



TEXAS A&M SEMICONDUCTOR INSTITUTE

CHIPS IN SPACE

Part II: Advanced
Materials

Contents

Executive Summary	2
Background	3
Key Facts.....	3
Evolution of Computing Architectures	3
Crystalline Quality as a Determinant of Semiconductor Device Performance.....	4
Exploiting Microgravity for Superior Semiconductor Crystal Quality	4
The “Growth Front”	7
Gallium Nitride (GaN).....	8
Silicon Carbide (SiC).....	9
GaN vs. SiC	9
III–V crystalline materials (e.g., GaAs, InP, GaSb, InAsSb and their alloys).....	9
Diamond.....	11
2D Crystals.....	13
Market Summary.....	13
GaN	13
SiC.....	14
Classic III–V	14
Diamond.....	15
2D Crystals.....	15
Strategic Positioning for LEO Manufacturing Roadmaps	16
Recommended Primary Focus for LEO Manufacturing	16
Parallel Capability-Driven Effort.....	16
Long-Term Integration Pathway	17
Conclusion: Strategic Implications for National Security and U.S. Leadership.....	17
Appendix A: Acronyms and Abbreviations	20
Appendix B: References and Resources	21

Executive Summary

The United States faces a growing strategic vulnerability in upstream semiconductor materials manufacturing, particularly in bulk, defect-limited crystalline materials that underpin next-generation power electronics, RF systems, secure communications, and space and defense platforms. While significant public and private capital have been directed toward advanced logic fabrication, the crystalline substrates on which these systems depend remain overwhelmingly produced outside the United States. More than 95% of semiconductor wafers are silicon-based, and East Asia dominates both silicon wafer production and advanced compound-semiconductor substrates.

At the same time, transistor scaling at advanced logic nodes is encountering fundamental physical and economic limits. As a result, system-level performance, energy efficiency, and reliability are increasingly constrained by materials quality rather than lithography alone. For wide-bandgap and compound semiconductors, crystalline defects — not transistor geometry — often define the ceiling on achievable performance, yield, and lifetime.

Decades of experimental evidence demonstrate that microgravity fundamentally alters the physics of crystal growth. By suppressing buoyancy-driven convection, sedimentation, and gravity-coupled thermal transport, microgravity shifts crystal growth into a diffusion-dominated regime that reduces defect incorporation, improves compositional uniformity, and stabilizes growth interfaces. These effects are especially pronounced for bulk, multicomponent, and wide-bandgap semiconductors whose terrestrial manufacturing is intrinsically limited by gravity-driven transport instabilities.

From an economic perspective, low-Earth-orbit (LEO) manufacturing is not a substitute for terrestrial fabs or a pathway to bulk production in space. Instead, it represents a high-leverage industrial capability that unlocks step-function improvements in material quality for a narrow set of defect-limited materials. These improvements propagate downstream into higher yield, improved reliability, reduced system cost, lower supply-chain risk, and the creation of new high-performance markets on Earth.

This analysis concludes that GaN and SiC represent the highest-leverage near-term opportunities for LEO manufacturing, followed by selected III–V compounds and electronic-grade diamond for high-value defense, space, energy, and quantum applications. Two-dimensional materials are best positioned as longer-term, low-volume, capability-driven targets rather than primary production outputs.

Lastly, the U.S. leadership should increase efforts in space-based advanced materials research to maintain its competitive advantage over adversarial nations — now and when the International Space Station is ultimately retired. Doing so ensures international partners, sets global standards, and feeds orbital breakthroughs directly into the U.S. defense and manufacturing base.

Background

The United States is strategically behind in several upstream segments of semiconductor materials manufacturing, particularly silicon feedstocks and wafer substrates. Over 95% of semiconductor wafers globally are silicon-based and are ultimately derived from polysilicon feedstock. East Asia accounts for more than 80% of global polysilicon and silicon wafer production, with China by far the dominant supplier. U.S. capacity in crystalline silicon wafer production remains limited, creating upstream dependencies that pose economic and national-security risks.

Key Facts

Evolution of Computing Architectures

As transistor-level scaling continues to yield diminishing performance benefits, the broader computing ecosystem is transitioning toward heterogeneous system architectures that integrate specialized accelerators with advanced packaging approaches such as chiplet-based designs and three-dimensional integration. These architectural shifts are essential not only for extending performance scaling in combination with software and algorithmic advances, but also for meeting the stringent requirements of data-intensive and mission-critical workloads. In such systems, parameters including energy efficiency, latency, reliability, and operational resilience are now as critical as peak computational throughput.

These challenges are compounded by escalating fabrication costs and diminishing performance returns. In parallel, there is growing exploration of materials and device concepts beyond conventional silicon CMOS to sustain future performance gains.

For national-security systems that depend on trusted, resilient, and long-lived electronics—from advanced weapons platforms to space, cyber, and intelligence infrastructure—this trajectory of rising cost and diminishing performance returns introduces an additional, critical concern: heightened supply-chain risk.

As the requirements for computing architecture continue to evolve, so do the critical materials that make that evolution possible.

Materials evolution: Next-generation semiconductor performance is increasingly driven by advanced materials, including III–V compounds (notably gallium nitride), and ultra-wide-bandgap materials such as silicon carbide and diamond and two-dimensional (2D) semiconductors (such as graphene and molybdenum disulfide). These materials offer advantages in carrier mobility, bandgap engineering, thermal conductivity, and radiation tolerance that extend beyond the fundamental limits of silicon CMOS. However, as device dimensions approach atomic scales and system performance becomes more sensitive to interfaces and material quality, these materials exhibit heightened sensitivity to crystalline defects, impurities, and non-uniformities — making defect control a primary constraint on both performance and manufacturability.

