Comparison Between Competing Requirements of GaN and SiC Family of Power Switching Devices

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Abstract. GaN and SiC have been widely investigated for future power switching systems with high efficiencies. So far, prototypes of working transistors using these wide bandgap materials have demonstrated the superior performances suggesting the great potential. This article compares two materials over three main requirements in the power switching realm: the blocking voltage, the conduction loss (power efficiency) and the cost. Based on the comparison, a conclusion is drawn that GaN and SiC will be coexistent for each of them has own advantages and neither of them can replace the other.

1. Introduction
Since the 1950s wide band-gap semiconductors have been announced to be the next step, once silicon reaches its limits [1]. The advantages of power switching devices are low conduction and switching losses, high temperature capability, and high thermal conductivity. Nowadays, Gallium Nitride (GaN) and Silicon Carbide (SiC) are very promising wide band gap semiconductors, more suitable for power switching applications than silicon[8]. So far, working transistors with low on-state resistances and high breakdown voltages by these two materials have been demonstrated together with highly efficient switching systems with them[8]. Now the question becomes how these two materials and the various devices made out of them will prevail on the market[7]. To answer it, a comprehensive comparison between them is necessary. However, it is always some particular pivotal qualities that make a significant difference. Therefore, in the following part, three core factors, namely, the blocking voltage, the conduction loss (power efficiency) and the cost, will be analyzed and a comparison based on these aspects will be conducted. This article aims to find out whether GaN or SiC has superiority over the other one or neither of them can replace the other one in the future.

2. Comparison Between GaN and SiC Devices

2.1. Material
There is a great disparity between Silicon carbide and gallium nitride, as SiC has usually held the heated competent position on devices for power and high temperature and never got an important status in the field of high frequency or optoelectronic. By contrast, optoelectronics is the major market for GaN[9]. However, SiC and GaN share similar material characteristics compared to the standard material silicon and the ultimate semiconductor diamond (table 1)[9]. In most parameters, GaN is slightly superior to SiC and it provides a three times higher Baliga’s FoM for power devices[9]. However, GaN’s thermal conductivity is lower than that of SiC, which means SiC device should have a better performance under high temperature conditions. However, due to the poor material quality, some of the theoretically
superior properties of GaN in the table are not yet achieved in commercial devices or at least not simultaneously achieved in the same device[9].

Table 1. Material properties of SiC and GaN in comparison with those of silicon and diamond [3].

| Parameter       | SiC | 4H-SiC | GaN | Diamond |
|-----------------|-----|--------|-----|---------|
| $W_g$ [eV]      | 1.12| 3.26   | 3.39| 5.47    |
| $E_{opt}$ [MV/cm]| 2.32| 2.2    | 3.6 | 5.6     |
| $e_r$           | 11.8| 9.7    | 9.0 | 5.7     |
| $\mu_n$ [cm$^2$/V·s] | 1400| 950    | 800/1700$^2$| 1800 |
| BFoM relative to Si | 1   | 500    | 1300/2700$^2$| 9000 |
| $n_i$ [cm$^{-3}$] | $1\times10^{10}$| $8\times10^{-9}$| $2\times10^{-10}$| $1\times10^{-20}$ |
| $\lambda$ [W/cm·K] | 1.5 | 3.8    | 1.3/3$^3$ | 20      |

As table 2 is shown, the performance of different material is compared. Secondly, the salient differences between bulk and 2DEG is presented. Thirdly, there is a comparison between epitaxial layers and the bulk material.

The epitaxial growth of GaN layers is largely mastered the pivotal question with respect to the material is the substrate. Four substrates are mentioned, GaN itself, SiC, Sapphire and silicon. Of course, the ideal substrate would be GaN itself, bulk GaN, since GaN shows significant properties superior to other materials. Bulk GaN allows for homo-epitaxy without any mismatches between substrate and epitaxial layer while other substrates suffer different level of mismatch. Those mismatch will lead to degradation of GaN device’s superiority. But the cost of bulk GaN is prohibitively high and still only available in small size wafer.

