

Defects Involved in TDDB-Stressed SiC MOSFET

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Abstract— We report electrically-detected magnetic resonance, electron spin resonance, charge pumping and transfer characteristics of SiC lateral MOSFETs before and after accelerated TDDB stress at 9 MV/cm field. The different responses measured via each technique provide insight to the rich interplay between defect creation and defect charging that underlies dynamic reliability responses of these devices.

Keywords— SiC, MOSFET, reliability, defects, charge pumping, EDMR

I. INTRODUCTION

Silicon carbide is the leading candidate to replace silicon in power semiconductor devices, owing to its favorable combination of physical properties which reduce power losses during conversion.[1] Higher thermal conductivity and temperature stability reduces cooling requirements; greater blocking voltage and reduced ON-state resistance reduce resistive losses, and higher switching speeds reduce the required size of passive components. SiC technology has also reached a maturity level where numerous manufacturers now offer a variety of SiC based power devices with demonstrated advantages over silicon. However, SiC's maturity still lags behind silicon technology in performance and reliability.[2] The physical/chemical identification of the performance- and reliability-limiting defects in SiC devices is central to efforts to close this maturity gap.

Charge pumping (CP) is a well-established electrical characterization technique for measuring MOSFET interface trap density. In CP, a voltage waveform is applied to the gate, with the source and drain contacts grounded, and a DC recombination current is measured through the substrate. CP yields the number and/or density of electrically active defects at the semiconductor/dielectric interface [3], [4], but does not provide any direct chemical or physical information about the defect entity from which the charge trapping arises. Therefore, additional analytical characterization is needed to directly link device electrical parameters to defect chemical information to obtain a more wholistic understanding of defects and their effect on device performance and reliability.

The chemical and physical identity of paramagnetic defects, such as atomic orbital(s), elemental composition, lattice structure, charge state, and spatial orientation can be measured via electron spin resonance (ESR) and electrically detected magnetic resonance (EDMR). Both ESR and EDMR have a long history of addressing challenging reliability

related problems.[5] Briefly, in ESR, a large, slowly varying magnetic field and a microwave frequency magnetic field are simultaneously applied to a sample. The polarizing magnetic field causes Zeeman splitting of paramagnetic species, and resonance occurs when this splitting equals the energy of the microwaves (described by the g-tensor). The resonance condition is described by eq. 1:

$$h\nu = g\mu B \quad (1)$$

Where h is the Plack constant, ν is the frequency of the microwave field, μ is the Bohr magneton, B is the polarizing magnetic field and g is the Landé g- factor. The g-factor is a second-rank tensor and the value of its components can be used as fingerprints to identify paramagnetic defects within a sample. [6] While incredibly powerful, conventional ESR has two major drawbacks; (1) low sensitivity, therefore requiring excessively large samples (2) detection involves an amalgamation of every paramagnetic species in the sample chamber, even those that may or may not be directly involved in the relevant reliability or performance issues.

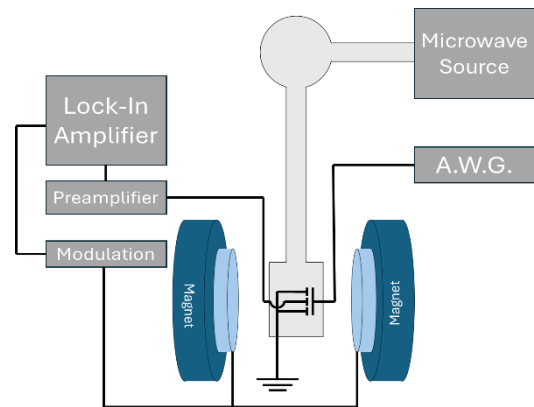


Figure 1 – Schematic of SDCP instrumentation.

