FEATURE

Opportunities for a US–India Strategic Partnership in Nanoelectronics

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Abstract

The acute global chip shortage that disrupted the military supply chain highlighted the need for the United States to be independent in terms of semiconductor manufacturing and chip design. This need is further intensified as China threatens the sovereignty of Taiwan, the chip-manufacturing powerhouse of the world. The recently passed CHIPS Act instills much-needed lifeblood into the semiconductor industry with renewed funding for growth and innovation, although the United States needs to find strategic partner countries to keep up with the new production capacities. India, a long-standing defense and strategic partner of the United States, can be vital in this regard with its large pool of science and technology manpower and international chip-design expertise. In this article, we establish the pressing need for partnership with India in areas such as chip manufacturing and translational new nanoelectronics research. A strong US–India partnership will help strengthen a fractured global supply chain and propel global stability in a military-critical area.

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Semiconductor chips are the lifeblood of modern society, with more than 100 billion of these nano-sized chips in active use around the world daily. The beginning phase of the COVID-19 pandemic in 2020 created a discernable gap in the supply-and-demand chain of semiconductor chips, leading to a worldwide chip shortage. This shortage fundamentally disrupted the normal functioning of a wide range of industries from defense applications to automobiles to consumer electronics. While global lockdowns during the pandemic slowed chip production, under-investment in the primarily Asian 8-inch chip-manufacturing plants also contributed substantially to the squeeze, with colossal escalation in the demand for 5G phones and laptops.[1] To top it off, a massive fire severely damaged Japan's Renesas Electronics Corporation's factories, which is a major supplier of automobile chips, and the Texas winter storm in 2021 shutdown operations of some of the only manufacturing units in the United States.[2] Port shutdowns in Asia during COVID further added to the woes, with 90 percent of the world's electronics being transported through China's Yantian Port. As the global economy gradually opens up with signs of a declining pandemic, the backlogs and bottlenecks of supply and transportation may cause the chip shortage to persist well into 2023.[3]

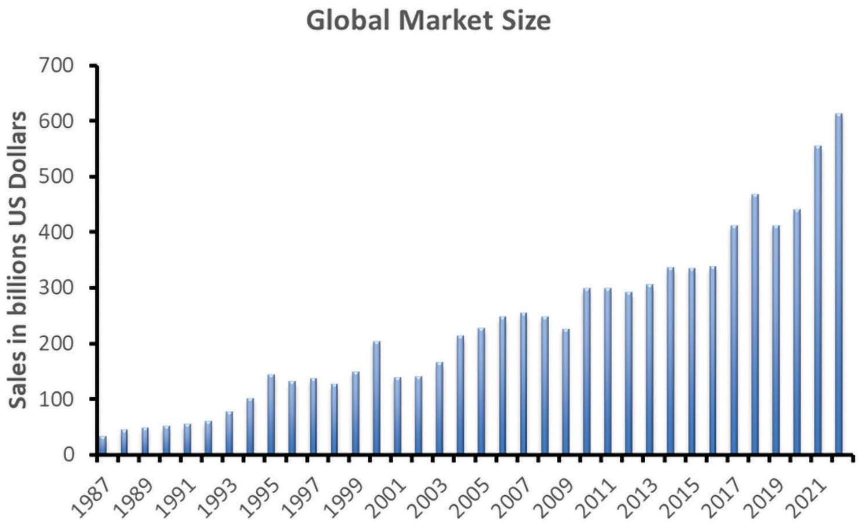

Figure 1. The escalating global market size of the semiconductor industry between 1987–2021. (Statista.com)

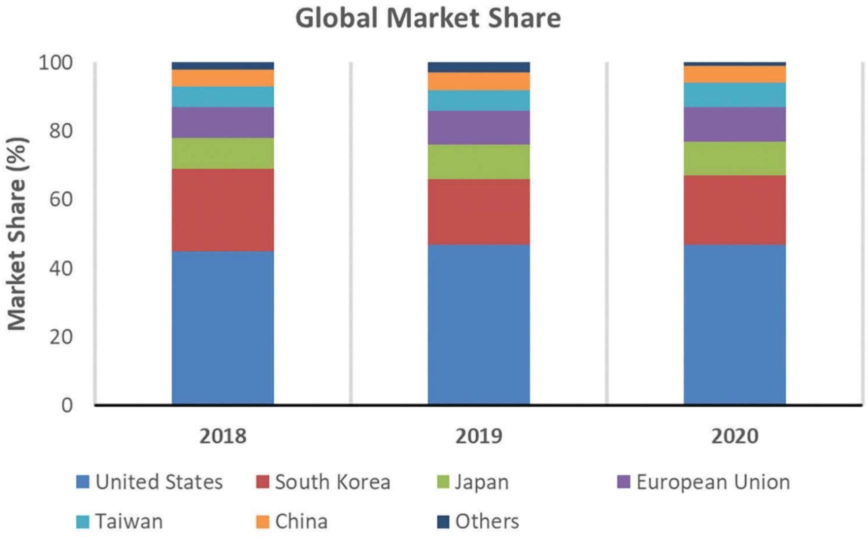

Figure 2. Region wise global market share of semiconductor sales. (Statista.com)

