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Pulsed Forward Bias Body Diode Stress of 1200 V SiC MOSFETs with Individual Mapping of Basal Plane Dislocations

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Abstract. Bipolar degradation is a known problem in the development of SiC MOSFETs when the body diodes(p+ body/ n- drift layer) are forward biased. Mostly higher voltage classes like the 1.7 kV or 3.3 kV SiC MOSFETs have been studied in literature resulting with significant Rdson increase [1-2]. In this work, body diode stress was conducted for planar 1.2kV SiC MOSFETs, which were mapped with Infra-Red photoluminescence (IR-PL) to determine and localize the exact number of BPDs present in the drift layers of each die [3, 4] and grouped by this criterion. Devices were stressed at extremely high current densities (1200 – 1700 A/cm^2) under pulsed conditions. The post-stress analysis shows non-negligible increase of Rdson. Bipolar degradation occurring from stressing the body diodes at high forward current densities was confirmed by electroluminescence analysis.

Introduction

Bipolar degradation is a severe reliability issue and extensively researched in SiC technology development. The carrier recombination mainly occurs in lightly doped regions, where a high-density electron-hole plasma is created by forward biasing of the body diode [5]. The bipolar operation of SiC MOSFETs cause BPDs to nucleate SF expansion [6]. These BPDs could originate from the substrate region and during the epitaxial growth propagate to the epilayer. In [7] has been concluded that SF expansion is highly dependent on the forward current density.

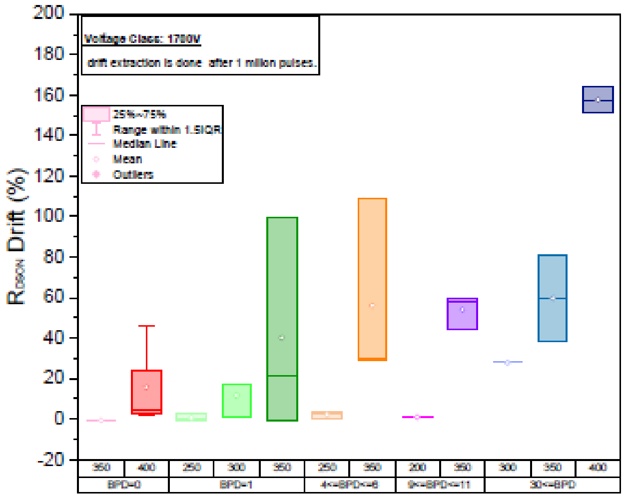


Fig. 1. Rdson drift in 1.7kV SiC MOSFETs grouped by the number of BPDs in the epi layer [4].

In this work, body diode stress was conducted for 1.2 kV SiC MOSFETs, which were fabricated using a SiC epitaxial process that converts most but not all basal plane dislocations (BPDs) from the substrate to threading edge dislocations. The wafers were mapped with Infra-Red photoluminescence (IR-PL) to determine and localize the exact number of BPDs present in the epitaxial drift layers of each die [3, 4]. The SiC MOSFETs were then packaged in two groups, one with individual BPD counts in the epi ranging from 22 to 50 per device and second group without BPDs. Fig. 1 from [4] shows Rdson drift for 1.7kV SiC MOSFETs, grouped in various groups by the number of BPDs present in the device and stressed at extremely high forward current densities. In this work, 1.2kV SiC MOSFETs were categorized by number of BPDs present in epi layer, stressed at extremely high current densities (1200 – 1700 A/cm^2) and the degraded samples were analyzed by electroluminescence.

Experimental Analysis

The following analysis consist of three main aspects: electrical characterization, continuous pulse stress test of the body diode of SiC MOSFETs and electroluminescence. The electrical characterization has been performed by using Keysight's B1505A power analyzer with focus on following parameters: Igss, Vth, Rdson, Idss, BV and Vf. The continuous pulsed forward stress test is conducted on a special surge current tester with high currents capabilities rated for up to 2kA. Fig. 2 shows the procedure of testing the devices subject to bipolar degradation on the left side and the measured transient forward current If and forward voltage Vf waveforms from the continuous pulsed stress tests on the right side.
The surge current tester provides a controllable almost square shaped current pulse with length of 50