Table 2. Pros and cons of typical substrate materials for GaN-epitaxy (data relative to GaN properties) [4].

| Substrate        | Bulk GaN | SiC | Sapphire | Silicon |
|------------------|----------|-----|----------|---------|
| Lattice mismatch | none     | +3.5%| -16%     | -17%,   |
| Thermal mismatch | none     | +33%| -25%     | +116%   |
| Electrical resistance | low | low$^1$| $\infty$| very low$^1$ |
| Thermal resistance | same    | 0.3x$^1$| 3x       | 0.9x$^1$ |
| Available wafer size | 2” (3”) | 4” (6”)| up to 8” | any     |
| Cost [€/cm$^2$]  | 100      | 10  | 1        | 0.1     |

2.2. Blocking Voltage

The blocking voltage can be used across a switch in OFF mode, which is also the reverse-bias voltage that can be applied across a device[2]. The maximum accessible blocking voltage is in accordance with the breakdown voltage of a planar structure and in line with the lowest possible doping concentration of the semiconductor region to support the electric field because of the reverse bias[2]. Under the situation of SiC and GaN, this region is n-type doped and is called the drift region[2]. For a planar structure, the relationship between the breakdown voltage and the critical field that leads to breakdown can be obtained by solving the one-dimensional Poisson equation [5]:
In this equation, $V_B$ stands for the breakdown voltage and $E_{cr}$ represents the critical or breakdown electric field, $N_D$ means the n-type doping level, $\varepsilon_s$ is the semiconductor permittivity, and $q$ is the value of electron charge\[2\]. From table 1, the critical field of SiC is about $E_{cr} = 2.2\,\text{MV/cm}$, nearly ten times bigger than it of silicon. The critical field is related to the strength of the atomic bonds, also further related to the energy of band gap of the material (1.12 eV in Si)[2]. The wider energy band gaps in SiC(3.26eV) and GaN(3.39eV) is conformed with stronger atomic bonds and critical field[2]. Consider the doping of $N_D = 5 \times 10^{14} \, \text{cm}^{-3}$ keeps same for each material and the breakdown voltage of silicon is about 600 V, thus the breakdown voltage of SiC should be about 45000 V. Nevertheless, the value of GaN increases to 94000 V roughly, which is higher than SiC. According to these values of breakdown voltages, it is obvious that Si-based power electronics are more suitable for applications below 600 V, which can be labeled as power management in information technology and consumer electronics[2]. For those applications needing blocking voltages higher than 600 V can be sorted as switching applications, which is the core discussion content of the paper, can only be accessed by materials with wider energy band gaps than Si, especially SiC and GaN[2].

The breakdown voltage of GaN is one times higher than SiC, does this mean GaN devices are more suitable than SiC devices when it comes to high-voltage applications? Well the answer is not really. If the GaN device is a pure GaN device without a substrate, it do have much higher breakdown voltage than a SiC one, but a pure GaN device is hard to yield. Nearly all of the GaN devices in the market nowadays are Si-substrate, which is easier for volume production, and they have about 1000V breakdown voltage because of the mismatches between substrate. Before we find the way to eliminate those mismatches in Si-substrate GaN devices, or use pure GaN devices in a wide range, SiC devices are always better than GaN devices when it comes to breakdown voltage.

2.3. Conduction Loss (Power Efficiency)

The requirement for high power efficiency, which should be possibly approach to 100%, is the main reason for the use of switching circuits for converting power. During the process of conversion, power losses can be categorized as static and dynamic[6]. The dynamic losses are due to charging and discharging of parasitic capacitance ($C$) during switching[2]. In the case of transistors, the parasitic capacitance can be considered as the equivalent input ($C_{in}$) and the equivalent output ($C_{out}$) capacitance[2]. The equivalent input capacitance is usually higher, and it may dominate the dynamic power loss in low-voltage applications[2]. However, the dynamic power loss due to the output capacitance will dominate and can be very large when these capacitance are charged to very high voltages in high-voltage applications[2]. So the dynamic losses is:

$$P_{\text{dynamic}} = f C_{\text{out}} V_B^2$$

Where $f$ is the switching frequency and $V_B$ is the breakdown voltage.

