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Effect of nitric oxide annealing on the interface trap density near the conduction bandedge of 4H–SiC at the oxide/$(11\bar{2}0)$ 4H–SiC interface

S. Dhar[a]
Interdisciplinary Materials Science, Vanderbilt University, Nashville, Tennessee 37235

Y. W. Song and L. C. Feldman[b]
Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235

T. Isaacs-Smith, C. C. Tin, and J. R. Williams
Department of Physics, Auburn University, Auburn, Alabama 36849

G. Chung
Dow Corning Inc., Tampa, Florida 33619

T. Nishimura, D. Starodub, T. Gustafsson, and E. Garfunkel
Laboratory for Surface Modification, Rutgers University, Piscataway, New Jersey 08854

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Nitric oxide postoxidation anneal results in a significant decrease of defect state density (D_{it}) near the conduction bandedge of n-4H–SiC at the oxide/$(11\bar{2}0)$ 4H–SiC interface. Comparison with measurements on the conventional (0001) Si-terminated face shows a similar interface state density following passivation. Medium energy ion scattering provides a quantitative measure of nitrogen incorporation at the SiO_2/SiC interface.
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The 4H polytype of silicon carbide (4H–SiC) is one of the most promising materials for power electronics applications. The ability to grow a thermal oxide has lead to the development of SiC metal oxide semiconductor field effect transistors (MOSFET). Although this oxide is similar to SiO_2 grown on Si,[1] the SiO_2/SiC interface results in much poorer electronic properties than the SiO_2/Si interface. MOSFETs fabricated on the (0001) Si-terminated face of 4H–SiC have typically shown very low inversion channel mobilities ($\mu_{\mathrm{inv}} \sim 0.1–25\ \mathrm{cm^2/V\,s}$) due to the high density of interface states present within the bandgap of SiC. The fact that 4H–SiC MOSFETs show lower mobilities than 6H devices is attributed to a broad distribution of interface states lying $\sim$2.9 eV above the valence band.[2] These states fall within the bandgap of 4H–SiC ($E_g = 3.26$ eV), but lie in the conduction band for 6H–SiC ($E_g = 3.02$ eV). Thus, the channel mobility is reduced in 4H–SiC by field termination, carrier trapping, and Coulomb scattering associated with this high density of interface states.

Recent studies have reported an order of magnitude reduction of D_{it} on the (0001) Si terminated face near the conduction bandedge of 4H–SiC by using a nitric oxide (NO) postoxidation anneal (POA).[3–6] Reports by other groups have indicated improved properties of MOS structures built on the $(11\bar{2}0)$ oriented substrates using wet oxidation[7–9] and suggested an intrinsic low density of acceptor like interface states near the conduction band edge.[8] Others have indicated good $(11\bar{2}0)$ properties after passivation of these interface states by hydrogen.[9] In this letter, we report the effects of the NO POA on the interface state density for dry oxides on $(11\bar{2}0)$ 4H–SiC. Our results indicate that dry oxidation of the $(11\bar{2}0)$ face results in comparable D_{it} to that of the (0001) Si face ($\sim 10^{13}\ \mathrm{cm^{-2}\,eV^{-1}}$) at $\sim$0.2 eV below the conduction band. NO annealing results in a substantial improvement, reducing the value to $\sim 10^{12}\ \mathrm{cm^{-2}\,eV^{-1}}$, which is comparable to the best values obtained for the Si face.

The main feature distinguishing the (0001) and $(11\bar{2}0)$ crystal faces is the polar structure. The first monolayer of the Si face is 100% Si, while that of the $(11\bar{2}0)$ face is 50% C and 50% Si. Interface studies of these structurally different surfaces is important not only for fabricating devices utilizing wafers of different orientation, but also for the development of UMOSFETs,[10] where the gate is "U" shaped. Since the inversion channel formation takes place along the $(11\bar{2}0)$/oxide interface, it is critical to realize high inversion layer mobility and low interface state density on this face.

