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Abstract: Results are reported for the passivation of interface states near the conduction band edge in SiO_2/SiC MOS capacitors using post-oxidation anneals in nitric oxide, ammonia and forming gas ($N_25\%H_2$). Anneals in nitric oxide and ammonia reduce the interface state density significantly for 4H-SiC, while forming gas anneals are largely ineffective. Results suggest that interface states in SiO_2/SiC and SiO_2/Si have different origins, and a model is described for interface state passivation by nitrogen in the SiO_2/SiC system. The peak inversion channel mobility measured for lateral 4H-SiC MOSFETs increases following NO passivation.

INTRODUCTION

Silicon carbide (SiC) is a wide band gap semiconductor that has many properties that make it well suited for electronics applications under extreme conditions such as high temperature, high power, high frequency and high radiation [1]. One particular advantage is that SiC is the only member of the wide band gap family (SiC, the group III-nitrides and diamond) that has a native oxide. Silicon carbide can be thermally oxidized to form a device quality silicon dioxide dielectric layer [2]. For device fabrication, the 4H and 6H polytypes of SiC are currently available, and metal - oxide - semiconductor field effect transistors (MOSFETs) have been demonstrated for both polytypes. However, inversion channel mobilities are very low for 4H MOSFETs compared to 6H devices (~ 50 - 100$cm^2V^{-1}s^{-1}$ compared to 10 $cm^2V^{-1}s^{-1}$). This is an unexpected result, since 4H-SiC has higher bulk carrier mobilities than 6H-SiC [3].

Schorner, et al. [4] attribute the lower 4H inversion channel mobility to the presence of a high, broad density of interface states fixed in both polytypes at approximately 2.9eV above the valence band edge. We have measured the distribution of interface states across the SiC band gap using capacitance - voltage techniques to characterize MOS capacitors fabricated with both

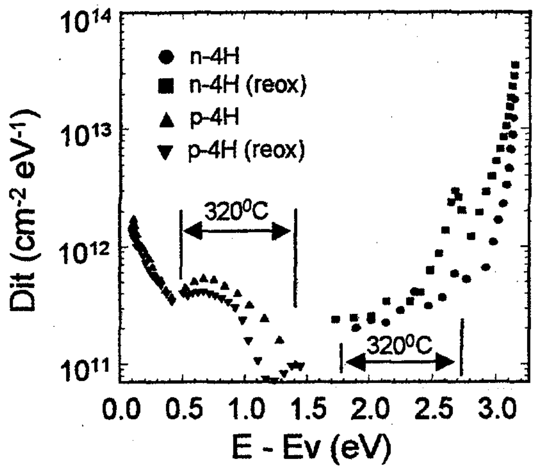


Fig. 1. Simultaneous Hi-Lo C-V measurements of the interface state density in the band gap of 4H-SiC.

p- and n-4H-SiC (Fig.1). The states in the upper half of the band gap described by Schomer, et al. cause the distribution of states across the band gap to be asymetric. The majority of these states lie in the conduction band for 6H-SiC ($E_g \sim 3$eV) and have little effect carrier mobility in the inversion layer. However, a substantial fraction of these states may lie within the band gap for 4H-SiC ($E_g \sim 3.3$eV), so that in inversion, channel mobility is substantially reduced by field termination, carrier (electron) trapping and coulomb scattering. Afanasev, et al. [5] attribute interface states in SiO_2/SiC to residual carbon that is present still following oxidation and to defects in a sub-oxide region that is formed at the interface when the oxidation process is terminated. Much attention is currently focused on characterizing the interface state density near the conduction band in SiO_2/4H-SiC and finding methods by which to passivate these states.

