Evaluation of a 4 mm x 4 mm SiC GTO at Temperatures up to 150 °C and Varying Pulse Width

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***Abstract* –The U. S. Army Research Laboratory (ARL) is evaluating silicon carbide Super GTOs (SGTOs) [1] to determine the extent of silicon carbide's capabilities as a possible replacement for silicon in future pulsed switching applications. Individual SiC die measuring 4 mm x 4 mm were pulsed at high temperatures and varying pulse widths. These SGTOs were switched in an RLC circuit at temperatures up to 150 °C. At this peak temperature, they were switched as high as 3.2 kA and repetitively pulsed at 2.6 kA and 5 Hz for greater than 14,000 pulses. A pulse forming network (PFN) was also designed to increase the pulse width and the action seen by the SiC devices. At ambient temperature and a peak current of 2 kA, SiC SGTOs were switched in the PFN at a 50% pulse width of 40 µs and an action of 150 A^2s. This report includes further data on high temperature and wide pulse width testing, as well as analysis of the devices' failure points.**

I. INTRODUCTION

Silicon carbide is attracting attention as a useful material for high power, high temperature switches because of its advantages over the more commonly used silicon. 4H-SiC has greater temperature tolerance and high electric breakdown strength [2]. It can be operated at higher junction temperatures than silicon and has been shown to handle higher current densities, giving SiC-based switches the potential to be used in applications that include large temperature swings and small overall switch volumes [3, 4]. The SGTOs evaluated in this study have the added bonus of a fine interdigitated gate structure (25-40 µm gate pitch) which improves turn-on time and current-handling capabilities over other gate design [1].

This work builds upon previous ARL studies of 2 mm x 2 mm SiC GTOs and these same 4 mm x 4 mm SiC SGTOs switched at single shot and repetitive rates for narrow pulse widths [3, 4]. At ambient temperature with a pulse width of 2 µs, the 4 mm x 4 mm die were switched as high as 3.9 kA and 7.8 kA/µs. They were also pulsed at 2 kA and 5 Hz for greater than 99,000 shots.

II. DESIGN

The 4 mm x 4 mm SiC SGTO was designed by Cree, Inc. and packaged at ARL (Fig. 1). Each device is rated for 1000 V holdoff and 16 A of continuous current. The top surface of each device has four corner anode pads and one central point for gate wire connections. The bottom surface of the device serves as the cathode. The active area is about 0.07 cm^2. The typical voltage drop is about 2.9 V, and the gate current required to turn the devices on can vary from -25 mA to -173 mA. Negative gate current is applied with respect to the anode. Prior to switching, devices typically show less than 1 µA of leakage current between the gate and the anode with up to 17 volts applied. Anode-cathode leakage varies more from one SGTO to another, with the best ones showing less than 10 µA when the voltage is greater than 800 V.

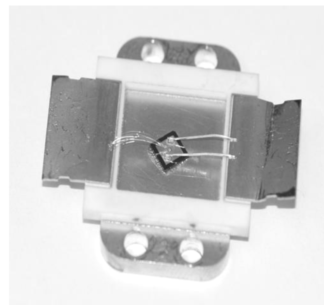

Fig. 1. Packaged SiC SGTO (overall dimensions approximately 30 mm x 36 mm x 4.8 mm).

III. EVALUATION AT TEMPERATURE

A. *Methods of Evaluation*

The first step of high temperature evaluation was to use the curve tracer to compare how increasing temperature affects the steady-state characteristics of the SiC SGTOs. Six devices were raised to 75, 100, 125 and 150 °C. At each temperature, the voltage drops, holding current, reverse anode-gate leakage current, and forward anode-cathode leakage current were recorded. Two of the devices were packaged with a green, silicon-based potting compound for high voltage insulation, two were packaged without insulation, and two were packaged with a hard, high-temperature epoxy. It was found that above 125 °C, the silicon-based compound expanded and contracted, pulling at the fine anode and gate wires. The hard epoxy, however, appeared to maintain its form as high as 175 °C.

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Curve tracer data presented here is from tests conducted using the bare devices and the epoxied ones.

The SiC package was heated by a high wattage resistor attached underneath the cathode plate (Fig. 2). Current of up to 0.9 A was run through the resistor to raise the temperature. Temperature was monitored via a k-type thermocouple attached with thermal paste at the cathode plate. The temperature difference between this point and the actual SGTO was assumed to be less than 2 °C.

A ring down RLC circuit (Fig. 3) that was used for earlier ambient pulsing was reused for high temperature switching. The capacitance was 20 μF, and the resistive load was 0.11 ohm. Inductance was minimized to limit the pulse width of the current to 2 μs and to obtain fast rise times. The gate was triggered by a driver that was capable of -1.3 A and was isolated by a pulse transformer. An identical high wattage resistor was attached underneath the cathode, though the resistor current had to be increased as high as 1.1 A to account for heat sinking by other circuit components. Some devices were switched at a single shot rate at increasing current levels until failure. Other SGTOs were pulsed at 5 Hz at lower currents until failure at some number of pulses.

