Dynamic Performance of 4H-SiC Power MOSFETs and Si IGBTs over Wide Temperature Range

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***Abstract*—The temperature dependence of the static and dynamic performance of 1.2kV 4H-SiC planar/trench MOSFETs are compared with 1.2kV Si IGBTs over a wide temperature range of 90K to 493K. The static characterization includes static on-resistances (R_{on}) and threshold voltages (V_{th}). The dynamic characterization focuses on the temperature dependence of switching energy losses (E_{sw}). For the first time, the interface traps related degradation of the dynamic on-resistance is analyzed at cryogenic temperatures. The turn-on transients of the SiC planar MOSFET exhibit a smaller delay time. However, the 4H-SiC trench MOSFET suffers much longer delay at switch-on process, especially at lower temperatures due to more interface traps. The effects of interface traps on degradation of dynamic on-resistance are examined.**

Keywords—silicon carbide (SiC); MOSFETs; switching transient; cryogenic temperature; dynamic on-resistance

I. INTRODUCTION

The concept of more electric systems is being applied to more and more applications, such as electric vehicles, electric aircraft and superconducting motors [1-3]. In addition, electronic systems are required to be capable of working at extreme environments of cryogenic or high temperatures to achieve high conversion efficiency and high power density.

SiC offers superior material properties [4]. Its higher carrier saturation velocity allows devices to operate at higher frequencies, and wider bandgap enables higher temperature operations. Excellent thermal conductivity improves heat dissipation in SiC power devices. These excellent material properties combined with novel device structures [5] make SiC power devices an ideal candidate to increase power density and conversion efficiency in power electronics systems.

As the operating temperature range of power devices continues to expand, more and more research has focused on device performance at extreme environments in order to make full use of the advantages of SiC MOSFETs [6]. Static and dynamic characterization of 900 V and 1.2 kV SiC MOSFETs up to 200℃ revealed almost constant losses versus temperature [7]. The performance of 3.3kV SiC MOSFETs on conversion efficiency and power density was also investigated at 150℃ [8]. The dV/dt and peak current capabilities of SiC devices were tested at 150 °C [9]. However, switching performance of 4H-SiC MOSFETs associated with interface states has not been investigated at cryogenic temperatures.

In this paper, we compared dynamic and static performance of 1.2 kV 4H-SiC MOSFETs with Si IGBTs over a wide temperature range of 90K-493K. The temperature dependence of threshold voltage and static on-resistance is analyzed. A double pulse testing setup is used for dynamic characterization at cryogenic and high temperatures. Switching energy losses and turn-on transients for the three devices over a wide temperature range are examined and trap related dynamic on-resistance degradation is quantified for all devices at cryogenic temperatures, especially in the 4H-SiC trench MOSFET.

II. DOUBLE PULSE TESTING SETUP FOR TEMPERATURE-DEPENDENT CHARACTERIZATION

The double pulse testing circuit (DPT) including the under-test-device (DUT), a freewheeling diode (FWD) and a load inductor [10] is used for evaluating the switching performance of the DUT, as shown in Fig. 1. In order to accurately characterize the transient process in the DUT with an inductive load, parasitic parameters in the circuit must be optimized [11].