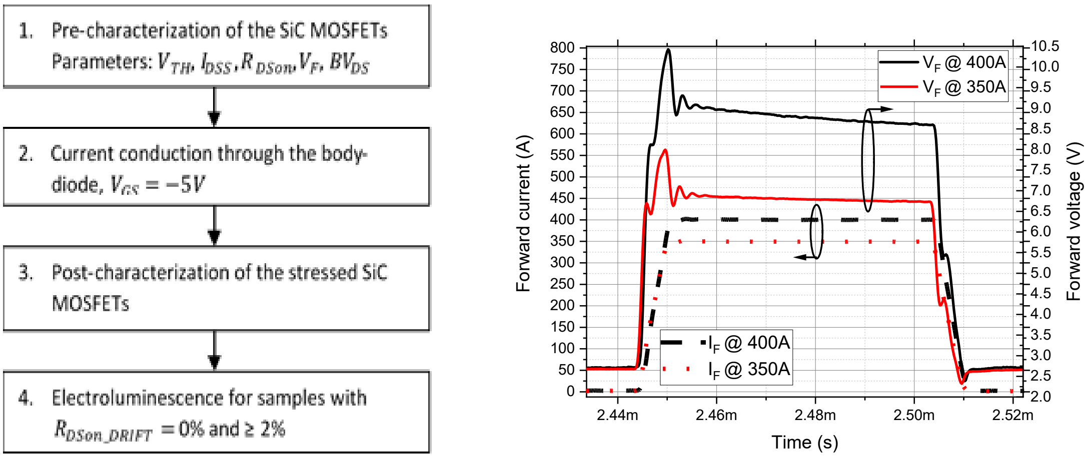
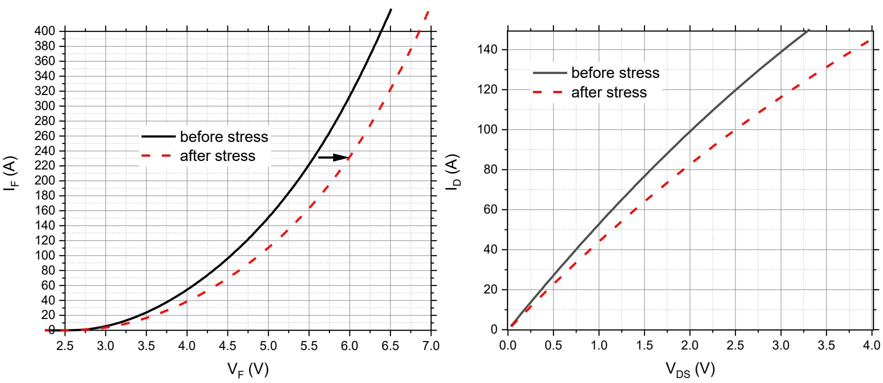


Fig. 2. a) Testing procedure for bipolar degradation [4] b) Measured transient voltage Vf and current waveforms at controlled Id pulse of 350A and 400A, while maintain DUT at Vgs = -5V.



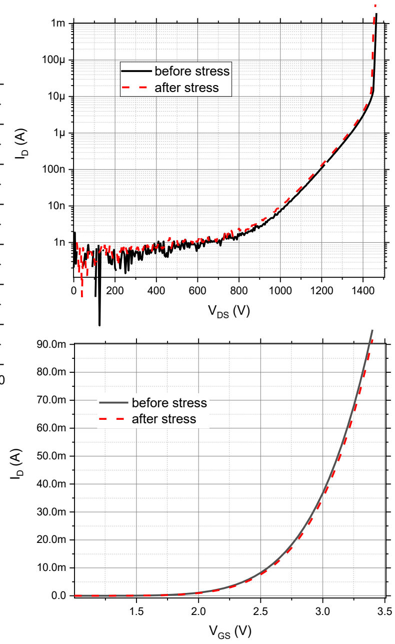


Fig. 3. Electrical characterization before and after stress test on one sample from the BPD=0 group and stress pulse current 400A: a. the If-Vf curves of the body diode of SiC MOSFETs, b. Id-Vds curve, c. BVds (IDss) curve and d. Vth curve.

µs at a frequency of 100 Hz. The measurements are performed at ambient temperature. The pulse width of 50 µs is sufficiently short to keep the junction temperature of the device within the temperature specification limits, where a small decrease of Vf observed for the full pulse. The observed overshoot in forward voltage Vf originates from the system parasitic inductance. Pulsed body diode measurements are conducted with high currents of 300-400 A (around 1200-1700 A/cm^2) with electrical characterization before and after to check for drift of key electrical parameters. Fig 3 shows the If-Vf curves of the body diode of SiC MOSFETs and Id-Vds curve, before and after forward body diode stress where increased values of the Rdson and Vf are observed. BVds, IDss and Vth curves were, on the other hand, not affected by the body diode stress as can be seen in Fig. 3. As mentioned before, SiC MOSFETs were grouped by the number of BPDs, and set for forward body diode stress tests at various high current densities as described in Table 1.

Table1. Grouping of the SiC MOSFETs by the number of BPDs criteria, testing currents and current densities, pulse parameters, frequency and number of stress cycles.

