

COMPARISON OF WIDE BANDGAP SEMICONDUCTORS FOR POWER APPLICATIONS

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Abstract

Recent development 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 can not 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 band gap 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 paper compares all the aforementioned wide bandgap semiconductors with respect to their promise and applicability for power applications and predicts the future of power device semiconductor materials.

1. Introduction

With an increasing percentage of the electricity generated in the future being processed by power electronic converters in motor drives, dc-dc converters, distributed energy resource interfaces, flexible AC transmission systems (FACTS), and high voltage DC (HVDC) systems, the efficiency and reliability of these converters is of the utmost importance. Several of these applications require voltage-blocking capabilities in the tens and hundreds of kV and thus need a series connection of many silicon-based power electronic devices to achieve the necessary voltage rating. In the near future, power electronic converters will process gigawatts of power at some point between where it is generated and where it is ultimately utilized; this emphasizes the need for highly efficient power electronic converters and systems.

Most present commercial power electronic devices (diodes, thyristors, IGBTs, MOSFETs, etc.) are silicon-based. The performance of these systems is approaching the theoretical limits of the Si fundamental material properties. The emergence of new power electronic devices based on wide bandgap (WBG) semiconductor materials will likely result in substantial improvements in the performance of power electronics converter systems in terms of higher blocking voltages, efficiency, and reliability as well as reduced thermal requirements.

2. Properties of Wide Bandgap Semiconductors

Wide band gap semiconductor materials have superior electrical characteristics compared with Si. Some of these characteristics are tabulated for the most popular wide bandgap semiconductors and Si in Table I.

Among all 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 Si and GaAs. Semiconductors with wider bandgaps can operate at higher temperatures; therefore, diamond power devices have the capability to operate at higher ambient temperatures than the other materials. In addition, a higher electric breakdown field results in power devices with higher breakdown voltages. For example, the breakdown voltage of a diode is expressed in [1] as follows:

$$V_B \approx \frac{\epsilon_r E_c^2}{2qN_d} \quad (1)$$

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

Using (1), the breakdown voltages of diodes made of the materials in Table I are calculated assuming the same doping density, and the results are plotted in Fig. 1 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. This number for 6H-SiC, 4H-SiC, and GaN is 56, 46, and 34 times that of a Si diode, respectively. Note that with a higher electric breakdown field, more doping can be applied to the material which will further increase the gap between the upper breakdown voltage limits of the wide bandgap semiconductors compared to Si.

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

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

Table I: Physical characteristics of Si and main wide bandgap semiconductors [1-3].

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^1	11.9	13.1	9.66	10.1	9	5.5
Electric Breakdown Field, E_c (kV/cm)	300	400	2500	2200	2000	10000
Electron Mobility, μ_n (cm ² /V·s)	1500	8500	500 80	1000	1250	2200
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

¹ $\epsilon = \epsilon_r \cdot \epsilon_0$ where $\epsilon_0 = 8.85 \times 10^{-12}$ F/m

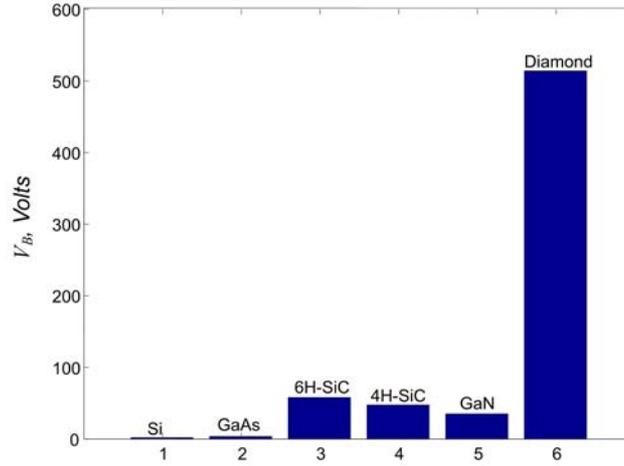


Fig. 1: Maximum Breakdown Voltage of a power device at the same doping density normalized to Si

The width of the drift region is calculated for all the semiconductors in Table I, and the results are plotted in Fig. 2 for a breakdown voltage range of 100 to 10,000 V. Diamond, as expected, requires the minimum width, while 6H-SiC, 4H-SiC, GaN follow diamond in the order of increasing widths. Compared to these, Si requires approximately a 10 times thicker drift region.

