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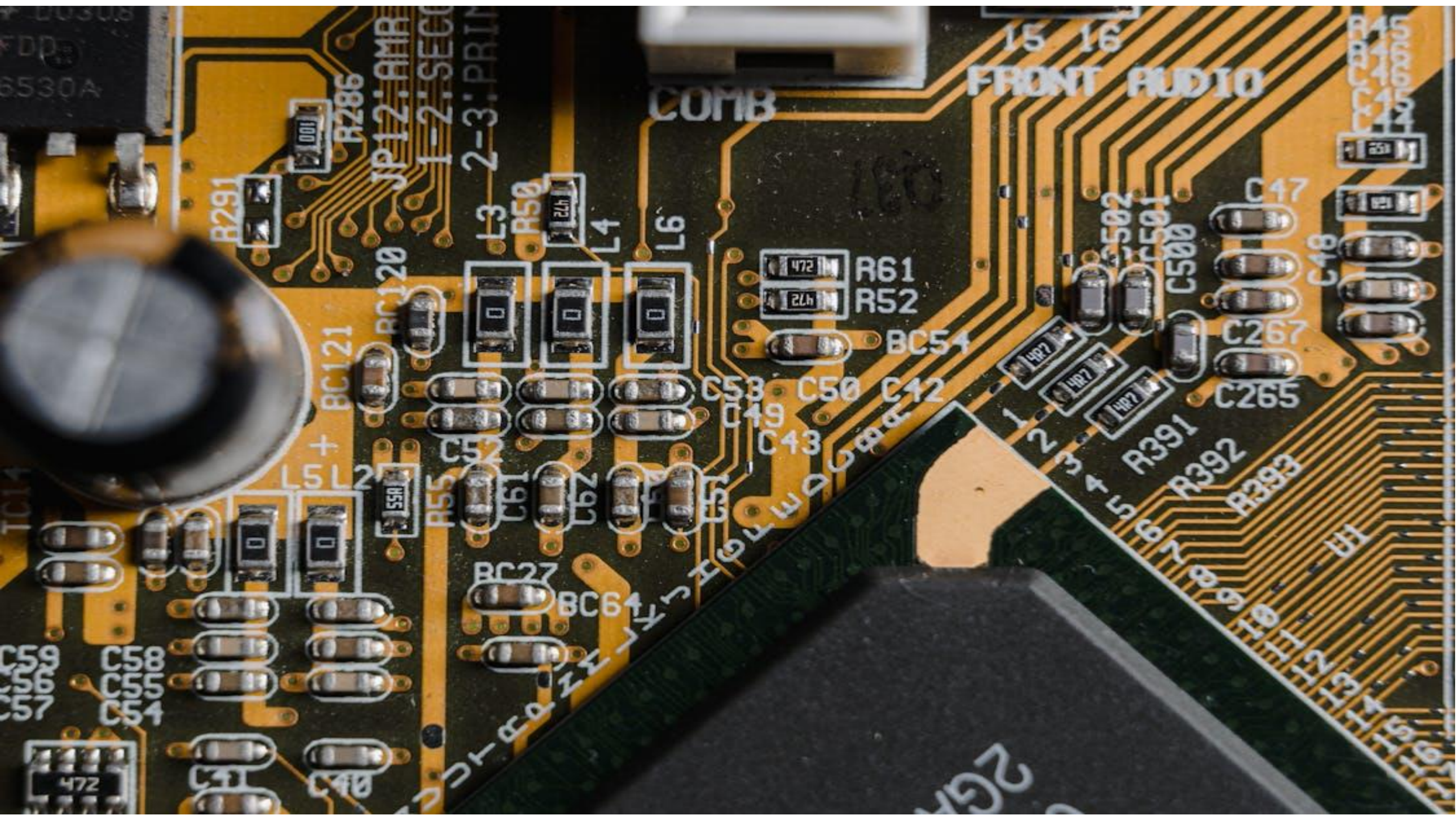
Building India's Semiconductor Ecosystem: Capabilities, Resources & Global Prospects



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Content

Executive Summary

Semiconductors are indispensable to the digital economy, powering critical sectors such as electronics, telecommunications, and computing. Despite their global importance, manufacturing remains concentrated in a few countries, creating a strategic imperative for diversification. India, as the world's fourth-largest economy, is aggressively pursuing a transformative semiconductor mission to evolve from a predominantly import-dependent market into a significant player in research, design, and manufacturing.

This paper offers an analysis of India's semiconductor ecosystem by examining:

- The current state of manufacturing capabilities, including fabs, design houses, and supportive infrastructure, alongside government initiatives like the India Semiconductor Mission (ISM) and production-linked incentives that aim to accelerate domestic fabrication capacity.
- The availability and strategic importance of critical raw materials such as rare earth elements, lithium, and gallium, which underpin semiconductor production and supply chain resilience.
- India's future prospects in establishing a competitive semiconductor industry, assessing policy frameworks, industrial projects, scientific expertise, and workforce development.

To contextualize India's ambitions, the paper benchmarks its semiconductor ecosystem against global leaders like the United States, China, and Taiwan, each representing distinct strategic approaches and industrial maturity. These comparisons illuminate the challenges and opportunities India faces as it strives to build a sustainable, globally integrated semiconductor industry.

Importantly, this analysis takes a pragmatic approach, presenting a realistic picture of India's current capabilities without unwarranted optimism. It focuses on identifying realisable opportunities where India can strategically position itself- particularly in mature-node fabrication, chip design, and assembly/testing to make a meaningful mark in the global semiconductor value chain.

The paper attempts to serve as a guide for policymakers, industry stakeholders, and investors committed to advancing India's semiconductor vision and contributing to a more diversified and resilient global technology landscape.

Introduction

Semiconductor chips are often called the "oil" of the digital age – foundational components that drive modern electronics, computing, telecommunications, and critical infrastructure. The global semiconductor industry has historically been dominated by a few countries, notably the United States (in chip design and equipment), East Asian economies like Taiwan and South Korea (in fabrication), and more recently China (through massive investments in manufacturing capacity) (Miller, 2022). In this context, India – the world's fifth-largest economy – has launched an ambitious quest to become a significant player in semiconductors, aiming to transform from a predominantly chip-importing country into a hub for semiconductor research, design, and manufacturing.

The rationale for India's semiconductor mission is multifaceted. Geopolitically, the "chip war" in the global tech landscape has underscored the strategic importance of chip self-sufficiency for economic security and military power (Miller, 2022). Economically, India's domestic semiconductor market is poised to expand dramatically – from around US$38 billion in 2023 to over $100 billion by 2030 – fuelled by surging demand for smartphones, computing, automobiles, and other electronics in a fast-growing economy. This growing market creates strong incentives to develop in-country manufacturing and reduce reliance on imports. Furthermore, India boasts strengths such as a large talent pool of engineers and a well-established semiconductor design services sector. Indeed, India already hosts over 200 semiconductor design and embedded systems companies and accounts for roughly 20% of the world's chip design engineers. Major global firms like Intel, Texas Instruments, NVIDIA, Qualcomm, AMD and others have long operated design R&D centres in India, making the country a top destination for chip design talent – "second only to the United States" (Nair, 2025). However, India has historically lagged in chip manufacturing, with minimal on-shore fabrication capacity. The government's renewed push via the "Make in India" initiative, the production-linked incentive (PLI) schemes, and the dedicated India Semiconductor Mission (ISM) launched in late 2021 is intended to change this scenario.

This paper is structured to analyse three key aspects of India's semiconductor mission:

(1) **Current Manufacturing Capabilities** – examining existing fabs, foundries, design houses, and infrastructure, and how government policy is bolstering these;

(2) **Rare Earth Elements and Critical Materials** – detailing India's resources (and gaps) in materials like rare earths, lithium, gallium, etc., which are crucial for chipmaking supply chains; and

(3) **Future Prospects** – evaluating whether India can realistically build itself into a leading semiconductor-producing nation, in light of its policy framework, industrial projects, and scientific capabilities.

The analysis also includes comparisons with the semiconductor ecosystems of the United States, China, and Taiwan. These three make for instructive benchmarks: the U.S. pioneered the semiconductor revolution and remains a leader in chip design and innovation; China has declared semiconductors a national priority, investing tens of billions to attain self-reliance (yet still struggling for cutting-edge mastery under export controls); and Taiwan offers a striking success story of how consistent policy focus and cluster development created TSMC, a company that today manufactures around 50% of the world's semiconductors and an estimated 92% of the most advanced chips. By comparing India's approach and progress with these nations, we can better gauge India's potential trajectory in the global semiconductor race.

India's Current Semiconductor Manufacturing Capability

2.1. Government Policy and Initiatives for Semiconductor Manufacturing

2.1.1. Historical context and policy shifts

India's efforts to establish semiconductor manufacturing are not entirely new – the country made initial forays as far back as the 1980s when it set up the government-owned Semiconductor Complex Limited (SCL) in Mohali. SCL, however, remained a relatively small facility focused on older-generation chips for strategic use, and a 1989 fire setback its progress. For decades thereafter, India's semiconductor policy environment was relatively dormant, with no major commercial fabs being built. High capital costs, fast-evolving technology, and competition from East Asia deterred investment. Consequently, by the 2010s, India had virtually no modern fabs, even as it excelled in chip design talent. Recognizing this strategic gap, the government's stance changed markedly in the 2020s. In December 2021, the Union Cabinet approved a comprehensive semiconductor development program with a roughly **₹76,000 crore (US$10 billion)** outlay to attract chip fabrication and display fabrication units to India (Abbas, 2024). This initiative, under the banner of the **India Semiconductor Mission (ISM)**, signaled a major policy commitment to build an end-to-end semiconductor ecosystem domestically.

2.1.2. India Semiconductor Mission (ISM) and incentive schemes

The ISM provides a policy framework and financial incentives to potential investors in different parts of the chip value chain. For semiconductor wafer fabs (silicon CMOS fabs), the government initially offered to cover up to 50% of the capital expenditure of approved projects (with additional incentives from states). Similar support was extended to display panel fabs. For assembly, testing, marking, and packaging (ATMP/OSAT) units, incentives of around 30% of capital expenditure were provided. Additionally, a Design-Linked Incentive (DLI) scheme was launched to support 50% of eligible costs for domestic chip design startups and firms, aiming to foster design IP creation in India. These incentives are part of a Production-Linked Incentive (PLI) approach, which ties benefits to actual investments and output over time. By 2023, the government sweetened the offer further-- it re-opened applications under ISM with more flexible terms, such as raising the fiscal support for all technology nodes to 50% (previously, only fabs up to 28 nm were eligible for maximum 50% support) and including compound semiconductors and silicon photonics in the scheme.

2.1.3. Policy execution and project approvals

Since 2022, India has evaluated multiple proposals for fabs. Initially, three consortiums applied: (1) **Vedanta-Foxconn JV**, which proposed a 28 nm logic fab and a separate display fab in Gujarat; (2) **ISMC** (a consortium including Abu Dhabi-based Next Orbit Ventures and Tower Semiconductor of Israel) proposing a fab in Karnataka; and (3) **IGSS Ventures** from Singapore proposing a fab in Tamil Nadu. By mid-2023, these early proposals encountered roadblocks – for instance, Foxconn withdrew from the Vedanta JV amid disagreements on technology partnerships, and the others stalled due to funding and technical tie-ups (Reuters, 2023). The government subsequently invited fresh proposals and also moved to revamp SCL Mohali by involving a commercial partner. In February 2023, SCL was transferred from the Department of Space to the Ministry of Electronics and IT (MeitY) to be modernized as a research fab and potentially act as a training ground for talent. Nine companies (including Tata and Tower) reportedly showed interest in the SCL revamp.

A major breakthrough came in late 2023 and early 2024. Tata Electronics, part of India's Tata conglomerate, in partnership with Taiwan's Powerchip Semiconductor Manufacturing Corp (PSMC), submitted a proposal for a new fab. This was approved by the Cabinet in February 2024 as India's first significant commercial semiconductor fabrication project. The government signed a fiscal support agreement with Tata, committing to cover 50% of the project cost through ISM. Around the same time, the government also approved several assembly/test plants and reconstituted some earlier proposals:

2.1.3.1. Micron Technology's ATMP

In mid-2023, the U.S. memory maker Micron agreed to set up a semiconductor assembly and test facility in Sanand, Gujarat, with a $2.75 billion investment (with $825 million by Micron and the rest subsidized by central and state governments). The project moved swiftly – by September 2023, construction had begun, and Phase I of the plant (500,000 sq. ft clean room) was slated to be operational by early 2025, producing packaged memory chips by end-2024. This demonstrated the government's ability to attract a top global chip firm for downstream manufacturing (TIMESOFINDIA.COM, 2023).