Interface states near the conduction band edge can be studied using SiO_2/n-4H-SiC MOS capacitors. Room temperature high / low capacitance - voltage measurements determine the distribution of states over the approximate energy range $E_c - E = 0.15$ to 0.55eV where E_c is the energy of the conduction band edge, and E is the interface state energy. MOS capacitors fabricated using n-4H-SiC are studied under the assumption that p-4H-SiC, which is the material used to construct an n-channel, inversion mode MOSFETs, has the same distribution of interface states near the conduction band. Herein, we report the results of attempts to passivate interface states near the conduction band for SiO_2/n-4H-SiC using post-oxidation anneals in three different ambients - nitric oxide (NO), ammonia (NH_3) and forming gas (N_2/5%H_2). We also report preliminary results for channel mobility measurements made with 4H-SiC MOSFETs that were passivated using post-oxidation anneals in NO.

EXPERIMENTAL DETAILS

Five micron 4H-SiC epilayers ($N_d = 8 \times 10^{16}$cm^{-3}) on heavily doped substrates ($N_d \sim 5\times10^{18}$cm^{-3}) purchased from Cree Research, Inc. were oxidized using standard, wet oxidation techniques that have been described elsewhere [6]. Our standard oxidation process is terminated with a "re-oxidation" step that is identical to the oxidation process itself except that the re-oxidation anneal is carried out at 900°C rather than at 1100°C. No additional oxide is grown during the re-oxidation process, and the process has been shown to reduce the interface state density near mid-gap for SiO_2/p-SiC samples [7]. However, as shown in Fig. 1, the re-oxidation process does not reduce D_{it} near the band edges for either p- or n-SiC [8].

Following oxidation to produce 40nm oxide layers, the samples were annealed in a second furnace in either NO, NH_3 or N_2/5%H_2 (forming gas). The post-oxidation anneals were carried out for various times at temperatures between 1050 and 1175°C. Gas flow was maintained at 0.5l/min at a pressure of 1atm during the post-oxidation anneals. Following these anneals, molydenum was sputter deposited to form oxide gate contacts, and large area backside ohmic contacts were formed to the N^+ substrates using Ag colloidal paste. Standard high frequency (1MHz) and quasi-static capacitance - voltage techniques were applied to characterize the SiO_2 /n-4H-SiC MOS capacitors.

Oxide layers for n-channel planar MOSFETs were grown on p-type 4H epilayers ($N_a = 8 \times 10^{16} cm^{-3}$) with the same oxidation process that was used for the MOS capacitors. Source and drain regions were formed by multiple energy nitrogen implantation, and post-implantation activation anneals were carried out at 1575°C for 30 min in flowing Ar. All samples were placed inside a polycrystalline SiC pillbox during the activation anneals. Source / drain ohmic contacts were formed using thin Ni layers (~ 200nm) annealed at 920°C for 3min. The gate electrode was Mo, and the MOSFET channel length and width were 90 and 410μm, respectively.

RESULTS

Results for post-oxidation anneals of SiO_2/n-4H-SiC MOS capacitors in NO, NH3 and forming gas are shown in Figs. 2, 3 and 4, respectively. Results labeled "re-ox" in these figures were obtained from measurements using samples that were not annealed following oxide layer growth using our standard oxidation process. The re-ox samples were used as control samples. Post-oxidation anneals in NO (Fig. 2) and NH_3 (Fig.3) result in a significant reduction in the interface state density near the conduction band [$D_{it}(E_c)$]. The NO anneals were conducted for 2hr, and $D_{it}(E_c)$ was found to decrease monotonically over the temperature range 1050 to 1175°C (data not shown). Following a 2hr anneal at 1175°C, $D_{it}(E_c)$ was reduced by a factor of about ten - from approximately 2×10^{13} to $2\times10^{12} cm^{-2}eV^{-1}$. Two hour post-oxidation anneals in NH_3 also result in good passivation of the interface states near the conduction band. However, the temperature dependence for the passivation process is different compared to NO. The value of $D_{it}(E_c)$ appears to have a minimum value of about $2\times10^{12} cm^{-2}eV^{1}$ for an anneal temperature of 1100°C.

