

# High-Temperature and High-Frequency Performance Evaluation of 4H-SiC Unipolar Power Devices

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**Abstract-** Silicon carbide (SiC) unipolar devices have much higher breakdown voltages because of the ten times greater electric field strength of SiC compared with silicon (Si). 4H-SiC unipolar devices have higher switching speeds due to the higher bulk mobility of 4H-SiC compared to other polytypes. Four commercially available SiC Schottky diodes at different voltage and current ratings, an experimental VJFET, and MOSFET samples have been tested to characterize their performance at different temperatures. Their forward characteristics and switching characteristics in a temperature range of -50°C to 175°C are presented. The results of the SiC Schottky diodes are compared with those of a Si pn diode with comparable ratings.

## I. INTRODUCTION

With the increase in demand for more efficient, higher power, and higher temperature operation of power converters, the design engineers face the challenge of increasing the efficiency and power density of converters. Increasing the frequency of operation results in compact design of the system. Also, the high temperature operation capability increases the power density because of reduced thermal management and heat sink requirements. An increase in power density results in reduced weight and cost.

Development in power semiconductors is vital for achieving the design goals set by the industry. Si power devices have reached their theoretical limits in terms of higher temperature and higher power operation by virtue of the physical properties of the material. SiC has been identified as a material with the potential to replace Si devices because of their superior material advantages such as large bandgap, high thermal conductivity, and high critical breakdown field strength. SiC devices are capable of operating at higher voltages, higher frequencies, and at higher junction temperatures. SiC unipolar devices such as Schottky diodes, VJFETs, and MOSFETs have much higher breakdown voltages compared to their Si counterparts, which make them suitable for use in medium voltage applications. At present, SiC Schottky diodes are the only commercially available SiC devices.

These diodes are being used in several applications, and have proved to increase the system efficiency compared with Si device performance [3]. Significant reduction in weight and size of SiC power converters with an increase in the efficiency is projected [1, 2]. In the literature, the performance of SiC converters has been compared to traditional Si converters and was found to be better than Si power converters [4, 5].

The gate drive is an important aspect of the converter design which contributes to the device performance and hence the system. The SiC power switches listed above and some SiC VJFETs reported in [6, 7] were switched using several gate drive circuits designed with discrete components. However, in the circuit design presented in this paper, a commercial gate drive IC chip IXDD414 is used which makes it more reliable in operation. These gate drives can be applied to SiC MOSFETs and also VJFETs by selecting different values for the passive components and modifying the output voltage polarity. This paper presents the characteristics for several SiC diodes and power switches, and compares their performance. Some applications require that devices be able to handle extreme environments that include a wide range of operating temperature. In the following sections, the static and dynamic performance of some commercially available SiC Schottky diodes and experimental samples of SiC VJFETs and MOSFETs in a wide temperature range will be presented.

## II. SiC SCHOTTKY DIODES

SiC Schottky diodes are majority carrier devices and are attractive for high frequency applications because they have lower switching losses compared to pn diodes. However, they have higher leakage currents, which affect the breakdown voltage rating of the device [8]. SiC Schottky diodes tested in this paper are S1 (1200 V, 7.5 A), S2 (600 V, 4 A), S3 (600 V, 10 A), and S4 (300 V, 10 A).

### A. Static Characteristics

The static characteristics of different SiC Schottky diodes at room temperature are shown in Fig. 1. The threshold voltage or the knee voltage and the on-state resistance are different for the diodes because of differences in device dimensions for different ratings. The threshold voltage also varies with the contact metal used in the Schottky diodes because of the variation in the Fermi level for different metal to semiconductor contacts. The static characteristics of one of

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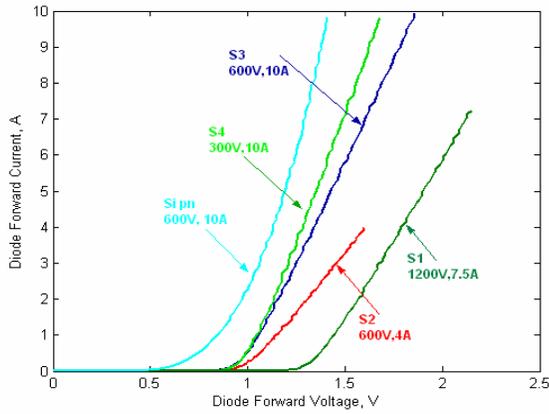


Fig. 1.  $i$ - $v$  characteristics of Si pn and SiC Schottky diodes at 27°C.

the diodes (S3) in a temperature range of  $-50^{\circ}\text{C}$  to  $175^{\circ}\text{C}$  is shown in Fig. 2. The on-state voltage drop of a Schottky diode is dependent on barrier height and the on-state resistance. Both parameters vary with temperature and hence contribute to the temperature dependence of forward characteristics.

