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Body Diode of 1.2kV SiC MOSFET: Unipolar and Bipolar Operation

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Abstract. In this work, we investigate the Body Diode (BD) of a 40mOhm, 1.2kV SiC MOSFETs. We performed DC measurements and switching measurements, at Room Temperature (RT) and High Temperature (HT) (T=175°C), together with TCAD simulation and calibration. In switching measurements, we focused on the low side (LS) switch turn-on event, i.e., the BD turn-off event. We demonstrated that unipolar and bipolar BD can both be achieved with different V_{GS}. With V_{GS}=-5V, BD conducts in bipolar mode with carriers being injected via pn junction. This is rather well known in literature and is well characterized by the Negative Temperature Coefficient (NTC) of BD V_F. Switching with BD V_{GS}=-5V show strong reverse recovery-temperature dependent that caused by the augmented minority carrier injection at high temperature. Unipolar BD is achieved by channel conduction at V_{GS}=0V and it is well characterized by BD V_F - Positive Temperature Coefficient (PTC). Thanks to the unipolar nature, turn-on switching with BD V_{GS}=0V show no reverse recovery-temperature dependent.

Introduction

SiC MOSFETs, especially 1.2kV rated devices, are now widely used in numerous applications, especially automotive applications such as traction inverters and fast charging stations. One important advantage of MOSFETs is the internal BD can be used as a Free-Wheeling Diode (FWD) without using external anti-parallel diode in the switching applications. Although a SiC BD has low injection at RT, at HT carrier injection and the resulting reverse recovery current can be significant. For instance, the reverse recovery introduces an increased turn-on (Eon) switching loss [1] or, in the worst case, it can even introduce the catastrophic faults to the system [2]. It is therefore important to reduce the "HT BD reverse recovery" effects so that the BD can be used as a FWD with maintained good performance. One approach to mitigate the problem is to utilize the integrated Schottky Barrier Diode (SBD) [3, 4] where unipolar current will flow through the SBD and reduce reverse recovery effects. Nevertheless, this approach increases process integration complexity, and it consumes some active area of the die.

As shown in previous works, in case of BD conduction, current can flow through either the pn junction path and/or the MOS channel path [5, 6]. Fig1.a represents a planar type SiC MOSFET device structure and the BD viable current paths. In this work, it is shown that unipolar and bipolar BD operation can be achieved in a 40mΩ, 1.2 kV planar SiC MOSFETs via the mentioned current paths using V_{GS}=0V and V_{GS}=-5V, respectively. Detailed device investigations were done by electrical characterization and TCAD simulations, of DC characteristics and switching characteristics, at RT and HT. BD turn-off switching with V_{GS}=0V show no reverse recovery-temperature dependence thanks to the unipolar current via channel conduction.

Experiment and Simulation Set-Up

Measurements in this work were done based on TO-247-3L package devices. A Keithley S500 integrated test system were used for DC measurements and for pulsed high current measurements, using a pulse width of 230 µs. Switching measurements were done using a Double Pulse Test (DPT) set-up equipped with the NCP51705 gate driver from onsemi [7]. For switching current measurements, a Pearson probe with 100MHz bandwidth was used.

Fig.1b depicts the simplified circuit diagram of the DPT measurements. In our measurements, the Low Side (LS) device is the active switch and High Side (HS) device is the BD. This paper will focus on the turn-on event of LS switch, which is equivalent to the HS BD turn-off process. For the purpose of BD investigations, LS switching conditions (e.g., V_{GS}, Temperature, R_{G_ext}) were kept constant to maintain a fixed di/dt. HS BDs were varied in V_{GS} (0V and -5V) and in temperature (from RT to 175°C).

For TCAD simulation, device structures were generated based on actual fabrication process using sprocess. Sdevice and mixed-mode simulation were used to simulate DC characteristics and switching characteristics [8]. Further details of simulation model were described elsewhere [9].

