# Comparative TCAD Simulation Study of Silicon and Silicon Carbide IGBTs for Power Applications


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***Abstract*—A comparison of silicon (Si) and silicon carbide (SiC) insulated gate bipolar transistors (IGBTs) for high-power applications is presented in this paper using simulation. In the early stages, the device architectures were modeled, the breakdown voltage behavior was evaluated, and baseline I-V parameters were extracted using TCAD simulations with Silvaco ATLAS. However, the analysis was mostly carried out using a MATLAB-based framework calibrated against TCAD outputs because of the substantial runtime requirements and difficulties with convergence in high-field SiC models. Simulations using forward and reverse bias were used to describe the electrical behavior of both devices across a range of gate-emitter voltages. Because SiC IGBTs have a larger critical electric field and fewer tail current effects, the results show that they have better switching efficiency, decreased leakage current, and improved breakdown capability. The combined modeling technique validates SiC's benefits over conventional Si-based counterparts in next-generation power electronics by highlighting its adaptability for high-frequency and thermally demanding situations.**

***Index Terms*—IGBT, Silicon Carbide (SiC), Power Electronics, TCAD, MATLAB Simulation, Forward I-V, Breakdown Voltage, Switching Losses.**


## I. Introduction

Insulated Gate Bipolar Transistors (IGBTs) play a vital role in the power electronics domain as it has a huge capacity to handle demands for high voltage and great efficiency. IGBTs offer a reliable solution for demanding applications such as electric vehicles, solar inverters, motor controllers, and industrial power systems by fusing the fast switching of MOSFETs with the robust current handling of BJTs. [4] The first invention of IGBTs started around the 1980s and significantly developed over time—from planar designs to advanced trench-gate architectures—improving current density and switching behavior.

Silicon (Si) is a common material in the semiconductor industry due to its mature processing technology and cost-effectiveness. Still, it presents limitations[5] under high-frequency, high-temperature, and high-voltage operating conditions. This led to the invention of new materials to replace traditional silicon. This made it possible to adopt silicon carbide as the alternating choice to overcome the disadvantages of silicon.

SiC IGBTs have progressed from initial trench-gate prototypes to commercial devices which is capable of handling more than 12kV [6], These were possible as a result of innovations such as charge storage layers and low-defect substrates. SiC enables IGBTs with lower switching losses, improved voltage blocking, and excellent high-temperature stability. These advantages position SiC-based IGBTs as ideal candidates for next-generation power systems that demand compactness, reliability, and high energy efficiency.

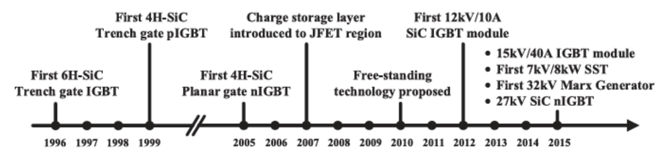


Fig. 1. Timeline of key advancements in SiC IGBT technology.

However, despite its promising physical features, simulating SiC devices in TCAD settings adds complexity. Full-scale TCAD analysis can be limited by issues such as carrier lifetime adjustment, interface trap modeling, and simulation convergence, particularly under high-field and high-temperature events, when compared to silicon-based devices. These limitations restrict the practicality of full-scale TCAD analysis for SiC, making it necessary to adopt complementary tools like MATLAB to effectively analyze and compare device performance.

## II. Device Structure and Material Properties

IGBTs are vertically constructed semiconductor devices. The adoption of this technique was mainly to support high voltages and current levels in power applications. The basic IGBT structure consists of many layers of n and p type of different doping levels: an n+ emitter region at the top, followed by a p-base (or body) region, an n-drift region for voltage blocking, and a heavily doped p+ collector at the bottom [4]. The gate terminal is located above the p-base, separated by a thin oxide layer, these thin oxide is made up of a polysilicon gate electrode. When a positive gate voltage is applied, an inversion channel is induced in the p-base, allowing electrons to flow from the emitter into the drift region. Simultaneously, holes are injected from the collector, contributing to conductivity modulation of the drift region and reducing on-state voltage drop.