At lower current levels, the barrier potential decreases with increasing temperature due to reduction in barrier height [9]. As the temperature increases, the thermal energy of electrons increases, which causes lowering of the barrier height. The approximate on-state voltage drop equation of the diode is given as,

$$V_f = V_d + I_d \cdot R_d \quad (1)$$

where  $V_d$  is the forward voltage drop and  $R_d$  is the series resistance of the diode obtained from the piece-wise linear (PWL) model of the diode. The PWL model parameters were extracted from the experimental test data. The variation in  $V_d$  with temperature is plotted in Fig. 3 for all the diodes tested in this paper.

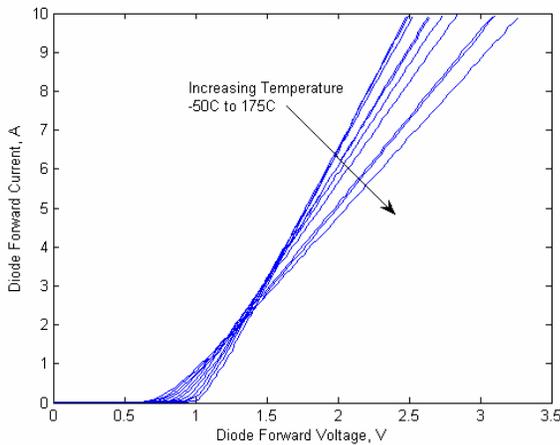


Fig. 2.  $i$ - $v$  characteristics of S3 (600V, 10A) at different operating temperatures.

At higher current levels the voltage drop is mainly due to the series resistance of the diode. The on-state resistance is one of the critical parameters which determines the performance of the device and is a temperature sensitive parameter.  $R_{on,sp}$  specific on-resistance is a dominant component in the  $R_d$  on-state resistance.  $R_{on,sp}$  increases with temperature because the mobility decreases at higher temperatures. This results in the positive temperature coefficient of the device. With a positive temperature coefficient, the conduction losses increase at high temperatures; however, this is advantageous for current sharing and paralleling.

The on-resistance  $R_d$  for the diodes is calculated from the slope of the  $i$ - $v$  characteristics at high currents and is plotted for different temperatures as shown in Fig. 4. The on-state resistance varies for each diode because of the difference in blocking voltages. The  $R_{on,sp}$  for majority carrier devices can be expressed as a function of breakdown voltage and critical electric field [8].

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

where  $\epsilon$  is the permittivity ( $\text{C/V}\cdot\text{cm}$ ),  $V_B$  is the breakdown voltage,  $E_c$  is the breakdown field ( $\text{V/cm}$ ), and  $\mu_n$  is the electron mobility ( $\text{cm}^2/\text{V}\cdot\text{s}$ ). To withstand high breakdown voltages, the blocking layer thickness must be increased, and doping concentrations must be reduced. This results in increased series resistance of the diode. Hence, device S1 rated at 1200 V, 7.5 A has more on-resistance compared to S3 (600 V) and S4 (300 V). The resistance also varies with the area of the device. It is evident from Fig. 4 that S2 and S3 with the same voltage and different current ratings have different on-state resistances.

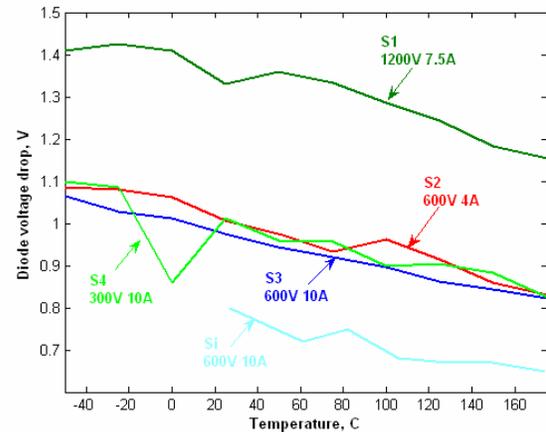


Fig. 3.  $V_d$  for Si and SiC diodes at different operating temperatures.