The US military alone requires approximately 1.9 million chips annually for communication, weapons, and other defense equipment.[4] The commercial shortage of chips also has spilled over to affect the military supply chain and has specially impacted the startups and smaller defense suppliers.[5] Additionally, the fact that most of the chips in use are imported is a matter of concern since the scope of the Defense Production Act and the ability to prioritize military needs above others is rather limited.[6] The military and aerospace semiconductor market is expected to grow by USD 3.89 billion between 2020 and 2025, as predicted by market forecast consultant Tecnavio. Moreover, the latest technology in automobile and telecommunications industries has started to use specific semiconductor devices that were earlier used only in military and aerospace applications, further fueling the scarcity. For example, gallium arsenide– and gallium nitride–based chips used in radiofrequency integrated and monolithic microwave integrated military communications, space capabilities, or active electronically scanned antenna (AESA) are required for the production of 5G electronics.[7] The sudden scarcity of chips has also affected the global light vehicle production, with major automobile corporations and smart gadget leaders scaling down their productions significantly.[8] The situation worsens as all the corporations panic-buy to stock up chips, causing squeezed capacity and driving up costs of even the cheapest microchip components.[9] The production of semiconductors, termed as "the new oil" by economist Rory Green, are almost entirely controlled by Taiwan, China, and South Korea (figs. 1–4).[10] Additionally, South Korea and Taiwan are heavily reliant on China for their economic growth. The strained relationship with China and restrictive sanctions on trade relationships with China have further heightened apprehensions regarding chip supply. Although semiconductor chips were an American invention, there has been a sharp decline in the number of US manufacturers creating them, from 37 percent of the chips being produced globally in 1990 to merely 12 percent in 2020 (fig. 3).[11] In contrast, US companies accounted for 47 percent of global chip sales in 2020 (fig. 2).[12] Currently, US chip companies rely almost exclusively on Asian contractors for advanced processes, and the US share of global capacity is predicted to drop to 10 percent by 2030, while Asia's will climb to 83 percent.[13] The absolute necessity to gain global economic leadership in the current scenario is to gain independence in terms of manufacturing and production of semiconductors. This is especially true in the present situation where China is threatening the sovereignty of Taiwan, the chip powerhouse of the world.

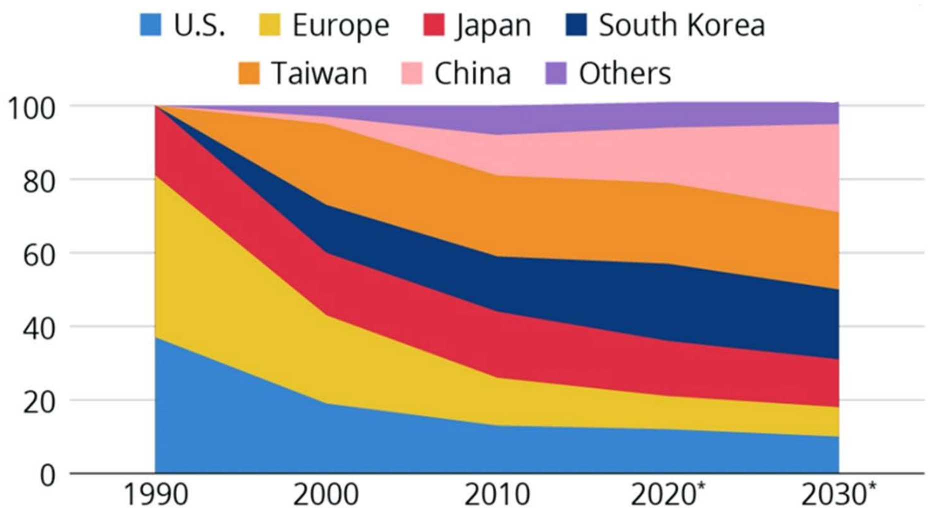

Figure 3. Region wise global manufacturer market share. (Statista.com)

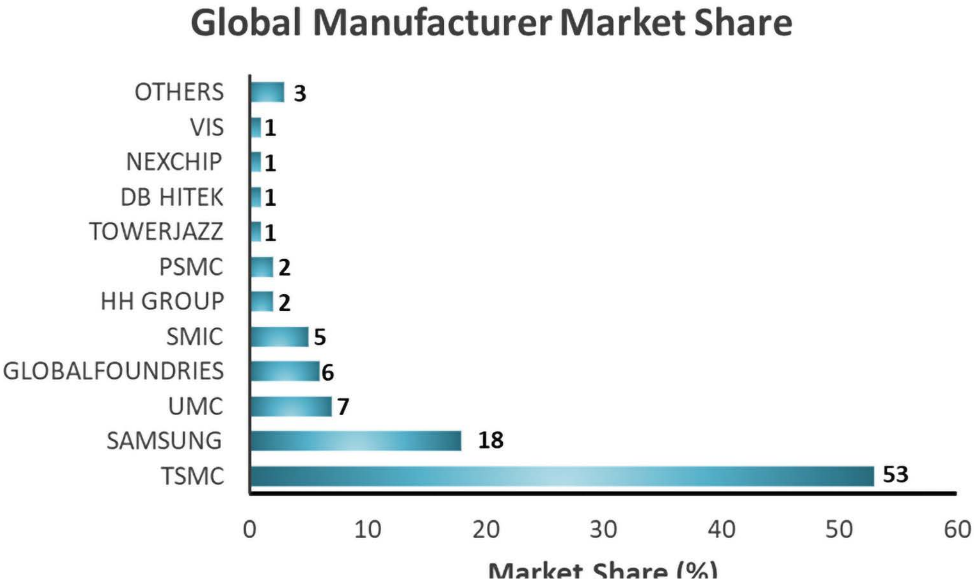

Figure 4. Companies leading the global manufacturer market share. (Statista.com)

