

Investigation on the Parallel Operation of Discrete SiC BJTs and JFETs

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Abstract— This paper presents an analysis of single discrete silicon carbide (SiC) JFET and BJT devices and their parallel operation. The static and dynamic characteristics of the devices were obtained over a wide range of temperature to study the scaling of device parameters. The static parameters like on-resistance, threshold voltage, current gains, transconductance, and leakage currents were extracted to show how these parameters would scale as the devices are paralleled. A detailed analysis of the dynamic current sharing between the paralleled devices during the switching transients and energy losses at different voltages and currents is also presented. The effect of the gate driver on the device transient behavior of the paralleled devices was studied, and it was shown that faster switching speeds of the devices could cause mismatches in current shared during transients.

I. INTRODUCTION

The theoretical promise of SiC devices to improve the performance of power electronics converters continues to drive the development of this technology for several applications. The performance based analysis will be one aspect to prove the potential of SiC based devices; however, the reliability and the cost aspects need to be assessed as well for the commercialization of the technology.

Even though significant progress has been made on the quality and size of the SiC wafer, some material defects such as basal plane and screw dislocations have been the roadblocks for devices, especially the bipolar devices. The unipolar switches like MOSFET and JFET have been improved over the years and may be closer to commercialization. MOSFET has the inherent oxide interface issues at high temperatures that need to be solved [1]. JFET does not have any interface issues; however, the normally-on and normally-off structures have been pursued and each structure has its own advantage and disadvantages. The normally-off structure is the preferred choice of the circuit designers.

Recently the BJT, which is a normally-off device and also free of oxide interface problems, has been developed and could be an alternate solution to the Si IGBT. However,

being a current controlled device, the drive power requirements for the BJT are much higher than the MOSFET or JFET.

Parallel operation is an important feature of any semiconductor device in a power module. The gate drive requirements and the current sharing during the dynamic switching impacts the operation of the module and the switch utilization factor of the switches paralleled. SiC switches have positive temperature coefficient which makes the current sharing during conduction easier. However, the dynamic current sharing is very critical and depends on the gate drive and the parasitics associated with it. Several SiC device based power modules have been reported [2-5]. However, performance of the individual devices during parallel operation in the module has not been studied. Analysis of parallel operation of devices in a module is difficult because of lack of access to the individual devices unless it is specially packaged.

The characterization of single SiC JFET and SiC BJT devices has been reported in several papers [6-13]. The parallel operation of SiC BJTs has been studied with pulse power for current sharing on a special package [14]. A comparison of SiC JFET (normally-on) and a similar SiC BJT has been compared in [15]. This paper presents characterization of paralleled discrete SiC JFETs (normally-off) and paralleled SiC BJTs. The static and dynamic characteristics of the devices were obtained over a wide range of temperatures to study the scaling of device parameters. The freewheeling SiC JBS diode also has been characterized, and its dynamic characteristics are presented.

II. STATIC CHARACTERISTICS

A. SiC Bipolar Junction Transistor

The forward characteristics of SiC bipolar junction transistor (BJT) rated at 1200 V, 10 A were obtained for both single and paralleled devices at different temperatures from 25 °C to 175 °C as shown in Fig. 1 and Fig. 2. Since

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the BJT is a current driven device, in order to drive more than one device it requires additional base current to drive both devices. The base current of the device was chosen from the forward characteristics obtained at different base currents. To make sure the devices are operated under linear region at rated current, 350 mA for single BJT and 600 mA for paralleled BJT of base current were chosen.

The on state resistance calculated from the forward characteristics is shown in Fig. 3. It has positive temperature coefficient, which means with the temperature increasing, the resistance also increases. This feature makes it easier for parallel operation. The single BJT has almost twice the resistance as paralleled BJTs at the same temperature. However, in order to achieve the lower on state resistance of paralleled BJTs, larger base current is required and this clearly will increase the gate drive power requirements.

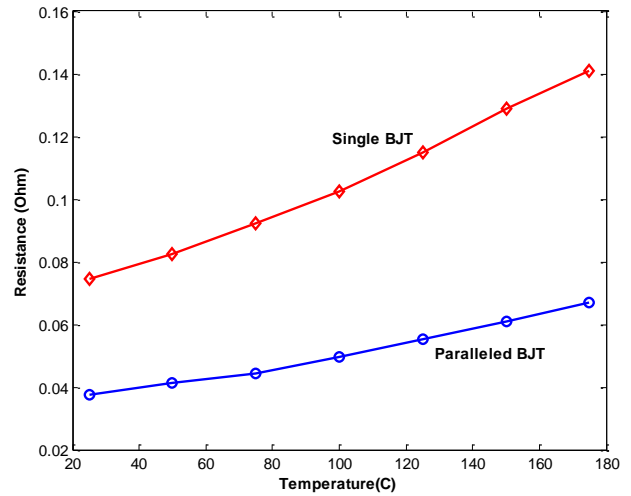


Fig. 3. On state resistance of SiC BJT.

