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Sensitivity Analysis of a New Technique for Trapped Charge Extraction in SiC MOSFETs from Subthreshold Characteristics

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***Abstract*— A method for extracting D_{IT} profiles from subthreshold I-V characteristics is used to analyze data on a SiC MOSFET stressed for thirty minutes at 175°C with a gate bias of -20 V. Without knowing the channel doping, the change in D_{IT} can be calculated when referenced to an energy level correlated with the threshold voltage.**

Keywords – silicon carbide, subthreshold slope, interface traps, trapped charge, power electronics, elevated temperature, reliability

I. Introduction

Trapped charge in gate oxides can have significant impact on the I-V characteristics and reliability of MOS devices. This has been a concern for silicon carbide (SiC) MOS devices due to high defect densities present at the SiC/SiO_2 interface [1]. While this wide bandgap technology has many promising characteristics that make it desirable for manufacturing power devices (such as a low intrinsic carrier concentration and high thermal conductivity), the high interface trap density and increase in charge trapping at elevated temperatures and biases [2] have prompted investigations into device reliability and how trapped charge evolves with stress.

One of the promising uses for SiC MOSFETs is in power applications, potentially replacing silicon IBGTs. The structure used in most power SiC MOSFETs makes extracting defect densities though traditional methods like charge pumping difficult since there is no body tie. In most cases, the extraction of D_{IT} profiles and N_{OT} concentrations require C-V measurements performed on capacitors fabricated using the same process, which are not always readily available. A recent method characterizes the trapped charge in SiC MOSFETs based solely on subthreshold I-V curves [3]. In this work we evaluate the capabilities and sensitivity of this method and apply it to data taken on SiC MOSFETs under elevated temperature and bias stress. The method produces ΔD_{IT} profiles that calculate relative changes in interfacial defect concentration at energy levels referenced to the calculated potential of the threshold voltage. This result is independent of the value used for channel doping. If the channel doping is known, the exact concentration of defects before and after stress and their location within the bandgap can be calculated. Variations in capacitance have a proportional variation in the calculated change in defect concentration, but this is easily accounted for and the typical oxide thickness ranges from 50 nm to 70 nm, changing the results by at most a factor of 1.4 for that range. The results are sensitive to the method of threshold voltage extraction. The transconductance derivative method and transconductance method produce results that are a better match to expected trends than the constant drain current method.

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II. Method Details

A high, non-uniform D_{IT} profile will cause a varying subthreshold slope, enabling extraction of the D_{IT} profile from subthreshold I-V curves [3]. The non-constant D_{IT} profile in SiC devices make them ideal candidates for this method. The profile is extracted by solving for changes in V_{IT} (a voltage term representing the contribution of trapped interfacial charge) over short intervals of surface potential. Values of surface potential are calculated using the following simplified equation for drain current in the subthreshold region [4]:

$$I_D = I_{D0}(V_D)exp(\beta\varphi_s)(\beta\varphi_s)^{-1/2} \quad (1)$$

In this equation $\beta = q/kT$, $I_{D0}(V_D) = \mu_n(Z/L)(aC_i/2\beta^2)(n_i/N_A)^2(1 - e^{-\beta VD})$, $a = (\varepsilon_s/L_D)/C_i$, C_i is the insulator capacitance, and L_D is the Debye length. Many constants (some of which are not well known for SiC or require knowledge of the fabrication details) are contained within the term $I_{D0}(V_D)$, which does not vary with gate voltage. Instead of attempting to determine the values of all the parameters contained within $I_{D0}(V_D)$, it is possible to solve for $I_{D0}(V_D)$ if values for I_D and the corresponding φ_s are known. The first step is to solve for $I_{D0}(V_D)$ by determining the threshold current from the I-V curve and setting φ_s equal to twice the bulk potential φ_p (or equal and opposite in sign to the bulk potential, depending on how you choose to define the surface potential). There are multiple methods of determining threshold voltage and the implications of choosing one technique over another will be discussed later in the paper. Once $I_{D0}(V_D)$ has been calculated, values of V_G and the corresponding φ_s calculated from equation (1) can be substituted into the following equation [3]-[5] to solve for $(V_{FB} + V_{IT})$:

$$\varphi_s = (V_G - (V_{FB} + V_{IT})) - (a^2/2\beta)\{[1 + (4/a^2)(\beta V_G - (\beta V_{FB} + \beta V_{IT}) - 1)]^{1/2} - 1\} \quad (2)$$