Crystalline Quality as a Determinant of Semiconductor Device Performance

Crystalline quality is a primary determinant of semiconductor device performance, reliability, and manufacturability, directly influencing carrier mobility, leakage behavior, thermal transport, radiation response, and overall yield. Defects spanning atomic to macroscopic length scales degrade electronic behavior, narrow performance margins, and reduce process robustness across fabrication and integration workflows.

At the electrical level, lattice imperfections scatter charge carriers and introduce trap states, leading to reduced mobility, elevated leakage currents, threshold voltage instability, and shortened device lifetimes. These effects are often coupled with longer term reliability concerns, as both native and extrinsic defects, including vacancies, interstitials, and oxygen related complexes—can serve as precursors for stacking faults and other extended defects that drive parametric drift and long-term instability.

Crystalline defects also directly impact manufacturability and scalability. Processes induced microdefects, oxygen precipitation, and dislocations constrain very large-scale integration (VLSI) feasibility and reduce die yield. In silicon substrates grown using the Czochralski (CZ) method, growth in defect populations further limit electrical uniformity and wafer level consistency, increasing variability across large area devices.

Thermal and high-power performance are similarly sensitive to crystal quality. Imperfections in the lattice increase phonon scattering and degrade thermal conductivity, effects that are particularly consequential for wide and ultra-wide bandgap materials such as silicon carbide and gallium nitride. In these systems, elevated power densities and stringent thermal management requirements make crystalline defects a direct limiter of achievable performance and operational reliability.

Finally, crystal quality plays a critical role in radiation hardness. Preexisting defects act as nucleation sites for radiation induced damage, amplifying leakage currents and accelerating parametric degradation under irradiation. As a result, precise control of intrinsic point defect populations is essential for ensuring stable operation in space, defense, and other radiation exposed environments.

Exploiting Microgravity for Superior Semiconductor Crystal Quality

Gravity on Earth induces buoyancy-driven convection, sedimentation, hydrostatic pressure gradients, and thermally driven flow, all of which promote defect formation during crystal growth. In Low Earth Orbit (LEO), these gravity-driven transport mechanisms are strongly suppressed, enabling diffusion-dominated heat and mass transport. This regime reduces defect densities and improves both compositional and structural uniformity.

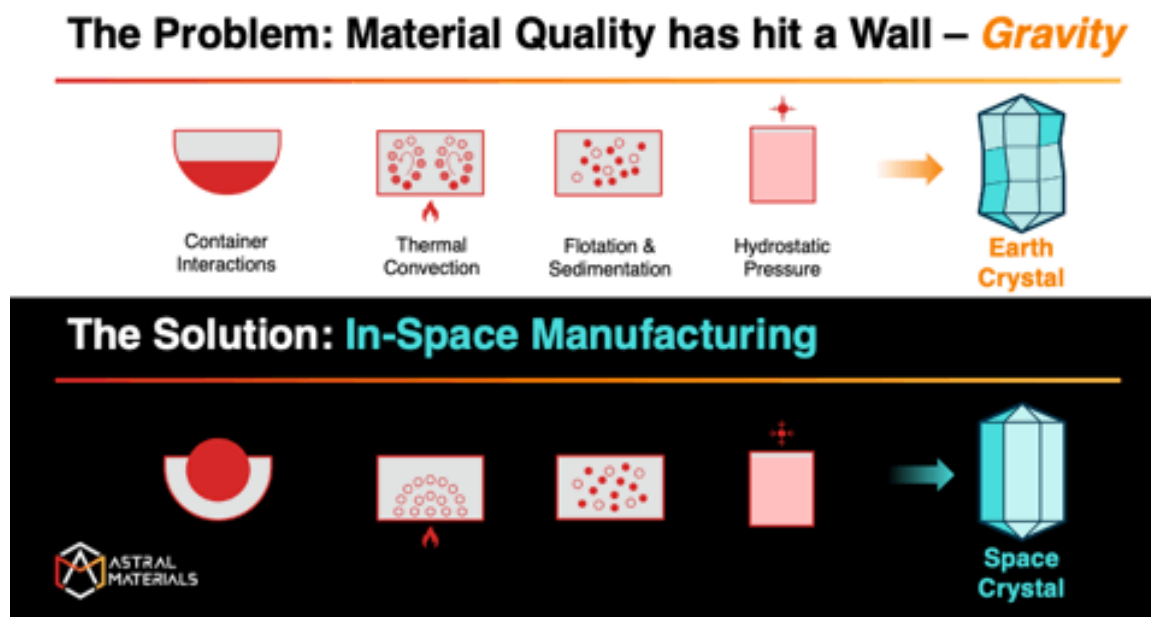
- *Buoyancy (flotation)*: In Low Earth Orbit (LEO), suppression of buoyancy-driven flow reduces bubble migration and entrapment, stabilizing the growth interface and mitigating dislocation clustering. These effects can indirectly reduce defect interactions and growth instabilities that exacerbate extended defects—such as micropipes in materials like SiC—

although primary micropipe nucleation remains governed by intrinsic crystal growth conditions and dislocation dynamic

- *Hydrostatic pressure and container interactions:* In microgravity, the absence of hydrostatic pressure gradients allows surface-tension-dominated behavior and facilitates detached or weakly coupled crystal growth. This reduces mechanical stress and minimizes defect formation associated with container contact, thermal expansion mismatch, and heterogeneous nucleation.
- *Sedimentation:* In microgravity, suppression of sedimentation minimizes gravity-driven segregation of impurities and second phases—such as unintended precipitates or inclusions with different composition or structure from the host crystal—thereby improving compositional uniformity and reducing defect formation during crystal growth.
- *Thermal convection:* With convection suppressed, heat and mass transport become diffusion-dominated, stabilizing the growth interface and reducing the kinetic drivers for point-defect generation, accumulation, and aggregation.

A meta-analysis of 160 semiconductor crystal experiments in microgravity reported that 86% showed gains in size, structural quality, uniformity, or performance versus Earth-grown crystals. NASA has explicitly identified AI chip manufacturing as a terrestrial beneficiary of improved space-grown materials. NASA has identified advanced semiconductor and microelectronics manufacturing as a key terrestrial beneficiary of space-enabled materials research, with clear relevance to high-performance and AI-driven computing systems.