Figure2 illustrates the cross-sectional view of a typical IGBT, along with its equivalent circuit and standard circuit symbol.

The structural architecture of Silicon (Si) and silicon carbide (SiC) IGBTs are similar, but the material properties lead to

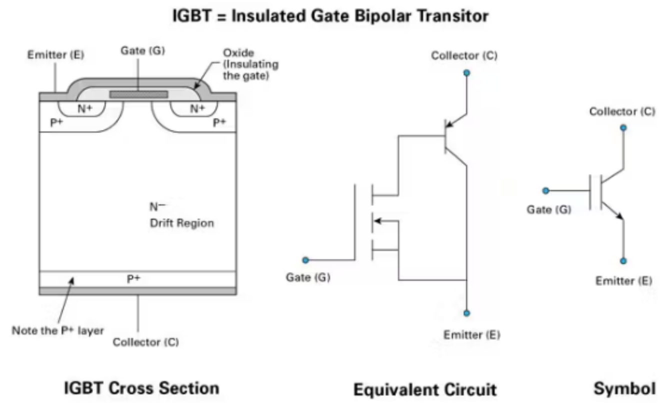


Fig. 2. IGBT cross section, equivalent circuit, and symbol representation.

distinct design optimizations. Silicon IGBTs usually require a thick and lightly doped drift region to endure high breakdown voltages. This increases the on-resistance and switching losses. In Comparison, SiC's drift region is much thinner and heavily doped compared to silicon without compromising the same breakdown strength. Hence, SiC IGBTs exhibit significantly lower conduction and switching losses, particularly at high voltages.

A comparison of key material parameters relevant to IGBT design is shown in Table I. These values highlight the intrinsic advantages of SiC for high-voltage, high-efficiency applications [6].

TABLE I
COMPARISON OF KEY MATERIAL PROPERTIES: SILICON VS SILICON CARBIDE

| **Property** | **Silicon (Si)** | **Silicon Carbide (SiC)** |
|---|---|---|
| Bandgap (eV) | 1.12 | 3.26 |
| Critical Electric Field (MV/cm) | 0.3 | 3.0 |
| Thermal Conductivity (W/cm·K) | 1.5 | 4.9 |
| Saturation Electron Velocity (cm/s) | $1 \times 10^7$ | $2 \times 10^7$ |
| Electron Mobility ($cm^2$/V·s) | 1350 | 1000 |
| Max Junction Temperature (°C) | 150 | 600 |

## III. Fabrication and Production

The fabrication of IGBTs follows the same standard CMOS-compatible processes, especially for silicon-based devices [4]. The typical process flow involves the formation of multiple epitaxial layers, precise ion implantation or diffusion for doping regions. Photolithography steps are used in entire process to define critical geometries, and thermal annealing is performed to activate dopants and repair implantation damage.

On the other side, SiC-based IGBTs presents several challenges during fabrication process. One of the preliminary issue is the growth of high-quality, defect-free SiC single crystals. First most criteria for SiC is that it as to be grown at extremely high temperatures (above 1500°C) using physical vapor transport (PVT), a slower and more complex process compared to silicon's Czochralski method. Moreover, the wafers are typically smaller (100–150 mm), more brittle, and prone to micropipe defects, which can severely affect device reliability and yield [6].

Doping processes also differs between Si and SiC . The diffusion techniques that used silicon will not suit for SiC, they are largely ineffective in SiC due to its low diffusivity at practical temperatures. SiC fabrication relies heavily on ion implantation, followed by high-temperature annealing (1600°C) to activate dopants. To support these requirement and to provide better yield, it uses of robust encapsulation and thermal management techniques during processing.

Current SiC device production faces additional limitations in terms of reproducibility, defect control, and manufacturing scalability. Sic prone to lower yields and higher failure rates compared to advanced silicon technologies because of its difficulty of high-temperature processing and the sensitivity to crystalline defects result in. These factors, combined with limited foundry support and higher wafer costs, contribute to SiC IGBTs being 5–10 times more expensive per unit than their silicon counterparts [6]. However, as crystal growth and fabrication technologies continue to improve, the cost gap is expected to narrow over time.