Equation (2) can be rearranged as follows:

$$(V_{FB} + V_{IT}) = V_G - (\varphi_s + [(a^2\beta^3\varphi_s - a^2\beta^2)^{1/2}]/\beta^2) \quad (3)$$

Taking differences in $(V_{FB} + V_{IT})$ to be equal to ΔV_{IT}, it is possible to calculate D_{IT} over a short interval of φ_s of using the equation:

$$D_{IT} = (C_i/q)(\Delta V_{IT}/\Delta\varphi_s) \quad (4)$$

Note that the doping is required to calculate the bulk potential, φ_p, and the Debye length, L_D. The insulator capacitance is also used in the various equations. The implications of whether or not these values are known are explored in the next section.

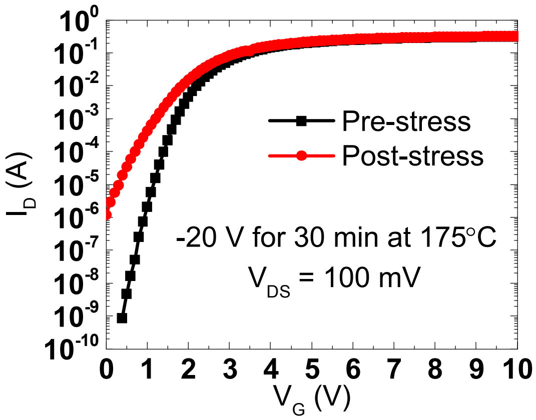

Fig. 1. I_D-V_G curves for a 1200 V SiC power MOSFET taken at 175°C before and after a gate stress of -20 V for thirty minutes.

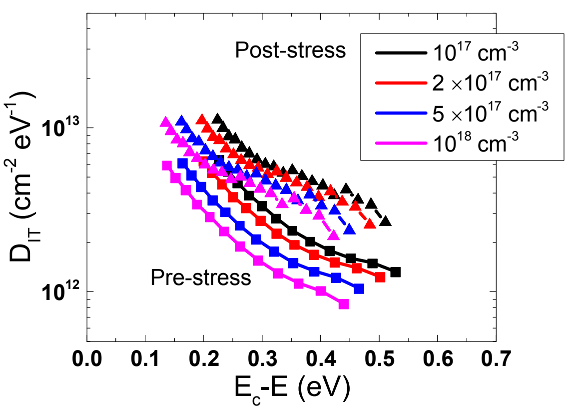

Fig. 2. Extracted D_{IT} profiles from the I_D-V_G curves in Fig. 1. Calculations for pre-stress and post-stress were each performed for four different doping values.

III. Data Analysis

This method was applied to I_D-V_G curves (plotted in Fig. 1) from a 1200 V SiC power MOSFET recorded before and after a thirty minute stress at a temperature of 175°C and a gate bias of -20 V, with a drain bias of 0.1 V. The oxide thickness was taken to be 50 nm (results for 70 nm will be presented as well). A range of doping values from 10^{17} cm^{-3} to 10^{18} cm^{-3} were used. ΔD_{IT} values were calculated using different threshold voltage extraction techniques.

A. Transconductance Derivative Method

Assuming that the channel doping is unknown, Fig. 2 plots the calculated D_{IT} profile for the pre-stress and post-stress data in Fig. 1 for a range of doping values from 10^{17} cm^{-3} to 10^{18} cm^{-3}. The threshold current used in equation (1) is determined using the transconductance derivative method, which defines the threshold voltage as the voltage at the maximum of the derivative of the transconductance [6]. This method tends to produce similar results as the linear extrapolation method (where the linear part of the I_D-V_G curve