EDMR directly addresses these two drawbacks by implementing an electrical detection scheme in which a spin-dependent change in some device current is monitored while ESR is performed. This results in EDMR providing $\sim 10^7$ increase in sensitivity that enables the measurement in fully processed devices and is only sensitive to electrically active defects that are actively participating in the charge transport mechanism responsible for the current flow. While several EDMR detection modes exist, this study focuses on spin-dependent charge pumping (SDCP) in which the measured spin dependent current is a MOSFET CP current

(electron/hole recombination at interface traps).[7], [8] A schematic of the SDCP measurement setup is provided in Figure 1. In SDCP, an arbitrary waveform generator (AWG) is used to apply a CP waveform to the gate of a planar MOSFET placed inside a microwave resonator, which is placed within a polarizing magnetic field. The substrate current is processed through a preamplifier before being sent to a lock-in detector. Phase sensitive detection is achieved through modulation of the magnetic field.

In this work, we use conventional electrical characterization (including I-V and CP) along with both conventional ESR and SDCP techniques to obtain a wholistic understanding of the dynamic nature of defect creation and charge trapping in SiC MOSFETs subjected to time dependent dielectric breakdown (TDDB) stress.

II. EXPERIMENTAL DETAILS

The devices used in this study were fabricated on a commercial foundry process technology and consist of n-type, planar SiC MOSFETs, 150 μm x 40 μm , with 48 nm SiO₂ gate dielectrics subject to post oxidation NO anneals.

Measure-stress-measure experiments involved I_D, V_D, CP, and SDCP measurements on devices subjected to 9

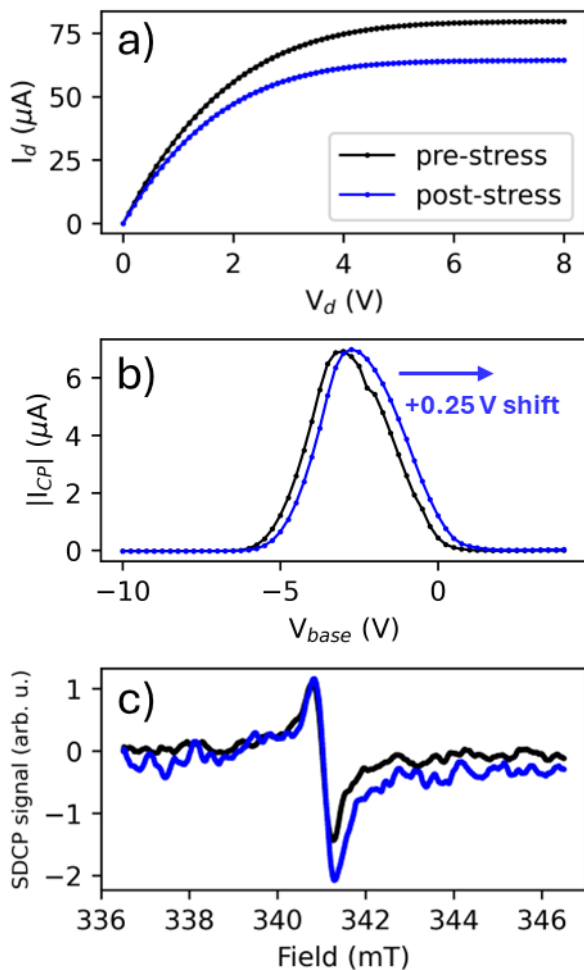


Figure 2 – [a] I_d - V_d of the SiC MOSFET before and after applying a 9 MV/cm stress to the gate for 10 s. $V_G = 16$ V. Note, the post stress measurements occur two days post-stress. [b] CP curves before and after stress. [c] SDCP before and after device stress.

MV/cm gate stress for various stress times and post-stress relaxation times. Post-stress, the devices were stored ungrounded in ambient conditions. CP and SDCP data were collected via custom-built data acquisition system, while I_D-V_D was collected via a commercially available semiconductor parameter analyzer.