Another important parameter of BJTs is current gain. Fig. 4 and Fig. 5 show the current gain for single and paralleled BJTs over a temperature range. The gains were measured at a fixed collector-emitter voltage to ensure that the BJTs are in the forward active region. The figures illustrate that the gain decreases as the temperature increases and the gain increases with increase in collector current. The increasing gain with the collector currents suggests that this device is suitable for higher current operation. The range of gain for the parallel device is much higher than the single device at all temperatures. This shows that the gain also scales proportionally with the device base current.

The leakage current of the single device was obtained over the temperature range of 25°C to 150°C and up to 600 V (Fig. 6). The voltage was limited to 600 V, because the leakage current was of interest rather than the avalanche characteristics of the device. At, 600 V the leakage current increased from 1.3 uA at 25°C to 3.6 uA at 150°C.

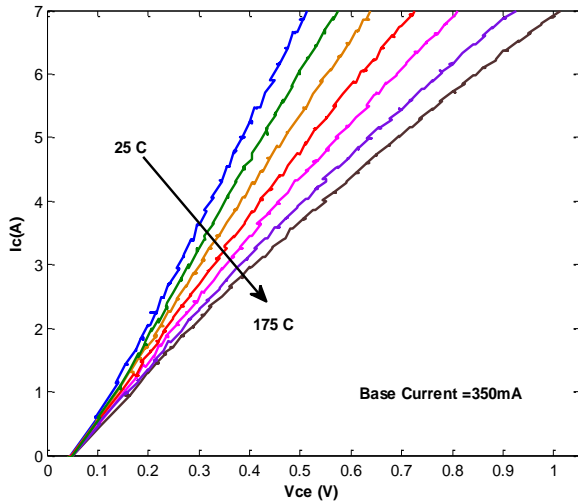


Fig. 1. Forward characteristic of single SiC BJT.

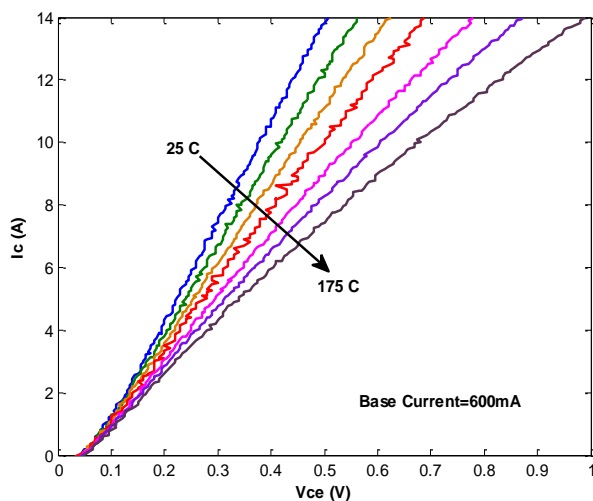


Fig. 2. Forward characteristics of two paralleled SiC BJTs.

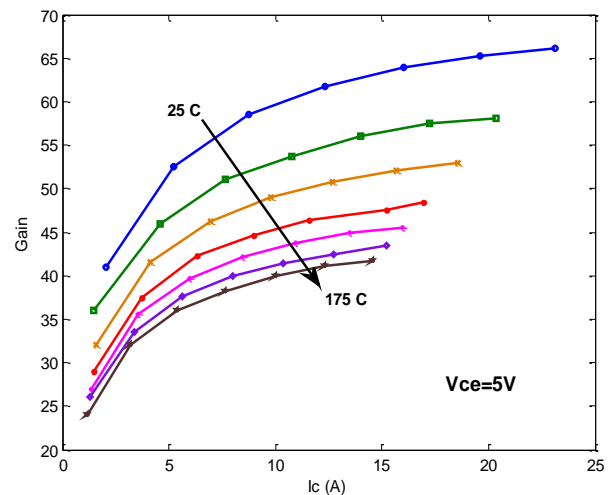


Fig. 4. Gain of single SiC BJT.

