Silicon Carbide Power Transistors for Photovoltaic Applications

S. Tiwari*, I. Abuishmais*, Member, IEEE, T. Undeland*, Fellow, IEEE, and K. Boysen**

Abstract—Silicon Carbide is the promising technology for the applications in high frequency, high voltage, high power and high temperature, principally due to their low conduction losses and fast switching capability. The aim of this paper is to test and evaluate the dynamic characteristics of SiC transistors and describe the utilization of full performance of SiC for photovoltaic applications. A standard double pulse test with a clamped inductive load has been used for dynamic characterization of the power transistors at different temperatures and load conditions.

Index Terms—Choppers, JFETs, Power Transistors, Snubbers, Wide band gap semiconductors.

I. INTRODUCTION

The advancement of power semiconductor devices has always been an impulsive force for power electronics system. Photovoltaic system needs efficient converters and inverters for power conversion. Silicon carbide has superior material properties. The wide band gap of SiC allows higher junction temperature thereby reducing heatsink size, cooling efforts, weight and cost of the converter [1]. High electric breakdown field allows thinner and shorter drift layer structures, resulting in very low specific on-state resistance even at higher blocking voltages thus reducing the conduction loss [2]-[3]. High thermal conductivity enables fabrication of high current density device and can operate at extremely high power levels and still dissipate the large amount of heat generated [4]. Higher saturation electron drift velocity significantly minimizes conduction as well as switching losses thereby increasing the efficiency. Radiation immunity empowers for higher operating voltages compared to silicon devices in higher voltage range with high ruggedness [5]. High switching frequency reduces the weight and cost of passive components thereby improving the power density [6].

Thus, SiC is beneficial for energy efficient operation of power conversion and power management as well as in improving the power density in PV system [7]. SiC transistors make possible to build single and three-phase inverters with a conventional bridge and bipolar switching with at least 98% maximum efficiency. Special circuits with additional freewheeling paths for unipolar switching, such as the HERIC® and H5 single phase inverters or three-phase three level inverters, can achieve maximum efficiencies of up to 99% [8].

The comparison of different semiconductor material properties is shown in Fig. 1 [9].

SiC power devices manufactured today have the maximum voltage rating 1700V, temperature 250°C and current 30 A.

Prior to the use of switching device in any converters, it is important to know its dynamic performance. Hence the double pulse test is performed in the chopper circuit with inductive load for studying the dynamic performance of the power device.

II. METHODOLOGY

The double pulse switching setup is the well-known method for studying the dynamic behavior of switching device both at turn-on and turn-off. The method makes convenient to record the turn-on and turn-off switching waveforms. Basically, this setup is an inductive load buck converter as shown in Fig. 2 where the switching device is tested by injecting the two switching pulses, composed of one long-pulse and one short-pulse, at the same time. The silicon carbide Schottky diode is used as freewheeling diode and has almost zero reverse recovery current, and acts only as a capacitance during turn-on and turn-off, thereby reducing the effects of reverse recovery and enabling high speed switching. After the injection of pulse at the gate, the drain source is biased so the DUT is turned-on and the current in the inductive load is ramped up to the value of interest. The transistor is then turned-off, and the turn-off waveforms are recorded. After the turn-off, almost constant current circulate in the inductance and the freewheeling diode as shown in Fig. 3. When the transistor is then turned-on after a short period of time, the turn-on waveforms, for almost the same current, are recorded. The DUT junction temperature is then simply controlled by hotplate so that the electrical measurements such as drain current and drain source voltage and switching waveforms can be recorded at different operating temperatures.

Fig. 1. Comparison of different semiconductor material properties
Switch Power Dissipation

Load, temperature coefficient of BJT and cosmic radiation during transition processes. The thinner structure also leads to lower charge requirement during transition processes. VJFET has no body diode. With positive temperature coefficient property, paralleling of the device is reliable at higher temperatures. Fig. 4 shows a cross-sectional view of a VJFET. Vertical channel develops between two gate trenches. Finger width (d) affects the nature of device operation i.e. normally-off or normally-on, and its current carrying capability.

