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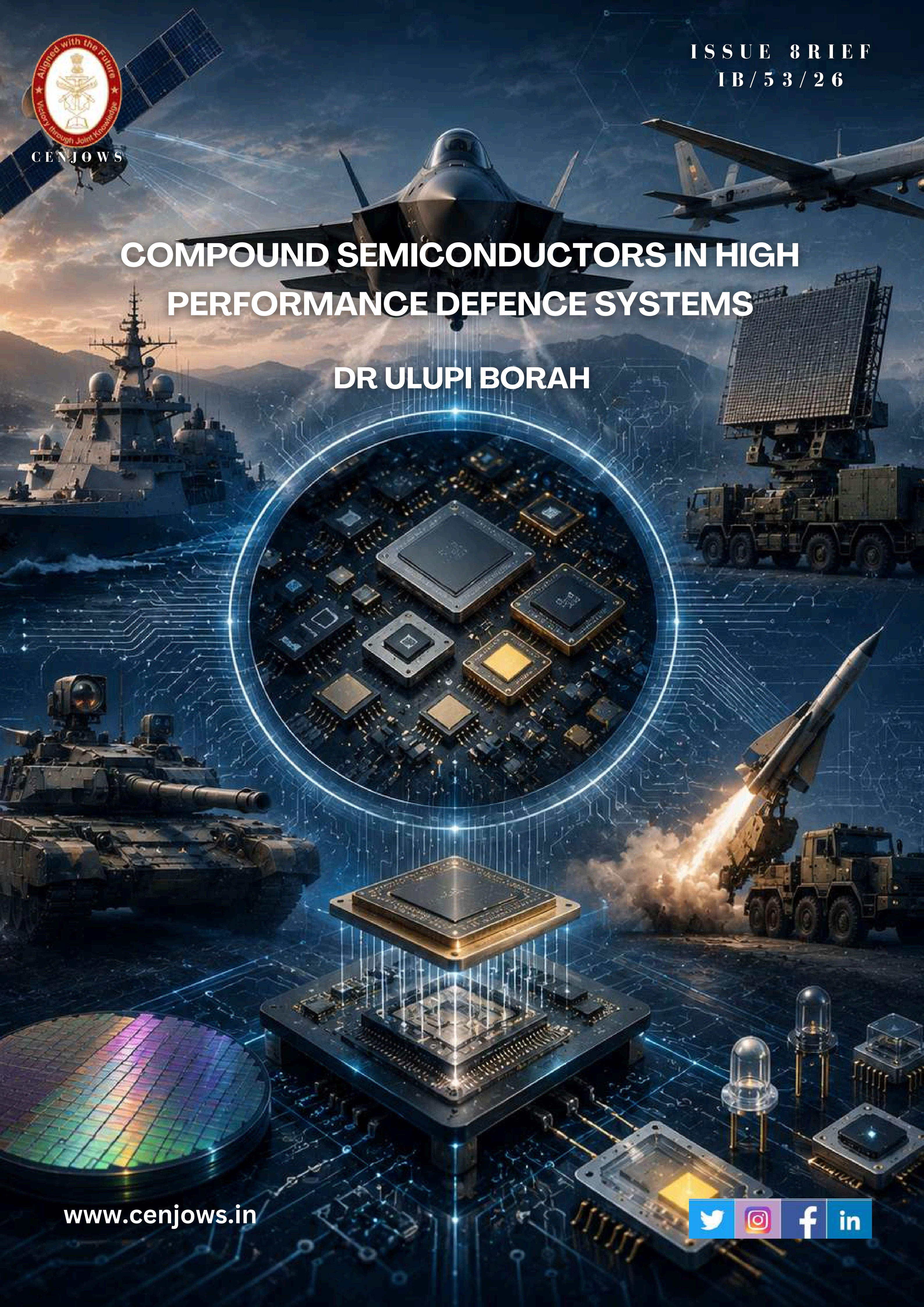

COMPOUND SEMICONDUCTORS IN HIGH PERFORMANCE DEFENCE SYSTEMS

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Compound Semiconductors in High Performance Defence Systems

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Abstract

The rapid evolution of modern warfare has significantly increased the importance of semiconductors, particularly compound semiconductors, in enabling the development of advanced defence technologies. Unlike conventional silicon-based semiconductors, compound semiconductors such as Gallium Nitride (GaN), Gallium Arsenide (GaAs), and Silicon Carbide (SiC) offer superior power efficiency, thermal stability, high-frequency performance, and radiation resistance, making them critical for radar systems, electronic warfare, satellite communication, directed energy weapons, and autonomous military platforms. As global technological competition intensifies, the control of semiconductor supply chains and critical materials has emerged as a major national security concern. In this context, India is increasingly focusing on strengthening indigenous capabilities and trusted semiconductor ecosystems for strategic applications. This article examines the growing role of compound semiconductors in high-performance defence systems and their strategic significance in future warfare. It further analyses India's emerging indigenous ecosystem, key technological challenges, supply-chain vulnerabilities, and the policy measures required for strengthening strategic semiconductor capabilities and technological self-reliance.

