**Comparative Report: GaN vs SiC vs Si in Power Electronics**

**CHAPTER 1 – INTRODUCTION**

**Comparative Analysis of Semiconductor Materials: Silicon (Si), Gallium Nitride (GaN), and Silicon Carbide (SiC) in Power Electronics**

**1.1 Background**

The global demand for energy-efficient and high-performance power electronic systems is growing rapidly. From electric vehicles (EVs) to renewable energy inverters and high-frequency chargers, the efficiency and compactness of power conversion systems have become critical design constraints. In this landscape, **semiconductor materials** play a foundational role, directly affecting **device performance**, **energy losses**, **thermal behavior**, and **cost-effectiveness**.

Historically, **Silicon (Si)** has been the workhorse of the semiconductor industry due to its excellent balance between performance and cost, as well as its mature manufacturing ecosystem. However, the physical limitations of Si — particularly its relatively narrow bandgap and low critical electric field — have constrained its application in high-voltage, high-frequency, and high-temperature environments.

In response to these limitations, **wide bandgap (WBG) materials** such as **Gallium Nitride (GaN)** and **Silicon Carbide (SiC)** have emerged as promising alternatives. These materials offer superior electronic and thermal properties, making them ideal for **next-generation power devices**. Consequently, understanding the trade-offs between Si, GaN, and SiC is essential for system designers and materials scientists seeking to optimize performance in power-critical domains.

**1.2 Motivation**

The motivation for this comparative study arises from the need to provide a **comprehensive material-based perspective** to guide decisions in semiconductor device design. As WBG semiconductors gain traction in industry, engineers must weigh their benefits — such as **higher efficiency, faster switching speed, and smaller form factors** — against challenges like **higher cost, packaging complexity**, and **immature supply chains**.

Rather than evaluating devices based on application-specific performance alone, this study seeks to investigate the **material-level parameters** that underpin device behavior. By doing so, we aim to inform not only the "what" (device performance) but the "why" (material science principles) that govern the suitability of Si, GaN, and SiC.

**1.3 Objective**

This report aims to provide a **quantitative and qualitative comparative analysis** of Si, GaN, and SiC in the context of power electronics. The core objectives are:

* To present a clear comparison of key **material properties** such as:
  + Bandgap energy
  + Electron mobility
  + Breakdown electric field
  + Thermal conductivity
  + Saturated electron velocity
  + Cost per unit area
* To **link these properties** to real-world applications, particularly:
  + Electric vehicle inverters
  + High-frequency and high-efficiency chargers
  + Grid-level and renewable energy power modules
* To analyze **trade-offs** and **design implications** stemming from each material's strengths and weaknesses
* To provide **visual summaries** (e.g., comparison tables, radar charts) for quick reference and technical communication

**1.4 Methodology Overview**

This report integrates data and analysis from:

* **Peer-reviewed journal articles**
* **Datasheets from semiconductor manufacturers** (e.g., Infineon, Wolfspeed, STMicroelectronics)
* **Whitepapers and technical blogs**
* **Simulation models** and empirical benchmarks (where applicable)

The material comparison will be supported by:

* Quantitative tables of physical parameters
* Charts and visualizations to show performance-space coverage
* Application case studies to illustrate real-world relevance

**1.5 Scope and Limitations**

The study focuses strictly on **bulk material properties** and their **system-level implications**. Device-level factors (such as gate oxide stability, lifetime, or packaging effects) are mentioned only when relevant to material behavior. Compound semiconductors beyond GaN and SiC (e.g., GaAs, InP) are excluded due to their niche use cases in optoelectronics rather than power electronics.

This report does not aim to design devices or simulate circuits but rather to offer a **material-first perspective** grounded in semiconductor physics and engineering trade-offs.

**CHAPTER 2 – OVERVIEW OF SEMICONDUCTOR MATERIALS**

**2.1 Introduction to Material Selection in Power Electronics**

In power electronics, **material selection is not merely a theoretical exercise**; it directly influences the **efficiency, size, cost, and reliability** of the final device. Each semiconductor material embodies a unique set of **electrical, thermal, and mechanical properties**, which ultimately define the **operating limits** and **target applications** of the devices built from them.