The other alternative to SiC VJFET is Bipolar Junction Transistor (BJT). This normally-off, current controlled transistor is also free from turn-off tail current and has low on-resistance and positive temperature coefficient similar to JFET. It offers a great ability to withstand cosmic radiation and can work in an extended temperature range from −80 to +550 °C. SiC BJTs have a saturation voltage of roughly 0.5–1V depending on temperature. Fig. 5 is the example of the cross-sectional view of 4H-SiC BJT.

Both of these power devices are optimized for use in high-voltage, high-power, high temperature and high frequency power management applications and are designed to be the replacement for silicon MOSFETs and IGBTs. However, employing normal driver circuit e.g. MOSFET driver, to drive aforementioned SiC devices can lead to inefficient driving processes limiting transition speed and increasing switching losses.
The driver used for SiC VJFET is a two-stage gate driver optimized for high speed (frequency up to 250 kHz) and hard switching purpose [11]. The first driving stage provides a quick charging current to device input capacitance while the second stage which has lower voltage, maintain the device in on-state.

The driver-IC, TC4422 from Microchip, which has high current and high speed capability, is chosen to drive a SiC BJT. This driver can source and sink 9 A of peak current while producing voltage rise and fall times of less than 30 ns [12].

IV. TEST PCB LAYOUT DESIGN

For high switching frequency applications the layout design is significant and the following design guidelines is followed [13]-[14]-[15].

• The trace length in the high current power loop is minimized to reduce the stray inductance that may cause large over voltage during turn-off of the device.

• The small filter capacitor and damping resistor is added across the base/gate and emitter/source terminals to avoid oscillations and problem of retriggering at the turn-off of the device.

• The length of the trace that connects the base drive circuit to the source/emitter of the power device and between the drain of device and the diode is minimized to reduce stray inductance; otherwise unwanted oscillations may occur.

• The lead temperature for soldering the SiC devices is chosen to be 260˚C as the measurements are to be taken at various temperatures.

• The low power series R-C snubber circuit is added to reduce the high frequency ringing.

• The proper heat sink and snubber for the power devices are used.

V. DYNAMIC CHARACTERIZATION

For the calculation of switching energy, the range of integration time is taken from the current zero to voltage zero during the turn-on and from voltage zero to current zero during the turn-off. The oscilloscope used was Tektronix TDS2000B/200MHz; the single ended voltage probe was Tektronix P2220/200MHz and Rogowski coil was PEM CWT3/17MHz. As the measuring instruments have to track the waveforms with 10-15 ns of rise and fall time, the current waveforms were shifted to the left side by 42ns considering the delay of Rogowski coil.

A. JFET Switching

The switching waveforms for JFET at drain source voltage ($V_{DS}$) =250V and drain current ($I_D$) =20A at normal room temperature (20˚C) is shown in Fig. 6. CH1 represents $I_D$, CH2 is gate source voltage ($V_G$) and CH3 is $V_{DS}$. The details of transition i.e. the turn-on and turn-off waveforms are shown in Fig.7 and Fig. 8 respectively.

The effect of stray inductance on the switching waveforms was also analyzed by simulation in LT-spice. It is apparent that the layout optimization is indispensable for reducing the ringings in order to realize the fast switching for obtaining high efficiency.

![Fig. 6. Switching waveforms $V_{DS}=250V$, $I_D=20A$](image6)

![Fig. 7. SiC-VJFET turn-on waveform, $V_{DS}=250V$, $I_D=20A$](image7)

![Fig. 8. SiC-VJFET turn-off waveform, $V_{DS}=250V$, $I_D=20A$](image8)
Considering the delay in the current measurement coil, $I_D$ during the turn-on reaches its maximum value when $V_{DS}$ starts to collapse. The voltage plateau seen before this voltage start to drop is caused by parasitic inductance between the DC sources i.e. decoupling capacitors and the chopper leg. Moreover, voltage ringing seen when device is fully on is dependent on parasitic inductance in series with clamping diode. Same ringings during the turn-off can be observed. It is evident that to realize fast switching with low switching loss, optimizing circuit structure to avoid parasitic inductance is the must.