Introduction

The character of modern warfare is undergoing a profound technological transformation, driven increasingly by the integration of advanced electronics, artificial intelligence, autonomous systems, and real-time data processing architectures.

Contemporary military operations are no longer shaped solely by conventional kinetic capabilities. Increasingly, success depends on the ability to sense, process, communicate, and respond across multiple domains with speed and precision. This shift has accelerated the "semiconductorisation" of warfare, with semiconductors becoming the essential building blocks of almost every advanced defence system. From radar and electronic warfare systems to satellite communications, missile guidance, infrared imaging, autonomous platforms, and directed-energy weapons, the effectiveness of modern military forces is now closely tied to sophisticated semiconductor technologies.

Modern warfare is becoming ever more sensor-intensive, network-centric, AI-enabled, and spectrum-dominant. Defence platforms today operate in highly contested electromagnetic environments that demand rapid signal processing, high-frequency communications, secure networks, and real-time decision-making. As a result, the operational Observe–Orient–Decide–Act (OODA) loop has become significantly compressed, making computational speed, sensing accuracy, and electronic resilience critical determinants of battlefield advantage. In this context, semiconductors are no longer merely hidden components embedded within military equipment; they have emerged as strategic technologies that directly influence combat capability, survivability, and operational reach.

While silicon continues to dominate the global semiconductor industry due to its scalability and mature manufacturing ecosystem, the operational requirements of advanced defence systems increasingly exceed the physical limitations of conventional silicon-based devices. Modern military systems demand semiconductors capable of operating at extremely high frequencies, elevated temperatures, and high voltages and under intense radiation and electromagnetic conditions. Such requirements have intensified the importance of compound semiconductors such as Gallium Nitride (GaN), Gallium Arsenide (GaAs), Silicon Carbide (SiC), Indium

Phosphide (InP), and Mercury Cadmium Telluride (HgCdTe), which possess superior electronic, thermal, and optical properties compared to silicon.

Compound semiconductors have therefore become critical for the next generation of defence technologies. Their applications extend across Active Electronically Scanned Array (AESA) radars, electronic warfare systems, high-power microwave systems, infrared seekers, satellite payloads, photonics, quantum sensing, terahertz technologies, and advanced power electronics. In many respects, they form the technological backbone of future warfare architectures. As geopolitical competition increasingly extends into technological and supply-chain domains, mastery over compound semiconductor ecosystems is emerging not merely as an industrial priority but as a strategic imperative linked directly to military preparedness, technological sovereignty, and national security.

FUNDAMENTALS OF COMPOUND SEMICONDUCTORS

What are Compound Semiconductors?

Semiconductors constitute the foundational building blocks of modern electronic systems. While silicon has historically dominated the global semiconductor industry owing to its abundance, mature fabrication ecosystem, and cost efficiency, the growing operational demands of advanced defence and aerospace systems have accelerated the importance of compound semiconductors. Unlike silicon, which is a single-element semiconductor, compound semiconductors are formed by combining two or more elements from different groups of the periodic table. These materials exhibit superior electronic, optical, thermal, and high-frequency properties that make them particularly suitable for strategic and military applications.[1]

Compound semiconductors are broadly classified into three major categories[2]:

- **III-V Compound Semiconductors**
  These are formed by combining elements from Group III and Group V of the periodic table. Examples include Gallium Nitride (GaN), Gallium Arsenide (GaAs), and Indium Phosphide (InP). These materials are particularly important for high-frequency radio frequency (RF) electronics, radar systems, photonics, satellite communication, electronic warfare systems, and laser technologies.