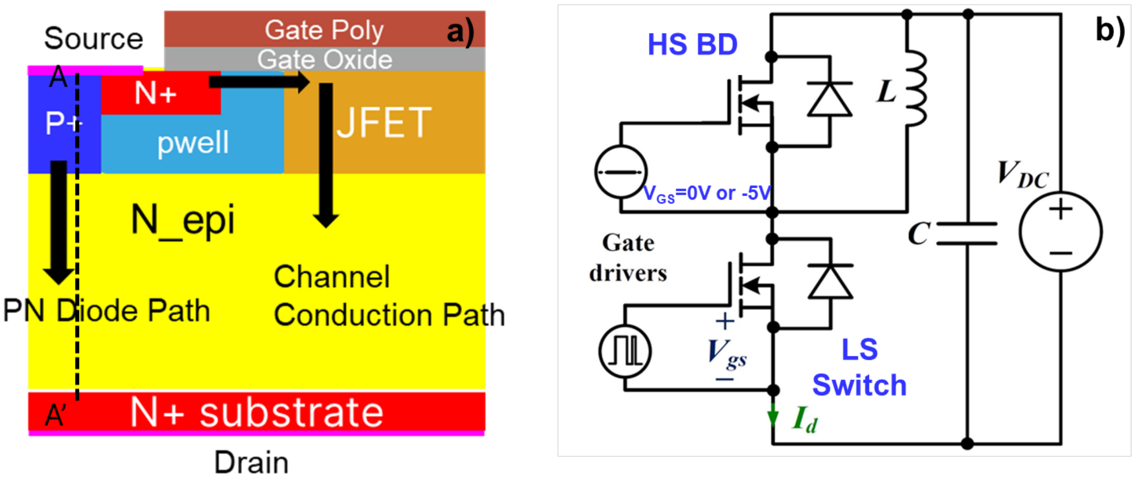

Fig.1: a) Device structure of a planar type SiC MOSFETs and its viable current paths during a BD conduction; b) Simplified circuit diagram of a DPT measurements.

Body Diode DC Characteristics

Fig.2a describes the measured and the simulated BD DC characteristics at RT with different V_{GS} (V_{GS}=0V to V_{GS}=-6V, step -1V), in log-scale. The figure shows that BD built in potential can be controlled by the gate bias and the characteristics can be well simulated. The V_{GS} control of the potential barrier in Fig. 2a demonstrates the importance of BD channel conduction when V_{GS} is close to zero, due to the low potential barrier of the MOSFET channel.

Fig.2b represents linear-scale BD DC characteristics at V_{GS}=-5V with temperatures varied from RT to 175ºC, with steps of 50ºC. In this case, V_{ON} at RT is about V_{DS}=-3V, which is typical for a SiC pn diode. Both V_{ON} and V_F (e.g., I_F=20A) have NTC. This NTC is due to temperature dependence of the pn junction built-in potential and can also be influenced by incomplete ionization of dopants, and the carrier lifetime.

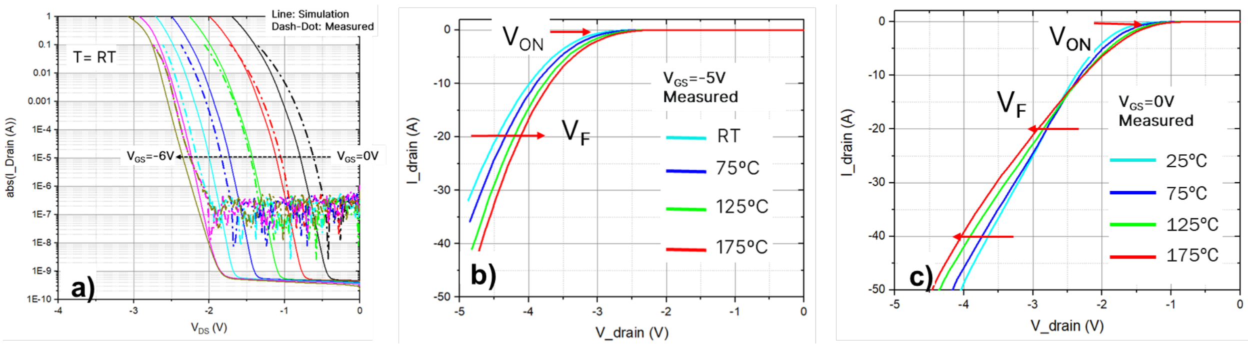

Fig.2: a) Measured and simulated body diode characteristics at different V_{GS}; b-c) BD DC characteristics measured at different temperatures with V_{GS}=-5V and V_{GS}=0V, respectively.

Fig.2c shows the linear-scale BD DC characteristics at V_{GS}=0V with temperatures varied from RT to 175ºC, with steps of 50ºC. It is noticeable that RT V_{ON} is about V_{DS}=-1.5V, which is well below

SiC pn junction built-in potential. While V_{ON} have NTC, there is a shift for currents exceeding 15A where BD V_F has PTC.