## IV. Device Operation Principles and Physics

Insulated Gate Bipolar Transistors (IGBTs) are hybrid semiconductor devices that integrate the gate-controlled behavior of a MOSFET with the current amplification of a BJT. When a positive gate-emitter voltage is applied, an inversion layer is formed in the p-base region beneath the gate oxide, allowing electrons from the n+ emitter to flow into the n drift region [4]. This MOSFET-like input stage enables voltage-controlled operation with high input impedance.

Once the device is turned on, holes are injected from the p+ collector into the drift region, while electrons flow from the emitter. This two-carrier injection results in *conductivity modulation* of the drift region—greatly reducing its resistance and enabling high current flow. The total collector current ($I_C$) is the sum of the electron and hole contributions:

$$I_C = I_n + I_p \tag{1}$$

where $I_n$ and $I_p$ represent the electron and hole current components, respectively. The voltage drop across the drift region is reduced due to the increased carrier concentration, resulting in low on-state power losses—one of the key advantages of IGBTs.

During switching, IGBTs exhibit distinct behaviors at turn-on and turn-off. The turn-on process is rapid due to the formation of the MOS channel. However, turn-off is slower, especially in silicon devices, because of the need to extract the stored holes in the drift region. This *tail current* increases turn-off losses and limits switching speed [5]. SiC IGBTs, on the other hand, benefit from shorter carrier lifetimes and faster recombination, leading to significantly reduced tail currents and faster switching transitions.

Temperature has a substantial effect on IGBT performance. In silicon devices, increased temperature can enhance carrier generation but also raise the risk of thermal runaway due to lower breakdown strength and poor heat dissipation. In contrast, SiC IGBTs demonstrate excellent thermal stability due to their wide bandgap, higher thermal conductivity, and lower intrinsic carrier concentration [6]. This allows reliable operation at junction temperatures exceeding 200°C, whereas traditional silicon devices are typically limited to 125–150°C.

Breakdown in IGBTs primarily occurs in the lightly doped n– drift region when the electric field exceeds the material's critical level. Silicon has a critical breakdown field of approximately 0.3 MV/cm, necessitating thick drift layers for high-voltage operation. SiC, with a much higher breakdown field of around 3 MV/cm, allows for thinner drift regions and more compact device structures, further reducing conduction losses. This property is a key advantage for high-voltage, high-frequency power electronics applications.

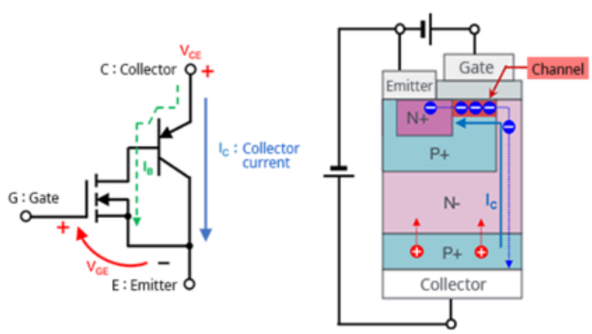


Fig. 3. Illustration of carrier injection and conductivity modulation in IGBT.

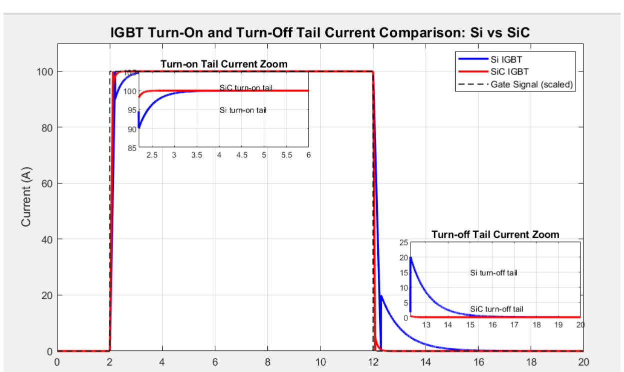


Fig. 4. Comparison of turn-off tail current behavior in Si and SiC IGBTs.

