IEICE Electronics Express, Vol.2, No.3, 97–102

Switching characteristics of SiC JFET and Schottky diode in high-temperature dc-dc power converters

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Abstract: This paper reports on SiC devices operating in a dc-dc buck converter under extremely high ambient temperatures. To this end, the authors packaged SiC JFET and Schottky diodes in thermally stable packages and built a high-temperature inductor. The converter was tested at ambient temperatures up to 400°C. Although the conduction loss of the SiC JFET increases slightly with increasing temperatures, the SiC JFET and Schottky diode continue normal operation because their switching characteristics show minimal change with temperature. This work further demonstrates the suitability of the SiC devices for high-temperature power converter applications.

Keywords: SiC, JFET, Schottky diode, high-temperature packaging, 400°C operation, dc-dc buck converter

Classification: Electron devices

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DOI: 10.1587/elex.2.97
Received January 31, 2005
Accepted February 02, 2005
Published February 10, 2005

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1 Introduction

Silicon Carbide (SiC) is a semiconductor material with several superior characteristics when compared to Silicon (Si) [1, 2, 3]. In particular, SiC semiconductor devices are expected to have high-temperature, high speed operation and high voltage capabilities which cannot all be obtained with conventional Si-based semiconductor devices. This paper focuses on the inductive switching characteristics of SiC devices operating under high ambient temperatures. High-temperature operation requires not only the SiC bare dies be capable of operating at high temperatures, but also their packaging and the auxiliary components when used in an electric circuit like a dc-dc buck converter. To this end, the authors mounted SiC JFET and Schottky diodes in thermally stable packages, and designed and built an inductor using high-temperature toroidal magnetic core and wires to implement a dc-dc buck converter. Otherwise, the converter can only operate up to 200°C if the components are not suitable for operation at high temperatures [4]. This paper evaluates the switching response of SiC devices operating in a dc-dc buck converter with a resistive load up to ambient temperatures of 400°C.

2 SiC Devices and Experimental Setup

A dc-dc buck converter is one of the simplest power conversion circuits consisting of a controlled switching device, a diode, an inductor, and input and output capacitors when required. Although a SiC bare die can withstand high temperatures because of its material characteristics, it cannot form part of a circuit by itself; it requires packaging that must be suitable for high temperatures. The SiC JFET supplied by SiCED is a research sample bare die, which is usually supplied as a cascode device with Si MOSFET [5, 6]. It has a vertical channel structure, a 2.8 mm^2 surface area, and 2.5 A and 1200 V current and blocking voltage ratings. The SiC Schottky diode produced by Cree is a commercially available device having 1.9 mm^2 surface area and 4 A and 600 V current and blocking voltage ratings, whose operation is guaranteed up to 175°C.

The authors attached the JFET and Schottky diode bare dies on a Ni-plated JEDEC TO-258 package to allow high temperature operation. The dies have Ni or Al-based Ohmic terminal contacts, and metallization on their

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Received January 31, 2005
Accepted February 02, 2005
Published February 10, 2005

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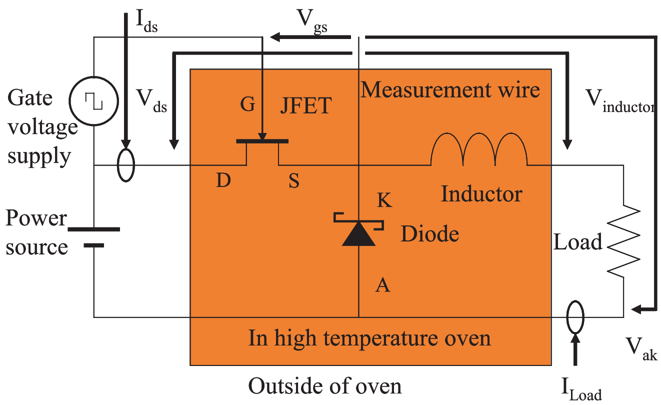

Fig. 1. Experimental setup for high temperature operation of the SiC dc-dc buck converter.

top surface and backside. The drain and cathode contacts were attached to the package. The source, gate and anode contacts were wire bonded to the respective terminals in the package with 3 mil Al wire.

The inductor was built using a high-temperature magnetic toroidal core from Magnetics Inc. The core is made of ferrous alloy powder (Kool-Mu 97907-A7) with 26 relative permeability and a 500°C Curie temperature. The inductor has 0.6 mH inductance using 124 turns of a wire having a high-temperature withstanding capability of 450°C.