The static losses are due to non-zero voltages ($V$) when the switches conduct current ($I$) in ON mode ($P_{\text{static}} = VI$). In the case of both diodes and transistors, the main source of static power losses is the On resistance of the drift region, which is necessary for achieving high blocking voltages. There’s always a tradeoff between On resistance and breakdown voltage in a semiconductor device. If the device wants a higher breakdown voltage, it’ll have to make its drift region bigger, which means the increase of the length and cross sectional area. As the length should not be smaller than the width, the increase of the length of drift area lead to the increase of On resistance, is applied:

$$R_{\text{SP}} = \rho I_N = \frac{I_N}{q\mu_n N_D}$$

where $\rho$ is the resistivity of the material, and the following relationship is obtained between the specific On resistance and the blocking voltage.
Therefore, a higher blocking voltage requires a wider depletion layer, which results in a longer drift-region with larger resistance when the device is turned ON.

In equations, $\mu_n$ is the mobility of electrons in the drift region. Commercial GaN power transistors are based on a structure that is known as the high-electron-mobility transistor (HEMT). The name HEMT indicates that the mobility in the channel of the transistor is high, typically around 2000cm$^2$/Vs, which is almost 100 times higher than in the case of electron mobility in the channel of SiC MOSFETs. This is a huge advantage in terms of the ability to achieve low ON resistance values by devices with a much smaller area. The relationship between the specific ON resistance and the breakdown voltage, which determines the maximum blocking voltage by the drift region, is illustrated in figure 1. Based on the plot for SiC and GaN, if we apply a voltage of 1000V on both a SiC and a GaN device, the ON resistance of GaN device is about 0.1mΩ•cm$^2$, but the resistance of SiC device is up to over 1mΩ•cm$^2$, which is ten times higher than GaN device. So the static loss of SiC device is 10 times higher than GaN device, which leads to a lower power efficiency.

\[
R_{\text{on}} = \frac{4V_d^2}{e_0\mu_n F_{\text{dr}}^3}
\]

Figure 1. The relationship between blocking voltage and $R_{\text{on}}$ area of GaN devices [2].

2.4. Cost

Every competition of products always mentions cost, since the expense of the products is a great concern for companies.

For SiC devices, the cost of main material SiC is about 10€/cm$^2$. As for GaN, pure GaN is about 100€/cm$^2$, 10 times more expensive than SiC. That’s one reason the commercial GaN devices nowadays do not use bulk GaN, but Si-substrate GaN device instead. The content of GaN on a Si-substrate is way too low and since silicon is such an ideal material for a substrate with the cost of only 0.1€/cm$^2$, the price of Si-substrate GaN device offers an unrivalled cost advantage over other substrate and SiC device. Also due to the high mobility of GaN device, it become more smaller on size than a SiC one.

Besides, the cost reduction is not only due to the size of the device and the substrate, but also because of the inherently simpler fabrication of GaN-HEMTs compared with the SiC MOSFETs[2]. It is
unnecessary for semiconductor doping or the growth of a gate oxide. Beside, the number of needed photolithography steps is much smaller[2].

3. Summary
After the comparison above, we reach an answer of the winner on main technologies. SiC devices offer a higher breakdown voltage, while GaN devices offer a lower conduction loss (higher power efficiency) and lower cost. Besides, SiC do hold a great advantage on temperature endurance and reliability, and GaN have an overwhelming performance in high frequency and optoelectronic realm which are not specifically mentioned in the comparison.

![Figure 2. Possible applications of GaN and SiC from the aspects of outpower and operating frequency](image)

Figure 2 shows the way that the future markets of the wide bandgap semiconductors are shared by GaN and SiC[8]. As the increase of the breakdown voltage of GaN transistors is constricted up to 1000V by the existing GaN on Si substrates epitaxial growth technology, the target for GaN is the medium range of the output power with relatively high operating frequencies[8]. By taking advantages of the SiC’s high breakdown voltages and better thermal conductivity, SiC should cover higher output power[8]. Therefore, at this late hour, coexistence between these two materials is the most realistic situation.

4. Conclusion
The capability of GaN and SiC and the devices based on two materials are analyzed and compared. Three key qualities—blocking voltage, conduction loss (power efficiency), cost—are compared. Though GaN provides a higher power efficiency and lower cost, SiC has its own advantage when it comes to the breakdown voltage. Both materials are important at present. Each of them can be applied to different ranges of voltage, power and operating frequency. That reflects a coexistence situation in the semiconductor market. However, the discussion above only referred to three factors, and a more meticulous analysis need further relevant qualities involved. Heat endurance, FOM, switching speed and erosion endurance, even size of the device should also be seriously considered.
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