Body Diode Characteristics with V_{GS}=-5V: Bipolar Device

Fig.3a describes measured and simulated BD high current characteristics with V_{GS}=-5V, at RT and 175ºC. In the simulation, empirical models with fitting parameters were used for spatially dependent carrier lifetime due to ion implantation induced defects, carrier lifetime-temperature dependence and contact resistance-temperature dependence. Here, relatively good agreement regarding V_F and V_{ON} was obtained. It is also worth to mention that there is still discrepancy for the BD high current, that could be due to contributions from peripheral structures. Simulation of I_D vs time and V_{DS} vs time during LS switching turn-on process (Fig.3b-c) shows good agreement compared to measurements. It is notable that, with HS BD V_{GS}=-5V, a strong temperature dependence of the current overshoot is observed. This phenomenon was reported previously [1,10,11] and this effect is attributed to the augmented carrier injection at high temperatures of a typical bipolar diode [12]. In the event of fast switching, these carrier plasma effects become much severe (data not shown).

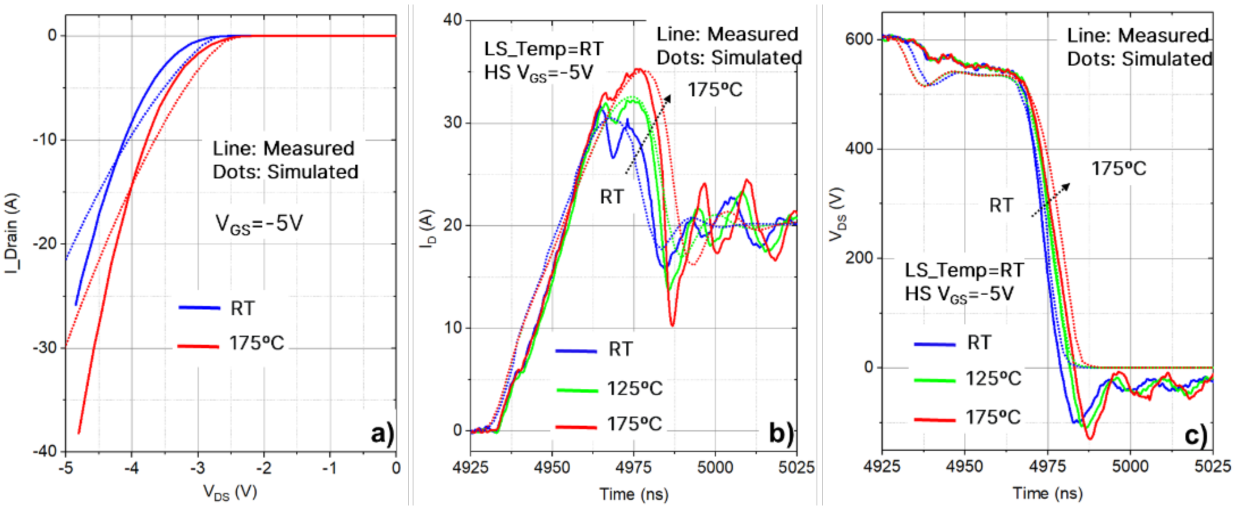

Fig.3: Measured and simulated RT and HT of a) DC characteristics with V_{GS}=-5V; b-c) LS switch turn-on switching characteristics with HS V_{GS}=-5V.

Fig.4a displays the simulated electrical characteristics of the HS BD turn-off event, for HS V_{GS}=-5V and HS T=175ºC. Internal device structures were saved at 10 different intervals, as marked in the figure.

