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High-Speed and High-Temperature Switching Operations of a SiC Power MOSFET Using a SiC CMOS Gate Driver Installed Inside a Power Module

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Abstract. In this study, the simultaneous realization of high-speed and high-temperature switching operations is demonstrated using a custom-made high-speed and high-temperature power module installed with a silicon carbide (SiC) CMOS gate driver, which can reduce gate loop inductance and operate at high temperatures. Approximate switching speeds of 70 and 60 V/ns are achieved during the turn-on and turn-off operations, respectively, at 300°C, 600 V DC bus voltage, and 20 A load current using the developed module. The switching speed remained above 50 V/ns in the temperature range from room temperature to 300°C. Numerical calculations based on the static properties of the SiC power MOSFET and CMOS gate driver can predict the actual switching properties over a wide temperature range when the developed module incorporating the fabricated SiC CMOS gate driver is used.

Introduction

Silicon carbide (SiC) power metal-oxide-semiconductor field-effect transistors (MOSFETs) have been extensively studied because they enable high-speed switching and high-temperature operations[1, 2, 3, 4]. Such high-speed switching operation reduces switching losses while high temperature operation reduces the size of cooling systems in power converters. High-temperature power modules exceeding 250°C have been recently developed and an Si gate driver was placed outside its high-temperature module[2, 3]. It is extremely difficult to install the Si gate driver and main power device (SiC power MOSFET) in the same module at high temperatures (above 250°C) because Si devices cannot operate in the same high-temperature range as SiC devices. Decreasing the impedance of the gate loop wiring between the power MOSFET and gate driver is crucial[5, 6] to achieve high-speed switching. Thus, in principle, it is difficult to simultaneously achieve high-speed (e.g., more than 50 V/ns) and high-temperature switching operations by using conventional high-temperature power modules with external Si gate driver.

Unlike conventional Si gate drivers, SiC complementary MOS (CMOS) gate drivers[5, 6, 7, 8] can be used over wider high-temperature operations, enabling them to be positioned near a SiC power MOSFET in the same high-temperature power module, shortening the gate loop wires. However, the switching properties of SiC power MOSFETs with SiC CMOS gate drivers have only been examined at room temperature (RT)[5, 6, 7, 8], and its simultaneous high-temperature and high-speed switching behavior have not been demonstrated.

In this study, for the first time, we achieved simultaneous high-speed and high-temperature switching operations using a custom-made high-speed and high-temperature module that incorporates a SiC CMOS gate driver. The developed module reduces the gate loop impedance, achieving high-speed switching operations of a 1200 V class SiC power MOSFET at high temperature (300°C). Furthermore, the switching properties are effectively reproduced over a wide temperature range using the proposed simple numerical calculation method based on static properties of the SiC power MOSFET and CMOS gate driver.

Fabrication

To simultaneously realize high-speed and high-temperature switching operations of the SiC power MOSFET, we developed a module capable of operating at high-speed and high-temperature by incorporating the fabricated SiC CMOS gate driver, hereafter referred to as the "HSHT module". Fig. 1 (a) and (b) display photographs of the developed HSHT module, without and with the case, respectively. The module is composed of the fabricated SiC CMOS gate driver, fabricated 1200 V class SiC MOSFET, and fabricated 1200 V class Schottky barrier diode (SBD). Within the module, the gate loop wire is shorter and the gate loop inductance is smaller than the case when the gate driver is placed outside the module. The distance between the gate pad of the SiC power MOSFET and the output pad of the SiC CMOS gate driver is designed to be less than about 5 mm.

In designing the high-temperature module, it is crucial to ensure the same thermal stress in each material. Additionally, the coefficients of thermal expansion (CTEs) should be matched to the greatest extent possible. Based on [2] and [3], the CTEs (4.4 ppm/°C and 7.0 ppm/°C) of silicon-nitride active metal-brazed copper (SiN–AMC) as the substrate and a Cu–Mo–Cu (CMC) composite material as the base plate were matched with that of the SiC device (4.0 ppm/°C) shown in Fig. 1 (c). To examine the impact of temperature (from RT to 300°C) on the switching phenomenon, the developed HSHT module was placed on a hot plate ([2, 3, 7] present details on the method of directly applying heat to the module.).

Fig. 1 (d) shows a photograph of the fabricated SiC CMOS gate driver [6, 8]. The active area is 1.2×2.8 mm^2 without the electrode pads. Owing to multiple parallelization, the NMOS and PMOS of the fabricated SiC CMOS gate driver could achieve several amperes of output current across the tested temperature range. Note that the internal resistance of the SiC CMOS gate driver serves as the gate resistor for the SiC power MOSFET.