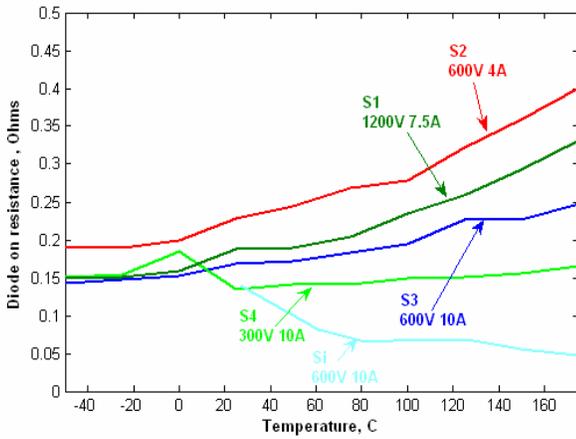


Fig. 4.  $R_d$  for Si and SiC diodes at different operating temperatures.

### B. Dynamic Characteristics

A buck chopper with an inductive load is built to evaluate the switching characteristics of the diodes. A Si IGBT is used as the main switch and is switched at 20 kHz with a 25% duty ratio.

The energy losses for various forward peak currents and different temperatures are shown for the Si diode and SiC diode S4 in Fig. 5. The switching loss for the Si diode increases with temperature while the switching loss for diode S4 is almost independent of the change in temperature.

The reverse recovery current of a diode is dependent on charge stored in the drift region. Schottky diodes have no stored charge because they are majority carrier devices, and hence have virtually constant turn on energy loss for a wide temperature range. The low losses result in increased efficiency. Also, the reduced blocking layer thickness, due to the high breakdown field SiC material, contributes to the low switching losses of the SiC diode because of reduced charge.

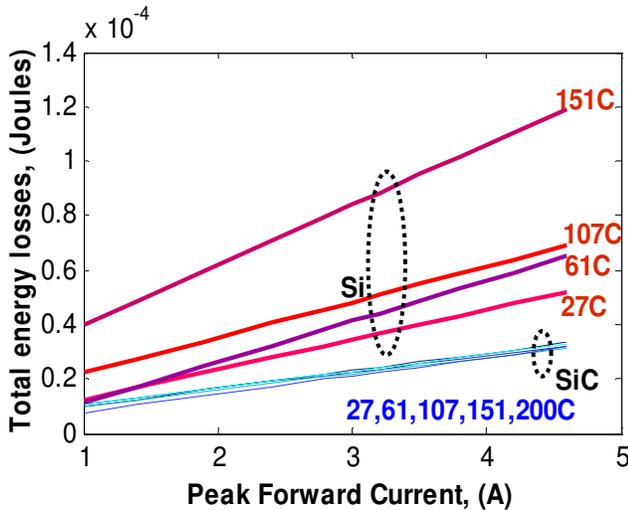


Fig. 5. Total energy losses with respect to forward current at different operating temperatures.

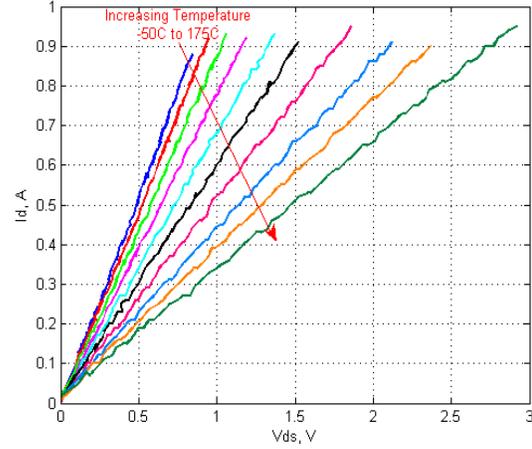


Fig. 6.  $i-v$  characteristics of SiC VJFET at different temperatures.

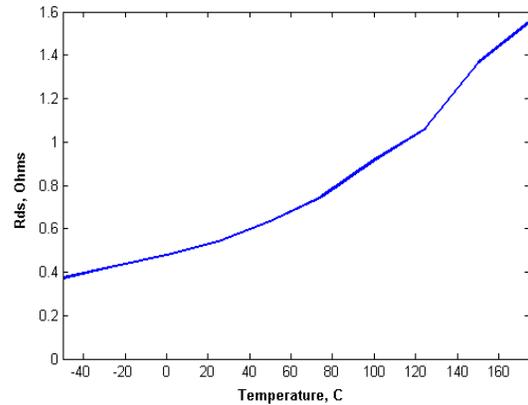


Fig. 7. On resistance of SiC VJFET at different temperatures.

## III. SiC FET DEVICES

### A. Static Characteristics

#### 1. SiC Vertical JFET (VJFET)

A JFET is a unipolar device and has several advantages compared with MOSFET devices. A JFET has a low voltage drop and a higher switching speed, and JFET is free from the gate oxide interface problems unlike the MOSFET [10]. A JFET is typically a normally-on device and conducts even though there is no gate voltage applied. A gate voltage has to be applied for it to stop conduction. A normally-on device is not desirable since it requires additional protection circuitry to prevent a dc bus short if the gate signals fail. This normally-on feature also demands special gate drive designs increasing the complexity of design.