A 1.2 kV SiC Schottky diode (SBD) is choose as free-

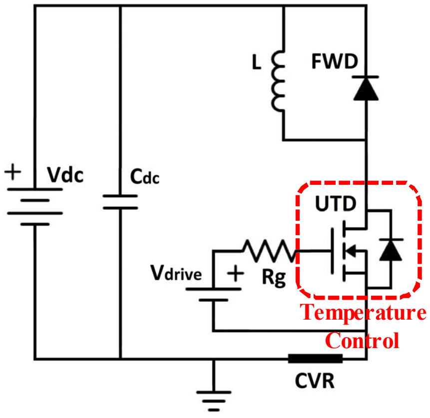

Fig. 1 Equivalent test circuit of measurements

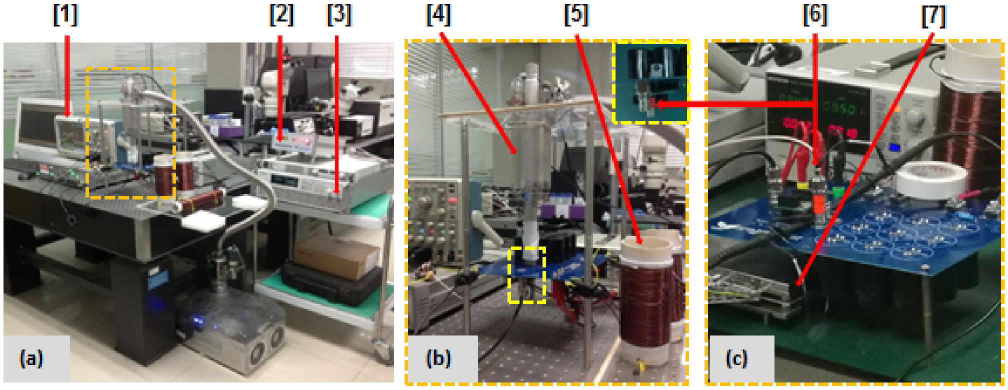

Fig. 2. Hardware set-up with [1] digital phosphor oscilloscope [2] temperature controller, [3] programmable dc-power supply, [4] cryogenic vacuum chamber, [5] load Inductor, [6] current view resistor, [7] hot plate.

wheeling diode paralleled with the load inductor of 344uH. A 42.3uF capacitor (nine 4.7uF capacitors in parallel) is used to ensure a constant DC voltage (V_{dc}) during the DUT switching process. The coaxial current shunt (CVR) (SSDN-414-01) is used to accurately measure the current (Ids) of the DUT while a Tektronix voltage probe is used to obtain the source-drain voltage (V_{ds}) signal during switching transients. The current and voltage is displayed and stored using Tektronix Digital Phosphor Oscilloscope (DOP 4104B-L) with 0.4ns sampling interval.

The DPT setup for temperature-dependent switching characterization is shown in Fig. 2. A liquid nitrogen thermostat system is used to provide a cryogenic test platform, with temperature accuracy of 0.1K over temperature range of 77K to 300K. The DUT is attached on a large copper plate in a vacuum chamber and is cooled by liquid nitrogen. Fig. 2(b) shows the zoom-in detail of the thermostat system and DUT location in the characterization system. For high temperature characterization, a hot plate is used with precise temperature control as shown in Fig. 2(c). The hot plate can achieve 0.1K temperature accuracy from room temperature to 523K.

III. STATIC DEVICE PERFORMANCE

The on-resistance (R_{on}) of the three devices are shown in Fig. 3. The 4H-SiC MOSFETs and the Si IGBT exhibit lowest R_{on} around 200K to 300K and 150K, respectively. Due to lower R_{on} of the two SiC MOSFETs compared with the Si IGBT for temperatures greater than 150K, SiC based power electronic system will have smaller energy consumption compared with Si based system. However, the on-resistance of the trench SiC MOSFETs rises sharply when the temperature is decreased, and even is even higher than that of the Si IGBT at temperatures less than 150K.

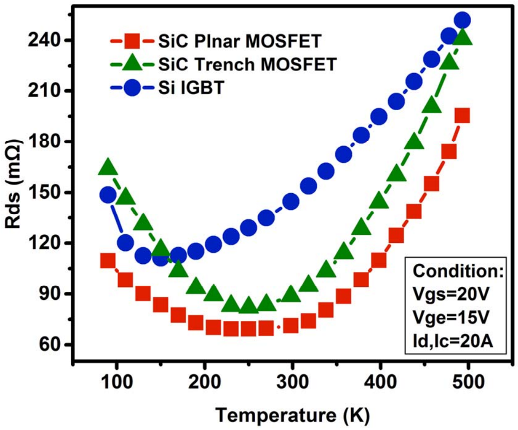

Fig. 3. Temperature dependence of on-resistance.