## V. Scaling Laws for the Device

The scaling of IGBTs, unlike digital transistors, is not primarily aimed at reducing feature sizes for speed, but rather at optimizing performance for higher voltage, current, frequency, and power density. As power devices are scaled, the underlying trade-offs between blocking capability, conduction losses, switching performance, and thermal limits must be carefully balanced.

**Voltage Scaling:** The breakdown voltage ($V_{BR}$) of an IGBT is predominantly determined by the thickness ($W$) and doping concentration ($N_D$) of the drift region. For silicon devices, sustaining higher voltages requires a thick and lightly doped n drift layer to avoid premature avalanche breakdown [4]. This results in increased on-state resistance and forward voltage drop. The relationship between drift region parameters and breakdown voltage is governed by:

$$V_{BR} \propto \frac{W^2}{\varepsilon \cdot N_D} \tag{2}$$

Here, $\varepsilon$ is the permittivity of the semiconductor material. In practice, this sets a hard limit on how thin the drift region can be for a given voltage rating. In contrast, Silicon Carbide (SiC), with a critical electric field approximately ten times higher than silicon, allows for drift layers that are both thinner and more heavily doped—enabling higher voltage operation with lower conduction losses.

**Current Scaling and Power Density:** The IGBT current capacity depends on the device's cross-sectional area of emitter and drift region . As current requirements increase, the chip size must scale accordingly. However, larger die area results in higher gate charge and parasitic capacitance, which degrade switching speed and efficiency. In monolithic integration, parallel cell arrays are used to distribute current evenly and mitigate localized heating [4]. The power density, defined as power handled per unit chip area, increases with improved material properties and thermal dissipation strategies.

Due to its lower on-resistance, better heat conduction SiC IGBTs inherently support higher power densities, their scaling is also thermally constrained. Doubling the power output from a die of the same size leads to a fourfold increase in power density, necessitating advanced cooling techniques, efficient packaging, and thermally stable materials.

**Frequency Scaling Limitations:** Scaling toward higher switching frequencies is critical for reducing the size of passive components in converters and inverters. However, switching losses increase with frequency due to energy dissipated during transition periods. The tail current observed during turn-off, especially in silicon IGBTs, arises from the slow recombination of stored carriers in the drift region [1]. SiC devices benefit from shorter carrier lifetimes and lower stored charge, allowing operation at much higher frequencies with reduced switching losses.

Miller capacitance and gate drive requirements is another main limiting factor is the . As device area scales for higher current, the gate charge ($Q_g$) also increases, requiring more powerful gate drivers and increasing dynamic power loss.

**Thermal Constraints on Scaling:** Another limit on device scaling is of thermal constraints. As current density increases,heat generation increases, mainly in the drift and junction regions. Silicon's relatively low thermal conductivity (1.5 W/cm·K) restricts its ability to dissipate heat, often need of large heatsinks and derating in high-temperature environments [5]. SiC, with a thermal conductivity of 4.9 W/cm·K, supports more aggressive scaling and operate at elevated junction at higher temperatures (up to 300°C) compared to Si, reducing the need for excessive thermal management infrastructure.

Nonetheless, scaling must be accompanied by innovations in packaging (e.g., double-sided cooling, low thermal resistance substrates) and interconnect design to maintain long-term reliability under thermomechanical stress.

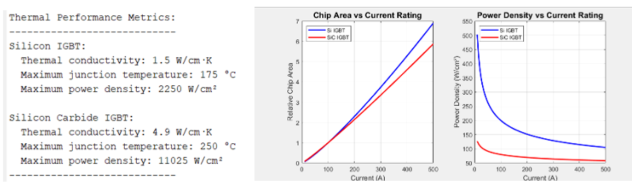


Fig. 5. Thermal performance comparison between Si and SiC IGBTs. Left: Relative chip area required vs. current rating. Right: Maximum achievable power density vs. current rating. SiC offers significantly higher thermal efficiency and compactness at higher currents.

## VI. Noise and Limitations

IGBTs has various drawbacks including switching noise, thermal behavior, and long-term reliability [1]. Switching noise is basically due to high di/dt and introduction to parasitic inductance, leading to voltage overshoot and EMI. Thermal noise becomes more relevant at high junction temperatures, particularly in silicon-based devices.

