Characterization and Modeling of Silicon Carbide Power Devices and Paralleling Operation

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***Abstract*- This paper presents recent research on several silicon carbide (SiC) power devices. The devices have been tested for both static and dynamic characteristics, which show the advantages over their Si counterparts. The temperature dependency of these characteristics has also been presented in this paper. Then, simulation work of paralleling operation of SiC power MOSFETs based on a verified device model in Pspice is presented to show the impact of parasitics in the circuit on the switching performance.**

I. INTRODUCTION

Even though the technologies with silicon (Si)-based power devices are mature, inherent material restrictions limit their performance in high voltage, high power, high switching frequency and high temperature applications. Bipolar power devices, such as insulated-gate bipolar transistors (IGBTs), can handle high power, but the switching speed is limited by the devices' structure [1]. Unipolar power devices, like metal-oxide semiconductor field effect transistors (MOSFETs), can be switched at high frequency, but suffer from relatively high on-state resistance. Furthermore, Si power devices generally can only withstand operational temperature of 150°C and can require a substantial cooling system.

Because of these limitations in Si power devices, wide bandgap (WBG) power devices like silicon carbide (SiC) and gallium nitride (GaN) are becoming more attractive. SiC power devices are more developed and have the potential to replace Si in the near future within certain application areas. SiC has many superior properties compared to Si, like higher critical electrical field, relatively high electron mobility, and higher thermal conductivity. Higher critical electrical field allows thinner device and higher doping density for the same blocking voltage. Correspondingly, the on-state resistance can be reduced. Higher thermal conductivity can increase thermal dissipation capability and reduce the requirement of the cooling system. SiC has the potential to be operated at much higher temperature (> 300°C) compared to Si devices [2]. These properties make SiC power devices a worthy substitution for their Si counterparts for high voltage, high temperature, and high frequency applications [3-6].

In this paper, different types of SiC power devices are tested and analyzed, and their advantages have been shown in the testing results. Furthermore, the issues of paralleling devices are discussed in simulation as well.

II. UNIPOLAR POWER DEVICES

A. SiC JFET

SiC junction field effect transistor (JFET) is a commercially available SiC active power device with both normally-on and normally-off structures. The application of SiC JFETs in power converters has been under research and development [7-9].

A 1200 V/ 20 A normally-off SiC JFET has been tested for characterization. Fig. 1 is the forward characteristics of the SiC JFET at 3 V gate voltage from 25°C to 175 °C. The on-state resistance of the SiC JFET was calculated at 3 V gate voltage when the device is fully ON and shown in Fig. 2. This JFET has a positive temperature coefficient, which is helpful for paralleling operation. Transfer characteristics were tested and shown in Fig. 3, which clearly indicates this is a normally-off JFET as the threshold voltage is positive. Transconductance is calculated from the transfer curves and the value decreases with increasing temperature as shown in Fig. 4.

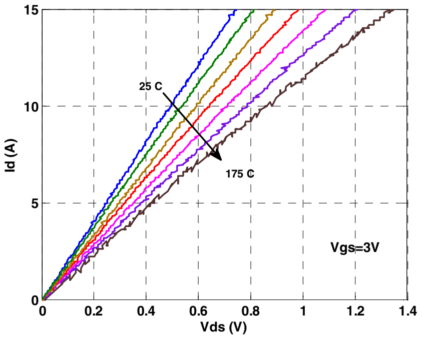


Fig. 1. Forward charcteristic of 1200 V / 20 A SiC JFET.

Fig. 5 shows the switching waveforms of the SiC JFET tested in the double pulse tester (DPT) with SiC JBS diode as the free wheeling diode at 400 V and 5 A. The gate circuit used here was a 15 Ω resistor for steady state in parallel with a series connection of a 5 Ω resistor and a 22 nF capacitor for transient. The gate voltage varied from 15 V to -15 V to inprove the switching speed [10]. The transient time is less than 40 ns based on current, which shows the fast switching capability of the SiC JFET.