According to Dr Rawal, GaN and GaAs based technologies are central to next-generation radar and RF applications, including airborne radars, electronic warfare systems, satellite communication, SDR/data links, and photonic applications.[3]

- **II-VI Compound Semiconductors.**

  These materials are formed using Group II and Group VI elements. Mercury Cadmium Telluride (HgCdTe) and Cadmium Zinc Telluride (CdZnTe) fall under this category. Such semiconductors are extensively used in infrared detector technologies, thermal imaging systems, missile seekers, surveillance systems, and space imaging applications. SSPL's work on cooled and uncooled infrared focal plane arrays (IRFPAs) based on HgCdTe reflects the strategic significance of these materials for missile seeker and thermal imaging applications.[4]

- **IV-IV Compound Semiconductors**

  These are formed using Group IV elements. Silicon Carbide (SiC) and Silicon Germanium (SiGe) are key examples. SiC has emerged as a strategically important wide-bandgap semiconductor due to its high-voltage handling capability, high thermal conductivity, and suitability for power electronics and harsh operational environments. SSPL has indigenously developed SiC ingot (raw semiconductor crystal) and wafer fabrication technologies, recognising their importance for high-power defence electronics.[5]

The Workshop Report on Energising Semiconductor Ecosystems for Defence Applications highlighted that compound semiconductors outperform silicon in three critical domains: power, speed, and light. Their superior electronic properties, such as high electron mobility and direct bandgap characteristics, make them highly suitable for electromagnetic spectrum operations, radars, secure communications, electronic countermeasure systems, and guidance systems.

SEMICONDUCTOR PHYSICS AND MATERIAL PROPERTIES

The strategic importance of compound semiconductors lies fundamentally in their material physics. Defence and aerospace systems require semiconductors capable of operating under extreme thermal, electromagnetic, high-frequency, and radiation-intensive conditions. Material properties such as bandgap, breakdown voltage, electron mobility, saturation velocity, thermal conductivity, and radiation tolerance directly determine the operational performance of semiconductor devices in military applications.

Bandgap Energy

Bandgap energy refers to the amount of energy required to move an electron from the valence band to the conduction band within a material. It is measured in electron volts (eV). Materials with larger bandgaps generally exhibit better high-temperature performance, higher voltage tolerance, and lower leakage currents.[6]

Material	Bandgap (Eg)	Primary Strength
Silicon (Si)	~1.12 eV	Logic and integration
Gallium Arsenide (GaAs)	~1.42 eV	RF and low-noise applications
Gallium Nitride (GaN)	~3.4 eV	High-power RF systems
Silicon Carbide (SiC)	~3.26 eV	Power electronics

Table 1: Bandgap Values and Functional Advantages of Semiconductor Materials. Source: Author's Compilation

The larger bandgap values of GaN and SiC classify them as wide-bandgap semiconductors, enabling operation at higher temperatures and voltages than silicon-based devices.

Breakdown Voltage

Breakdown voltage refers to the maximum voltage a semiconductor device can withstand before electrical failure occurs.[7] A higher critical electric field enables the device to operate at higher voltages while maintaining lower ON resistance and higher efficiency.[8]

Material	Breakdown Voltage Characteristics
GaN	≈3.3MV/cm
Si	≈0.3MV/cm

Table 2: Critical Electric Field Strengths of Semiconductor Materials. Source: Author's Compilation

As reflected in Table 2, the critical electric field strength of GaN is nearly ten times higher than that of conventional silicon-based materials. This significant improvement enables GaN devices to operate at much higher power densities and voltages, making them highly suitable for high-power radar systems, electronic warfare systems, and high-frequency RF applications with greater efficiency and performance.

Electron Mobility and Saturation Velocity

Electron mobility determines how quickly electrons move through a semiconductor material under an electric field, directly influencing switching speed and RF performance.[9]

Material	Electron Mobility ($cm^2/V \cdot s$)	Saturation Velocity (cm/s)
Si	~1400	$\sim 1 \times 10^7$
GaAs	~8500	$\sim 2 \times 10^7$
GaN	~2000	$\sim 2.5 \times 10^7$
SiC	~900	$\sim 2 \times 10^7$

Table 3: Electron Mobility and Saturation Velocity for Materials. Source: Author's Compilation

From table 3, it can be seen that:

- GaAs is preferred for low-noise RF systems,
- GaN is preferred for high-power RF applications,
- SiC is preferred for high-voltage switching and power electronics.