This chapter introduces the three key semiconductor materials in this study — **Silicon (Si)**, **Gallium Nitride (GaN)**, and **Silicon Carbide (SiC)** — outlining their physical characteristics, technological maturity, and strategic significance in modern and future electronic systems.

**2.2 Silicon (Si)**

**Material Overview**

Silicon is the most widely used semiconductor in the world and has been the foundation of the modern electronics industry for over five decades. It features a **moderate bandgap (1.12 eV)** and **high electron mobility (~1400 cm²/Vs)**, making it suitable for a wide range of low- to medium-power applications.

**Key Strengths**

* Mature and low-cost manufacturing ecosystem
* Highly refined wafer processing and lithography techniques
* Excellent for **logic circuits, analog ICs, and standard power MOSFETs**

**Limitations**

* **Low breakdown electric field (~0.3 MV/cm)**
* **Limited performance at high voltages and temperatures**
* Increasingly unsuitable for **high-efficiency, compact power converters**

**Role in Industry**

Despite the emergence of WBG materials, silicon continues to dominate in:

* Microcontrollers and digital logic
* Industrial control systems
* Automotive control units (non-inverter)

**2.3 Gallium Nitride (GaN)**

**Material Overview**

GaN is a **wide bandgap (3.4 eV)** semiconductor with **high electron mobility and saturation velocity**, making it exceptionally suited for **high-frequency and high-efficiency** power conversion.

GaN devices are fabricated on substrates like silicon (GaN-on-Si) or silicon carbide (GaN-on-SiC), offering flexibility and scalability in integration.

**Key Strengths**

* High-frequency switching (MHz range)
* Enables miniaturization of power systems
* Lower gate charge and capacitance than Si MOSFETs
* Reduced conduction and switching losses

**Limitations**

* Expensive and less mature than Si
* Packaging and thermal management challenges
* Reliability data is still maturing for large-scale applications

**Role in Industry**

GaN is increasingly adopted in:

* Smartphone and laptop fast chargers
* Data center power modules
* Lidar systems and 5G RF power amplifiers

**2.4 Silicon Carbide (SiC)**

**Material Overview**

SiC is a **wide bandgap semiconductor (3.26 eV)** with **outstanding thermal conductivity (~490 W/m·K)** and **high breakdown voltage (~3 MV/cm)**. Its robustness makes it ideal for **high-voltage, high-temperature** applications.

SiC devices are predominantly used in **power MOSFETs**, **Schottky diodes**, and **inverter modules**.

**Key Strengths**

* Superior thermal stability
* High voltage blocking capability
* Low switching loss at high current
* Operates reliably in harsh environments

**Limitations**

* More expensive than Si
* Processing is complex (e.g., harder wafers, advanced etching)
* Gate drive requirements differ from conventional Si devices

**Role in Industry**

SiC is the preferred choice for:

* **EV powertrain inverters** (e.g., Tesla Model 3 SiC modules)
* **Solar inverters and industrial motor drives**
* **Railway traction systems and aerospace power units**

**2.5 Strategic Comparison**

| **Criteria** | **Silicon (Si)** | **Gallium Nitride (GaN)** | **Silicon Carbide (SiC)** |
| --- | --- | --- | --- |
| Bandgap (eV) | 1.12 | 3.4 | 3.26 |
| Electron Mobility (cm²/Vs) | ~1400 | ~1500 | ~1000 |
| Breakdown Field (MV/cm) | ~0.3 | ~3.3 | ~3.0 |
| Thermal Conductivity | 150 W/m·K | ~130 W/m·K | ~490 W/m·K |
| Switching Frequency | Moderate | High | Moderate-High |
| Device Cost | Low | High | High |
| Maturity in Power Apps | High | Emerging | Advancing |

**2.6 Summary**

Each material has a unique performance envelope:

* **Si** is economical and universally supported — but limited in performance.
* **GaN** is transformative in applications requiring **high frequency and efficiency**.
* **SiC** excels in **high-voltage and high-temperature** domains.

Choosing the right material is therefore **application-dependent**, and often influenced by **cost, size constraints, thermal environment, and voltage requirements**.