The last device parameter to be calculated from the properties in Table I is the on-resistance of the drift region for unipolar devices, which is given by the equation below [3]:

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

The calculation results for on-resistance are plotted in Fig. 3 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 resistance order. The on-resistance of the drift region for the Si device is approximately 10 times more than the SiC polytypes and GaN devices. Note that contact resistance and/or channel resistance must also be considered when the device on-resistance is calculated. These two resistances are dominant at low breakdown voltages but can be neglected at high breakdown voltages; therefore (3) is a better approximation of the device on-resistance for higher breakdown voltage devices.

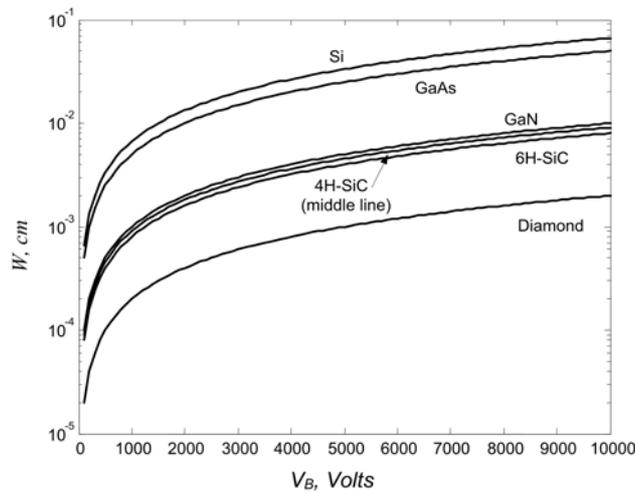


Fig. 2: Width of the drift region for each material at different breakdown voltages.

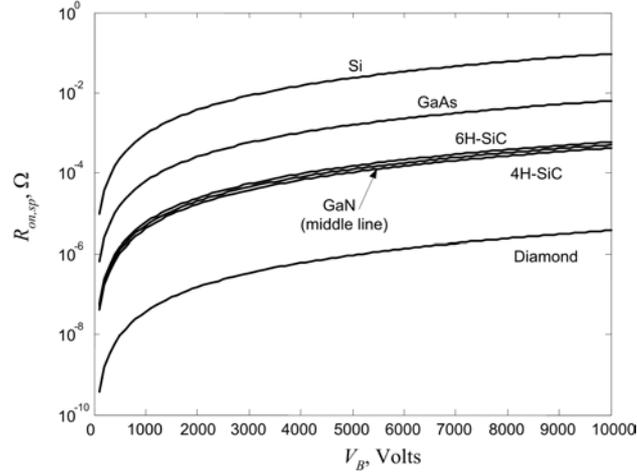


Fig. 3: Resistance of the drift region for each material at different breakdown voltages.

Another parameter to highlight in Table I is the thermal conductivity. The greater this parameter is, the better the material conducts heat to its surroundings, which means the device temperature increases more slowly. For higher temperature operation, this is a critical property of the material. Diamond still leads the other materials by at least a factor of five, with the SiC polytypes as the next best materials. GaN has the worst thermal conductivity - even lower than Si.

For a better comparison of the possible power electronics performances of these materials, some commonly known figures of merit are listed in Table II. 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 any other semiconductor in the table. SiC polytypes and GaN have similar figures of merit, which implies similar performances.

The performances of Si and GaAs have the poorest performance among the semiconductor materials listed in Tables I and II, 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.

3. Silicon Carbide

SiC technology is the most mature one among the wide bandgap semiconductors. 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 (600V) of Si Schottky diodes (300V).

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

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 [5-8], 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 required heatsink for the drive reduces to one-third of the original size. In [8], moreover, a dc power supply is considered and 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.

Table II: Main figures of merit for wide-bandgap semiconductors compared with Si [2].