CP was collected using a trapezoidal gate voltage waveform ($V_{pp} = 6$ V) at 400 kHz with 250 ns rise/fall time. Conventional capacitance versus voltage measurements (not shown) were used to determine CP gate voltage amplitudes ensuring full coverage from accumulation through inversion. SDCP measurements were taken with identical CP waveforms that correspond to the maximum measured CP current (peak).

III. RESULTS AND DISCUSSION

Figure 2 shows I_D-V_D, CP and SDCP measurements of a device before and after TDDB stress (10 s). The post-stress drain current displays significant degradation (-19 % at saturation) compared to the pre-stress response (Fig. 2a). The CP peak shifts by about +0.25 V post stress, but the amplitude (typically proportional to the number of defects) remains relatively unchanged (Fig. 2b). The SDCP amplitude shows a significant increase in amplitude, 28 %, indicating an increase in the number of paramagnetic defects participating. Meanwhile, the pre- and post- stress g-factor remains unchanged (Fig 2c) at $g = 2.0020 \pm 0.0003$, indicating no measurable change to defect type/structure. The uncertainty value was obtained by characterizing the drift of the g-value over time using a separate, well-known SiC sample in the same spectrometer. Note, the post stress measurements in Figure 2 occur two days post-stress.

Figure 3 shows conventional constant amplitude swept base CP measurements illustrating the evolution of the CP peak location following a 40 s TDDB stress at 9 MV/cm. Pre-stress, the peak is centered at -0.5 V (Fig. 3a). Immediately after stressing, the CP peak shifts to -1.5 V and the amplitude increases only slightly, by about 6 % (Fig. 3b). Measured one day after stress (Fig. 3c), the CP peak has now shifted to +0.5 V, and the amplitude has increased by 26 %. The peak continues to shift slightly positive when measured one week after stressing (Fig. 3d).

Figure 4 shows EPR results measured on the entire SiC die, which includes the device under test and additional test structures. The g-factor for the measured signal is $g = 2.0038 \pm 0.0003$, where the uncertainty value is the manufacturer reported accuracy of the EPR spectrometer. This g-factor is similar to other reports of the g-factor of silicon vacancies, V_{Si} , in 4H-SiC[9], but is significantly larger than numerous reports of g-factor assigned to V_{Si}^- 4H-SiC as identified via EDMR[10], [11], and also differs from the results we obtain in SDCP. The g-factor of the EPR signal in Figure 4 is isotropic with respect to the c-axis of 4H-SiC (Figure 4b), which is expected for V_{Si} [12]

The full width at half max (FWHM) of the signal in Figure 3a decreases as the magnetic field modulation amplitude is decreased from 1.1 mT to 0.3 mT and settles at a value of 0.57 mT at modulation amplitudes less than 0.3 mT. (Figure 5a), indicating that this is the intrinsic signal width. The signal shows weak saturation as the microwave power is increased (Figure 5b). Together these results

validate the proper measurement conditions used for obtaining the signals in Figure 4.

The g-factor obtained via SDCP is lower than that measured via EPR, and is lower than typically reported for silicon vacancies. This implies that the defect detected via SDCP differs from that detected over the whole die via EPR. SDCP is sensitive to defects at the SiC/SiO₂ interface, the populations of which may differ from those of the whole die. More work exploring the SDCP parameter space is required to better understand the defect detected via SDCP.