Fig. 9 elucidates that the switching energy losses increase with increasing current and is minor dependency on temperature. Total switching energy is considerably low compared to counterpart Si device. This boosts PV inverter efficiency and enables higher switching frequency inverter with smaller passive elements.

**B. BJT Switching**

An important feature of the drive circuit is the 22 nF capacitor parallel to the 56 Ω external base resistor connected between the output of driver and the base of BJT. The capacitor speeds up turn-on and turn-off by providing high dynamic forward and reverse drive charging currents to the BJT base. The high dynamic base current is required mainly for charging the BJT parasitic base-collector capacitance and turning on the base-collector diode. The constant drive voltage is applied to the driver IC, TC4422, thereby the constant voltage in the base of BJT for all collector current levels and hence the base current is approximately constant for all collector current levels.

The switching waveform at collector-emitter voltage ($V_{CE}$) =200V and collector current ($I_C$) =6A at normal room temperature (20°C) is shown in Fig. 10. Here CH1 represents input control signal to driver IC, CH2 is base current $I_B$, CH3 is $V_{CE}$ and CH4 is collector current $I_C$. The voltage applied to RC network at device base is shown in Fig. 11 CH1. Current and voltage at device base are designated with CH2 and CH3, respectively. The effect of speed up capacitor is clear as it provides a negative voltage across base-emitter speeding up turn-off transient. This negative voltage forces the sweep out of minority carriers from the base.

**Fig. 10. Switching waveforms $V_{CE}=200V$, $I_C=6A$**

**Fig. 11. Base voltage and current waveforms**

The turn-on and turn-off waveforms for BJT are shown in Fig. 12 and Fig. 13 respectively.

**Fig. 12. SiC-BJT turn-on waveform, $V_{CE}=200V$, $I_C=6A$**
The ringings which appear in the voltage and the current waveforms in Fig. 12 and Fig. 13 is due to the stray inductance between the collector of BJT and diode. The current rise in Fig 13 is due to the inductance between the emitter and the ground. These ringings were also analyzed from the device simulation and found to be in good agreement with measurements.

It could also be observed that with the increase in DC-link voltage, the rise and fall time of collector-emitter voltage \( (V_{CE}) \) was also increased as the ramping rate is related to charging/discharging rate of the base-collector parasitic capacitance.

The table 1 summarizes the turn-on, turn-off time and energies at different temperature for \( V_{CE}=200V \).

<table>
<thead>
<tr>
<th>Temp(°C)</th>
<th>Ic (A)</th>
<th>T-on (ns)</th>
<th>T-off (ns)</th>
<th>E-on (µJ)</th>
<th>E-off (µJ)</th>
<th>E-Total (µJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_j = 20 )</td>
<td>2</td>
<td>80</td>
<td>68.3</td>
<td>17.846</td>
<td>21.993</td>
<td>39.839</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>85</td>
<td>59</td>
<td>20.762</td>
<td>35.135</td>
<td>55.897</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>102</td>
<td>57</td>
<td>34.368</td>
<td>42.673</td>
<td>77.041</td>
</tr>
<tr>
<td>( T_j = 50 )</td>
<td>2</td>
<td>81.01</td>
<td>67.7</td>
<td>22.193</td>
<td>9.4065</td>
<td>31.5995</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>87</td>
<td>57.1</td>
<td>29.499</td>
<td>20.535</td>
<td>50.034</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>104.01</td>
<td>54.4</td>
<td>39.012</td>
<td>29.37</td>
<td>68.382</td>
</tr>
<tr>
<td>( T_j = 100 )</td>
<td>2</td>
<td>80</td>
<td>67</td>
<td>22.838</td>
<td>11.052</td>
<td>33.89</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>98</td>
<td>54.97</td>
<td>26.446</td>
<td>19.998</td>
<td>46.444</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>110.5</td>
<td>49.7</td>
<td>64.286</td>
<td>27.74</td>
<td>92.073</td>
</tr>
<tr>
<td>( T_j = 150 )</td>
<td>2</td>
<td>90</td>
<td>66.2</td>
<td>22.734</td>
<td>21.339</td>
<td>44.073</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>54.6</td>
<td>35.646</td>
<td>24.493</td>
<td>60.139</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>112.3</td>
<td>47.65</td>
<td>51.897</td>
<td>31.743</td>
<td>83.64</td>
</tr>
</tbody>
</table>