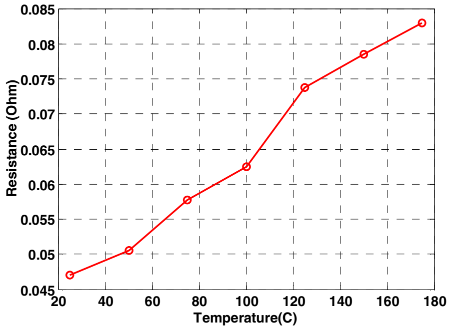


Fig. 2. On-state resistance of 1200 V / 20 A SiC JFET.

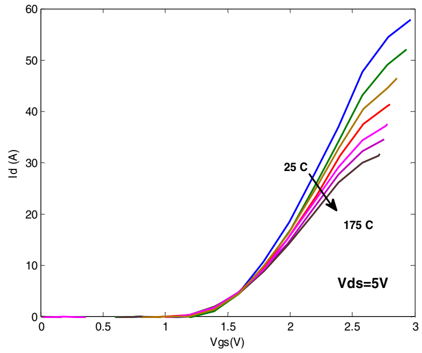


Fig. 3. Transfer characteristics of 1200 V / 20 A SiC JFET.

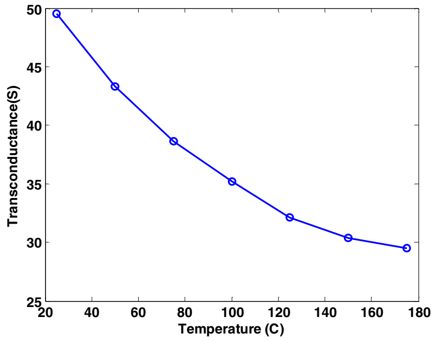


Fig. 4. Transconductance of 1200 V / 20 A SiC JFET.

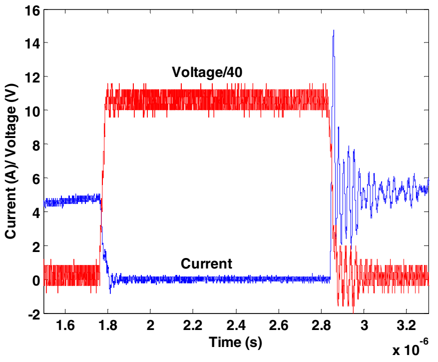


Fig. 5. Switching waveform of 1200 V / 20 A SiC JFET.

The switching losses of the SiC JFET have also been obtained from experiments at 400 V and 600 V DC voltage with different conducting current and are shown in Figs. 6 and 7. The switching losses change little with temperature, while increasing with conducting current and voltage.

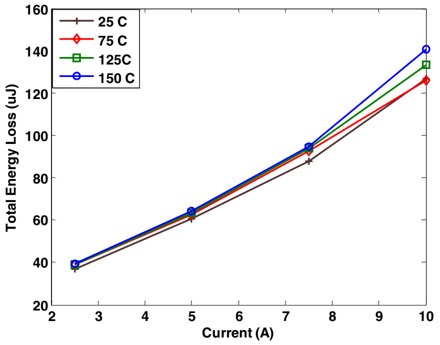


Fig. 6. Switching losses of 1200 V / 20 A SiC JFET at 400 V.

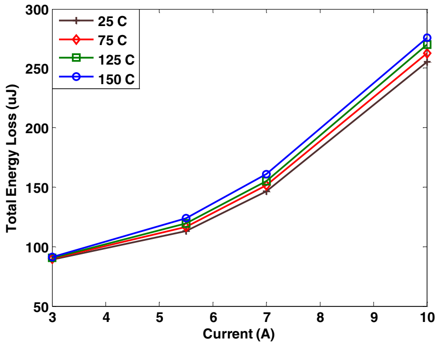


Fig. 7. Switching losses of 1200 V / 20 A SiC JFET at 600 V.

B. *SiC MOSFET*

SiC MOSFET is an attractive unipolar power device, capable of high switching frequency, high temperature, and high efficiency operation [11, 12]. A 1200 V / 30 A SiC MOSFET has been tested here.

