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The Effect of Nitrogen on the 4H-SiC/SiO$_2$ Interface Studied with Variable Resonance Frequency Spin Dependent Charge Pumping

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Abstract. In this work, we study the effects of NO anneals on the interface of 4H-SiC MOSFETs via spin dependent charge pumping, an electrically detected magnetic resonance technique. We make measurements at high and ultra-low resonance frequencies. Our results indicate that the NO anneals both change the silicon vacancy energy levels as well as induce disorder at the interface. In addition, our results indicate that the changes in energy levels involve N atoms very close to V_{Si} sites.

Introduction

Introducing N (typically via post-oxidation annealing in NO) to the SiC/SiO$_2$ interface of SiC MOSFETs significantly improves device performance. We utilize electrically detected magnetic resonance (EDMR), an approach derived from electron paramagnetic resonance, to explore atomic scale effects of the anneals. Resonance techniques have unrivaled ability to obtain direct information about the physiochemical nature of defects in semiconductors. Earlier EDMR studies of SiC MOSFET interfaces have nearly always utilized spin dependent recombination (SDR) [1-3]. Unfortunately, SDR is effectively sensitive only to deep level trapping centers. However, defects through most of the gap can limit MOSFET performance. We have overcome this problem with spin dependent charge pumping (SDCP) [4-5]; it offers the capability to explore the great majority of the 4H-SiC band gap (about 88% in our case). In our study, we compare SDR (via the bipolar amplification effect (BAE) [3]) and SDCP measurements in order to distinguish between defects which dominate deep levels and defects which dominate most of the 4H-SiC band gap (deep levels in addition to levels closer to the band edges).

SDCP utilizes the powerful MOSFET interface characterization measurement called charge pumping (CP). The most straightforward CP approach involves application of a continuous trapezoidal waveform to the MOSFET gate to alternately invert and accumulate the interface, filling and emptying traps at the interface region. This process produces current, the CP current (I_{CP}), which is measured at the body contact [6]. I_{CP} is the product of the electronic charge, the frequency of the trapezoidal gate pulse (f_{CP}), the effective channel area, and the mean density of interface states within the measured band gap energy window, ΔE_{CP}. ΔE_{CP} is nearly symmetric about mid gap [6] and, in our case, is about 88% of the 4H-SiC bandgap. This allows us to, at least in principle, measure traps within most of the band gap. SDCP detects the spin dependent change in I_{CP} (ΔI_{CP}) via magnetic resonance. For the discussion in this paper, though not a full treatment of the resonance for defects studied [2], an appropriate Hamiltonian for an electron experiencing only spin-orbit coupling and electron-nuclear hyperfine interactions is:

$$\mathcal{H} = \mu_B \boldsymbol{B} \cdot \boldsymbol{g} \cdot \boldsymbol{S} + \sum_i \boldsymbol{I}_i \cdot \boldsymbol{A}_i \cdot \boldsymbol{S}. \tag{1}$$

Here, μ_B is the Bohr magneton, $\boldsymbol{B}$ is the applied magnetic field vector, $\mathbf{S}$ is the electron spin operator, and $\mathbf{I}_i$ is the nuclear spin operator for the i^{th} nucleus. $\boldsymbol{g}$ and $\boldsymbol{A_i}$ are essentially tensors which describe a defect's local environment and are usually referred to as the g and A tensors. Spin-orbit coupling causes the g tensor components to deviate from the free electron g_e, and A provides a measure of electron-nuclear hyperfine interactions.

