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Power Loss Estimation in SiC Power BJTs

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Abstract

Silicon Carbide (SiC) Bipolar Junction Transistors (BJTs) are promising power devices for high power and high temperature applications. For the improvement of transient speeds, effect of the driver base capacitor and anti-saturation diode are studied. To outline their switching performances, SiC BJTs with a blocking voltage of 1200 V are characterized under different base and load currents. Switching speeds and losses are investigated for temperature as high as 200°C.

1. Introduction

Silicon Carbide (SiC), as a wide band gap semiconductor material, is a promising candidate material for the next generation power devices, due to its superior physical and electrical properties [1-4]. High critical field and wide band gap make SiC material attractive for high power, and high temperature applications when compared to silicon. Moreover material properties make SiC a good candidate for high switching frequency conversion systems. The need for SiC power devices with excellent operation performances is therefore growing.

SiC bipolar junction transistors (BJTs) allow to reduce the conduction losses substantially. As the SiC BJT solves the issue of “second breakdown” [5], it also shows a strong robustness under extreme operating conditions. Both of them result in the SiC BJT having more reliability and more efficiency in the high power applications.

This paper, in the first step, presents the electrical and calorimetric power loss measurement [6]. A comparative study is performed between them by measuring 1200 V SiC BJTs losses for a frequency ranging from 100 kHz to 600 kHz. After that, the effect of the base driver capacitor in the driver circuit (responsible for a base current over-shoot) and the use of an anti-saturation diode on the SiC BJTs switching transients is investigated. SiC BJTs switching characteristics and losses are measured under 600 V for different base currents and under different load current conditions. Finally, SiC BJTs are characterized for temperatures up to 200°C.

2. Experimental bench

Fig.1 shows a circuit including a typical buck converter with an inductive load and a base driver circuit for switching the SiC BJT. To ensure galvanic isolation, a high-speed digital insulator (HCPL9000) is connected to a fast driver (IXDD614PI) by which desired base signals are processed. The driver voltage is switched between -8 V and +11 V. An adjustable resistor R_b is used to set up the base current and a capacitor (connected in parallel) is used to rapidly charge/discharge the SiC BJT input capacitance by applying an over-shoot and under-shoot respectively at turn-on and at turn-off.

The experimental bench allows us to measure the base-emitter voltage with a Tektronix P6139B probe (10X, 500MHz), the collector-emitter voltage with a Tektronix P5100A probe (100X, 500MHz), the collector current with a shunt of 0.01Ω and the base current with a Tektronix TCP0030 probe (120MHz).

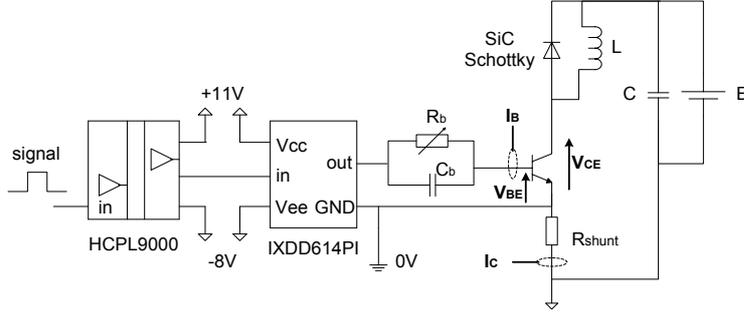


Fig. 1. Circuit diagram of the test setup.

3. Power loss measurement

The power loss measurement for high speed power semiconductor devices is crucial. Calorimetric determination of switching device losses results in a high accuracy by measuring the dissipated heat [7-8]. However, for all characterization measurements, it is essential to limit the self heating effects by the use of a “double pulse” method [9] that produces very short test pulses ($<8\ \mu\text{s}$) and does not heat up the DUT. Double pulse method allows determining switching losses at different junction temperature by controlling case temperature of the DUT. In the case of that, the electrical method is proposed to measure the power losses after demonstrated to be sufficient accurate, which is detailed in the section 3.

