

**COMPARISON OF WIDE-BANDGAP
SEMICONDUCTORS FOR
POWER ELECTRONICS APPLICATIONS**

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Comparison of Wide-Bandgap Semiconductors for Power Electronics Applications

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ACRONYMS AND ABBREVIATIONS

BJT	bipolar junction transistor
EMI	electromagnetic interference
EV	electric vehicle
FACTS	flexible ac transmission system
GTO	gate turn-off thyristor
HEV	hybrid electric vehicle
HVDC	high voltage dc (transmission system)
IGBT	insulated gate bipolar transistor
MCT	mos-controlled thyristor
MOSFET	metal oxide semiconductor field effect transistor
MTO	MOS turn-off thyristor
PiN	(same as) pn junction diode
Si	silicon
SiC	silicon carbide
VAR	reactive power
WBG	wide bandgap

ABSTRACT

Recent developmental advances have allowed silicon (Si) semiconductor technology to approach the theoretical limits of the Si material; however, power device requirements for many applications are at a point that the present Si-based power devices cannot handle. The requirements include higher blocking voltages, switching frequencies, efficiency, and reliability. To overcome these limitations, new semiconductor materials for power device applications are needed. For high power requirements, wide-bandgap semiconductors like silicon carbide (SiC), gallium nitride (GaN), and diamond, with their superior electrical properties, are likely candidates to replace Si in the near future. This report compares wide-bandgap semiconductors with respect to their promise and applicability for power applications and predicts the future of power device semiconductor materials.

1. INTRODUCTION

Over the past decade, several changes have drawn more attention to electric and hybrid electric vehicles. Increasing oil prices and worries about a diminishing oil supply are creating a need for alternatives to traditional gasoline and diesel engines. Consequently, more and more companies in the transportation industry are introducing electric or hybrid electric vehicles. In addition, the military is ready for all-electric warships and more-electric fighter planes, while various industries are gearing up to convert from all gasoline or all diesel vehicles to all electric or hybrid electric ones. The hurried demand for electric or hybrid electric vehicles (EV/HEV) enhances the significance of the power electronics in these vehicles. Furthermore, the present silicon (Si) technology is reaching the material's theoretical limits and cannot meet all the requirements of the transportation industry. New semiconductor materials called wide-bandgap (WBG) semiconductors, such as silicon carbide (SiC), gallium nitride (GaN), and diamond, are possible candidates for replacing Si in transportation applications. The next sections will discuss why wide-bandgap semiconductor-based power devices are required for transportation applications.

1.1 TRANSPORTATION REQUIREMENTS

Power electronics converters for transportation applications have to comply with strict requirements because of space and weight limitations and extremely harsh operating conditions. In a vehicle, there is limited space for the electrical and/or mechanical units; therefore, all the units have to be compact, occupying as little volume as possible. Moreover, they are expected to be lightweight so that the weight of the vehicle stays constrained. A lighter vehicle means less load on the engine and/or motor, faster acceleration, and higher efficiency. Higher efficiency results in less fuel or battery charge consumption. Finally, converters have to be able to function at high temperatures for long periods of time without failure— i.e., they have to be highly reliable, and they must be available at a reasonable price.

In summary, the general requirements for any power converter in a transportation application are compactness, lightweight, high power density, high efficiency, and high reliability under harsh conditions.

1.2 WHY NOT SILICON?

All vehicles contain power converters used as rectifiers, power supplies, battery chargers, etc. Separating HEVs from conventional vehicles, however, is the electrical traction drive. This drive, as the vital part of an HEV, carries the most power among all the HEV power converters.

The electronics in a vehicle must continue to operate under harsh conditions, with the most detrimental condition being high temperature. Since heat is generated by the engine, the motor, the semiconductor device losses, and the environment, the electronics have to be cooled so that they will continue to perform. The maximum junction temperature limit for most Si electronics is 150°C; therefore, the temperature of the Si chips and power devices should remain under this value. Even then, the variation in the electrical characteristics of Si devices with temperature and time remains a substantial reliability issue.

Three standard options for cooling power devices are natural air, forced air, or water-cooled heatsinks. However, as the temperature of the environment increases, the capacity of the cooling system decreases. The power rating of the converter determines the type of heatsink to use. For low-power converters, bulky, natural-air heatsinks are sufficient, whereas high-power converters require the more expensive, but smaller liquid-cooled heatsinks. However, the latter require a pump to circulate the coolant as well as a radiator and a fan to cool it. A heatsink, typically, occupies one-third of the total volume of a power converter and usually weighs more than the converter itself. Building electronics that can withstand higher temperatures is one way of decreasing the cooling requirements, size, and cost of the converter, but Si devices have reached their theoretical temperature limits.

A major source of heat affecting vehicular electronics is the heat generated by the semiconductors themselves. These power devices have losses associated with conducting and switching high currents. The amount of loss depends on the type of power devices utilized. In high-power transportation applications like the traction drive, insulated gate bipolar transistors (IGBT) and PiN diodes are presently used. Both are bipolar devices and have higher losses compared to their unipolar counterparts, such as metal oxide semiconductor field effect transistors (MOSFET) and Schottky diodes. Although, these unipolar devices have superior properties compared to bipolar devices, they are not used in traction drives because they do not exist at high power ratings. Building higher-voltage-rating MOSFETs and Schottky diodes would not be feasible because as the breakdown voltage increases, the device requires a large silicon die area, and this results in reduced manufacturing yields and increased costs. For higher breakdown voltages, a material with a higher electric breakdown field is required.

The switching frequency of the devices is also limited because of the heat generated by the devices, primarily the switching losses. Higher-frequency operation is preferred because of filtering requirements, less audible noise, and smaller passive components. The outputs of high-frequency power converters are smoother, and a small filter would be sufficient to filter the harmonics. Additionally, with high frequency,

the size of the passive components decreases, so there is an overall gain in size and weight. Moreover, with higher frequency, the converters could work at an inaudible frequency range, which would be comfortable for the user.