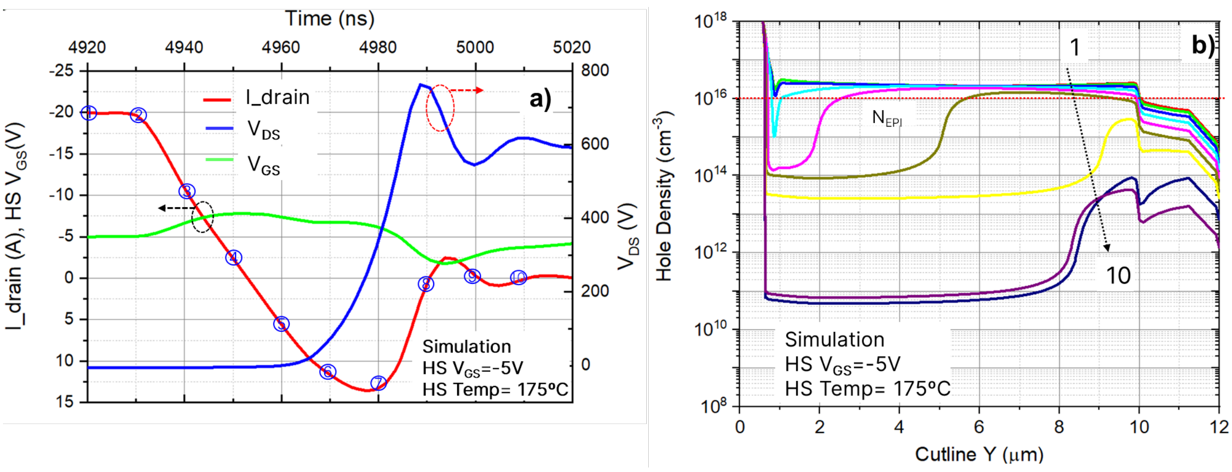

Fig.4: a) Simulated electrical characteristics of HS BD turn-off process with HS V_{GS}=-5V and HS T=175°C; b) Simulated hole density at different interval during the HS BD turn-off process.

Fig.4b shows the simulated hole density along the HS BD drift region at the mentioned intervals, along cutline AA′ in Fig.1a. In this case, the hole density is a few times higher than epi doping concentration at the start of BD turn-off process, and about half of the n-epi has been cleared from holes as the peak reverse recovery current is reached. BD turn-off process therefore related to the sweeping-out of minority carriers along with electric field develop and Space Charge Region (SCR) extension, as in a bipolar diode. The "reverse recovery" of these carrier plasmas is causing the increased current with increase temperature.

Body Diode Characteristics with V_{GS}=0V: Unipolar Device

Fig.5a shows the measured and the simulated BD DC characteristics at RT and HT with V_{GS}=0V. Simulated results shows good agreements with its measured counterpart for the NTC of V_{ON}, the PTC of V_F and for the high current V_F. Simulated internal device structures at identical high current levels reveal that electron mobility decreases with increasing temperature in JFET region, drift region and substrate region is responsible for the PTC of the BD.

Fig.5b-c depict the measured and the simulated I_D vs time and V_{DS} vs time during LS switch turn-on process with V_{GS}=0V applied to the HS device. Good agreement between measurements and simulation is obtained. The significance of this figure is that with BD temperature varied from RT to 175°C, no difference is observed between the switching waveforms, i.e., no variation on the BD reverse recovery with increasing temperature.