**CHAPTER 3 – COMPARATIVE PROPERTY ANALYSIS**

**3.1 Introduction**

To understand the material suitability for various power electronics applications, it is essential to compare the **key physical, electrical, and thermal properties** of semiconductor materials. This chapter presents a **quantitative analysis** of Silicon (Si), Gallium Nitride (GaN), and Silicon Carbide (SiC), highlighting how these properties impact **device performance**, **efficiency**, and **application feasibility**.

The properties analyzed in this chapter include:

* Bandgap energy
* Electron mobility
* Critical electric field (breakdown strength)
* Thermal conductivity
* Saturation velocity
* Dielectric constant
* Cost and scalability

**3.2 Tabular Comparison of Key Properties**

| **Property** | **Silicon (Si)** | **Gallium Nitride (GaN)** | **Silicon Carbide (SiC)** |
| --- | --- | --- | --- |
| **Bandgap Energy (eV)** | 1.12 | 3.4 | 3.26 |
| **Electron Mobility (cm²/V·s)** | ~1400 | ~1500 | ~1000 |
| **Breakdown Electric Field (MV/cm)** | 0.3 | 3.3 | 3.0 |
| **Thermal Conductivity (W/m·K)** | 150 | ~130 | 490 |
| **Dielectric Constant (εr)** | 11.9 | 9.0 | 10.0 |
| **Saturation Velocity (cm/s)** | 1.0 × 10⁷ | 2.5 × 10⁷ | 2.0 × 10⁷ |
| **Electron Affinity (eV)** | 4.05 | 4.1 | 3.7 |
| **Wafer Cost ($/cm²)** | Very low | High | High |

**3.3 Comparative Insights**

**3.3.1 Bandgap Energy**

* **GaN** and **SiC** both exhibit wide bandgaps (~3 eV), enabling operation at **higher voltages and temperatures**.
* **Si**, with a narrower bandgap (1.12 eV), suffers from higher leakage currents and lower breakdown voltage.

**3.3.2 Electron Mobility**

* **GaN** has slightly higher mobility than Si, which contributes to **faster switching speeds**.
* **SiC** has lower mobility, but compensates with high field strength.

**3.3.3 Breakdown Electric Field**

* GaN and SiC can withstand **10× higher electric fields** than Si, enabling **smaller devices** with thinner layers for the same voltage rating → better **power density**.

**3.3.4 Thermal Conductivity**

* **SiC** leads significantly in thermal performance (490 W/m·K), making it ideal for **harsh thermal environments** like EV inverters and aerospace.
* **Si** performs moderately, while **GaN** has the lowest thermal conductivity in the group.

**3.3.5 Saturation Velocity**

* **GaN’s high saturation velocity** enables high-frequency operation (MHz range), reducing magnetic components size.

**3.4 Visual Comparison**

**3.5 Application Implications of Property Differences**

| **Property** | **Advantage For…** | **Notes** |
| --- | --- | --- |
| High Bandgap | EVs, high-voltage circuits | Enables small, rugged devices |
| High Mobility | Fast chargers, switching apps | Faster response time |
| High Breakdown | Power conversion (solar, EV) | Lower ON resistance |
| High Thermal | Harsh environments (aerospace, motors) | Requires less cooling |
| Low Cost | Mass production, logic ICs | Only Si fits here |

**3.6 Summary**

The **synergistic interplay** between material properties determines device behavior under specific conditions. There is no “best” material universally — only **contextually optimal** choices:

* **GaN** leads in **switching frequency** and **size reduction**
* **SiC** is unmatched in **thermal and voltage performance**
* **Si** remains the **go-to choice** for general electronics due to its **low cost and maturity**

**CHAPTER 4 – APPLICATION-BASED EVALUATION**

**4.1 Introduction**

The properties of semiconductor materials directly influence their performance in real-world systems. In power electronics, selecting the appropriate material for a given application depends not only on its **physical parameters**, but also on factors such as **operating voltage and current**, **switching frequency**, **thermal constraints**, and **cost sensitivity**.

This chapter evaluates the suitability of **Silicon (Si)**, **Gallium Nitride (GaN)**, and **Silicon Carbide (SiC)** for specific application domains by **mapping material characteristics to design requirements** in each use case.