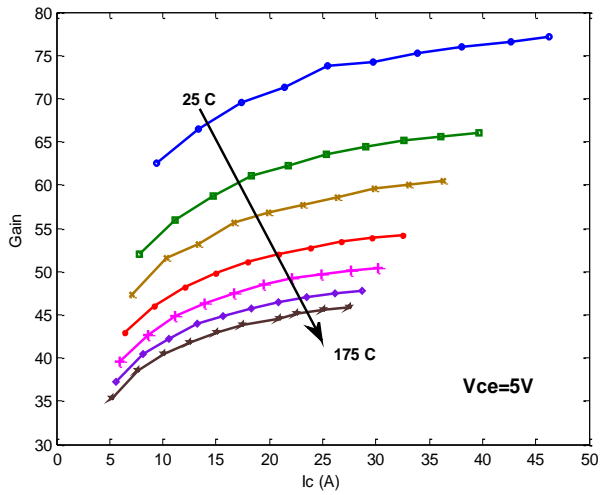


Fig. 5. Gain of two paralleled SiC BJTs.

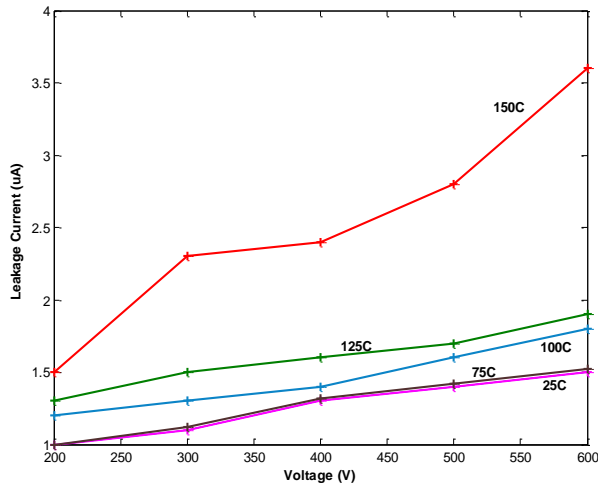


Fig. 6. Leakage current of single SiC BJT.

B. Junction Field Effect Transistor

The forward characteristics of a SiC Junction Field Effect Transistor (JFET) rated at 1200 V, 20 A were also obtained for both single and paralleled devices at different temperatures from 25 °C to 175 °C as shown in Fig. 7 and Fig. 8. The forward characteristics were obtained at a gate-source voltage of 3 V since it is a normally off device. The JFET also has positive temperature coefficient as shown in Fig. 8.

Fig. 9 shows the on state resistance for a single JFET and for two paralleled JFETs over a temperature range from 25 °C to 175 °C. As expected, the on state resistance for the two paralleled JFETs is approximately one half that of a single JFET.

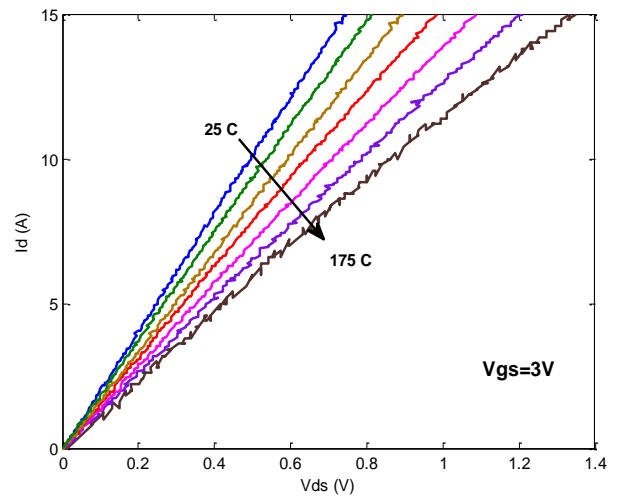


Fig. 7. Forward characteristic of single SiC JFET.

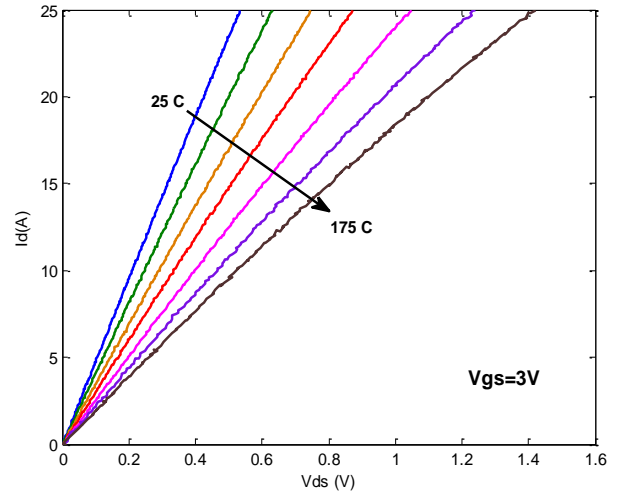


Fig. 8. Forward characteristic of two paralleled SiC JFETs.