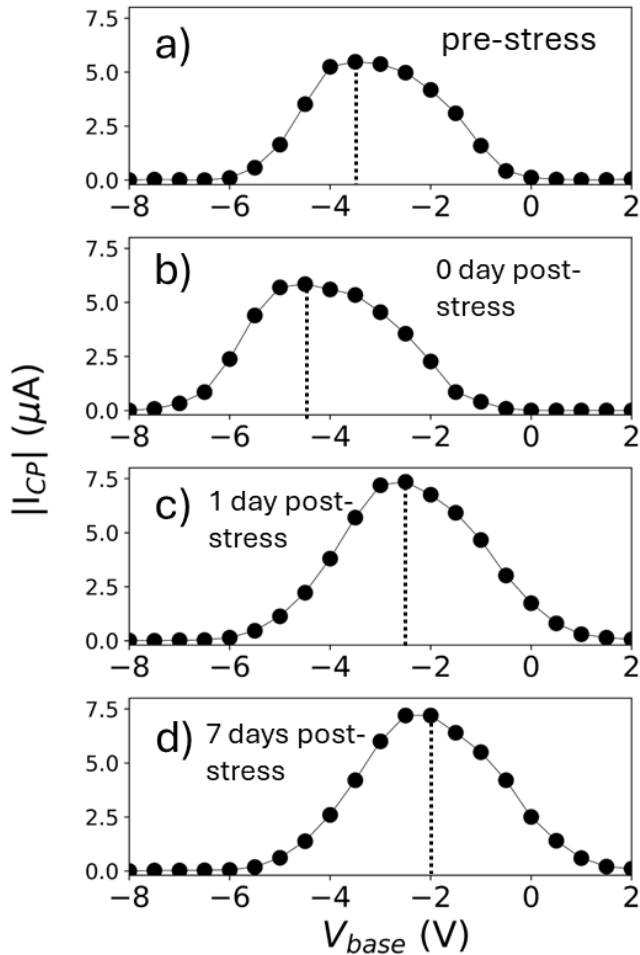


Figure 4 – CP measurements before and after device stress. The dashed lines are guides for the eye placed at the peak maximum. [a] CP curve measured before stressing. [b] CP curve measured immediately after stressing at 9 MV/cm for 40 s. [c] CP curve measured on the same device 1 day later. [d] CP curve measured on the same device 7 days after stressing.

The decrease in the drain current post-stress is a clear indication that additional negative charge is trapped in the dielectric (Fig. 2a). The positive shift in the CP peak also indicates negative charge trapping post stress, but not necessarily an increase in the number of defects since the peak amplitude remains nearly constant. However, the increase in SDCP amplitude implies an increase in the number of paramagnetic defects post stress. The discrepancy certainly requires further investigation but may be due to the complicated spin physics involved in the magnetic resonance measurements. Various paramagnetic defects in SiC are known to possess rather complicated charge states and spin states, which could explain the discrepancy between the CP and SDCP amplitude results.[13] It is possible a change in the

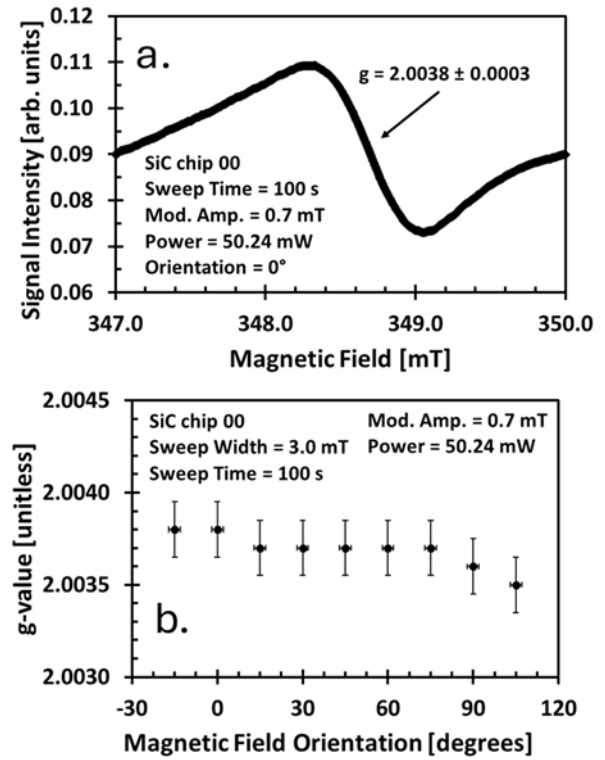


Figure 3 – EPR results from the whole SiC die. [a] Magnetic field sweep, from which the g-factor is extracted. [b] Values of the g-factor as a function of the angle between the SiC c-axis and the polarizing magnetic field.

defect spin/charge state could impact the size of the magnetic resonance effect (more allowed spin dependent recombination events relative to all recombination events) while not impacting the electrical measurement.