is

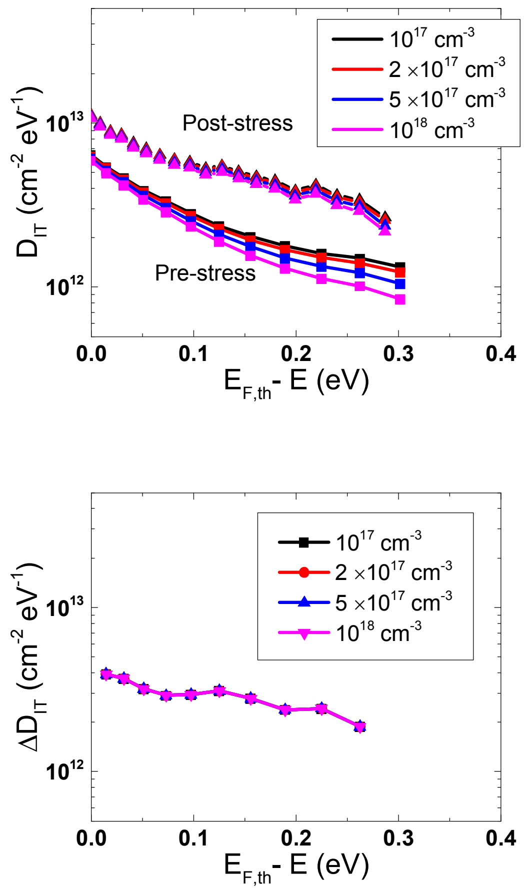

Fig. 3(a) Extracted D_{IT} profiles from Fig. 2 with the energy levels normalized relative to the level of the threshold voltage for each measurement, and (b) the change in D_{IT} between pre- and post-stress curves. Each graph shows results for four doping values.

extended to I_D = 0), but the transconductance derivative method is not affected by series resistance or mobility degradation [6]. The results of the calculation show that varying the doping shifts the curve in terms of both D_{IT} concentration and energy level. The numbers are changed because different doping values lead to different bulk potentials; however, this is a constant offset for each data point, and the shape of the curve remains the same. By choosing a reference energy level at a set voltage (in this case, the threshold voltage is used) and plotting each data set relative to that reference, the curves align along the x-axis. This means that for each calculation, the position of the Fermi level at the threshold voltage (which is constant for a given doping) is defined as zero and the D_{IT} profile is referenced to the distance from $E_{F,th}$. Fig. 3(a) re-plots the D_{IT} profiles extracted from both the pre-stress and post-stress I_D-V_G curves from Fig. 1 for a range of doping values with the x-axis being referenced to the energy level of the threshold voltage for each measurement. Different doping concentrations result in variations in the concentration of interface traps, but do not affect the difference between the pre-stress and post-stress D_{IT} profiles. Fig. 3(b) plots ΔD_{IT} for each doping value and the

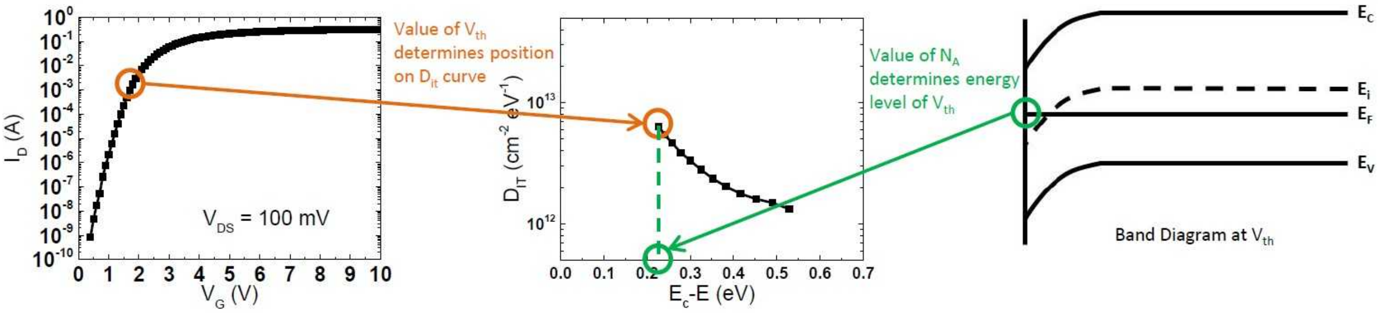

Fig. 4. The value of Vth on an I-V curve(left) determines the value of D_{IT} at E_C-E_{th}. The value of E_C-E_{th}, shown in the band diagram (left), is determined by the doping.