Figure#1



Source: Astral Materials

Decades of orbital experiments show that microgravity suppresses buoyancy-driven convection, sedimentation, and gravity-coupled thermal transport, causing crystal growth to proceed in a diffusion-dominated regime rather than a convection-dominated one.

This diffusion-dominated regime leads to:

- Lower dislocation and defect densities
- More uniform composition and dopant distribution
- Flatter solid–liquid interfaces with reduced strain
- Improved chemical homogeneity, particularly in compound semiconductors

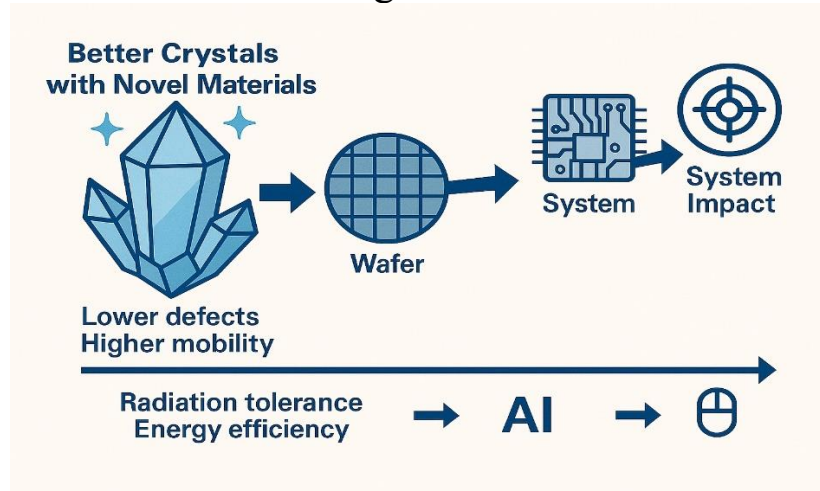
These effects have been demonstrated repeatedly for Si, Ge, GaAs, InGaSb, GaN, SiC, and related alloys grown on the ISS and other orbital platforms, with space-grown samples consistently outperforming 1-g controls in structural quality and etch-pit density. Emerging results for materials such as GaN and SiC indicate similar trends and Diamond is being actively investigated.

NASA and JAXA programs, along with ESA and emerging China National Space Agency (CNSA) efforts, identify semiconductor crystals and advanced electronic materials as high-priority microgravity manufacturing targets. Decades of orbital experiments demonstrate that microgravity does more than increase crystal size—it suppresses gravity-driven transport mechanisms, enabling reduced defect incorporation and improved atomic-scale order that are difficult to achieve under terrestrial process control.

NASA’s In-Space Production Applications initiatives list “semiconductor crystals/wafers” as core technologies intended for terrestrial benefit, citing improved uniformity, yield, and device performance enabled by microgravity. Similarly, JAXA’s Kibo utilization program emphasizes that suppressing gravity-driven convection allows diffusion-dominated transport, making it possible to grow high-quality, compositionally uniform semiconductor crystals that are difficult to achieve under 1-g conditions. Together, these agencies underscore that microgravity does not merely produce larger crystals — it enables reduced defect incorporation and improved atomic-scale order that terrestrial process control struggles to replicate.

Mechanism to impact: Microgravity → diffusion-dominated crystal growth → reduced defects and improved material uniformity → higher-performance, higher-efficiency semiconductor devices → improved power, thermal, and reliability envelopes for AI, quantum, and secure-communications systems.

Figure #2



The “Growth Front”

Crystal growth is fundamentally a transport problem. Crystals grow as atoms or molecules are transported to the edge of the crystal—known as the growth front. Growth does not occur uniformly throughout the material; it occurs only at the boundary where the solid crystal meets a melt (liquid), vapor, or solution.

At the growth front, transported atoms must be incorporated into the crystal lattice by finding energetically favorable lattice positions and bonding to the existing atomic structure, thereby extending the crystal. This delivery of atoms to the growth front constitutes the transport process, while incorporation governs defect formation and structural quality.

Crystal growth therefore proceeds atom by atom, or layer by layer, at the growth interface.

On Earth, heat and mass transport are dominated by gravity-driven phenomena such as buoyancy-driven convection and sedimentation. Thermal and compositional density gradients generate vigorous natural convection that typically govern macroscopic transport, often overwhelming purely diffusive and interfacial processes.

If atoms arrive at the crystal growth front in a highly fluctuating or non-uniform manner — due to convection-driven transport or instability — the resulting crystal is more likely to incorporate defects. In contrast, when atoms arrive at the growth front in a steady, uniform flux, the growth interface remains stable, atoms are more likely to occupy correct lattice positions, and the crystal exhibits lower defect density and higher overall quality.

The microgravity environment suppresses buoyancy-driven convection, sedimentation, and hydrostatic pressure gradients, shifting heat and mass transport from convection-enhanced to diffusion-dominated regimes. As a result, macroscopic transport is slower but more spatially

uniform, enabling direct investigation of fundamental diffusive and interfacial processes that are typically masked by gravity-driven flows under terrestrial conditions.

This slower and more spatially uniform, diffusion-dominated transport regime enabled by microgravity is broadly important across crystal systems — including GaN, SiC, other III–V compounds (e.g., GaAs, InP, InGaAs), diamond, and 2D (MoS₂ and related transition-metal dichalcogenides) materials — because all are sensitive to non-uniform mass transport and interface instability, even though the specific benefits manifest differently across material classes.

Gallium Nitride (GaN)

GaN is commonly discussed separately from other III–V materials because its nitride chemistry, extreme growth difficulty, wide-bandgap performance, unique applications, and independent market evolution distinguish it fundamentally from classic III–V semiconductors such as GaAs or InP.