**4.2 Use Case 1: Electric Vehicle (EV) Powertrain Inverters**

**System Requirements:**

* High voltage (400–800 V)
* High current (up to 600 A)
* Robust thermal management
* High reliability under vibration and wide temperature swings

**Material Suitability:**

| **Material** | **Evaluation** |
| --- | --- |
| **Si** | High losses at elevated temperatures; requires larger cooling systems. Not ideal for high-efficiency EV powertrains. |
| **GaN** | Limited to <650 V devices; thermal management not sufficient for high-current EV inverters. Rarely used. |
| **SiC** | ✅ **Best fit** – High breakdown voltage, excellent thermal conductivity, compact design. Used by Tesla, BYD, etc. |

**Real-World Example:**

* **Tesla Model 3** uses **SiC MOSFETs** in the main inverter for improved efficiency and range.

**4.3 Use Case 2: Fast Charging Power Supplies (Smartphones, Laptops, EV Chargers)**

**System Requirements:**

* High-frequency switching (>100 kHz)
* Compact size and lightweight
* Energy efficiency under light load
* Cost-sensitive consumer market

**Material Suitability:**

| **Material** | **Evaluation** |
| --- | --- |
| **Si** | Works but requires large passive components due to lower switching frequency; limited power density. |
| **GaN** | ✅ **Best fit** – Fast switching enables miniaturized inductors, high power density, and lower losses. |
| **SiC** | Overkill for low-voltage chargers; more expensive and harder to integrate. |

**Real-World Example:**

* **Anker & Apple** use **GaN transistors** in high-efficiency compact fast chargers (up to 140W).

**4.4 Use Case 3: Solar Inverters and Grid-Level Converters**

**System Requirements:**

* Voltage range: 600 V – 1500 V
* High efficiency at full load
* Long-term reliability (>10 years)
* Harsh environments (heat, dust, humidity)

**Material Suitability:**

| **Material** | **Evaluation** |
| --- | --- |
| **Si** | Used in older designs; requires derating and large heatsinks. |
| **GaN** | Still emerging; thermal management challenges limit scale-up to >1 kW. |
| **SiC** | ✅ **Best fit** – High-voltage capability, reduced cooling needs, long lifetime. Adopted in modern solar farms. |

**Real-World Example:**

* **SMA Solar Technology** uses **SiC MOSFETs** in large-scale inverters for grid-tied solar installations.

**4.5 Use Case 4: Data Centers and Servers**

**System Requirements:**

* High-frequency conversion (DC-DC, AC-DC)
* Low latency, high-efficiency UPS
* Compact design
* Thermal optimization

**Material Suitability:**

| **Material** | **Evaluation** |
| --- | --- |
| **Si** | Still used, but reaching performance limits |
| **GaN** | ✅ **Best fit** – Enables compact, high-efficiency power modules for rack-mount systems |
| **SiC** | Viable but more expensive; suited for higher voltage segments |

**Real-World Example:**

* **Google** and **Amazon** experiment with **GaN** in 48V server power modules for improved energy usage efficiency (PUE).

**4.6 Summary of Application Fit**

| **Application Domain** | **Best Material** | **Rationale** |
| --- | --- | --- |
| EV Power Inverters | SiC | High voltage, high current, thermal robustness |
| Fast Chargers | GaN | High frequency, compact size, low switching loss |
| Solar/Grid Inverters | SiC | Harsh conditions, voltage >1000V, long lifetime |
| Data Centers | GaN | Power density and efficiency in tight spaces |
| General Purpose Devices | Si | Mature, low-cost, widely supported |

**4.7 Key Takeaways**

* **Silicon** remains relevant in cost-sensitive or legacy systems but faces physical limits.
* **GaN** excels in size-constrained, high-frequency environments like consumer electronics and cloud infrastructure.
* **SiC** is the undisputed leader for high-power, high-temperature, and high-reliability applications such as electric transportation and solar energy.

**CHAPTER 5 – TRADE-OFFS AND MATERIAL SELECTION GUIDELINES**

**5.1 Introduction**

Selecting a semiconductor material is rarely a straightforward decision. In most design scenarios, engineers must navigate **trade-offs between competing factors** such as performance, efficiency, thermal management, cost, scalability, and long-term reliability.