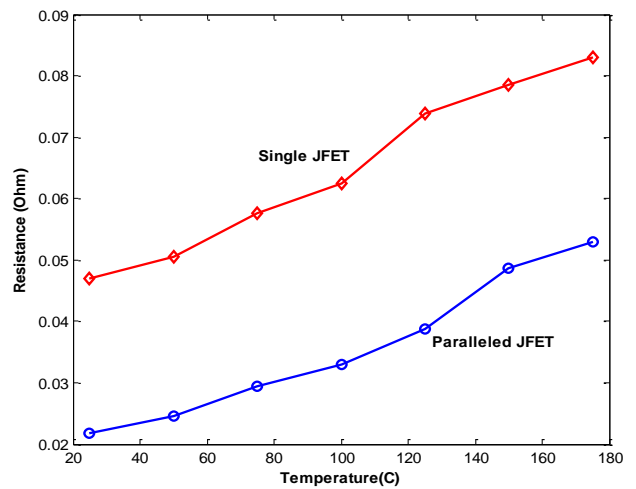


Fig. 9. On state resistance of SiC JFET.

Fig. 10 and Fig. 11 show the transfer characteristics of single and paralleled JFETs. The JFET is normally-off, so the threshold voltage is positive. The threshold voltage decreases with increase in temperature for both the single and paralleled devices. However, as shown in Fig. 12, the transconductance g_m of the paralleled devices is higher than the single device. This increase in g_m will impact the switching speed of the device as they are paralleled. For both the single and paralleled devices, the value of g_m decreases with increase in temperature.

The leakage current of the single device was obtained over the temperature range of 25°C to 150°C and up to 600 V (Fig. 13). The voltage was limited to 600 V because the leakage current was of interest rather than the avalanche characteristics of the device. At 600 V the leakage current increased from 37 μ A at 25°C to 46 μ A at 150°C.

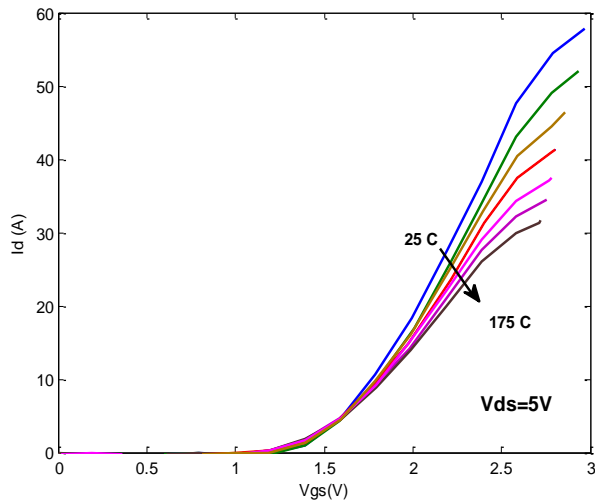


Fig. 10. Transfer characteristic of single SiC JFET.

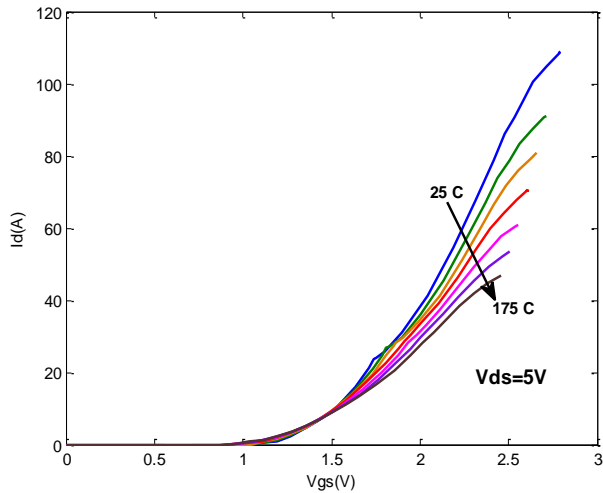


Fig. 11. Transfer characteristic of two paralleled SiC JFETs.

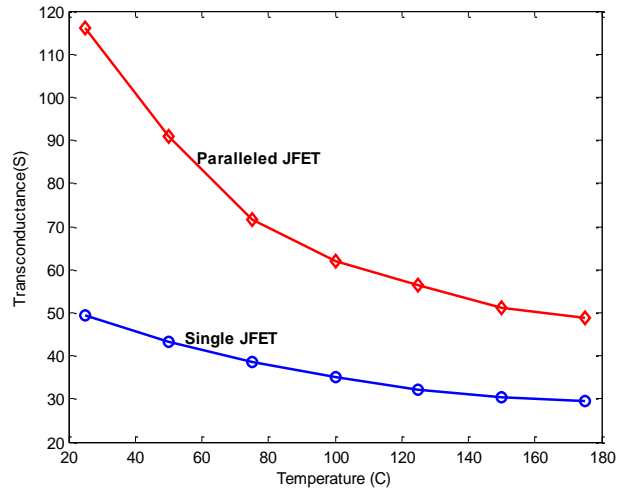


Fig. 12. Transconductance of SiC JFET.