2.1.3.2. HCL-Foxconn joint venture

In 2024, a joint venture of Indian IT firm HCL and Taiwan's Foxconn (Hon Hai) was approved to set up a semiconductor manufacturing facility near Noida, Uttar Pradesh. Uniquely, this project focuses on producing display driver ICs – chips used in screens for phones, laptops, cars, etc. – with a planned capacity of 20,000 wafers per month. The investment is relatively modest at ₹37 billion (~$434 million), indicating this will be a mature-node fab (display drivers typically use 28 nm to 130 nm processes). This project's approval in May 2025 signified an expansion of India's semiconductor foray beyond just one big fab, into specialized chips manufacturing (Barik, 2025).

2.1.3.3. Tata's OSAT in Assam

Alongside its fab, Tata is also investing in an Outsourced Semiconductor Assembly and Test (OSAT) facility in Jagiroad, Assam. This ₹270 billion (~$3.2 billion) project was allotted 170 acres at a defunct paper mill site, and construction is underway (*Tata Group to Build the Nation's First Fab in Dholera | Tata Group*, n.d.). The Assam government is a major partner, contributing up to ₹210 billion via incentives. This plant will encapsulate and test chips (likely those made at the Gujarat fab and elsewhere) and is expected to produce its first semiconductor chips by 2025, according to Assam's Chief Minister. It is also coupled with a new Skill Development Centre on-site for workforce training in semiconductors and AI. The choice of a Northeastern state for such a high-tech unit underscores the national spread of the mission.

2.1.3.4. Renesas–Murugappa OSAT

A collaboration involving Renesas Electronics (Japan), Murugappa Group's CG Power (India), and Stars Microelectronics (Thailand) is establishing another OSAT plant in Sanand, Gujarat. A pilot assembly facility is to be completed by mid-2025, with the main plant by 2026–27. The total investment (~$220 million) is smaller, suggesting a focus on particular package types or a phased growth. Renesas' involvement indicates international interest in India as an assembly base, leveraging India's expertise in semiconductor packaging and testing.

2.1.3.5. Kaynes Semiconductor fab

In September 2024, the government approved a proposal by Kaynes Technology, an Indian electronics firm, to set up a semiconductor manufacturing unit in Sanand with ₹33.07 billion (~$394 million) investment. The unit – dubbed "Kaynes Semicon" – will have capacity for 6.3 million chips per day and cater to sectors like automotive, telecom, and consumer electronics. While details on the node/technology are scant, such output volume suggests it could be an ATMP facility or a compound semiconductor fab producing simpler device (e.g., silicon power devices or microcontrollers) at scale (P, 2025). This became the fifth project approved under ISM (*Cabinet Approves One More Semiconductor Unit Under India Semiconductor Mission (ISM)*, n.d.).

Table 1 below summarizes the major semiconductor manufacturing projects in India as of 2024–2025, reflecting the surge of activity initiated by government policy support:

Project (Company)	Type	Location (State)	Investment	Capacity / Output	Timeline
Tata-PSMC Fab **(Tata Semiconductor Manufacturing)**	**Wafer Fabrication (Silicon CMOS)** – targeting 28–65 nm nodes (logic & mixed-signal)	Dholera, Gujarat	₹910 billion (≈ US$10.4 billion) – 50% government-funded	50,000 wafers/month capacity (300 mm wafers); products: power management ICs, MCUs, logic for automotive/AI	Construction underway (foundation in 2024), production expected ~**2026**.
Tata "TSAT" OSAT **(Tata Assembly & Test)**	**Assembly & Test (OSAT)** – packaging chips (incl. memory, logic, etc.)	Jagiroad, Assam	₹270 billion (≈ US$3.2 billion) – with major state incentives (Assam)	Est. ~**70 million chips/day** when fully operational (assembly output; includes multiple package types)	Land allotted 2023; first chips expected by **2025**. Workforce training centre on-site.
Micron ATMP **(Micron Technology)**	**Assembly & Test (Memory)** – DRAM/NAND packaging and testing	Sanand, Gujarat	US$2.75 billion (₹225 billion) – (30% Micron, 70% govt support)	Phase 1: 500,000 sq ft cleanroom, packaging memory chips (e.g. DRAM modules) by Dec **2024**; full capacity after Phase 2 (~late 2020s) – ~**5,000 jobs** created.	MoU signed 2023; construction started Sep 2023; operations from **2024–25**.

HCL-Foxconn JV Fab	**Wafer Fab (200 mm)** – specialized in Display Driver ICs (mature node CMOS)	Noida, Uttar Pradesh	₹37 billion (≈ US$430 million)	20,000 wafers/month capacity (likely 200 mm wafers); producing **display driver chips** for smartphones, laptops, automotive displays, etc.	Approved May 2025; land allotted at YEIDA Industrial Park; expected operational by **2026–27** (estimated).
Renesas-CG (Murugappa) OSAT	**Assembly & Test (OSAT)** – Outsourced assembly/test for various chips	Sanand, Gujarat	US$222 million (pilot + phase 1)	Initial pilot line by mid-**2025**; main plant by **2026–27**; will output finished chip packages (targeting mid-volume specialty chips). Renesas to use facility for automotive and industrial semiconductors.	Under development (pilot facility completion by Jul 2025; full production by Oct **2027**).
Kaynes Semicon Fab **(Kaynes Technology)**	**Wafer Fab or OSAT** – exact tech not public (likely discrete semiconductors or sensors)	Sanand, Gujarat	₹33.07 billion (≈ US$394 million)	Projected output **6 million chips per day** (assuming small devices); will support automotive, EVs, consumer electronics, etc.	Approved Sep 2024; expected commissioning by **2025–26**.

Table 1. Major Semiconductor Manufacturing Initiatives in India (Approved or Underway)

As Table 1 illustrates, India's nascent semiconductor manufacturing landscape (through ISM) is presently focused on mature and mid-range technologies – e.g. 28 nm and above for logic, packaging of memory and other chips, and specialty semiconductors like display drivers and power electronics. Notably absent (so far) are any facilities for cutting-edge logic nodes (sub-10 nm processes) or large-scale memory fabrication. This is by design – India has chosen to start with older nodes where technology transfer is more feasible and the learning curve less steep.[1] Officials have openly stated that the first Tata-PSMC fab "will not produce cutting-

[1] Mature-node semiconductor technologies—typically 28 nm and above—play a critical role in supporting high-volume, cost-sensitive applications such as automotive electronics, power management, and IoT devices, offering a strategic entry point for nations looking to build a domestic semiconductor base (Awasthi, 2024; Mandavia, 2024). These nodes are more economically accessible, technologically resilient, and better supported by existing lithography infrastructures compared to sub-5 nm chips, which require highly advanced—and costly—EUV tooling (Awasthi, 2024). While smaller, cutting-edge nodes (e.g., 5 nm, 3 nm) drive high-performance computing and AI, they demand enormous R&D investment, manufacturing complexity, and mature ecosystems—barriers that make them almost inaccessible to emergent players like India in the near term (Firstpost, 2024; The Indian Express, 2024). India's landmark initiative with Tata–PSMC to set up a 28 nm fab underscores this pragmatic approach, enabling the country to bootstrap its semiconductor ambitions via mature-node production before attempting advanced-node capabilities (Mandavia, 2024; Business Today, 2024). Ultimately, while advanced-node fabs hold long-term prestige, building a robust mature-node ecosystem is essential for India's immediate industrialization, supply-chain resilience, and scaling toward future nodes.

edge nodes" beyond current capabilities of those companies. Instead, it will produce chips for high-demand areas like automotive MCUs, power management ICs, and some high-performance computing (HPC) logic on trailing-edge nodes (likely 65 nm, 45 nm, or 28 nm). This strategy reflects awareness that jumping straight into 5 nm or 3 nm fabrication would be unviable without existing infrastructure and IP – as Chris Miller noted, attempting advanced nodes "overnight" is unrealistic and even countries like Taiwan and South Korea took decades to achieve their current capabilities.

2.1.4. Infrastructure and cluster development

The Indian government is also treating semiconductor manufacturing as an ecosystem play. Policies are encouraging the formation of cluster hubs – for example, in Gujarat's Sanand/Dholera and in Uttar Pradesh's Noida – where fabs and OSATs are co-located with infrastructure and suppliers. The Dholera Special Investment Region in Gujarat, where the Tata fab is sited, is being developed with reliable power, water, and logistics specifically for high-tech industries. Likewise, the Yamuna Expressway Industrial Zone near Noida (Greater Noida) has earmarked land for the HCL-Foxconn plant and possibly future fabs, complete with proposals for a semiconductor hub and training facilities. These efforts echo the cluster model of Taiwan's Hsinchu Science Park or Texas's Silicon Hills – aiming to create an enabling environment with nearby suppliers of gases, chemicals, and equipment. In fact, for the HCL-Foxconn facility, key global suppliers like Applied Materials (equipment) and Linde (industrial gases) are already mentioned as partners.

The United States has also partnered with India to assess and bolster India's chip infrastructure. In September 2024, the U.S. State Department announced a collaboration with ISM to conduct a comprehensive assessment of India's semiconductor infrastructure and regulatory framework, funded by the CHIPS Act's International Technology Security and Innovation (ITSI) Fund. This joint effort will involve U.S. experts working with Indian stakeholders (state governments, academia) to identify gaps and recommend improvements in power supply, water purification, transport, and other critical infrastructure for fabs. Such international cooperation is a positive sign, potentially accelerating India's learning curve by drawing on U.S. experience in fab logistics and facility requirements.

From a policy perspective India has moved rapidly in the past 2–3 years – from virtually no semiconductor manufacturing strategy to a full-court press involving heavy subsidies, fast-tracked approvals, foreign partnerships, and ecosystem building. Government policy has been the prime driver in kick-starting projects that the private sector considered too risky on its own. However, policy is just one piece; ultimately, the success of these initiatives will depend on translating plans into execution – which brings us to the industrial and technical capacity on ground.

2.2. Industrial Capability: Fabs, Foundries, and Design Houses in India

Prior to the ISM-driven projects described above, India's semiconductor *industrial* capability was heavily concentrated on chip design and design services rather than fabrication. By 2020, India had built a reputation as a global centre for semiconductor R&D, chip design, and electronics engineering services. Nearly all the world's top 25 semiconductor companies operated design centres in India. Estimates suggest that over 100,000 VLSI design engineers work in India, contributing to chip designs for CPUs, GPUs, mobile SoCs, and telecom chips designed by firms like Intel, Qualcomm, NVIDIA, AMD, Texas Instruments, Broadcom, and MediaTek. Chips that end up being manufactured in TSMC's or Samsung's fabs are often partly designed or verified by teams in Bangalore, Hyderabad, Noida, or Pune. This strong design base is a key asset – as noted, "India is arguably one of the world's top countries in chip design talent" – and provides a foundation for developing indigenous products and fabless startups (India currently contributes 20% of the global semiconductor design talent, with over 35,000 engineers engaged in chip design) (Sonam Srivastava, 2024).

However, on the manufacturing side, industrial capability has been limited. Aside from the small SCL Mohali (which at last report operates a 180 nm CMOS line on 6-inch wafers, primarily for space and defence circuits), India does not have an existing commercial fab. SCL's output (if any for external customers) and scale are negligible in global terms, and it is now slated for modernization with private participation. Another niche facility is the GaN and GaAs fabs under the Defence Research and Development Organisation (DRDO) and ISRO, which have worked on compound semiconductor processes for radar, microwave, and space electronics. For example, DRDO's Solid State Physics Laboratory (SSPL) and GAETEC in Hyderabad have run Gallium Arsenide foundry lines for defence needs. These, too, are relatively small-scale and focused on strategic components like RF amplifiers. Thus, until the new ISM projects come online, India's wafer production capacity is minimal.