The R_{on} consists of two parts, namely channel resistance (R_{ch}) and remaining part (R_s). At higher temperatures, the contact resistance and channel resistance are relatively small[6], while R_s is dominant and has a negative correlation coefficient with temperature due to bulk electron mobility [12]. At lower temperature part, R_s is much smaller due to the increase of bulk electron mobility. There are numerous factors that affect the value of R_{ch}, such as incomplete ionization of dopant, columbic interface trap scattering, velocity saturation, etc. However, the dominant mechanism of the R_{ch} increase at cryogenic temperature is due to the increase of trapped electrons [13]. The slope of the trench-gate MOSFET is greater

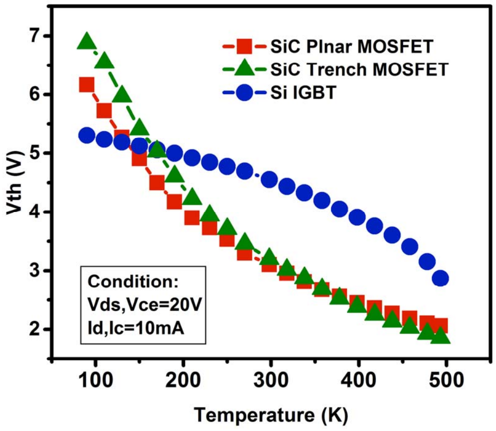

Fig. 4. Temperature dependence of threshold voltage.

as a result of the higher SiO_2-SiC interface states.

As shown in Fig. 4, threshold voltage of the three devices increases when temperatures decrease. However, the V_{th} of the SiC MOSFETs increases about 4.5V from 500K to 90K, which is much larger than that of the Si IGBT (about 2.3V). It has been shown that the V_{th} increase is related to trapped interface electrons [14]. Since the SiO_2-SiC interface is much worse than the SiO_2-Si interface, the temperature effects on threshold voltage of the 4H-siC MOSFET are more serious at low temperature compared with that of the Si IGBT.

IV. SWITCHING CHARACTERIZATION

The DC bus voltage in the DPT circuit is fixed at 800V considering the actual power conversion system applications for 1.2kV devices. The switching energy and switching transients of the DUT at temperatures from 90K to 493K are examined and traps related dynamic degradation is analyzed.

A. *Switching Energy losses Characterization*

The switching energy losses include turn-on loss (E_{on}) and turn-off loss (E_{off}). The switching energy (E_{sw}) can be calculated by integrating the product of the current and the source-drain voltage. The integration interval for E_{on} is between the time when I_{ds} rises to 10% of the switching current and the time when V_{ds} falls to 10% of the bus voltage. The integration interval of the turn-off process is similar to that of the turn-on process.

The temperature dependence of the switching energy losses at 800V dc bus voltage is shown in Fig. 5. The E_{sw} of the 4H-SiC planar MOSFET decreases from 500μJ to 381μJ, while the E_{sw} of the Si IGBT increases from 734.2μJ to 3500.8μJ. In the high temperature range (>190K), the E_{sw} of the SiC MOSFETs have a negative temperature coefficient exactly opposite to that of the Si IGBT. However, the E_{sw} of the SiC MOSFETs decreases with decreasing temperature when temperatures are lower than 190K. The difference in temperature coefficient of is caused by interface states and the traps, which will be discussed later. The SiC MOSFETs offer obvious advantages compared with the Si IGBT especially at high temperature, and the E_{sw} of the Si IGBT will be 10 times of that of the SiC planar MOSFET at 493K.

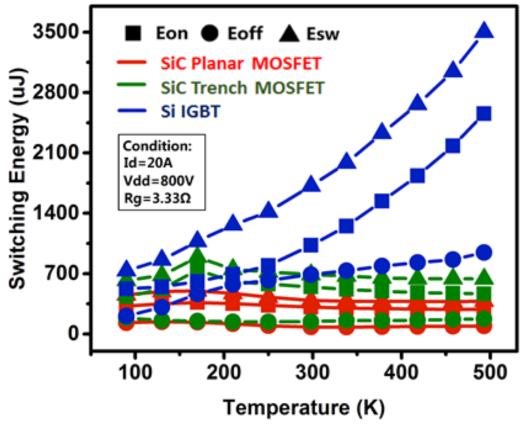

Fig. 5 Comparison of switching energy as a function of temperature from 90K to 493K.