3.1. Electrical method

Power losses in power switching devices are the combination of the conducting and switching losses. Assuming the collector-emitter on resistance $R_{CE(on)}$ and the threshold voltage $V_{CE(th)}$ are known based on static characterization, the conducting losses can be calculated by (1).

$$P_{cond} = V_{CE(th)}\langle i(t) \rangle + R_{CE(on)}\langle i(t)^2 \rangle. \quad (1)$$

In the case of high-frequency switching ($>100\ \text{kHz}$) systems, switching losses are dominating. The switching energy losses (E_{sw}) are divided into the turn-on energy (E_{on}) and turn-off energy (E_{off}) which is independently calculated by integrating the instantaneous dissipated power, the product of collector current and collector-emitter voltage, over the turn-on and turn-off duration. Calculation of E_{on} and E_{off} are not representative for dissipated energy during each switching; only the total energy has a physical meaning.

3.2. Calorimetric method

As power losses of power devices are dissipated as heat, assuming the heat is completely absorbed by a medium assembled to the device under test (DUT). The power losses can be directly determined by measuring the temperature elevation of the medium. In the case where the heat dissipation to the outside can be neglected, the power dissipation, P_{loss} , of the DUT, equal to the increased heat, ΔP_{med} , in the medium, can thus be determined as function of medium heat capacity $C_{th,med}$, its temperature rise $\Delta\theta_{med}$ and test duration Δt is given by (2).

$$P_{loss} = \Delta P_{med} = C_{th,med} \Delta\theta_{med} / \Delta t. \quad (2)$$

$\Delta\theta_{med}$ is measured by a thermocouple and Δt is recorded by using a stopwatch. In this work, an aluminum block is used as the medium and a dedicated experimental circuit used to

determine the block heat capacity C_{th} is developed (fig.2 (a) and (b)). The MOSFET is mounted into the same package (TO 247) as that of the SiC BJT for the thermal calibration. A Zener diode keeps the drain voltage approximately constant thereby imposing constant power dissipation on the MOSFET as well. Fig.2 (c) shows the temperature variation of the block with test duration for a dissipated power fixed to 20 W for all four calibration tests which have been done at different ambient temperatures. The heat starts to transfer from the DUT to the block and the temperature ramps linearly 10 seconds after the beginning of each test. As the power dissipation, the increase in the temperature and test duration are known, the average of the block heat capacity C_{th} for four tests is estimated around 58.4 J/K over time interval from 20 to 60 seconds after the heat diffusion into the block. Losses in the SiC BJT then can be estimated by using the calibrated aluminum block, after a delay of about 20 seconds when linear region of the temperature occur which is similar to the fig.2 (c).

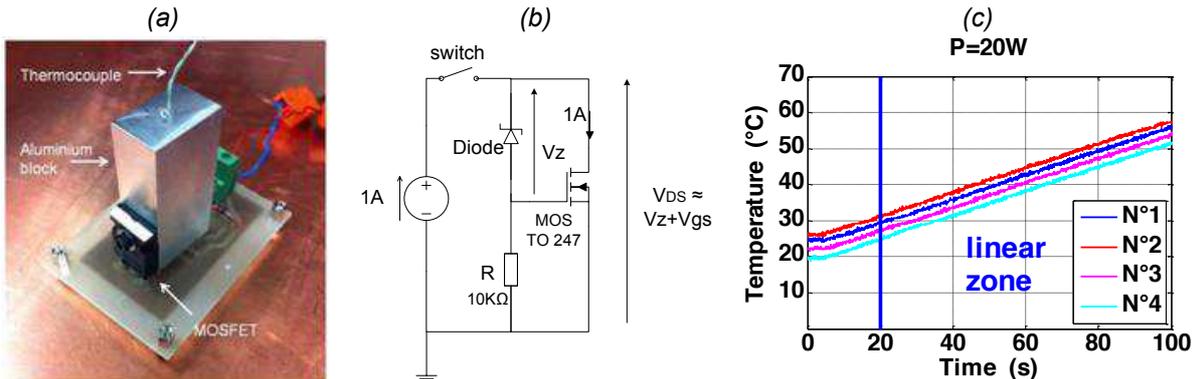


Fig. 2. heat capacity measurement, (a) photograph of the thermal calibration circuit board (b) principle schematic and (c) variation of temperature during calibration process.

