Comparison of conventional and cascode drive of SiC BJTs

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Abstract: This study compares simple conventional and cascode driver circuits for the SiC bipolar junction transistor (BJT). A low-voltage silicon metal-oxide-semiconductor field-effect transistor is used in the emitter of the BJT to realise the cascode variant. The circuits are experimentally evaluated when switching a current of 2.5 A and a voltage of 600 V in a buck converter.

1 Introduction

Out of the main SiC devices [1], the SiC bipolar junction transistor (BJT) exhibits low switching and conduction losses, and good short-circuit withstand times [2], and has been evaluated in several applications [3–5]. Although it needs an on-state base current, it does not have the gate reliability concerns of the metal-oxide-semiconductor field-effect transistor (MOSFET) [6], and unlike the junction gate field-effect transistor (JFET), it is a normally off device.

Various base driver circuits can be used for the SiC BJT [7]. However, instead of driving a power device directly by its control electrode, it can be driven by a second lower voltage device connected in series with its reference electrode, namely the cascode arrangement. This technique has been used with silicon MOSFETs [8, 9] and also with emerging devices including the SiC JFET [10, 11] and GaN FETs [12, 13]. Since the second device only needs to have a low voltage rating, its on-state resistance for a given die area is low and losses in it are consequently low despite it conducting the full load current. An advantage of the cascode drive with JFETs is that it allows the realisation of a normally off switch with a normally on JFET. Although the BJT is a normally off device, the objective of this paper is nonetheless to assess the efficacy of a cascode driver with an SiC BJT. Potential advantages of the cascode driver include immunity to \( \frac{dv}{dt} \)-induced conduction and energy recovery. An initial performance comparison of it and a conventional driver using two simple circuits to drive an SiC BJT is presented and topics are identified for further investigation.

2 Conventional and cascode base driver circuits used for experimentation

A conventional base driver circuit and a simple cascode base driver circuit are shown in Figs. 1 and 2, respectively. In each case, a driver IC, U1, is used and \( V_{BB} \) is the driver stage supply voltage.

In Fig. 1, the driver IC directly drives the BJT’s base terminal. \( R_1 \) provides the steady-state current required to hold the device on. The peaking capacitor \( C_p \) provides a high current pulse into the base of TR1 at turn-on. \( R_2 \) acts as a damping resistor [7].

In Fig. 2, TR2 is a low-voltage silicon N-channel enhancement-mode MOSFET. The components \( R_1, R_2, \) and \( C_p \) essentially perform the same functions as those in Fig. 1.

3 Experimental circuit details

A buck converter was used, as shown in Figs. 1 and 2. In each case, the SiC BJT, TR1, was of GA05JT12-263 type, and the complementary diode, D1, was a C4D08120E SiC Schottky device. The supply voltage \( V_{RAIL} \) was set at 600 V. Local decoupling of

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Fig. 1 Conventional base driver circuit

Fig. 2 Proposed cascode driver circuit

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Table 1 Principal component data for the experimental conventional base driver circuit

| Component | Details |
|-----------|---------|
| $R_1$     | 47 Ω, film |
| $R_2$     | 10 Ω, film |
| $C_p$     | 22 nF, ceramic |
| $U_1$     | UCC27511 |

$V_{RAIN}$ was provided by a 2 μF plastic capacitor, four 8.2 nF ceramic capacitors, and four 150 nF ceramic capacitors, all connected in parallel. The choke $L_1$ in the load circuit had an inductance of 1.1 mH. $V_{RAIN}$ was set at 15 V. The converter was then driven with the arrangements as shown in Figs. 1 and 2. Details of the driver circuitry in each case are given in Tables 1 and 2.

A photograph of the circuitry is shown in Fig. 3. Two half-bridge power conversion stages are shown. One is configured with conventional base drivers and another is configured with cascode base drivers. In each case, the upper power device was replaced with a passive diode $D_1$ as shown in Figs. 1 and 2, and only the lower device $TR_1$ was driven. The isolation stage in Fig. 3, and outlined in Fig. 4, was used to provide the signal and driver power transfer to the device being switched via an Si8642 digital isolator and an isolated output switched-mode power supply, respectively, as documented in [14].

Fig. 5 shows the circuitry connected for testing. The local decoupling capacitance across $V_{RAIN}$ on the power stage printed circuit board (PCB) was augmented with a 50-μF polypropylene capacitor across the supply wires, a few centimetres away from the PCB. The switch voltage, $V_{CE}$ or $V_{BB}$ as applicable, was sensed with a PMK PHV 100 voltage probe. The switch current $i_C$ was sensed with a small current transformer (CT) and $TR_1$ was stood off the PCB to physically accommodate the CT. A fan mounted on the bench surface as partially shown in Fig. 5 was used to apply forced cooling. The CT was constructed with a TN9/6/3 core in 3F3 material carrying a secondary winding $N_2$ of 33 turns of the 0.2-mm diameter copper wire. The CT was connected as shown in Fig. 6. Its output signal was rectified by $Dr$, a 1N4148 signal diode.