The SiC VJFET can be used in high current and voltage applications, unlike a Si JFET because of its vertical structure and the intrinsic properties of SiC. A normally-on SiC VJFET rated at 1200 V and 2 A was tested to study the high temperature behavior of the device. The forward characteristics of this device at different temperatures are shown in Fig. 6. The on-resistance of the VJFET increases from 0.36  $\Omega$  at  $-50^\circ\text{C}$  to 1.4  $\Omega$  at  $175^\circ\text{C}$  as shown in Fig. 7. The values of the on-resistance are high; however, these

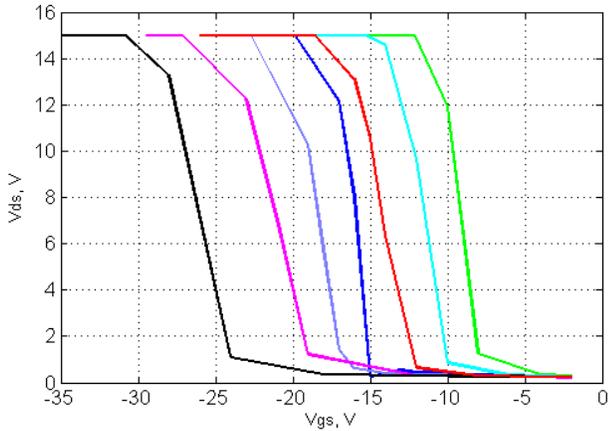


Fig. 8. Transfer characteristics of SiC VJFET.

devices are low current rated devices. Since they have positive temperature coefficient which enables easy paralleling of devices.

The transfer characteristics of different VJFET samples are shown in Fig. 8. The negative gate pinch-off voltage required to turn-off the device varies from sample to sample. This variation is attributed to the fact that these devices are experimental samples. Since the pinch-off voltage determines the voltage requirement of the gate drive circuit, the gate driver needs to be designed for this variation in mind so that it can switch any of these devices.

## 2. SiC MOSFET

A MOSFET is a unipolar device and is normally off. A SiC MOSFET can block voltages up to 3 kV unlike a Si MOSFET (300 V) because of the high electric breakdown field strength of SiC. Also, it has lower on-state resistance. Forward characteristic curves of a 1.2 kV, 15 A SiC MOSFET at room temperature are shown in Fig. 9.

The gate voltage changes from 0 to 20 V. For  $V_{gs}=20$  V, there is a 6.7 V drain-to-source voltage drop corresponds to 15 A drain current. It would be reasonable to operate the device at 5 A with a  $V_{gs}=20$  V because of a low voltage drop of 1.5 V. The forward characteristics of a SiC MOSFET are

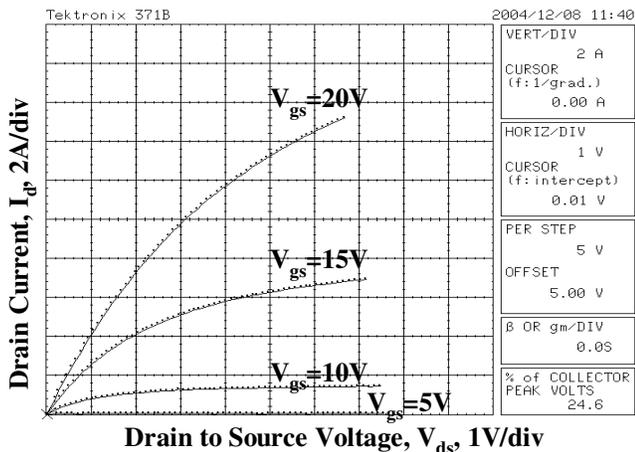


Fig. 9. Forward characteristics of SiC MOSFET at room temperature.

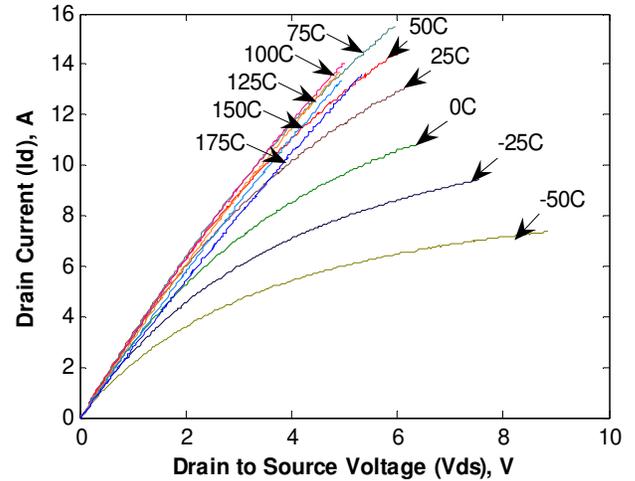


Fig. 10. Forward characteristics of SiC MOSFET at different temperatures.