3.3. Comparative results

Two power loss measurements of the SiC BJT have been simultaneously performed for a DC bus voltage of 265 V with a switching frequency ranging from 100 kHz to 600 kHz. A digital scope records switching transient. Fig.3 shows an example of the transient response at the frequency of 100 kHz. Turn-on and turn-off losses are estimated respectively at 3.39 W and 0.79 W by electrical measurement. The sum of them corresponding to the total switching losses, E_{sw} , is 4.18 W. The switching losses can be estimated at higher frequency by the same method.

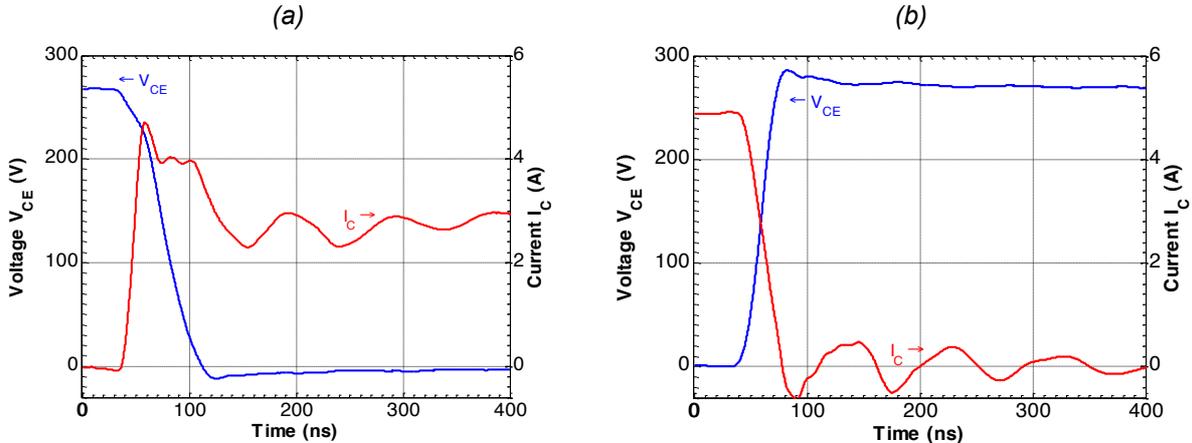


Fig. 3. Switching behavior (a) at turn-on and (b) at turn-off.

The calorimetric losses measurement is not carried out at a fixed junction temperature, but the next part of this paper will prove the weak temperature dependence of the power losses in BJTs.

For the calorimetric power loss measurement, similar to the fig.2 (a), the calibrated aluminum block is connected to a SiC BJT mounted into the buck converter in order to monitor the variation in temperature by a thermocouple over a measuring duration. The measuring duration is reduced as we increase the switching frequency in order to limit an excessive junction temperature. The power losses estimated by calorimetric measurement are shown in table 1.

Frequency (kHz)	100	200	300	400	500	600
Measuring duration (s)	60	60	60	50	40	30
Initial temperature (°C)	30.7	31.7	31.2	31.0	31.0	31.9
Final temperature (°C)	35.8	43.1	48.2	49.6	50.2	49.0
Power losses (W)	4.96	11.10	16.55	21.73	28.03	33.29

Table 1 dissipated power measured by calorimetric method at 100 kHz to 600 kHz

Fig 4 reports that the computation deviation of these two methods is less than 1 watt, while only the switching losses are estimated by electrical method. In addition, based on the static characteristics and the equation (1), the conduction losses are estimated to be in the range of 0.58 W to 0.73 W for junction temperatures ranging from 25°C to 150°C, which can explain the error between calorimetric and electric measurements.

This demonstrates that the determination of total switching losses by electrical method is sufficiently accurate for our study. In the following section, it will be used to estimate switching losses, instead of calorimetric measurement, as the double pulse method does not heat up the device.

4. SiC BJT switching characteristics

The double pulse test is well known for switching measurement, as shown in fig.5. The current in the inductance first increases up to the desired value. At the end of the first pulse, the turn-off waveform can be recorded. After turn-off, the current decreases slightly through the freewheeling diode until the transistor is turned-on again, allowing us to record the turn-on waveform.

