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Bias temperature instabilities in 4H SiC metal oxide semiconductor field effect transistors: Insight provided by electrically detected magnetic resonance

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ABSTRACT

We present insight with regard to the physical mechanisms of negative bias temperature instabilities (NBTI) in 4H SiC based metal oxide semiconductor field effect transistors (MOSFETs) based upon electrically detected magnetic resonance measurements (EDMR). Most of this insight results from EDMR studies not directly focused upon NBTI but studies more broadly focused upon two fundamental questions. (1) What as-processed defects are present at and near the SiC/oxide interface? (2) How does the presence of oxide charge alter electrically active defects at the SiC/dielectric interface? We compare the SiC results to magnetic resonance studies of bias temperature instabilities in silicon based devices. Although our analysis admittedly provides only a partial understanding of the phenomena in SiC devices, the analysis does allow for some reasonably definitive conclusions. The NBTI phenomena in 4H SiC MOSFETs are certainly different than in Si based MOSFETs. (1) Interface dangling bonds do not appear to play a significant role in SiC MOSFET interface traps under multiple circumstances, suggesting strongly that they are not significant contributors to NBTI. (2) Although oxide defects, almost certainly including the well-known E′ family of oxide traps, play an important role in SiC device NBTI, other defects, surprisingly including defects within the SiC substrate, are also involved.

1. Introduction

Metal-oxide-semiconductor field-effect transistors (MOSFETs) based upon the 4H polytype of SiC have great promise in high power and high temperature applications, at least in part, due to its 3.3 eV band gap [1]. Although these SiC based devices have enormous promise, this promise may not be fully achieved without the amelioration of materials problems involving the transistor semiconductor-dielectric interface. Among potential reliability and performance issues, bias temperature instabilities (BTI) are arguably among the most important [2–4]. SiC-based devices can experience significant threshold voltage shifts when the gate is subjected to modest voltage at elevated temperature, a problem that could severely limit the performance and range of applications for the technology. The negative bias temperature instability (NBTI) involves defects at or very near the channel/gate oxide interface. In the SiC literature, it is generally argued that NBTI processes take place in the oxide near or at the SiC channel/SiO_2 interface [2–4]. This is also generally thought to be the case for NBTI in Si-based MOS devices [5].

In this paper, we present evidence regarding the atomic scale mechanisms of NBTI in SiC MOSFETs. Our analysis is largely based upon electron paramagnetic resonance (EPR) studies [6,7]. The family of EPR techniques have unrivaled analytical power to identify the physical and chemical nature of point defects in semiconductors and insulators. Conventional EPR measurements are limited in their capabilities for the exploration of most reliability issues as these issues, more often than not, generally require measurements to be made in fully processed devices. Conventional EPR sensitivity, roughly ten billion total defects within the sample under study, usually precludes such measurements since very few devices of technological importance would have such high numbers of defects. Electrically detected magnetic resonance (EDMR) [8–12] overcomes this limitation, providing sensitivities typically at least ten million times higher than that of conventional EPR while providing essentially all of its analytical power. EDMR studies of

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instabilities in 4H-SiC MOSFETs are complicated by the ubiquitous presence of a spectrum due to silicon vacancies on the silicon carbide side of the SiC/SiO_2 interface [9]. The presence of this strong signal somewhat complicates the interpretation of the EDMR results in that it can, to some extent, obscure the presence of other spectra.

Nevertheless, a comparison of EDMR results on SiC and Si based MOS devices strongly indicates both gross differences and some similarities in the NBTI mechanisms in the two varieties of devices. In silicon dioxide based silicon MOSFETs, silicon dangling bonds at the Si/SiO_2 boundary are clearly generated by NBTI stressing and clearly dominate the EDMR response to NBTI. Thus, these dangling bond defects likely dominate the Si/SiO_2 NBTI interface traps. Our observations strongly suggest no such role for either silicon or carbon interface dangling bonds in the SiC based devices. The absence of such interface dangling bond defect generation is inconsistent with the widely utilized (but controversial [5]) reaction–diffusion models [13] for NBTI in silicon/silicon dioxide MOSFETs. However, we do observe EDMR spectra in SiC transistors which are surely due to an E′ variant [14,15]. The E′ centers are oxygen deficient silicon sites within the oxide very close to the SiC/SiO_2 boundary. E′ centers are strongly implicated in EDMR studies of NBTI in silicon/silicon dioxide based devices [16]. These defects play important roles in multiple silicon/silicon dioxide device instabilities. Our results also offer some surprising insights. We find that elevated temperature and negative bias also results in changes in the defect structure below the SiC/oxide boundary, within the SiC.