Results and Discussion

First, the static properties of the SiC power MOSFET and CMOS gate driver were evaluated within the temperature range from RT to 300°C. Fig. 2 (a) and (b) illustrate the temperature dependence

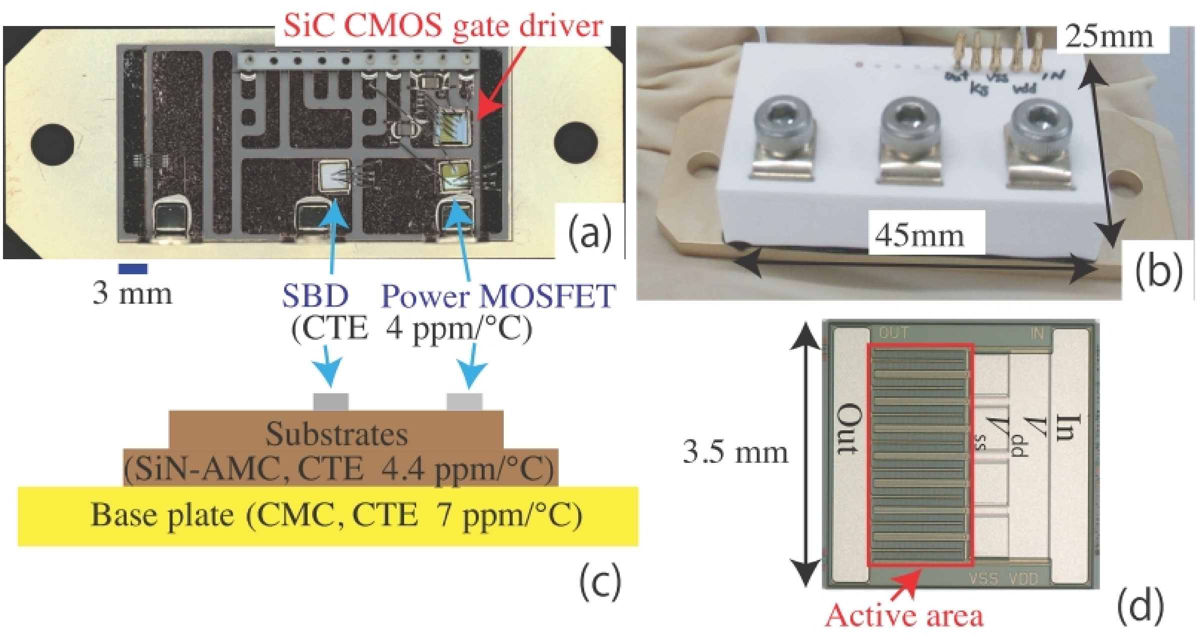

Fig. 1: (a) and (b) Photographs of the developed high-speed and high-temperature module without and with the case, respectively; (c) cross section of the module; (d) photograph of the fabricated SiC CMOS gate driver.

of the current-voltage (I-V) characteristics of the PMOS and NMOS, respectively, in the fabricated SiC CMOS gate driver. The I-V curves were measured using a curve tracer (CS-3200, Iwatsu Electric Co., Ltd.) at gate-source voltages of V_{gsnmos} = 25 V and V_{gspmos} = −25 V, respectively. As the temperature increased, the drain-source current I_{dsnmos} increased under the same V_{dsnmos}, while I_{dspmos} increased up to approximately 200°C and decreased thereafter under the same V_{dspmos}. The temperature dependence of the output current shown in Fig. 2 was mainly determined by a combination of the temperature dependence of the threshold voltage and the channel mobility caused by the MOS interface state density[9].

Fig. 3 depicts the temperature dependence of the gate charge (Q_{g}) waveforms of the SiC power MOSFET under a load current (i_{L}) of 20 A and drain-source voltage (v_{ds}) of 600 V. These Q_{g} waveforms are derived from the results of a power device analyzer/curve tracer (B1505A, Keysight Technologies, Inc.)[5] and by extrapolating the temperature-dependent trends of the threshold voltage based on Ref.[10].

Subsequently, we examined the experimental switching properties of the turn-on and turn-off waveforms as the temperature was increased from RT to 300°C. Fig. 4 (a) shows the experimental circuit configuration in which the switching phenomenon was measured via a double-pulse test. The DC bus voltage was 600 V and i_{L} was 20 A. For the SiC CMOS gate driver, the positive voltage (V_{dd}) and negative voltage (V_{ss}) were set to 20 V and −5 V, respectively, and the maximum and minimum V_{in} values were also set to 20 V and −5 V, respectively. In the double-pulse test, the i_{L} and v_{ds} were measured using a mixed signal oscilloscope (MSO58, Tektronix, Inc.), a current probe (TCP0030A, Tektronix, Inc.), and a voltage probe (TPP0850, Tektronix, Inc.). The inductance L was 1 mH.