$(11\bar{2}0)$ n-type 4H–SiC substrate wafers ($N_d = 5 \times 10^{18}\ \mathrm{cm^{-3}}$) supplied by CREE, Inc. were used to grow thin lightly doped n-epilayers (5 μm, $N_d \sim 10^{16}\ \mathrm{cm^{-3}}$). After a standard RCA clean, the samples were oxidized at 1150 °C in dry oxygen to yield an oxide thickness of about 30 nm. For the sample subjected to the NO POA process, the temperature was ramped up to 1175 °C in flowing Ar, and the NO anneal was performed for 2 h. The NO POA process is completed by ramping down the temperature from 1150 to 900 °C at a ramp rate of 4 °C/min in flowing Ar and unloading the samples under these conditions. A standard sample was made by annealing in Ar at the oxidation temperature for 30 min after oxidation. Gate metallization was performed by sputtering Mo and Au in succession and colloidal Ag paste was used for a large area backside ohmic contact. Simultaneous hi–lo capacitance–voltage (C–V) measurements (high frequency-100 kHz and quasistatic) were performed at room temperature, with the gate bias swept from accumulation to depletion. Similar sets of samples were prepared on

[a]Electronic mail: sarit.dhar@vanderbilt.edu
[b]Also at: Oak Ridge National Laboratory, Oak Ridge, TN 37831.

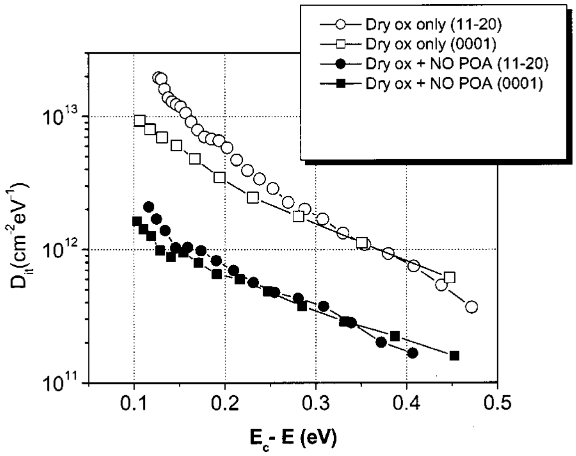

FIG. 1. Interface state density profile $D_{it}(E)$ near E_c measured for $(11\bar{2}0)$ (circles) and (0001) (squares) with (solid symbols) and without (open symbols) NO postoxidation anneal The NO POA significantly reduces the D_{it} near the conduction band for both the orientations.

the (0001) oriented samples for comparison between these two crystal faces.

Medium energy ion scattering (MEIS)[11] using 100 keV H^+ ions at normal incidence and 125° scattering geometry was performed on the $(11\bar{2}0)$ 4H–SiC samples to determine nitrogen incorporation at the interface. Two sets of samples were made with and without the NO anneal as described before. The oxide layer was carefully etched with HF to thin the layer in order to preserve the interface resolution for MEIS analysis.

Interface state density profiles for the $SiO_2/(11\bar{2}0)$ 4H–SiC interface are shown in Fig. 1. The NO POA process resulted in an order of magnitude reduction in D_{it} close to the conduction band edge. At $E_c - E = \sim 0.1$ eV, the density of defects traps is reduced from $\sim 10^{13}$ to $\sim 10^{12}$ cm^{-2} eV^{-1}. Reduction of D_{it} also occurs further from the conduction band, but the effect is most pronounced near the conduction band edge. This reduction is similar to that observed for the nitric oxide anneal for the (0001) Si face MOS capacitors, as shown on the same plot. The results also show that the interface state density before passivation by NO for the $(11\bar{2}0)$ face is of the same order of magnitude as for the (0001) Si face, at least in the case of dry oxides. This is contrary to the observations made for wet oxides

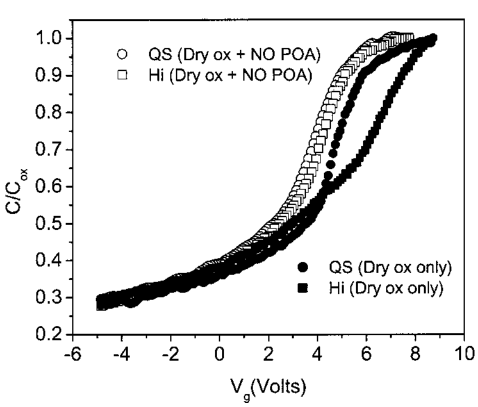

FIG. 2. High frequency (squares) and quasistatic (circles) $C-V$ curves for as-oxidized (solid symbols) and NO annealed (open symbols) $(11\bar{2}0)$ 4H–SiC capacitors.