1.1. A brief introduction to electrically detected magnetic resonance

Because EDMR is a derivative of EPR, like conventional EPR, it has the ability to directly extract physiochemical information about electrically active defects in fully processed MOSFETs. In addition, EDMR via spin dependent recombination (SDR) utilizing the bipolar amplification effect (BAE) [17] or spin-dependent charge pumping (SDCP) [18,19] can exclusively access traps at or very near the SiC/SiO_2 interface. EDMR via SDR can provide EPR detection of defects because recombination is a spin-dependent process [8]. Recombination occurs when a paramagnetic charge carrier in either the valence or conduction band transitions to a deep level defect and recombines through the subsequent capture of a charge carrier of the opposite charge. Its spin dependence can be understood by considering the physics involved as the charge carrier transitions to the deep level defect. Before the charge carrier can transition, it forms an intermediate state with the deep level defect. The charge carrier-defect pair may form two types of intermediate states: singlets and triplets. The singlet state allows recombination because charge capture conserves angular momentum (total spin = 0 before and after charge capture). Conversely, the triplet state does not allow conservation of angular momentum (total spin = 1 before charge capture) and therefore does not lead to recombination. In EDMR via SDR, SDR is induced by increasing the ratio of singlet to triplet intermediate states by EPR. Increasing the singlet states thus increases recombination current. It is this current change as a function of magnetic field which provides the EDMR signal.

In the studies discussed herein, we utilize three forms of SDR/EDMR. In the simplest case, we apply a negative gate bias large enough to populate the interface region exclusively with holes, while modestly forward biasing source and drain. Under these biasing conditions, we measure spin dependent recombination induced changes in the source/drain to body current. The absence of electrons at the interface “turns off” any possible contribution from the interface and allows us to explore defect centers in the SiC below the interface. To greatly increase our sensitivity at the SiC/SiO_2 interface and eliminate “bulk” SiC defect contributions to the measurement we utilize two other approaches. In one case, we utilize the bipolar amplification effect (BAE) which uses SDR, to detect EPR in a lateral channel MOSFET current (current moving between source and drain). In the BAE measurement, the source-body diode is forward biased. The gate is biased as to attract the charge carriers injected by the source; however, the bias is not sufficient to create an inversion layer. Current is measured at the drain (the drain is at virtual ground) and is strongly influenced by interface/near interface recombination events. The BAE EDMR signal is optimized by selecting a gate voltage which maximizes the change in interface/near interface recombination current. This change in recombination current as a function of magnetic field is the BAE signal. The BAE is only sensitive to deep levels, as they must be efficient recombination centers. In a second interface sensitive approach we utilize spin dependent charge pumping (SDCP).

SDCP detects EPR in the current produced by charge pumping (CP) [18,19]. SDCP, like SDR, exploits the spin dependent nature of charge capture. Unlike SDR, however, it can be sensitive to defect levels throughout most of the band gap. CP is a powerful electrical MOSFET interface trap characterization technique. In the most straightforward approach used in this study, CP involves application of a continuous trapezoidal waveform to the MOSFET gate in order to alternately invert and accumulate the interface, filling and emptying traps at the interface region. The transistor base current generated by the trapezoidal wave forms thus provides a direct measure of the interface trap density within most of the semiconductor/oxide interface band gap. Since the charge capture sequences involved in the CP process must, almost inevitably, be spin dependent in a manner analogous to simple SDR, SDCP can provide a measure of defects with levels throughout almost all of the interface band gap.

To understand the underlying physical principles and the utilization and analytical power of this resonance-based approach, a few words about the magnetic resonance condition may be useful. In the simplest case, for an electron in free space, magnetic resonance occurs when the electromagnetic photon energy, $h\nu$, is equal to the electron Zeeman energy [6,7]. The resonance condition is met by

$$h\nu = g_e \mu_B B \tag{1}$$

Here, h is Planck's constant, ν is the electromagnetic radiation frequency, g_e is the Lande's g-factor, $g_e = 2.0023193\ldots$, μ_B is the Bohr magneton, and B is the magnetic field at resonance. When resonance occurs, the electron flips spin states from $+1/2$ to $-1/2$ (or vice versa).

The analytical power of EPR (and EDMR) comes from deviations from this simple case, changes in the resonance condition caused by the paramagnetic site environment [6,7]. The most important and obvious deviations result from electron interactions with orbital angular momentum and nearby magnetic nuclei. (Additional causes for deviation are also possible but beyond the scope of this very brief introduction.) Spin orbit coupling alters the free electron's g_e from 2.0023193… to a number that varies with defect orientation in the magnetic field. The g-value (g) is generally expressed as a second rank tensor. Nearby magnetic nuclei alter the local magnetic field experienced by the electron; these contributions to the resonance condition are called hyperfine interactions. Spin orbit coupling and hyperfine interactions modify the resonance condition, yielding expressions of the form

$$h\nu = g\mu_B B + \sum_i A_i I_i. \tag{2}$$

Here again, h is Planck's constant, ν is the electromagnetic radiation frequency, and B is the magnetic field at resonance, but now g is essentially a second rank tensor, A_i represents the hyperfine interaction with the ith magnetic nuclei, and I_i is the nuclear spin quantum number of the ith magnetic nuclei. The A_i values are also usually expressed in terms of a second rank tensor. Analysis of resonance spectra in terms of equations of this form allows definitive identification of the physiochemical structure of defects [6,7].

2. Experimental details

In a typical EDMR measurement, a MOSFET is placed into an EPR