Fig. 4 (b) illustrates the experimental waveforms of v_{ds} and i_{L} at 300°C. Here, we realized, for the first time, high-speed switching operation by simultaneously using an SiC power MOSFET and its SiC CMOS gate driver in a high-temperature range via an integrated study of device, mounting, and circuit technology. Fig. 4 (c) and (d) show the experimental turn-on and turn-off waveforms, respectively, at different temperatures. At RT, 100°C, 200°C, and 300°C, the experimental switching time were 8.5, 7.1, 6.8, and 7.2 ns, respectively, during the turn-on operation, and the switching times were 6.9, 6.9, 7.2, and 7.4 ns, respectively, during the turn-off operation. At 300°C, the turn-on switching speed $\mathrm{d}V/\mathrm{d}t$ was approximately 70 V/ns and the turn-off switching speed was approximately 60 V/ns. Switching speeds above 50 V/ns were experimentally sustained within the temperature range from RT to 300°C. The switching speed was almost constant even when the temperatures of both the SiC power MOSFET and SiC CMOS increased.

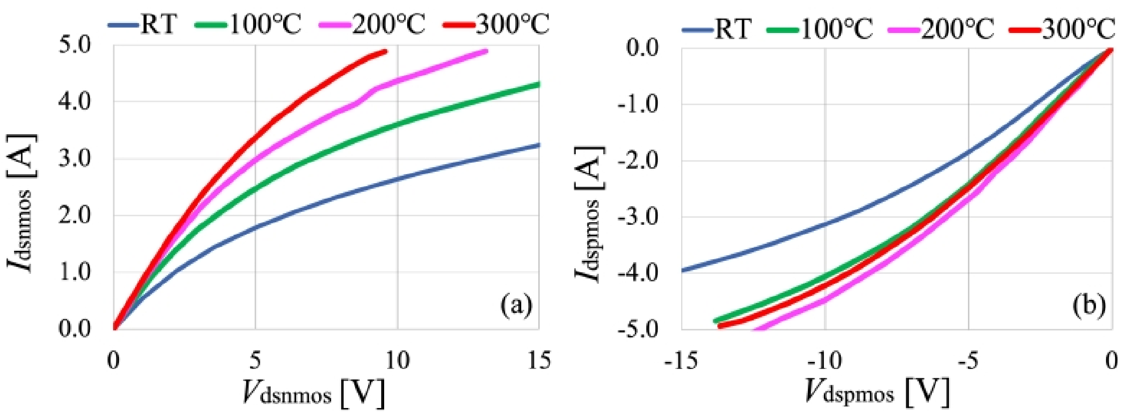

Fig. 2: Temperature dependencies of the I-V characteristics of the fabricated SiC CMOS gate driver: (a) NMOS and (b) PMOS.

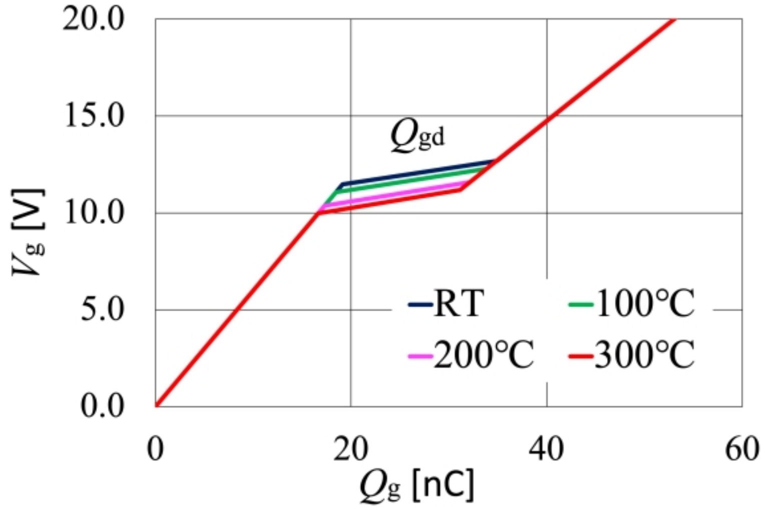

Fig. 3: Temperature dependence of the gate charge (Q_g) waveforms of a SiC power MOSFET operating at 600 V and 20 A.