GaN surpasses silicon's performance limits by enabling much higher efficiency, switching speed, and power density, supporting technologies such as fast chargers, LEDs, radar systems, advanced power electronics, and high-power RF infrastructure. GaN has become the material of choice for high-power, high-frequency RF systems, including 5G/6G base stations, satellites, and radar.

GaN operates at higher temperatures than silicon, enabling more compact and reliable electronics while reducing energy loss in data centers, EV chargers, and power supplies. Notably, GaN's wide bandgap enabled the blue LED, which in turn made white LED lighting possible and delivered substantial global energy savings.

Microgravity growth environments are expected to improve GaN semiconductor quality by suppressing convective flow, reducing dopant segregation, and eliminating gravity-driven thermal gradients that contribute to stress and defect formation during crystal growth. By enabling diffusion-limited, near-equilibrium growth, microgravity has the potential to reduce dislocation density, impurity inhomogeneity, and structural defects that currently limit terrestrial GaN.

It should be noted that United Semiconductors has recently publicly demonstrated microgravity crystal growth on the ISS for advanced III–V and wide-bandgap semiconductor materials relevant to GaN, reporting improved uniformity, yield, and device-relevant performance compared to terrestrial growth. These results have been acknowledged by NASA's In-Space Production Applications program and are now being scaled toward dedicated LEO manufacturing platforms.

Silicon Carbide (SiC)

Silicon carbide (SiC) is critically important because its wide bandgap, high breakdown field, and exceptional thermal stability enable far more efficient, compact, and reliable power electronics, making it a cornerstone material for electric vehicles, renewable energy systems, and modern power grids. SiC has become the dominant semiconductor for high-voltage, high-power applications.

SiC improves EV efficiency by reducing power-conversion losses, enabling high-voltage architectures, and reducing cooling and weight penalties—so more battery energy is converted into motion rather than heat. As a result, SiC outperforms silicon wherever electricity must be converted at high voltage, high power, or elevated temperature with extreme efficiency and reliability, making it a foundational semiconductor for electrification, grid modernization, and resilient energy infrastructure.

However, SiC is unusually defect-intolerant. It is grown using physical vapor transport (PVT) at extreme temperatures (2000–2400 °C) and exhibits polytype instability and defect-formation mechanisms such as micropipes—hollow-core screw dislocations that are tightly coupled to convection and thermal stress. These defects can severely reduce breakdown voltage, trigger early device failure, limit wafer yield, and dramatically increase cost. Unlike silicon, SiC power devices are often rejected due to a single killer defect.

Microgravity can improve silicon carbide material quality by suppressing gravity-driven vapor convection and thermal stress, stabilizing growth fronts and polytype formation, and reducing extended defect nucleation. By enabling diffusion-limited, near-equilibrium growth, microgravity has the potential to directly address the fundamental defect mechanisms that constrain terrestrial SiC crystal growth.

GaN vs. SiC

Gallium Nitride (GaN) is the material of choice when your priority is higher switching speed, higher efficiency at lower voltages (≤ 650 V), smaller size, and higher operating frequency, rather than extreme voltage or current handling.

Silicon Carbide (SiC) is the material of choice when you need high voltage, high current, or extreme ruggedness (> 800 V).

III–V Crystalline Materials (e.g., GaAs, InP, GaSb, InAsSb and Their Alloys)

In contrast to two-dimensional (2D) materials, which are fundamentally surface- and interface-dominated systems whose performance depends critically on atomic-scale environmental control, III–V semiconductors are bulk crystalline materials. These materials consist of macroscopic, three-dimensionally continuous single crystals whose electronic and optical properties are governed primarily by the interior crystal lattice rather than by surfaces or interfaces. As a result, their performance is directly coupled to bulk crystal quality, including defect density, compositional uniformity, and internal stress distributions.

Microgravity crystal growth provides substantial and well-understood advantages for bulk III–V semiconductors by suppressing gravity-driven transport instabilities that are intrinsic to terrestrial growth environments. Space-grown III–V materials consistently exhibit reduced dislocation densities, improved compositional homogeneity, and enhanced electronic and optical characteristics. These material-level improvements translate directly into higher device performance, lower noise, greater reliability, and improved yield — capabilities that are critical for national security systems, space-based platforms, advanced photonics, and emerging quantum technologies, and that are increasingly difficult to achieve through terrestrial scaling alone.

Under Earth’s gravity, III–V crystals are typically grown from a melt or solution and are subject to several gravity-induced phenomena that degrade crystal quality. Buoyancy-driven convection produces non-uniform solute transport, resulting in compositional striations and spatial inhomogeneity. Sedimentation and mass segregation cause heavier atomic species to preferentially settle, further exacerbating alloy non-uniformity. In addition, gravity-induced instabilities at the solid–liquid (or solid–vapor) interface promote the formation of voids, inclusions, and extended defects. These effects are particularly severe for multicomponent III–V alloys, which possess narrow thermodynamic stability windows and are therefore especially sensitive to perturbations in temperature, composition, and flow.

Recent experimental evidence underscores the magnitude of microgravity’s impact on III–V crystal growth. A 2026 white paper published by Nature Partner Journal Microgravity reports an approximately ten-fold reduction in dislocation density for InAsSb crystals grown aboard the Tiangong (China Space Station). This result is significant because it provides direct, quantitative confirmation that microgravity alters the fundamental physics of crystal growth, rather than simply producing incremental improvements to terrestrially limited processes.

At the physical level, microgravity profoundly modifies the transport mechanisms governing crystal growth. Buoyancy-driven convection is strongly suppressed, forcing atomic species to reach the growth interface primarily through steady, diffusion-dominated transport rather than through fluctuating convective flow fields. Sedimentation is eliminated, preserving uniform melt or vapor composition, while hydrostatic pressure gradients effectively vanish. Together, these effects stabilize the solid–liquid (or solid–vapor) interface, maintain improved planarity, and reduce localized stress concentrations, thereby lowering the probability of defect nucleation and propagation.