In an effort to understand the observed differences for NO and NH_3, we have undertaken a series of ion beam measurements (RBS / channeling) to characterize nitrogen uptake in the annealed oxide layers. The kinetics for the two processes are quite different. Results indicate

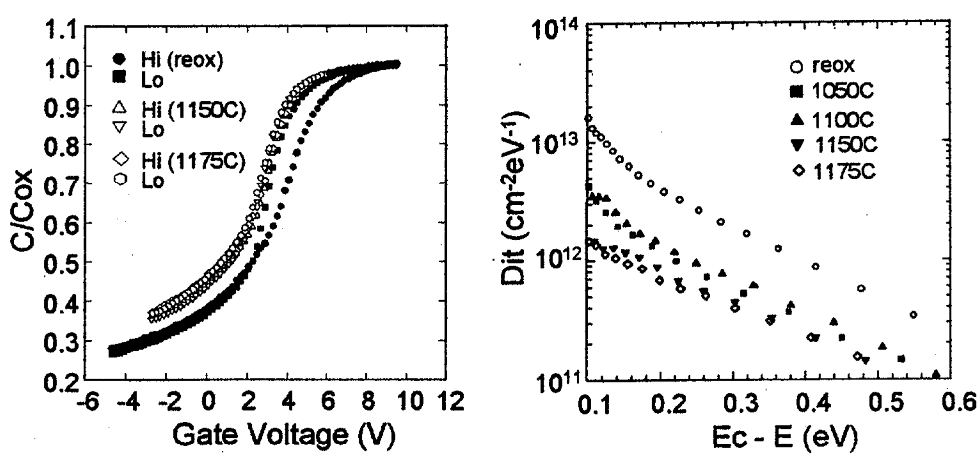


Fig. 2. Typical C-V plots and interface state densities for n-4H-SiC MOS capacitors following 2hr anneals in NO.

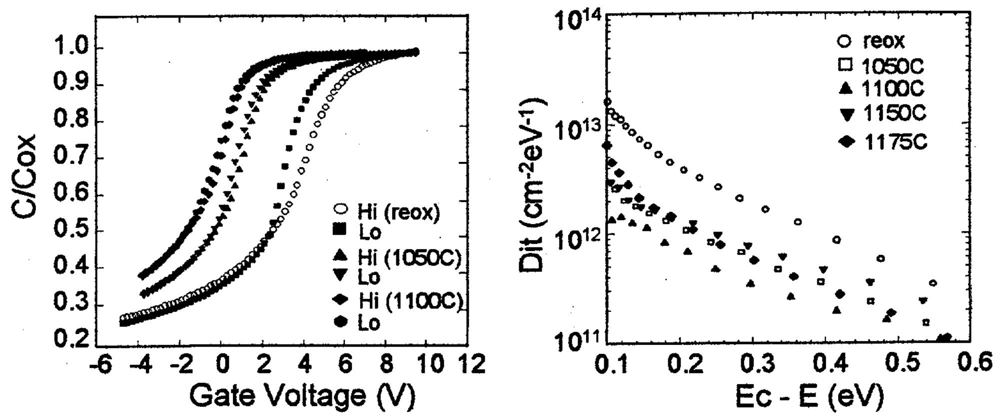


Fig. 3. C-V curves and interface state densities for n-4H-SiC MOS capacitors following 2hr anneals in ammonia.

that nitrogen introduced with NO remains very near the SiO_2/SiC interface [9], while anneals in NH_3 introduce nitrogen throughout the entire oxide layer in concentrations almost two orders of magnitude higher than the concentrations introduced with NO [10]. Our ion beam measurements are ongoing, and at this time, we do not have a satisfactory explanation of the differences in the temperature dependencies of the NO and NH3 two passivation processes.