Our study also utilizes high resonance frequency (HRF) and ultra-low resonance frequency (ULRF) measurements. These measurements allow for partial separation of spin-orbit coupling and hyperfine effects on magnetic resonance spectra, as well as observation of otherwise forbidden half-field effects which make EDMR, at least in principle, quantitative [7]. Spectrum broadening due to g is virtually eliminated at ULRF frequencies. These measurements are ideal to observe hyperfine broadening from nearby magnetic nuclei which is, to first order, independent of resonance frequency [8]. Additionally, comparing HRF and ULRF measurements can give a measure of the g broadening. The difference between the HRF and ULRF line width (ΔLW) is a measure of disorder because, in a perfect crystal, the g tensor components would all be the same for defects aligned in the same direction (each defect's surroundings would be identical). In this case, the line width would be nearly frequency independent. In an imperfect crystal, small variations in the g values of individual defects (slightly varying defect surroundings) would introduce a broadening component proportional to the frequency.

Experimental Details

Three types of planar n-channel 4H-SiC MOSFETs called sample A, sample B, and sample C were studied. All samples had thermally grown oxides. Sample A had an as-grown oxide, sample B received a post oxidation anneal in NO at 1175 °C for 2 hours, and sample C received a post oxidation anneal in NO at 1250 °C for 2 hours. Samples A, B, and C had a $\overline{D_{it}}$ of 3.1 x 10^{12} cm^{-2}eV^{-1}, 0.46 x 10^{12} cm^{-2}eV^{-1}, and 0.51 x 10^{12} cm^{-2}eV^{-1}, respectively. They had effective channel mobilities of 1 cm^2/Vs, 19 cm^2/Vs, and 17 cm^2/Vs. $\overline{D_{it}}$ was extracted from CP measurements. For all SDCP measurements, a gate waveform with a 50% duty cycle and a 50 ns rise time and fall time was utilized. All measurements were made at room temperature.

EDMR measurements were made on two homemade EDMR spectrometers operating at HRF ($\nu \approx 16$ GHz), and ULRF ($\nu = 85$ and 360 MHz). The HRF spectrometer consists of a 4-inch electromagnet, a Hewlett-Packard 6268B power supply, a temperature-compensated Gaussmeter and Hall probe, a TE$_{102}$ microwave cavity, a K band microwave bridge, a lock-in amplifier, and a computer which provides magnetic field control and the data acquisition system. The ULRF spectrometer consists of a custom-made electromagnet, a Kepco BOP 100-4M power supply, a temperature-compensated Gauss meter and Hall probe, a Stanford Research Instruments SG382 signal generator, and a computer which provides lock-in detection, magnetic field control, and data acquisition. A Tabor Electronics WW2572A waveform generator was used for the gate waveform.

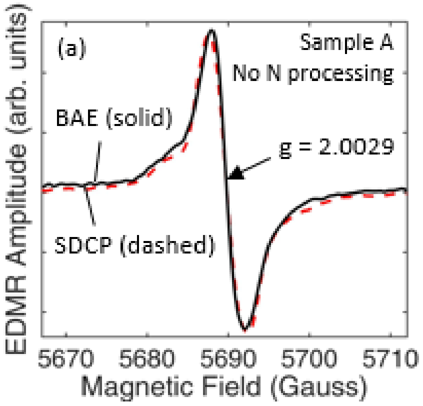

Figure 1. Comparison of high frequency (K band) SDCP and BAE spectra of sample A. f$_{CP}$ is 600 kHz.

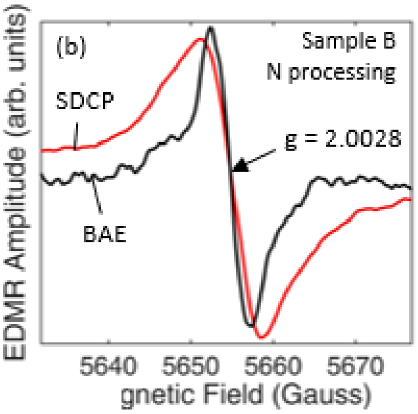

Figure 2. Comparison of high frequency (K band) SDCP and BAE spectra of sample B. f$_{CP}$ was 600 kHz.