The current wave of projects – Tata's fab, the Foxconn-HCL fab, etc. – will change this scenario in the coming 2–5 years if they stay on schedule. By around 2026, India could have its first 300 mm fab (Tata-PSMC) operational, producing tens of thousands of wafers monthly at nodes like 65–28 nm. Additionally, at least three new assembly/test plants (by Micron, Tata, and possibly Foxconn or Renesas) will be ramping up in parallel. This would establish India in the semiconductor back-end (packaging) segment in a way not seen before. Packaging is a labour-intensive but value-adding part of the chain, and India's large skilled workforce can be advantageous there. Indeed, Malaysia's Deputy Trade Minister noted in 2025 that Malaysia (an established OSAT hub) sees room to collaborate with India in assembly and equipment, leveraging India's growing ecosystem and talent pool. Such partnerships could integrate Indian packaging plants into global supply chains.

Another dimension of industrial capability is the emergence of domestic semiconductor companies and startups. With government support through schemes like DLI, India has started nurturing homegrown fabless semiconductor firms. Over 20–30 startups have sprung up in areas like chip design for wireless communications, processors, and IoT. For example, Saankhya Labs (wireless chips), Signalchip (which designed India's first 4G/5G baseband chipset), Morphing Machines (reconfigurable computing), InCore (RISC-V processors from IIT Madras), and Mindgrove are among promising Indian chip design ventures. The government's DLI scheme has approved financial support for at least 12 startups as of 2024. While these firms are small, they contribute to the industrial base by creating IP that could eventually be manufactured in India's new fabs. Large Indian conglomerates, too, are entering the fray: Larsen & Toubro (L&T) announced plans to invest $300 million to establish a fabless chip company aiming to design 15 products by 2027. This indicates that Indian industry is not just relying on foreign tech; it is also developing domestic design capabilities that align with the manufacturing push (Bloomberg, 2024).

Additionally, foreign semiconductor firms are expanding their presence in India's ecosystem beyond R&D. For instance, Applied Materials, the leading chip equipment maker, is investing $400 million in an engineering centre in Bangalore, and Lam Research and KLA have also increased hiring, partly in response to the CHIPS Act requirement to support allied countries. AMD (Advanced Micro Devices) in 2022 announced a 500,000 sq. ft design centre in Bangalore that will employ 3,000 engineers, its largest such centre globally (TIMESOFINDIA.COM, 2023b). These moves bolster India's industrial know-how and could facilitate technology transfer indirectly (through human capital and supplier networks) to new fabs.

2.2.1. Supporting industries and supply chain

A semiconductor fab needs a robust local supply chain for inputs like ultra-pure chemicals, silicon wafers, specialty gases, and precision components. India is in early stages of developing these ancillary industries. There are encouraging signs – e.g., industrial gas giants Linde and Air Liquide operate in India and can supply gases like nitrogen and argon; chemical suppliers like Merck have India units (Merck India is cited as a partner for the Noida display driver fab) (India Today, 2025). The presence of a sizable pharmaceutical and chemicals industry in India could be leveraged to produce some high-purity chemicals for chipmaking (though currently many, like photoresists or CMP slurries, would likely be imported). On the equipment front, India has very limited capability – no indigenous lithography or etching tools of advanced scale. But companies like Applied Materials have longstanding R&D in India (their Indian engineers contribute to tool software and design), and in 2024, Tokyo Electron (TEL) of Japan signed an MoU with Tata Electronics to support its fab by supplying equipment and co-developing talent (Pti, 2024b). This partnership includes workforce training and R&D cooperation to ensure Tata's fab can efficiently absorb TEL's equipment. Such tie-ups are critical given that high-end fab tools are dominated by a few U.S., Japanese, and Dutch companies – India will rely on imports of tools from the likes of ASML, Applied, Lam, TEL, etc. The government's strategy is to invite these vendors to set up local bases.

In terms of infrastructure companies, Singapore's IGSS Ventures, although its fab proposal was shelved, has set up a semiconductor park project in Tamil Nadu to attract suppliers and SMEs in the chip sector. Another is Sahasra Semiconductors, an Indian firm that in 2022 opened a memory chip assembly unit (for packaging flash memory) in Rajasthan – a smaller scale project under the older MSIPS scheme. All these contribute, albeit modestly, to industrial capability.

India's industrial semiconductor capability is transitioning from *design-centric* to a more balanced portfolio that includes *manufacturing and packaging*. By 2025, if timelines hold, India will have a few operational wafer fabs (albeit at mature nodes) and multiple ATMP/OSAT facilities, marking its entry into semiconductor production. The presence of domestic corporations (Tata, L&T), foreign players (Micron, Foxconn, Renesas), and a thriving design sector indicates a holistic growth. Still, the scale is small relative to global leaders – for instance, TSMC alone has ~64% of global foundry market share and manufactures hundreds of thousands of wafers monthly on advanced nodes (Tran, 2025). In contrast, India's entire planned output by 2026 might be on the order of tens of thousands of wafers and primarily older technology. The next section on scientific and technical capabilities will discuss whether India has the skilled workforce and R&D ecosystem to support this industrial expansion.

2.3. Scientific and Technical Capabilities: R&D and Workforce

A strong semiconductor industry rests not only on capital investment but also on human capital – highly skilled scientists, engineers, and technicians – and continuous innovation through research and development (R&D). India's situation **contrasts**: on the one hand, India has abundant engineering talent and an extensive education system, graduating hundreds of thousands of engineers annually. On the other hand, specific semiconductor manufacturing skills (e.g., process engineering, tool maintenance, clean-room operations) are scarce in a country without a commercial fab. Moreover, domestic R&D spending in this field has historically been low, and industry-academia linkages are weak. Here, we examine the workforce development and R&D aspects of India's semiconductor push.

2.3.1. Engineering workforce and education

The existing semiconductor workforce in India is predominantly in design and software domains – VLSI design engineers, chip verification specialists, embedded software developers, etc. These numbers are in the tens of thousands, and they often have advanced degrees. For manufacturing, however, India is essentially starting from scratch in creating a pipeline of fabrication experts, equipment technicians, yield engineers, and so on. Recognizing this, the government and academia have launched targeted skill development programs. A flagship initiative is the Chip to Startup (C2S) program, which was announced in 2022 under the Digital India banner. C2S aims to train 85,000 specialized engineers in semiconductor design and related fields at B. Tech, M. Tech, and Ph.D. levels over five years (Rajesh Abraham, 2023). Under this program, 30 academic institutions (including IITs, NITs, and universities) were selected as "cohort" institutions to receive funding, updated labs, and mentoring from industry to produce industry-ready semiconductor professionals. The curriculum is being aligned with industry needs in areas like chip design, verification, and fabrication process basics.

In addition, the India Semiconductor Mission has partnered with leading technical institutes to start new courses on semiconductor fabrication and microelectronics. For example, IIT Madras, IIT Bombay, IIT Delhi and others have announced or expanded post-graduate programs in microelectronics manufacturing (Abbas, 2025). The government allocated over ₹6,000 crore in 2023 specifically for capacity building in the semiconductor sector (doubling the previous year's budget). The Electronics Sector Skills Council of India (ESSCI), an industry-led body, has rolled out short-term certification courses for semiconductor manufacturing technicians. There are collaborations with foreign institutions: in October 2023, it was reported that Belgium's IMEC (a renowned nanoelectronics research institute) might help train Indian engineers, and U.S. universities through the American Semiconductor Academy initiative are exploring exchanges.

Corporate efforts are complementing these initiatives. IBM and Cadence have donated Electronic Design Automation (EDA) software tools to Indian engineering colleges to ensure students get hands-on chip design experience. Synopsys and Mentor Graphics (Siemens) have similar university programs (P, 2024). Moreover, companies like Intel and Micron have partnered with IITs to set up semiconductor research labs (e.g., a Micron-sponsored memory design lab in IIT Madras). In July 2023, AMD announced a $400 million investment in India, including a new campus with training facilities.

A notable development is the creation of a dedicated institution: the National Institute of Semiconductor Training and Skill Enhancement (NISE) (proposed), and consortia like SemiconIndia FutureSkills by the India Electronics and Semiconductor Association (IESA). In the coming years, these aim to coordinate the skilling of 50,000–100,000 engineers in various sub-domains – from fabrication process technology to chip design (Pti, 2024c).

Despite these efforts, scaling up a skilled fab workforce is a challenge. When Micron starts operations in late 2024, it will need hundreds of technicians and engineers trained in cleanroom protocols. Reports indicate Micron has already hired 200+ people for the Sanand plant and sent them for training to Micron's US, Malaysia, and Singapore facilities (Pti, 2024). Similarly, Tata is sending Indian engineers to partner Powerchip's fabs in Taiwan for hands-on experience. This reverse brain circulation will help jumpstart operations. However, long-term, India seeks to establish local training fabs or simulation-based training (using tools like SEMulator3D as IISc's program does). The steep learning curve means initial productivity might be low, and foreign experts will likely remain involved in Indian fabs for some years.

2.3.2. R&D and innovation

On the research side, India has pockets of strength in semiconductors, mainly in academia and strategic research labs. The leading institutes – IIT Bombay, IIT Madras, IIT Delhi, IIT Kanpur, IISc Bangalore – have active microelectronics research groups that have developed analog and digital circuits, MEMS devices, and even prototype chips (often fabricated via multi-project wafer runs abroad). For instance, IIT Madras designed the SHAKTI microprocessor (an open-source RISC-V design) as an academic project and got it fabricated on 180 nm in 2018 (Shruti Tripathi, 2025). Such projects show capability in design. However, in materials and process R&D, India's output has been limited. There is the Centre for Nano Science and Engineering (CeNSE) at IISc Bangalore, which has a state-of-the-art lab capable of 100 mm wafer processing for research; CeNSE works on nanofabrication, MEMS and photonics, and can prototype sensors and devices for research purposes. But these are far from the scale of IMEC or Leti in Europe, which drive cutting-edge semiconductor R&D.

The government is trying to boost R&D via the ISM as well. In 2023, MeitY announced it would set up a Semiconductor Research Center in collaboration with industry, to focus on compound semiconductors, advanced packaging, and materials. Additionally, India's space and defence programs continue to invest in specialized semiconductor tech (like radiation-hardened chips, microwave transistors), which can spill over to civilian sector. For example, ISRO reportedly achieved fabrication of ~0.25 μm CMOS at SCL for certain applications; DRDO has developed GaN transistor tech domestically for radars. These show that given focus and time, Indian scientists can innovate even with limited resources.

It is worth noting that the United States and India have launched a Bilateral Strategic Tech Partnership that includes semiconductors – under the iCET (Initiative on Critical and Emerging Technologies). Part of this involves joint R&D. In mid-2023, the US National Science Foundation (NSF) and India's science agencies announced joint funding for semiconductor research projects in areas like beyond-CMOS devices and chip packaging. The idea is to leverage India's strong theoretical research base in electronics and the US's advanced facilities (*India-U.S. Emerging Technologies Working Group*, n.d.).

One example of leveraging Indian research talent is a July 2023 partnership in which AMD teamed up with the Society for Innovation and Entrepreneurship at IIT Bombay to support startups working on energy-efficient chip designs (specifically spiking neural network chips). The first grant under this partnership went to a startup developing neuromorphic chips on SOI (silicon-on-insulator) technology. This indicates private R&D interest aligning with academia.

Despite these efforts, India's R&D spending on semiconductors remains relatively low. China, for instance, poured billions into research through its National IC Fund and has multiple national semiconductor labs. Taiwan's ITRI was crucial in developing 7 nm, 5 nm processes for TSMC. In India, perhaps the most comparable entity would be a future upgraded SCL or a new national semiconductor lab, which is still on the drawing board. One telling statistic: the Indian government's allocation for the entire semiconductor program (including capacity building) is a few billion dollars at most, whereas leading firms like Intel and TSMC each spend over $3–4 billion on R&D annually. Bridging this gap will require sustained and increased investment. The Economic Survey of India 2023–24 highlighted the need for higher GERD (Gross Expenditure on R&D) and specifically pointed out semiconductors as a field needing research boost, potentially through public-private partnerships.

India's scientific and technical capacity is a mix of robust talent availability and emerging training programs, contrasted with a lack of prior experience in high-volume manufacturing and modest indigenous R&D infrastructure. The government's steps – training 85,000 engineers, integrating academia with industry needs, and seeking international cooperation in training – are laying a foundation. Whether India can cultivate the level of specialized expertise found in Taiwan's TSMC (with its thousands of process engineers) or America's semiconductor firms will play out in the coming decade.