For SiO_2/Si technology, interface state densities can be substantially reduced by passivation with hydrogen, resulting in D_{it} values typically the order of $10^{10}eV^{-1}cm^{-2}$. This passivation process can be carried out by low temperature annealing (450°C) in hydrogen or forming gas either before or after gate metal deposition. For post-metalization anneals in gas ambients other than hydrogen (e.g., N_2 or Ar), Deal, et al. [11] have suggested that water molecules in the oxide react with the gate metal to produce hydrogen that subsequently diffuses to the SiO_2/Si interface and passivates the interface traps through a chemical reaction that makes the traps electrically inactive. Campi, et al. [12] reported that a post-metalization anneal in hydrogen reduces the interface state density near mid-gap for SiO_2/p-4H-SiC capacitors. Suzuki, et al. [13] studied MOS capacitors fabricated with n-4H-SiC and reported reductions in the interface state density near the conduction band edge following post-oxidation anneals in hydrogen at temperatures between 800°C and 1000°C. Results are shown in Fig. 4 for post-oxidation anneals in forming gas ($N_2$5%H_2). Each data point is an average value determined in the following manner. Typically, eight MOS capacitors were characterized for each anneal temperature, and an average value of the interface state density was determined for each capacitor by averaging D_{it} over the energy range E_c -E = 0.15 to 0.6eV. These eight average values were then averaged a second time to produce the data points shown in Fig. 4.

DISCUSSION

As can be seen in Fig. 4, the forming gas anneals do not significantly reduce $D_{it}(E_c)$ compared to anneals in NO. This suggests that the interface states in SiO_2/SiC and SiO_2/Si have different precursors - in agreement with results reported by Afanasev, et al. [5] who did not observe Si dangling bonds in SiO_2/SiC. These authors attribute interface states in SiO_2/SiC to residual carbon and point defects created by missing oxygen atoms in a near-interface sub-oxide that forms when the oxidation process is terminated. Fig. 5 shows the effect on $D_{it}(E_c)$ of anneals in nitric oxide for 6H and 4H-SiC. These results support the supposition of Schorner, et al. [4] that 4H-SiC has a much higher density of interface states in the band gap near the

Fig. 4. Measured average interface state densities for SiO_2/n-4H-SiC following anneals in forming gas $N_2/5\%H_2$). Results for anneals in NO are included for comparison. The averaging method for D_{it} is described in the text.

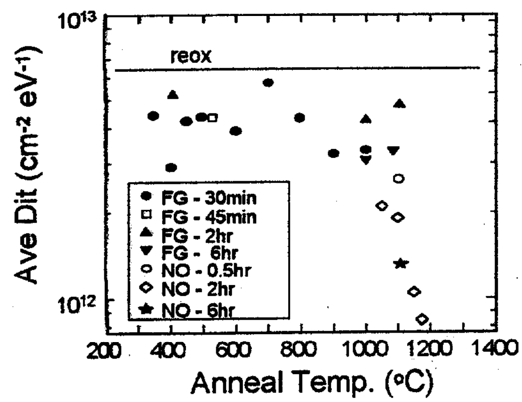
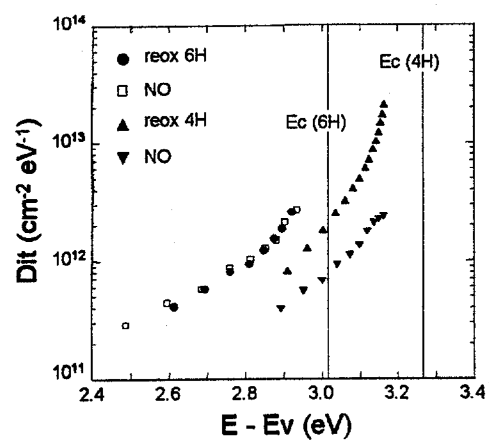


Fig. 5. Interface state passivation for SiO_2/n-4H-SiC following post-oxidation anneals in NO. Similar results can also be obtained using NH_3.



conduction band edge than does 6H-SiC. We have recently reported that carbon interstitials re-bond within the SiC lattice to form carbon clusters. Isolated carbon interstitials and carbon clusters have energy levels in the upper part of the gap. The levels go slightly higher in energy with each additional carbon atom added to a cluster. Nitrogen atoms passivate the isolated carbon interstitials entirely, and drop the gap level into the valence band. The gap level for two carbon interstitials drops to about the valence band edge, and for larger clusters, the gap levels drop below mid-gap. We have suggested that this effect persists when carbon atoms cluster as interstitials at the interface. Such a phenomenon accounts for observations of the passivation effects reported in this paper.