This chapter presents a **structured decision-making framework** for choosing between **Silicon (Si)**, **Gallium Nitride (GaN)**, and **Silicon Carbide (SiC)**, using application-driven criteria and a set of strategic evaluation matrices.

**5.2 Key Trade-Off Dimensions**

| **Dimension** | **GaN** | **SiC** | **Si** |
| --- | --- | --- | --- |
| **Switching Speed** | ✅ Ultra-fast | ✅ Fast | ❌ Limited |
| **Voltage Handling** | ❌ <650 V typical | ✅ Up to 1700 V+ | ❌ Limited (600–900 V) |
| **Thermal Handling** | ❌ Moderate (130 W/mK) | ✅ Excellent (490 W/mK) | ❌ Moderate (150 W/mK) |
| **Cost** | ❌ High | ❌ High | ✅ Very low |
| **Maturity** | ❌ Emerging | ✅ Growing | ✅ Mature |
| **Footprint** | ✅ Compact designs | ✅ Smaller than Si | ❌ Larger passives required |

**Insight**: No material dominates all categories. Selections must reflect application constraints and trade-off priorities.

**5.3 Performance vs Cost Curve**

You can represent the relationship in a **material selection space** where:

* **X-axis** = Application Voltage / Complexity
* **Y-axis** = Performance Index (efficiency, switching, thermal)

| **Zone** | **Recommended Material** |
| --- | --- |
| Low voltage + low cost | **Si** |
| Mid voltage + high switching | **GaN** |
| High voltage + high power | **SiC** |

This can be visualized as a **decision triangle** with each material occupying a corner based on strengths.

**5.4 Material Selection Guidelines by Design Objective**

| **Design Objective** | **Optimal Material** | **Reasoning** |
| --- | --- | --- |
| Maximize Power Efficiency | GaN or SiC | Lower switching loss and conduction loss |
| Reduce System Size | GaN | Higher frequency = smaller passives |
| Withstand High Temperature | SiC | Highest thermal conductivity |
| Cost-Constrained Design | Si | Mature and cheapest option |
| Automotive Harsh Environment | SiC | Robust against vibration and heat |
| Consumer Electronics | GaN | Compact, efficient, moderate power |
| General Logic and Analog | Si | Ubiquitous and CMOS-friendly |

**5.5 Decision-Making Framework: Multi-Criteria Evaluation Table**

| **Criteria Weight (%)** | **Si** | **GaN** | **SiC** |
| --- | --- | --- | --- |
| Switching Speed (25%) | 3 | 5 | 4 |
| Thermal Handling (20%) | 3 | 2 | 5 |
| Cost (20%) | 5 | 2 | 2 |
| Voltage Range (15%) | 3 | 2 | 5 |
| Maturity (15%) | 5 | 3 | 4 |
| **Weighted Score** | 3.9 | 3.65 | 4.2 |

🔍 **Example**: For a design prioritizing voltage and thermal performance (like EV), SiC scores highest. For budget-sensitive products (e.g., phone chargers), GaN wins on performance-to-size ratio.

**5.6 Strategic Considerations Beyond Physics**

* **Packaging technology**: GaN often requires advanced packaging for heat dissipation.
* **Supply chain availability**: Si has global infrastructure; GaN/SiC are fab-dependent.
* **Design expertise**: GaN/SiC require new driver circuits and layout strategies.
* **Standardization & reliability data**: More abundant for Si, emerging for GaN.

**5.7 Future Outlook and Evolving Trade-Offs**

| **Trend** | **Impact on Selection** |
| --- | --- |
| Cost of GaN/SiC decreasing | Makes WBG more accessible |
| Foundry support for GaN | Accelerates adoption |
| EV market boom | SiC demand to outpace Si in traction systems |
| 3D packaging & integration | GaN’s compactness will be a key enabler |

**5.8 Summary**

Material selection is a **multidimensional optimization problem**. The ideal choice depends on:

* **Technical requirements** (voltage, frequency, thermal constraints)
* **Market constraints** (cost, time-to-market)
* **Operational environments** (harsh vs controlled)

By applying a structured, trade-off-driven evaluation, engineers can navigate the growing ecosystem of semiconductor materials with confidence.

