A Comparison between Si and SiC MOSFETs

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Abstract. The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) has developed quickly and become one of the most important devices for a wide range of applications. There is an increasing need for power MOSFET devices with low power consumption and high energy efficiency. Silicon (Si) and Silicon Carbide (SiC) are two kinds of materials used in power MOSFET devices, which have their own advantages of performance for each use. This paper makes a comparison of the on-resistance and high-temperature performance between Si and SiC MOSFETs. The analysis of the differences between the two will mainly come out from the perspective of material properties, and the conclusion of what is the ideal material for power MOSFET devices will be finally drawn.

1. Introduction
Power electronic systems are of great significance in many areas, as they can proceed and control the flow of electric power[1]. One of the most important devices in power electronic systems is the metal-oxide-semiconductor (MOS) capacitor. The metal-oxide-semiconductor field-effect transistor (MOSFET) is composed of an MOS capacitor and two p-n junctions placed closely to the MOS capacitor[2]. MOSFET was firstly demonstrated in the 1960s and has developed quickly to become an important device for advanced integrated circuits, such as microprocessors and semiconductor memories. A lot of researchers have contributed to developing power MOSFET devices with many unique and unprecedented features, including low-power consumption and high switching speed and good efficiency[3].

Silicon (Si) and silicon carbide (SiC) are two kinds of important semiconductors, which are widely used by power MOSFET devices, thanks to their low-power loss and high-power efficiency[4,5,6]. Figure 1 shows an overview of Si and SiC based on physical material parameters which fundamentally affect the performance of any power switch in a power system[7]. However, based on these different properties of materials, few researchers have made the comparison of their properties of devices. This paper will mainly focus on the comparison of resistance and high-temperature performance between Si and SiC MOSFETs from the perspective of material.
2. On-resistance comparison

2.1. The role of on-resistance in MOSFET

On-resistance is the total resistance between drain and source in on-state. It is an important parameter to determine the highest allowed current. For the same kind of MOSFET devices, lower on-resistance means lower power loss which could be essential for this industry. Figure 2 shows the composition of the total on-resistance of the VD-MOSFET and it could be calculated by the equation:

\[ R_{\text{on}} = J_c (R_{N^+sp} + R_{CHsp} + R_{A-sp} + R_{fsp} + R_{Dsp} + R_{Ssp}) \]

where \( R_{N^+sp} \) is the source diffusion resistance, \( R_{CHsp} \) is the channel resistance, \( R_{A-sp} \) is the accumulating layer resistance, \( R_{fsp} \) is the JETF region resistance, \( R_{Dsp} \) is the drift-layer resistance and \( R_{Ssp} \) is the substrate resistance.

Figure 2. The VD-MOSFET cellular on-resistance schematic diagram

In the idealized case, it is assumed that the structure can support the blocking voltage without degrading due to the edge termination or local electric field enhancement. Additionally, all the resistance in device structure could be seen as parasitic resistance with zero resistance, except the drift region. In such a case, the drift region resistance is called ideal on-resistance. An equation was derived for the resistance per unit area for the drift region:

\[ R_{\text{on-sp,ideal}} = \frac{4B_{\text{PP}}^2}{\varepsilon_S \mu E_c^3} \]

Where \( B_{\text{PP}} \) is the parallel-plane breakdown voltage, \( \varepsilon_S \) is the dielectric constant for the semiconductor, \( \mu \) is the mobility, and \( E_c \) is the critical electric field for breakdown.

2.2. Comparison of on-resistance between Si and SiC MOSFET

The relationship between ideal on-resistance and breakdown voltage based on the equation above may be more directly shown by Figure 3 which plots the minimum specific on-resistance against the breakdown voltage for Si and SiC unipolar devices[8].
Figure 3. Minimum specific on-resistance for Si and SiC unipolar devices (Si limit and SiC limit) versus the blocking voltage

For Si power devices, it is assumed that the mobility is constant due to low doping concentration in the drift region. For the case of an N-type drift region that is utilized for n-channel power MOSFETs, the ideal specific on-resistance is given by[9]

$$R_{on-sp \: ideal}(n \: \text{- channel}) = 5.93 \times 10^{-9}BV_{PP}^{2.5}$$

The resistance of high voltage power Si MOSFET is close to the ideal on-resistance in drift region. The equation above gives the 2.5th ergs increasing relationship between ideal on-resistance of Si and breakdown voltage, which means the on-state voltage drop is more than 10V when on-current density is 100A/cm$^2$. As a result, a large power loss will happen inside the device. Although the power loss can be drained by decreasing on-current density, such measure is implausible because it will increase the chip area and finally increase the cost of the chip.