Si IGBTs are prone to cosmic-ray which inturn leads to failures or error in device at high voltage and altitude, while SiC IGBTs offer improved immunity but still require caution in critical applications [1]. However, SiC devices typically have lower short-circuit withstand times due to faster switching and reduced thermal capacity.

One of the major concerns in fabricating SiC devices is gate oxide degradation [1]. The $SiC/SiO_2$ interface has a higher density of interface traps compared to that of silicon, which results in shifting threshold voltage generally know as body effect , mobility degradation, and switching losses increases over time.

TABLE II
Comparison of Key Limitations in Si vs. SiC IGBTs

| Feature | Si IGBT | SiC IGBT |
| --- | --- | --- |
| Switching Noise | Moderate | Higher (due to faster dv/dt) |
| Cosmic Ray Failure | More susceptible | Lower rate |
| Short-Circuit Tolerance | Higher | Lower |
| Gate Oxide Reliability | Stable | Sensitive to traps |
| Interface Trap Density | Low | High |
| Thermal Noise Sensitivity | Higher | Lower |

## VII. Current Application

IGBTs has its application in a wide range of high-power electronics applications due to their efficiency and high-voltage switching capabilities [3]. Traditional silicon IGBTs are commonly found in industrial motor drives, HVAC systems, uninterruptible power supplies (UPS), and general-purpose inverters, where cost-effectiveness and mature manufacturing are priorities.

In electric vehicles (EVs), IGBTs are central to traction inverter systems, which require fast switching, low conduction loss, and compact packaging. While older systems relied heavily on Si IGBTs, SiC IGBTs are increasingly favored due to their ability to switch at higher frequencies, reduce thermal stress, and shrink passive components—resulting in greater power density and extended vehicle range[1].

Renewable energy systems, particularly photovoltaic (PV) inverters and wind turbine converters, benefit from the high efficiency of SiC devices in DC–AC conversion [5]. SiC IGBTs reduce losses at high switching speeds, making them well-suited for grid-tied systems and maximum power point tracking (MPPT) controllers.

IGBTs are used in multi-level converters and solid-state circuit breakers in heavy-duty power infrastructure, likely high-voltage direct current (HVDC) transmission and railway systems. SiC-based devices provides better thermal stability and reduced cooling requirements, which are critical in space- and reliability-constrained environments.

Continuous power supplies is also another plus which improved Sic IGBTs efficiency and reduces switching losses, and smaller magnetic components, enabling more compact designs for data centers and critical systems.

TABLE III
Application-Specific Suitability of Si and SiC IGBTs

| Application | Si IGBT | SiC IGBT |
| --- | --- | --- |
| EV Traction Inverters | Good | Excellent (high power density) |
| Solar/Wind Converters | Moderate | Excellent (high frequency, low loss) |
| Industrial Drives | Excellent | Moderate (in low-end systems) |
| HVDC Systems | Adequate | Preferred (high voltage, thermal) |
| Railway Traction | Good | Excellent (compact, efficient) |
| UPS Systems | Good | Excellent (thermal, compact) |

## VIII. TCAD Simulation and Results

This section presents simulation results obtained using Silvaco ATLAS. Planar IGBT structures were modeled for both silicon and silicon carbide, and forward and reverse characteristics were simulated under steady-state (DC) conditions[2] All simulations used identical geometric and doping structures where applicable.

*Although the I-V curves follow expected trends, the absolute current values—particularly for SiC—remained lower than* *expected (in the microampere range). This is likely due to conservative mobility, lifetime, and numerical model settings within TCAD. The comparative behavior, however, remains valid.*

### *A. Device Structure in TCAD*

Both devices were designed using a planar architecture consisting of an $n^+$ emitter, p-base, $n^-$ drift region, and $p^+$ collector. A polysilicon gate sits above the p-base, separated by a thin oxide layer. The SiC model used 4H-SiC for active regions. Doping profiles were carefully defined using Gaussian distributions to replicate real-world profiles.