Thermal Conductivity

Thermal conductivity is critical for defence systems operating under high-power conditions such as AESA radars, directed energy weapons (DEWs), and electronic warfare systems.[10]

Material	Thermal Conductivity (W/m·K)
Silicon	~150
GaAs	~50
GaN on SiC	~200
SiC	~370

Table 4: Materials and their Thermal Conductivity. Source: Author's Compilation

Higher thermal conductivity allows efficient heat dissipation, improving device reliability and reducing cooling requirements in military platforms.

Radiation Tolerance

Space and strategic defence systems require semiconductor devices capable of operating in radiation-rich environments. The silicon devices are vulnerable to total ionizing dose effects and latch-up phenomena, whereas GaN and SiC exhibit significantly better radiation tolerance.[11]

GaN devices are particularly resistant to latch-up effects because they lack parasitic silicon-controlled rectifier structures, while SiC demonstrates superior displacement damage tolerance. Such properties make compound semiconductors highly suitable for satellite systems, missile electronics, and space payloads.

WIDE BANDGAP SEMICONDUCTORS (WBG)

Wide-bandgap semiconductors represent one of the most significant advancements in modern defence electronics. Materials such as Gallium Nitride (GaN) and Silicon Carbide (SiC) possess substantially larger bandgaps than silicon, enabling them to operate at higher voltages, frequencies, and temperatures.

Dr D.S. Rawal emphasised that many critical military functions cannot be achieved using silicon alone, particularly high-speed electronics, high-power systems, ultraviolet detection, and high-temperature electronics. This has accelerated the transition toward wide-bandgap semiconductor technologies.[12]

Gallium Nitride (GaN)

GaN has emerged as the dominant material for high-power RF systems. GaN technologies are being used for:

- Airborne radars,
- Electronic warfare systems,
- AESA radar architectures,
- Satellite communication,
- SDR/data links,
- Beamforming systems.[13]

Its high breakdown field, high electron saturation velocity, and superior power density allow compact yet highly powerful RF systems. SSPL's development of X-band and Ku-band GaN MMIC technologies demonstrates India's progress in this domain.

Silicon Carbide (SiC)

SiC is strategically important for defence power electronics because of:

- High thermal conductivity,
- High-voltage operation,
- Low switching losses,
- High-temperature tolerance.

The SSPL presentation notes that SiC wafer fabrication technologies have been indigenously developed due to the strategic restrictions imposed globally on such materials. Future developments include PIN diodes, Schottky diodes, and Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) devices based on SiC for high-power military systems.

Wide-bandgap semiconductors are therefore becoming central to the next generation of high-performance defence architectures, particularly in radar systems, electronic warfare, directed energy weapons, missile systems, autonomous platforms, and future quantum-enabled technologies.

Why Compound Semiconductors are Critical for Modern Warfare

Evolution of High-Performance Defence Systems

The character of warfare in the twenty-first century is increasingly being shaped by digital technologies, artificial intelligence, autonomous systems, and high-speed communication networks. Military operations today are no longer platform-centric or driven solely by conventional kinetic capabilities. Instead, they are becoming increasingly network-centric, sensor-intensive, AI-enabled, and multi-domain in character. Contemporary warfare depends upon the seamless integration of sensors, communication systems, satellites, unmanned platforms, electronic warfare suites, and precision-guided systems across the land, air, maritime, cyber, and space domains. This interconnected battlespace facilitates real-time information sharing, improves situational awareness, and enables faster operational coordination.

At the same time, the compression of the OODA loop has made the speed of sensing, processing, and response a decisive factor in combat effectiveness. Advanced semiconductors now form the backbone of high-speed signal processing, AI-enabled decision-making, radar systems, and electronic warfare capabilities. As a result, semiconductors have evolved from being passive electronic components into strategic enablers of military capability, operational superiority, and information dominance.

Defence Requirements Beyond Silicon

Although silicon continues to be the dominant semiconductor material for commercial electronics owing to its mature manufacturing ecosystem and scalability, the operational requirements of modern defence systems are increasingly pushing beyond the physical limitations of conventional silicon-based devices. Contemporary military platforms demand semiconductors that can function at higher frequencies, higher voltages, elevated temperatures, and within intense electromagnetic and radiation-rich environments. These requirements have accelerated the shift towards compound semiconductors such as Gallium Nitride (GaN), Gallium Arsenide (GaAs), Silicon Carbide (SiC), and Indium Phosphide (InP).