Fig. 6 shows the switching energy losses as a function of load current, with load current from 3A to 31A. As the switch time increases proportionately with current, the E_{sw} increases quadratically with the current. But the increase of switching energy for the Si IGBT is more significant compared with that of the SiC MOSFETs.

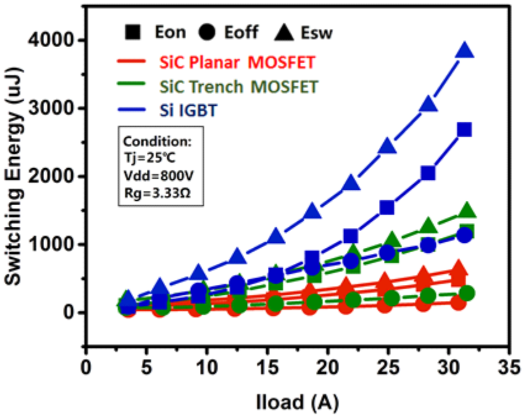

Fig. 6 Comparison of switching energy as a function of load current.

B. *Switching Trascient Analysis*

In order to accurately characterize the switching performance of the devices at cryogenic temperatures, a more detailed transient analysis is conducted to analyze the turn-on transient of V_{ds} and I_{ds}.

Fig.7 shows the turn-on transients of the Si IGBT at low temperatures. As temperatures decrease, collector-Emitter voltage (V_{ce}) tailing of the Si IGBT become smaller and smaller, resulting in faster switch process. This trend is consistent with the trend of E_{sw} as shown in Fig. 5. The bipolar modulation in the Si IGBT is controlled by the lifetime of minority carriers, which directly affect the switching process.

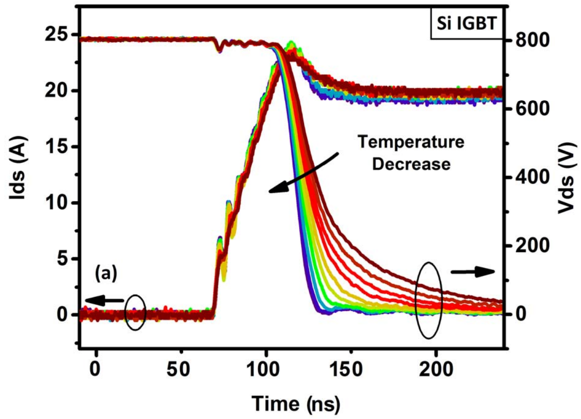

Fig. 7 Turn-on transient of the Si IGBT with 20K temperature decrease step from 290K to 90K

Fig. 8 shows the turn-on transient of the SiC planar MOSFET. The di/dt of the device increases as temperatures decrease. It can be seen that the turn-on delay and the Miller

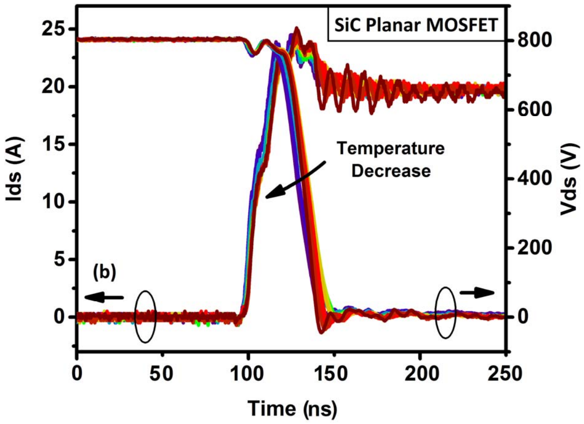

Fig. 8 Turn-on transient of the SiC Planar MOSFET with 20K temperature decrease step from 290K to 90K

plateau length is reduced at lower temperatures, which is confirmed by the gate transient waveforms (not shown). This effect is more pronounced in the SiC Trench MOSFET at cryogenic temperature as shown in Fig. 9.

The turn-on transient waveform shows that the V_{ds} of SiC planar MOSFET exhibits a delay time of 375ns and returned to the original value finally. In contrast the V_{ds} of the 4H-SiC trench MOSFET suffers much longer delay, especially at lower temperatures. This trailing phenomenon is mainly caused by the dynamic on-resistance degradation during the turn-on process, which is related with trapped electrons at cryogenic temperatures [15,16].