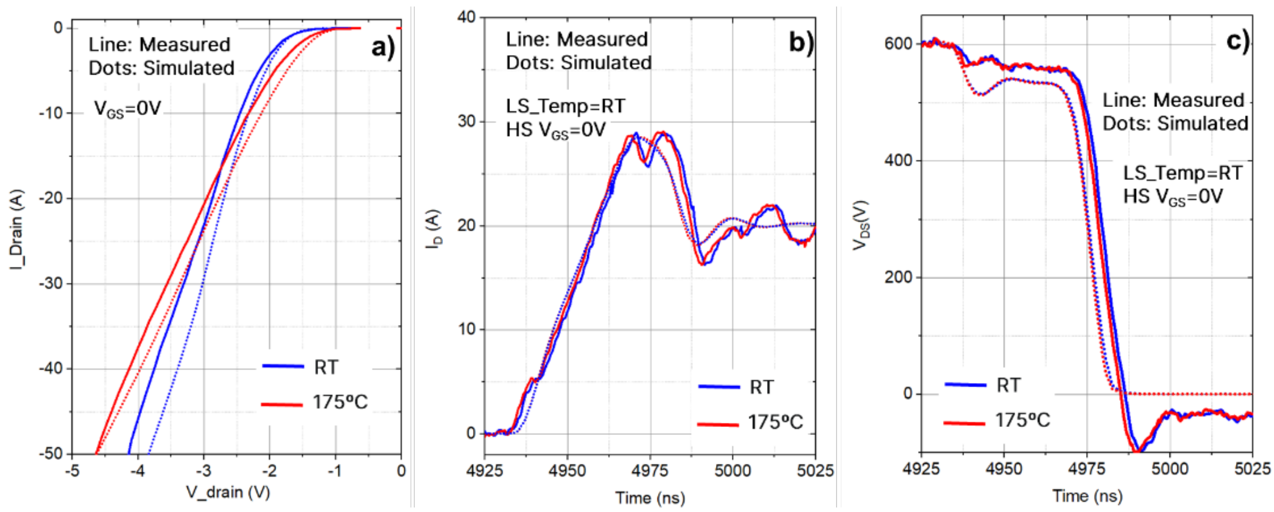

Fig.5: Measured and simulated RT and HT of a) DC characteristics with V_{GS}=0V; b-c) Turn-on switching characteristics with HS V_{GS}=0V.

Fig.6a represents the simulated electrical characteristics of the HS BD during its turn-off process with HS V_{GS}=0V and HS T=175ºC. Internal device structures were also saved at 10 different intervals. Fig. 6b displays hole density along the HS BD drift region at the marked intervals during BD turn-off process, along cutline AA' in Fig.1a. It is shown that, in this case, at the start of BD turn-off process, the hole density is about *10^6* time lower compared to the epi doping concentration. During BD turn-off process, hole densities remain significantly lower than epi doping concentration. BD turn-off process therefore solely related to electric field development and SCR extension as in a typical unipolar device. The reason for the unipolar operation with V_{GS}=0V is a reduced anode emitter injection efficiency due to channel conduction. The drain current peak observed in LS switch turn-on is due to capacitive current and therefore temperature independent.

The effect remains in fast switching (e.g., di/dt=5A/ns), highlights the capacitive nature of the mentioned unipolar body diode. Since current overshoot in LS turn-on with HS BD V_{GS}=0V are temperature independent with different di/dt, parasitic turn-on can be ruled-out in this measurement.

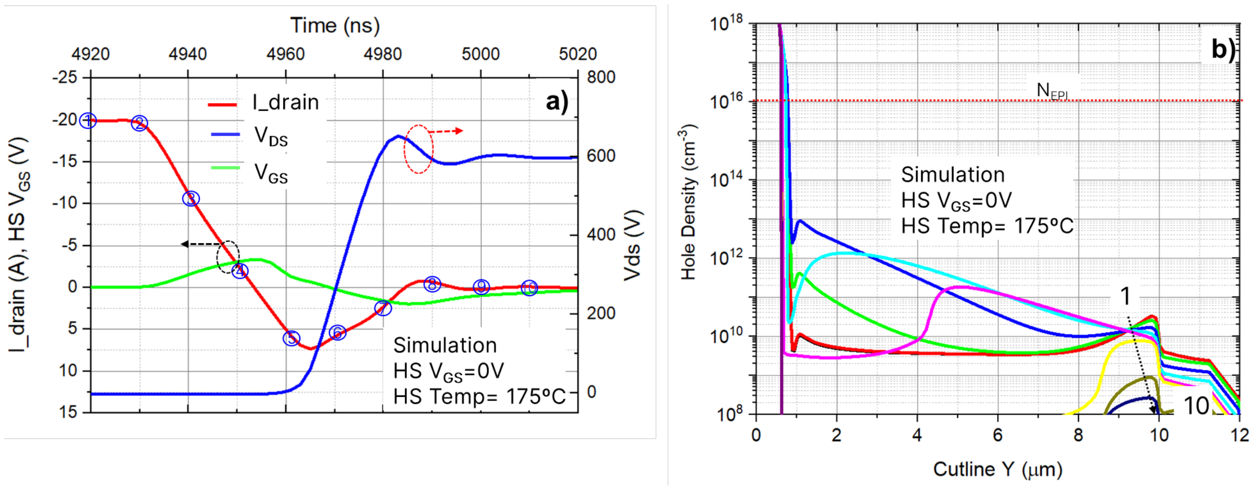

Fig.6a: Simulated electrical characteristics of HS BD tun-off process with HS V_{GS}=0V and HS T=175°C;
Fig.6b: Simulated hole density at different interval during HS BD turn-off process.

Summary

In summary, we demonstrated that the BD of planar 1.2 kV SiC MOSFETs can operate in both unipolar and bipolar diode, depending on V_{GS}. The features of unipolar BD with channel conduction presented in this work highlights the possibility to reduce the body diode reverse recovery current and associated power losses by operation with V_{GS}=0 V.

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