



# Switching Characteristics of a 4H-SiC Based Bipolar Junction Transistor to 200 °C

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## Abstract

Static curves and resistive load switching characteristics of a 600 V, 4 A rated, SiC-based NPN bipolar power transistor (BJT) were observed at selected temperatures from room to 200 °C. All testing was done in a pulse mode at low duty cycle (~0.1 percent).

Turn-on was driven by an adjustable base current pulse and turn-off was accelerated by a negative base voltage pulse of 7 V. These base drive signals were implemented by 850 V, gated power pulsers, having rise-times of roughly 10 ns, or less. Base charge sweep-out with a 7 V negative pulse did not produce the large reverse base current pulse seen in a comparably rated Si-based BJT. This may be due to a very low charge storage time. The decay of the collector current was more linear than its exponential-like rise.

Switching observations were done at base drive currents ( $I_B$ ) up to 400 mA and collector currents ( $I_C$ ) up to 4 A, using a  $100\ \Omega$  non-inductive load. At  $I_B = 400\text{ mA}$  and  $I_C = 4\text{ A}$ , turn-on times typically varied from 80 to 94 ns, over temperatures from 23 to 200 °C. As expected, lowering the base drive greatly extended the turn-on time. Similarly, decreasing the load current to  $I_C = 1\text{ A}$  with  $I_B = 400\text{ mA}$  produced turn-on times as short as 34 ns. Over the 23 to 200 °C range, with  $I_B = 400\text{ mA}$  and  $I_C = 4\text{ A}$ , turn-off times were in the range of 72 to 84 ns with the 7 V sweep-out.

## Testing Circuits

A constant voltage source feeding a resistive load in the collector circuit was chosen to make up a most simple power side of the circuit. A nearby charged capacitor served well as the power source, since operation was with sub-microsecond pulses at no more than 0.1 percent duty cycle. The BJT itself was mounted to a temperature-controlled plate, with a thermocouple attached directly to the BJT. A general circuit diagram is provided in figure 1.

A fast rise, high voltage pulser is suitable for providing a very fast-rise current pulse to the base of a BJT. The DEI model HV-1000 is capable of pulse heights up to 850 V into a  $50\ \Omega$  load at a low duty cycle, with a rise-time of 10 ns and durations up to 10  $\mu\text{s}$ . Figure 2 shows the basic arrangement, omitting the required external high voltage supply and trigger pulser. Since the forward  $V_{BE}$  is only of the order of 10 V, good quality current pulses can be obtained into the base of the BJT. The duty cycle can be set as low as one pleases and about 0.1 percent was used.

A turn-off circuit was devised to accelerate the charge carrier sweep-out from the base region by providing a negative  $V_{BE}$  of about 7 V to terminate the collector current from its steady state value. In this way, turn-off transients comparable in duration, or even shorter, than the turn-on transients could be obtained. Such a circuit was implemented by adding a negative pulser (a DEI model HV-1000N) to the circuit in figure 2. A Zener diode was used to set the negative voltage level. The passive components in these circuits need not have a high power rating, due to the very low duty cycle.

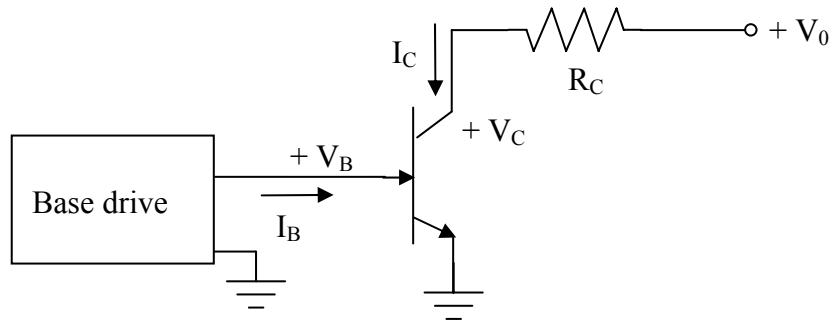


Figure 1.—Basic resistive load turn-on switching test circuit. Currents  $I_B$  and  $I_C$  are sensed by high-speed current transformers (Tektronix CT1 and CT2). Potential  $V_B$  is sensed by a  $1\text{ k}\Omega$  input impedance, fast-rise probe and potential  $V_C$  by a Tektronix 10X probe.  $R_C$  is a carbon composition resistor, normally set to  $100\Omega$ .