Collectively, these changes drive crystal growth toward a near-equilibrium regime that is substantially closer to the thermodynamic ideal than what is attainable under terrestrial gravity. This regime is particularly beneficial for defect-sensitive III–V materials, where small perturbations in growth conditions can otherwise produce disproportionately large impacts on crystalline quality.

III–V compounds benefit especially strongly from this microgravity environment because their growth physics is unusually sensitive to gravity-driven transport. Compared with elemental semiconductors, III–V materials are multicomponent systems with lower melting points and narrower stability margins, making them far more vulnerable to convection-driven solute

redistribution, segregation, and interfacial instability under Earth gravity. The mitigation of these effects in microgravity therefore produces outsized gains in material quality relative to simpler elemental systems.

The resulting improvements in bulk crystal structure translate directly into value-added benefits across a wide range of application domains. These include dual-use and mission-critical technologies such as high-speed and low-noise electronics (including RF and microwave amplifiers and radar front ends), optoelectronic and photonic devices, quantum and cryogenic sensor platforms, and infrared and electromagnetic sensing systems—applications for which defect density and compositional uniformity are fundamental performance drivers.

In high-speed and low-noise electronic systems, bulk crystal defects act as irreducible sources of electronic noise and as carrier-scattering centers that limit mobility and operating speed. Suppressing defect nucleation during crystal growth therefore directly reduces system noise, increases carrier mobility, improves frequency response, and extends device performance beyond limits achievable through circuit-level design optimizations alone.

Diamond

Electronic-grade diamond is a uniquely exceptional semiconductor material and is frequently described in the materials-science community as the “ultimate” wide-bandgap semiconductor. Unlike naturally occurring diamond, electronic-grade diamond is a synthetic material, typically produced using chemical vapor deposition (CVD), and must satisfy extraordinarily stringent requirements for purity, crystallinity, and defect density. These requirements exceed those of nearly all conventional semiconductor materials and reflect the extreme sensitivity of diamond’s electronic and quantum properties to even isolated lattice imperfections.

When these conditions are met, diamond exhibits unparalleled electrical, thermal, and charge-transport characteristics that are governed primarily by the intrinsic diamond lattice rather than by extrinsic defect populations or impurity scattering. As a result, electronic-grade diamond occupies a fundamentally distinct class of semiconducting materials, in which ultimate performance is lattice-limited rather than process-limited. This distinguishes diamond from other optical or thermal materials (such as silicon, sapphire, etc.) by its exceptional combination of thermal conductivity, optical transparency, high damage threshold, and mechanical robustness—properties that are especially valuable for high-power laser and advanced photonics applications.

Microgravity has the potential to enable higher-quality diamond for semiconductor and quantum applications by promoting diffusion-dominated, low-stress crystal growth environments. By suppressing buoyancy-driven convection and gravity-induced stress gradients, microgravity can reduce specific classes of parasitic defect formation, impurity clustering, and strain that are difficult to fully eliminate under terrestrial growth conditions. In particular, the absence of gravity-driven transport asymmetries may enable growth conditions that are closer to thermodynamic equilibrium than those achievable on Earth.

In such near-equilibrium regimes, reductions in defect density and residual strain can directly improve electronic transport, enhance spin coherence times in color-center defects, and increase

the reproducibility and stability of diamond-based quantum devices. Microgravity growth may also improve the spatial uniformity of nitrogen incorporation — a critical parameter for nitrogen-vacancy (NV) and related defect-based quantum systems — thereby supporting higher-fidelity qubits and more scalable diamond quantum platforms.

The exceptional properties of diamonds are realized only when the crystal is extraordinarily pure and exhibits extremely low defect density. Because the diamond lattice is exceptionally stiff, even isolated point defects or dislocations generate long-range strain fields that have an outsized impact on electronic, thermal, and quantum behavior. Once introduced, such defects are difficult or impossible to compensate through post-growth processing, placing an unusually high premium on defect suppression during crystal formation itself.

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Consequently, electronic-grade diamond remains challenging and costly to produce, and its use is currently confined to niche but performance-critical applications where unparalleled material properties justify the associated complexity and expense. These include extreme-power electronics, radiation-hard devices, precision sensing, and quantum information technologies.

As with other bulk crystalline materials, microgravity strongly suppresses buoyancy-driven convection, shifting atomic transport toward slower, diffusion-dominated, and more spatially symmetric regimes. While terrestrial CVD methods already operate in partially diffusion-limited conditions, microgravity offers the possibility of further reducing subtle growth asymmetries, interfacial stress, and impurity-transport instabilities that become increasingly relevant as material quality approaches intrinsic limits.

Silicon has been optimized over decades for the economical switching of billions of low-voltage transistors, enabling dense logic and memory technologies that prioritize integration density, yield, and cost. Diamond, by contrast, is optimized for surviving extreme electric stress with exceptional stability and margin. Diamond and silicon share the same diamond-cubic crystal structure, and diamond's electronic band structure places it within the semiconductor class; however, their electronic behavior diverges sharply due to diamond's ultra-wide bandgap, which is nearly five times larger than that of silicon.

Bandgap fundamentally governs when a material conducts electricity, the maximum electric field it can sustain, its thermal tolerance, and the classes of devices it enables. Consequently, silicon excels in high-density digital logic and memory, while diamond is uniquely suited for operation under extreme electric fields, elevated temperatures, and demanding reliability environments. For these reasons, diamond is attractive not only as an active semiconductor material but also as a thermal management and hardware-security-enabling substrate in advanced electronic and quantum systems.

Nevertheless, for the foreseeable future, diamond will not replace silicon in mainstream logic or memory technologies such as CPUs, GPUs, or commodity electronics, where integration density, manufacturing yield, and cost dominate system requirements. Instead, electronic-grade diamond is best understood as a complementary material platform — one that enables classes of performance and reliability unattainable with conventional semiconductors, rather than as a wholesale substitute for silicon-based technologies.