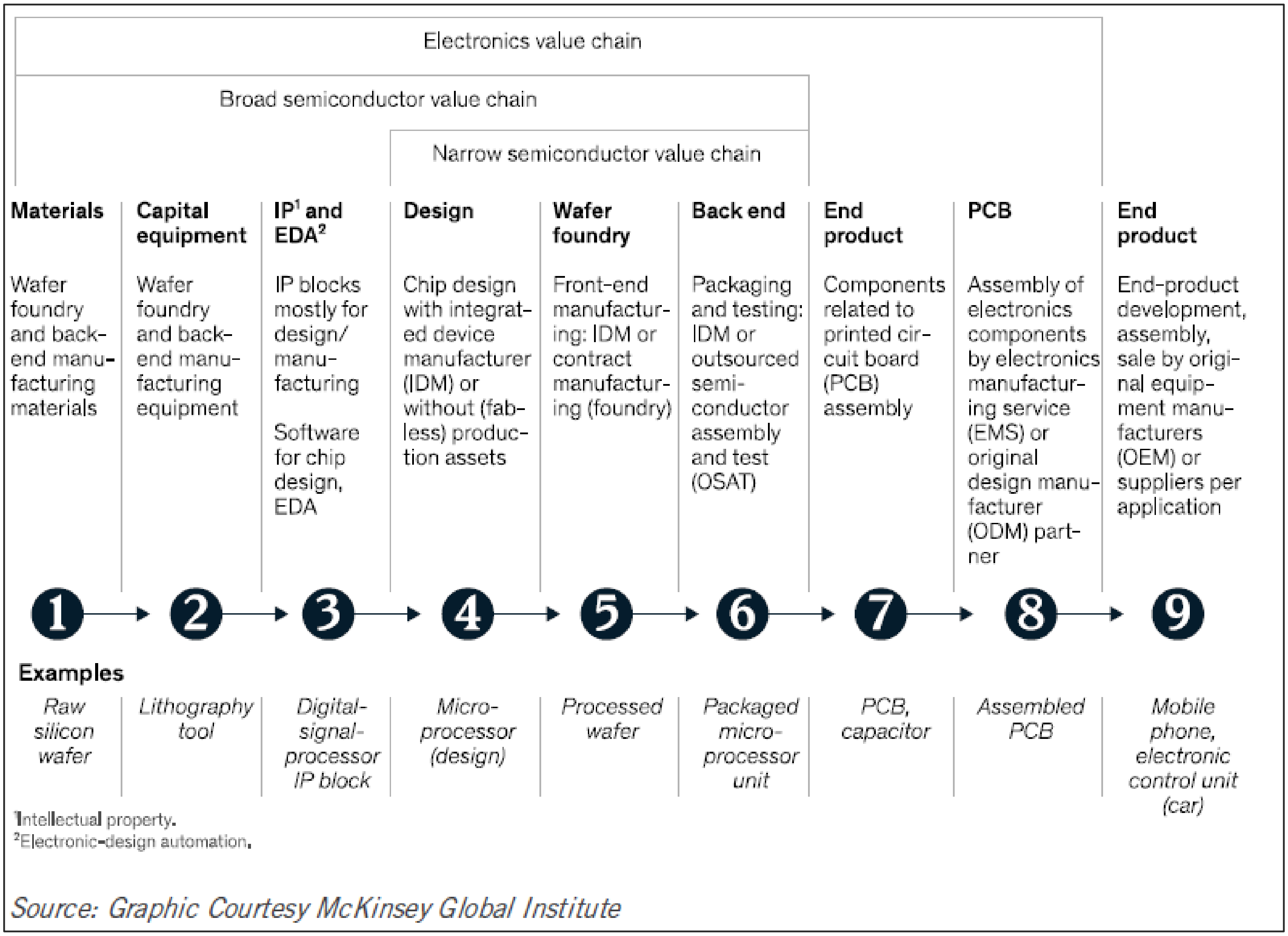

Image 1: Semiconductor value chain from raw materials to end-product assembly, highlighting key stages and industry roles. (Source: The Microcap Minute)

Rare Earth Elements and Critical Materials: India's Assets and Gaps

Semiconductor manufacturing is not just about fabs and talent – it also critically depends on materials: ultra-pure silicon, specialized metals and gases, and minerals like rare earth elements (REEs) for certain components and equipment. The global semiconductor supply chain has revealed vulnerabilities in recent years, such as dependence on China for gallium and germanium (used in chips and fibre optics) or on Ukraine for neon gas (used in laser lithography) (Wishart-Smith, 2024). This section explores what rare earths and critical minerals India possesses that are essential for semiconductors, and the state of India's mining, refining, and supply chain for these materials.

3.1. Rare Earth Reserves and Production in India

Rare earth elements (REEs) – the set of 17 metallic elements including neodymium, dysprosium, etc. – are used across high-tech industries. In electronics and semiconductors, they find use in manufacturing equipment (e.g., high-strength permanent magnets in lithography machines use neodymium and dysprosium), in chip packaging (e.g., some specialized alloys), and in end devices (for example, yttrium and europium in display phosphors, or gadolinium in sensors). While REEs are not used in bulk to make silicon chips, they are strategically important for the broader electronics ecosystem and for advanced compound semiconductors.

India is geologically endowed with significant rare earth resources. The country is estimated to have the **world's fifth-largest reserves of rare earth oxides**. **Most of India's REE resources are found in the form of monazite sands on beaches in states like Odisha, Andhra Pradesh, Tamil Nadu, and Kerala** (*Union Minister Dr Jitendra Says, India Is Not Reliant on China for Accessing Rare Earth Minerals*, n.d.). Monazite is a phosphate mineral rich in cerium, lanthanum, neodymium and has significant thorium (which is radioactive). According to India's Atomic Energy Department, India has about 13.07 million tons of monazite ore in situ on its coasts, containing roughly 55–60% total rare earth oxides (REO) (*Union Minister Dr Jitendra Says, India Is Not Reliant on China for Accessing Rare Earth Minerals*, n.d.). This equates to a considerable quantity of extractable REEs (primarily Light REEs like cerium, lanthanum, neodymium, praseodymium). However, Heavy REEs (like dysprosium, terbium, which are crucial for magnets) are scarce in Indian deposits. Indian monazite's composition yields lots of cerium and lanthanum (of lower commercial value) and smaller fractions of Nd and Pr, and virtually no heavy REEs like Tb/Dy in extractable amount.

Despite large reserves, India's current production of rare earths is modest – less than 1% of global output. China dominates over 60% of mined production and 90% of refining of REEs (Shetty, 2024) (Castellino, 2025). India's production is limited by both policy and technology factors. Historically, REE extraction in India has been a monopoly of a government-owned company, Indian Rare Earths Ltd (IREL) (now renamed *IREL (India) Ltd*), established in 1950. IREL, under the Department of Atomic Energy, mines beach sands for monazite and other heavy minerals (ilmenite, zircon, etc.), and extracts rare earth compounds as a by-product. Because monazite has thorium (a potential nuclear fuel), its handling is tightly controlled – only IREL and a few other public sector entities were allowed to process it, to ensure thorium is safeguarded. This regulatory environment essentially banned private sector involvement in rare earth mining for decades. In 2019, the government went further and completely disallowed private companies from even processing mineral sands by setting the monazite "threshold" to zero (any presence of monazite made the deposit reserved for government). This stopped the operations of some private heavy mineral miners. As a result, IREL has been the only game in town, and its capacity remained under-utilized.

IREL operates rare earth separation plants at Orissa (Chhatrapur) and Kerala (Udyogamandal) that can produce limited quantities of rare earth oxides like neodymium oxide, praseodymium oxide, cerium oxide, etc. According to recent reports, IREL currently produces on the order of 5,000 tons of rare earth oxides per year (Bloomberg, 2023). For perspective, global rare earth oxide production is ~240,000 tons/year (2020s), so India's share is ~2% or less. IREL's output includes oxides of cerium, lanthanum (which have uses in catalysts, glass polishing), and smaller quantities of Nd-Pr oxide (which could be converted to magnet alloy). Critically, India produces almost no refined dysprosium or terbium, since those are not present in significant amounts in its ore. These heavy REEs usually have to be imported (mostly from China or via Japan).

On the positive side, India's government has recognized this underperformance. A Ministry of Mines committee in 2022 explicitly pointed out that although India has large REE resources, it "lags in all stages of rare earth development – mining, processing, refining, and magnet production". In 2023 and 2024, steps were taken to change the policy regime: rare earths have been put on the national critical minerals list, and there are moves to open up beach sand mining to private companies under strict regulation. The National Critical Mineral Mission (NCMM) launched in April 2025 emphasizes expanding domestic sourcing of critical minerals including REEs. It calls for 1,200 exploration projects by 2030 and recommends establishing a Centre of Excellence in Critical Minerals. Furthermore, the Mines Ministry in 2023 listed REEs as one of 30 critical minerals and gave the central government authority to auction their mining licenses, which could break IREL's monopoly in the future and encourage more players with better tech to enter.

IREL itself has ambitious plans: it aims to mine 50 million tons of rare-earth ore per year by 2032, up from 10 million tons now – a 400% increase. This would raise India's refined rare earth output to ~13,000 tons/year by 2032 (still modest but more than double current). IREL's chairman has urged faster permits and pointed out that currently even IREL's existing refineries run at <40% capacity due to lack of raw monazite feed (stemming from permit and extraction issues). So, scaling up production is feasible if regulatory hurdles are removed and new monazite sources developed.

India holds ample rare earth reserves, especially of light rare earths, but current production is low. The government is beginning to liberalize this sector and invest in scaling extraction. For the semiconductor industry, what matters is whether India can become a stable, alternate source for certain REEs used in manufacturing equipment and high-tech components, reducing reliance on China.

3.2. Refining and Supply Chain: From Minerals to High-Tech Materials

Mining rare earth ore is only the first step – the more complex part is chemical processing and refining the individual rare earth oxides, then converting them to metals and alloys used in products (like Nd-Fe-B magnets). Here, China's dominance is overwhelming: ~90% of rare earth refining is done in China, even ores mined in the US or Myanmar often end up in Chinese separation plants. India has some capacity for refining *light* rare earths to oxide and even to metal. According to a 2023 PIB report, India has existing facilities from mining up to separation and refining in oxide form, and has developed capability for metal extraction for light REEs. In fact, IREL produced small amounts of neodymium metal in the past at its Rare Earths Division. However, the value-added steps beyond that – making alloys (NdFeB alloy, SmCo alloy) and magnets – are absent in India. There are no domestic manufacturers of high-performance rare earth permanent magnets at scale, meaning industries like electric vehicles and wind turbines (and by extension any semiconductor equipment requiring such magnets) must import them.

One bright spot is an Indo-Japanese collaboration: Toyota Tsusho's subsidiary in India, called Toyotsu Rare Earths, set up a plant in Visakhapatnam (Andhra Pradesh) around 2012–2015 to process rare earth oxides (*Mining of Rare Earth Elements*, n.d.). Toyota's interest was to secure non-Chinese sources after China's rare earth embargo on Japan in 2010. This plant has been processing rare earth concentrates supplied by IREL and exporting refined rare earth oxides to Japan. It reportedly produces didymium (Nd-Pr) oxides for use by Japanese magnet makers. While modest in scale, this Indo-Japan partnership is a template for building downstream capacity – leveraging Japanese separation technology and Indian raw materials. The new India-Japan agreements under QUAD might further expand such cooperation, potentially moving into magnet-making in India. For instance, there are talks of Japanese firms setting up NdFeB magnet factories in India to support EV manufacturing (though nothing concrete has been announced as of 2025) (NITI Aayog et al., 2022).

For other critical materials relevant to semiconductors, India's status varies:

3.2.1. Silicon

Semiconductor-grade silicon (polysilicon for electronics, and ingots/wafers) is a highly specialized industry. India does not currently produce electronic-grade polysilicon or semiconductor wafers at scale. (India does have a nascent solar-grade polysilicon initiative, but solar PV polysilicon is lower purity than needed for chips.) All silicon wafers for any Indian fab will be imported from global suppliers in Japan, Taiwan, Germany, or the US. Recognizing this vulnerability, the critical minerals list has **"silicon"** (implying high-purity silicon) as a strategic material. However, establishing a polysilicon and wafer slicing facility is capital intensive and may not be immediately in scope for India. In the short term, ensuring reliable imports via trade partnerships is key. (For example, Taiwan or Japan could be long-term suppliers of wafers as part of tech partnerships.)