Need for Partnership

The US government has recently taken several steps to bridge this gap, prevent such shortages in the future, and cater to the huge domestic and international markets. The recently passed USD 53 billion CHIPS Act is one of the most positive steps in this direction, offering 40-percent investment tax credits to companies manufacturing semiconductors in the United States.[14] Additionally, the act also authorizes the defense ecosystem to conduct research, workforce training, testing, and evaluation for chip-related projects. It also appeals to the government to act as a default customer for the domestic semiconductor industry.[15] However, while this funding may renew the interest in domestic chip-making, adding in numbers to the 75 odd chip-manufacturing units already present (fig. 5), the United States lacks the workforce to maintain this capacity. More than 40 percent of the highly skilled workers in the US semiconductor industry were born in foreign countries, and the number of foreign-born students in the relevant graduate programs has tripled since 1990.[16] However, the current immigration policy is a deterrent to retaining this talent pool. Moreover, the US education system is not producing enough domestic graduates with the appropriate skill sets to join this workforce. Since 2000, the share of foreign-born workers in the science, technology, engineering, and mathematics (STEM) workforce has increased by 40 percent from 1.2 million in 2000 (16.4 percent in STEM workforce) to 2.5 million in 2019 (23.1 percent of STEM workforce). Additionally, these foreign-born STEM workers often have higher levels of educational qualifications than domestic workers. A recent report by the American Immigration Council noted that while 67.3 percent of US-born STEM workers had at least a bachelor's degree, the percentage of the same was 86.5 percent among immigrant STEM workers in 2019. Additionally, almost half (49.3 percent) of immigrant STEM workers hold advanced degrees as compared to 21.8 percent of US-born STEM workers.[17] An older report had also shown how the majority of the immigrant STEM workers are PhD holders, many of whom have obtained their doctoral degrees from US universities.[18] The number of American students enrolled in semiconductor-related graduate programs (~90,000) has not increased since 1990, while the number of international students has nearly tripled from 50,000 to 140,000. About 40 percent of the highly skilled workers working in the US semiconductor industry were born abroad, the majority of whom are from India, followed by China. And, 87 percent of the total semiconductor-related patents awarded to top US universities in 2011 had at least one foreign-born inventor. Between 2000–2010, the United States saw a net influx of 100,000 electrical engineering patent holders, while India and China saw a net outflux.[19] However, not being able to retain this talent owing to immigration and other issues becomes a loss on the part of the United States, while other competing countries gain immensely from this situation. For example, the Taiwan Semiconductor Manufacturing Company (TSMC) was founded and staffed mainly by returnees trained in the United

States. China also seeks to attract semiconductor talent from abroad, and although significant outflow of talent from the United States to China has not been observed yet, even a small number of skilled returnees can help further accelerate China's already booming semiconductor manufacturing industry.[20] As the pandemic slowed down immigration processes and created huge backlogs, the dearth of domestic skill sets and expertise became even more glaring. For example, a chip foundry being built in Arizona by TSMC is straining to employ enough engineers to operate and, as a result, has been delayed by months.[21] A study by Eightfold AI notes that to become self-sufficient in chip fabrication, the United States must recruit engineers and technicians for at least 300,000 additional fabrication jobs, a number that will be impossible to achieve at the current state of higher education in STEM among US citizens or under the restrictions of current immigration policies.[22] A defined partnership in this aspect with a foreign country with a highly motivated workforce can be a solution to this problem by creating a common platform for knowledge and resource sharing. Such a partnership may also enable easy recruitment of experts who can work remotely from the parent country or be hosted as short-term visitors to the United States to train and share expertise with the local workforce. Outsourcing of the workload to different locations in the partner country after building appropriate facilities is also an option that can be explored.

Why India?

India, with its huge human resource and a rich history of excellent technical education, is expected to become an important partner in enhancing and collaborating in the semiconductor manufacturing landscape. The United States and India have a long history of cooperation, which was further strengthened by the New Framework for the US–India Defense Relationship in 2005. The second Defense Technology and Trade Initiative Industry Collaboration Forum (DICF) Virtual Expo was held in November 2021 and co-chaired by US Deputy Assistant Secretary of Defense for Industrial Policy Jesse Salazar and Anurag Bajpai, Joint Secretary (Defence Industries), India, in partnership with US–India Strategic Partnership Forum (USISPF) and the Society of Indian Defence Manufacturers (SIDM). This forum, which represents the basis of the US–India Defense Technology and Trade Initiative (DTTI), aims to strengthen industrial cooperation between the United States and India by identifying opportunities and areas to jointly research, develop, and produce war-fighting capabilities.[23] Earlier this year, the fourth Ministerial Dialogue was held, during which US Secretary of Defense Lloyd J. Austin III and Secretary of State Antony J. Blinken hosted their Indian counterparts, Defense Minister Rajnath Singh and Minister of External Affairs S. Jaishankar, and discussed increased cooperation toward "technological innovation and cooperation in emerging defense domains, including space and cyberspace."[24] The Air Force Research Laboratory (AFRL) nano team has also taken up a recent initiative in exploring nano manufacturing opportunities in partnership with India as a collaborative effort between AFRL, Rice University, and the Indian Institute of Technology Kanpur (IIT–Kanpur).[25] In 2020, Rice University opened a collaborative center at IIT–Kanpur for joint research in the areas of sustainable energy, alternative fuels, and nanomaterials. This center was the first of its kind where a US university will have a physical presence within an Indian campus. Rice is also looking toward signing memoranda of understanding with a few other Indian institutes. All these have nurtured an environment for collaborative research and long-term strategic partnership that can be beneficial to both countries.