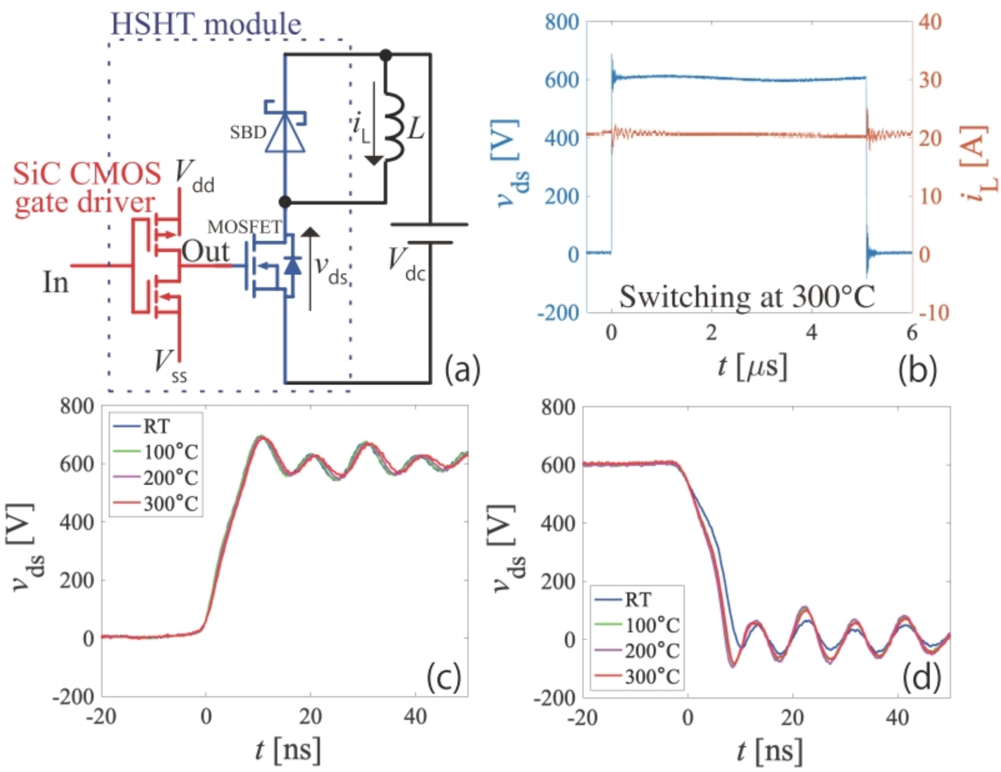

Fig. 4: (a) Schematic of the experimental circuit configuration; (b), (c), and (d): experimental waveforms of the SiC power MOSFET in the developed HSHT module, which includes both the SiC power MOSFET and the fabricated SiC CMOS gate driver, obtained at different temperatures under a bus voltage of 600 V and load current of 20 A. Panel (b) shows the i_L (red line) and v_{ds} (blue line) waveforms at 300°C, (c) shows the v_{ds} waveforms during the turn-off operation, and (d) shows the v_{ds} waveforms during the turn-on operation.

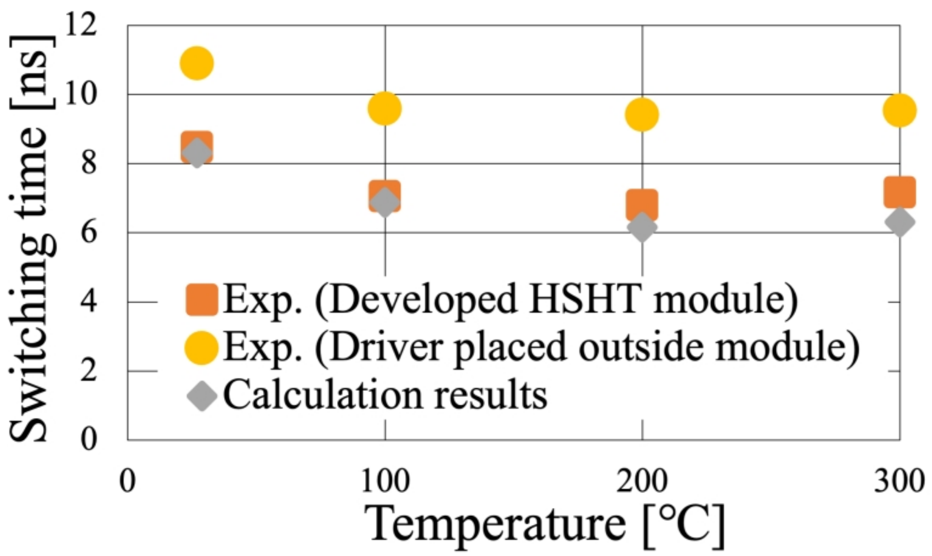

Fig. 5: Experimental and calculated switching time of v_{ds} during turn-on operation of at different temperatures. The orange and yellow points show experimental results with the SiC CMOS gate driver placed inside and outside the module, respectively. The gray points are calculated using Eqs. (1) and (2).