1.3 WHY WBG SEMICONDUCTORS?

As seen above, increasing the effectiveness of Si to meet the needs of the transportation industry is not viable because it has reached its theoretical limits. However, it is already proven that even the first WBG semiconductor-based (SiC-based) power devices surpass Si's theoretical limits. WBG semiconductor power devices, with their superior characteristics, offer great performance improvements and can work in harsh environments where Si power devices cannot function. Some of the advantages compared with Si based power devices are as follows:

- WBG semiconductor-based unipolar devices are thinner and have lower on-resistances. Lower R_{on} also means lower conduction losses; therefore, higher overall converter efficiency is attainable.
- WBG semiconductor-based power devices have higher breakdown voltages because of their higher electric breakdown field; thus, while Si Schottky diodes are commercially available typically at voltages lower than 300 V, the first commercial SiC Schottky diodes are already rated at 600 V.
- WBG devices have a higher thermal conductivity (4.9 W/cm-K for SiC and 22 W/cm-K for diamond, as opposed to 1.5 W/cm-K for Si). Therefore, WBG-based power devices have a lower junction-to-case thermal resistance, R_{th-jc} . This means heat is more easily transferred out of the device, and thus the device temperature increase is slower. GaN is an exception in this case.
- WBG semiconductor-based power devices can operate at high temperatures. The literature notes operation of SiC devices up to 600°C. Si devices, on the other hand, can operate at a maximum junction temperature of only 150°C.
- Forward and reverse characteristics of WBG semiconductor-based power devices vary only slightly with temperature and time; therefore, they are more reliable.
- WBG semiconductor-based bipolar devices have excellent reverse recovery characteristics. With less reverse recovery current, switching losses and electromagnetic interference (EMI) are reduced, and there is less or no need for snubbers. As a result, there is no need to use soft-switching techniques to reduce switching losses.
- Because of low switching losses, WBG semiconductor-based devices can operate at higher frequencies (>20 kHz) not possible with Si-based devices in power levels of more than a few tens of kilowatts.

Although WBG semiconductor-based power devices have these advantages compared with Si, the present disadvantages limit their widespread use. Some of these disadvantages are

- low processing yield because of defects for SiC and processing problems for GaN and diamond;
- high cost;
- limited availability, with only SiC Schottky diodes at relatively low power are commercially available; and
- the need for high-temperature packaging techniques that have not yet been developed.

These drawbacks are to be expected, given that WBG semiconductor technology has not yet matured.

1.4 OTHER WBG SEMICONDUCTOR APPLICATION AREAS

Some power electronics application areas will benefit from WBG semiconductor-based power device development more than others. These areas are aerospace, power systems, and transportation. Since the main focus of this study is the transportation area, the impact of WBG semiconductors on the other two areas will be summarized only briefly.

1.4.1 Aerospace Applications

Some of the requirements for a power converter in a spacecraft are small mass, small volume, and high/low temperature operation. The high-temperature operation capability and lower losses of WBG semiconductor-based power devices would provide mass and volume advantages in these applications. In addition, WBG semiconductor-based power devices are radiation-hard, which means that they are less susceptible to the damaging effects of radiation. Therefore, use of these devices would allow for less radiation shielding, which also results in a gain in mass.

1.4.2 Power Systems Applications

With the recent advances, power electronics interfaces to power systems like static transfer switches, dynamic voltage restorers, static VAR compensators, high voltage dc (HVDC) transmission, and flexible ac transmission systems (FACTS) are getting more and more attention. Presently, there are no high-voltage/high-current single-Si devices available for these applications. Instead, lower-rated devices are put in series and parallel. With the high voltage capability of WBG semiconductors, in the near future it will be possible to replace many Si devices in series and/or in parallel by one WBG semiconductor-based power device. This will decrease the device count and the size of these converters. If single power devices can be used, balancing resistors and capacitors can be discarded, saving even more space and avoiding

voltage balancing and/or current-sharing problems. Moreover, because of the high -temperature operability and the lower losses of WBG semiconductor-based power devices, cooling system size will also decrease. Finally, with less reverse recovery, fewer or no snubbers will be required.

2. PROPERTIES OF WIDE-BANDGAP SEMICONDUCTORS

Wide-bandgap semiconductor materials have superior electrical characteristics compared with Si. Some of these characteristics for the most popular WBG semiconductors and Si are shown in Table 2.1.

Table 2.1. Physical characteristics of Si and the major WBG semiconductors

Property	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap, E_g (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric constant, ϵ_r^a	11.9	13.1	9.66	10.1	9	5.5
Electric breakdown field, E_c (kV/cm)	300	400	2,500	2,200	2,000	10,000
Electron mobility, μ_n (cm ² /V·s)	1,500	8,500	500 80	1,000	1,250	2,200
Hole mobility, μ_p (cm ² /V·s)	600	400	101	115	850	850
Thermal conductivity, λ (W/cm·K)	1.5	0.46	4.9	4.9	1.3	22
Saturated electron drift velocity, v_{sat} ($\times 10^7$ cm/s)	1	1	2	2	2.2	2.7

^a $\epsilon = \epsilon_r \cdot \epsilon_o$ where $\epsilon_o = 8.85 \times 10^{-14}$ F/cm.

Source: Refs. [1]–[3].

Presently, two SiC polytypes are popular in SiC research: 6H-SiC and 4H-SiC. Before the introduction of 4H-SiC wafers in 1994, 6H-SiC was the dominant polytype. Since then, both of these polytypes have been used in research, but recently 4H-SiC has become the more dominant polytype. Although both of these polytypes have similar properties, 4H-SiC is preferred over 6H-SiC because the mobilities in 4H-SiC are identical along the two planes of the semiconductor, whereas 6H-SiC exhibits anisotropy, which means the mobilities of the material in the two planes are not the same.

The most important properties of the WBG semiconductors are explained in the following sections.

2.1 WIDE BANDGAP

In a solid, electrons exist at energy levels that combine to form energy bands. A simplified energy band diagram is shown in Fig. 2.1. The top band is called the conduction band, and the next lower one is called the valence band. The region between the valence band and the conduction band is called the forbidden band, where, ideally, no electrons exist. (There are other bands below the valence band, but these are not important for this study.)