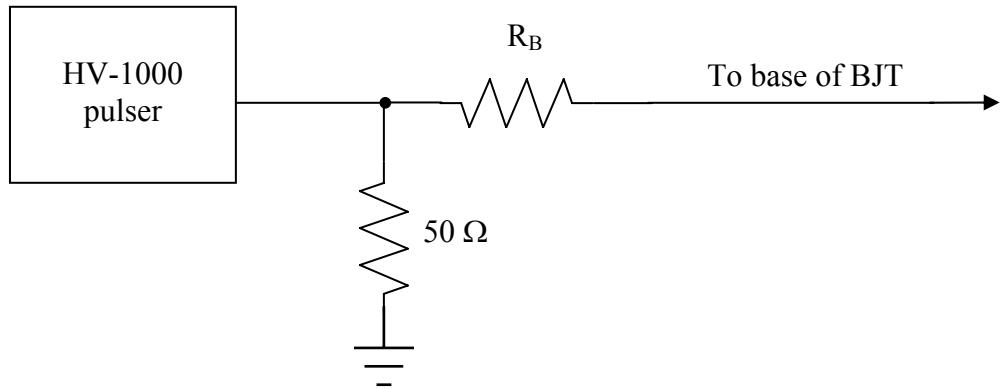


Figure 2.—Block circuit diagram for a pulsed constant current base drive.  $R_B$  values of  $300\Omega$  to  $1\text{ k}\Omega$  were used.

Figure 3 provides a diagram of the combined circuit, used primarily for capturing the turn-off transient, once steady  $I_C$  has been established by the positive base drive part. The two high voltage pulsers are timed by trigger signals from two channels of a delay trigger pulse generator, a Berkeley Nucleonics model 555. And the output from the HV-1000N overcomes that from the HV-1000 sufficiently to activate the Zener diode, thus setting the negative base drive level. This circuit was constructed with low power resistors and diodes for use at very low duty cycle only. Moreover, the model 555 was unable to gate the high voltage pulsers at duty cycles exceeding 10 percent. But using this somewhat elaborate setup, base voltage transition times, from positive to negative in less than 10 ns, could be achieved.

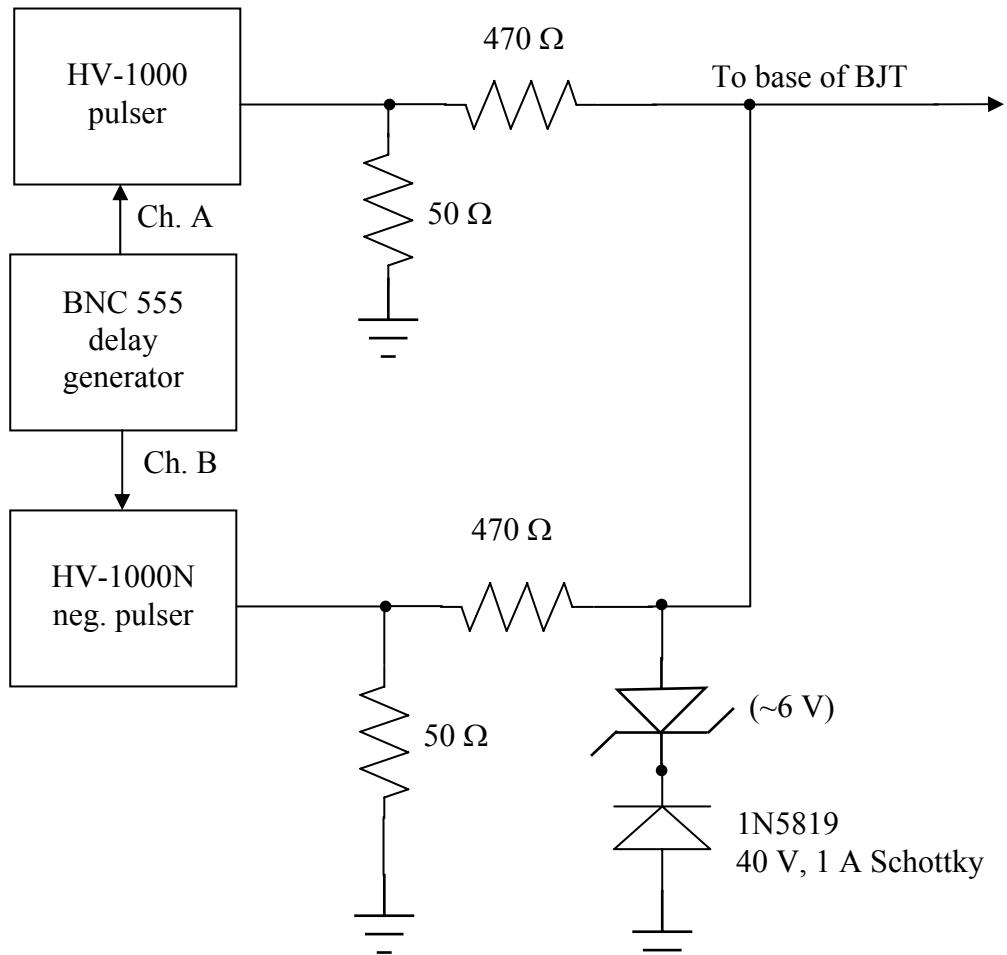


Figure 3.—Block circuit diagram of a pulsed constant voltage base sweep-out drive added to the constant current base drive of figure 2. The reverse  $V_{BE}$  is set by the Zener diode. The delay generator provides timed gating pulses, Channels A and B, to the positive and negative high voltage pulsers.

