and inclusive economic growth. In this direction, as of September 2024, 12 Indian startup firms are receiving financial assistance under the DLI scheme, and 21 applications are under review (Barik, 2024). An advantage of this strategy is that unlike larger corporations, which tend to have higher profit margins primarily for investor returns, MSMEs operate on relatively thinner margins and ensure their earnings are reinvested into the economy. Further, semiconductor companies employ more software engineers than chip designers, giving the MSME a significant advantage due to India's software scalability and expertise (Manickam et al., 2024).

Conclusion

Across the world, countries are spending wagonloads of taxpayer money to develop or support their semiconductor industries. This cash pipeline has yielded some successes and failures; the difference usually depends on how strategically the money has been spent. The Indian government is focused on identifying the spots in the supply chain where India can enter quickly and scale up effectively. Several strategic locations have been earmarked for establishing chip fabrication units in India, with a particular focus on states like Karnataka, Tamil Nadu, Telangana, and Gujarat. These states have been selected for their advantageous attributes, such as their existing infrastructure, which can expedite semiconductor fab setup and reduce initial costs, making them well-suited for semiconductor manufacturing. However, fabrication is not the only place money is made in the chip supply chain. The Indian government has also focussed on design, assembly and packaging units, representing about half the previously discussed revenue.

The Indian government has taken several measures to encourage international companies to establish manufacturing units in the country. India has approved five semiconductor units that will all receive central and state government subsidies under the programme for the development of semiconductors and display manufacturing ecosystem in India: Micron and C.G. Power, in partnership with Renesas Electronics Corporation, Japan and Stars Microelectronics, Thailand, both ATMP focussed units would be based in Sanand, Gujarat; Kaynes Semicon (OSAT facility) and a fabrication unit, Tata Electronics Private Limited (TEPL) in partnership with Powerchip Semiconductor Manufacturing Corp (PSMC), Taiwan, both in Dholera, Gujarat; Tata Semiconductor Assembly and Test Pvt Ltd (TSAT), ATMP unit in Assam. PSMC is renowned for its expertise in logic and memory foundry segments; Renesas is a leading semiconductor company focused on specialized chips; TSAT is developing indigenous advanced semiconductor packaging technologies, including flip chip and integrated system in package technologies (Suraksha P, 2024b).

Still, there are several projects that are in the pipeline. For instance, India is awaiting a formal proposal from Israel chip maker. Suchi Semicon will begin production at its Gujarat OSAT in November 2024 (Suraksha P, 2024b). Moreover, the government has entered into Memorandums of Understanding (MoUs) with international consortia such as IGSS Ventures, ISMC, and Vedanta Foxconn. These agreements are a pivotal move towards establishing semiconductor fabrication facilities within the country. To further incentivize and facilitate this endeavour, the Indian government has committed to providing substantial fiscal support, covering up to 50% of the project costs for these fabs (Business India, 2023).

These developments represent positive strides for India's semiconductor industry. Yet the government is not obsessed over self-reliance when even a giant like the U.S. is only one cog in a global machine. As India eyes global semiconductor hub status, the Indian government is building a complete semiconductor value chain, with plans to attract more U.S., European, and Asian semiconductor manufacturers to invest in the country.

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