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Introduction

In modern joint warfare, dominance in the electromagnetic spectrum relies on Gallium Nitride (GaN) compound semiconductors, which form the core technology behind advanced active electronically scanned array (AESA) radars and electronic warfare systems.[1] The Defence Research and Development Organisation's (DRDO) achievement in designing and pilot-fabricating indigenous GaN Monolithic Microwave Integrated Circuits (MMICs) marks a major milestone towards the tactical self-reliance of the Indian Air Force (IAF).[2] It was partly born of necessity during the 2016 Rafale fighter jet negotiations when France reportedly refused to share GaN chip technology under the offset clause, citing the Wassenaar Arrangement.[3] That denial catalysed what seven years of sustained research finally delivered India's emergence as one of the seven nations capable of independently producing GaN semiconductors, alongside the United States, France, Russia, Germany, South Korea, and China.[4]

Yet a serious problem remains. While domestic laboratories like the Solid State Physics Laboratory (SSPL) which works under DRDO and the Gallium Arsenide Enabling Technology Centre (GAETEC) have mastered the chip design architecture, India's physical supply chain remains highly vulnerable.[5] The nation is entirely dependent on imports for raw gallium, silicon carbide (SiC) substrates, and ultra-pure precursor gases (99.99% purity) required for cleanroom fabrication.[6] Beijing's export controls, first imposed in August 2023 and later expanded into a targeted ban on shipments to the United States in December 2024, have turned gallium from a lesser-known industrial byproduct into a strategic tool of great power competition.[7] International gallium prices subsequently surged over 141 percent between early 2025 and mid-2026.[8] Against this backdrop, India's challenge is to build lasting capability in GaN devices and supply networks. Catching up in the semiconductor sector requires more than assembly. It also needs strong domestic firms, trusted partnerships, and control over critical chokepoints.[9]

GaN Chips: Military Relevance, and India's Programme

Gallium Nitride (GaN) is a compound semiconductor, built by fusing gallium with nitrogen rather than relying on pure silicon, the material that has powered electronics for seven decades. It belongs to what engineers call the "third generation" of semiconductor materials, following silicon and gallium arsenide (GaAs).[10] In defence and aerospace applications, GaN is typically produced as a High Electron Mobility Transistor (HEMT) and used in a Monolithic Microwave Integrated Circuit (MMIC), a chip that integrates several active and passive components to transmit and receive radio-frequency signals.[11] These MMICs form the basic components of transmit-receive (T/R) modules, which are assembled in large numbers to create an Active Electronically Scanned Array (AESA) radar.[12] DRDO scientists describe compound semiconductors like GaN as the "thoroughbred racehorses" of high-performance electronics, built for demanding, sustained loads rather than everyday use.[13]

While Silicon has a bandgap of 1.1 eV, GaN has a much wider bandgap of 3.4 eV. As a result, GaN can operate at temperatures of up to 1,000°C and withstand much stronger electric fields.[14] It also has higher electron mobility (around 2,000 cm²/Vs compared to 1,500 cm²/Vs for silicon), enabling faster switching with lower heat loss.[15]

Furthermore, GaN can tolerate electric fields of about 3.3 MV/cm before breakdown, compared to about 0.3 MV/cm for silicon, allowing devices to operate at much higher voltages using thinner material layers.[16] These advantages, together with lower on-resistance and higher power density, make GaN HEMTs highly suitable for fighter radar transmit/receive (T/R) modules and compact airborne microwave electronics.[17]

For the Indian Air Force (IAF), GaN is not just a laboratory technology; it has real operational value.[18] The IAF operates in environments ranging from extreme desert heat to sub-zero temperatures at high altitudes, making GaN's reliability under such conditions especially valuable.[19] Traditional silicon and Gallium Arsenide (GaAs) components perform less effectively under large temperature variations and require heavy liquid-cooling systems that add weight and reduce payload.[20] GaN's high thermal conductivity lowers cooling requirements, making it suitable for lightweight AESA radars and electronic warfare (EW) jammers.[21] The adoption of GaN-on-Silicon Carbide (GaN-on-SiC) technology for the Tejas's Uttam radar and the Su-30MKI's upcoming Virupaaksha AESA radar is expected to improve target detection range and resistance to hostile jamming.[22]