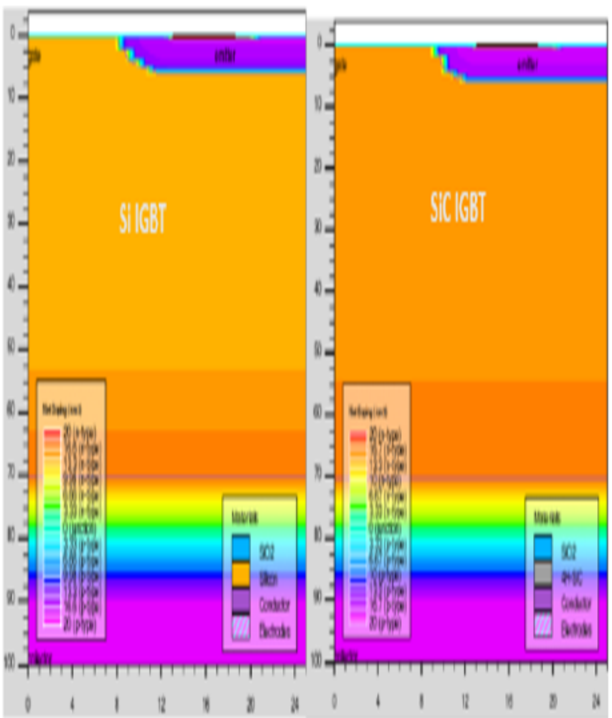


Fig. 6. TCAD structure and doping profile of Si and SiC IGBTs. Both follow similar vertical architecture.

*SiC's higher breakdown field enables a thinner and more highly doped drift region, leading to superior blocking and conduction performance.*

### *B. Forward Characteristics*

Forward I-V characteristics were obtained by sweeping $V_{CE}$ from 0 to 20V for Si and up to 40V for SiC at different gate voltages [3]. For Si IGBT, $V_{GE}$ = 5V and 10V were used; for SiC, $V_{GE}$ = 10V and 15V.

*SiC IGBTs show a sharper turn-on at lower collector-emitter voltages and support higher current density, making them more suitable for fast-switching and high-efficiency applications.*

### *C. Reverse Characteristics*

Reverse I-V characteristics were simulated with negative collector bias. The Si IGBT was biased from 0 to –1000V, while the SiC IGBT was biased up to –20V due to higher field strength. Both devices remained in blocking mode until breakdown [3].

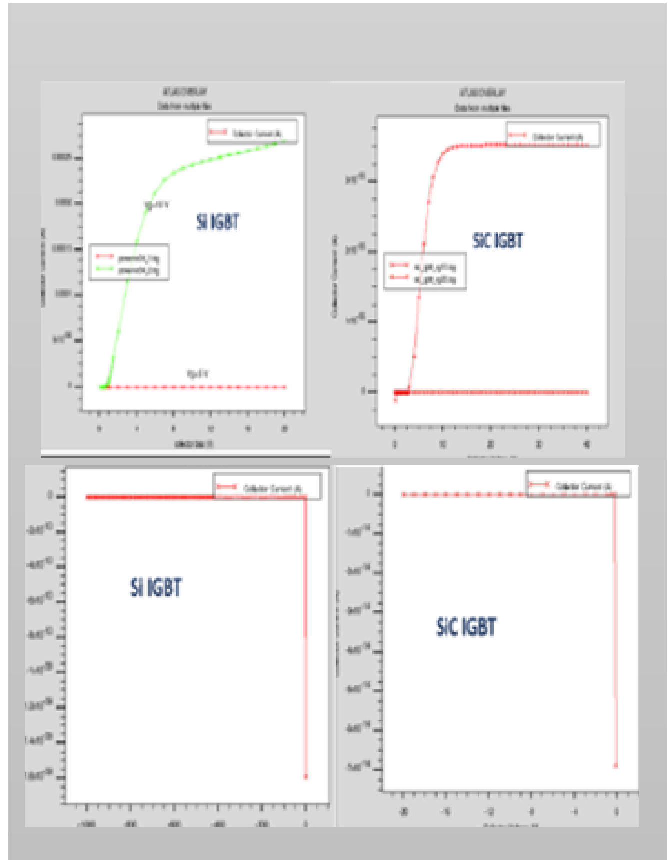


Fig. 7. Forward and Reverse I-V characteristics of Si and SiC IGBTs. SiC shows significantly lower leakage current.