B. Results and Discussion

Device characteristics varied little during high temperature curve tracer measurements. Only one SGTO that showed anode-cathode current leakage at room temperature seemed to be affected by increasing package temperatures. At an ambient temperature of about 29 °C, device #223, which had no high voltage potting compound, had a leakage current of about 60 μA when 270 V were applied A→K (Fig. 4). As temperature was increased, the slope of the leakage current also increased until at 150 °C, the device was leaking 60 μA at only 230 V. Other un-potted devices that were heated on the curve tracer were checked up to 550 V for leakage and showed less than 1 μA at each temperature up to 150 °C.

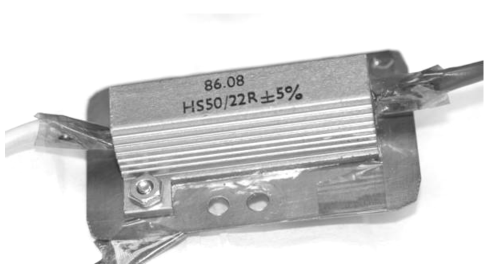

Fig. 2. High wattage resistor attached to cathode plate to apply heat.

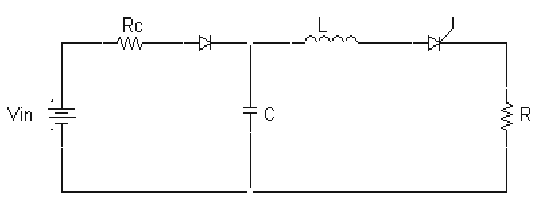

Fig. 3. Generic ring down RLC circuit for pulsing SGTO.

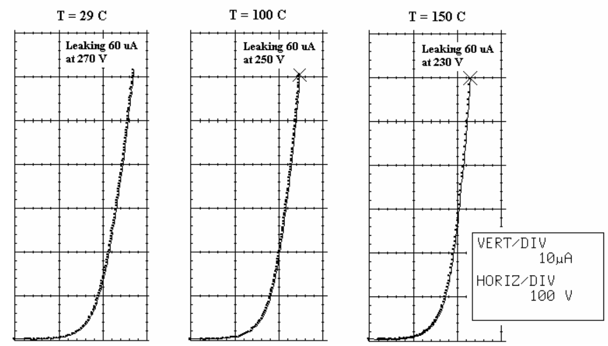

Fig. 4. Increase in anode-cathode current leakage as a function of device temperature.

At a single shot rate and 150 °C, devices were switched as high as 3.2 kA before failure (Fig. 5). The 10%-90% rise time was less than 300 ns, resulting in a dI/dt of 8.6 kA/μs. At ambient temperatures, the SGTOs' rise times in this circuit were typically closer to 400 ns, so the dI/dt never reached this high of a value. It seemed that either the devices' switching behavior changed at higher temperature, or the characteristics of the RLC changed. Because the cathode plate of the switch was attached directly to the load buss, the heat that was being applied to the switch package was also being applied to the load resistors. An LCR meter displaying units to the milliohm decimal place was used to measure the amount of resistance at different temperatures without switching. The load resistance did not vary at any temperature up to 150 °C. An investigation into earlier 4H-SiC studies found that temperature dependence of the injection coefficient at the anode-gate junction has been shown to affect the rise time of SiC thyristors [5]. That information supports the findings of this study: that the rise time of the SGTOs will decrease with increasing temperature across the range 25-150 °C.

The SiC SGTOs were repetitively switched at 150 °C and 5 Hz up to a current level of 2.6 kA. Two devices completed more than 14,000 pulses at this level before developing excessive anode-cathode leakage (in the tens of milliamps) that prevented the RLC capacitor from charging. During the thousands of successful pulses, no degradation in the waveform was noted (Fig. 6). At time of failure, multiple

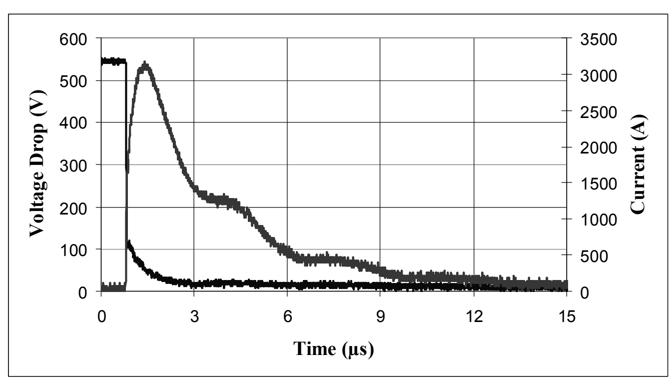

Fig. 5. Peak single shot voltage and current at 150 °C.