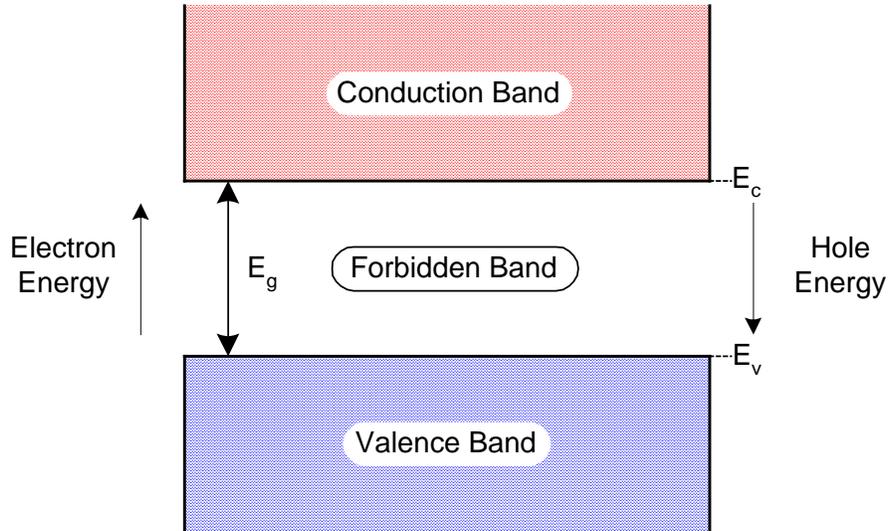


Fig. 2.1. Simplified energy band diagram of a semiconductor.

If the electrons in the valence band are excited externally, they can move to the conduction band. In the valence band, they have energy of E_v . In order to move to the conduction band, they need an $E_g = E_c - E_v$ amount of energy, where E_g is the bandgap.

For a conductor like copper, the forbidden band does not exist, and the energy bands overlap. For an insulator, on the other hand, this band is so wide that the electrons need a lot of energy to move from the valence band to the conduction band. For semiconductors, the gap of the forbidden band is smaller than for an insulator.

Some semiconductors are classified as “wide-bandgap” semiconductors because of their wider bandgap. Silicon has a bandgap of 1.12 eV and is not considered a wide-bandgap semiconductor. The bandgaps of WBG semiconductors are about three times or more that of Si as can be seen in Table 2.1. Among these semiconductors, diamond has the widest bandgap; consequently, it also has the highest electric breakdown field. SiC polytypes and GaN have similar bandgap and electric field values, which are significantly higher than those of Si and GaAs.

WBG semiconductors have the advantage of high-temperature operation and more radiation hardening. As the temperature increases, the thermal energy of the electrons in the valence band increases. At a certain temperature, they have sufficient energy to move to the conduction band. This is an uncontrolled conduction that must be avoided. The temperature at which this happens is around 150°C for Si. For WBG semiconductors, the bandgap energy is higher; therefore, electrons in the valence band need more

thermal energy to move to the conduction band. This intrinsic temperature for SiC is around 900°C, and this value is much higher for diamond.

The wider the bandgap is, the higher the temperatures at which power devices can operate; therefore, diamond power devices have the capability to operate at higher ambient temperatures than power devices based on other WBG materials.

The above reasoning is also true for radiation hardening. Radiation energy can also excite an electron like the thermal energy and make it move to the conduction band.

As a result of the wide bandgap, devices built with WBG semiconductors can withstand more heat and radiation without losing their electrical characteristics. They can be used in extreme conditions where Si-based devices cannot be used.

2.2 HIGH ELECTRIC BREAKDOWN FIELD

Wider bandgap means a larger electric breakdown field (E_c). A higher electric breakdown field results in power devices with higher breakdown voltages. With a high electric breakdown field, much higher doping levels can be achieved; thus, device layers can be made thinner at the same breakdown voltage levels. The resulting WBG-semiconductor-based power devices are thinner than their Si-based counterparts and have smaller drift region resistances.

For example, the breakdown voltage (V_B) of a pn diode is expressed in Ref. [1] as follows:

$$V_B \approx \frac{\epsilon_r E_c^2}{2qN_d}, \quad (2.1)$$

where q is the charge of an electron and N_d is the doping density.

Using the semiconductor parameters in Table 2.1, this expression can be simplified as follows:

$$V_B^{Si} \approx \frac{2.96 \times 10^{17}}{N_d}, \quad (2.2)$$

$$V_B^{4H-SiC} \approx \frac{135 \times 10^{17}}{N_d}, \quad (2.3)$$

$$V_B^{6H-SiC} \approx \frac{166.7 \times 10^{17}}{N_d}, \quad (2.4)$$

$$V_B^{GaN} \approx \frac{99.4 \times 10^{17}}{N_d}, \quad (2.5)$$

$$V_B^{diamond} \approx \frac{1519.2 \times 10^{17}}{N_d} \quad (2.6)$$

Using the above equations, the breakdown voltages of diodes made of the materials listed in Table 2.1 were calculated assuming the same doping density, and the results are plotted in Fig. 2.2 with the breakdown voltages normalized to that of a Si diode. As seen in this figure, the theoretical breakdown voltage of a diamond diode is 514 times more than that of a Si diode. For 6H-SiC, 4H-SiC, and GaN, this number is 56, 46, and 34 times, respectively, that of a Si diode. With a higher electric breakdown field, more doping can be applied to the material, further increasing the gap between the upper breakdown voltage limits of WBG semiconductors compared to Si.

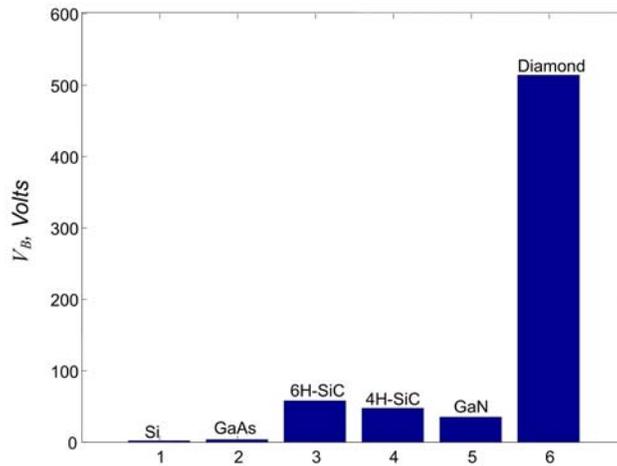


Fig. 2.2. Maximum breakdown voltage of a power device at the same doping density normalized to Si.