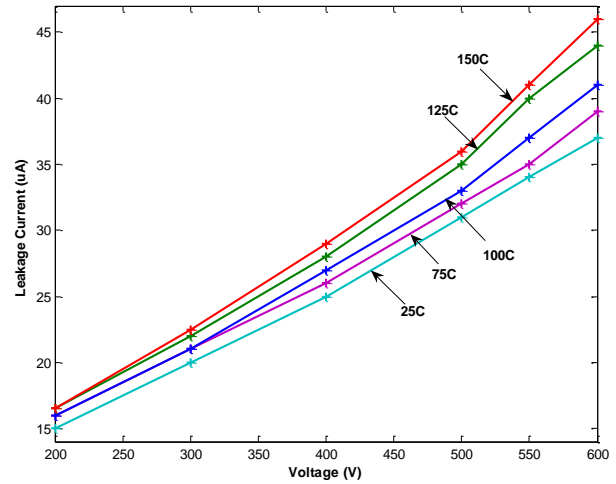


Fig. 13. Leakage current of single SiC JFET.

III. DRIVE REQUIREMENTS AND DESIGN

The drive requirements for the normally-off JFET and BJT are very similar even though the JFET is a voltage drive based device. Both devices require steady state current from the drive to keep the device turned on and a dynamic current several times higher than the steady state current during the turn on and turn off to achieve faster switching times. The JFET steady state current is much lower than the BJT, and maximum peak dynamic current is dependent on the internal gate/base resistance of the individual device. However, one major difference is the BJT does not require negative voltage to turn-off unlike the voltage controlled JFET. The output driver stage as shown in Fig. 14 for both devices is the same, and the values of the components were changed based on the requirements of the device.

A standard commercial driver IC from IXYS was used in the drive circuit for both devices. The driver IXDN509 can provide a peak output current of 9 A with a maximum output resistance of 1 Ω . The maximum rise time is 45 ns for a capacitive load of 10 nF with $V_{CC}=18$ V according to

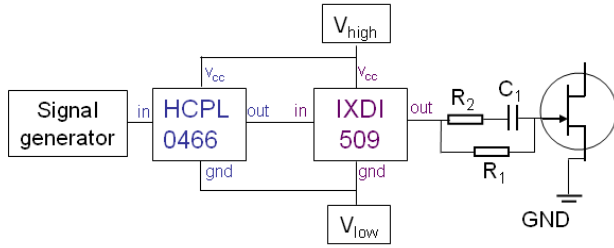


Fig. 14. Schematic of the drive circuit.

datasheet specifications. This feature enables the supply of a high dynamic base/gate current to the SiC BJT/JFET with short rise-time. However, parasitic inductance of the circuit and the connections from the driver to the BJT/JFET on the PCB become very critical to minimize the oscillations.

The output stage of the drive includes resistor R_2 and capacitor C_1 for transient current and parallel resistor R_1 for static current. The turn-on and turn off times of the devices are controlled by selecting the values of capacitor C_1 , and the resistor dampens the oscillation caused by C_1 and the parasitic inductance of the circuit. The higher the voltage of the gate drive, the higher the dynamic current will be for a given value of R_2 and C_1 . However, the value of R_1 has to be increased to limit the current to the required base current value. This results in higher power dissipation in the gate drive circuit. The V_{CC} range 5-15 V was investigated for the SiC BJT and the SiC JFET. Typically, a negative gate voltage is required for the SiC JFET to ensure that the device remains turned-off. For the SiC BJT, no negative voltage is required since it is a current driven device. A negative gate voltage of -15 V was chosen for the SiC JFET.

The resistor R_1 in the range of 3-5 Ω was tried for V_{cc} of 5V and 9-15 Ω for V_{cc} of 15 V. The capacitor C_2 in the range of 10-100 nF and the resistor R_2 in the range of 1-7 Ω was tried to achieve a high dynamic base/gate current during switching. As mentioned earlier, 15 V was chosen to increase the switching speed of the devices and the optimum values chosen for different passive elements are shown in Table I.