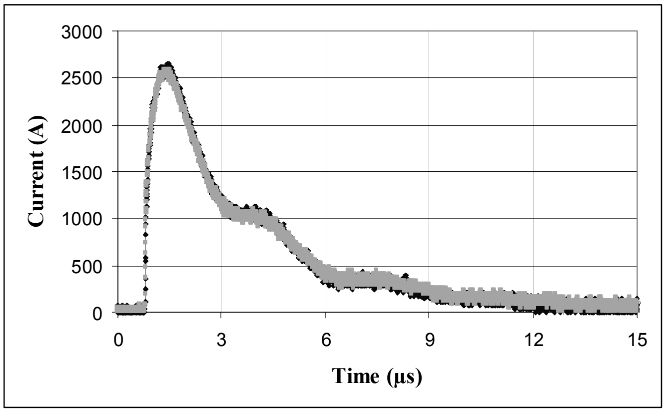

Fig. 6. Overlapping current waveforms at first test shot and at greater than 5,000 shots.

devices showed breakdown/burning at the point where the anode wires connected to the device or to the tab on the packaging (Fig. 7). Repetitive switching at higher currents was attempted at ambient temperature, but two devices tested did not survive more than four 5 Hz pulses at a peak of 3 kA. The number of pulses the devices could handle increased when current was limited to 2.6 kA or below. Heat imaging experiments are planned to view how the current is distributed across the area of the devices and whether repeated test shots increase the number of internal dislocations, forcing the anode-cathode current through smaller areas until failure.

IV. Pulse Width Expansion

A. Methods of Evaluation

All SGTO switching prior to this point was done at narrow pulse widths. In order to determine the maximum amount of action that the SGTOs could handle, a pulse forming network was designed to expand the width of the current pulse to 11 µs and beyond by incrementally adding stages of capacitance and inductance. The basic circuit began with two capacitors (Fig. 8) measuring 35 µF (closer to the SGTO) and 42 µF (at the charging end). The inductance between them was about 70 nH, and the resistive load was 0.14 ohm. The resulting current pulse was 11 µs wide at 50% height. In this circuit, devices were pulsed at increasing current increments until failure.

Each additional stage of capacitance and inductance added

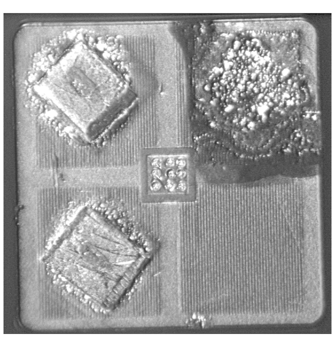

Fig. 7. Device #425 with one burnt anode after 100 °C, 5 Hz testing.

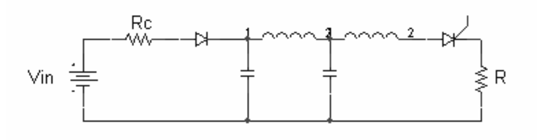

Fig. 8. Circuit producing 11 µs pulse width.

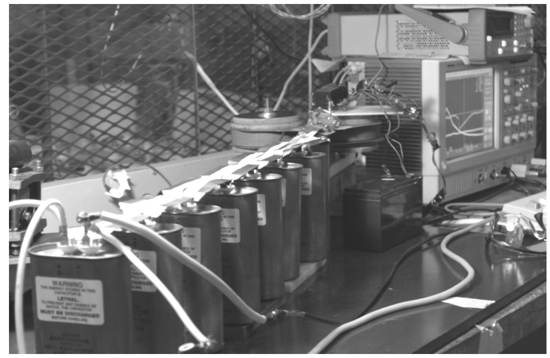

Fig. 9. Eight-capacitor PFN with device and load connected at the far end.

another 5 µs to the pulse width (Fig. 9). Additional devices were purposely limited to 1.5 kA as the pulse width was increased so that failure would be forced by a build-up of heat over the length of the pulse rather than by the level of current.

At each width, devices were switched twice at 1.5 kA for repeatability. The entire process was redone with the current limited to about 2 kA. SGTOs with both hard epoxy and Krytox voltage insulation were used. Also, some devices had wires applied at only three of the four anode pads, while others had all four wires. The rise time for these circuits was about twice as long as that of the high temperature RLC because of the PFN's extra inductance that was added to shape the pulse.