3.2.2. Gallium and Germanium

These are minor metals crucial for III-V compound semiconductors (like GaAs, GaN, InGaAs chips used in RF, LED, solar, etc.) and for fiber-optic communication devices. China absolutely dominates gallium (producing ~98% of the world's refined gallium as of 2022) and germanium (~67% of world output). In mid-2023, China imposed export licensing on gallium and germanium products, causing concern globally. India's position: Gallium can be extracted as a by-product of aluminium refining (from bauxite ore), and India is one of the world's top aluminium producers. In fact, India's bauxite refining (run by companies like NALCO) contains recoverable gallium in the process liquor. The Ministry of Mines identified gallium as a critical mineral and reported 74 million tonnes of gallium-bearing ore in India. Currently, India produces only a *very small* amount of gallium. The June 2023 "Critical Minerals for India" report stated India "produces a little gallium as a by-product" of alumina refining and depends entirely on imports for germanium. There have been R&D efforts: CSIR labs have developed pilot processes to extract gallium from bauxite residue, and NALCO had set up a pilot plant which produced some kilograms of gallium. With China's restriction, India could look to scale this up. Notably, gallium (especially in forms like GaN) is vital for next-gen power electronics and 5G RF chips, an area India is interested in (some startups are working on GaN power devices). In 2024, India's NCMM explicitly called out gallium and indium as critical for solar and electronics and aimed to secure them.

For germanium, India has negligible known resources. Germanium is often a by-product of zinc refining. India does mine zinc (Hindustan Zinc is a big producer), so theoretically germanium could be extracted if present in the ore. But any such program is nascent or absent. Thus, India will need to import germanium for the foreseeable future for its fiber-optic industry or night-vision devices.

3.2.3. Lithium and Cobalt

While not directly used in silicon chip fabrication, lithium and cobalt are critical for *semiconductor-adjacent* industries like batteries and also for certain semiconductor processes (lithium is used in some EUV photoresists, cobalt is used as an interconnect material in advanced chips). India historically had no domestic lithium production, but a significant lithium ore deposit (14,000 tons Li metal equivalent) was discovered in Jammu in 2023, which created optimism. India has also been acquiring lithium assets abroad via **KABIL** (Khanij Bidesh India Ltd), a JV set up to secure overseas minerals. Similarly, cobalt resources in India are minimal. These materials, while important, impact semiconductors indirectly (through powering the devices and EV revolution which drives chip demand). For completeness: India's strategy for lithium and cobalt is heavily import-focused with attempts to invest in mines in Australia, Argentina, etc.

3.2.4. Neon and other gases

Neon, krypton, and xenon gases (especially neon) are critical for the lasers used in semiconductor lithography (DUV and some older lasers). A lesson from the 2022 Ukraine crisis was that neon supply (a by-product of Ukrainian/Russian steel industry) was at risk, causing chip industry concerns. India does not produce noble gases like neon in significant quantity; these are usually obtained from cryogenic distillation of air or as steel by-products. Companies like Air Liquide can supply them if economically viable. For now, any neon for an Indian fab will likely be imported, but since India has a steel industry, in theory it could capture neon if it invests in the necessary purification units.

3.2.5. Other materials

The critical minerals list for India includes many that pertain to semiconductors: e.g., **nickel, copper, tin, tungsten, molybdenum** – these are used in various chip processes or packaging. India has some domestic production of copper, nickel (small), tin (small in Northeast), tungsten (very little). For example, India has modest tungsten reserves in Rajasthan and Karnataka but produces negligible amounts (imports come from China, etc.) Tungsten and molybdenum are used in chip interconnects and contacts. Silicon photonics and advanced chips also use indium (for InP lasers or indium tin oxide in displays) – India's indium comes as by-product of zinc and is not produced at scale. The list goes on, but the overarching theme is: **India has a broad**

array of mineral resources on paper, yet for most high-purity semiconductor-grade materials, it currently relies on imports.

3.2.6. Supply chain initiatives

Realizing the need for supply security, the government has taken steps such as forming the aforementioned **KABIL** to acquire stakes in mineral assets abroad (particularly lithium and cobalt mines in Argentina, Australia, etc.). In rare earths, India and Australia have cooperated – India has invested in an Australian critical mineral mine (like Lynas or others) through KABIL's efforts, though details are not public. In July 2023, the US and India announced a partnership to develop secure supply chains for critical minerals, including joint research and perhaps sharing of processing know-how. For instance, the U.S. could assist India in rare earth separation technology as part of diversifying from China. This is part of a larger decoupling trend where democracies want to create alternative supply chains for critical minerals.

Additionally, India's corporate sector shows interest: Tata Steel has a materials research centre which has studied extraction of rare elements from waste, Reliance Industries has shown interest in lithium battery materials, etc. If semiconductors become a large industry in India, one can expect these conglomerates to integrate backwards into materials to some extent.

India's critical materials scenario is one of latent potential but current dependency. The country has significant rare earth reserves and some other critical mineral deposits, but bureaucratic, technical, and environmental challenges have impeded their exploitation. Efforts are underway to augment mining (quadrupling rare earth ore output by 2030) and to bring in private and foreign participation to improve refining. In the short term, for its semiconductor mission, India will still depend on imports for key materials: wafers, gases, photoresists, specialty chemicals, and many critical minerals in refined form. Over the longer term, if India can streamline rare earth production (e.g., become a supplier of Nd-Pr oxide/metal to magnet makers) and maybe produce niche materials like gallium, it would not only support its own industry but also position India as a player in the global supply chain. Already, India being part of QUAD and other alliances gives it a seat at the table for critical mineral collaboration – a recognition that India "could play a crucial role in reducing global overdependence on China" for rare earths if it addresses its internal hurdles.

The combination of government policy shifts (like NCMM), industrial steps (IREL expansion, Toyota partnership), and strategic alliances (US-India, India-Australia agreements) suggests India is beginning to leverage its resource base for tech self-reliance. Whether it can execute effectively remains to be proven.

Global Semiconductor Strategies: The U.S., China, and Taiwan – A Comparison

Before evaluating India's future prospects, it is instructive to compare India's semiconductor approach and capabilities with those of three major players: **the United States**, **China**, and **Taiwan**. Each of these countries (or economies) offers lessons and context – the U.S. for its innovation and recent reshoring efforts, China for its state-driven massive push, and Taiwan for its focused strategy that achieved global leadership. We compare across the familiar dimensions of policy, industrial capacity, and scientific/technical base.

4.1. United States

4.1.1. Policy and Government Support

The United States historically led the semiconductor revolution – the transistor was invented in the U.S. (1947), and companies like Fairchild and Intel built the integrated circuit industry. For decades, direct federal intervention in the industry was minimal (apart from funding basic research and military procurement) because U.S. firms were dominant. However, as U.S. manufacturing capacity fell from 37% of world share in 1990 to ~12% by 2020, policy thinking shifted (Varas et al., 2023). In 2022, the U.S. enacted the **CHIPS and Science Act**, a landmark $52 billion initiative to incentivize domestic semiconductor manufacturing and research. This includes $39 billion in manufacturing subsidies (grants, loans) and $11 billion for R&D (funding for a National Semiconductor Technology Center, etc.) (Department of Commerce, 2024). The CHIPS Act also has a strategic intent: to on-shore chip production, especially for advanced nodes and secure chips for defence, and to reduce reliance on East Asia (particularly given geopolitical risks). Additionally, the U.S. has used export control policy to maintain an edge: in 2022–23 it imposed sweeping **export controls on semiconductor technology to China**, restricting sales of advanced chips and equipment. This has shaped global industry dynamics and is relevant to India as the U.S. has signalled support for India's semiconductor ambitions as part of a broader tech partnership.

4.1.2. Industrial Capability

The U.S. remains a powerhouse in many parts of the chip industry. U.S.-headquartered firms hold around **46% of global semiconductor market share by revenue** (including fabless and IDM firms). Giants like Intel, Qualcomm, NVIDIA, Broadcom, and AMD are American. The U.S. also dominates semiconductor equipment (Applied Materials, Lam Research, KLA, etc.) and EDA software (Cadence, Synopsys, Mentor). However, in pure manufacturing capacity, the U.S. has ceded ground: only ~12% of global fab capacity is in the U.S. Intel is the only U.S. company with leading-edge logic fabs (though struggling at 7 nm/4 nm), and Micron in memory (mostly at 3D NAND, since it exited 3D DRAM). There are also specialty and older fabs (GlobalFoundries operates fabs at 12 nm and above). The CHIPS Act incentives have led TSMC and Samsung to build new fabs in Arizona and Texas respectively (TSMC's 4 nm/3 nm fab in Arizona is underway, Samsung's 5 nm fab in Texas as well). Intel is also investing in new fabs in Arizona and Ohio aiming for 20A (≈2 nm) processes by 2024–25.

In summary, the U.S. industrial strategy is to reclaim some advanced fab capacity (target ~20% global share by decade's end) for economic resilience and defence needs.

4.1.3. Scientific & Technical Strength

The U.S. has an unparalleled R&D ecosystem in semiconductors – top universities (MIT, Stanford, Berkeley, etc.), national labs, and corporate research. Many fundamental advances (e.g., new transistor architectures, material science breakthroughs) originate in the U.S. The U.S. also produces a large number of PhDs in electrical engineering (though many are international students who may return home). It is noteworthy that the U.S. continues to design the highest-value chips (CPUs, GPUs, AI accelerators) and the most advanced equipment. For India, the U.S. model underscores the importance of investing in R&D and protecting/championing domestic firms, as well as now the importance of incentives to localize manufacturing. The U.S. approach has shifted from laissez-faire to a mix of funding and protectionism (e.g., the *"Chip 4"* alliance with Japan, Taiwan, South Korea to secure supply chains, and excluding China).

4.2. China

4.2.1. Policy and Government Initiative

China views semiconductors as a cornerstone of national power and has mobilized immense state resources to try to catch up. The effort accelerated since the mid-2010s: the **"National Integrated Circuit Plan"** of 2014 created the first **National IC Investment Fund** (known as the "Big Fund"), which raised over $20 billion to invest in domestic chip companies. A second round of the Big Fund in 2019 raised another ~$30–35 billion. Additionally, local governments in China set up dozens of smaller funds; by one estimate, China poured well above $50 billion into semiconductors from 2014–2020 alone. "Made in China 2025" explicitly set targets for 70% self-sufficiency in chips by 2025 (a target unlikely to be met, as China remains only ~20% self-sufficient as of 2023). Nonetheless, Beijing's policies – ranging from subsidies, tax breaks, procurement preferences, to talent recruitment programs – have built a broad if uneven semiconductor sector. China has also used **trade and industrial policy** to its advantage: for example, leveraging rare earth dominance as a bargaining chip (as seen in 2010 with Japan, and implicitly in 2023 with gallium/germanium export curbs). Importantly, after U.S. export controls, China is doubling down on indigenous R&D (for instance, attempts to develop its own lithography tools via SMEE, and chip architectures that circumvent U.S. tech). The government's guiding principle is to achieve **self-reliance**, so it cannot be strangled by foreign sanctions. According to World Population Review, China aims to produce **25% of the world's semiconductors by 2030** (up from roughly 15% now, including foreign firms in China).

4.2.2. Industrial Capacity

China has made significant gains in certain areas. On sheer capacity, if one includes foreign-operated fabs in China, the country accounts for ~15–20% of global chip manufacturing (nodes spanning from 14 nm to >40 nm mainly). Chinese foundries like SMIC have achieved 14 nm production, and reportedly even a 7 nm-like process in limited volume (using older DUV tools creatively, since EUV is restricted) – demonstrated by a 7 nm Bitcoin mining chip in 2022. China also leads in some mature tech: it is the largest producer of microcontrollers and discrete chips; Yangtze Memory (YMTC) was making competitive 3D NAND flash (until sanctions hit equipment supply). Packaging is a strong suit: companies like JCET are among top OSAT providers globally. And of course, China dominates in assembly of end electronics – which doesn't equal chip prowess but gives it influence over the electronics supply chain. However, China's weakness remains cutting-edge logic and certain crucial parts of the supply chain (like EDA software, advanced lithography, and some materials) where it still lags the West and its Asian neighbours.