2D Crystals

Two-dimensional (2D) crystals (such as graphene, MoS₂, WS₂, WSe₂, and hBN) are uniquely sensitive to transport conditions at the growth interface. Because they are only one or a few atoms thick, grow primarily laterally rather than volumetrically, and are stabilized by weak out-of-plane forces, their structure and properties are governed almost entirely by interfacial processes.

In microgravity, buoyancy-driven convection, sedimentation, and gravity-induced stress are strongly suppressed, allowing 2D crystals to grow under diffusion-dominated, mechanically quiet conditions. This regime reduces defect formation, improves thickness and compositional uniformity, and stabilizes fragile atomic layers—outcomes that are difficult to achieve consistently under terrestrial gravity.

Because the entire material is effectively surface, even small transport asymmetries or single impurities can have outsized effects on performance. Improvements in 2D crystal structure therefore translate directly to value-added benefits across applications, including higher carrier mobility and lower power operation in electronics, brighter and more spectrally pure emitters in photonics, and more stable, unclonable, and tamper-resistant hardware primitives for quantum and security applications.

Market Summary

From a commercial and supply-chain perspective, III–V materials — particularly GaN — together with SiC represent the highest-leverage near-term opportunities for space manufacturing. Secondary opportunities include other III–V compounds (GaAs, InP, InGaAs) and diamond. Two-dimensional materials are expected to remain longer-term and niche, with value driven primarily by ultra-clean integration and assembly rather than bulk growth.

This ranking of opportunity is based on technical leverage, readiness for space and the ultimate driver market pull and will ultimately be driven by the marketplace.

GaN

GaN is the leading candidate because it combines large and growing terrestrial markets, a strong microgravity manufacturing advantage, and existing flight heritage. Market demand for GaN continues to expand across defense, EV charging, data centers, and telecom infrastructure.

Analyst forecasts estimate the GaN power device market growing from roughly \$350 million in 2024 to approximately \$3 billion by 2030 ($\approx 40\%$ + CAGR), while the broader GaN device market—including power, RF, and optoelectronics—is projected to expand from $\sim$ \$3 billion in 2024 to $\sim$ \$12–13 billion by 2030, implying mid-20% CAGR. This growth reflects strong commercial pull across consumer fast charging, data centers, telecom infrastructure, automotive electrification, and defense.”

GaN crystal growth remains challenging due to high defect density, impurity inhomogeneity, and thermally induced stress.

Microgravity directly addresses these quality-limiting mechanisms through suppressed convection, reduced dopant segregation, and minimized thermal stress, offering a credible pathway to materially improved substrate and epitaxial quality.

SiC

SiC follows as the second-highest near-term opportunity, with growth driven primarily by EV traction inverters (DC–AC), the transition to 800 V vehicle platforms, fast-charging infrastructure, renewables, and industrial power electronics. Market analyses estimate the global SiC power semiconductor market growing from approximately \$3 billion in 2024 to roughly \$9–11 billion by 2029–2030 (high-teens to mid-20% CAGR), with longer-term forecasts projecting $\sim$ \$18–22 billion by the mid-2030s, corresponding to a moderated mid-teens CAGR as capacity expansions, yield improvements, and price normalization take effect.”

SiC benefits from many of the same physical advantages as GaN in a microgravity environment, including diffusion-limited transport and reduced thermo-mechanical stress during crystal growth. However, SiC bulk-growth and wafer manufacturing infrastructure on Earth is more mature, slightly reducing urgency relative to GaN. Even so, SiC remains an excellent near-term space-manufacturing candidate, particularly for premium, defect-reduced substrates where marginal quality improvements translate directly into device yield and performance.

Classic III–V

Next are the classic III–V arsenides and phosphides (GaAs, InP, InGaAs), which are used primarily in photonics and lasers, optical communications, space solar cells, and high-speed / RF electronics. Space solar cells are called out specifically because III–V arsenides and phosphides combine radiation hardness, ultra-high efficiency, and multi-junction capability, making them uniquely well suited for space environments. In the longer term, space-manufactured III–V materials tied to solar applications could potentially act as a catalyst for in-space power generation concepts, including power-hungry space-based data centers.

The associated markets are smaller and relatively stable, rather than exponential-growth markets.

Classic III–V arsenide and phosphide markets — spanning GaAs-based RF electronics, InP/InGaAs optical communications, and specialty space photovoltaics — collectively represent an estimated $\sim$ \$13–15 billion market today. Analyst forecasts project growth to approximately

~\$22–27 billion by the early 2030s, corresponding to ~7–12% CAGR over the next five years and moderating to ~6–9% CAGR over a 10-year horizon, reflecting steady, infrastructure-anchored expansion rather than explosive adoption.

Diamond

Electronic-grade diamond represents a future-facing opportunity in semiconductor materials. While researchers first recognized diamond’s electrical properties in the 1950s and shortly thereafter its potential for semiconductor use, diamond can still be in the introductory phase of its product life cycle.

Owing to its exceptional material properties, diamond semiconductors are typically viewed across three overlapping segments: electronic-grade diamond substrates and wafers, diamond as an active ultra-wide-bandgap semiconductor, and diamond as a thermal and packaging material (e.g., GaN-on-diamond). Key use cases include power electronics, advanced thermal management, quantum technologies, sensors, and optical applications.

To date, controlled doping, cost, and scalable wafer size have been the primary gating factors limiting broader adoption. Diamond is uniquely well suited for quantum applications because its ultra-pure, low-noise crystal lattice hosts exceptionally stable, optically addressable spin defects with long coherence times, combined with high thermal and mechanical stability and room-temperature operation — capabilities unmatched by other solid-state materials.