Fig. 8 shows the forward characteristics of the SiC MOSFET over temperature. On-state resistance is calculated around 10 A of conducting current and shown in Fig. 9. Unlike the SiC JFET, the on-state resistance of the SiC MOSFET dropped at temperatures near 50°C. The resistance of a power MOSFET mainly comes from three parts: channel resistance, R_{CH}, JFET region resistance, R_{JFET}, and drift layer resistance R_{DRIFT} [13]. R_{CH} has a negative temperature coefficient, while the other two components have positive temperature coefficient. At temperatures less than 50 °C, the change of R_{CH} is dominant, which makes the whole resistance decrease with increasing temperature. At higher temperature, R_{JFET} and R_{DRIFT} changes more than R_{CH}, which lead to the positive temperature coefficient [13,14]. Fig. 10 shows the transfer characteristics over temperature. It can be seen that the threshold voltage decreases with temperature increasing.

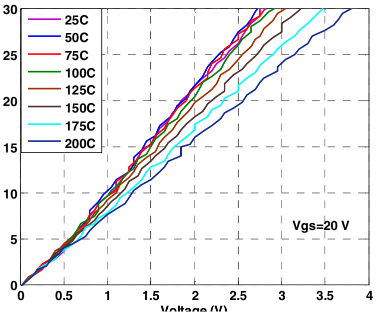


Fig. 8. Forward characteristics of 1200 V / 30 A SiC MOSFET.

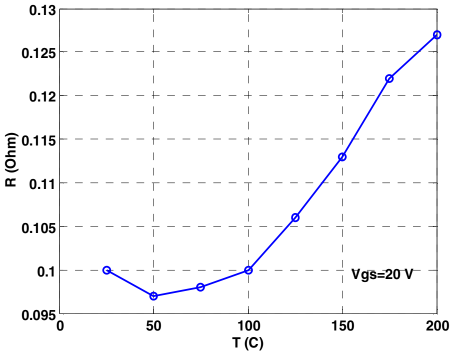


Fig. 9. On-state resistance of 1200 V / 20 A SiC MOSFET.

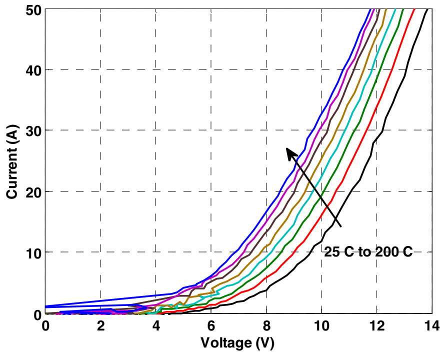


Fig. 10. Transfer characteristics of 1200 V / 30 A SiC MOSFET.

Fig. 11 is the switching waveform of the SiC MOSFET at 400 V and 15 A. A similar parallel structure between gate driver and the MOSFET's gate was used here like that used for the JFET earlier. A 15 Ω resistor paralleled with a series connection of a 3 Ω resistor and a 30 nF capacitor was implemented for the switching test [15]. The testing circuit for this SiC MOSFET was not targeted for high switching speed and some parasitics were added to the circuit for modeling purpose intentionally [15], yet the transient times of the MOSFET were around 60 ns based on current as shown in Fig. 11. When specially designing circuits for high frequency operation, the transient time can be even shorter, and SiC MOSFETs can be used for high frequency operation without using soft switching techniques [16, 17].

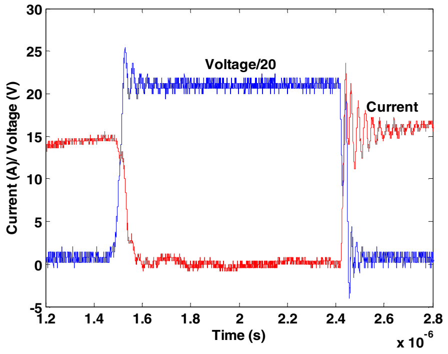


Fig. 11. Switching waveform of 1200 V / 30 A SiC MOSFET.

The losses of the SiC MOSFET were also measured and shown in Figs. 12 and 13. It was tested under 400 V and 600 V DC voltage at multiple temperatures. As expected, the losses are quite consistent at different temperatures, and obviously increased with current and voltage.