It's worth noting China's **talent strategy**: they have rapidly expanded microelectronics programs at universities, graduating tens of thousands of engineers annually in this field, and have tried to lure back Chinese engineers from TSMC, etc. Some high-profile missteps occurred – e.g., the collapse of the Wuhan Hongxin fab project (a $20 billion fiasco) due to mismanagement, and instances of fraud or underperformance by state-backed firms. This shows that money alone isn't sufficient; execution and oversight matter, a lesson also for India (which thankfully has been more cautious in vetting proposals).

4.2.3. Scientific and R&D Base

China's R&D spending in semiconductors is ramping up. Companies like Huawei (via HiSilicon) were designing 7 nm chipsets and investing in EUV research before sanctions. SMIC and Tsinghua Uni have research programs for 5 nm and beyond (though handicapped by lack of EUV access). China also excels in certain niche tech – for example, Silicon Photonics (through Academy of Sciences), or in raw research papers (Chinese scholars publish extensively on nanoelectronics). Still, China has not yet produced an iconic breakthrough like the transistor or the single-step advancement that leapfrogs the West. Its approach has been integrative innovation: absorb and re-engineer existing tech at scale. One strategic move is focusing on **mature nodes and specialty chips** that are less controlled – e.g., power semiconductors (IGBTs, where China wants self-sufficiency by leveraging its raw materials like SiC).

For India, China's experience is both a model and a cautionary tale: a model in demonstrating how government impetus can build an industry from very little (China had negligible chip capability in 1990s and now is a top 5 producer). But a cautionary tale in that despite investing perhaps $70+ billion over a decade, China is still a generation behind the bleeding edge, showing the extreme difficulty of catching up in this field. It also underscores how important geopolitical factors are – U.S. sanctions effectively kneecapped some of China's advances (e.g., Huawei's Kirin chips can no longer be manufactured at TSMC 5 nm). India might avoid sanctions issues by aligning with the U.S., but it will not be immune to the steep competition and the need for sustained funding.

4.3. Taiwan

4.3.1. Policy Evolution

Taiwan is the poster child of semiconductor success through strategic government vision and partnership with private enterprise. In the 1970s, Taiwan was a relatively small economy and decided to invest in high-tech industries. The government, via institutions like the **Industrial Technology Research Institute (ITRI)**, imported technology (e.g., an RCA 7 μm process in 1976) and began a series of state-led projects to develop local semiconductor know-how. This led to the founding of **Taiwan Semiconductor Manufacturing Company (TSMC)** in 1987, with backing from the government and led by Dr. Morris Chang. The **foundry model** – making chips for others – was a novel approach that TSMC pioneered, and it aligned perfectly with the fabless revolution of the 1990s. Taiwanese policy nurtured this by creating **science parks (Hsinchu Science Park)** with clustered infrastructure, offering tax incentives, and ensuring a steady supply of engineers through education reforms. The government also fostered multiple companies to avoid single points of failure: UMC, VIS, and others in foundry; and later Mediatek in design.

4.3.2. Industrial Scale and Capability

Today, Taiwan produces the largest share of semiconductors of any single economy. As noted, **TSMC alone fabricates ~50% of the world's semiconductor output by revenue**, and an astonishing **92% of advanced (sub-10 nm) chip production** is in Taiwan. Taiwan specializes in *logic chips* – microprocessors, GPUs, AI chips, etc. – with TSMC generations ahead of any competitor (its 3 nm node entered volume production in 2022, 2 nm is in development). Taiwan also has substantial capacity in *memory packaging* and testing, though not in memory fabrication (that's South Korea's forte). Taiwanese companies like ASE and SPIL are among the biggest OSAT players as well. Moreover, Taiwan's supply chain is extremely deep locally: from silicon wafer fabs (GlobalWafers in Taiwan produces wafers), to chemical suppliers, gas suppliers, and equipment maintenance – a *robust end-to-end ecosystem*. This means a fab in Taiwan can source most needs domestically or via nearby Japanese imports, reducing bottlenecks.

One unique characteristic is how concentrated the talent and suppliers are in Hsinchu and Tainan clusters – facilitating quick problem-solving and innovation. For instance, when a new process is developed, local tool suppliers and chemical suppliers are in constant collaboration with the fabs. Taiwan's example highlights the benefit of **geographical clustering and focus on a core competency (manufacturing excellence)**.

4.3.3. Scientific & Technical Aspects

Taiwan leveraged education heavily – universities like National Tsing Hua University and National Chiao Tung University became semiconductor talent factories, often in partnership with industry. While Taiwan doesn't do as much upstream scientific research as the U.S. (it often licenses or co-develops tech with companies like ASML or academia elsewhere), it has mastered the **application of research to manufacturing**. TSMC's R&D spending is huge (over $3 billion annually in recent years) and is very targeted at process engineering and yield improvement. The result: unparalleled know-how in running mega-fabs at high yields and quickly scaling new nodes. This is a very different skill set than just doing research; it's a combination of engineering discipline, supply chain orchestration, and incremental innovation. Taiwan has also generally stayed neutral geopolitically, serving all customers – an approach that may be hard for India which must manage strategic alignments.

For India, Taiwan's success offers several lessons: (1) **Consistency and Long-term Vision** – Taiwan stuck with semiconductors for 40+ years with unwavering support; (2) **Focus on Strengths** – Taiwan chose manufacturing specialization rather than trying to do everything (it doesn't design CPUs or do basic research on new transistors, it excels in implementation); (3) **Cluster Development** – the importance of providing all needed inputs (talent, power, water, tax breaks, supplier base) in one place; and (4) **Public-Private Partnership** – TSMC, though private, always worked closely with government (e.g., in workforce training, setting up new fabs). India's challenge will be replicating some of this focus and integration, albeit at a later stage of industry maturity and with current leaders far ahead.

4.3.4. Security context

One cannot talk about Taiwan without noting the geopolitical cloud – China's claims on Taiwan. Ironically, this risk factor (often dubbed the "Silicon Shield") has up to now ensured global support for Taiwan's independence, because the world economy relies on its chips. But it also motivates others to diversify. The U.S. is encouraging TSMC to invest in the U.S. (which it is, but slowly), and even TSMC is considering future fab expansion in places like Japan. India has expressed interest in TSMC investing in India, but TSMC has not made any commitment – likely because TSMC prioritizes locations with existing ecosystems or guaranteed infrastructure. In any event, Taiwan's dominance in advanced chips is likely secure for at least the next 5–10 years, given how far ahead it is.

4.4. Comparative Summary

To synthesize the comparisons: **the United States** leads in design and innovation, and is rebuilding its manufacturing via hefty subsidies (CHIPS Act) and tech alliances, relying on strong R&D and industrial base.

China leads in scale of investment and is rapidly catching up in capacity at mature nodes, but is held back at the cutting-edge by technology access issues; its strategy is heavily state-driven with focus on self-sufficiency. **Taiwan** leads in manufacturing efficiency and advanced process technology, thanks to decades of consistent policy and the cluster effect; it however is exposed to geopolitical risk and has limited domestic market or raw materials (but compensates via global trade networks).

India, in comparison, is a new entrant. Its strengths lie in its large domestic market (which can absorb chips, unlike Taiwan which produces mostly for export) and its huge pool of engineering talent (especially in design and software). Policy-wise, India is now following in the footsteps of the U.S. and Taiwan by offering subsidies and building clusters, though at a scale (few tens of billions) that is smaller than what those countries have invested over decades. Industrially, India is at the very beginning of building capacity – far behind the production scale of the big three. Technically, India has top design minds but minimal manufacturing experience; whereas the U.S., China, Taiwan each have thousands of experienced fab engineers.

One interesting comparison is **cost**: India aims to leverage its lower labour costs as an advantage for labour-intensive parts of the chain like packaging and perhaps older-node fabs (which employ more manpower per output than advanced fabs which are highly automated). For example, packaging and testing operations in India could be ~10–20% cheaper than in Taiwan or China due to labour cost differentials. Indeed, Malaysia's interest in partnering with India hints at India becoming a complementary hub in South/Southeast Asia for assembly/test. But for capital-intensive advanced fabs, cost advantages are less about labour and more about efficiency and yield – areas where Taiwan and the U.S. excel.

Relative to these nations, India is **not yet in a position to compete on leading-edge technology or volume**, but it doesn't need to *beat* them to find a significant role. The global supply chain is expanding, with projections of over 70 new fabs needed worldwide by 2030. Many of those will be in the U.S., Taiwan, China, etc., but some could be in India to serve its market and as part of supply chain diversification for allies. The next section will directly assess whether and how India can become a "leading global semiconductor-producing state," incorporating the insights from these comparisons.

Can India Become a Leading Global Semiconductor Producer? – An Assessment

With the groundwork laid on India's current capabilities, resource base, and by benchmarking against global leaders, we now address the core question: *Can India realistically build itself into a leading semiconductor-producing nation?* This entails evaluating India's prospects of achieving a significant share of global semiconductor manufacturing and influence in the industry. We analyse this along three facets – opportunities/strengths, challenges/weaknesses, and a realistic timeframe and niche in which India could excel.

5.1. Strengths and Opportunities Supporting India's Ambition

Several factors give India a credible opportunity to become an important player in semiconductors:

5.1.1. Political Commitment and Strategic Clarity

The Indian government's resolve is evident. Unlike in the past, top leadership (Prime Minister's Office) is directly championing the semiconductor mission as vital to economic security (often invoking the goal of "Atmanirbhar Bharat" or self-reliant India). The creation of enabling policies – ISM, PLI incentives, infrastructure push – demonstrates commitment. Additionally, semiconductors are now a key element of India's international diplomacy (e.g., U.S.-India joint statements, Quad working group on semiconductors). This high-level focus ensures that issues like approvals, land acquisition, etc., which often plague Indian projects, are expedited for semiconductor ventures. For example, the speed with which Micron's project went from announcement to ground-breaking (3 months) was unprecedented in India. Such government support will remain crucial over the long gestation of this industry.

5.1.2. Large and Growing Domestic Market

India is one of the fastest-growing electronics markets. Its burgeoning consumer class and initiatives like Digital India mean exploding demand for smartphones, PCs, data centres, IoT devices, automotive electronics, and solar panels – all of which drive semiconductor consumption. Analysts project India's semiconductor consumption to grow to US$110 billion by 2030 from ~$38 billion in 2023. This home market can underpin local manufacturing – fabs set up in India will have nearby customers (e.g., Indian assembly plants of mobile phones or automobiles). This contrasts with, say, Taiwan which has almost no local consumption and must export everything. A local market can also absorb chips made at older nodes for longer (for instance, India's huge two-wheeler automotive sector might still use 90 nm microcontrollers, which a domestic fab could supply). Thus, India can tailor production to its market needs initially, achieving economies of scale domestically before aiming for exports.

5.1.3. Human Capital – Design Prowess and Young Workforce

As detailed earlier, India's talent pool in semiconductor design and software is a big asset. Leading in design is not the same as leading in production, but it provides a foundation. Many expatriate Indian engineers work in fabs and companies abroad; if opportunities open up back home, some of this diaspora expertise could return (similar to how Taiwan benefited from U.S.-educated engineers returning in the 1980s). Moreover, India's demographic dividend (median age ~28) means a pipeline of young engineers who can be trained in new fabs. A related strength is English language proficiency and rule of law, which makes collaboration with Western firms/institutions easier. Chris Miller pointed out that India's chip journey will be decades-long but emphasized that *starting now* is crucial – India has begun that journey, and its abundant talent will be the engine, provided it is skilfully directed and retained in India.

5.1.4. Some Resource Security

While India lacks certain materials (as discussed, it will rely on imports for silicon wafers, etc.), it does have leverage in others. For example, India's control of heavy mineral sands (monazite for rare earths, titanium minerals, etc.) is an advantage as these minerals become strategically important. If India successfully scales rare earth production (e.g., providing Nd-Pr for magnets), it could attract parts of the supply chain (like magnet manufacturing or motor manufacturing) to India, which in turn would support its electronics and EV industries. Also, India is a leading producer of steel and aluminium – which, while not directly going into chips, means domestic availability of construction materials for cleanrooms, fab modules, etc., at competitive cost. India's sizeable chemical industry might be repurposed or upgraded to make some ancillary chemicals (photoresist solvents, gases like WF_6, etc.) domestically in future, especially since companies like BASF, Merck already operate in India and could expand into electronics chemicals.