	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
JFM	1.0	1.8	277.8	215.1	215.1	81000
BFM	1.0	14.8	125.3	223.1	186.7	25106
FSFM	1.0	11.4	30.5	61.2	65.0	3595
BSFM	1.0	1.6	13.1	12.9	52.5	2402
PPFM	1.0	3.6	48.3	56.0	30.4	1476
FTFM	1.0	40.7	1470.5	3424.8	1973.6	5304459
BPFM	1.0	0.9	57.3	35.4	10.7	594
BTFM	1.0	1.4	748.9	458.1	560.5	1426711

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

BFM : Baliga's figure of merit is a measure of the specific on-resistance of the drift region of a vertical FET

FSFM : FET switching speed figure of merit

BSFM : Bipolar switching speed figure of merit

PPFM : 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

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 are 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 of the latter's anisotropy, which means the mobilities of the material in the vertical and horizontal planes are not the same whereas the mobilities in 4H-SiC are identical along the two planes of the semiconductor.

4. Gallium Nitride

Applications of GaN devices are mainly focused on optoelectronics and radio frequency uses because of its direct bandgap and high frequency performance, respectively. As seen in Section II, however, GaN also has a potential for high power electronics applications. In the last few years, some papers have been published in the literature on high voltage GaN Schottky diodes [9-13]. The comparison of GaN Schottky diodes with SiC Schottky and Si pn diodes at similar blocking voltages show a performance advantage of the GaN Schottky diode similar to SiC compared to the Si pn diode, mainly negligible reverse recovery current and consequently lower switching loss that is independent of the operating temperature. The switching speed and losses of GaN Schottky diodes have been shown to be slightly better than similarly rated SiC diodes [9]. On the other hand, because of its wider bandgap, GaN Schottky diode's forward voltage drop is much higher than both Si pn and SiC Schottky diodes.

In the literature, up to 2 kV [10] GaN Schottky diodes and up to 6 kV [11] GaN pn diodes have already been demonstrated; however, 4.9 kV [3] SiC Schottky diodes and 19.2 kV pn diodes have also been demonstrated. These figures show how advanced SiC technology is at this point compared to GaN technology.

GaN has some disadvantages compared to SiC. The first one is that it 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 underway to find a suitable oxide; without it, GaN MOS devices are not possible. The second important problem is that with the present technology, GaN boules are difficult to grow. Therefore, pure GaN wafers are not available (see section 6 for more information); instead GaN wafers are grown on sapphire or SiC [9-13]. 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 to SiC is its thermal conductivity, which is almost one-fourth of 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 is, the quicker the heat is dissipated. Growing GaN on SiC wafers increases the overall thermal conductivity but still does not reach the performance of SiC.

5. Diamond

Diamond shows the best theoretical performance as shown in Section II, with several times improvement in every category compared with every other wide bandgap semiconductor. However, its processing problems have not been solved yet. After several years of research, SiC still has processing issues because of the high temperatures required in the process; diamond is a harder material and needs even higher temperatures for processing, and not as much research has been done on its processing yet.

In the literature, diamond is used in sensors [14] and field emission devices [15]. There are no diamond power devices available yet.

6. Commercial Availability of Wafers

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

GaN and SiC wafers are not abundant; therefore, they are expensive, in the \$2000 – \$3000 U.S. range. Even though the prices of SiC and GaN wafers are expensive; with mass production, the prices will likely decrease to close to Si and GaAs wafer price levels.

SiC wafers are available up to 7.5 cm with a thickness of 254-368 μm . The best SiC wafers have less than one micropipe per square-cm; however, the most common wafers have less than ten micropipes per square-cm with less than five micropipes per square-cm 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 thickness.

7. Commercially Available WBG Semiconductor-based Power Devices

As of April 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 20A at 600V or 10A at 1200V. Note that Si Schottky diodes are typically found at voltages less than 300 V. GaAs Schottky diodes, on the other hand, are available at ratings up to 7.5A at 500V. Some companies have advertised the availability of controlled SiC switches, but none of these are commercially available yet.

8. Forecasting the Future

With further development, wide bandgap 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 its preliminary stages. Its processing problems are more difficult to solve than 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 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 sufficient to change gears and use GaN instead of SiC. SiC is the best suitable transition material for future power devices.

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