Figure 1 shows the experimental setup for operating and measuring the performance of the SiC-based dc-dc buck converter. Only the JFET, Schottky diode and inductor are exposed to ambient temperature variations in the oven since capacitors and gate drivers capable of operating at such high-temperatures were not available to the research team; this is ongoing research at the present time. Thus, this circuit does not have the filter capacitors typical of these converters. The measurements were performed outside the oven through relatively long wires. Therefore, the effects of some parasitic components are noticeable in the measurement results. The converter operated at 100 kHz switching frequency with 50% duty cycle, 100 V input dc voltage and a 100 Ω load resistance. The drain current capacity of the JFET degrades with increasing temperature (i.e., to 20% of that at room temperature at 450°C [7]), so the rated output current is set to 0.5 A for high temperature operation. The gate drive voltage applied to the JFET is $V_{gs} = 0\,V$ for the "on" condition and $V_{gs} = -18\,V$ for the "off" condition, which is lower than the threshold gate voltage of −15 V at 450°C [7].

3 Switching characteristics of SiC devices under high ambient temperatures

Figure 2 shows the measured voltage and current waveform in the dc-dc buck converter as function of ambient temperature. Fig. 2 (a) shows the load voltage whose average value is about 50 V, which agrees with the set operating condition of 100 V input and 50% duty cycle. This waveform also shows the effect of not having an output filter capacitor. The buck converter circuit

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Received January 31, 2005
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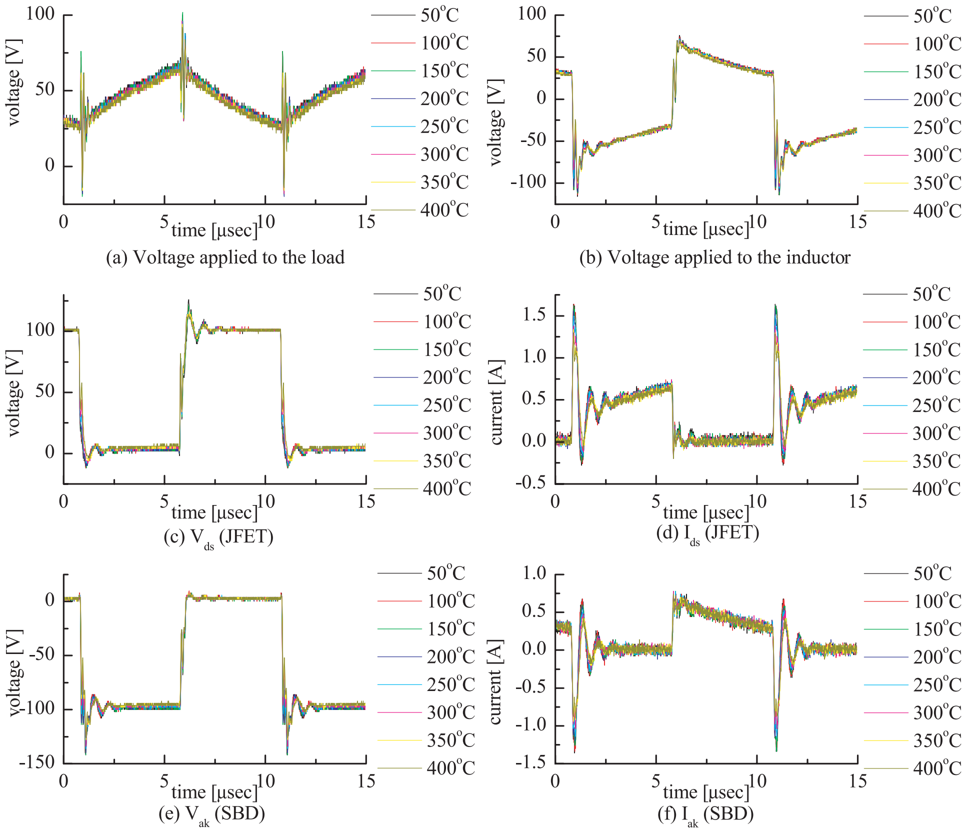

Fig. 2. Experimental results of the SiC-based dc-dc buck converter.

works normally from room temperature to an extremely high temperature of 400°C. The output voltage decreases a few volts at 400°C (i.e., 5 V) from the values at lower temperatures, but the reduction is relatively small when compared to the output voltage. The spike voltages observed at the peak and bottom of the waveform in Fig. 2 (a) are caused by the switching operations of the SiC JFET and Schottky diode, and the long wires used for the measurements. The waveform of the output voltage is basically the same as the temperature changes. This means that the inductance of the inductor is not greatly affected within the considered temperature range. The normal operation of the inductor as temperature changes can also be confirmed from the voltage across the inductor shown in Fig. 2 (b). The operation of this passive component under extremely high temperature conditions is fairly satisfactory.