## High Temperature Switching Data Overview

The data in table I presented below shows the amount of base drive needed to get acceptable switching at selected temperatures and load currents for the SiC-based BJT labeled as P2. This data was taken using the constant current base drive mode, primarily because it is easier to set the current to a given value. The values of currents indicated are their steady state values, reached typically in less than a microsecond.

At the 0.1 percent duty cycle used, no temperature rise above ambient of the BJT's case could be resolved. The case was, however, fastened to a BN substrate to provide good heat conductivity. An estimate of the switching loss of  $10^{-4}$  J per on-off cycle thus gives an estimate of an average power loss of only 0.1 W. Device temperature rise can then be estimated from either the specific heat (range 0.3 to 1.0 J/(g K)) or the thermal conductivity (range 2 to 5 W/(cm K)) of SiC. Assuming a chip 1 mm thick and

3 mm on side, either estimate gives a temperature rise less than 1 K. Hence it seems safe to assume that the junction temperature is within a degree or so of that of the case in these pulse measurements.

TABLE I—SWITCHING DATA, WITH  $100\ \Omega$  LOAD RESISTOR AND  $-7\text{ V}$  BASE SWEEP-OUT

(a) Data at  $23\text{ }^{\circ}\text{C}$

| $I_B$<br>(mA) | $I_C$ (A) | $V_0$<br>(V) | $\tau_{IC, ON}$ (ns)<br>(10 to 90%) | $\tau_{IC, OFF}$ (ns)<br>(10 to 90%) |
|---------------|-----------|--------------|-------------------------------------|--------------------------------------|
| 400           | 4.0       | 402          | 80                                  | 84                                   |
| 300           | "         | 402          | 116                                 |                                      |
| 200           | "         | 402          | 198                                 |                                      |
| 100           |           |              |                                     |                                      |
|               |           |              |                                     |                                      |
| 400           | 3.0       | 308          | 65                                  | 74                                   |
| 300           | "         | 308          | 92                                  |                                      |
| 200           | "         | 308          | 156                                 |                                      |
| 100           | "         | 304          | >370                                |                                      |
|               |           |              |                                     |                                      |
| 400           | 2.0       | 208          | 49                                  | 64                                   |
| 300           | "         | 206          | 71                                  |                                      |
| 200           | "         | 206          | 116                                 |                                      |
| 100           | "         | 204          | 288                                 |                                      |
|               |           |              |                                     |                                      |
| 400           | 1.0       | 106          | 34                                  |                                      |
| 300           | "         | 106          | 45                                  |                                      |
| 200           | "         | 104          | 70                                  |                                      |
| 100           | "         | 104          | 162                                 |                                      |

(b) Data at  $150\text{ }^{\circ}\text{C}$

| $I_B$<br>(mA) | $I_C$<br>(A) | $V_0$<br>(V) | $\tau_{IC, ON}$ (ns)<br>(10 to 90%) | $\tau_{IC, OFF}$ (ns)<br>(10 to 90%) |
|---------------|--------------|--------------|-------------------------------------|--------------------------------------|
| 400           | 4.0          | 410          | 90                                  | 72                                   |
| 300           | "            | 410          | 132                                 |                                      |
| 200           | "            | 408          | 248                                 |                                      |
|               |              |              |                                     |                                      |
| 400           | 3.0          | 308          | 74                                  | 63                                   |
| 300           | "            | 306          | 103                                 |                                      |
| 200           | "            | 308          | 181                                 |                                      |
| 100           | "            | 306          | >361                                |                                      |
|               |              |              |                                     |                                      |
| 400           | 2.0          | 206          | 56                                  | 57                                   |
| 300           | "            | 206          | 78                                  |                                      |
| 200           | "            | 204          | 125                                 |                                      |
| 100           | "            | 202          | 334                                 |                                      |
|               |              |              |                                     |                                      |
| 400           | 1.0          | 106          | 36                                  |                                      |
| 300           | "            | 106          | 49                                  |                                      |
| 200           | "            | 104          | 76                                  |                                      |
| 100           | "            | 104          | 170                                 |                                      |

TABLE I—Concluded.