Figure 4. Ideal specific on-resistance for Si and 4H-SiC power devices

The ideal specific on-resistance for the drift region in 4H-SiC devices is compared with that for silicon in Figure 4 with breakdown voltages ranging from 100V to 100,000V. It shows that there is a significant reduction of specific on-resistance of drift regions between Si and 4H-SiC devices. The ratio of the specific on-resistance for Si to that for 4H-SiC increases from 527 at a breakdown voltage of 100V to 1280 for breakdown voltages above 40,000V.

Table 1. The doping concentration, electron mobility, energy barrier width and on-resistivity versus the breakdown voltage

| Breakdown voltage/V | Doping concentration/cm$^2$ | Electron mobility/cm$^2$/(V·s) | Energy barrier width/μm | On-resistivity/Ω·cm$^2$ |
|---------------------|-----------------------------|-------------------------------|-------------------------|-------------------------|
| 6H-SiC              |                             |                               |                         |                         |
| 200                 | $1.60 \times 10^{17}$      | 267                           | 1.16                    | $1.69 \times 10^{-5}$   |
| 1000                | $1.81 \times 10^{16}$      | 435                           | 7.69                    | $6.11 \times 10^{-4}$   |
Table 2 shows that for a given breakdown voltage, the on-resistance of SiC MOSFET will at least 2 orders of magnitude lower than in their Si counterparts for the same blocking voltage, and SiC exhibits more excellent conduction characteristic under higher breakdown voltage. This is particularly important because lower on-resistance contributes to lower on-state loss. The on-resistance ratio of Si to SiC is shown in Table 2.

Table 2. Ratio of Si to SiC for on-resistance ($R_{on·sp}^{Si} / R_{on·sp}^{SiC}$)

| Breakdown voltage/V | Si / 6H-SiC | Si / 3C-SiC |
|---------------------|-------------|-------------|
| 50V                 | 92.9        | 49.3        |
| 200V                | 198.2       | 88.8        |
| 1000 V              | 305.7       | 177.4       |
| 5000 V              | 355.9       | 229.8       |

Figure 5. Si MOSFET and SiC MOSFET under the voltage of 5000V

As can be seen from figure 5, if a withstand voltage of 5000V is to be obtained, the Si power device with a substrate material doped with 2.5×10¹³/cm³ requires a drift layer thickness of 0.5mm and an area resistance of 10Ω/cm², while the SiC MOSFET with a drift layer doped with a concentration of 2.0×10¹⁵/cm³ only requires a thickness of 0.05mm and an area resistance of 0.02 Ω/cm². SiC power devices allow the use of thinner drift regions to maintain higher blocking voltages, significantly reducing forward voltage drop and conduction losses.

2.3. Conclusion
From the analysis above, it can be sure that SiC can be used to make the device which has lower area of specific on-resistance.

In conclusion, the on-resistance of SiC power MOSFET is much lower than Si power MOSFET at the same breakdown voltage. This is significant for MOSFET’s application.

3. High temperature characteristics comparison

3.1. The role of high temperature characteristics in MOSFET
As is known to all, the efficiency of a MOSFET device will never be 100% because it will unavoidably lose energy mainly by heat generation when operating. In addition, the heat energy will make
temperature rise up gradually and the device will work in a higher temperature, thus some properties of the device will be influenced, especially the electrical characteristics.