B. Results and Discussion

Devices #3311 and #332 were pulsed in the 11 µs, two-capacitor circuit and failed at about the same level (Table I). Each had wires extending to all four anode pads and was insulated with Krytox. The current and action at failure for device #3311 were 2.7 kA and 53 A^2s (Fig. 10); for device #332, they were 2.8 kA and 61 A^2s. During the final test shots, a

TABLE I
PEAK DATA FOR DEVICES TESTED AT WIDE PULSE WIDTHS

Device No.	50% Pulse Width (µs)	Current (A)	Action = I^2t (A^2s)
3311*	11	2700	53
332*	11	2800	61
2321	21	2200	66
3211	21	2100	67
"	25	1700	52
423 *	25	2200	85
"	30	2100	99
2320	40	1500	67
431	40	1500	68
2315 *	40	2200	150

* Devices which had wires to all four anode pads

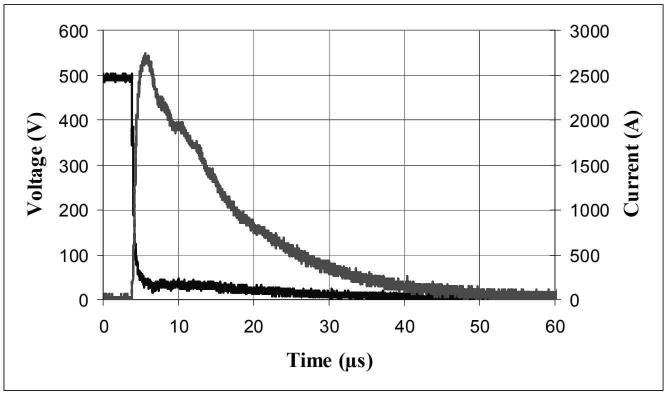

Fig. 10. Peak single shot voltage and current at 11 µs pulse width.

small flash of light was seen at the devices. Afterward, the anode-gates were shorted and the anode-cathodes were very low impedance.

At wider pulse widths, it was clear that the devices with current applied across all four anode connection points fared better than those with only three anode wires (Table I). Device #431's three wires blew off after one 1.5 kA, 40 µs pulse (Fig. 11), while device #2315 completed two test shots at 2.2 kA and the same pulse width (Fig. 12). If the plasma could not spread quickly enough to the unwired area of the device before the three wired portions turned on, then only about ¾ of the assumed active area was carrying current. Heat would be building up more quickly and cause the dramatic failure seen with device #431 (Fig. 13). SGTO #2320 failed under similar circumstances, but the anode wires did not actually blow off, due in part to the hard epoxy coating that particular switch.

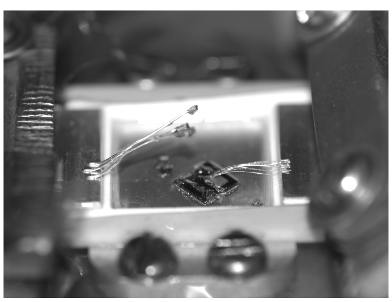

Fig. 11. Three anode wires blown off of device #431.

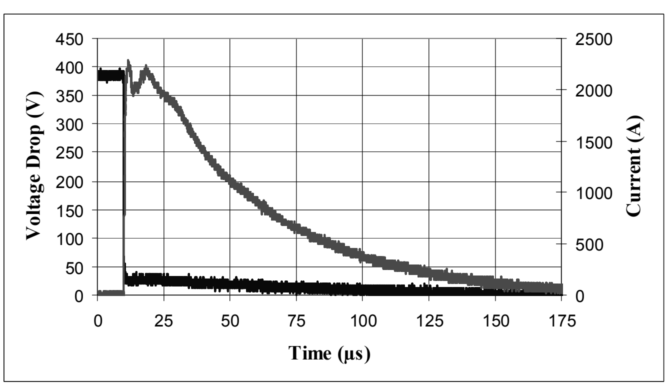

Fig. 12. Maximum pulse width achieved at about 2 kA with 4-wire package

Fig. 13. Device #431 with three burnt anode pads after 40 µs pulse.

The maximum pulse width attained at the 1.5 kA and 2 kA levels was 40 µs. Devices reaching this pulse width either began to leak too much anode-cathode current to continue pulsing, or they shorted anode-gate such that the required voltage drop could not be induced to trigger the device. Those which shorted anode-gate without shorting anode-cathode were being triggered using a slightly different driver which did not have an isolating pulse transformer.

V. Conclusions

4 mm x 4 mm SiC SGTOs were successfully switched at 150 °C and 2 µs pulse width up to 3.2 kA and 8.6 kA/µs at a single shot rate, then at 5 Hz up to 2.6 kA for greater than 14,000 pulses. Both anode-cathode leakage and rate-of-current-rise increased as device temperature was increased. These devices were found to be capable of a 40 µs pulse width at ambient temperature for current up to 2 kA when the full device was turned on. Device performance was improved when anode currents were directly applied to all four anode pads and when a hard epoxy or Krytox was used for high voltage insulation.

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