**CHAPTER 6 – CONCLUSION AND FUTURE DIRECTIONS**

**6.1 Conclusion**

This report conducted a detailed comparative study of three major semiconductor materials — **Silicon (Si)**, **Gallium Nitride (GaN)**, and **Silicon Carbide (SiC)** — in the context of their use in **power electronics**. Through a property-based and application-oriented lens, several key insights emerged:

* **Silicon**, while historically dominant, is now technically limited for high-frequency and high-power applications due to its **narrow bandgap**, **lower thermal tolerance**, and **limited breakdown strength**.
* **Gallium Nitride (GaN)** excels in **high-frequency, compact, and energy-efficient systems** such as smartphone fast chargers and data center modules, thanks to its **high electron mobility** and **saturation velocity**.
* **Silicon Carbide (SiC)** demonstrates unparalleled performance in **high-voltage**, **high-temperature**, and **high-power** environments like electric vehicles and solar inverters, largely due to its **thermal conductivity** and **breakdown voltage**.

Importantly, no single material is superior across all metrics. Instead, **each material represents an optimal trade-off in a specific application domain**, reinforcing the need for material-aware system design.

**6.2 Strategic Applications Summary**

| **Application Domain** | **Best-Fit Material** | **Strategic Rationale** |
| --- | --- | --- |
| EV Powertrains | SiC | Handles high voltage, heat, and load |
| Fast Charging Systems | GaN | Enables compact, efficient designs |
| Grid-Tied Solar Inverters | SiC | Robust under outdoor, long-lifetime conditions |
| General Consumer ICs | Si | Cost-effective and mature ecosystem |
| Cloud Infrastructure | GaN | High-frequency switching and small size |

**6.3 Technology Maturity & Adoption**

| **Material** | **Technology Maturity** | **Adoption Level** | **Main Industry Drivers** |
| --- | --- | --- | --- |
| Si | Fully Mature | Mass Production | Cost, Infrastructure |
| GaN | Emerging-Mature | Accelerating | Miniaturization, Efficiency |
| SiC | Mature-Expanding | Industry-wide | EVs, Renewables, Industrial Power |

**6.4 Challenges Ahead**

While WBG semiconductors offer compelling advantages, there remain several **barriers to large-scale adoption**:

* **Cost of manufacturing and wafer production** (especially SiC)
* **Packaging technology** for heat dissipation (notably for GaN)
* **Lack of standardization** in design and testing protocols
* **Design expertise gap** in WBG-specific circuit topologies
* **Supply chain maturity**, especially for GaN-on-Si wafers

These challenges are being addressed as global investment increases and more universities and industries embrace **wide-bandgap material research**.

**6.5 Future Directions**

As the **energy, transportation, and data sectors** continue to push the boundaries of power density, efficiency, and thermal reliability, the role of semiconductor materials will become increasingly strategic. Below are **5 future-forward directions** for the industry:

**1. Monolithic Integration of GaN Power ICs**

* Full integration of **gate drivers, protection, and control** in a single GaN chip
* Reduces size, improves efficiency

**2. Scalable SiC MOSFETs for 1700V+**

* Wider adoption in **heavy-duty vehicles**, **aerospace**, and **industrial power**

**3. Advanced Substrates & Wafer Scaling**

* **GaN-on-Si** and **SiC-on-Si** to reduce cost
* **200mm+ wafers** for better economy of scale

**4. AI-Guided Material Simulation & Device Design**

* Use of **machine learning** to predict dopant behavior, optimize geometry

**5. Sustainable & Eco-Friendly Material Processes**

* Focus on reducing toxic by-products in wafer fabrication (e.g., replacing hazardous etching chemicals)

**6.6 Final Remarks**

The semiconductor industry is entering an era where **material science decisions are no longer secondary** — they are **strategic and foundational**. Understanding the physical trade-offs, system-level implications, and industrial readiness of GaN, SiC, and Si allows engineers to:

* Design better systems
* Improve energy utilization
* Enable more sustainable, compact, and high-performance technologies

For students and early-career engineers, this understanding is not just academically valuable, but **professionally essential**.

✅ *The future belongs to those who not only know how to build the system, but understand the material it's built from.*

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