Firstly, the threshold voltage will be influenced. The threshold voltage for a power MOSFET structure is given by

\[
V_{TH} = \sqrt{\frac{4\varepsilon_s kT N_A}{C_{OX}}} \ln\left(\frac{N_A}{n_i}\right) + \frac{2kT}{q} \ln\left(\frac{N_A}{n_i}\right) - \frac{Q_{OX}}{C_{OX}}
\]

The equation shows that the threshold voltage for a given power MOSFET structure decreases with increasing temperature because the concentration of intrinsic carrier increases. Figure 6 shows the change of the threshold voltage, in which a P-base doping concentration is \(1 \times 10^{17}\) cm\(^{-3}\). It shows that the threshold voltage in 200°C decreases about 50% of it in -50°C.

![Figure 6. Impact of increasing temperature on the threshold voltage of the power MOSFET](image1)

In addition, the on-resistance increases with the increasing temperature due to the reduction of the mobility in the drift region and the inversion layer. Figure 7 shows the change in the on-resistance with temperature for the case of 30 V power VD-MOSFET structure with a gate width of 10µm and a cell pitch of 18µm. It shows that the on-resistance increases about 70% at 150°C and about 100% at 200°C. Thus, a positive feedback between the device resistance and its junction temperature will occur when such device is conducting significant current in reality, which causes further increases in both. As a result, increasing on-resistance in high temperature environment will bring out a huge on-state power loss[11].

Therefore, superior high-temperature operating capability is very important. A comparison of high temperature characteristics for SiC and Si MOSFET devices will be discussed in the following section.

### 3.2. Comparison of high temperature characteristics between Si and SiC MOSFET

R.Kibushi conducted numerical simulation to investigate thermal properties of Si and SiC power MOSFET[12]. Figure 8 and 9 show the temperature of Si and SiC power MOSFET with different drain...
As can be seen from these figures, the temperature of SiC power MOSFET is much lower than Si device, despite the same structure and operating condition.

![Figure 8. Temperature of Si power MOSFET](image1.png)  ![Figure 9. Temperature of SiC power MOSFET](image2.png)

Figure 10 shows the temperature dependence of thermal of Si and SiC. As is shown in the figure, thermal conductivity of both devices decreases when temperature increases. However, the thermal conductivity of SiC device is always much higher (about 2 times higher) than that of Si device. This can be one reason why SiC power MOSFET can be used in higher temperature environment and it can be explained by the strong chemical bonding between Si and C atoms.

![Figure 10. Temperature dependence of thermal conductivity](image3.png)

Figure 11 shows the heat generation density around hot pot in Si and SiC MOSFET device. Obviously, SiC generates much lower heat than Si, though the Heat generation density of Si MOSFET decreases with increase in drain voltage and that of SiC MOSFET increases. Therefore, the SiC power MOSFET produce much lower heat and thus the temperature will rise much more slowly. As a result, SiC power MOSFET, at the same time, will lose less energy in the operating process. Additionally, the different tendency can be explained by the electrical current through power MOSFET shown in figure 12. Although drain current of Si MOSFET decreases with increase in drain voltage, it is already saturated in calculation condition and it decreases due to high heat generation and high temperature of the device. However, in SiC power MOSFET, the drain current increases with the increase in drain voltage because of high saturation electron velocity of SiC. Consequently, the two types of power MOSFETs have different tendency of heat generation.
Moreover, Shenai proved that the junction temperature of Si power MOSFET is limited by 200℃, while SiC power MOSFET can still operate in a high temperature of 600℃.

3.3. Brief Summary
Since SiC has higher thermal conductivity, the temperature will rise amid lower speed. Moreover, while Si power MOSFET is in the condition of saturated current and calculation voltage, drain current of SiC power MOSFET still rises with the increase of applied drain voltage.

Consequently, SiC power MOSFET has a more superior high-temperature operating capability than Si power MOSFET's.

4. Discussion
Apparently, improving the performance of Si MOSFET devices has been limited by the physical properties of the material itself. Nowadays, Si power device technology is almost mature and it is hard to get innovative breakthroughs. Therefore, SiC becomes an ideal replacing material for power MOSFET due to its excellent physical properties. SiC power MOSFET has not been widely used in electric industry, due to the cost and low efficiency of electron drift mobilities in the channel of MOSFETs, which is caused by the extremely high density of interface states close to conduction band edge[13,14]. SiC is an ideal replacing material for power MOSFET, which is full of opportunities and challenges.