One of the most critical requirements of modern defence systems is the ability to operate at high frequencies. Advanced radar systems, electronic warfare suites, satellite communication networks, and missile seekers are increasingly functioning within X-band, Ku-band, Ka-band, and millimetre-wave frequency ranges.[14] Silicon-based devices face limitations at such frequencies due to lower electron saturation velocity and thermal inefficiencies. Compound semiconductors, particularly GaN and GaAs, possess superior electron mobility and high-frequency performance, making them ideal for RF and microwave applications.

Modern military systems also require extremely high-power density. Active Electronically Scanned Array (AESA) radars, jamming systems, directed energy weapons, and electronic attack systems demand compact semiconductor devices capable of generating high RF output power with greater efficiency. GaN-based High Electron Mobility Transistors (HEMTs) have emerged as critical technologies in this regard due to their high breakdown field, superior power density, and reduced cooling requirements.[15]

Radiation tolerance constitutes another major operational requirement, especially for space systems, satellites, missile electronics, and high-altitude defence platforms. Conventional silicon devices are vulnerable to radiation-induced degradation, total ionizing dose effects, and latch-up phenomena. Compound semiconductors such as GaN and SiC demonstrate superior radiation resilience, making them suitable for strategic and aerospace applications.

Thermal resilience has become equally important in advanced defence systems. Radar systems, electronic warfare systems, hypersonic platforms, and power electronics generate substantial thermal loads during operation.[16] Silicon-based systems often face reliability challenges under extreme temperatures, whereas wide-bandgap semiconductors such as GaN and SiC can operate efficiently at significantly higher temperatures and voltages. Their superior thermal conductivity allows efficient heat dissipation, thereby improving operational reliability and reducing system size.

In addition, modern warfare increasingly demands miniaturisation without any loss of performance. Military platforms require compact, lightweight, and multifunctional electronics capable of integrating sensing, communication, computation, and power management within constrained operational environments. Compound semiconductors support such miniaturisation through greater power efficiency, smaller component footprints, and reduced cooling requirements.

Survivability also remains a fundamental operational requirement. Military systems operating in contested electromagnetic environments must continue to function under conditions of jamming, electromagnetic interference, thermal stress, and hostile battlefield pressures. The superior electrical and thermal characteristics of compound semiconductors significantly improve the survivability and operational endurance of advanced military systems.

Beyond their technological advantages, compound semiconductors have emerged as strategic assets that are directly linked to national security, technological sovereignty, and geopolitical competition. The growing weaponisation of technology supply chains and the increasing use of export controls across advanced semiconductor sectors have exposed the vulnerabilities associated with excessive dependence on external suppliers.

Semiconductor supply chain security has therefore become a critical national security concern. Advanced military systems depend upon uninterrupted access to semiconductor materials, wafers, fabrication technologies, high-purity chemicals, and specialised equipment. Any disruption to these supply chains can significantly affect defence preparedness, operational sustainability, and technological progress. The strategic restrictions imposed globally on technologies such as Silicon Carbide wafers and advanced semiconductor manufacturing equipment illustrate the geopolitical sensitivity of these sectors.

In the Indian context, compound semiconductors have become closely associated with the broader objectives of strategic autonomy and Atmanirbhar Bharat. Institutions such as Defence Research and Development Organisation’s (DRDO) Solid State Physics Laboratory (SSPL), and Gallium Arsenide Enabling Technology Centre (GAETEC) and other indigenous semiconductor initiatives reflect India’s growing emphasis on developing a secure and resilient compound semiconductor ecosystem.

Compound Semiconductors in Defence Applications

- **Radar Systems and AESA Architectures.** GaN-based High Electron Mobility Transistors (HEMTs) have emerged as one of the most critical technologies for modern radar and electronic warfare systems due to their high breakdown voltage, high power density, superior electron saturation velocity, and high-frequency operational capability.[17] GaN (High Electron Mobility Transistor) HEMTs enable the development of Monolithic Microwave Integrated Circuits (MMICs), which integrate multiple microwave and RF functions onto a single compact chip, thereby improving efficiency, reducing size, and enhancing thermal performance. These MMICs form the core of modern Transmit/Receive (T/R) modules used in Active Electronically Scanned Array (AESA) radars, where each module independently transmits and receives signals for rapid beam steering, multi-target tracking, and enhanced electronic counter-countermeasure capability.[18]