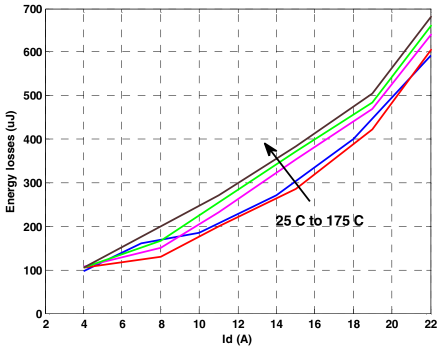


Fig. 12. Switching losses of 1200 V / 30 A SiC MOSFET at 400 V.

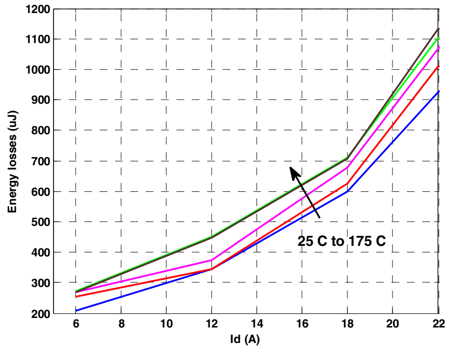


Fig.13. Switching losses of 1200 V / 30 A SiC MOSFET at 600 V.

III. BIPOLAR POWER DEVICES

A. SiC BJT

SiC bipolar junction transistor (BJT) is a current-driven, normally-off power device, which could be an alternative to a Si IGBT [10]. A SiC BJT rated at 1200 V and 6 A has been tested and characterized.

The forward characteristics of the SiC BJT were obtained at different temperatures from 25°C to 175°C when the base current is 350 mA as shown in Fig. 14. It can be seen that the SiC BJT has a positive temperature coefficient.

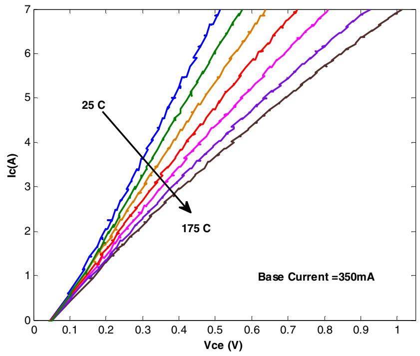


Fig. 14. Forward characteristics of 1200 V / 6 A SiC BJT.

Another important parameter of BJTs is current gain. Fig. 15 shows the current gain of the BJT over a wide temperature range. The gain was calculated when the BJTs were in the forward active region [10]. Fig. 15 illustrates that the gain decreases as the temperature increases while increasing with collector current.

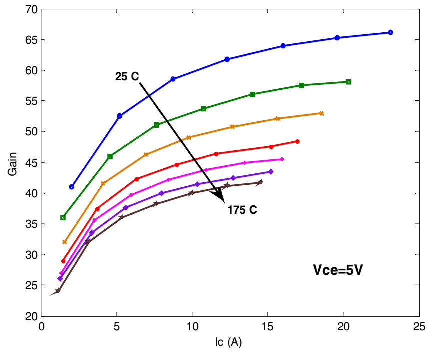


Fig. 15. Gain of 1200 V / 6 A SiC BJT.

B. *SiC SJT*

SiC super junction transistor (SJT) is a current-controlled normally-off device rated at 1200 V/ 10 A [18]. The devices tested were experimental samples. Fig. 16 shows the forward characteristics of the SJT at different temperatures with a 350 mA base current recommended by datasheet. The gain of the SJT was calculated correspondingly for different base currents and shown in Fig. 17, which decreases with temperature and collector current.

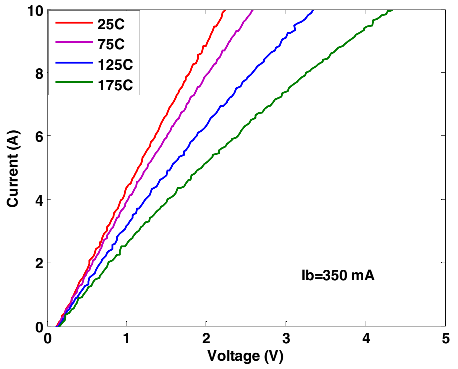


Fig. 16. Forward characteristics of 1200 V / 10 A SiC SJT.