5. Conclusion
In this research, it makes the comparison of characteristics of on-resistance and high-temperature between Si and SiC power MOSFET devices, and analyzes the result. It can’t be ignored that the experiments above still have lots of defects. For example, in the electro-thermal analysis, if applied voltage becomes much higher and saturation current condition appears, the temperature of SiC power MOSFET may rise sharply. Therefore, in future work, the condition of higher voltage and smaller scale will be examined. Moreover, it is expected to use more professional analyzing methods to examine the material structure, and to explore ways to improve some physical properties of MOSFET.

In conclusion, SiC power MOSFET has lower on-resistance and better performance amid high
temperature. More researches about SiC, as an ideal replacing material for power MOSFET, is waiting to be conducted.

Reference
[1] Flack, T. J., Pushpakaran, B. N., Bayne, S. B. (2016). GaN technology for power electronic applications: a review. J. of Electronic Materials., 45(6). 2673-2682.
[2] Nicollian, E. H., Brews, J. R., Nicollian, E. H. (1987). MOS (metal oxide semiconductor) physics and technology. New York et al.: Wiley.
[3] Sze, S. M. (2008). Semiconductor devices: physics and technology. John wiley & sons.
[4] Borgeest, K. (2015). Tested once, forever right? Influence of aging and temperature on susceptibility and emissions. In: 2015 IEEE International Symposium on Electromagnetic Compatibility (EMC). Dresden. pp. 271-276.
[5] Yin, L., Chen, C. P., Kapusta, C., Ghandi, R. (2015). Electronic packaging of SiC MOSFET-based devices for reliable high temperature operation. In: 2015 IEEE International Symposium on Circuits and Systems (ISCAS). Lisbon. pp. 1170-1173.
[6] Avenas, Y., Dupont, L., Baker, N., Zara, H., & Barruel, F. (2015). Condition monitoring: A decade of proposed techniques. IEEE Industrial Electronics Magazine, 9(4): 22-36.
[7] Nawaz, M., Ilves, K. (2016). Replacing Si to SiC: Opportunities and challenges. In: European Solid-State Device Research Conference (ESSDERC). Lausanne. pp. 472-475.
[8] Kimoto, T. (2015). Material science and device physics in SiC technology for high-voltage power devices. Japanese Journal of Applied Physics, 54(4): 040103.
[9] Baliga, B. J. (2010). Fundamentals of power semiconductor devices. Springer Science & Business Media.
[10] Zhu, R., Chow, T. P. (1998). A comparative study of the quasi-saturation in the high voltage vertical DMOS for different cell geometries. In: Proceedings of the 10th International Symposium on Power Semiconductor Devices and ICs. ISPSD’98 (IEEE Cat. No. 98CH36212). Kyoto. pp. 343-346.
[11] Zhou, W., Zhong, X., & Sheng, K. (2013). High temperature stability and the performance degradation of SiC MOSFETs. J. IEEE Transactions on Power Electronics, 29(5): 2329-2337.
[12] Kibushi, R., Hatakeyama, T., Yuki, K., Unno, N., & Ishizuka, M. (2017). Comparison of thermal properties between Si and SiC power MOSFET using electro-thermal analysis. In: 2017 International Conference on Electronics Packaging (ICEP). Yamagata. pp. 188-192.
[13] Pensl, G., Bassler, M., Ciobanu, F., Afanas' ev, V., Yano, H., Kimoto, T., Matsunami, H. (2000). Traps at the SiC/SiO 2 interface. MRS Online Proceedings Library Archive., 640.
[14] Schörner, R., Friedrichs, P., Peters, D., Stephani, D. (1999). Significantly improved performance of MOSFETs on silicon carbide using the 15 R-SiC polytype. J. IEEE Electron Device Letters, 20(5): 241-244.