India is steadily building its indigenous GaN capability.[23] DRDO's Solid State Physics Laboratory (SSPL), together with the Gallium Arsenide Enabling Technology Centre (GAETEC) in Hyderabad, has established limited production of GaN-on-Silicon Carbide (GaN-on-SiC) HEMTs of up to 150 W and X-band MMICs.[24] Private companies such as Agnit Semiconductors, supported by the Ministry of Defence's iDEX programme,[25] and the Indo-US "Shakti" military fabrication facility at Jewar[26] are also contributing to this effort. However, because India still relies on imports for ultra-high-purity precursor gases and specialised reactor equipment, DRDO has partnered with Indian academic institutions to develop indigenous alternatives and strengthen the supply chain.[27]

Global GaN Supply Chain: Its Structure and Players

GaN's supply chain consists of two distinct stages: the raw material and the finished semiconductor chip. The raw material supply is particularly vulnerable because gallium is not mined directly. Instead, it is mainly recovered as a by-product of bauxite and zinc processing, with coal and industrial waste serving as secondary sources.

Nearly 90% of primary gallium production is linked to aluminium production.[28] Raw gallium also does not occur naturally in its elemental form; it exists only in small quantities within bauxite and zinc ores, making its extraction a complex process.[29]

China produces around 98–99% of the world's primary low-purity gallium, largely because of its extensive aluminium refining industry rather than the availability of unique deposits.[30] Since August 2023, Beijing has required export licences for gallium, and in December 2024 it banned shipments to the United States, turning this little-known by-product metal into a strategic chokepoint.[31] As a result, the main risk lies in the concentration of processing capacity rather than the availability of gallium itself.[32]

In contrast, the semiconductor manufacturing stage is far more diversified. Companies such as Infineon (which acquired GaN Systems for $830 million in 2023), Wolfspeed, Qorvo, MACOM, and Navitas Semiconductor design and manufacture GaN devices across the United States, Germany, and Japan, serving a global GaN device market valued at an estimated $4.83 billion in 2026 and projected to reach $10.55 billion by 2031.[33] Despite this diversified manufacturing base, most companies continue to rely on gallium refined in China.

Where does India Currently Stands at this race

India's position reflects both opportunity and challenge. While the country has abundant bauxite reserves, it has historically lacked the processing capacity needed to produce gallium. Bauxite residue (red mud) in Odisha and Jharkhand is estimated to contain extractable gallium worth around ₹32,928 crore, yet limited domestic processing has kept India dependent on imports for raw gallium.[34] To reduce this dependence, the National Aluminium Company Limited (NALCO), in partnership with the Bhabha Atomic Research Centre (BARC) and the Heavy Water Board (HWB), began construction of a demonstration plant at Damanjodi, Odisha, on 20 November 2025.[35] Using a proprietary Ion-Exchange (IX) process, the plant is expected to recover 10–20 tonnes of 99.99% semiconductor-grade gallium annually from Bayer process spent liquor, strengthening India's domestic supply of compound semiconductors.[36]

On the fabrication side, India is gradually expanding its capabilities. DRDO's Solid State Physics Laboratory (SSPL) and the Gallium Arsenide Enabling Technology Centre (GAETEC) produce defence-grade GaN wafers and MMICs, while Agnit Semiconductors, an IISc spin-off supported by the Ministry of Defence's iDEX programme, is India's only private vertically integrated GaN chip manufacturer.[37] The proposed Indo-US "Shakti" fabrication plant at Jewar is expected to further strengthen India's compound semiconductor manufacturing capacity for national security applications,[38] while RIR Power Electronics is establishing a ₹618-crore silicon carbide (SiC) wafer epitaxy facility in Bhubaneswar.[39] These developments show that raw materials alone are not enough. Countries also need strong refining, high-purity processing, and semiconductor fabrication capabilities to build a secure and resilient supply chain.[40]