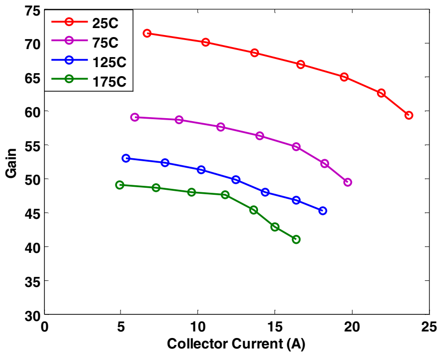


Fig. 17. Gain of 1200 V / 10 A SiC SJT.

IV. PARALLELING OPERATION ISSUES

In order for power converters to be operated at high current and high power, paralleling of power devices is necessary. Paralleling devices can ensure each device is operated in its linear region, which can reduce the conduction losses. It is a complex procedure when paralleling devices as all the parasitics in the circuit and junction capacitances within the devices will be involved. SiC power devices are expected to operate at high switching frequency, which may cause the parasitics to be even more critical. Gate signal and current sharing are important issues for paralleling operation [10]. Most SiC power devices have a positive temperature coefficient, which helps current sharing during paralleling operation.

Several papers discuss paralleling operation of SiC power devices, most of which are for power modules [19-22]. Some papers mention the paralleling of discrete SiC power devices [10, 23, 24]. The results presented in these papers showed relatively good current match, however, some mismatch of transient current did exist. In this paper, some mechanism of mismatching is simulated and discussed.

A. *Experimental Results of Paralleling Operation*

Double pulse testing of two paralleled devices was performed with the SiC JFET, BJT and MOSFET discussed earlier. Figs. 18 to 20 were the experimental switching waveforms for these devices. The gate circuit for BJTs and JFETs was a 10 Ω resistor in parallel with a 3 Ω (for BJTs) or a 7 Ω resistor (for JFETs) in series connection with a 100 nF capacitor. For the paralleled MOSFETs, an external 5 Ω resistor was used. Seen from these figures, the current sharing during turn off process is relatively even; however, the transient currents are slightly mismatched, yet they become even after achieving steady state during turn on [10]. Some reasons for the mismatch are discussed in [10]. Simulation work for reasons causing mismatch is presented in the following section.

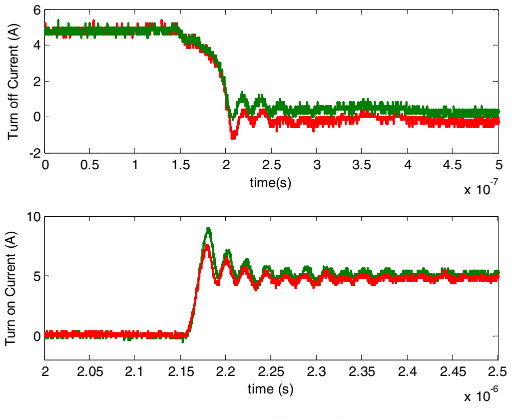


Fig. 18. Turn-on and turn-off waveforms of two paralleled BJTs at 400 V and 10 A.

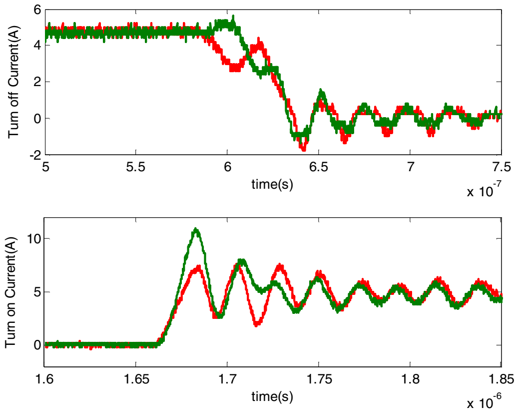
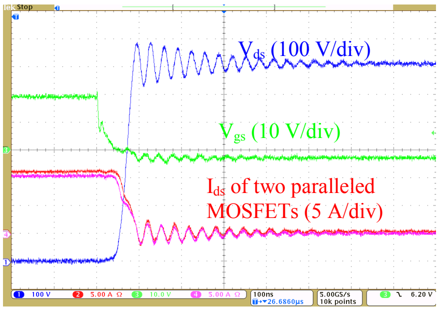
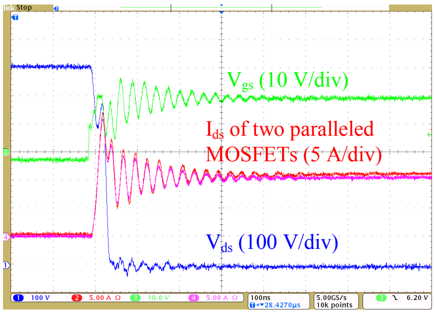