  The SSPL, DRDO, has developed indigenous GaN HEMT and MMIC technologies for X-band and Ku-band applications, including beamforming chips, wideband electronic warfare chips, power amplifiers, low-noise amplifiers, and front-end T/R modules. These technologies significantly enhance India's indigenous capabilities in radar modernisation, spectrum dominance, and next-generation RF warfare systems.
- **Electronic Warfare and Spectrum Dominance.** GaN-based RF technologies have become central to modern electronic warfare systems due to their ability to support high-power RF transmission, wideband jamming, beamforming, and software-defined radio (SDR) architectures. SSPL has developed wideband beamforming chips, electronic warfare front-end chips, and high-power amplifiers for next-generation EW applications operating across X-band and Ku-band frequencies.
- **Directed Energy Weapons and Laser Technologies.** GaAs and GaN-based laser diode technologies are becoming increasingly important for directed energy weapons (DEWs), optical communication, underwater communication, and laser proximity fuses. SSPL has developed high-power laser diodes and fibre-coupled laser diodes (FCLDs) to support various defence applications. It

has also developed blue-green GaN lasers and Vertical Cavity Surface Emitting Lasers (VCSELs) for defence and quantum technology applications.[19]

- **Power Electronics for Defence Platforms.** Silicon Carbide (SiC) wide-bandgap semiconductor technologies are becoming increasingly important for high-voltage defence power electronics, including naval propulsion systems, aircraft power systems, hypersonic platforms, and advanced radar power architectures. SSPL has indigenously developed SiC crystal growth and wafer fabrication technologies and is further developing SiC-based PIN diodes, Schottky diodes, and MOSFET devices.
- **Space and Satellite Systems.** Compound semiconductors such as GaAs, GaN, and InP are highly suitable for space and satellite systems due to their superior radiation tolerance, high-frequency capability, and photonic integration potential. These materials are extensively used in satellite communication payloads, RF systems, optical communication links, and high-reliability aerospace electronics operating in radiation-intensive environments.

India's Indigenous Ecosystem for Compound Semiconductors

India's compound semiconductor ecosystem is gradually evolving from a research-driven framework into a strategically important defence-industrial capability. Driven primarily by DRDO laboratories, pilot production facilities, and emerging industry participation, the ecosystem increasingly focuses on indigenous material development, device fabrication, trusted supply chains, and strategic self-reliance in critical semiconductor technologies. Some of the important aspects have been highlighted in the following paragraphs:

- **DRDO and SSPL Ecosystem.** India's indigenous compound semiconductor ecosystem is being significantly driven by the DRDO, particularly through the SSPL. SSPL has adopted an integrated "material-to-device-to-system" approach for strategic semiconductor technologies, supported by dedicated pilot production facilities such as the GAETEC and Semiconductor Technology Applied Research Centre (STARC). These institutions collectively support material growth, device fabrication, packaging, testing, and limited-scale production for strategic defence applications.

- **Indigenous Technology Development.** SSPL has developed a wide range of indigenous compound semiconductor technologies, including GaN-based MMICs, high-power laser diodes, SiC wafer fabrication technologies, infrared detector systems, cryocoolers, ZnTe crystals for terahertz applications, and CdZnTe substrates for infrared imaging systems. These technologies are directly linked to strategic applications such as AESA radars, electronic warfare systems, missile seekers, directed energy weapons, thermal imaging, and space-based sensing systems.
- **Technology Transfer and Pilot Production.** A major feature of India's emerging semiconductor ecosystem is the pilot production and technology transfer model adopted by SSPL and GAETEC. Several technologies, including laser diode fabrication, SiC wafer technologies, cryocoolers, and ZnTe crystals, have been opened for Transfer of Technology (ToT) and industry participation through Expressions of Interest (EOIs). This approach aims to bridge the gap between laboratory-scale innovation and scalable industrial production while strengthening indigenous manufacturing capabilities and defence-industrial partnerships.
- **India Defence Semiconductor Mission for Military Applications.**
  At the Centre for Joint Warfare Studies (CENJOWS), Headquarters Integrated Defence Staff, sustained research and policy discussions on semiconductors and national security have consistently highlighted the need for a comprehensive policy framework to address the semiconductor requirements of India's defence sector. These issues were also discussed in the August 2024 issue of Synergy, the flagship journal of CENJOWS. The publication reflected the growing recognition of semiconductors as a critical component of India's defence and strategic ecosystem.[20]
  This was further reinforced during the First Workshop on Energising Semiconductor Ecosystem for Defence Applications in 2024, which strongly emphasised the need for an India Defence Semiconductor Mission for Military Applications (IDSM^{2}A).