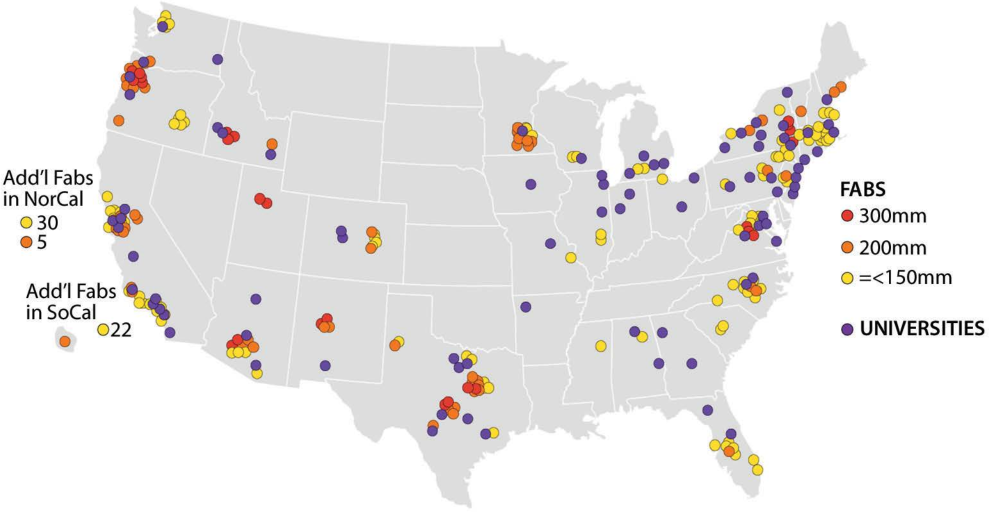

Figure 5. Distribution of different chip manufacture units over USA, including universities, with their capacities. Constructed using data from SEMI World Fab Projections, "World Fab Forecast," November 2021, https://www.semi.org/; and SEMI World Fab Projections, "American Semiconductor Academy Initiative," November 2021, https://www.semi.org/.

India, a chip-design powerhouse, is facing a similar situation in chip supply, as 100 percent of the chips used are imported, primarily from China. Several thousand engineers in India, employed by premier design companies with major presences in the Indian market, work on chip design and very large-scale integration. However, post-design, all these chips are fabricated in Taiwan, China, or South Korea. In 2019, India spent an estimated USD 21 billion on semiconductor imports, 37 percent of which was from China.[26] India has a long tradition of annually producing a large number of highly qualified engineers and science graduates, and the total number of engineering undergraduates in the major streams like computer science, electrical, and electronics engineering in 2020 was more than 3 million (fig. 8). Moreover, 19 percent of the total school-leaving students in India opted for technical courses, including sciences and engineering, according to the Indian National Statistical Service 75th Round Report (2017–18). This percentage is even higher in the southern Indian states, reaching 45 percent (fig. 6).[27] India has a total of 23 Indian Institute of Technologies campuses and 31 National Institutes of Technologies campuses, which are present in almost every state, giving students access to technical education (fig. 6). To a significant degree, this explains why Indians comprise 29 percent of the foreign-born STEM workers in the United States, accounting for one in every four individuals in these streams (fig. 7). What the United States lacks in human resources can be easily made up by highly qualified scientists and engineers from India. Also, many of the IITs work in close collaboration with US universities, which can be leveraged for resource and knowledge sharing.