The results in Figure 3 indicate a more dynamic charge state measured post-stress, that changes on the order of a few days. While the longer post stress relaxation time data is consistent with the data of Fig. 2 (shifts indicative of negative charge trapping), the shifts measured immediately post-stress indicate overall positive charge trapping. Also requiring further elucidation, this is consistent with other literature reports that highlight overall positive charge trapping immediately post stress which eventually de-traps completely to reveal only the net negative trapped charge. [2]

Letten et. al. have recently identified two distinct paramagnetic defect centers in 4H-SiC MOSFET via SDCP.

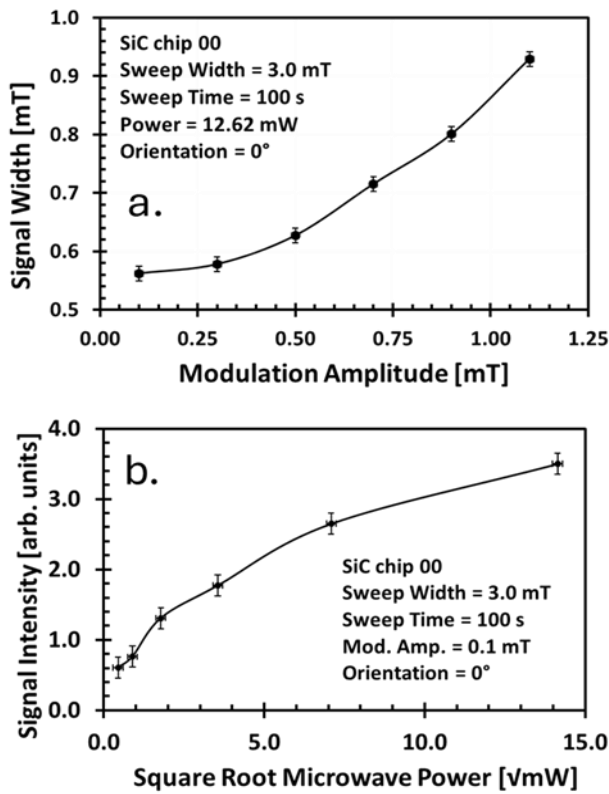


Figure 5 - EPR results from the whole SiC die. [a] The width of the signal in Figure 4a as a function of the magnetic field modulation amplitude. [b] The intensity of the signal in Figure 4a as a function of the applied microwave power

By modulating the CP waveform parameters, they were able to measure two distinct EDMR signals that differ in signal polarity, despite differing in g by only $\Delta g = 0.000\ 10 \pm 0.000\ 03$. [14] While the g -factors they measured differ from those in our study, together these works support the conclusion that SDCP is a powerful technique to continue to link device operation with atomic-scale defect structure. Further experiments exploring the SDCP parameter space in conjunction with electrical stressing and characterization will be useful to better understand the defect dynamics affecting device reliability.

IV. CONCLUSIONS

The combination of purely electric measurements combined with analytical magnetic resonance measurements provides a direct link between device operation and underlying defect structure. The measurements clearly demonstrate a rather complicated interplay between readily measured device parameters pre- and post-TDDDB stress, defect dynamics and charge capture. EPR measurements of the SiC die indicate silicon vacancies dominating the bulk of the material, but a more dynamic response measured via charge pumping and spin-dependent charge pumping suggest more complicated dynamics. Beginning to reconcile these dynamics takes an important step towards ultimately more reliable and commercially successful SiC technology.

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