5.1.5. Geopolitical Alignment and Friendshoring

India is uniquely positioned as a partner to both Western and East Asian tech leaders. The U.S., Europe, Japan all see India as a potential counterweight to China and have shown willingness to include India in global semiconductor initiatives (for instance, the US-led "Chip 4" could one day become "Chip 5" if India's capacity grows, at least in packaging). Already, American companies (Micron, AMD) and Japanese companies (Renesas, TEL) are actively engaging in India's semiconductor push. The recent U.S.-India iCET agreement and creation of a joint task force on semiconductors means India can tap into expertise from IBM, Applied Materials, etc., through structured programs. *Friendshoring* – the concept of moving supply chains to trusted countries – works in India's favour; for example, U.S. officials have explicitly mentioned India as a destination for diversifying chip supply chains. If India can maintain political stability and improve ease of doing business, it stands to gain investment that might have otherwise gone to China or others, due to this trust factor.

5.1.6. Potential to Leap in Niche Technologies

India does not need to replicate everything; it can aim for leadership in selected niches. One possibility is compound semiconductors and advanced packaging. ISM already has a focus area for compound semiconductors (like SiC, GaN) which are crucial for EVs, 5G, etc. Setting up a GaN fab (for power electronics) is somewhat less capital intensive than leading-edge silicon and could address a growing market. Similarly, India could invest in Advanced Packaging (2.5D/3D integration, chiplet integration) – an area where even the U.S. and others are ramping up because as Moore's Law slows, packaging is key. India's large OSAT investments (Micron, Tata, etc.) could evolve into advanced packaging hubs. With the trend of chiplets, even if India doesn't make the most advanced logic chip, it could assemble and package multi-chip modules for AI accelerators or processors (for instance, putting together a package with HBM memory stacks and chiplets made elsewhere). This would be a valuable capability, making India part of leading-edge product supply chains.

India's opportunities lie in leveraging its talent and market, aligning with global partners, and carving out strategic segments (like mature-node foundry, OSAT, and specialty chips) where it can be competitive cost-wise or scale-wise.

5.2. Challenges and Constraints on India's Path

Balanced against the above strengths are significant challenges that could limit India's ability to become a true "leading" producer:

5.2.1. Technology Gap and Dependence

Despite plans, India currently has no domestic IP or expertise in advanced process technology. The Tata-PSMC fab will rely entirely on PSMC's transferred process (likely 55 nm or 65 nm CMOS) to start with. This means India is dependent on foreign partners for know-how. If geopolitical issues or commercial considerations change, sustaining technology upgrades might be hard. For leading-edge (sub-10 nm), India is nowhere in the picture – those processes are the crown jewels of TSMC, Samsung, Intel, none of which they would share easily. So, India faces the risk of being perpetually behind the cutting-edge, unless it invests billions in indigenous R&D (which it is beginning to, but results will take time). Becoming a "leading producer" often implies being at or near the forefront of technology – this will be a multi-decade endeavour for India, if ever. Chris Miller noted that it took Taiwan and Korea decades from starting in the 1970s to reach where they are, and India starting in the 2020s might not reach parity until much later, if it stays the course.

5.2.2. Scale and Investment

Semiconductor fabs are extremely capital-intensive. A single modern fab can cost $5–10 billion (as seen with Tata's $10 billion plan, or TSMC's ~$20 billion for an advanced node fab). To be a *global leader*, a country typically hosts many such fabs. For example, Taiwan has dozens of fabs across TSMC, UMC, etc., and keeps investing. India's current budget of $10 billion incentives might support 1–2 large fabs and a handful of smaller plants – which is a good start but not sufficient to catapult India into the top tier of producers by volume. Maintaining a leading position would require continuous investment. As nodes advance, older fabs become obsolete for leading products, requiring new fabs. Will India have the political will and economic capacity to continue pouring money beyond the initial phase, especially if early results are slow? This is a question. Other countries aren't standing still – the U.S., EU, Japan all launched their own subsidy programs; China is reportedly planning a $40 billion new fund in 2023 after U.S. sanctions hit. India's investment, while significant for its economy, may need to grow further to keep pace.

5.2.3. Infrastructure and Ease of Operation

Building and running fabs demands impeccable infrastructure – 24/7 power with no outages, high purity water in huge volumes, cleanroom construction expertise, logistics for sensitive equipment, etc. India has struggled with infrastructure in other industries (power outages, project delays). Although special steps are taken for these projects (e.g., Gujarat is providing robust power and water for Dholera fab), any lapse could be disastrous – a power glitch of even a second can ruin an entire batch of wafers, which can cost millions. Taiwan can handle typhoons and earthquakes with minimal fab disruption because of experience and engineering; California fabs handle minor quakes. India will have to prove it can similarly ensure stability (the fact that Micron chose Gujarat and not, say, an earthquake-prone or flood-prone area, is deliberate). Moreover, doing business in India can involve bureaucratic red tape, although the government is trying to cut that for strategic investments. If companies face unexpected hurdles (e.g., customs delays for importing tools, or difficulties in hiring expats due to visa issues, etc.), it could slow progress and deter others. A *Business Standard* op-ed quipped that the excitement of announcements (like Semicon India conferences) must not cloud the need to "go back to the drawing board" to address basic bottlenecks. So, execution risk is high.

5.2.4. Workforce Skill Gaps

As discussed, India is training people, but initially it will likely face a shortage of experienced professionals for manufacturing. This could lead to lower yields and output in initial years compared to global standards. Low yields make a fab uneconomical. There will be a steep learning period where Indian fabs might produce chips at higher cost until they catch up in efficiency. During that time, global tech will have moved further ahead. It's a race where India is a late starter. Additionally, retaining talent is a concern: if an engineer gains valuable experience at, say, the Tata fab, they may be poached by overseas firms offering higher pay. Building a semiconductor culture domestically akin to what Taiwan or even China has, will take time and consistent successes to motivate people to stay in this challenging industry.

5.2.5. Global Market Competition

Even if India ramps up production, it enters a highly competitive market. Other foundries (GlobalFoundries, SMIC, TSMC) might cut prices for older nodes to keep customers. For instance, if India's fab offers 65 nm wafers, they will be competing with excess 65 nm capacity in China or elsewhere that might be cheaper (given subsidized Chinese fabs or fully depreciated older fabs abroad). India might have to initially rely on domestic demand or niche demand to keep fabs utilized. Achieving high utilization is key – an idle fab is a money sink. So, India must cultivate customers (fabless companies) who will use Indian fabs. This requires building trust in quality and establishing business relationships which historically didn't exist (most fabless firms are used to TSMC/GlobalFoundries, etc.). Government can help by preferential procurement – e.g., for defence or government electronics, use "Made in India" chips, even if slightly costlier, to give local fabs business. Without such measures, purely market-driven dynamics might not favour a new entrant.

5.2.6. Upgrading and Staying Relevant

It's not enough to build one generation of fab; to be leading, India must upgrade tech every few years. This is a huge challenge. It would require continuous partnerships or developing in-house R&D for process improvement. For example, suppose Tata's fab starts at 65 nm in 2026. By 2030, for it to remain useful, it might need to move to say 28 nm or a specialized process like FD-SOI. That needs either licensing new tech or extensive R&D. Without tech advancement, there is the risk India's fabs become outdated and unable to attract new customers (like what happened to some early fabs in China that got stuck at one node and struggled). Thus, a sustainable industry means a pipeline of technology – which typically is what companies like TSMC handle with their massive R&D. In India, currently only government can orchestrate such a pipeline by maybe bringing in new partners or funding joint R&D centres (one idea floated is a partnership with a tech-leading country to create a semiconductor research institute in India; discussions with IMEC or Leti from Europe could be beneficial).

5.2.7. Financial Viability

Chip manufacturing is a low-margin, high-volume business (except at the very high end). There's a reason many companies have exited or never entered: it's tough to make profits. The initial Indian projects are heavily subsidized, which is fine to start. But in the long run, either products made must be competitive or subsidies would become an endless requirement. If fabs run at a loss and need continuous bailouts, it will be politically and economically hard to justify (especially if outcomes like jobs or tech transfer don't clearly materialize). The Vedanta-Foxconn saga (which collapsed due to lack of a technology partner and perhaps overestimation of government support) highlights the financial tightrope – Foxconn likely pulled out because they saw unclear returns and issues. Now Foxconn is re-approaching with smaller steps (like OSAT) which have a clearer path to profit. So, India might progress more in packaging where business viability is better and less in bleeding-edge fabs which burn cash. That path still helps but would not qualify as "leading producer" in the sense of high-tech leadership. It might, however, qualify in terms of volume for certain segments.

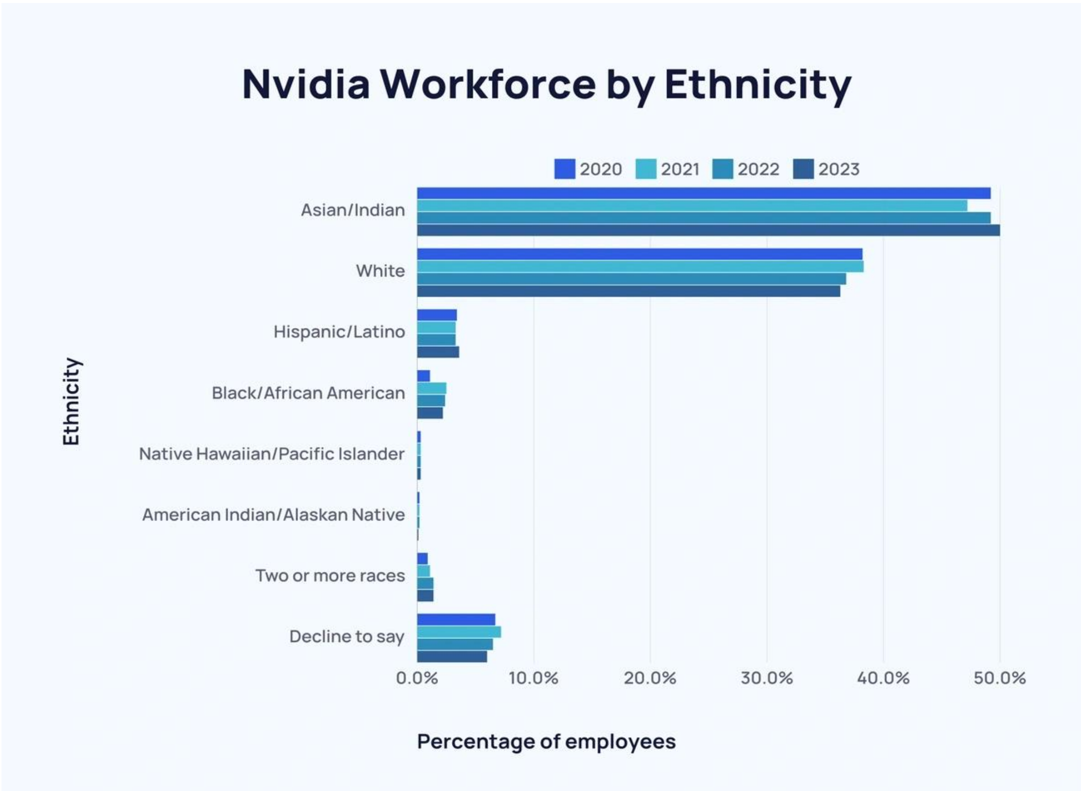

Image 2: Ethnic composition of Nvidia's workforce from 2020 to 2023, showing a consistent increase in Asian/Indian representation and a gradual decline in White representation over the years. (Source: Exploding Topics)

The Brain Drain Dilemma

The image showing Nvidia's workforce by ethnicity highlights a striking trend: individuals of Asian/Indian origin made up over 40% of Nvidia's workforce by 2023, surpassing White employees and reflecting a broader pattern of brain drain from India. This outmigration of highly skilled STEM professionals, particularly in fields like semiconductors, has significantly impacted India's ability to advance its domestic semiconductor ecosystem. Despite policy pushes like the India Semiconductor Mission, India struggles to retain and utilize top-tier talent due to limited R&D infrastructure, few high-end fabrication facilities, and underdeveloped industry-academia linkages. Reports indicate that nearly 90% of Indian STEM graduates in the U.S. prefer to stay abroad for better opportunities (Chakravartty, 2021), and over 50% of Indian-origin semiconductor professionals hold senior roles outside India (NASSCOM & Zinnov, 2022). While these professionals contribute extensively to the global tech industry, including key firms like Nvidia, their absence at home continues to hinder India's semiconductor ambitions.