Fig.19. Turn-on and turn-off waveforms of two paralleled JFETs at 400 V and 10 A.



(a) Turn off transient.



(b) Turn on transient.

Fig. 20. Switching waveforms of two paralleled MOSFETs at 680 V and 20 A.

B. *Current Sharing Issues*

Parasitics in the power device and testing circuit can cause current mismatching during transients and will be discussed in this paper through simulation in Pspice. The device model used here is a 1200 V, 30 A SiC MOSFET, which has been validated [15]. To simplify the simulation, the gate driver was not included in the simulation, and an ideal voltage source with 40 ns transient time was implemented to supply gate signal.

Fig. 21 is the current comparison of two paralleled MOSFETs. Except for a 10 nH inductance difference between drain of one MOFET and the free-wheeling diode, all the other elements were the same. Under ideal conditions, each MOSFET should carry half of the load current. The influence of the external 10 nH inductance is clearly shown in Fig. 21. The overshoot value dropped dramatically and the transient time became longer with larger drain inductance during turn on transient.

Fig. 22 shows the influence of the gate resistance. An additional 100 mΩ resistor was inserted between gate signal and the gate of one MOSFET. The turn off current sharing is almost even, however, the turn on current was mismatched in overshoot current value, current turn on delay time, and current rising time

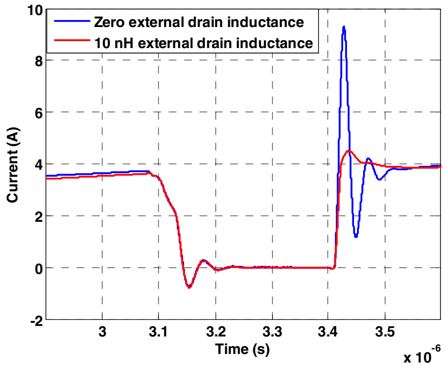


Fig. 21. Current sharing with 10 nH difference of external L_d.

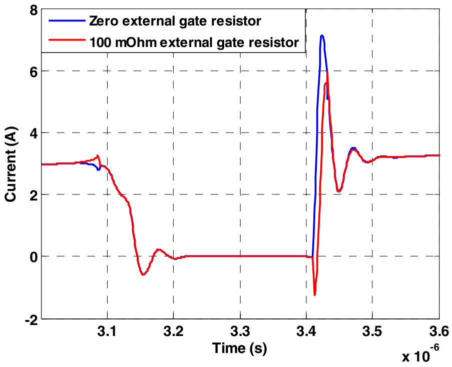


Fig. 22. Current sharing with 100 mΩ difference of external R_g.

V. CONCLUSION

The characterization of several SiC active switches was presented in this paper. The static characteristics, such as the forward and transfer characteristics, the on-state resistance, threshold voltage for unipolar device, and current gain for bipolar devices, were tested over temperature to show the performance of SiC power devices. The switching characteristics were also tested with a double pulse tester, and switching transients and switching losses were presented here. The tested static and switching characteristics illustrated the advantages of SiC power devices, such as less dependency on temperature, higher transient speed, and lower switching losses compared to their Si counterparts at higher temperature. At last, the paralleling operation of SiC power BJT, JFET and MOSFET was discussed and experiment results were presented. Then, simulations were performed that showed current mismatch during switching transients, which shows more effort is required to obtain a matched performance for paralleled devices.

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