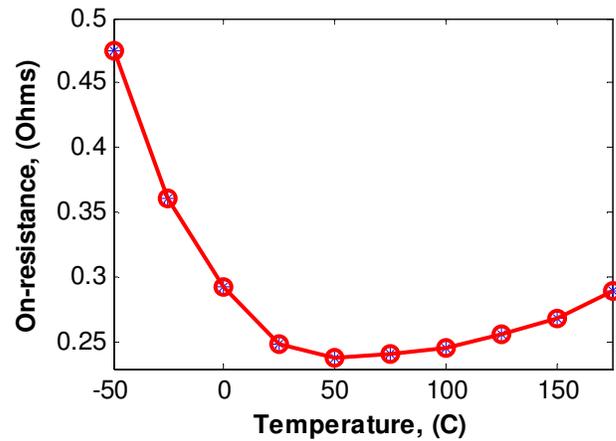


Fig. 11. On resistance of SiC MOSFET at different temperatures.

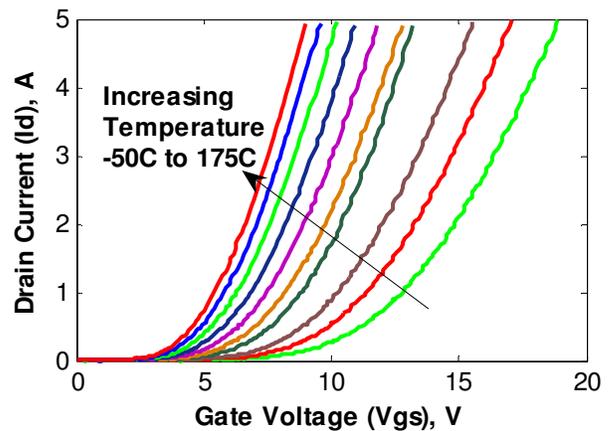


Fig. 12. Transfer characteristics of SiC MOSFET at different temperatures.

shown in Fig. 10 for a temperature range of -50C to 175C. The on-state resistance calculated from the slopes of the

different curves is plotted as shown in Fig. 11. It is interesting to note that resistance decreases as the temperature increases from  $-50^{\circ}\text{C}$  to  $50^{\circ}\text{C}$  and then increases as the temperature increases beyond  $50^{\circ}\text{C}$ .

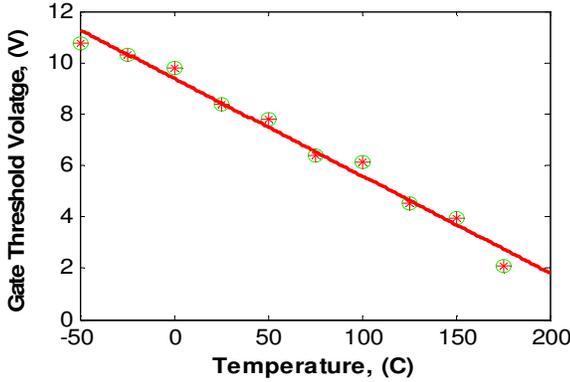


Fig. 13. Gate threshold voltage of SiC MOSFET at different temperatures.

The on-state resistance of a MOSFET can be expressed as the sum of several different resistances because of different regions of the MOSFET structure:

$$R_{on} = R_{cont} + R_{sub} + R_{ch} + R_{acc} + R_{jfet} + R_d$$

where  $R_{cont}$  is contact resistance,  $R_{sub}$  is substrate resistance,  $R_{ch}$  is channel resistance,  $R_{acc}$  is accumulation layer resistance,  $R_{jfet}$  is resistance of JFET like region,  $R_d$  is resistance of the drift region [11].

The channel resistance depends on the mobility and applied gate voltage. At lower temperatures, the contribution of the channel resistance to the total on-state resistance is dominant [12]. The channel resistance decreases with an increase in temperature, because of the increase in the channel mobility with temperature for SiC MOSFETs as reported in [12, 13]. The increase in channel mobility with temperature is due to the interface traps closer to the conduction bandgap, and this is contradictory to the unipolar device physics of operation.