The workshop highlighted the importance of building a dedicated ecosystem focused on compound semiconductors, trusted electronics, and secure supply chains for defence and national security applications.

- **Indigenous MMIC Development Using MESFET Technology.** GAETEC, DRDO developed India's indigenous 0.7 µm Metal-Semiconductor Field-Effect Transistor (MESFET) based MMIC technology for microwave and satellite applications. These MMICs were space-qualified and supplied to ISRO missions such as CARTOSAT, RISAT, Chandrayaan, NISAR, and Aditya-L1. India successfully built its own microwave chips for X-band communication systems, high power amplifiers (HPAs), gain modules, and satellite data links, reducing dependence on foreign semiconductor technologies.[21]
- **Advanced pHEMT MMIC Technologies for High-Frequency Systems.** GAETEC further advanced from MESFET technology to high-speed pHEMT MMICs with gate lengths of 0.5 µm, 0.25 µm, and 0.13 µm for operation up to 40 GHz. Smaller gate lengths improve transistor speed and allow operation at higher microwave frequencies. These MMICs were developed for ISRO and DRDO laboratories and used in radar, electronic warfare (ECCM), bidirectional amplifiers, and satellite communication systems. Today, India is making significant strides in developing capabilities in advanced compound semiconductor RF technologies.[22]
- **Development of THz Schottky Barrier Diodes**. GAETEC also developed GaAs-based Schottky Barrier Diodes capable of operating at terahertz (THz) frequencies. These ultra-fast diodes are used in mixers, frequency multipliers, and high-frequency communication systems.
- **Vertically Integrated Indigenous MMIC Ecosystem**. GAETEC functions as a vertically integrated MMIC foundry, meaning it performs all major activities including MMIC design, fabrication, assembly, measurement, and reliability testing within a coordinated ecosystem. The organisation is also developing advanced GaN HEMT technologies with gate lengths down to 0.1 µm for future high-power microwave systems. This reflects India's effort to establish a complete indigenous compound semiconductor ecosystem for strategic and defence applications.[23]

- **Packaging and Supply of Indigenous MMICs**. GAETEC supplies MMICs in multiple forms such as bare die, QFN packages, metal-ceramic packages, and multi-chip module (MCM) configurations depending on the application requirement. These packaging technologies are important for protecting sensitive microwave chips and integrating them into satellite, radar, and defence electronic systems. Precisely, indigenous capability is not limited to chip fabrication alone but also includes advanced packaging and system-level integration.[24]

Strategic Challenges and Technological Gaps

- **Material Dependency.** Despite significant progress in indigenous compound semiconductor technologies, India continues to face substantial dependence on foreign sources for critical semiconductor inputs such as high-quality wafers, epitaxial growth systems, high-purity chemicals, speciality gases, and advanced fabrication equipment. The limited domestic availability of semiconductor-grade materials and precision manufacturing infrastructure remains a major bottleneck for scaling strategic semiconductor production and sustaining long-term defence requirements.
- **Technology Denial Regimes.** Advanced compound semiconductor technologies remain heavily influenced by export controls, strategic restrictions, and technology denial regimes imposed by a limited number of technologically advanced countries. Critical technologies related to SiC wafers, semiconductor fabrication equipment, advanced RF devices, and high-purity materials are often tightly regulated, making trusted and secure supply chains increasingly important for defence preparedness, strategic autonomy, and indigenous technological resilience.
- **Strategic Vulnerability of MMIC Ecosystem.** MMIC technologies remain concentrated within a highly specialised and strategically sensitive domain primarily supporting radars, electronic warfare systems, RF front-end architectures, and military-space communication systems. Due to limited global suppliers and the possibility of export controls or embargo pressures, dependence on foreign MMIC technologies can jeopardise critical strategic programmes and defence missions.