Fig. 14 illustrates the variation of switching energy with collector current and temperature. It is evident that the switching energy losses increase with increasing collector current. The turn-on energy loss is lower than turn-off energy loss at normal room temperature but vice versa at high temperature. In fact, it could be observed from the switching waveform that turn on time increases with increasing temperature and turn-off time decreases with increasing temperature. Therefore, in overall the total switching energy losses are almost uniform at all temperature.

**Fig. 13.** SiC-BJT turn-off waveform, \( V_{CE}=200V \), \( I_C=6A \)

**Fig. 14.** Variation of switching energy with collector current and temperature

As the load current increases, the BJT turn-on speed slows down and the turn-off speed ups. Since the constant drive voltage is applied to the base for all collector current levels and hence the base current is approximately constant for all collector current levels. Therefore, there is an increase in the turn-on time even if the current gain, beta was constant independent of the collector current level since it would take longer to inject the higher stored charge needed for larger collector currents.

The reduction in turn-off times at increasing collector current levels is observed. This is due to the fact that higher collector current, when the base current and DC-link voltage are kept constant, the shorter the time needed to discharge device capacitances during turn-off.

**VI. CONCLUSIONS**

The results from double pulse test performed on SiC VJFET and SiC BJT are illustrated. Turn-on and turn-off times and energy losses are calculated. The two SiC transistors prove ability of fast switching with low losses. PV inverters could significantly benefit from these devices. Inverter efficiency can be improved due to reduced switching losses and low on-state resistance that SiC devices offer. These losses have a low dependency on operating temperature which means stable operating for PV inverters at elevated temperatures. This reduces thermal management requirements e.g. active cooling and heatsink size. The high switching frequency feature leads to smaller passive elements size and thus compact, high power density inverters.

**VII. REFERENCES**


for SiC-JFETs”, Proceedings PCIM Europe 2009 Conference, pp. 431-437


VIII. BIOGRAPHIES

Subhadra Tiwari obtained her Bachelor in Electrical Engineering from Tribhuvan University, Kathmandu, Nepal in 2007. She is currently working on her Master Degree in Electrical Power Engineering in Norwegian University of Science and Technology (NTNU). Her research interests are Power electronic application for renewable energy and power system modeling and control.

Ibrahim Abuishmais (SM’00–M’05) is born in 1982. He got his master degree in Electric Power Engineering from Chalmers University of Technology in 2007. Currently he is a Ph.D. candidate at Norwegian University of Science and Technology. His research interest includes SiC power electronic devices, subsea power electronics and high temperature electronics.

Tore M. Undeland (M’86–SM’92–F’00) is Professor of power electronics, Norwegian University of Science and Technology, Trondheim, Norway, teaching since 1972, as a Professor since 1984. He has published in the field of power converters, snubbers, and control in power electronics. He has co-written the book Power Electronics: Converters, Applications, and Design (New York: Wiley, 2003). Dr. Undeland was the Chairman of the EPE 1997 Conference, Trondheim, and is presently Vice President of EPE. He is active as AsCom Member, IEEE Power Electronics Society, where he also has been a Distinguished Lecturer.

Kjetil Rostoft Boysen got his master degree in Electrical Power Engineering at the Norwegian University of Science and Technology (NTNU) in 2000. He has since 2000 worked as a development engineer within the field of Power Electronics. He is currently working as Power Electronics manager for Eltek Valere Renewable energy. His field of interests are designing and controlling high efficiency inverters in for photovoltaic applications.