The gate threshold voltage decreases with increase in temperature. The variation in gate threshold voltage is measured from the transfer characteristics as shown in Fig. 12. Fig. 13 shows the change in threshold voltage from 10.7 V at  $-50^{\circ}\text{C}$  to 2.8 V at  $175^{\circ}\text{C}$ . This change is due to the trapped charge in the  $\text{SiO}_2$  as well as the impurities at the  $\text{SiO}_2$  interface. These trapped charges become active at high temperatures, which results in a Fermi level shift towards the bandgap causing the drain current to flow at low threshold voltages. However, at high temperatures the series resistance increases and the channel resistance decreases. Because the series resistance has a larger effect on the overall resistance, the net resistance increases. In summary, the on-resistance at lower temperatures is dependent on the gate voltage because of the dominance of channel resistance whose effect decreases at higher temperatures.

### B. Gate Drive Requirements

SiC FET switches can be operated at higher switching frequencies and higher temperatures; therefore, they have

different gate drive requirements than traditional Si power switches. The switching performance of the FET devices is determined by charging and discharging of the parasitic capacitances across the three terminals, input capacitance  $C_{iss} = C_{gs} + C_{ds}$ ,  $C_{rss} = C_{gd}$  reverse transfer capacitance, and  $C_{oss} = C_{ds} + C_{gd}$  output capacitance. These capacitances are proportional to the area of the device [5]. Since SiC devices have smaller areas, even for high blocking voltages, the capacitances are reduced. This enables devices to operate at higher switching speeds. A comparison of capacitance values for SiC MOSFET and Si power switches is reported in [14].

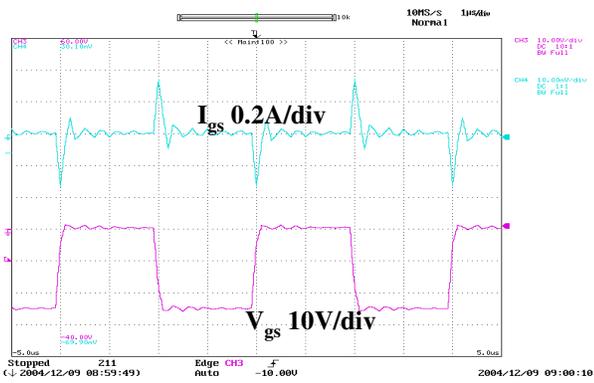
One of the important parameters in gate drive design is the stray capacitance between the gate and the other terminals. Total input capacitance of VJFET,  $C_{iss}$ , determines the current required by the gate and the rate at which the applied gate voltage is built across the gate and source terminals. Therefore, the gate drive circuit is required to have the capability of providing peak currents to be able to charge the input capacitance quickly. The peak gate current is limited by series resistor between the gate and the gate driver output. The gate series resistance decreases the ringing effect due to the internal impedance of the device. However, increasing the gate resistance value results in slower turn-on times.

As mentioned earlier, there are several gate drive circuits designed for SiC VJFETs using discrete devices [6], [7]. The main objective of the project was to build a gate driver using commercially available gate driver chips in order to achieve reliable operation for faster switching speeds. In the circuit design presented in this paper, a commercial gate drive IC chip IXDD414 is used. These gate drives can also be applied to SiC MOSFETs by redesigning the passive components and modifying the output voltage polarity. The gate drive was tested with several capacitors as load before testing the driver circuit with the device. The peak gate currents and gate voltage waveforms with SiC MOSFETs and SiC VJFETs are shown in Fig. 14.

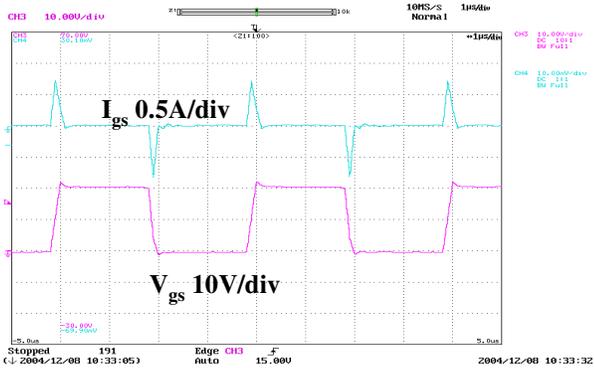
### C. Dynamic Characteristics

The gate drive circuit discussed in the previous section was used to determine the dynamic characteristics of the SiC MOSFET and VJFET. The gate drive voltage for the MOSFET was selected to be 20 V as determined from the forward characteristics to obtain the optimum performance. A 250 kHz operation was achieved with a resistance of 7.2  $\Omega$  and with a peak gate current of 0.6 A. The gate and switching waveforms for SiC MOSFET are shown in Fig. 15. The device has a turn-off delay  $t_{d,off}$  of 40 ns, fall time  $t_f$  of 100 ns, turn-on delay  $t_{d,on}$  of 20 ns, and  $t_r$  rise time of 100 ns.