TABLE I. DRIVE PARAMETERS FOR SiC BJT AND JFET

	R_1 (Ω)	R_2 (Ω)	C_1 (nF)	V_{high} - V_{GND} (V)	V_{low} - V_{GND} (V)
Single BJT	15	1	22	15	0
Single JFET	15	5	22	15	-15
Parallel BJTs	10	3	100	15	0
Parallel JFETs	10	7	100	15	-15

IV. BJT AND JFET DYNAMIC CHARACTERISTICS

To characterize the SiC BJT and SiC JFET dynamically, switching measurements (double pulse test) were performed. A schematic of the circuit topology used in the switching measurements is shown in Fig. 15. The actual test setup is shown in Fig. 16. The same power board layout was used for both BJTs and JFETs for single and parallel

measurements. The load inductance of 120 μ H and a 1200V, 30 A SiC JBS freewheeling diode was used for all the tests. The equipment used in the measurements is Tektronix DPO 7104 1GHz, a TEK differential probe P5205 100 MHz, and a Pearson current probe 2877 MHz range bandwidth. Two current probes were used to measure the current through each device during parallel operation measurements. The dynamic behavior of the switches during the parallel operation of two BJTs or for two JFETs at 400V, 10 A (5 A each device) is shown in Fig. 17 and Fig. 18, respectively. The figure shows a very close match of the waveforms during turn-off. However, during the turn-on the device currents are slightly off and finally match after the ringing settles down. This mismatch during the initial transient during turn-on could be because of several factors like layout parasitic inductance or the difference in device parameters due to sample mismatch.

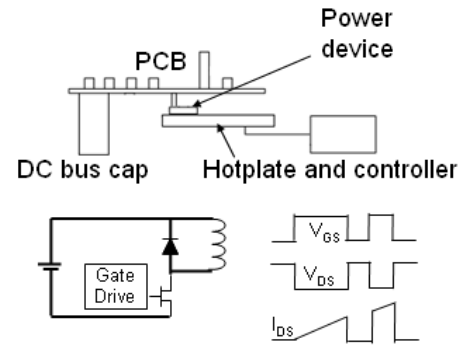


Fig. 15. Schematic of the double-pulse test setup.

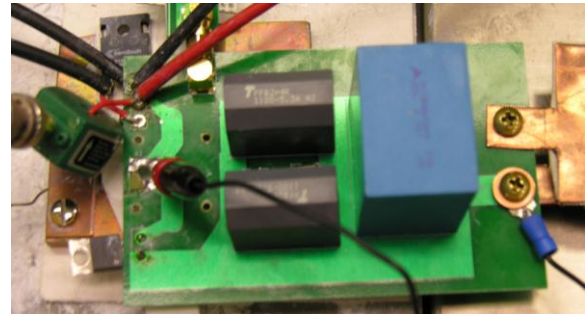


Fig. 16. Experimental test setup.

The device switching speed was slowed by changing gate voltage from +15V to +5 V thereby adjusting the peak gate current, and the currents of the devices matched perfectly as shown in Fig. 19. The currents were superimposed and they are so identical that the difference in the two waveforms could not be distinguished. This clearly shows that the faster transients could cause unwanted ringing due to the resonance of the circuit parasitics and cause mismatches. This also illustrates the importance of packaging for faster switching devices. The other interesting observation is the ringing in the JFET single and paralleled devices is much higher than the paralleled BJT even though the same diode was used for both tests. Again this difference

could be because of the parasitic inductance and device switching mechanisms. A detailed analysis is required to further explain the mismatch in the switching behavior during turn-on.

The total energy losses of the devices were obtained at 400 V, 600 V and at different currents up to 10 A for the single device and up to 20 A for the paralleled devices shown in Figs. 20-23. It should be noted that only switches were heated and not the diode so that the temperature effects of the diode would not affect the device measurements. The energy losses of a single BJT at 400 V are almost the same as the two paralleled devices at the same current. On the other hand, the two JFET paralleled device energy losses are two times more than the single device losses. However, at 600 V, the energy losses of paralleled BJT are almost two times the losses of the single device. While the JFET paralleled device losses are up to 1.5 more than the single device losses at 600 V.

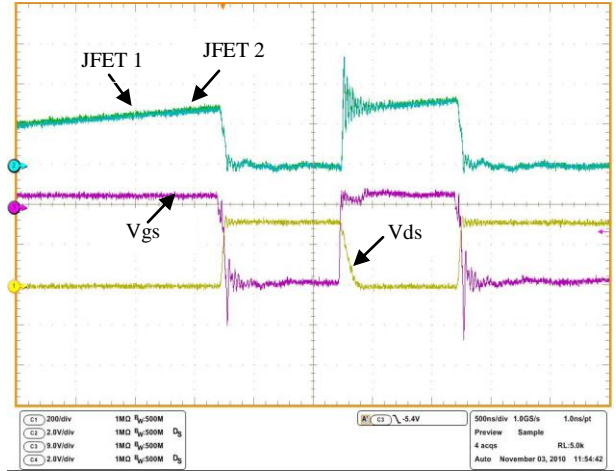


Fig. 19. Turn-on and turn-off waveform two paralleled SiC JFETs at 300 V and 5 A.