Supply Chain Vulnerabilities

India's semiconductor sector remains heavily dependent on imports. Around 85% of the country's chip demand is met by imports, mainly from Taiwan, China, South Korea, and the United States.[41] The dependence is even higher for electronic hardware, with nearly 80% of components sourced from China and Hong Kong. Past incidents involving power-grid intrusions and compromised defence equipment have highlighted the security risks like espionage associated with relying on foreign-built hardware.[42] India has made significant progress in semiconductor design, but its defence-grade GaN ecosystem still faces major supply-chain challenges.[43] The main weakness lies in semiconductor fabrication, as India continues to import ultra-high-purity precursor gases (99.99999% purity), Metal-Organic Chemical Vapor Deposition (MOCVD) reactors, and high-purity Silicon Carbide (SiC) substrates required for manufacturing GaN-on-Silicon Carbide (GaN-on-SiC) devices.This dependence leaves the Indian Air Force vulnerable to external supply disruptions.[44]

The complexity of semiconductor manufacturing adds to these challenges. Producing an advanced semiconductor chip typically involves 70 to 90 processing steps carried out over two to three months and depends on a global workforce of fewer than 50,000 specialised engineers.[45] In India, manufacturing risks are further increased by supplier concentration, long lead times, dependence on critical component suppliers, and the complexity of semiconductor production.

In the defence sector, these challenges are reflected in inventory management gaps, inconsistent demand forecasting, limited coordination among the armed services, and the slow adoption of digital supply-chain systems.[46] To address these vulnerabilities, the Government of India launched the National Critical Minerals Mission with an allocation of ₹16,300 crore to secure the supply of 30 critical minerals, including gallium and germanium, by 2030–31.[47] This is an important step towards strengthening India's semiconductor supply chain. However, the timeline may not fully match immediate operational requirements, since systems such as the Virupaksha and Uttam Mk2 AESA radars are already entering production now, not in 2031.

The Long Term Adversary

From an adversary's perspective, India's dependence on imported semiconductor inputs represents a strategic advantage. China's export controls on gallium have shown how restrictions on critical minerals can disrupt another country's high-technology manufacturing even before a conflict begins.[48] Because India still relies on imported precursor gases, Silicon Carbide (SiC) substrates, and semiconductor fabrication equipment, any interruption in these supplies could seriously affect defence programmes such as the Uttam and Virupaaksha AESA radars.[49] India's broader trade relationship with China further adds to this vulnerability. China remains one of India's largest trading partners, with Chinese exports to India exceeding US$100 billion. This makes it harder for India to reduce external dependence while strengthening strategic autonomy.[50]

The challenge becomes even more significant because China is Pakistan's largest defence supplier. Over the years, it has supplied fighter aircraft, missile technology, and, by 2026, stealth aircraft, further strengthening the China-Pakistan military partnership along India's western border.[51] This puts India in a difficult position on two fronts. China not only dominates the supply of critical materials used in semiconductor manufacturing but also plays a central role in strengthening the military capabilities of India's principal regional adversary. This combination increases India's strategic vulnerability, and diplomacy alone cannot fix it.

India's continued dependence on imported semiconductor chips and critical manufacturing inputs also creates operational risks. During a military conflict, disruptions in foreign supplies or restrictions imposed by supplier countries could delay access to essential components, technical support, or spare parts, affecting the availability of key defence systems.[52] In the short term, port congestion, geopolitical tensions, or disruptions in supplier networks can delay deliveries and interrupt production. Over the longer term, continued dependence on foreign technology, limited domestic refining capacity, and the absence of trusted supplier networks could weaken India's technological self-reliance and leave it vulnerable to external pressure in areas critical to national security.[53]

This concern is not just theoretical. In 2016, France declined to transfer GaN technology under the Rafale offset agreement, demonstrating that even close strategic partners may withhold advanced semiconductor technologies when doing so aligns with their commercial or strategic interests.[54]

Indian Government Initiatives and the Road Ahead: Policy, Budget, and Key Recommendations

New Delhi has responded through three key areas: defence spending, research and innovation, and critical mineral policy. In the Union Budget 2026–27, the Ministry of Defence received a record allocation of ₹7.85 lakh crore, 15.19% higher than the previous year.[55] DRDO's allocation was also increased to ₹29,100.25 crore, of which ₹17,250.25 crore has been set aside for capital R&D to support advanced technologies such as GaN and compound semiconductors.[56] To strengthen domestic capabilities, the government has reserved about 75% of the defence capital acquisition budget for Indian industry and opened 25% of the defence R&D budget to private firms, startups, and academia.[57] The iDEX programme, supported by ₹498.78 crore up to 2025–26 and an additional ₹750 crore under its ADITI sub-scheme, has signed 551 design-and-development contracts with 676 startups and innovators. This has provided funding opportunities for companies such as Agnit Semiconductors that are developing indigenous GaN technologies.[58]