The orange and yellow points shown in Fig. 5 correspond to the temperature dependencies of the experimental switching time with the SiC CMOS gate driver placed inside and outside the module, respectively, for comparison purpose. When the SiC CMOS gate driver was placed outside the module, the wiring length between the SiC power MOSFET and its SiC CMOS gate driver was approximately 400 mm. The experimental switching time with the SiC CMOS gate driver placed outside the module were approximately 11, 9.6, 9.4, and 9.5 ns at RT, 100°C, 200°C, and 300°C, respectively. Compared to implementing the SiC CMOS gate driver outside the module, the experimental switching time with the HSHT module exhibit an improvement of approximately 40% by reducing the inherent parasitic inductance of gate loop wiring across a wide temperature range. Thus, in this study, we have demonstrated for the first time that the proposed HSHT module can reduce the switching time across a wide temperature range from RT to 300°C, compared to previous modules without a gate driver. These results show that simultaneously achieving high-speed and high-temperature switching operations reduces both the switching losses and the size of the cooling system in power converters.

Finally, the switching time t_{sw} of v_{ds} of the SiC power MOSFET during the turn-on operation was calculated by the simple numerical method that do not consider gate loop inductance. Based on the RT study[5, 11], t_{sw} is given as follows:

$$t_{\mathrm{sw}} \simeq 0.8 \times \frac{Q_{\mathrm{gd}}}{I_{\mathrm{g}}}, \tag{1}$$

where Q_{gd} denotes the gate-drain charge[11], 0.8 corresponds to 10%-90% of the total switching change, and I_{g} indicates the gate current of the SiC power MOSFET. Under the turn-on condition, the I_{g} of the MOSFET used with the SiC CMOS gate driver is given by[5]

$$I_{\mathrm{g}} = \frac{V_{\mathrm{dd}} - V_{\mathrm{g}}}{V_{\mathrm{dspmos}}/I_{\mathrm{dspmos}} + R_{\mathrm{gin}}}, \tag{2}$$

where V_{g} and R_{gin} denote the gate voltage and internal gate resistance of the SiC power MOSFET, respectively (here, R_{gin} was measured at V_{g} = 10 V using an impedance analyzer (4294A, Keysight Technologies, Inc.), and it is approximately 2.5, 2.6, 2.9, and 3.2 Ω at RT, 100°C, 200°C, and 300°C, respectively.). The gray points shown in Fig. 5 plot the calculated switching time of v_{ds} at different temperatures during the turn-on operation. These results were calculated using Eqs. (1) and (2) and the data shown in Figs. 2 and 3. The experimental (orange) and calculation (gray) results (points) agree well because the gate loop inductance can be effectively reduced by inserting the SiC CMOS gate driver into the module. However, the yellow points differ from the gray points owing to the influence of the inherent parasitic inductance of gate loop wiring. These results indicate that the numerical calculations based on the static properties of the SiC power MOSFET and CMOS gate driver can effectively predict the actual switching properties across a wide temperature range when the developed HSHT module incorporating the SiC CMOS gate driver is used. In the future, improving the output current of the SiC CMOS gate driver will be crucial[6] to realize further high-speed switching of the developed HSHT power module.

Conclusion

We reduced the gate inductance of the developed HSHT power module by installing a SiC CMOS gate driver and achieved simultaneous high-speed and high-temperature switching operations of a 1200 V class SiC power MOSFET. We realized approximate switching speeds of 70 and 60 V/ns at 300°C during the turn-on and turn-off operations, respectively, at a DC bus voltage of 600 V and load current of 20 A. In this study, we demonstrated for the first time that the proposed HSHT module can reduce the switching time across a wide temperature range from RT to 300°C, compared to previous modules without a gate driver. The proposed simple numerical calculations based on the static properties of the SiC power MOSFET and CMOS gate driver can predict the actual switching properties across a wide temperature range when the developed HSHT module is used because the gate loop inductance can be effectively reduced. Our findings pave the way toward realizing high-temperature and high-speed power circuits using a power module installed with a SiC CMOS gate driver, reducing the cooling required for the circuits, making them smaller and more power efficient.

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