*SiC IGBTs exhibit reverse leakage currents several orders of magnitude lower than silicon, improving efficiency and thermal reliability in blocking mode.*

### *D. Observations*

The forward and reverse characteristics analysis proves that Silicon based IGBTs Exhibit superior efficiency than conventional silicon-based devices, exhibiting enhanced electrical performance. Despite being associated with higher simulation complexity and fabrication costs, the benefits of enhanced conduction efficiency, lower leakage, and better scalability make SiC best option for high-voltage, high-efficiency power electronic applications.

### *F. Continued Analysis Using MATLAB*

In order to further anlayse the charcateristics of SiC IGBT we extended the TCAD simulation results and analyze higher voltage and thermal effects, further modeling was carried out in MATLAB. The same doping profiles and structure definitions were used to ensure consistency across platforms.

Forward and reverse characteristics were simulated across multiple gate voltages ($V_{GE}$ = 0–20V), including breakdown and thermal effects. The results confirmed that SiC IGBTs exhibited higher breakdown voltage, faster turn-on, and minimal self-heating compared to their silicon counterparts.

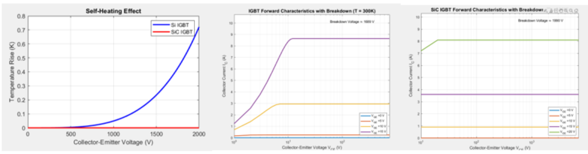


Fig. 8. MATLAB-based IGBT analysis showing forward I-V curves, breakdown voltage, and self-heating comparison for Si and SiC devices.

*These simulations further validate SiC IGBT superiority in high-voltage, high-efficiency, and thermally constrained environments.*

## IX. Discussion and Future Trends

Silicon Carbide(SiC) IGBTs have significant advantages compared to Silicon based IGBT, the advantages includes but not limited to faster switching, greater blocking voltage, and higher thermal performance. However their traditional architectures still impose some design constraints. Researchers have developed a number of sophisticated topologies to get around these, such as Bidirectional IGBT (BD-IGBT), Schottky Contact IGBT (SC-IGBT), Backside npn-IGBT, Diode Clamped Shield IGBT (DCS-IGBT), and Trench Cluster IGBT (TC-IGBT) [1]. These new designs allows to reduce turn-off energy losses (E¡sub¿off¡/sub¿) and forward voltage drop (V¡sub¿f¡/sub¿), but they have trade-offs that keep designers stumped.

Deployment of SiC technology is rapidly increasing across sectors such as EVs, renewables, and industrial inverters, driven by system-level efficiency gains despiteof its higher device costs. Meanwhile, wide-bandgap competitors like GaN and $Ga_2O_3$ are emerging, with GaN suited for high-frequency low-voltage applications and $Ga_2O_3$ showing potential for ultra-high voltage but still facing reliability barriers.

*Future research will focus on optimizing SiC structures and reducing fabrication cost while balancing trade-offs in conduction and switching behavior to further expand deployment in power-critical domains.*

## X. Conclusion

This project presented a comparative study of silicon (Si) and silicon carbide (SiC) IGBTs using both TCAD simulations and MATLAB-based analysis [4]. Device structures were designed and simulated to evaluate forward and reverse characteristics, breakdown performance, and thermal behavior. Initially, the Silvaco Atlas TCAS simulation tool was used to generate device structure based on varying doping levels, mesh, and other important parameters and simulated to evaluate initial trends and IV characteristics, and Matlab was used for extended analysis.

The result proves theoretically the benefits of using SIC-based IGBT compared to Si IGBT irrespective of its challenges in fabrication and its cost for manufacturing [1]. The study underlines the importance of structural innovation in attaining the full potential of SiC materials. With advances in device engineering and material processing, SiC IGBTs are set to be the core of future power electronics.

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