- **Sustainability Challenges of Indigenous Compound Semiconductor Foundries.** Despite its strategic importance, GAETEC continues to face sustainability and scaling challenges due to the limited commercial ecosystem surrounding compound semiconductor technologies. As India's first and only indigenous compound semiconductor foundry and the only space-qualified foundry in Asia, GAETEC represents a critical national asset built through more than three decades of specialised manpower development, technical expertise, and strategic knowledge accumulation. However, the niche nature of compound semiconductor applications and comparatively low commercial demand make sustained government support, long-term patronage, and strategic investment essential for preserving indigenous fabrication capabilities and ensuring continuity in defence semiconductor manufacturing.
- **Manufacturing and Scale-Up Constraints.** The development of compound semiconductor fabrication facilities involves extremely high capital expenditure, complex cleanroom infrastructure, and technologically demanding manufacturing processes. Challenges such as low production yield, reliability qualification, advanced packaging requirements, and limited economies of scale continue to hinder the transition from laboratory-scale innovation to large-scale strategic manufacturing. These constraints become even more critical for defence applications, where reliability and long operational lifecycles are essential.
- **Skilled Workforce and R&D Gaps.** The compound semiconductor sector requires a highly specialised workforce comprising material scientists, RF engineers, device physicists, packaging specialists, and process engineers. India continues to face limitations in advanced semiconductor research ecosystems, skilled manpower availability, and industry-academia integration, particularly in areas such as epitaxy, RF device engineering, advanced packaging, and defence-grade semiconductor qualification.
- **Dependence on Foreign Equipment.** India's semiconductor ecosystem remains significantly dependent on foreign suppliers for critical fabrication equipment such as lithography systems, Metal Organic Chemical Vapour Deposition (MOCVD) tools, metrology systems, and advanced semiconductor processing equipment. Such dependencies expose strategic semiconductor

programmes to supply-chain disruptions, export restrictions, and technological vulnerabilities, particularly in the context of defence and aerospace applications.

Recommendations

- **Strengthen Indigenous Semiconductor Material Ecosystems.** India could strengthen domestic capabilities in semiconductor-grade wafers, epitaxial growth technologies, high-purity chemicals, speciality gases, and strategic substrates. Targeted investments, defence-linked incentives (DLI), and strategic mineral policies are essential to reduce long-term external dependence.
- **Develop Trusted and Resilient Supply Chains.** India may focus on securing a trusted semiconductor supply chain for defence applications. This requires diversified sourcing, indigenous fabrication capabilities, strategic partnerships, and long-term stockpiling mechanisms to reduce vulnerabilities arising from export controls and technology denial regimes.
- **Establish a Dedicated MMIC and RF Semiconductor Programme.** A dedicated national programme for MMIC and RF semiconductor technologies should be developed. The programme must focus on indigenous GaN and GaAs fabrication, advanced packaging, testing, and defence-grade qualification for radar, electronic warfare, and military-space communication systems.
- **Expand Strategic Support for Indigenous Foundries.** Indigenous facilities such as GAETEC require sustained government support and assured procurement mechanisms. Long-term funding and strategic patronage are essential for preserving specialised expertise, maintaining fabrication continuity, and strengthening India’s sovereign compound semiconductor ecosystem.
- **Strengthen Manufacturing and Scale-Up Capabilities.** India should expand pilot production facilities, advanced packaging infrastructure, and reliability qualification centres for compound semiconductors. Focused support is required to address challenges related to fabrication cost, low production yield, and large-scale manufacturing transition for defence applications.

- **Develop Specialised Semiconductor Human Resources:** India must strengthen semiconductor education, advanced R&D centres, and industry-academia collaboration to build a skilled workforce in areas such as epitaxy, RF engineering, device fabrication, advanced packaging, and defence-grade semiconductor qualification.
- **Promote Indigenous Semiconductor Equipment Development.** Long-term policy support should encourage indigenous development of critical fabrication equipment such as lithography systems, MOCVD tools, metrology systems, and advanced processing technologies. Reducing dependence on foreign equipment is essential for strengthening strategic autonomy and supply-chain resilience in defence semiconductor manufacturing.

Conclusion

Compound semiconductors are emerging as strategic enablers of high-performance defence systems, shaping capabilities across radar architectures, electronic warfare, infrared sensing, directed energy weapons, space systems, quantum technologies, and autonomous warfare platforms. Their significance extends far beyond electronics; they now influence operational tempo, spectrum dominance, survivability, precision engagement, and strategic deterrence.

For India, the challenge is no longer limited to acquiring advanced semiconductor technologies but to building an indigenous and resilient ecosystem capable of sustaining strategic autonomy under conditions of geopolitical uncertainty, technology denial, and supply-chain disruptions. The evolution of institutions such as SSPL and GAETEC demonstrates that India has already established important foundations in strategic semiconductor research and pilot production. However, sustaining this momentum will require long-term investments, trusted manufacturing ecosystems, specialised human capital, and stronger integration between defence laboratories, academia, industry, and strategic policy frameworks.

Ultimately, compound semiconductors are transitioning from niche technological assets to foundational pillars of future military and national security architectures.

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.

ENDNOTES

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