5.3. The Likely Trajectory

In the short to medium term, India is unlikely to rival the likes of Taiwan, South Korea, or the U.S. in advanced chip production. It will, however, likely establish itself as a significant regional player in specific areas:

- By 2030, India could be a major centre for **chip assembly, packaging, and testing** – possibly handling a notable share of global OSAT capacity (for memory and maybe logic chip packaging). With Micron, Tata, and others, India might account for e.g. 5–10% of the world's assembly of certain chip types, especially if more OSAT companies invest. This alone is a multi-billion-dollar industry and will integrate India into supply chains.

- In **fabrication of mature semiconductors**, India could achieve self-sufficiency and even export capacity. For instance, it could meet a majority of its own need for 65 nm to 180 nm microcontrollers, analog chips, power devices by domestic fabs. It might also export such chips to developing markets or to global companies looking for second sources. This won't make India a "tech leader" but a reliable supplier in the global market for legacy nodes (which remain in use in automotive, industrial, etc.).

- India might also carve a niche in **specialty fabs** like gallium nitride, silicon carbide, or display fabs (Vedanta still plans a display glass fab in Gujarat). If, say, India becomes a top-3 producer of LED chips or power transistors, that is one form of leadership in a sub-sector.

In the long term, if India sustains its efforts, it could aim to be among the top global semiconductor manufacturing locations. For that, it would need multiple large fabs (maybe some run by multinational companies) and continuous tech upgrades. One scenario is that after initial success, global players like Intel, TSMC, or Samsung might decide to build fabs in India to diversify their footprint and tap the local market. If by 2030 India has proven capability in infrastructure and workforce (with the first fabs running well), it could attract one of the big players, which would be a game-changer. An Intel 5 nm fab or a TSMC 3 nm fab in India in the 2030s would indeed make India a leading producer in terms of both capacity and tech. This is speculative but not impossible – especially as these companies look to reduce over-concentration in Taiwan/South Korea and engage with India's market. Notably, there were rumours that India invited TSMC to consider setting up shop; TSMC has not agreed yet, but never say never if conditions become favourable.

However, we should temper expectations. "Leading" is a high bar. By most metrics (market share, technological edge), the leaders in 2030 will likely still be Taiwan (if no conflict), South Korea, the U.S., and possibly China (if it continues its march). India could realistically strive to be in the second tier – alongside say countries like Japan (which has significant industry but not top market share) or Germany (which has strong auto chip fabs but not broad dominance). That alone would be a huge achievement given India's starting point.

Chris Miller and other experts have frequently stated that India's effort is a decades-long game. Miller also noted that "it's crucial that we begin rather than engage in endless debate over the best starting point" – implying that India should start with whatever nodes or tech it can (28 nm, 40 nm, etc.) and build momentum. Encouragingly, this is exactly what India is doing: beginning at 28–65 nm range and in OSAT, which are sensible entry points. From that beachhead, improvements can be made.

Moreover, *leading* can also mean leading in terms of strategic importance, not just volume. If India becomes indispensable in certain parts of the chain (for example, an Indian OSAT ends up packaging many of Apple's chips, or Indian fabs produce chips for the global automotive industry), then India will hold leverage and significance beyond its pure market share. With geopolitical shifts encouraging diversification away from China, India is well placed to grab such opportunities – provided it maintains quality and reliability.

Risk factors that could derail India's mission include: a change in political will (e.g., a future administration not prioritizing this spending), a major project failure (if, say, Tata's fab fails to produce good yield chips and is deemed a white elephant, it could sour public perception), or external crises (war, pandemics) drawing focus away. Conversely, **success factors** would be early wins (Micron plant delivering on time, Tata producing chips by 2026 that go into Indian cars or phones, etc.), which would build confidence and justify further investment.

In conclusion, **India is on the path to becoming an important semiconductor producer, but becoming a top-tier leader will require perseverance over a generation**. In the near term, India will strengthen its position in the global value chain through packaging and mature node fabs, leveraging government incentives and its talent. It can reasonably aim to achieve self-reliance in semiconductors for strategic needs (defence, space, secure chips) and reduce import dependency for consumer electronics. Over time, with continuous learning and strategic partnerships, India can move up the value chain. The year **2047** has been mentioned (100 years of independence) as a horizon by which India envisions itself as a developed nation, and being a semiconductor powerhouse is part of that vision. By 2047, it is conceivable that India could have a mature ecosystem with multiple fabs (both local and foreign-owned), a robust fabless design sector, and significant contributions to global semiconductor output. But to get there, the 2020s must lay a solid foundation.

The comparison with the U.S., China, and Taiwan shows that India will need to blend elements of each of their strategies: the U.S.'s innovation and alliances, China's sheer investment and drive for scale, and Taiwan's focus and cluster efficiency. India may not fully catch up with those pioneers, but it does not have to replicate their entire history. It can chart a unique course that plays to its strengths – perhaps being the leader in **democratizing chip production** for the developing world, or pioneering new models like distributed manufacturing or open-source architectures (India is already big on open-source telecom, maybe in RISC-V chips too). These could redefine what leadership means.

Thus, while India faces steep challenges in becoming a leading semiconductor producer, it has taken critical initial steps and possesses complementary strengths that can, with sustained effort and international cooperation, establish it as a significant global semiconductor hub in the long run. The journey has begun, and the coming decade will be pivotal in determining just how far up the semiconductor value chain India can climb.

Conclusion

India's semiconductor mission represents one of the country's most ambitious technology initiatives to date – one that is strategic, resource-intensive, and long-term in scope. This paper analysed India's capabilities and plans in semiconductor manufacturing, its resources in critical materials, and the likelihood of India emerging as a leading producer, while comparing India's approach with those of the U.S., China, and Taiwan.

India's current semiconductor manufacturing capability is in a nascent stage but evolving rapidly. Supported by robust government policies like the India Semiconductor Mission and production-linked incentives, India is now establishing actual fabrication and assembly facilities. The country will soon witness its first modern 300 mm wafer fab (the Tata-PSMC plant in Gujarat) and has multiple assembly/test plants under construction (Micron's in Gujarat, Tata's in Assam, and others). These developments mark a historic shift from India's past, when chip design flourished domestically but all chips were fabricated abroad. Government policy has been the catalyst, providing generous subsidies and infrastructure support, while also investing in workforce development to address skill gaps.

India's industrial ecosystem for semiconductors is being built nearly from scratch. It leverages a strong design sector – with many global firms' R&D centres and emergent local startups – as a foundation to integrate backwards into manufacturing. Industrial capability remains limited at present: India has no legacy of high-volume chip production, which means initial ventures carry execution risks and steep learning curves. Yet, foreign partnerships (with firms from Taiwan, Japan, the U.S.) and the involvement of large Indian conglomerates (Tata, HCL, etc.) mitigate some risks by bringing in expertise and capital. If these projects stay on track, by the late 2020s India will have a small but significant chip manufacturing footprint and a more complete value chain (from chip design to packaging) on its soil.

Regarding **rare earths and critical materials**, India possesses substantial natural resources (e.g., fifth-largest rare earth reserves, substantial gallium in bauxite, some lithium, etc.), but has so far underutilized them. The analysis showed that India contributes under 1% of global rare earth supply despite its resource base. Challenges such as restrictive policies, lack of refining tech, and environmental concerns have held back extraction and processing. The situation is gradually changing: the government has identified 30 critical minerals and launched a Critical Mineral Mission to boost exploration and production. IREL, the state-run rare earth company, aims to greatly expand output by 2030. For semiconductors, India's immediate material dependencies (silicon wafers, ultra-pure chemicals, gases) will rely on imports and foreign suppliers – a reality acknowledged by policymakers who are fostering international partnerships to secure these supplies. In the longer term, if India can improve its refining of rare earths and production of certain semiconductor materials (like photoresist chemicals or specialty gases), it will enhance its supply chain resilience and even offer alternatives to the world (for instance, non-Chinese sources of gallium or REEs).

On the **question of India becoming a leading global semiconductor producer**, the research leads to a nuanced conclusion. India has definite strengths – government resolve, a vast talent pool, a huge market, and now, international support – which position it to become an important player in the semiconductor domain. Over the next decade, India is likely to establish itself as a major centre for chip *assembly and testing*, and a significant producer of chips on mature technology nodes. This will address domestic demand and also contribute to diversifying global supply chains, aligning with "China-plus-one" manufacturing strategies. However, displacing or matching the incumbents (U.S., Taiwan, South Korea, China) in cutting-edge semiconductor manufacturing is a far more challenging proposition. Those countries have built formidable lead in know-how, scale, and ecosystem over decades and have no intention of slowing down.

India's realistic trajectory, if consistently pursued, is to join the *second tier* of semiconductor producing nations by 2030 – akin perhaps to what Japan or Germany are: with some large fabs, strong niche specializations, and integration in global networks, but not the top producer overall. By 2030, a scenario where India supplies, say, 5% of the world's semiconductors (across various categories) would itself be a remarkable achievement from essentially 0% today. Looking further to 2040 or 2050, if India remains committed and dynamically upgrades its capabilities, it could inch higher in ranking, possibly approaching what China's level might be (if China reaches ~20–25% of world output by 2030 as projected, India might target high single digits or low teens a decade later with sufficient investment and strategic focus). But this is speculation and would depend on continuous heavy investment, successful knowledge accumulation, and the global geopolitical/economic climate.

One key finding is that **comparative advantages can allow India to lead in certain segments** even if it doesn't lead in all. For instance, India could become a global leader in semiconductor packaging or in chips for strategic sectors (like a hub for chips used in electric vehicles or solar inverters, leveraging its market in those areas). The Indian government's broad approach – simultaneously courting leading-edge tech (through partnerships) while also aiming for self-reliance in older tech and materials – could yield a diverse ecosystem that is robust. It mirrors in some ways China's two-pronged approach: attempt to catch up on advanced tech but also dominate legacy tech and new application-specific chips where possible.

The comparisons with the U.S., China, and Taiwan highlight that *there is no single path to success*, but all require unwavering commitment, significant public and private investment, and cultivating human expertise. The U.S. leveraged innovation and now subsidies, China leveraged capital and market size, Taiwan leveraged focus and cluster efficiency. India will likely need to borrow elements from each: incentivize innovation (as with partnerships on R&D and encouraging design startups), deploy patient capital (through government funding and attracting foreign investment), and create high-efficiency clusters (like the upcoming Silicon Parks in Gujarat and Uttar Pradesh). The end-goal is not simply to make chips domestically, but to create a self-sustaining semiconductor *ecosystem* – one that includes education, research, design, manufacturing, and a supply chain of materials and tools. Achieving this ecosystem will be the true mark of success for India's semiconductor mission, enabling it to continue progressing long after initial projects.

In conclusion, India's semiconductor mission has moved from aspiration to concrete action, reflecting a realization that in the modern world semiconductors are not optional – they are a strategic necessity. The journey will test India's industrial resolve and strategic patience. The academic analysis indicates cautious optimism: India *can* become a significant semiconductor-producing nation, though becoming a "leading" producer on par with the current giants will likely take longer than the 5–10-year horizon, perhaps stretching into the 2040s. Nonetheless, every step India takes now – whether setting up a new fab, training thousands of engineers, or refining rare earths – is building the foundation for a future where India is not just a consumer of advanced technology, but a creator and provider of it.

The global semiconductor landscape by 2030 will be more distributed and diversified than today. A more multipolar chip world can enhance supply chain resilience and innovation. India, with its democracy, talent, and market, becoming a strong node in that world, is a welcome development from both an economic and geopolitical standpoint. The coming years will reveal how effectively India can turn its policy vision into silicon reality.

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