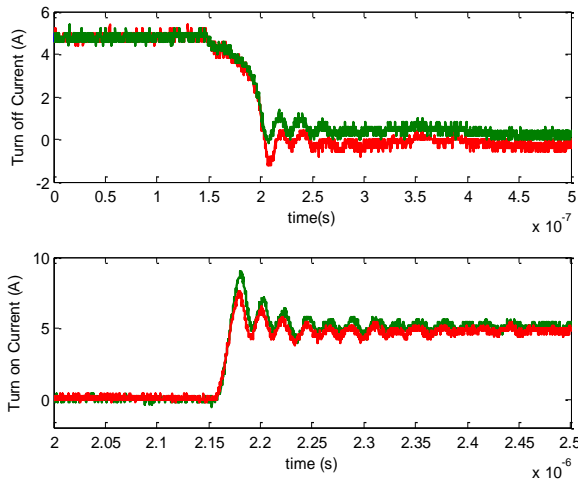


Fig. 17. Turn-on and turn-off waveforms of two paralleled SiC BJTs at 400 V and 10 A.

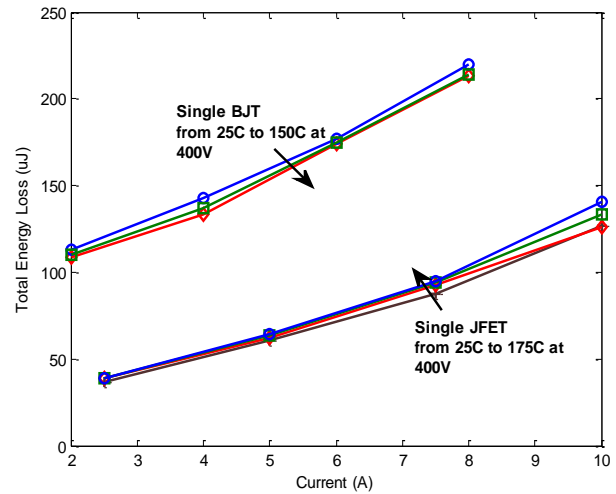


Fig. 20. Total energy loss of a single SiC BJT and a single JFET at 400V.

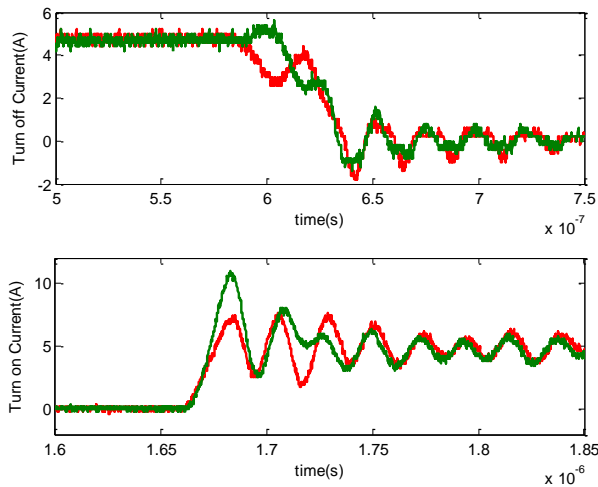


Fig. 18. Turn-on and turn-off waveforms of two paralleled SiC JFETs at 400 V and 10 A.

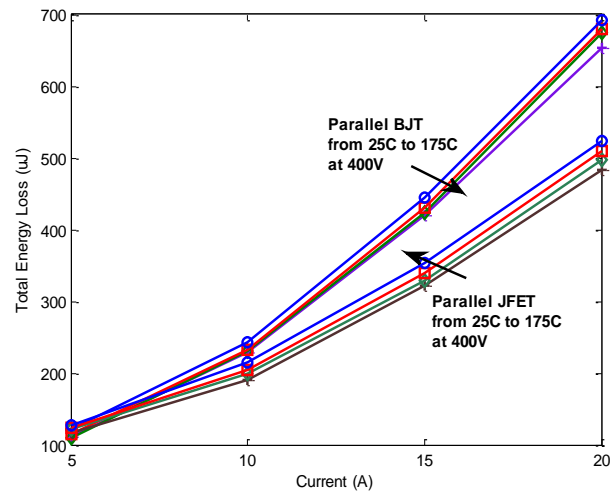


Fig. 21. Total energy loss of two paralleled BJTs and two paralleled JFETs at 400V.