Microgravity could potentially help mitigate some of the material-quality challenges in diamond growth and act as a catalyst for its longer-term development as a semiconductor platform. Reported growth rates are among the highest of any semiconductor material, largely because the current market base is small. Analyst forecasts place the diamond semiconductor market at roughly \$0.5–0.6 billion in 2024, expanding to approximately \$2–2.5 billion by 2030–2032 (~20–30% CAGR). Longer-term projections indicate growth to ~\$4–5 billion by the mid-2030s, corresponding to moderated ~15–25% CAGR as the technology transitions from pilot-scale demonstrations toward selective commercial deployment in power, RF, and extreme-environment applications.

2D Crystals

There is a credible but narrowly scoped case for manufacturing 2D crystals in microgravity—primarily for ultra-clean, defect-engineered, and quantum-grade materials where surface perfection, interface cleanliness, and controlled defect states directly determine functionality. In these domains, microgravity can provide incremental but mission-relevant advantages, particularly for quantum photonics, hardware trust primitives, and fundamental materials science.

However, 2D materials remain fundamentally interface-dominated and chemistry-limited systems. Microgravity does not remove their primary commercialization bottlenecks—namely substrate interactions, contact resistance, dielectric noise, and large-scale integration yield. As a

result, microgravity does not unlock a new manufacturing regime for 2D materials in the same way it does for bulk, defect-limited semiconductors.

By contrast, materials such as GaN, SiC, and selected III–V compounds are bulk crystals whose quality is fundamentally constrained by gravity-driven transport, segregation, and interface instability on Earth. For these materials, microgravity directly suppresses defect nucleation at the growth stage, enabling step-function improvements in crystal quality with immediate, system-level impact on power electronics, RF systems, space hardware, and defense applications. This makes them the clear near-term priority for LEO manufacturing.

Market analyses indicate that electronics-relevant 2D materials markets are currently on the order of \$1–3 billion globally and are projected to reach approximately \$3–6 billion over the next five years, corresponding to ~15–25% CAGR. Over a ten-year horizon, growth is expected to moderate to ~8–15% CAGR, with market sizes reaching roughly \$6–9 billion by the mid-2030s, reflecting gradual transition from research-driven adoption to selective commercial integration.

Strategic Positioning for LEO Manufacturing Roadmaps

Recommended Primary Focus for LEO Manufacturing

(Near term $\approx$ 0–5 years, high leverage)

Low Earth orbit manufacturing should prioritize **bulk, gravity-limited wide-bandgap materials**, including **gallium nitride (GaN), silicon carbide (SiC), diamond, and related III–V compounds**, where microgravity directly mitigates first-order physical constraints on crystal growth. For these materials, orbital processing offers the potential for wafer-scale improvements in crystalline uniformity, defect density, dopant control, and thermal properties—advances that are both technically consequential and economically meaningful within existing and emerging power electronics, RF, thermal management, and quantum-adjacent markets.

Diamond merits explicit inclusion in this primary category. Its exceptional thermal conductivity, breakdown field, and defect-sensitive electronic and quantum properties make it particularly responsive to improvements in bulk crystal quality. Microgravity-enabled growth and processing pathways offer a credible route to overcoming terrestrial limitations associated with stress, impurity incorporation, and defect formation, positioning diamond as a strategically important LEO-manufactured substrate rather than a speculative outlier.

Parallel Capability-Driven Effort

(Limited volume, high strategic value, $\approx$ 2–8 years (overlapping with near term))

A secondary, deliberately scoped LEO activity should focus on **two-dimensional materials and defect-engineered systems**, including 2D layers and color-center–based platforms in diamond. Target applications include quantum emitters, trusted hardware primitives, ultra-clean heterostructures, and foundational scientific research. In these domains, marginal gains in crystal perfection, interface cleanliness, strain control, or defect uniformity can justify orbital experimentation and limited production, despite inherently low volumes and extended commercialization timelines.

Long-Term Integration Pathway

(*≈ 7–15+ years*)

Over the longer term, LEO manufacturing efforts should converge toward **hybrid material architectures** that integrate **space-grown bulk substrates** (GaN, SiC, diamond, and other III–V materials) with **Earth- or space-assembled 2D and nanoscale layers**. This approach enables the co-optimization of bulk material performance and interfacial or quantum-scale functionality, while avoiding the economic and technical pitfalls of forcing inherently low-throughput material systems into high-volume manufacturing models.

Under this framework, 2D materials and defect-engineered platforms are not excluded from LEO manufacturing; rather, they are intentionally positioned as **enabling and exploratory capabilities**, complementary to a primary focus on bulk materials where microgravity provides immediate and defensible advantages. This distinction is essential to maintaining technical credibility, aligning orbital manufacturing investments with near-term return on investment, and establishing a scalable, strategically coherent pathway toward progressively more complex space-manufactured semiconductor systems.

Conclusion: Strategic Implications for National Security and U.S.

Leadership

The proposed LEO manufacturing strategy is not merely an industrial roadmap; it is a deliberate response to an evolving strategic competition in which materials supremacy increasingly underpins military, economic, and geopolitical power. As China makes sustained, state-directed investments in space-based materials science and semiconductor development, the United States must ensure that orbital manufacturing advances translate into concrete national security advantages rather than symbolic demonstrations of technical competence.

By prioritizing bulk, gravity-limited wide-bandgap materials — GaN, SiC, diamond, and related III–V compounds — the U.S. focuses LEO manufacturing on domains where microgravity offers immediate, defensible performance gains and where those gains directly reinforce defense-critical capabilities. These materials form the backbone of next-generation power electronics, RF systems, thermal management, and quantum-adjacent platforms that are essential to modern military systems and space resilience. Concentrating near-term investment here preserves U.S. leadership in high-leverage technologies while reducing dependence on fragile or contested terrestrial supply chains.

Equally important, the deliberate positioning of two-dimensional materials and defect-engineered platforms as secondary, capability-driven efforts prevents the misallocation of strategic resources. This approach enables the United States to build unique intellectual property, workforce expertise, and experimental capacity without overcommitting to low-volume manufacturing pathways that offer limited near-term security return. In doing so, it avoids a dynamic in which exploratory science outpaces its relevance to national defense or economic competitiveness.