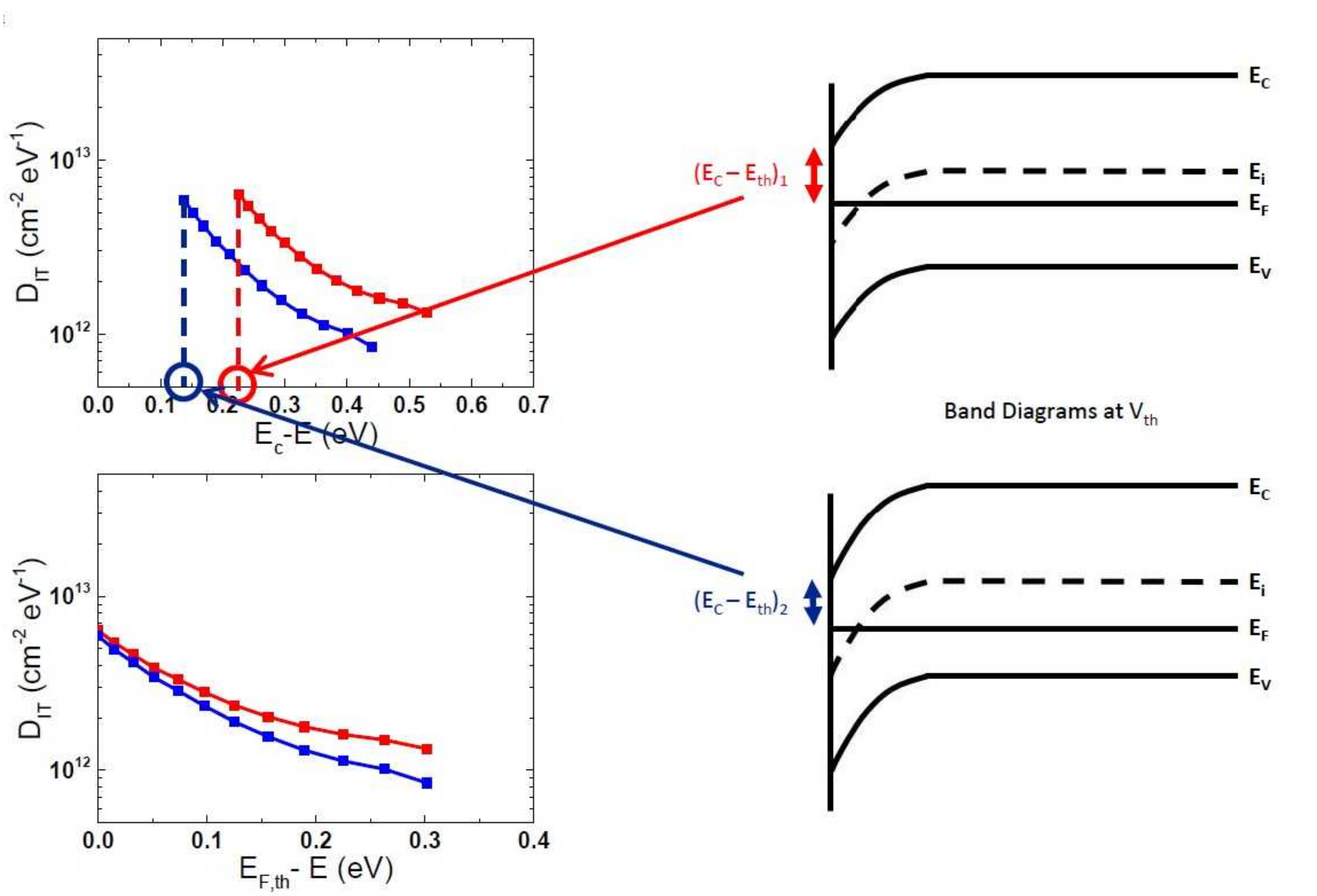

Fig. 5. Varying the doping changes the energy level at which the D_{IT} curve begins. After normalizing the energy level to the Fermi level (E_{th}), the curves align with minor differences in magnitude that can be removed by plotting ΔD_{IT}.

results are the same within the margin of error of the calculation. This means that the change in concentration of D_{IT} at a given energy level is independent of doping. If the doping is known, then the individual values of the concentration of defects prior to and after stress can be calculated, as well as their location in the bandgap.