Because SiC VJFETs are normally-on devices they can be turned off by applying a negative voltage that is higher than what a typical Si switch requires. The gate drive needs protection circuitry to prevent the short circuit failure. One solution to this problem is to ensure that the gate drive circuit is turned on before system power up. When these are operated at high frequencies, they also need high peak gate currents. Based on the transfer characteristics, the gate drive was designed for a voltage of -25 V since the pinch-off



(a)



(b)

Fig. 14. The peak gate currents and gate voltage waveforms with (a) SiC VJFET, (b) SiC MOSFET.

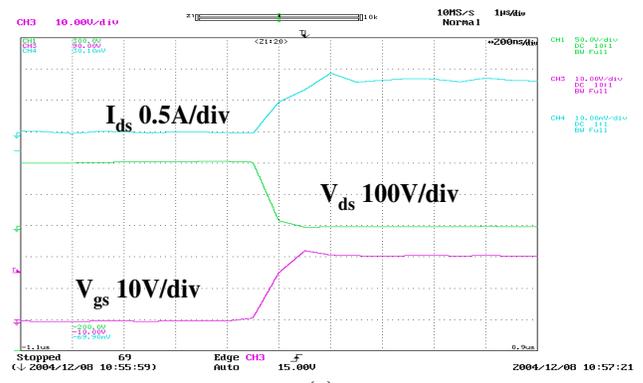
voltage for most of the samples tested was -20 V. The gate series resistance was changed to achieve high frequency operation. A 250 kHz operation was achieved with a resistance of  $7.2 \Omega$  and with a peak gate current of 0.38 A. The gate voltage and the switching waveforms of the VJFET are shown in Fig. 16. The device has a turn-off delay  $t_{d,off}$  of 40 ns, fall time  $t_f$  of 80 ns, turn-on delay  $t_{d,on}$  of 20 ns, and  $t_r$  rise time of 100 ns.

The faster switching times of these devices is because of the high bulk mobility of the 4H-SiC. The turn on and turn off energy losses for both the MOSFET and JFET were calculated by integrating the instantaneous power over the turn on ( $t_{on}$ ) and turn off times ( $t_{off}$ ).

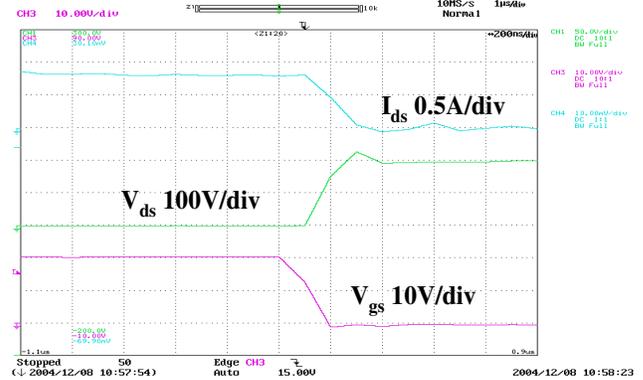
The energy losses calculated for the SiC MOSFET and JFET, for a 5 kHz, 50% duty cycle, 100 V, 0.8 A operation is shown in Fig. 17 at different temperatures. The total losses do not change much in the temperature range which shows the reliability of SiC devices.

#### IV. CONCLUSION

The static and dynamic performances of some SiC Schottky diodes, a SiC MOSFET, and a SiC VJFET were characterized. The on-resistances were found to be increasing with temperature for the SiC Schottky diodes and SiC VJFETs. However, the on-resistance for SiC MOSFET was decreasing at lower temperatures and increasing at higher temperatures. This is due to the interface trap defects

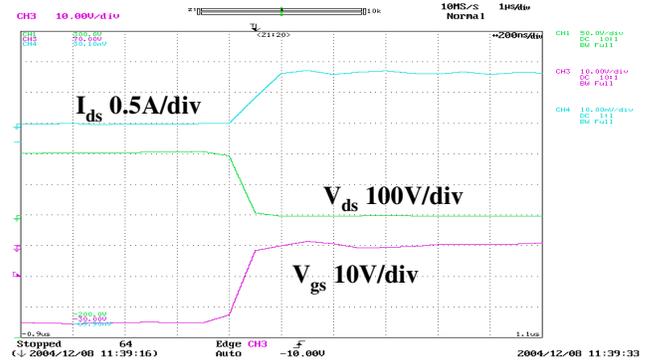


(a)