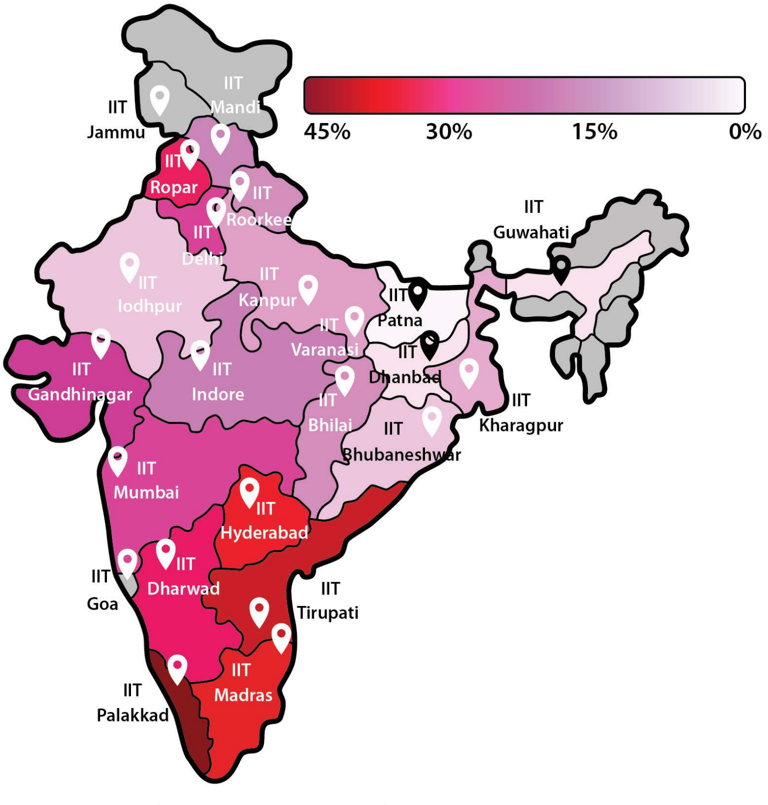

Figure 6. Percentage of students opting for technical courses in India after school in each state. Gray indicates the unavailability of data. The location of the IITs in each Indian state has also been marked. Constructed using data of Ministry of Statistics and Program Implementation, Government of India, "Social Consumption: Education," in Unit Level data & Report on NSS 75th Round for Schedule 25.2, (July 2017–June 2018), http://164.100.161.63/.

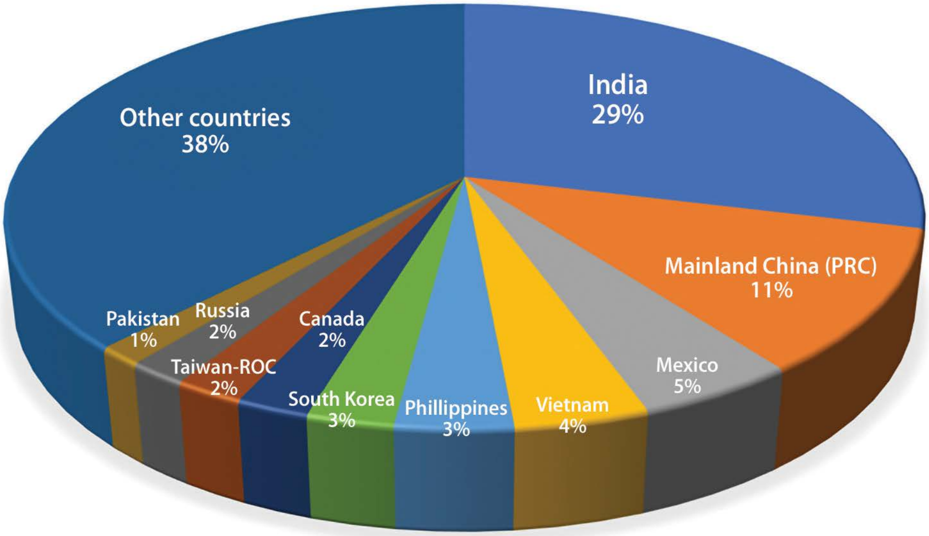

Figure 7. Percentage of foreign-born STEM workers in USA from different countries. Constructed using data from Statista.com.

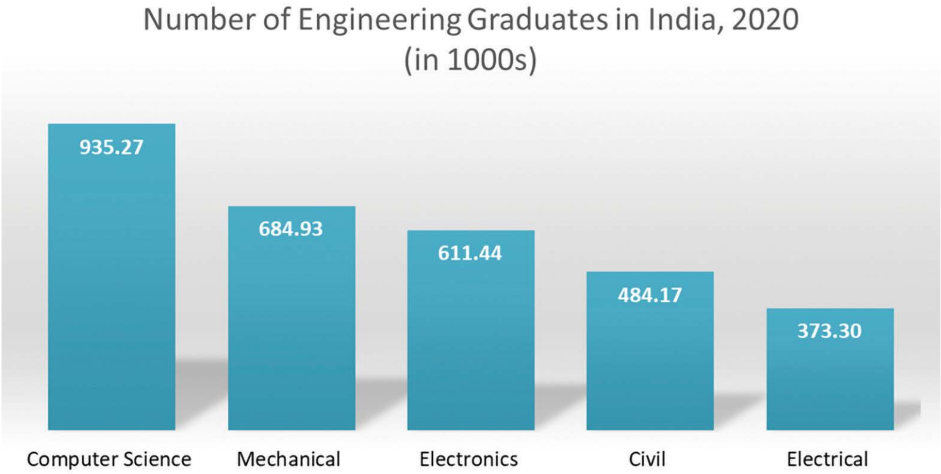

Figure 8. Number of engineering graduates in India in different disciplines in 2020. Constructed using data from Annual Report of American Immigration Council, 2021, https://www.americanimmigrationcouncil.org/.

The acute chip shortage has had severe adverse effects on the smart-gadget market of India, which is the second-largest smartphone manufacturer in the world.[28] Tense Sino–Indian relations have further raised apprehensions regarding sourcing chips easily.[29] Historically, India had sought to develop its own semiconductor fabrication system since the inception of the state-owned Semiconductor

Complex Ltd. in 1984.[30] However, a series of unfortunate events have hindered progress in that sector. In a parallel to the CHIPS Act in the United States, since 2013, the Government of India has lifted the import duties on all components of semiconductor manufacturing. Additionally, New Delhi offers incentives in the form of tax concessions, interest-free loans, and subsidies to anyone seeking to build a fabrication unit to boost domestic manufacturing of chips. Hence both countries have a common ground of interest in developing semiconductor manufacturing to cater to their domestic markets as well as to supply the global market, which makes the partnership an important step in achieving this goal swiftly.