Figure 2 (c) shows the drain-source voltage V_{ds} for the JFET indicating that it can remain in the "off" condition when applying a gate voltage V_{gs} of −18 V for V_{ds} equal to 100 V regardless of the ambient temperature. The voltage drop between the drain and source during the "on" condition increases at higher temperatures. The 5 V drop at 400°C coincides with the results from the dc characteristic measurements. The damping of the switching transient becomes more pronounced as the conduction loss increases. Fig. 2 (d) shows the drain current response of the JFET, which shows no reverse recovery or tail current. The turn on behavior has an interaction with the

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switching behavior of the Schottky diode for commutation, but the turn off behavior is dominated by the JFET itself. The JFET retains its high-speed switching capability up to an extremely high ambient temperature of 400°C. The di/dt of the drain current basically does not change with temperature; -1.45×10^7 A/s at room temperature vs. -1.44×10^7 A/s at 400°C.

Figure 2 (e) shows the voltage between the anode and cathode of the Schottky diode. The voltage drop during the conduction condition barely changes with temperature, similar to the JFET response. The imposed voltage during the non-conduction condition decreases a few volts at high temperatures because the voltage drop across the JFET increases with increasing ambient temperatures. Fig. 2 (f) displays the current flowing through the Schottky diode that turns on quickly when commutating current from the JFET, and has a fairly small forward recovery accompanied by small oscillations as shown in Fig. 2 (e). Contrarily, it produces a relatively large ringing current at turn off. The wires for connecting the devices are relatively long (resulting in some parasitic components), a Schottky diode does not produce reverse recovery current by carrier recombination and the turn on speed of the JFET is quite fast and has a large dv/dt. Then, the displacement current flows through the capacitance of the parasitic components and the diode [8] at the commutation. Since the amplitude of current oscillation does not change with temperature, it can be said that the switching speed does not deteriorate with temperature rise. This result indicates that the switching characteristics of the SiC JFET are excellent, and the turn-on speed of the SiC JFET must be reduced to cope with the SiC Schottky diode switching characteristics to prevent transient ringing.

4 Conclusion

This paper confirmed and evaluated the inductive switching operation of SiC devices in an application circuit consisting of a dc-dc buck converter operating from room temperature to extremely high ambient temperatures (~400°C). SiC JFET, SiC Schottky diode (both in thermally stable packages) and a high-temperature inductor were used to realize the buck converter that was designed by taking into account the drain current rating reduction of the JFET at high temperatures. Although the resistance between the drain and source increased with temperature and the power conversion efficiency deteriorated, the deterioration was not prominent and the increase in the voltage drop between the drain and source was relatively small in comparison to the blocking voltage. The superior switching characteristics of a SiC JFET were experimentally observed within the considered temperature range, although the very fast switching operation of the JFET induces oscillation with parasitic components. The results show that the inductive switching characteristics of SiC JFET and Schottky diode hardly deteriorate with increasing temperatures so these devices are very suitable for high temperature operation such as a dc-dc buck converter used in power supplies in aerospace applications.

DOI: 10.1587/elex.2.97
Received January 31, 2005
Accepted February 02, 2005
Published February 10, 2005

Acknowledgments

One of the authors [T.F.] received support for this research from Kyoto University Venture Business Laboratory. This research was partially supported by the 21st Century COE Program 14213201 (Japan). The authors acknowledge the SiC JFET devices supplied by Dr. P. Friedrichs (SiCED) and the experimental facilities by Dr. A. Lostetter (Arkansas Power Electronics International, Inc.). The authors from the University of Arkansas also acknowledge the support from the Office of Naval Research under Award No. N00014-04-1-0603 and the National Science Foundation under Award No. ECS-0424411.

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