On the civilian side, the India Semiconductor Mission (ISM) 2.0 has been allocated ₹1,000 crore for FY 2026–27 to promote domestic production of semiconductor equipment, materials, and chemicals.[59] This is expected to reduce dependence on imported inputs needed for semiconductor manufacturing. The Modified Programme for Development of Semiconductor and Display Manufacturing Ecosystem has also received ₹8,000 crore for 2026–27 to expand semiconductor fabrication and packaging capacity in India.[60] At the same time, the National Critical Minerals Mission has committed ₹16,300 crore through 2030–31 to secure supplies of 30 critical minerals, including gallium and germanium, supporting projects such as NALCO's Damanjodi gallium extraction programme.[61] These initiatives address different stages of the semiconductor supply chain, from raw materials and manufacturing to strategic capability development.

India's main challenge now is implementation, not ambition. The semiconductor supply chain remains vulnerable because manufacturing is spread across many firms and locations, while supply-chain risk management is still weak. In the defence sector, these challenges are reflected in inventory gaps, inconsistent forecasting, weak coordination between the armed services, and limited use of digital supply-chain systems. These weaknesses increase the risk that disruptions in critical midstream components could delay key defence programmes, including the Uttam and Virupaaksha AESA radars.[62]

Several policy measures could further strengthen India's GaN ecosystem:-

- First, gallium should be designated as a defence-critical mineral and given a dedicated strategic reserve, separate from the broader National Critical Minerals Mission. This is important because defence programmes, including AESA radar production, cannot wait until 2030–31 for secure access to raw materials.
- Second, the government should introduce a guaranteed offtake mechanism—a long-term procurement commitment—for NALCO's gallium production and private GaN manufacturers. Such a mechanism would provide assured demand, encourage private investment, and reduce financial risk for companies.

This is particularly important because the founders of Agnit Semiconductors have identified the lack of assured demand as one of the biggest challenges facing the company.[63]

- Third, ultra-high-purity precursor gases and Metal-Organic Chemical Vapor Deposition (MOCVD) reactors should be included in a dedicated Positive Indigenisation List on a priority basis. This would encourage domestic production, similar to how earlier Positive Indigenisation Lists supported the development of indigenous defence manufacturing.[64]
- Finally, India should consider adopting the Indo-US "Shakti" fabrication model with another trusted partner, such as Japan or France. Partnering with more than one country would reduce the risks associated with depending on a single international partner, a concern highlighted by France's refusal to transfer GaN technology in 2016. These recommendations do not require new institutions. Instead, they require better coordination and faster implementation of the policies and institutions that India has already established to support its semiconductor and defence manufacturing goals.

Conclusion

Gallium nitride is becoming a strategic technology that will shape the future of military systems such as AESA radars, weapons, and high-performance defence electronics. In military terms, GaN acts as a force multiplier, not just a better chip. India's GaN breakthrough is real, but there is still a long way to go. DRDO's success in designing and fabricating indigenous GaN MMICs, feeding directly into the Uttam and Virupaaksha radars, proves that India can compete at the frontier of semiconductor engineering. But a chip is only as sovereign as the material it is made from, and India still imports the gallium, precursor gases, and reactor equipment needed to make that chip. The Indian Air Force's march towards electromagnetic dominance does not begin with designing state-of-the-art GaN chips. It begins with securing the physical supply chain behind them.

Critical minerals and compound semiconductors are increasingly being used as tools of geopolitical pressure. Building a self-reliant GaN ecosystem is therefore an urgent operational need, not something India can plan for later. To achieve true strategic autonomy, India needs to treat GaN as a matter of national security rather than a niche electronics programme.

Declaration

I declare that this manuscript is being submitted exclusively to CENJOWS for publication consideration, is original, and has not been published or submitted elsewhere. I further certify that it contains no classified, restricted, or sensitive information and is based entirely on open-source material suitable for publication in the public domain.

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