Another consequence of the higher electric breakdown field and the higher doping density is the width reduction in the drift region. The required width of the drift region can be expressed as [4]:

$$W(V_B) \approx \frac{2V_B}{E_c} \quad (2.7)$$

Using the electric breakdown field values for Si and 4H-SiC from Table 2.1, the drift thickness of the drift region for these two semiconductors are found as

$$W_d^{Si} = 6.67 \times 10^{-6} V_B, \quad (2.8)$$

$$W_d^{4H-SiC} = 0.91 \times 10^{-6} V_B, \quad (2.9)$$

$$W_d^{6H-SiC} = 0.81 \times 10^{-6} V_B, \quad (2.10)$$

$$W_d^{GaN} = 1 \times 10^{-6} V_B, \quad (2.11)$$

$$W_d^{diamond} = 0.2 \times 10^{-6} V_B. \quad (2.12)$$

It can be concluded from Eqs. (2.8), (2.9), and (2.12) that for the same V_B , a 4H-SiC pn diode is 7 times, and a diamond pn diode is 33 times, thinner than their Si counterparts.

The width of the drift region was calculated for all the semiconductors in Table 2.1, and the results are plotted in Fig. 2.3 for a breakdown voltage range of 100 to 10,000 V. Diamond, as expected, requires the minimum width, while 6H-SiC, 4H-SiC, and GaN follow diamond in the order of increasing widths.

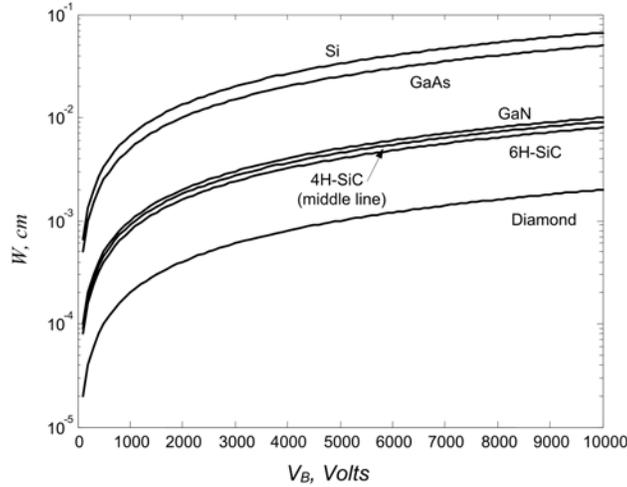


Fig. 2.3. Width of the drift region for each material at different breakdown voltages.

Compared to these, Si requires a drift region approximately 10 times thicker.

The last device parameter to be calculated from the properties in Table 2.1 is the on-resistance of the drift region for unipolar devices, which is given by Eq. (2.13) [3]:

$$R_{on,sp} = \frac{4 \left(V_B^2 \right)}{\epsilon_s (E_c)^3 \mu_n}, \quad (2.13)$$

where V_B is the breakdown voltage,

ϵ_s is the dielectric constant,

E_c is the electric breakdown field, and

μ_n is the electron mobility.

The calculation results for on-resistance are plotted in Fig. 2.4 with respect to the breakdown voltage of the device. Again, diamond shows the best performance, with 4H-SiC, GaN, and 6H-SiC following in increasing order of resistance. The on-resistance of the drift region for the Si device is approximately 10 times more than for the SiC polytypes and GaN devices. As the breakdown voltage increases, more doping can be applied to WBG semiconductors than to Si, so the specific on-resistance ratio between Si and WBG semiconductors increases further. Note that contact resistance and/or channel resistance must also be considered when on-resistance for the devices is calculated. These two resistances are dominant at low breakdown voltages (<1 kV) but can be neglected at high breakdown voltages; therefore, Eq. (2.13) is a better approximation of on-resistance for higher-breakdown-voltage devices.

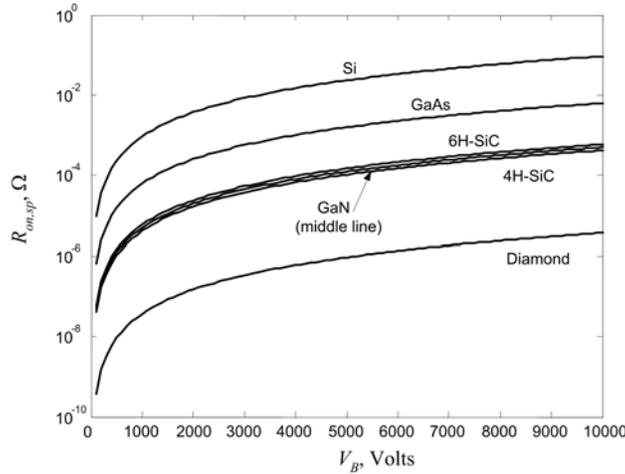


Fig. 2.4. Resistance of the drift region for each material at different breakdown voltages.

The storage of the minority carriers (Q_{rr} in diodes) is also reduced because of the thinner layers. Therefore, reverse recovery losses of WBG semiconductor-based diodes decrease, and this decrease allows higher-frequency operation.

2.3 HIGH SATURATED DRIFT VELOCITY

The high-frequency switching capability of a semiconductor material is directly proportional to its drift velocity. The drift velocities of WBG materials are more than twice the drift velocity of Si (1×10^7); therefore, it is expected that WBG semiconductor-based power devices could be switched at higher frequencies than their Si counterparts. Moreover, higher drift velocity allows charge in the depletion region of a diode to be removed faster; therefore, the reverse recovery current of WBG semiconductor-based diodes is smaller, and the reverse recovery time is shorter.

2.4 HIGH THERMAL STABILITY

As explained earlier, because of the wide bandgap, WBG semiconductor-based devices can operate at high temperatures. In addition to this, SiC has another thermal advantage not mentioned previously — its high thermal conductivity. As seen in Eq. (2.14), junction-to-case thermal resistance, R_{th-jc} , is inversely proportional to the thermal conductivity.

$$R_{th-jc} = \frac{d}{\lambda A}, \quad (2.14)$$

where λ is the thermal conductivity, d is the length, and A is the cross-sectional area. Higher thermal conductivity means lower R_{th-jc} , which means that heat generated in a SiC-based device can more easily be transmitted to the case, heatsink, and then to the ambient; thus, the material conducts heat to its surroundings easily, and the device temperature increases more slowly. For higher-temperature operation, this is a critical property of the material. As seen in Table 2.1, diamond still leads the other materials by at least a factor of 5, with the SiC polytypes as the next best materials. GaN has the worst thermal conductivity — even lower than that of Si.