Criteria	Current [A]	Current densities [A/cm^2]	Pulse width [µs] and Frequency [kHz]	Number of stress pulses
BPD = 0	400A	1700	50, 100	1 000 000
BPD = 0	350A	1500		
20<BPD>50	350A	1500		
20<BPD>50	300A	1250		

There are two groups of devices, one with BPD=0 and second with BPD count between 20 to 50. Fig. 4 shows drift in Rdson and V_F vs. BPD count after accelerated body diode stress with total of 1 million 350 A (J≈1500 A/cm^2), 50 µs pulses at 100 Hz. As observed, the tested 1.2 kV SiC MOSFETs show a significant acceleration of Rdson drift with the number of BPDs, and as expected it is less affected at these stress current levels compared to the 1.7 kV. Fig. 5 displays the results of 1.2 kV vs 1.7kV SiC MOSFETs stressed at the same conditions, the same amount of stress pulses and 350A pulsed

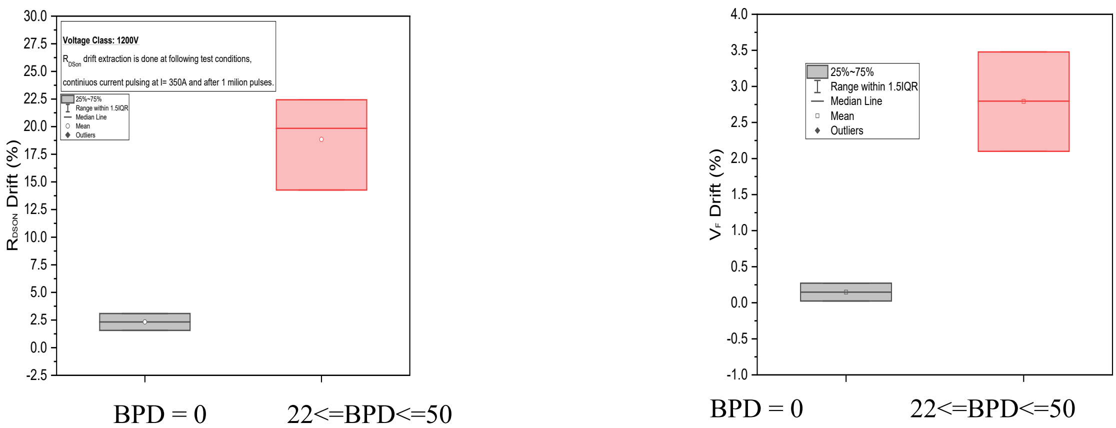


Fig. 4. Drift in Rdson and V_F vs. BPD count after body diode stress of 1200 V 20 mΩ SiC MOSFETs with 1 million 50 µs pulses with 350 A (as shown in Fig. 1b)

body diode current. The drift observed in forward voltage is not so significant as it is below 5% compared to the initial value in both groups. At stress forward current of 350A, the BPD=0 group shows stable low shift in Rdson< 3% but samples with more BPDs show Rdson shift ~ 20%. Fig. 6 displays comparison of two samples with BPD=0, which got tested at stress current of 400 A. The device A shows extreme Rdson drift of ~ 120% when stressed at these high currents, whereas in 1.7 kV analysis the maximal Rdson drift observed was 200%. The higher Rdson drifts noticed in 1.7 kV compared to 1.2 kV are reasonable results due to the thicker epi-layer, where bar-shaped stacking faults will propagate to cover a larger area. Even in lower voltage classes like 1.2 kV SiC MOSFETs, there can be higher drifts observed under extreme current stress conditions. The degradation, observed from the results presented in this paper, is not occurring due to a package or a bond-wires

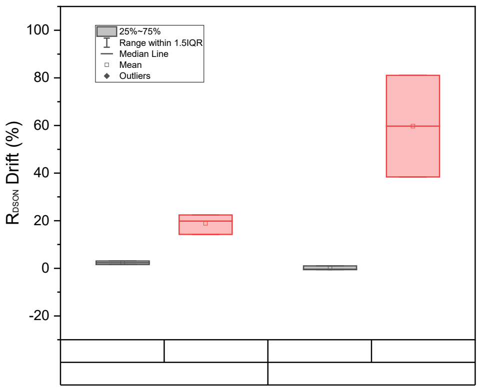


Fig. 5. Rdson drift comparison on 1.2 kV vs 1.7 kV SiC MOSFETs tested at 1 million 50 µs pulses with 350 A