Results and Discussion

Our HRF EDMR spectra for samples A (Fig. 1), B (Fig. 2), and C (not shown) show a single dominating line with an isotropic g = 2.0029±0.0002. This spectrum has been observed in many SiC MOSFETs [1,2,5] and has been identified as V$_{Si}$ via observation of the ^{13}C hyperfine

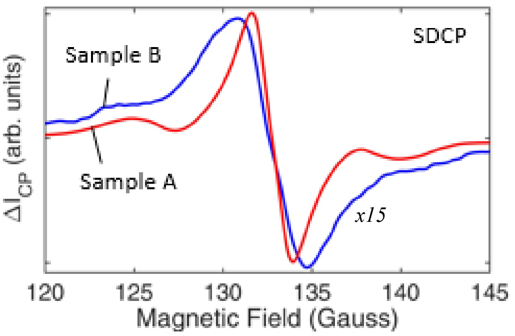

Figure 3. Comparison of ultra-low frequency (360 MHz) SDCP measurements from sample A and B. Sample C shows similar results. f_{CP} was 600 kHz.

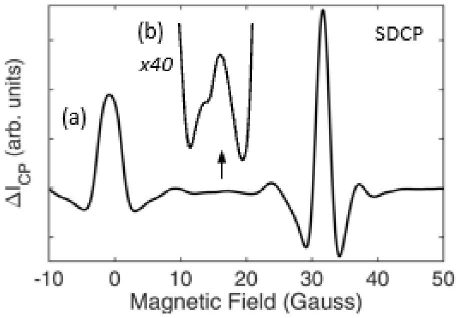

Figure 4. Illustration of (a) the derivative of ultra-low frequency (85 MHz) SDCP spectra from sample A. (b) is the half-field resonance spectrum increased by a gain of 40. f_{CP} was 600 kHz.

interactions [2]. We find that the SDCP spectra from samples which have received an NO anneal, B and C, have peak-to-peak line widths of 2.7 and 2.5 Gauss broader than sample A, respectively. This broadening is almost certainly due to N incorporated into the interface by the NO anneal [9]. Since, at HRF, the broadening may be due to *g*, hyperfine interactions, or a combination of both, we make ULRF SDCP measurements in order to gain insight into the broadening mechanism(s). When comparing the ULRF SDCP spectrum of sample A to that of samples B and C, we find that the spectra from samples B and C are about 1.7 and 1.2 Gauss broader than that of sample A, respectively (Fig. 3). This result is not necessarily unexpected as (non-resonance related) studies have reported post NO anneal N concentrations near the interface on the order of 10^{14} cm^{-2} [9]. With a 100% abundant spin 1 nucleus, N atoms quite close to the paramagnetic defect sites could be responsible for this broadening. Since the electron wave function decreases rapidly with increasing distance, the N must be extremely close to the defect, almost certainly at the first or second nearest neighbor locations. Additionally, we find that the N atoms are close to a large fraction of the defects. If the N atoms were, for example, close to only 50% of the defects, we would anticipate two spectra; one sharper line from the defects far from N and one broader line from defects close to N. Instead, we observe one broadened line. N hyperfine interactions only partially explain the line broadening of samples B and C observed in the HRF SDCP measurements. This result suggests that N may play a role in *g* broadening.