Over the longer term, the integration of space-grown bulk substrates with nanoscale and quantum-functional layers establishes a pathway toward complex, system-level architectures that are difficult to replicate without sustained access to space infrastructure, trusted industrial ecosystems, and advanced logistics. This integrated approach creates strategic depth: even as competitors pursue individual material advances, the United States retains an advantage in assembling those advances into operationally meaningful systems.

In aggregate, this strategic positioning ensures that U.S. leadership in LEO manufacturing reinforces deterrence, strengthens the defense industrial base, and sustains long-term technological advantage in an increasingly contested domain. Rather than chasing speculative or prestige-driven objectives, it aligns orbital manufacturing investments with national priorities—ensuring that superiority in space-enabled materials translates into enduring strategic power on Earth.

Property	2D Materials (Graphene, MoS ₂)	III–V Materials (Non-Nitride) (GaAs, InP, InGaAs)	Diamond	Silicon (Si)	Silicon Carbide (SiC)	Gallium Nitride (GaN)
Bandgap	Graphene: 0 eV (gapless) MoS ₂ : ~1.2 eV (indirect, bulk) ~1.8–1.9 eV (direct, monolayer)	Wide range; typically, direct bandgap (e.g., GaAs ~1.42 eV, InP ~1.34 eV)	Ultra-wide bandgap ~5.47 eV	~1.12 eV (indirect)	Wide bandgap ~3.26 eV	Wide bandgap ~3.4 eV
Carrier Mobility	Extremely high (graphene >200,000 cm ² /V·s reported)	Very high; excellent for RF and optoelectronics	Electrons ~4,000 cm ² /V·s Holes ~3,800 cm ² /V·s	~1,350–1,600 cm ² /V·s (electrons)	Moderate–good; optimized for power switching	High electron mobility; supports HEMTs
Thermal Conductivity	Very high in graphene (in-plane)	Moderate–high, material-dependent	~22 W/cm·K (highest semiconductor)	~1.48 W/cm·K	Higher than Si; critical for power devices	Higher than Si; supports high power density

Breakdown Field	Extremely high effective fields due to atomic thickness	High relative to Si	~20 MV/cm (exceptional)	Baseline for conventional electronics	Higher than Si; supports high-voltage devices	High; supports high-field, high-frequency operation
Primary Strengths	Ultimate thickness scaling; surface-dominated physics; quantum and sensing potential	High-speed electronics, photonics, lasers, space solar cells	Extreme power handling, radiation hardness, thermal stability	Mature, low-cost, ultra-high integration density	High-voltage, high-power, high-temperature switching	High-frequency RF, efficient power electronics (≤ 650 V)
Key Challenges	Integration, contacts, scalability, environmental sensitivity	Defect control, lattice mismatch, expensive substrates	Cost, scalable wafer size, controlled doping	Approaching physical and economic scaling limits	Killer defects (micropipes, dislocations, stacking faults)	Lattice/thermal mismatch, dislocation density, substrate availability
Typical Applications	Sensors, optoelectronics, flexible electronics, quantum materials	Lasers, LEDs, RF amplifiers, 5G/6G, high-speed logic	Extreme-environment power electronics, radiation-hard and quantum devices	CPUs, GPUs, memory, analog and mixed-signal ICs	EV inverters, grid power modules, industrial power electronics	RF power amplifiers, fast chargers, radar, satellite RF
Microgravity Advantage	Low–Medium: Better uniformity and reduced stress, but dominated by interface issues	Medium–High: Reduced convection and segregation improve bulk crystal quality	Medium: Reduced stress and impurity clustering near intrinsic limits	Low: Terrestrial processes already near physical limits	High: Suppressed vapor convection stabilizes polytypes and reduces extended defects	High: Reduced dopant segregation, stress, and dislocation formation

Appendix A: Acronyms and Abbreviations

AI	Artificial intelligence
ALD	Atomic Layer Deposition
AMD	Advanced Micro Devices, Inc.
ATI	Advanced Technology International
CHIPS	Creating Helpful Incentives to Produce Semiconductors
DoD	Department of Defense
EAGER	Early-Concept Grants for Exploratory Research
EDA	Electronic design automation
ESA	European Space Agency
EU	European Union
EV	Electric vehicle
GaN-on-Si	Advanced semiconductor technology that integrates Gallium Nitride (GaN) onto silicon substrates
IBAS	Industrial Base Analysis and Sustainment
III–V	A class of materials used in microelectronic applications
InP	Indium phosphide
IP	Intellectual property
ISMA	In-space Manufacturing Alliance
ISS	International Space Station
ISAM	In-space Servicing, Assembly, and Manufacturing
ISR	Intelligence, Surveillance, Reconnaissance
LEO	Low Earth orbit
MoS₂	Molybdenum disulfide
NAPMP	National Advanced Packaging Manufacturing Program
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
PUF	Physical unclonable function
R&D	Research & Development
RESHAPE	Re-shore Ecosystem for Secure Heterogeneous Advanced Packaged Electronics
RF	Radio frequency
SAM	Serviceable Available Market
SIA	Semiconductor Industry Association
SiC	Silicon carbide
SiGe	Silicon–germanium
SOM	Serviceable Obtainable Market (also called “Share of Market”)
STEM	Science, Technology, Engineering and Mathematics
TAM	Total Addressable Market
TAMU	Texas A&M University
TPM	Trusted platform modules
TRL	Technical Readiness Levels
TSIC	Texas Semiconductor Innovation Consortium
TSIF	Texas Semiconductor Innovation Fund
TSMC	Taiwan Semiconductor Manufacturing Company
USSF	United States Space Force
UWBG	Ultrawide-bandgap
WBG	Wide-bandgap

Appendix B: References and Resources

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