2.5 FIGURE OF MERIT COMPARISON

For a comparison of the possible power electronics performances of these materials, some commonly known figures of merit are listed in Table 2.2. In this table, the numbers have been normalized with respect to Si; a larger number represents a material's better performance in the corresponding category. The figure of merit values for diamond are at least 40–50 times more than those for any other semiconductor in the table. SiC polytypes and GaN have similar figures of merit, which implies similar performances.

Silicon and GaAs have the poorest performance among the semiconductor materials listed in Tables 2.1 and 2.2, and diamond has the best electrical characteristics. Much of the present power device research is focused on SiC. In the next sections, diamond, GaN, and SiC will be compared and contrasted with each other.

Table 2.2. Main figures of merit for WBG semiconductors compared with Si

	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
JFM	1.0	1.8	277.8	215.1	215.1	81,000
BFM	1.0	14.8	125.3	223.1	186.7	25,106
FSFM	1.0	11.4	30.5	61.2	65.0	3,595
BSFM	1.0	1.6	13.1	12.9	52.5	2,402
FPFM	1.0	3.6	48.3	56.0	30.4	1,476
FTFM	1.0	40.7	1,470.5	3,424.8	1,973.6	5,304,459
BPFM	1.0	0.9	57.3	35.4	10.7	594
BTFM	1.0	1.4	748.9	458.1	560.5	1,426,711

JFM : Johnson's figure of merit, a measure of the ultimate high-frequency capability of the material

BFM : Baliga's figure of merit, a measure of the specific on-resistance of the drift region of a vertical field effect transistor (FET)

FSFM : FET switching speed figure of merit

BSFM : Bipolar switching speed figure of merit

FPFM : FET power-handling-capacity figure of merit

FTFM : FET power-switching product

BPFM : Bipolar power handling capacity figure of merit

BTFM : Bipolar power switching product

Source: Ref. [2].

3. SILICON CARBIDE

Silicon carbide technology is the most mature among WBG semiconductor technologies. It has advanced greatly since 1987 with the foundation of CREE, Inc., which is the major supplier of SiC wafers. Pending material processing problems like micropipes and screw dislocations limit the die size, but these problems have not stopped the commercialization of the first SiC power devices, Schottky diodes with twice the blocking voltage (600 V) of Si Schottky diodes (300 V).

Apart from the commercial devices, many other SiC power devices in the kilovolt range with reduced on-resistances are being investigated; these include 4H-SiC and 6H-SiC pn diodes, Schottky diodes, IGBTs, thyristors, BJTs, various MOSFETs, GTOs, MCTs, and MTOs. Except for some of the diodes, these devices are all experimental devices with very low current ratings.

3.1 COMPARISON OF COMMERCIAL SiC SCHOTTKY DIODES WITH SI PN DIODES

Silicon carbide Schottky diodes used in this study are rated at 300 V and 10 A and have been obtained directly from Infineon AG [5] in Germany. The next two subsections describe testing, characterization, and loss modeling of Si pn and SiC Schottky diodes and compare the two. The main reason for comparing pn diodes with Schottky diodes is because SiC Schottky diodes are projected to replace Si pn diodes in the 300- to 1200-V range.

3.1.1 Conduction Losses

The circuit shown in Fig. 3.1 is set up with test diodes in a temperature-controlled oven to obtain the I - V characteristics of the diodes at different operating temperatures. The dc voltage supply is varied, and the diode forward voltage and current are measured at different load currents and several temperature values of up to 250°C (the temperature limit of the oven). The I - V curves obtained as a result of this test for both Si pn and SiC Schottky diodes are shown in Fig. 3.2; it can be seen that the forward voltage of the SiC diode is higher than that of the Si diode. This is expected because of SiC's wider bandgap. Another difference between these two diodes is their high-temperature behavior. As the temperature increases, the forward characteristics of the Si diode change severely, while those of the SiC diode stay confined to a narrow region. Note that the pn diode (negative) and the Schottky diode (positive) have different polarity temperature coefficients for on-state resistance; that is why the slope of the curve at higher currents is increasing in the Si diode case and decreasing in the SiC diode case with the temperature increase.

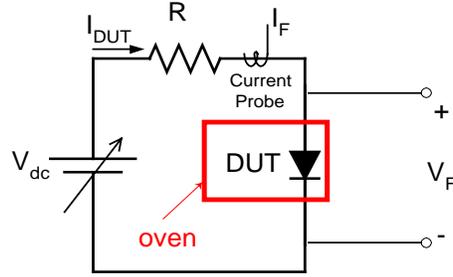


Fig. 3.1. *I-V* characterization circuit.

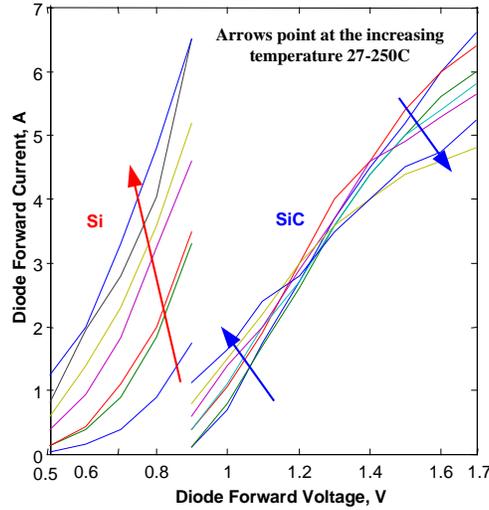


Fig. 3.2. Experimental *I-V* characteristics of the Si and SiC diodes in an operating temperature range of 27°C to 250°C.

If a line is drawn along the linear high-current portion of the *I-V* curves extending to the *x*-axis, the intercept on the *x*-axis is V_D , and the slope of this line is I/R_D . The parameters V_D and R_D thus obtained are plotted in Fig. 3.3. As mentioned previously, because of different temperature coefficients, R_D of the Si diode is decreasing and that of the SiC diode is increasing. For low temperatures, the SiC on-resistance is lower than that of Si's. In addition to the on-resistance, Si also has a lower voltage drop, which also decreases with temperature. Lower on-resistance and lower voltage drop imply lower conduction losses for the Si diode. (For more information, see Ref. [6].)

The changes in R_D and V_D are modeled using a curve-fitting method, as also plotted in Fig. 3.3. The equations describing the curves are

$$V_D^{SiC} = 0.2785 e^{-0.0046T} + 0.7042, \quad (3.1)$$

$$R_D^{SiC} = -0.1108 e^{-0.0072T} + 0.2023, \quad (3.2)$$

$$V_D^{Si} = 0.3306 e^{-0.0103T} + 0.5724, \quad (3.3)$$

$$R_D^{Si} = 0.2136 e^{-0.0293T} + 0.0529. \quad (3.4)$$

where T is in $^{\circ}\text{C}$.

