WIDE BANDGAP SEMICONDUCTORS FOR UTILITY 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 utility applications of power electronics 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 this limitation, new semiconductor materials for power device applications are needed. 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 for these high power requirements. Among these, SiC is the forerunner as the only wide band gap semiconductor with several commercially available power devices. This paper compares all the abovementioned wide bandgap semiconductors with respect to their applicability and promise for utility applications and predicts the future of power device semiconductor materials.

KEYWORDS

Power electronics devices, utility system, Silicon Carbide, Gallium Nitride, diamond, wide band gap semiconductor.

1. INTRODUCTION

With an increasing percentage of the electricity generated in the future being processed by power electronic converters in utility applications such as distributed energy resource interfaces, medium voltage motor drives, flexible AC transmission systems (FACTS), and high voltage DC (HVDC) systems, the efficiency and reliability of these converters is of 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 electronics 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 in these utility applications.

Most present commercial power electronics devices (diodes, thyristors, IGBTs, MOSFETs, etc.) are silicon-based devices. The performance of these systems is approaching the theoretical limits of the Si fundamental material properties. The emergence of new power electronics devices based on wide bandgap 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.

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

Property	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap, Eg (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] $\varepsilon = \varepsilon_r \cdot \varepsilon_o$ where $\varepsilon_o = 8.85\times10^{-12}$ F/m

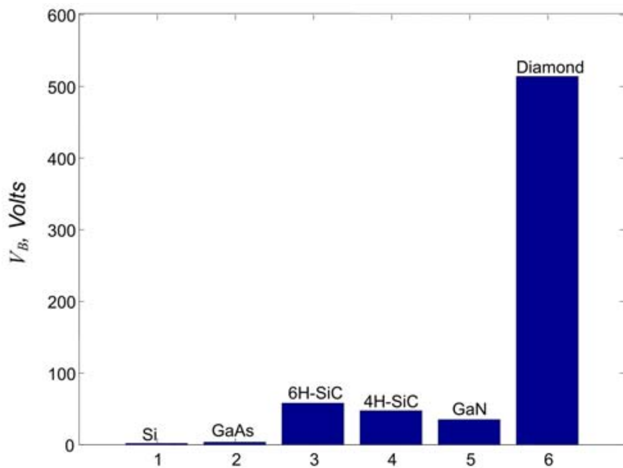

Fig. 1: Maximum Breakdown Voltage of a power device at the same doping density normalized to Si

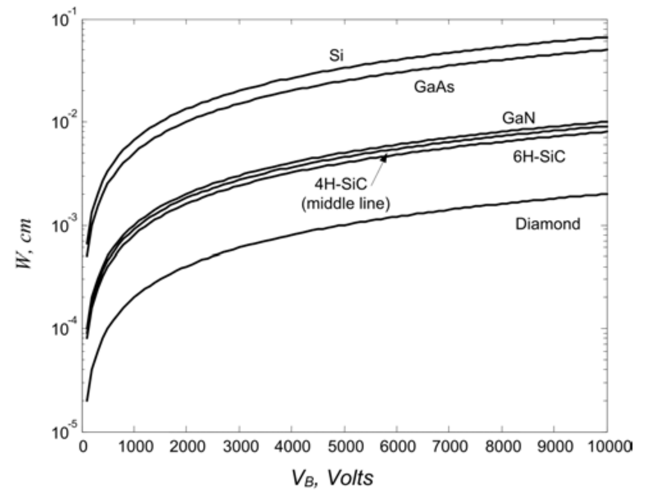

Fig. 2: Width of the drift region for each material at different breakdown voltages.

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. Further discussion and comparison among the different materials appears in the following paragraphs.

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, 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:

$$V_B \approx \frac{\varepsilon_r E_c^2}{2qN_d} \tag{1}$$

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 normalized to the breakdown voltage 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 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 reduction of the width of the drift region in devices. The required width of the drift region can be expressed as [1]:

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

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 10,000V. 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 around ten 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]:

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

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 around ten times more than the SiC polytype 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

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
FPFM	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	**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

approximation of the device on-resistance for higher breakdown voltage devices.

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. This is a useful property, especially for higher temperature operation capability of a device. Diamond still leads the other materials by five times with the SiC polytypes as the next best material. 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, and the larger the number, the better the material's 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 Table 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 with respect to their advantages and disadvantages with respect to each other.

3. SiC

SiC technology is the most mature one among the other 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 PiN 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 [2-3], 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 [4], however, a dc power supply is considered where in addition to the increase in efficiency, decrease in losses, size and volume of the heatsink, the effects of increasing switching frequency are also considered. The results have shown that as the switching frequency is increased, the sizes of the passive components, which include the transformer and the filter components, decrease proportionally.

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

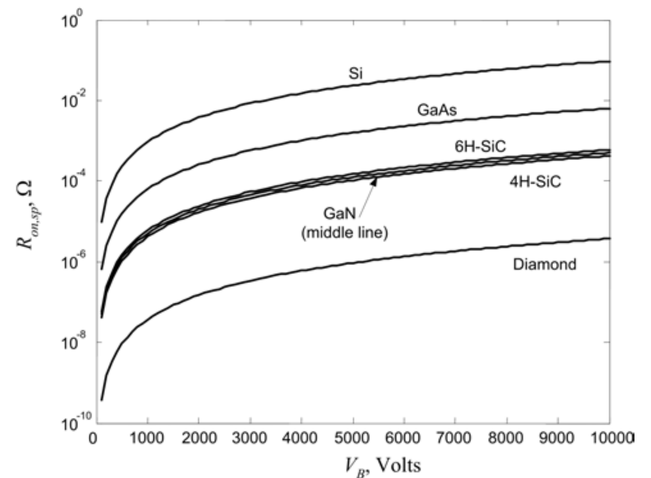

Fig. 3: Resistance of the drift region for each material at different breakdown voltages.

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 vertical and horizontal are not the same whereas the mobilities in 4H-SiC are identical along the two planes of the semiconductor.

4. GaN

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 [5-8]. 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, like negligible reverse recovery current and consequently lower switching loss that is independent of the operating temperature. The switching speed and losses of a GaN Schottky diode have been shown to be slightly better than similarly rated SiC diodes [5]. 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 2000V [6] GaN Schottky diodes and up to 6000V [7] GaN pn diodes have already been demonstrated; however, 4.9 kV [4] 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, SiO_2. 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 cannot be grown; therefore, pure GaN wafers are not available; instead GaN wafers are grown on sapphire or SiC [8-12]. 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 and field emission devices. There are no power devices available yet.

6. FORECASTING THE FUTURE – EVALUATION OF THE RESULTS

With further development, wide bandgap semiconductors have the opportunity to meet demanding utility 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, there needs to be a transition material. 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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