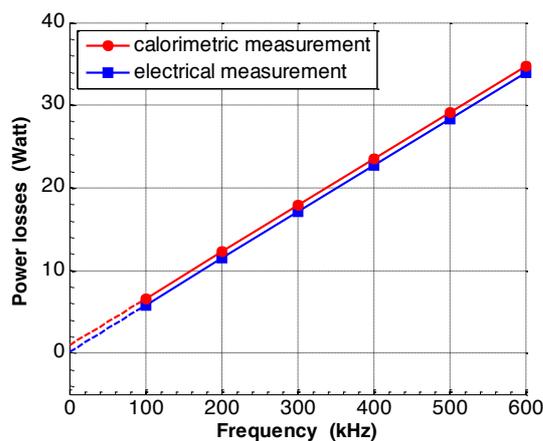


Fig. 4. Estimation of power losses by two methods

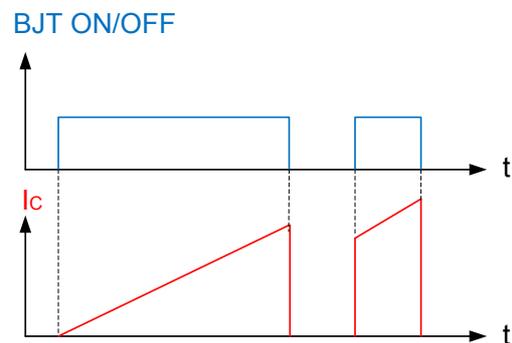


Fig. 5. Double pulse waveform

In high power and high frequency conversion systems, the rise and fall time of voltage and current and switching losses are significant switching performance parameters.

The influence on the switching characteristics of a base capacitor C_b and of an anti-saturation diode D_{AS} , are studied. Meanwhile, the tests have been realized under various base current, load current and junction temperature.

4.1. Influence of base current over-shoot

The purpose of this test is to optimize the value of the base capacitor, C_b , as shown in fig.7, to improve the switching speed for low base current ($I_B = 0.4$ A). The base current pulse presents a wider and higher over-shoot for higher values of the capacitor, which is expected. The SiC BJT turn-on speeds up while the capacitance value increases up to 22 nF (fig.6). This is caused by faster charging base-emitter capacitance and a faster injection of charges in the base of the BJT. For capacitors of 22 nF and 47 nF, the voltage fall times are almost the same, as the base currents through the BJT are very close until the end of turn-on. Turn-off speeds, however, show no significant change for different values of the base capacitor. It can be seen that the optimization of the base capacitor can only improve the turn-on speed and has no significant effect at turn-off. This is probably due to the very low level of stored charge in the base and drift regions, which does not require extraction of charge by the base at turn-off. In the following sections, it is easier to study the effects of other parameters on the switching performance when the capacitor of 3.3 nF is mounted into the driver circuit.

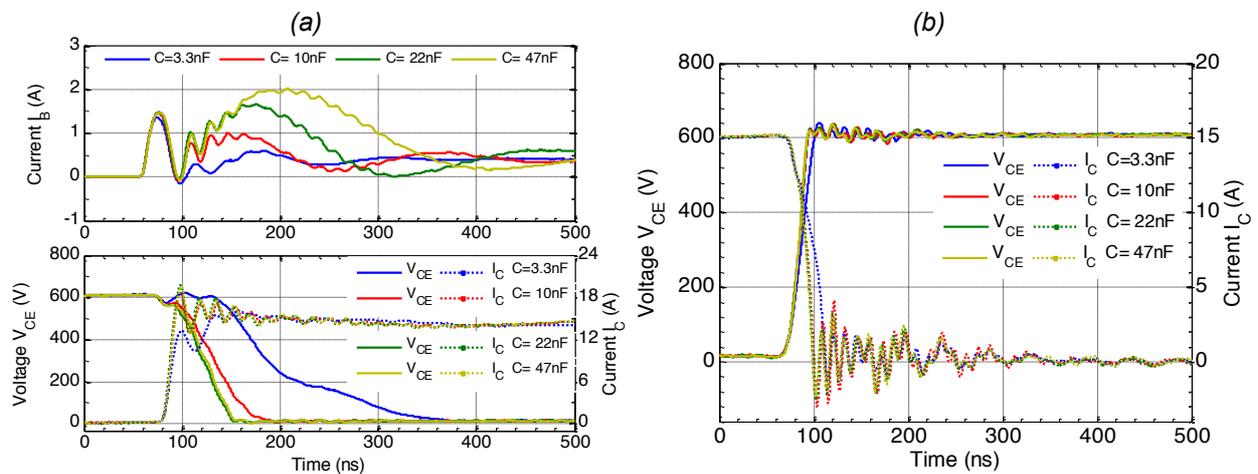


Fig. 6. Switching transients at $I_B = 0.4$ A, $I_C = 15$ A and DC bus voltage of 600 V for $C_b = 3.3$ nF, 10nF, 22nF and 47 nF (a) turn-on and (b) turn-off.