B. Doping and Threshold Voltage Dependance

The two major sources of variation in the D_{IT} profile extraction are the choice of doping and threshold voltage. As discussed in the previous section, doping dependence can be normalized out when looking at the change in D_{IT}, but the determination of threshold voltage cannot be. The choice of doping affects the value of E_c-E at which the chosen threshold voltage is set at, while the value of threshold voltage more directly determines the value of D_{IT} at that energy level. These dependencies are illustrated in Fig. 4, with the effects of variation for doping shown in Fig. 5 and for threshold voltage in Fig. 6.

The doping value determines the value of the surface potential at threshold. Different doping values result in the shifting of the D_{IT} profile since the threshold voltage is being set at different energy levels. This can be seen in equation (1)

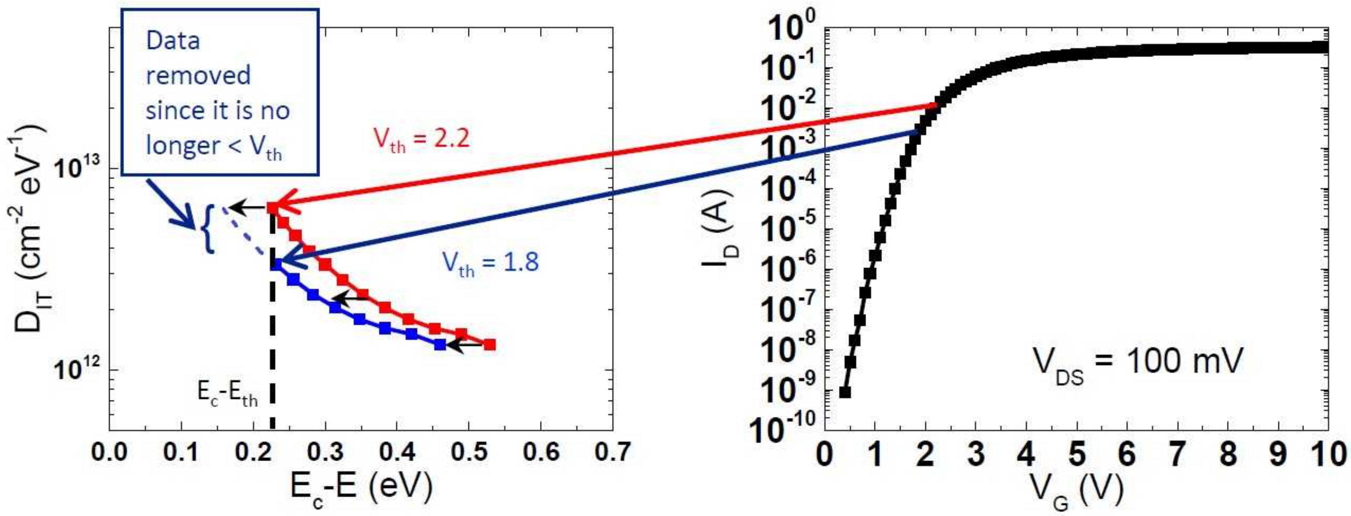

Fig. 6. Varying the threshold voltage changes the value of D_{IT} at the threshold voltage, effectively altering the length of the curve since data above threshold is not considered valid for the equations used to extract D_{IT}.

where varying the doping will vary the value of the surface potential at threshold. Since the position in the bandgap is arbitrary without the doping information, it makes sense to normalize the profiles to the energy level of the threshold voltage. In Fig. 5 these differences are illustrated and then the normalization process aligns the curves. There is a minor change in the calculation of D_{IT} after normalization, however, this change is removed when plotting the difference between two profiles calculated at that doping value, resulting in the identical ΔD_{IT} plots in Fig. 3(b) for a range of doping values.

The value of the threshold voltage (and the corresponding threshold current) determines the voltage and current that is equal to the surface potential at threshold via equation (1). The D_{IT} concentration calculated as a result of the subthreshold slope variation between two points will be the same regardless of which value is chosen for V_{th} (holding all other parameters like doping constant), so determining the value of the threshold voltage simply sets the corresponding D_{IT} value calculated at that voltage on the I-V curve to the energy level E_c-E_{th}. Thus, varying V_{th} effectively shifts the D_{IT} curve and removes any data calculated for gate voltages above V_{th} since equation (1) is only valid for subthreshold conditions. These effects are demonstrated in Fig. 6.