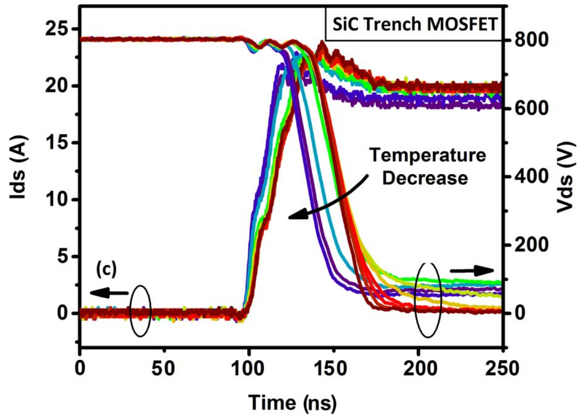

Fig. 9 Turn-on transient of the SiC Trench MOSFET with 20K temperature decrease step from 290K to 90K

The capacitance measurements of the interface states are carried out for the 4H-SiC trench MOSFET and 4H-SiC planar MOSFET. The flat-band voltage for the 4H-SiC trench MOSFET is -0.016V and -3.466V at 290K and 90K, respectively, as extracted from Fig. 10. In contrast, the flat-band voltage for the 4H-SiC planar MOSFET is 0.014V and -0.94V at 290K and 90K, respectively, showing a much smaller flat-band voltage shift. The extent of the flat-band voltage is consistent with that of the dynamic on-resistance degradation, It is a clear indication that a strong correlation exists between the SiC/SiO_2 interface states and the dynamic on-rsistance degradation at cryogenic temperatures.

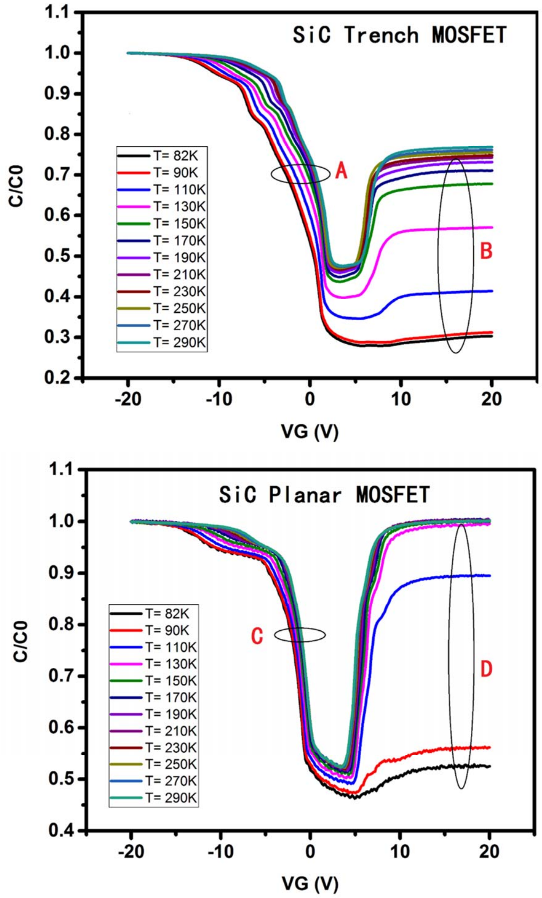

Fig.10. Interface characterization of the 4H-SiC trench MOSFET and 4H-SiC planar MOSFET.

V. CONCLUSIONS

The static and switching performance of the 1.2kV 4H-SiC planar MOSFET, the 4H-SiC trench MOSFETs and the Si IGBT over a wide temperature range of 90K to 493K are investigated. Compared with the Si IGBT, the SiC MOSFETs show smaller on-resistance and lower switching losses in the measured temperature range. For the first time, the trap related dynamic on-resistance degradation is correlated with the SiC/SiO_2 interface states in the 4H-SiC MOSFETs at cryogenic temperatures, especially for the 4H-SiC trench MOSFETs.

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