4.2. Effect of anti-saturation diode

The excess base current increases stored charges in the SiC BJT, which increases the turn-off time. The anti-saturation diode D_{AS} (fig.8) is a SiC Schottky diode (Cree C2D05120A) connected in parallel to the collector and base electrodes of the SiC BJT to reduce the storage time. It ensures that SiC BJT always operates in quasi-saturation while turned-on.

Fig.9 reports the effects of an anti-saturation diode on switching waveforms. Current and voltage rise/fall times are substantially increased by using an anti-saturation diode. This is due to an additional parasitic capacitance between base and collector generated by the additional diode. A greater amount of base-collector storage charge is needed.

The reduction of the turn-off time is not observed by using anti-saturation diode, which confirms the very low level of charge stored in the SiC BJT and the anti-saturation diode is not necessary for the SiC BJT under test in comparison to the silicon BJT.

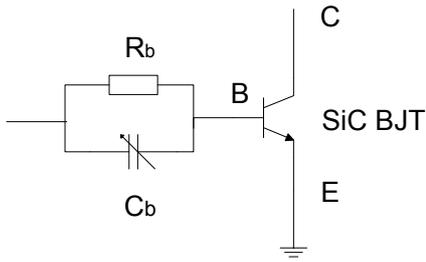


Fig. 7. BJT driver: $R_b = 15 \Omega$, $C_b = 3.3 \text{ nF} \sim 47 \text{ nF}$

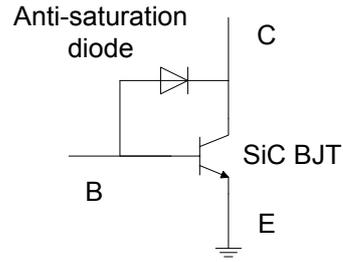


Fig. 8. SiC BJT with anti-saturation diode

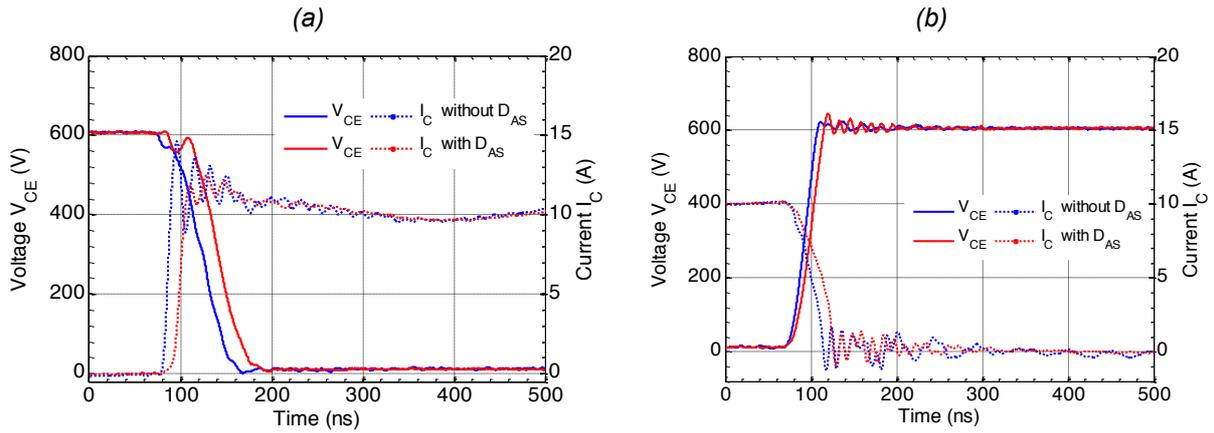


Fig. 9. Switching transients at $I_B = 1.2 \text{ A}$ and $I_C = 10 \text{ A}$ with/without clamping diode (a) turn-on and (b) turn-off

4.3. Effect of base current level

The SiC BJT is tested for bus voltage of 600V and collector current of 10 A, with base current of 0.4 A, 0.8 A and 1.2 A during on-state. The rise/fall times of the collector current as well as the voltage rise time (23 ns – 25 ns) are very fast and independent of the base current. The voltage fall time nonetheless decreases as the base current increases, as shown in fig 10. This is explained by faster charging the emitter-base capacitance and discharging base-collector capacitance at a higher base current. The switching losses of the SiC BJT decrease when base current increases, as shown in table 2.