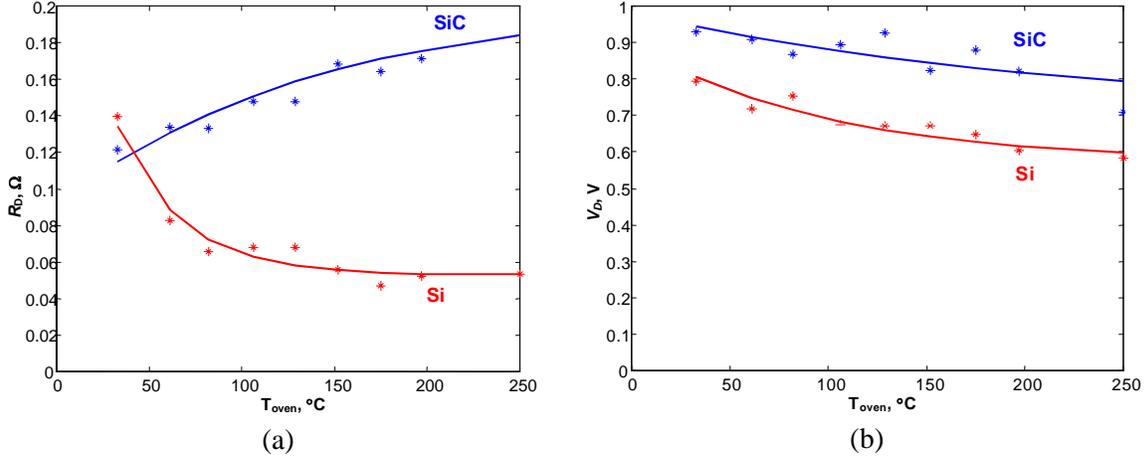


Fig. 3.3. Variation of (a) R_D and (b) V_D with temperature in Si and SiC diodes.

Equations (3.1)–(3.4) can be used to derive the diode loss equations in a power converter system. For a three-phase, sinusoidal PWM inverter, the conduction loss for a diode can be simply expressed as [6–7]

$$P_{\text{cond},D} = I^2 \cdot R_D \cdot \left(\frac{1}{8} - \frac{1}{3\pi} M \cos \phi \right) + I \cdot V_D \cdot \left(\frac{1}{2\pi} - \frac{1}{8} M \cos \phi \right), \quad (3.5)$$

where M is the modulation index and ϕ is the power factor angle.

3.1.2 Switching Losses

The most important part of the diode switching loss is the reverse recovery loss. The rest of the losses are negligible. In this paper, the energy lost during reverse recovery is calculated experimentally so that the switching losses can be calculated for any switching frequency.

Schottky diodes, unlike pn diodes, do not have reverse recovery behavior because they do not have minority carriers; however, they still show some reverse recovery effects. The main reason for these effects is parasitic oscillation due to parasitic device capacitance and inductances in the circuit. The second reason is the parasitic pn diode formed by the p-rings inserted to decrease the reverse leakage currents and n-type drift region.

For this test, the chopper circuit shown in Fig. 3.4 was set up with test diodes in a temperature-controlled oven. The main switch, Q , is turned on and off at 1 kHz with a duty ratio of 75%. The typical Si and SiC diode turn-off waveforms are given in Fig. 3.5 for three different forward currents. These experimental waveforms show that the Si diode switching losses are almost three times more than those of the SiC diode.

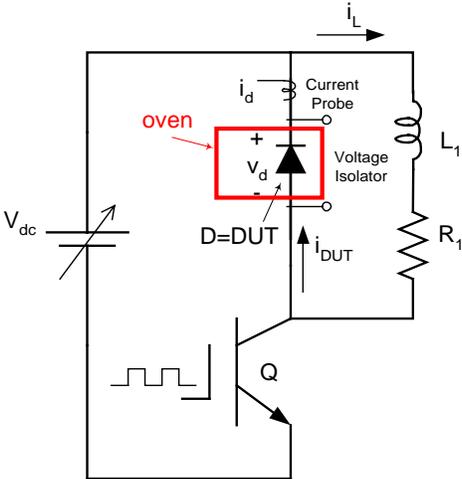


Fig. 3.4. Reverse recovery loss measurement circuit.

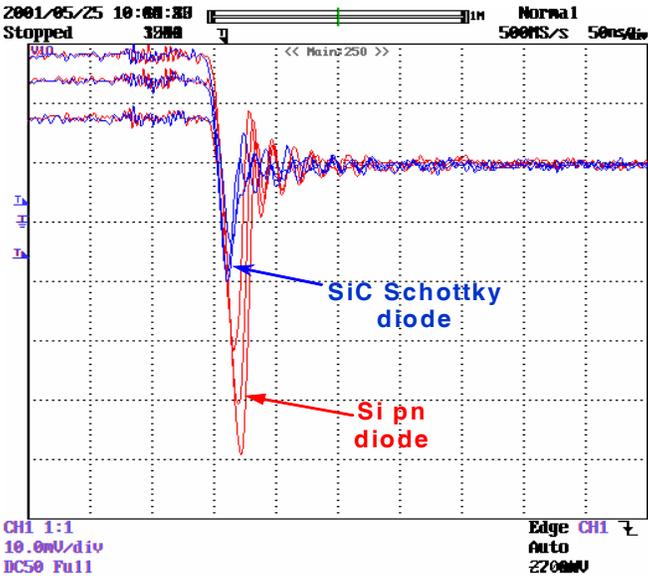


Fig. 3.5. Typical reverse recovery waveforms of the Si pn and SiC Schottky diode (2 A/div.).

The peak reverse recovery current, I_R , and the reverse recovery current-time integral of the diodes are measured at different operating temperatures with varying load currents. The peak reverse recovery current at different temperatures is plotted in Fig. 3.6 with respect to the forward current. The I_R of the Si

diode is higher than that of the SiC diode at any operating temperature. As the temperature increases, the difference increases because the I_R of the Si diode increases with temperature but that of the SiC diode stays constant.