Another benefit of ULRF EDMR is the increased sensitivity to half-field effects. We observe half-field spectra in our ULRF SDCP measurements in sample A (Fig. 4) as only sample A has a large enough defect density. The (V_{Si}) defect density can be estimated from the ratio of the half-field to classical resonance response as discussed in Ref. [7]. This discussion provides only a rough estimation of defect density for our case, as Ref. [7] assumes a random distribution of defects within the 4H-SiC, which is not the case here. Using equation (10) of Ref. [7], our half-field measurements yield a defect density of 8.3 x 10^{18} cm^{-3}. Since it is reported that N extends about 1 nm from the interface into the SiC [9] and we find N to be very close to a great majority of V_{Si}, we assume, in our calculations, that V_{Si} are about 1 nm from the interface. (Calculating the interface potential during CP measurements shows that CP can access defects about 4 nm into the SiC. Our assumption is within an order of magnitude.) This assumption yields an (areal) half-field D_{it} = 0.83 x 10^{12} cm^{-2} eV^{-1}. Because V_{Si} likely has 3 or 4 levels in the band gap [10,11], we estimate N_{it} = 2.5 x 10^{12} cm^{-2} (3 levels) or 3.3 x 10^{12} cm^{-2} (4 levels). Our CP measurements give N_{it} = 8.9 x 10^{12} cm^{-2}. These measurements match well, within an order of magnitude. Considering the limits of our calculations and estimations, the results are consistent with the conclusion that V_{Si} is the dominating defect in 4H-SiC MOSFETs with as-grown oxides. We also find that N significantly reduces the population of V_{Si} at the interface, which has been indicated in previous experiments [1].

Comparing BAE (deep levels) and SDCP (88% of band gap) spectra allows one to distinguish between defects that dominate at deep levels and defects that are present throughout most of the interface band gap. Figure 1 compares HRF BAE and SDCP spectra from sample A. As mentioned previously, both spectra are dominated by the V_{Si} spectrum. The sample A BAE and SDCP spectra are almost identical which suggests that the observed V_{Si} deep levels are all or mostly within the probed band gap energy window. Figure 2 shows a comparison of HRF BAE and SDCP spectra from sample B (sample C shows similar results). Both spectra are dominated by a single line with an isotropic g = 2.0028±0.0002, but, in this case, the SDCP spectrum is significantly broader than the BAE spectrum. This effect must be caused by the presence of N, as sample A shows almost identical BAE and SDCP spectra. Sample B's BAE spectrum is almost certainly due to the V_{Si}, but the SDCP spectrum is very different (broader). This suggests that N changes the energy levels of a large fraction of the V_{Si} and simultaneously alters their surroundings in such a way that their spectra are significantly broadened at HRF. This makes sense, as we found that N is very close to a large fraction of the V_{Si}. Therefore, our results indicate that nearby N is modifying both the energy levels and surroundings of the V_{Si}. Since this broadened spectrum is only observed in the SDCP measurements, we find that the V_{Si} energy levels move away from mid-gap. How then does the N modify the V_{Si} surroundings?

Table I. Difference in high and low resonance frequency line widths for all samples.

Sample	ΔLW (BAE) [Gauss]	ΔLW (SDCP) [Gauss]	NO anneal?
A	1.8	2.2	N
B	2.3	5.6	Y
C	2.0	5.3	Y

Disorder could explain the HRF line broadening between SDCP and BAE for samples B and C. Table I compares the difference between HRF and ULRF EDMR line widths (ΔLW) for all samples. ΔLW is about 2 Gauss for the BAE measurements. This indicates some disorder present at the interface. We find, for the SDCP measurements, that ΔLW is 2.2, 5.6, and 5.3 Gauss for samples A, B, and C, respectively. The broadening is about a factor of 2 larger in the samples which received the NO anneal. This result suggests that the NO anneal introduces more disorder at the interface. The additional N-induced disorder may be consistent with anisotropic strain introduced into the interface by the N as reported by Dycus *et al.* [12]. N-induced disorder may provide at least a partial explanation for why the addition of N quite substantially reduces D_{it} while only moderately improving the effective channel mobilities of nMOSFETs.

In summary, as several other reports indicate [1,5], the V_{Si} appears to be the most abundant defect in 4H-SiC MOSFETs with as-grown oxides on the SiC side. We find that V_{Si} play an important but reduced role in N processed devices. Additionally, we show that in NO annealed devices, N atoms are very close to a large fraction of V_{Si} and that the presence of N changes the V_{Si} energy levels away from mid gap. We also show, through multiple frequency SDCP measurements, that N creates a measurable type of disorder detected at the interface.

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