Base current (A)	0.4	0.8	1.2
E_{on} (μJ)	563	328	274
E_{off} (μJ)	80	88	89
E_{total} (μJ)	643	416	363

Table 2 turn-on, turn-off and total switching losses of the SiC BJT at $I_C = 10 \text{ A}$, $T = 25^\circ\text{C}$

4.4. Effect of collector current

The SiC BJT is also tested at $I_B = 1.2 \text{ A}$, for load current $I_C = 10 \text{ A}$ and 15 A. Fig.11 shows how the turn-on speed slows down when load current increases. The reason is that, for $I_C = 15 \text{ A}$, a higher di/dt induces a stronger negative feedback from the parasitic emitter inductance on the base-emitter voltage.

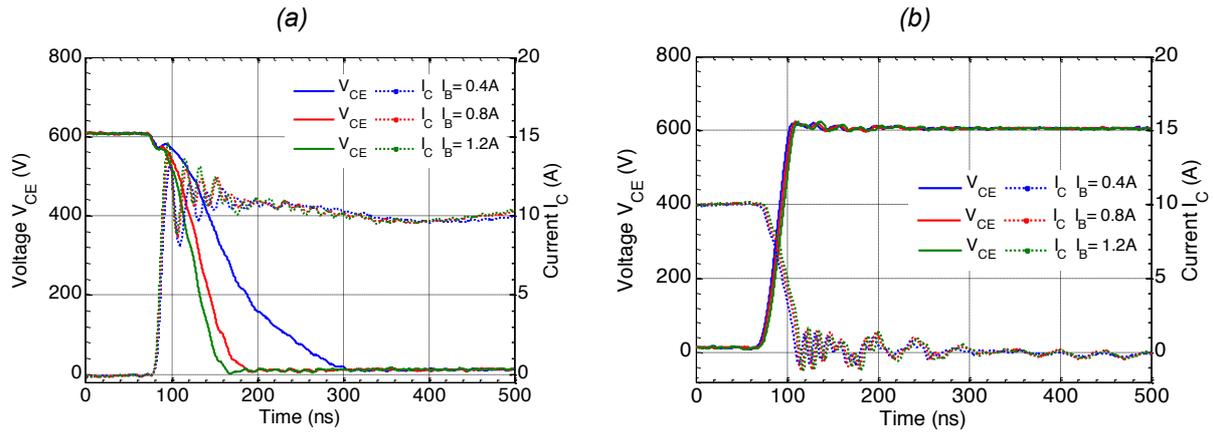


Fig. 10. Switching transients at $I_C = 10$ A for $I_B = 0.4$ A, 0.8 A and 1.2 A (a) turn-on and (b) turn-off