Table 4 gives the propagation delays between the input signal $V_{in}$ to the isolation PCB and $V_{CE}$ or $V_{BB}$ as applicable, measured between the 50% levels. The values in brackets refer to the propagation delays between the drain-source voltage of $TR_2$ in the cascode circuit and $V_{CB}$.

Table 5 gives switching energy losses at 100 kHz for the conventional and cascode switches. These were calculated by multiplying the $i_C$ product of the voltage and current and then integrating over the switching intervals. This is illustrated in Fig. 9 where, for example, the instantaneous product $w_{inst}$ of the $i_C$ trajectory is shown for the cascode driver at turn on. Similar losses are incurred. As with other SiC devices, losses are expected to be dominated by the effects of charging and discharging internal device capacitances [15]. A current of 0.37 A was drawn from $V_{supply}$ (which was 5 V) in Fig. 4 by the cascode driver circuit, and this was slightly lower than the current of 0.40 A drawn by the conventional driver circuit. As specified in Section 3, $R_1$ in both driver circuits was set at 47 Ω with $V_{RAIN} = 15$ V, and allowing for the base-emitter voltage drop of the SiC BJT of ∼3 V. This gives a base current $i_B$ of 255 mA. This is well in excess of that required to hold the GA05JT12-263 device fully on with $i_C = 2.5$ A, and results in a power draw of 1.13 W from $V_{BB}$ at the duty factor applied here of 29.5%.

5 Discussion

Simple conventional and cascode drive circuits for the SiC BJT have been compared. Experimental results have been presented for these arrangements when switching 2.5 A and 600 V. Similar switching losses have been recorded with comparable peaking capacitor and damping resistor values in the drive circuits. Expected further work is listed here:

- The performance of the respective drivers will be evaluated with various base driver component values, as optimal values of the peaking capacitance and damping resistance may differ.
- Trade-offs in switching losses and base driver power consumption will be assessed. It is noted that charge is supplied into the driver power supply rail at power switch turn-off with the cascode switch variant. Fig. 8. The potential for energy recovery, primarily from the peaking capacitance, will be quantified. The optimum nominal driver supply voltage $V_{supply}$ setting will be investigated.
- The drivers have been tested in a single-ended power converter circuit, in this case, a buck topology. In single-ended topologies, power switches are not normally subjected to reapplied dV/dt due to the turn on of the complementary device in a bridge leg. Further work will entail assessing the susceptibility of the cascode driver to dV/dt-induced conduction in voltage source converter circuits where this is a necessary consideration.
- SiC BJT base driver circuits using a CT for regenerative current feedback have been presented in [16, 17]. Cascode driver circuit arrangements for the SiC BJT with a CT incorporated for the same purpose will be evaluated.
- Single-ended voltage measurements were carried out in this paper. Further experimentation will use higher bandwidth techniques with improved common-mode signal immunity for measurements over a wider range of switched voltages and currents.

6 Conclusions

A simple conventional base driver for an SiC BJT has been compared with a cascode driver counterpart. Initial performance metrics have been measured for both variants, and topics have been identified for further investigation.
Table 2  Principal component data for experimental cascode driver circuit

| Component | Details |
|-----------|---------|
| $R_1$     | 47 Ω, film |
| $R_2$     | 10 Ω, film |
| $C_p$     | 22 nF, ceramic |
| $T_R_2$   | BSZ019N03LS |
| $U_1$     | ISL6208B |

Fig. 3  Experimental hardware. Top: half-bridge power conversion stages configured for cascode and conventional base drivers. Bottom: isolation stage.

Fig. 4  Functional outline of isolation stage.

Fig. 5  Experimental hardware under test. Only one isolation stage PCB is connected to the power conversion stage PCB as one of the transistors in the half-bridge is substituted with a diode for single-ended testing as a buck converter.

Fig. 6  CT arrangement used for sensing $i_C$.

Fig. 7  Waveforms from the conventional driver circuit in Fig. 1. Top: turn-on. Bottom: turn-off. $V_{BE} = 10$ V/div., $V_{CE} = 200$ V/div., $i_C = 1$ A/div. Time scale = 25 ns/div.
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### Table 3 Switch voltage rise and fall times

| Driver type | Time, ns |
|-------------|----------|
| conventional | t\(_{\text{rv}}\) | 31 |
| | t\(_{\text{fv}}\) | 23 |
| cascode | t\(_{\text{rv}}\) | 30 |
| | t\(_{\text{fv}}\) | 24 |

### Table 4 Switching delays

| Driver type | Time, ns |
|-------------|----------|
| conventional | turn-on | 51 |
| | turn-off | 87 |
| cascode | turn-on | 96(31) |
| | turn-off | 77(28) |

### Table 5 Switching losses

| Driver type | Loss, μJ |
|-------------|----------|
| conventional | turn-on | 17.0 |
| | turn-off | 24.1 |
| cascode | turn-on | 21.3 |
| | turn-off | 19.6 |

### Table 5 Switching losses

| Driver type | Loss, μJ |
|-------------|----------|
| conventional | turn-on | 17.0 |
| | turn-off | 24.1 |
| cascode | turn-on | 21.3 |
| | turn-off | 19.6 |