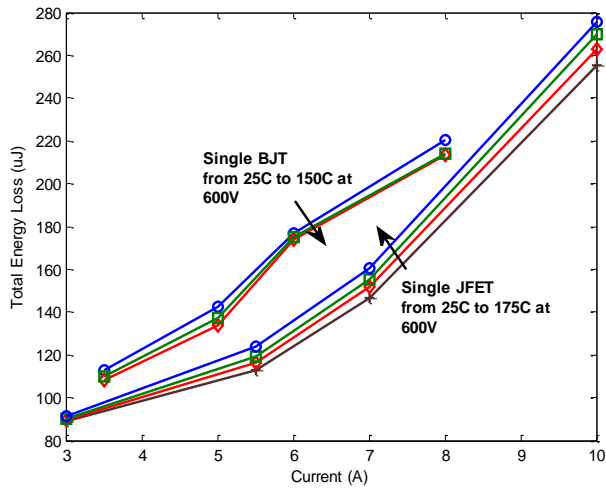


Fig. 22. Total energy loss of a single SiC BJT and a single JFET at 600V.

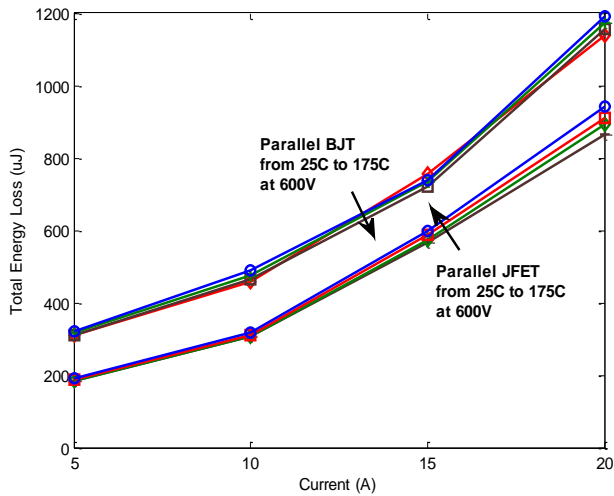


Fig. 23. Total energy loss of two paralleled BJTs and two paralleled JFETs at 600 V.

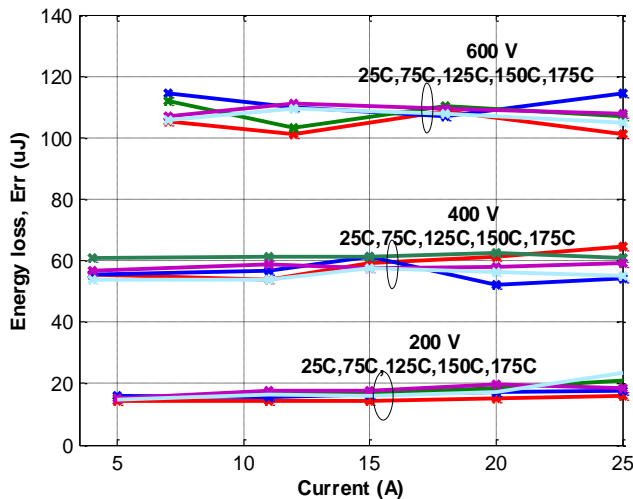


Fig. 24. Total energy loss of SiC JBS diode.

The SiC JBS diode was tested in the same chopper circuit as the SiC normally-off SiC JFET with double pulse switching to obtain its dynamic characteristics. The turn-off energy losses of the JBS diode at 200 V, 400 V, and 600 V over a wide temperature range are shown in Fig. 24. The turn-off losses do not change much with temperature or current exhibiting temperature independent switching loss behavior. However, the loss increases as the voltage increases. Only the dynamic characteristics of the diode are presented to show the effect of the diode on the energy loss of the switches.

V. CONCLUSIONS

The characterization of single and paralleled SiC JFETs and BJTs were presented. The static parameters like on-state-resistance, threshold voltage, current gains, transconductance, and leakage currents were extracted to show how these parameters would scale as the devices are paralleled. The dynamic current sharing between the paralleled devices was captured to show the effect of device drive and package on the device performance. The effect of the gate driver on the device transient behavior of the paralleled devices was studied, and it was shown that faster switching speeds of the devices could cause mismatches in currents shared during transients. However, both devices showed excellent current sharing capability during steady state current periods. The difference in energy losses of paralleled SiC BJTs compared to the single devices increased with increase in voltage. However, the difference in energy losses of paralleled SiC JFETs compared to the single devices decreased with increase in voltage.

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