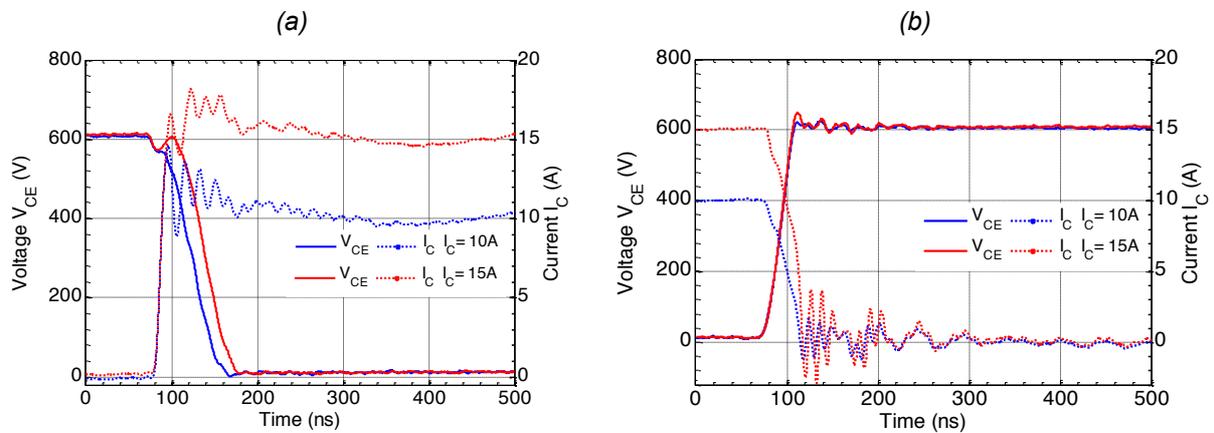


Fig. 11. Switching transients at $I_B = 1.2$ A for $I_C = 10$ A and 15 A (a) turn-on and (b) turn-off

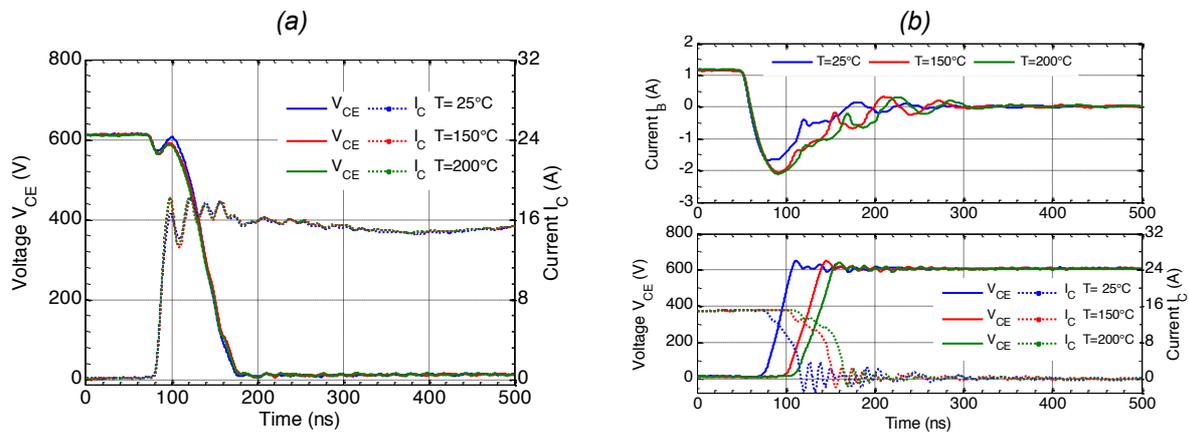


Fig. 12. Switching transients for $T = 25^\circ\text{C}$, 150°C and 200°C (a) turn-on and (b) turn-off

4.5. Effect of junction temperature

Switching transients are achieved at $I_B = 1.2$ A and $I_C = 15$ A for temperatures of 25°C , 150°C and 200°C . The waveforms reveal unchanged turn-on speeds at temperatures as high as 200°C and a temperature dependence of charge storage time at turn-off. The charge storage time refers to a time interval between base current falling into zero (before it reverses the direction) and the collector-emitter voltage starts to increase from 40 ns at 150°C to 50 ns at

200°C. This indicates that charge storage time increases with increasing junction temperature. Furthermore, turn-off losses are increased by around 33% at high temperature, as shown in table 3. Therefore, exceedingly high temperature slows down the BJT turn-off speed and lightly rises up the dissipated energy at turn-off.

Temperature (°C)	25	150	200
E_{on} (μJ)	518	520	513
E_{off} (μJ)	184	233	242
E_{total} (μJ)	702	753	755

Table 3 turn-on, turn-off and total switching losses of the SiC BJT at $I_B=1.2$ A, $I_C=15$ A

5. Conclusion

In this paper, the first section presents electrical and simplified calorimetric measurement of power losses. The comparable results validate accuracy and reliability of the electrical determination of the SiC BJT power losses. It can be used to estimate the switching power losses in the SiC BJT.

In the second part, switching behaviors and power losses of the BJT are focused on. It was found that the optimized value of base driver capacitor is 22 nF and there is no need of an anti-saturation diode for the SiC BJT. The SiC BJT was tested for various base driver currents, load currents and junction temperature. Results tend to show that switching losses are low temperature dependent that makes the SiC BJT attractive for high temperature applications at high switching frequency.

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