Electron Capture and Emission at Interface States in As-Oxidized and NO-Annealed SiO_2/4H-SiC

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The electrical and physical properties of silicon carbide (SiC) and its ability to form insulating SiO_2 layers by thermal oxidation make it a promising material for high power, high-temperature, and high-frequency metal-oxide-semiconductor field effect transistors (MOSFETs). However, the development of 4H-SiC MOSFETs has been hindered by the high-density of interface states (D_{it}) at the SiO_2/4H-SiC interface and a reduced electron mobility of <10cm^2/Vs in n-channel inversion layers. Interfacial nitridation via post-oxidation annealing in NO results in the incorporation of about a monolayer of N (~10^{15}cm^{-2}) at or near the interface and reduces D_{it} near the conduction band-edge of 4H-SiC by almost an order of magnitude,[1,2] leading to a significantly improved effective channel mobility in n-channel 4H-SiC MOSFETs. While nitridation has been established as the most efficient oxide processing scheme for SiC devices, the N related trap passivation mechanism and the electronic nature of residual traps at nitrided SiO_2/4H-SiC interfaces remains unclear. Here we present new insights on the capture and emission properties of interface traps from constant capacitance deep level spectroscopy (CCDLTS) measurements.

Samples are 5mm x 5mm pieces diced from an 8° off-axis (0001) Si face n-type 4H-SiC wafer with 10µm epilayer doped with nitrogen at 5.5x10^{15}cm^{-3}. Dry oxidation was performed at 1150°C for 8 hours followed by annealing at 1150°C for 30 minutes in Ar to grow SiO_2 layers with thickness of ~60 nm. Some samples were subsequently annealed in NO for 2 hours at 1175°C. MOS capacitors were fabricated on both sets of samples. Simultaneous high-low frequency C-V measurements at room temperature were performed to verify the reduction in interface state density near the conduction-band edge associated with NO annealing. The MOS capacitors were also characterized using C-V measurements at 1MHz in the temperature range 300-80K. CCDLTS and double-CCDLTS measurements were performed in the same temperature range.

Figs. 1 and 2 show saturated CCDLTS spectra for the AO and NO samples. Electrons are trapped during a 20ms filling pulse which biases the sample in accumulation and are subsequently emitted at constant capacitance, i.e. at constant depletion width. The voltage transient needed to maintain the constant value of the sample capacitance is sampled at times t_1 and t_2 after the filling pulse and the difference, the CCDLTS signal, is plotted as a function of temperature. The maximum CCDLTS signal intensity for the NO sample is smaller than that of the AO sample by a factor of ~10, demonstrating the reduction of the D_{it} in the upper half of the bandgap with NO annealing.

To measure the emission activation energy and capture cross section of these states, double-CCDLTS, which employs two 20ms filling pulses having different voltages to define a narrow energy window, was used. Scans were taken at various rate windows and the emission activation energy and capture cross sections were determined from Arrhenius plots in the usual way. Fig. 3 shows the capture cross section plotted as a function of the activation energy. The three distinctly different values for the capture cross section, ranging from 5x10^{-17} to 5x10^{-20}cm^2, clearly demonstrate that at least three different trap species are present in the AO samples (squares): (1) centered at E_c-0.46eV, with a capture cross section 4×10^{-17}cm^2, (2) centered at E_c-0.24eV, with σ=7×10^{-19}cm^2; and (3) centered at E_C-0.17eV with σ=4×10^{-20}cm^2. Two distributions of states are observed by double-CCDLTS in NO samples (triangles): one centered at E_c-0.21eV, with σ=2×10^{-20}cm^2, and another at E_c-0.16eV, with σ=8×10^{-21}cm^2. The fixed peak position of the E_c-

978-1-4244-1892-3/07/$25.00 ©2007 IEEE

0.16eV distribution with increasing filling voltage is the same as was observed for the E_c-0.17eV (group 3) traps in the AO sample. This anomalous behavior and the similar values of the emission activation energy and capture cross section indicate that these states are present in both samples, but with different densities. The activation energy and capture cross section for the deeper states at E_c-0.38eV, with $\sigma=5\times10^{-20}cm^2$, and at E_c-0.56eV, with $\sigma=7\times10^{-20}cm^2$, in the NO sample were determined from peaks in the CCDLTS scans (indicated by arrows on Fig. 2 and open symbols on Fig. 3) taken at different rate windows, since the intensity of the signal was too weak to obtain double-CCDLTS data for these traps. Note that all the interface states in the NO samples have very small capture cross sections, 8×10^{-21}-$7\times10^{-20}cm^2$, suggesting capture to a negatively charged state. *These results clearly show that the two dominant species of interface states in the AO samples, electron traps having capture cross section* 4×10^{-17} *and* $7\times10^{-19}cm^2$*, are completely passivated by annealing in NO. The density of the third species centered at* E_c*-0.17eV having* $\sigma\sim4\times10^{-20}cm^2$ *is significantly reduced as well.*

Fig. 4 shows the calculated D_{it} profile obtained from the CCDLTS measurements for both the AO and NO samples. For comparison, D_{it} determined from the high-low frequency C-V technique for these samples is also shown. The D_{it} obtained from CCDLTS data for the NO sample agrees well with the density obtained from the C-V technique. In contrast, the agreement is good only for energy >0.2eV for the AO sample. This discrepancy suggests that the majority of interface states in the AO samples that are passivated by NO annealing, are not accessible on the time scale of the CCDLTS measurement. These new results will be discussed in terms of current models for the SiO_2/4H-SiC interface.

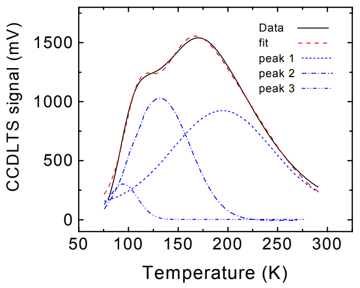

Fig. 1 Saturated CCDLTS spectrum for an AO sample. The rate window is 8.6ms. Data are fit as the sum of three trap distributions.

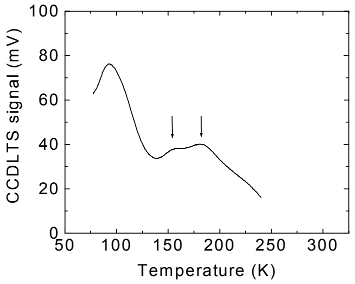

Fig. 2. Saturated CCDLTS spectrum for an NO sample. The rate window is 8.6ms.

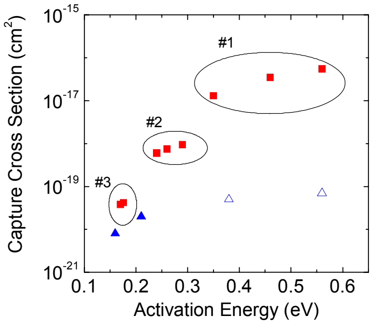

Fig. 3. Capture cross section vs. emission activation energy for AO and NO samples.

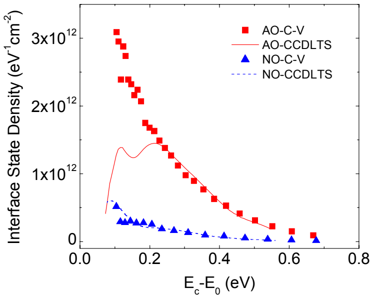

Fig. 4. D_{it} determined from Hi-Lo C-V and CCDLTS measurements.

References

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