C. Other Threshold Voltage Extraction Methods

The transconductance derivative method used in section A is one of many ways to extract threshold voltage from I-V curves. In this section the calculation of ΔD_{IT} profiles is repeated using the constant drain current and the transconductance methods. The transconductance method finds the maximum of the derivative of the transconductance and extrapolates the x-intercept of the tangent line through that point on the transconductance curve [6]. The constant drain current method defines the threshold voltage as the voltage at a specific drain current [6]. Fig. 7 plots the ΔD_{IT} profiles calculated for a doping value of 10^{17} cm^{-3} for all three threshold voltage extraction methods discussed in this paper (two values of drain current are used for the constant drain

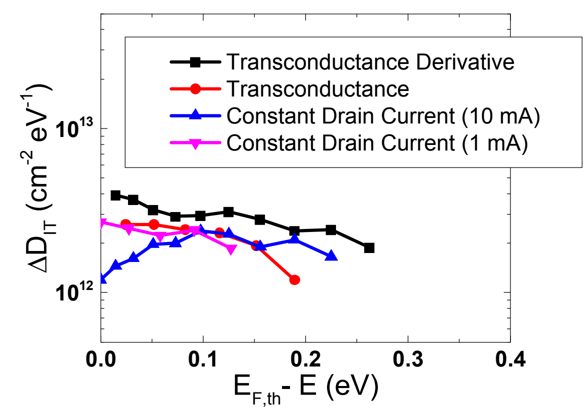

Fig. 7. Change in D_{IT} calculated for multiple methods of threshold voltage extraction for a doping of 10^{17} cm^{-3} for the pre- and post-stress I-V curves in Fig. 2.

current method). The values calculated using the transconductance derivative and transconductance methods tend to be within a factor of two. When using a constant drain current of 1 mA, the values are nearly identical to the transconductance method, but there are fewer data points. This is because at 1 mA the constant drain current method uses lower values for threshold voltage, ignoring some of the data points used by methods that calculate higher threshold voltages. When using 10 mA for the constant drain current method, the values decrease near E_{th}, an unexpected result considering D_{IT} concentration tends to increase towards the band edge [1]. Using a constant drain current may not be the most accurate method of calculating threshold voltage for these devices after stress.

D. Insulator Capacitance Dependence

The insulator capacitance will change depending on the thickness of the oxide. To assess the impact of changes in

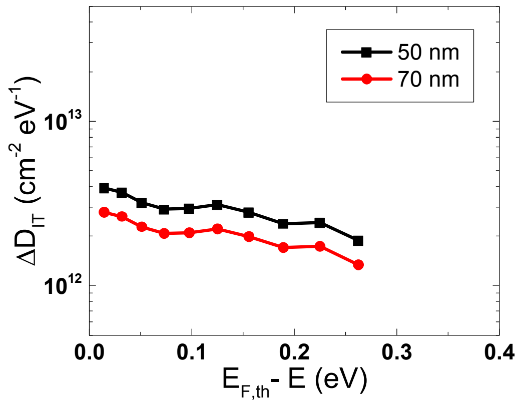

Fig. 8. ΔD_{IT} profiles calculated using an oxide thickness of 50 nm and 70 nm to assess the impact of changes in capacitance.

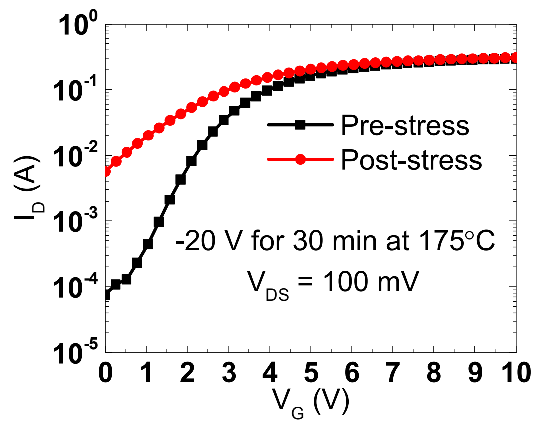

Fig. 9. I_D-V_G curves for a previous generation of a 1200 V SiC power MOSFET taken at 175°C before and after a gate stress of -20 V for thirty minutes.