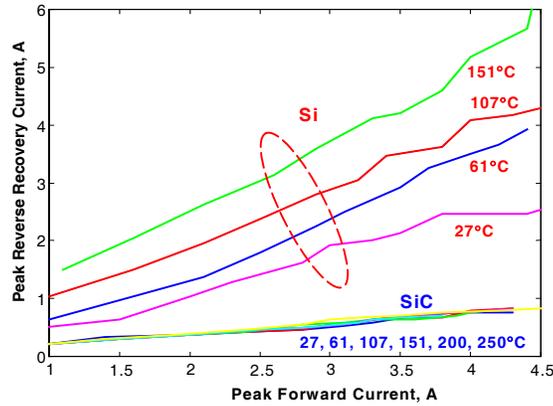


Fig. 3.6. Peak reverse recovery values with respect to the forward current at different operating temperatures.

The reverse recovery current-time integral can be used to calculate reverse recovery losses, and thus diode switching losses. Assuming that the diode “sees” a constant reverse voltage when it is off and that it is switched at constant frequency, then

$$P_{rr} = f_s \cdot V_R \cdot \int_a^b i_d dt . \quad (3.6)$$

Figure 3.7 shows reverse recovery losses for a 20-kHz operation with a 300-V reverse voltage, plotted using the experimentally measured values in Ref. [6]. As can be observed in this figure, the SiC Schottky diode switching losses, unlike those of the Si pn diode, do not change much with temperature.

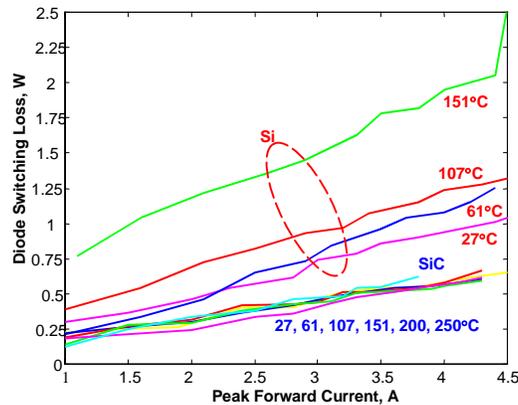


Fig. 3.7. Diode switching loss of Si and SiC diodes at different operating temperatures.

The reverse recovery time-integral current can be approximated linearly as a function of the forward current:

$$\int_a^b i_d dt = \alpha \cdot I_F + \beta . \quad (3.7)$$

Then,

$$P_{rr} = f_s \cdot V_R \cdot \int_a^b i_d dt = f_s \cdot V_R \cdot (\alpha \cdot I_F + \beta) \quad (3.8)$$

where for the SiC Schottky diode $\alpha (SiC) = 2.167 \times 10^{-8}$ and $\beta (SiC) = 2.33 \times 10^{-8}$, and for the Si pn diode

$$\alpha (Si) = 3.5 \times 10^{-8} + 2.5 \times 10^{-13} \cdot T^{2.31} , \quad (3.9)$$

$$\beta (Si) = 1.25 \times 10^{-8} + 2.3 \times 10^{-15} \cdot T^{3.53} , \quad (3.10)$$

and T is in °C.

Equations (3.8)-(3.10) can be used to calculate the switching losses of Si and SiC diodes in system level models to show the system level benefits of SiC devices [6–8].

Note that the curves in Figs. 3.6 and 3.7 are for up to 150°C for the Si diode and 250°C for the SiC diode. The reason for this is that during the tests the Si diode failed when operating at 150°C and 4.5 A, while the SiC diode survived that temperature and failed at a higher 250°C and 4 A. When the Si diode failed, the packaging was intact; however, when the SiC diode failed, its package popped open at the corner where the diode was positioned.

3.2 SYSTEM LEVEL BENEFITS

The use of SiC power electronics instead of Si devices will result in system level benefits like reduced losses, increased efficiency, and reduced size and volume. As shown in Refs. [6–9], when SiC power devices replace Si power devices, the traction drive efficiency in a hybrid electric vehicle (HEV) increases by 10 percentage points, and the heatsink required for the drive can be reduced to one-third of the original size. The studies cited in Refs. [6] and [10], moreover, consider a dc power supply; the effects of increasing the switching frequency by using SiC devices show that the sizes of the passive components, which include the transformer and the filter components, decrease proportionally.

4. GALLIUM NITRIDE

Applications of GaN devices have mainly focused on optoelectronics and radio frequency uses because of the material's direct bandgap and high-frequency performance, respectively. As seen in Section 2, however, GaN also has a potential for use in high-power electronics applications. In the last few years, some papers have been published in the literature on high voltage GaN Schottky diodes [11–15]. The comparison of GaN Schottky diodes with SiC Schottky and Si pn diodes at similar blocking voltages show a performance advantage for the GaN Schottky diode. The main advantage is the negligible reverse recovery current and consequently lower switching loss that is independent of the operating temperature. Figure 4.1 compares the switching performances of GaN, Si, and SiC diodes. As can be seen in this figure, GaN and SiC diodes have similar switching properties, but as the temperature increases, the switching performance of the GaN diode is better than that of the SiC diode. The switching speed and losses of GaN Schottky diodes have been shown to be slightly better than similarly rated SiC diodes as seen in Table 4.1 [11]. On the other hand, because of its wider bandgap, the GaN Schottky diode has a much higher forward voltage drop than the Si pn and SiC Schottky diodes.

GaN Schottky diodes up 2 kV [12] and GaN pn diodes up to 6 kV [13] have already been demonstrated; however, 4.9-kV SiC Schottky diodes [3] and 19.2-kV pn diodes have also been demonstrated. These figures show how advanced SiC technology is at this point compared with GaN technology.

GaN has some disadvantages compared to SiC. The first one is that GaN does not have a native oxide, which is required for MOS devices. SiC uses the same oxide as Si, SiO₂. For GaN, more studies are under way to find a suitable oxide; without it, GaN MOS devices are not possible. The second important problem is that with present technology, GaN boules are difficult to grow. Therefore, pure GaN wafers are not available (see Sect. 6.1 for more information); instead, GaN wafers are grown on sapphire or SiC [11–15]. Even then, thick GaN substrates are not commercially available. As a consequence, GaN wafers are more expensive than SiC wafers.