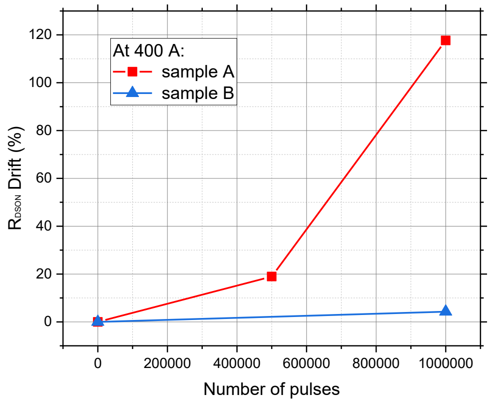


Fig. 6. Drift in Rdson after body diode stress with 1 million 50 µs pulses with 400A of the for 1200 V 20 mΩ SiC MOSFETs with 0 BPD

(thermomechanical) damage as reported by [8] but by stacking faults expansion. In the case of high current density of 1700 A/cm^2, the hole density increases significantly in the border region between the epi and substrate, where carrier recombination occur and causes SF expansion, which is corelating to the findings of bar-shaped stacking faults from the post-analysis. Fig. 7 shows electroluminescence images from degraded samples with BPD=0 and stressed at 400A pulsed forward current through the body diode. Lead frame and solder ware removed by mechanical polishing to uncover parts of the chip area where different EL patterns are seen. For the EL analysis the devices have been tested at I_{SD}=1 A, V_{DS}= -3.1 V and V_{GS}=-5 V. On both device EL images are observed trapezoidal shaped stacking faults. The amount of area covered by the SF in the region sampled by EL matches quite well to the Rdson drift.

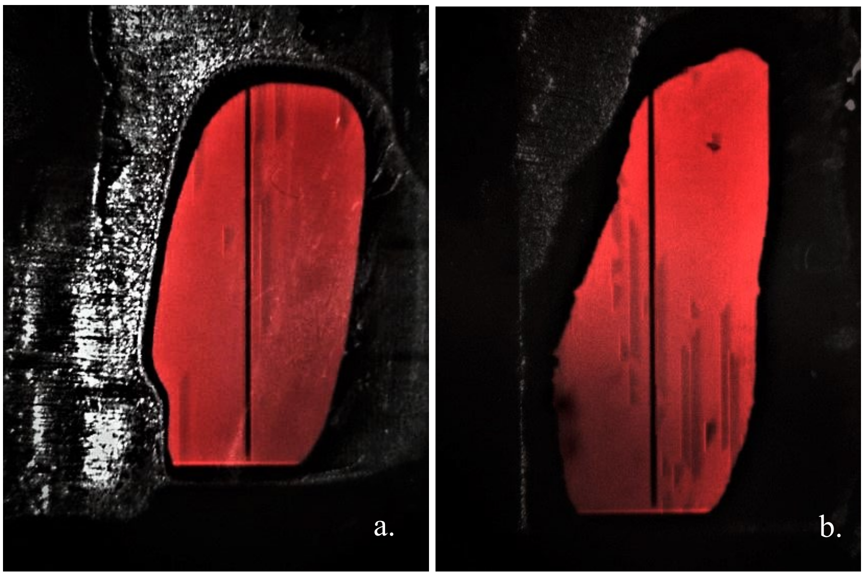


Image a	Image b
EL conditions: I_{SD}=1 A, V_{DS}= -3.1 V, V_{GS}=-5 V	
Rdson drift ~ 8.8%	Rdson drift ~ 20%
Area covered under EL: 10%	Area covered under EL: 13.5%

Fig. 7. Electroluminescence analysis of 1.2 kV SiC MOSFETs after body diode stress at very high current densities ~ 1700 A.cm^2 (400 A) with Rdson drift: a. 8.8% and b. 20%. The red color is added after EL measurement to improve the contrast and visibility of the stacking faults.

Conclusion

In this work, the bipolar degradation of a 1.2kV 4H-SiC planar MOSFETs has been experimentally investigated. Devices has been grouped by the amount of BPDs present in the epi layer. As observed also for 1200 V SiC MOSFETs, the reduction of BPDs in the epi region can efficiently suppress degradation and shift in device parameters, but not eliminate. At extremely high current densities significant drifts of forward voltage drop of the body diode and devices on resistance can still occur also for 1.2 kV. Such an example is the case of zero BPD sample A, if huge current densities ~1700 Acm^2 are applied, charge carriers diffuse deeper into the buffer region and excites stacking faults expansion from the substrate. Stress current densities above J>1600 Acm^2 are observed as a threshold current density above which bipolar degradation is triggered.

The pulsed forward measurements presented in this paper, done in a controlled way, maintaining very short high current pulses, without exceeding the thermal limitation of the devices (Tj<<175C) enables to accurately investigate the bipolar degradation phenomenon and avoid thermomechanical degradation of the devices. During the analysis no shift in the threshold voltage, BV or any other parameters has been observed except for Rdson and Vf. The correlation between the SFs and drift of the body diode Vf and Rdson has been supported by the EL images in this work.

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