Areas of Partnership

There are various areas of semiconductor and nano manufacturing that need immediate attention to maintain an unhindered military supply chain. All these areas will flourish when done in partnership with a country with the necessary resources, complimentary to those of the United States.

Chip Manufacturing

One of the most difficult feats to achieve in this context is the establishment of chip-manufacturing units to gain independence in terms of chip supply. At present, an entry-level chip factory that can produce 50,000 wafers a month, requiring a USD 12–15 billion investment and two to three years of establishment time. However, more capital is required to upgrade the equipment involved (including lithography, testing and evaluation, and cleanroom facilities), which becomes obsolete in the global market in roughly five years or less. The capital expenditure required for a semiconductor industry has an escalating annual growth rate, with that for 2021 being 34 percent.[31] Sustenance of conventional plants demands an annual profit of ~20 percent of initial investment with a 90-percent yield.[32] To maintain this profit model, global leaders like TSMC rely on large volumes and numbers to recoup cost. This again is a difficult task to achieve in an entry-level fabrication unit. Manufacture of a single silicon (Si) chip takes up to three months and involves the use of high-quality cleanrooms and extremely sophisticated machinery. The access to chip-making equipment has always remained a hurdle and was one of the focal points of the Pentagon's Sematech Program in the 1980s. Advanced Semiconductor Materials Lithography (ASML), Netherlands, is the only company in the world with the extreme ultraviolet lithography machines required to produce the most advanced microprocessors with geometries less than 10 nm. Typically, the handful of US companies in business manufacture machinery for producing chips with much larger geometries.[33] A newly established entry-level chip-fabrication unit will be especially difficult to sustain because once the current shortage of chips is mitigated, due to the scale of production, it will be almost impossible to provide chips at the same cost as global giants like TSMC. Additionally, as mentioned in the previous section, the United States majorly lacks the human resources necessary to maintain a highly productive chip-manufacturing facility. However, while the numbers and resources may be too hefty for a single country to invest in, it will be a much easier task done in partnership, in terms of achieving the scale required to compete globally. Since recent government policies of India and the United States have emphasized the need for domestic fabrication, with support in terms of tax exemptions, resources and monetary incentives, this partnership can become extremely fruitful in achieving the targets for both countries. In this aspect, India's greatest strength will be its large pool of human resource with high levels of technical education, while the US contribution will be its excellent infrastructural facilities.

Scalable Production of Novel Nanoelectronic Materials and Semiconductors

While it is important to invest in the establishment of an entirely new fabrication unit for semiconductor chips, it will probably be far more beneficial to invest in new and upcoming materials and processes that have the potential to replace the conventional silicon chip in the near future. The victory march of silicon over the world of electronics and technology began about 60 years ago, with the large-scale use of the Czochralski or floating zone methods to fabricate large, defect-free single crystals of silicon.[34] However, the recent global chip shortage,[35] coupled with silicon technology gradually approaching its performance limits,[36] has led to the exploration of nanoelectronic applications based on promising new 2D materials. While graphene is definitely one of the forerunners in this category, the absence of a natural energy band gap limits its applications in electric switches, sensors, and optoelectronic devices. However, alternative 2D materials—like transition material dichalcogenides (TMD)—with a sizable band gap have been showing great promise in filling the gaps in applications that cannot be bridged by conventional silicon-based semiconductors or graphene.[37] One of the major challenges in this aspect is the growth of single crystalline structures of TMDs for unhindered optoelectronic applications. Although the high-quality samples obtained by mechanical exfoliation with dimensions ranging from a few to a hundred nanometers may be sufficient to study the intrinsic properties of this material, they are not good enough for industrial applications.[38] To succeed in the electronics industry, the primary requirement is the formation of high-quality large-area single crystalline films. The mixture of grain sizes and presence of grain boundaries lowers the efficiency of performances of devices based on polycrystalline 2D materials, as compared to single crystalline materials, which makes the development of wafer-scale single crystalline (WSSC) 2D materials extremely important. Many recent developments in the synthesis of WSSC 2D TMDs have opened new vistas toward new electronic devices. Additionally, while engineers continue to make advancements with transistor technologies at the latest process nodes, interconnects within these structures are still struggling to keep pace. This is particularly true for nodes beyond 2 nm. The dual damascene procedure has been in use for a while, and unwanted resistance-capacitance delay issues will become even more pressing beyond 3 nm.[39] However, since the advancement of interconnect technology is crucial for transistor development, it is inherent to chip scaling. Hence, a nextgeneration, cost-effective interconnect scheme beyond 2 nm is of utmost importance for chip scaling. Methods like hybrid metallization, semi-damascene, supervias, or graphene interconnects are all technologies and material that are currently in research and development and require far more development for industrial scale production. Investing in the abovementioned problems and technological developments now is extremely important to become global leaders in the field in the future. There are several promising new 2D materials that have the potential of becoming steppingstones for future technology, and endeavors to refine them for industrial and defense applications now can be crucial for the future ahead.