An additional disadvantage of GaN compared with SiC is that its thermal conductivity is almost one-fourth that of SiC. This property is especially important in high-power, high-temperature operation because the heat generated inside the device needs to be dissipated as quickly as possible. The higher the thermal conductivity, the more quickly the heat is dissipated. Growing GaN on SiC wafers increases the overall thermal conductivity, but the material still does not equal the performance of SiC.

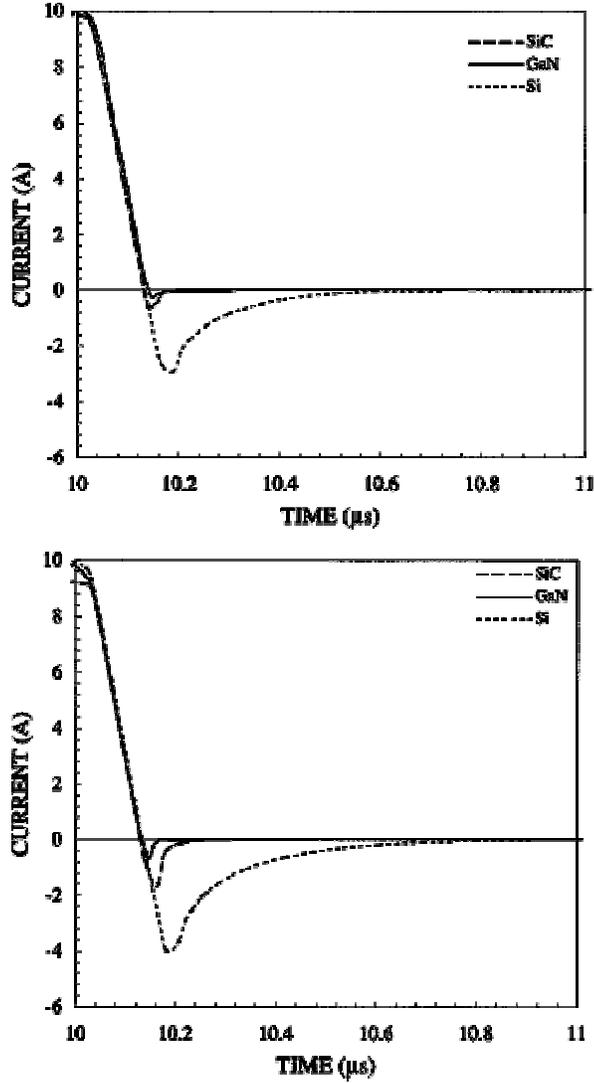


Fig. 4.1. Comparison of switching performances of Si, SiC , and GaN diodes at room temperature and at 623K [13].

Table 4.1. Reverse recovery performance of 6000-V Si, SiC, and GaN diodes

Material	300K			473K		
	I_{rr} (A)	T_{rr} (ns)	E_{off} (mJ)	I_{rr} (A)	T_{rr} (ns)	E_{off} (mJ)
Si	29.1	747	13.2	35.3	906	19
6H-SiC	5.8	132	0.178	12.11	214	0.299
GaN	3.45	144	0.21	4.06	162	0.278

Source: Table VI in Ref. [13].

5. DIAMOND

Diamond shows the best theoretical performance, as noted in Section 2, exceeding every other WBG semiconductor by a factor of several times in every category. However, its processing problems have not yet been solved. After several years of research, there are still processing issues with SiC because of the high temperatures required; diamond is a harder material and needs even higher temperatures for processing, and not as much research has been done on its processing yet.

The literature has reported the use of diamond in sensors [16] and field emission devices [17]. These field emission devices are vacuum tubes and should not be confused with the solid-state power devices discussed in the earlier sections. The reason for using field emission technique is to utilize diamond's high-temperature operation capability without worrying about the junction failure with high-temperature. A diamond field emission device has rows of "diamond tips" that have to turn on for current conduction; however, making sure all the tips are turned on is a major problem.

Ref [18] presents a diamond field emission diode that was tested at 0.109 A and 1650 V. More research is required to build high-power diamond device.

6. COMMERCIAL AVAILABILITY

6.1 COMMERCIAL AVAILABILITY OF WAFERS

Silicon and GaAs semiconductor wafers are available in diameters of up to 15 cm and in variable thicknesses from 225 to 675 μm . Because of their abundance, these wafers are cheap, with a price of less than U.S. \$100 each.

GaN and SiC wafers are not manufactured in large quantities; therefore, they are expensive, in the U.S. \$2000–\$3000 range. With mass production, the prices will likely decrease to close to Si and GaAs wafer price levels.

SiC wafers are available in diameters up to 7.5 cm with thicknesses of 254–368 μm . The best SiC wafers have fewer than one micropipe per square-centimeter; however, the most common wafers have fewer than ten micropipes per square-centimeter with less than five micropipes per square-centimeter around the center of the wafer.

GaN wafers generally come in two forms: GaN on SiC or GaN on sapphire. The former is suitable for power device applications and the latter for LEDs and other optical applications. Recently, a company claimed to have produced the first true bulk GaN, but no commercial products are available yet. The diameter and the thickness of the commercially available wafers are rather small at 5 cm in diameter and up to 25 μm in thickness.

6.2 COMMERCIALY AVAILABLE WBG SEMICONDUCTOR-BASED POWER DEVICES

As of October 2003, only GaAs and SiC Schottky diodes are available for low-power applications. SiC Schottky diodes are available from four manufacturers at ratings up to 20 A at 600 V or 10 A at 1200 V. Silicon Schottky diodes are typically found at voltages less than 300 V. GaAs Schottky diodes, on the other hand, are available at ratings up to 7.5 A at 500 V. Some companies have advertised controlled SiC switches, but none of these are commercially available yet.

7. FORECASTING THE FUTURE

With further development, WBG semiconductors have the opportunity to meet demanding power converter requirements. While diamond has the best electrical properties, research on applying it for high power applications is only in the preliminary stages. Its processing problems are more difficult to solve than for any of the other materials; however, it likely will be an important material for power devices in 20 to 50 years. In the meantime, transitional material will likely replace Si for many high-power applications. GaN and SiC power devices show similar advantages over Si power devices. GaN's intrinsic properties are slightly better than those of SiC; however, no pure GaN wafers are available, and thus GaN needs to be grown on SiC wafers.

SiC power device technology is much more advanced than GaN technology and is leading in research and commercialization efforts. The slight improvement GaN provides over SiC might not be a sufficient reason to use GaN instead of SiC. SiC is the best suitable transition material for future power devices.

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