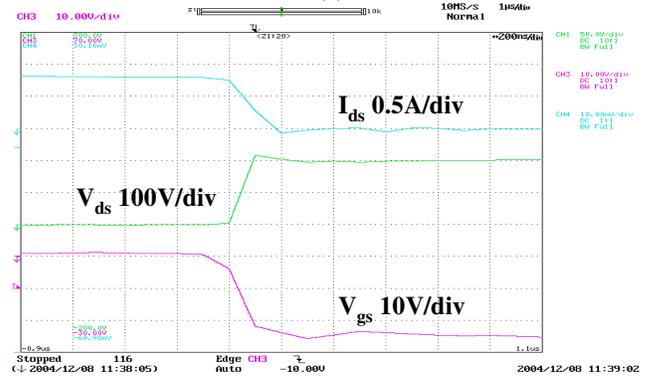


(b)

Fig. 15. The gate and switching waveforms of SiC MOSFET.



(a)



(b)

Fig. 16. The gate and switching waveforms of SiC VJFET.

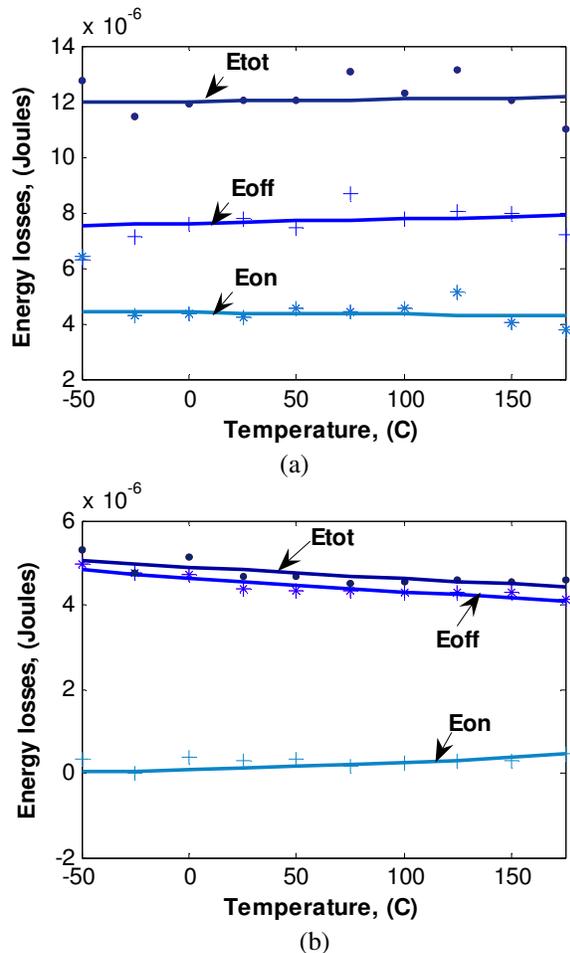


Fig. 17. Energy loss plots for (a) MOSFET, (b) VJFET.

in the SiC MOSFET. These defects will be addressed with improvements in manufacturing technology. All the SiC Schottky diodes tested showed excellent reverse recovery characteristics compared to Si pn diode. Thus, replacing Si devices with comparable SiC Schottky diodes will improve the performance of the power switches in a power converter by reducing the switching stress on the switches. In this paper, as opposed to the others in the literature, a commercial gate driver chip was used in the design a gate driver for a SiC power switch and the same circuit was used to switch both SiC MOSFETs and VJFETs.

The switching losses were almost constant for a wide temperature range for all the SiC unipolar devices reported in this paper. Also, the SiC power devices have very low switching times.

This shows that SiC unipolar devices are well suited for high frequency, high power and high frequency applications. Also, hard switching circuits at higher power levels and higher frequencies can be realized using SiC devices due to the excellent switching characteristics. With further

improvements in current ratings, the SiC unipolar devices can replace IGBTs which have higher ratings but suffer from high switching losses. MOSFETs would be the choice of device compared to VJFETs because of the normally-off feature. However, the gate oxide reliability still remains an issue for MOSFETs. Even though the SiC devices can operate at high temperatures and high frequencies, the system components and packaging techniques have to be developed to take advantage of these properties. The gate drive units also need to be designed for high temperature operation. Further research is required for higher temperature operation of these gate drivers. The devices presented in this paper will eventually be used to develop more realistic system level models to show the system level benefits of SiC devices.

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