Investing in the development of an industrial scale, roll-to-roll nanomanufacturing process for the unconventional fabrication of electronic devices for targeted applications is also an important step. As discussed before, typically the fabrication of silicon chips is highly demanding in terms of specialized equipment and cleanrooms. To lower the cost and complication toward their fabrication, it is important to investigate alternative methods for nanofabrication and eliminate the extensive use of specialized, high-cost cleanrooms and fabrication techniques required by traditional chip manufacturers. This would significantly diminish infrastructural and financial capital demands while still producing large quantities of semiconductor devices for regular use. Unconventional semiconductor manufacturing, such as molecular printing and roll-to-roll manufacturing, which has very few requirements in terms of specialized clean rooms and fabrication techniques, is an attractive approach that can be very lucrative to India and the United States. It diminishes the infrastructural and financial capital demands to a great extent, while producing large quantities of chips fit for regular use. Moreover, the reduction in use of cleanrooms for such unconventional fabrication can reduce health hazards to the professionals and potentially decrease the huge carbon footprint associated with chip manufacturing. Academia has already attempted to replicate minienvironments to conduct semiconductor fabs to reduce cost and environmental hazards.[40] Similarly, patterning and stenciling have also emerged as alternative cleanroom-free fabrication techniques.[41] Flexible hybrid electronics that uses chips other than silicon wafers—for example, ceramics, glass, plastic, polyimide, polymers, polysilicon, stainless steel and textiles, fabricated using different printing, patterning and ink-writing techniques—have also started gaining prominence.[42] Probing and developing such procedures can definitely reduce the capital required for manufacturing units and would help in establishing more such plants globally. Hence creating a concise knowledge base in this area can also factor into the agenda of forging a better partnership.

Nano/Flexible Electronics Devices

The demand for thin-film and conformable electronics, sensors, and wearable devices is ever increasing. Sensors of higher selectivity and sensitivity, and electronics of conformal form factors, are in demand for defense and commercial systems. A focus on scalable growth processes of emergent materials such as TMD, graphene, nanodiamonds, and their hybrids and heterostructures, which are attractive for expanded operational domain and tailored functionality for electronics, will be extremely beneficial for the future of military- and defense-related devices. Device performance testing related to defense-specific applications (harsh environment—temperature, moisture, durability) can be pursued in collaboration with the defense research agencies of the United States and India.

Energy Storage/Conversion Devices

The development of scalable manufacturing approaches for low-cost manufacturing of energy storage and conversion units, including thin-film batteries, supercapacitors, and fuel cells can also be another primary interest of this partnership. The manufacturing processes developed should also be tailored to suit these energy storage/conversion devices. Lithium-ion batteries (LiB) are crucial for the day-to-day functioning of the modern world. LiB production is also one of the industries that is heavily reliant on China to maintain its supply chain. The chip shortage highlights how the locational concentration of such an important industry can have severe detrimental effects on the entire world if the supply chain is disrupted. It is extremely important to be independent in terms of LiBs lest a similar shortage happen in the future. Globally, the use of LiBs is projected to increase almost threefold from 250 million units in 1998 to 700 million units in 2030.[43] The United States has been looking for a positive shift toward electric vehicles, with the Departments of Transportation and Energy recently announcing USD 5 billion for the construction of a national network of electric vehicle-charging stations.[44] This will significantly increase the LiB usage in the United States. The LiB usage in India is also expected to grow at a compound annual growth rate of 1 percent to more than USD 4.80 billion by 2026.[45] The manufacturing processes developed jointly should also satisfy the pressing needs for flexible and thin-film batteries and comply with the low-footprint energy requirements for forward-based operations, and more. Emphasis will focus on identifying alternatives to rare earth materials for fabrication of energy devices. The large-scale manufacture of printable renewable energy devices for their widespread commercialization should also be a goal of this partnership.

The exponential increase in LiB demand has culminated in the dual problems of LiB waste management on one hand and supply of critical component materials (e.g., cobalt, nickel, graphite, lithium, and manganese) for LiBs on the other. The current trends in mobile and stationary LiBs usage projects the demand for graphite, lithium, and cobalt to increase by almost 500 percent by 2050, and a shortage of nickel is estimated to arise within the next 5–6 years.[46] These crucial materials have merely finite reserves in the earth's crust, many of which lie in potentially conflicted regions and war zones. For example, more than 51 percent of lithium reserves lie in Chile, 47 percent of manganese reserves lie in South Africa and Ukraine, and 55 percent of the graphite reserves lie in Russia and China. One of the most critical elements for LiBs is cobalt, which makes up to 15 percent by weight of the cathode mass of a LiB. This is also one of the most at-risk elements, since almost 60 percent of the global reserves of cobalt lies in the Democratic Republic of Congo, another country that is heavily reliant on China for its economic growth. Additionally, the cobalt mines in Congo (many of them controlled by Chinese agencies) has been flagged for their extremely poor and hazardous working environment, exploitation of child labor, and disregard for worker rights.[47] Although several attempts are being made at the development of batteries with low to no cobalt content, these efforts are yet to match up with the commercial performance levels. Hence recycling of LiB systems is crucial in e-waste management while establishing circular economy by recovering the active materials, diminishing the need for extensive mining. The most commonly prevalent methods to recover the active materials of LiBs include pyrometallurgy,[48] hydrometallurgy,[49] bioleaching,[50] or mechanical methods,[51] although these methods require thorough research and fine-tuning to become scalable and economically viable. Another critical aspect of LiB recycling is also to secure a supply line of used batteries through the judicious segregation and transportation of e-waste. Since India and the United States have very little reserves of the materials required for LiBs, a partnership should definitely be explored for the collection of spent batteries and their subsequent recycling to recover the active materials.