capacitance, the ΔD_{IT} profile of the data in Fig. 1 was extracted assuming the oxide thickness was 70 nm instead of 50 nm, and the results are compared in Fig. 8 (since all ΔD_{IT} curves line up for all doping values at a given oxide thickness, only one curve is plotted for each thickness value). The ΔD_{IT} concentration at a given energy level is multiplied by the ratio of the two capacitance values (in this case, a factor of 1.4). Assuming that the range of typical oxide thicknesses is small, there should be little error introduced if the exact thickness is unknown. If the capacitance is known, the ΔD_{IT} concentration can be calculated with greater accuracy. Note that when comparing a D_{IT} profile extracted from a single I_D-V_G curve with two different thickness values, the ratio is 1.4 near the conduction band, but increases as the distance from the conduction band increases. The rate of increase is greater for higher doping concentrations. ΔD_{IT} remains at a ratio of 1.4 between each point on the curve for all doping values.

E. Larger Threshold Voltage Changes

The data presented in the previous sections was for a stress on a manufacturer's most recent generation of SiC MOSFETs. Fig. 9 plots I-V curves of an identical stress performed on a previous generation of SiC MOSFETs. The older MOSFETs showed much larger threshold voltage shifts due to stress [7]. Fig. 10 plots the calculated ΔD_{IT} profile and compares it to the 2^{nd} generation devices. There are fewer data points taken for the I-V curves, so the ΔD_{IT} profiles have fewer points. The transconductance derivative method was used for this comparison (the transconductance method may also have been an acceptable choice, but the lack of data points and the lower threshold voltages extracted from transconductance method would have produced even less data) with an oxide thickness of 50 nm. The calculation shows almost an order of magnitude increase in ΔD_{IT} for the previous generation, which is to be expected. In addition to having fewer data points, the calculations for the previous generation part do not extend as far into the bandgap. This is likely due to the fact that the presence of a larger concentration of traps stretches out the I-V curve and so for comparable ranges of voltage the part with

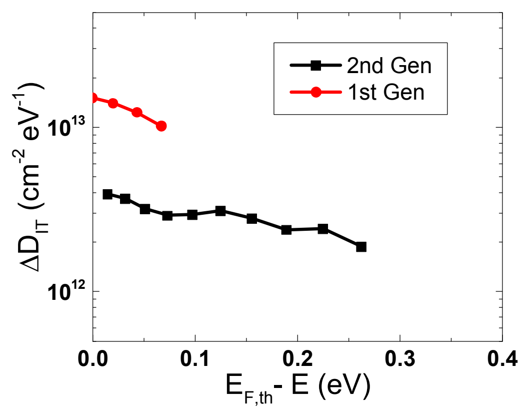

Fig. 10. Change in D_{IT} between pre- and post-stress curves for two different generations of 1200 V SiC power MOSFETs. Stress conditions were identical (-20 V for 30 min at 175°C).

the higher interface trap density will cover a smaller range of energies within the bandgap (i.e. it takes more voltage to shift the Fermi level when more interface traps are present).

IV. Conclusion

ΔD_{IT} profiles can be extracted from I-V curves for SiC MOSFETs based on the changes in subthreshold slope. This technique can be valuable whether the doping and capacitance are known or not. If the values are not known, the technique provides relative change in interface state density. If the values are known, the technique can be used to quickly evaluate the absolute interface trap density at specific energies within the bandgap, before and after stress.

The technique is sensitive to the value of the threshold voltage chosen, and there are multiple ways to extract it from I-V curves. Both the transconductance derivative and transconductance methods show similar results that qualitatively match typical D_{IT} profiles for these devices, while simply choosing a specific value for the threshold current can produce results that appear unphysical. Using methods that calculate lower threshold voltage values (the transconductance method calculates a value that is lower than the transconductance derivative method) will limit the length of the profile because the equations are only valid in the subthreshold regime. Additionally, since the D_{IT} extraction technique relies on small differences in slope between data points on the I-V curves, higher measurement resolution is likely to provide more accurate results.

Varying the doping of the device affects the energy levels of the D_{IT} profile and produces a minor difference in concentration, but the energy levels can be normalized to the Fermi level and differences in concentration fall out when comparing ΔD_{IT} profiles. Varying the oxide thickness changes the concentrations by the ratio of the thicknesses compared, but should have little effect since the range of typical oxide thicknesses is small.

With careful consideration of the method used to extract the threshold voltage, this technique is useful for estimating the change in D_{IT} concentration after stressing SiC MOSFETs without the need for testing MOS capacitors or knowledge of process information.

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