(c) Data at 175 °C

| $I_B$<br>(mA) | $I_C$<br>(A) | $V_0$<br>(V) | $\tau_{IC, ON}$ (ns)<br>(10 to 90%) | $\tau_{IC, OFF}$ (ns)<br>(10 to 90%) |
|---------------|--------------|--------------|-------------------------------------|--------------------------------------|
| 400           | 4.0          | 408          | 94                                  | 73                                   |
| 300           | "            | 406          | 133                                 |                                      |
| 200           | "            | 406          | 249                                 |                                      |
| 100           | "            | >402         | >360                                |                                      |
|               |              |              |                                     |                                      |
| 400           | 3.0          | 308          | 74                                  | 64                                   |
| 300           | "            | 306          | 104                                 |                                      |
| 200           | "            | 306          | 176                                 |                                      |
| 100           | "            | >306         | >373                                |                                      |
|               |              |              |                                     |                                      |
| 400           | 2.0          | 206          | 55                                  | 57                                   |
| 300           | "            | 206          | 79                                  |                                      |
| 200           | "            | 204          | 128                                 |                                      |
| 100           | "            | 204          | 334                                 |                                      |
|               |              |              |                                     |                                      |
| 400           | 1.0          | 106          | 36                                  |                                      |
| 300           | "            | 106          | 47                                  |                                      |
| 200           | "            | 104          | 75                                  |                                      |
| 100           | "            | 102          | 171                                 |                                      |

(d) Data at 200 °C

| $I_B$<br>(mA) | $I_C$<br>(A) | $V_0$<br>(V) | $\tau_{IC, ON}$ (ns)<br>(10 to 90%) | $\tau_{IC, OFF}$ (ns)<br>(10 to 90%) |
|---------------|--------------|--------------|-------------------------------------|--------------------------------------|
| 400           | 4.0          | 408          | 94                                  | 72                                   |
| 300           | "            | 408          | 135                                 |                                      |
| 200           | "            | 408          | 241                                 |                                      |
|               |              |              |                                     |                                      |
| 400           | 3.0          | 308          | 74                                  | 65                                   |
| 300           | "            | 306          | 107                                 |                                      |
| 200           | "            | 304          | 181                                 |                                      |
| 100           | "            | >302         | >373                                |                                      |
|               |              |              |                                     |                                      |
| 400           | 2.0          | 204          | 56                                  | 58                                   |
| 300           | "            | 204          | 78                                  |                                      |
| 200           | "            | 204          | 126                                 |                                      |
| 100           | "            | 204          | 340                                 |                                      |
|               |              |              |                                     |                                      |
| 400           | 1.0          | 106          | 36                                  |                                      |
| 300           | "            | 106          | 49                                  |                                      |
| 200           | "            | 104          | 77                                  |                                      |
| 100           | "            | 104          | 169                                 |                                      |

## Summary of Observations

The data tables indicate that collector current turn-on transition times of 100 ns, or less, can be readily achieved with a 4 A current and a 100 Ω resistive load. This, however, requires a 400 mA base drive current step, at which the  $V_{BE}$  steadies out to roughly 10 V, with 4 A of collector current flowing. As expected, this turn-on time is sensitive to the base drive and the load currents, with only a slight sensitivity to temperature, from 23 to 200 °C. If the load current is lowered, then similar times can be obtained at a lower base drive. Here the externally measured case temperature is thought to be a good

measure of also the junction temperature, because of the very low duty cycle pulse mode and the rather low switching loss per on-off cycle.

An abrupt base turn-off was implemented by sending a negative voltage pulse to the base to overcome the positive base current pulse. Due to the low base charge storage time in this SiC device (crystal defects?), there was no need to limit the reverse base current. Without emitter junction reverse breakdown data, about 7 V was thought to be conservative. This was sufficient to give collector current decay times of the same order as its rise times. Faster times may be possible, depending on the emitter breakdown characteristics. Also, clamping the base voltage to the emitter level would certainly elongate the turn-off time. Although zero level clamping seems difficult with the pulsers, data points for a plot below a 1 V level may be feasible by omitting the Zener diode in figure 3. This has not yet been done.

The setup shown in figure 3 produces a collector current turn-off waveform that is nearly linear in time, whereas its turn-on waveform approximates closer to exponential. This makes for a difference in the switching losses when calculating these from formulas to approximate the waveforms.

Although the P2 device can switch up to at least 1.6 kW at 200 °C in a low duty cycle pulse mode, thermal conductance to case is expected to significantly reduce its capability at say 50 percent duty cycle. The estimation of junction temperature rise for a given average power dissipation in the device is problematic, at best. An experimental attempt will be described in another report.

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