Figure 6 shows the I_D-V_G characteristics and channel mobility for 4H-SiC planar MOSFETs before (a,c) and after (b,d) NO passivation anneals at 1175°C for 2hr. The drain current was measured at $V_D = 50mV$. After NO annealing, the maximum effective channel mobility increases from 33 cm^2/Vs to 68 cm^2/Vs as a result of the passivation of interface states near the conduction band. The threshold voltage of the annealed MOSFET is negative - perhaps as the result of an increase in the number of deep, donor-type defects following the passivation anneal. We observe a similar increase in the positive effective charge in MOS capacitors annealed in NO. These results demonstrate that inversion channel mobility for 4H-SiC MOSFETs can be improved by passivation of the interface state density near the conduction band. However, these results are preliminary, and we should consider other factors such as the effect of the ohmic contact annealing process on the passivated interface and the effect of oxide leakage current following the NO passivation anneal.

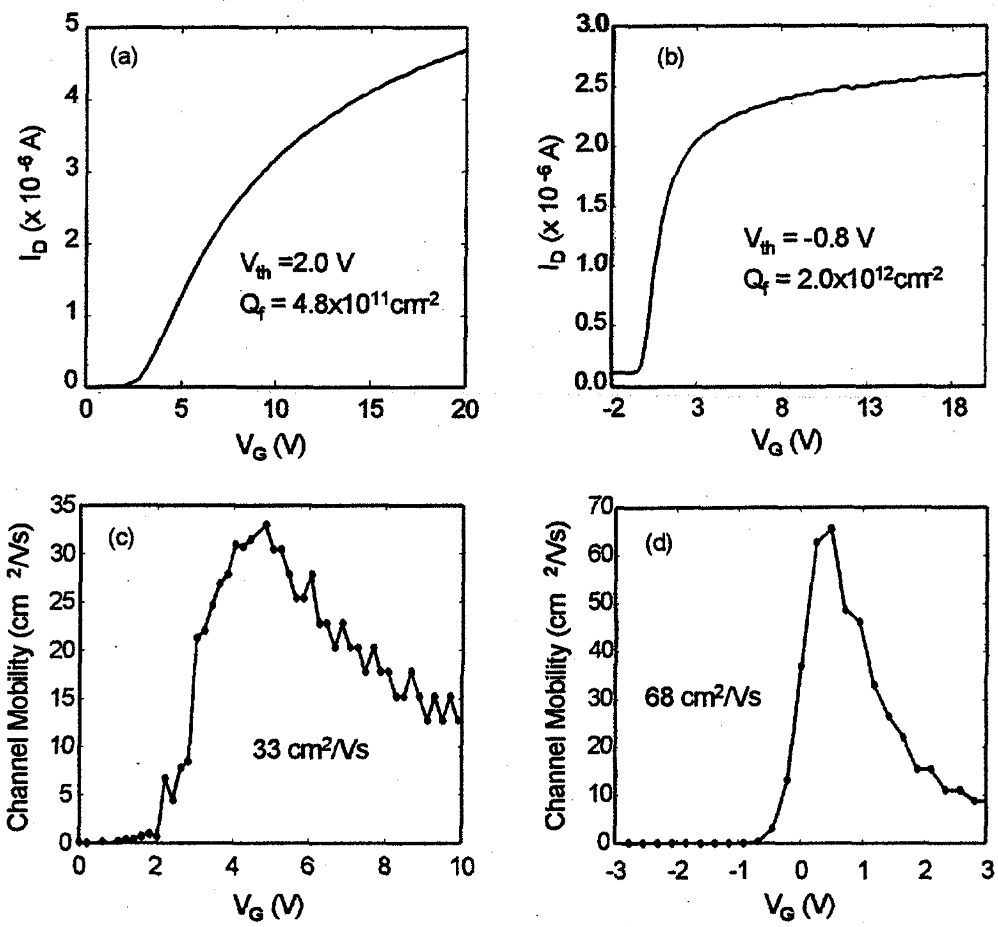


Fig. 6. I_D-V_G characteristics and channel mobility of 4H-SiC lateral MOSFETs before (a,c) and after (b,d) anneals in NO at 1175°C for 2hr.

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