Expected Outcomes

A unified approach to deal with the chip shortage and supply-chain monopoly is the need of the hour. While the recently passed CHIPS Act pumps new life into semiconductor research in the form of substantial capital investment, the United States struggles to recruit enough engineers and technicians to meet the needed capacity. On the other hand, India, with its excellent technical knowledge base, lacks major capital investment in semiconductor research and hence the required infrastructure, except for some private players. Using the technical know-how and human resource pool of India and the infrastructure and technology of the United States looks promising for the development of a joint venture. In this context, a collaborative center between the defense agencies and academic institutions of both countries may be favorable for the research and development of promising new materials with applications in electronics and their translation into defense applications. The huge financial and environmental concerns associated with chip manufacturing may be alleviated in part by investing in research and development of unconventional fabrication of semiconductors, involving materials other than Si wafers or different cleanroom-free techniques. In addition to semiconductor manufacturing, investment in the energy sectors, especially that of battery development, may be useful in order prevent such shortages in the future. Both countries stand to gain significantly from this initiative directly and indirectly. The direct outcome will obviously be building up a self-reliant semiconductor economy, with a head start in new materials or technologies that have the potential to dominate the market in the future. The indirect gains for India will be the ability to train and use the cutting-edge research facilities and infrastructure of the labs in the United States, while dividend for the United States will be the ability to procure a steady technically sound workforce to keep up with the increased production capacities. Overall, this can be an extremely fruitful partnership for both countries that can propel them to the forefront of semiconductor industry in the near future. ✪

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Dr. Bhattacharyya is a Rice Academy Postdoctoral Fellow in Ajayan group at the department of Materials Science and NanoEngineering, Rice University. She earned her PhD under the guidance of Prof. Tapas K. Maji at Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bangalore, on post-synthetic modification of metal-organic frameworks. Prior to this, she obtained her bachelor's degree in chemistry from Presidency College, Kolkata, and master's degree in materials sciences from Chemistry and Physics of Materials Unit, JNCASR, Bangalore. Her current research interests include exploring green and sustainable methods for recycling lithium-ion batteries. She was a recipient of the prestigious Innovation in Science Pursuit for Inspired Research (INSPIRE) Fellowship from the Department of Science and Technology, Government of India.

Dr. Soumyabrata Roy

Dr. Roy is currently a research scientist in Ajayan group at the department of Materials Science and NanoEngineering, Rice University. He received his PhD in chemical science from Jawaharlal Nehru Centre for Advanced Scientific Research, India, in the group of Sebastian C. Peter, after completing his master's in chemistry from IIT, Kharagpur. His current research interests are focused on developing advanced materials and integrated processes for energy conversion, catalysis, and greenhouse gases (CO2 and CH4) capture and utilization. He was a recipient of the prestigious Inspire Fellowship, Department of Science and Technology, Government of India, and Royal Society of Chemistry Commonwealth grants.

Dr. Michael E. McConney

Dr. McConney is senior materials engineer and lead of the Agile Electronic Materials and Processing Team (AEMPT) in the Materials and Manufacturing Directorate at Air Force Research Laboratory (AFRL). He received his BSE in chemical engineering from the University of Iowa in 2004 and his PhD in Polymer Materials Engineering from Georgia Tech in 2009. He started working at AFRL in 2009 as a National Research Council Post-Doctoral Fellow. He was the recipient of the AFRL Early Career Award. He has more than 90 publications with more than 4,500 citations in research that spans many areas including photonics, electronics, liquid crystals, microwave magnetic materials, surface science, scanning probe microscopy, responsive materials, and sensing.

Dr. Nicholas Glavin

Dr. Glavin is a senior materials engineer in the Materials and Manufacturing Directorate at the Air Force Research Laboratory (AFRL). He received his PhD in mechanical engineering from Purdue University in 2016 after completing his MS and BS in chemical engineering from the University of Dayton in 2012 and 2010, respectively. His research at the AFRL is primarily focused on industrially-relevant processes to enable two-dimensional nanomaterials and III-V electronic materials for applications in electronics and sensors. He is the recipient of several awards including the AFRL Early Career Award, the Air Force John L. McLucas Basic Research Award Honorable Mention, and the American Vacuum Society Paul Holloway Young Investigator Award.

Dr. Ajit Roy

Dr. Roy is a computational group leader at the Materials and Manufacturing Directorate at the Air Force Research Laboratory (AFRL) with years of leadership experience in materials innovations and development in structural, thermal, and electronic materials. He has published widely in the fields of integrating multiscale computational methods to materials processing for accelerated materials development and technology transition. He has pioneered carbon foam technology and nano-porous carbon as multifunctional materials for coatings, heat exchangers, flexible electronics, and battery electrodes. His durable thermal interface concept has transitioned to commercial production. He is recognized with American Society for Composites (ASC) Outstanding Research Award and Fellow of AFRL, American Institute of Aeronautics and Astronautics, American Society of Mechanical Engineers, and ASC, and serves on journal editorial boards, national and international review panels, awards and executive committees in professional societies, and advisory committees.

Dr. Pulickel M. Ajayan

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