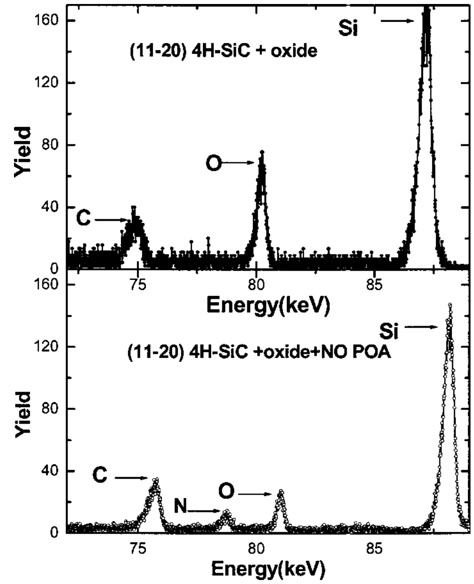

FIG. 3. MEIS spectra of $(11\bar{2}0)$ 4H–SiC: Sample as-oxidized at 1150 °C (top) compared to a sample that underwent a NO POA at 1175 °C for 2 h after the oxidation (bottom). Nitrogen incorporation at or near the interface can be observed from the spectra. The difference in amount of oxygen in the two samples is due to different thickness resulting from etching of the oxide.

where the $(11\bar{2}0)$ interface was found to have a lower D_{it} in comparison to the (0001) Si face.[7,8] This could be due to the wet oxidation bringing about some *in situ* passivation of traps during the wet oxidation process—a process that is associated with hydrogen. It should be noted that a significant anisotropy exists in the oxidation kinetics among the different crystal faces of SiC,[12,13] so it is likely that the interface chemistry is different for these two faces. However our observations indicate that the electrically active trap density behavior of dry oxides is similar for the two faces. Figure 2 shows the high frequency and quasistatic $C-V$ curves for as-oxidized and NO passivated $(11\bar{2}0)$ MOS capacitors. The nitridation process leads to a shift of the flat-band voltage towards less positive voltages. This can be attributed to the decrease in effective negative charge at the interface due to the NO anneal. A similar effect has been observed for the (0001) capacitors (not shown) in this work and in previous reports.[3]

Previous studies indicate the possibility of carbon clusters, suboxides or oxycarbides at the interface, and Si and C dangling bonds have also been considered.[3,5,8,14,15] Furthermore, it has been suggested that the NO POA may not physically remove these defects but may instead shift the energies of these defects in the band gap, thereby removing their detrimental effects.[5,16] Prior studies have also indicated that passivation depends only on the amount of nitrogen incorporated at the interface and is independent of anneal temperature and time.[1,3,5]

Figure 3 shows the MEIS spectrum of $(11\bar{2}0)$ sample oxidized and subjected to the NO POA process and a sample without the NO treatment. We observe incorporation of nitrogen at or near the interface from the MEIS measurement. It is possible that the NO anneal leads to the formation of a thin nitride at this interface. The areal density of N atoms was found to be 0.66×10^{15} and 1.16×10^{15} atoms/cm^2 for

TABLE I. Areal densities of Si, O, C, and N atoms obtained experimentally from MEIS. Theoretical values of the Si and C areal densities are shown for comparison.

Sample	Oxide thickness (A)	Si 10^{15} atoms/cm^2	O 10^{15} atoms/cm^2	C 10^{15} atoms/cm^2	N 10^{15} atoms/cm^2	$Si_{intrinsic}+Si_{SiO_2}$ (calculated) 10^{15} atoms/cm^2	$C_{intrinsic}$ (calculated) 10^{15} atoms/cm^2
$(11\bar{2}0)$ as-oxidized	≅6.7	3.77 ±0.19	3.01 ±0.15	3.84 ±0.19		1.6+1.51 =3.11	2.7
$(11\bar{2}0)$ With NO	≅2.2	2.79 ±0.14	0.97 ±0.05	4.27 ±0.21	0.66 ±0.03	1.6+0.485 =2.09	2.7
(0001) as-oxidized	≅9.7	4.24 ±0.21	4.36 ±0.22	3.39 ±0.17		2.9+2.18= 5.08	2.4
(0001) With NO	≅7.4	3.96 ±0.2	3.33 ±0.17	3.58 ±0.18	1.16 ±0.06	2.9+1.67 =4.57	2.4

the $(11\bar{2}0)$ and (0001) surfaces, respectively [spectrum for (0001) not shown]. These N atoms are distributed very close to the interface with a distribution that has a full width at half maxima of the order ~10 A, which is very close to the depth resolution limit of MEIS. In Table I the atomic areal densities of Si and C obtained from MEIS have been compared with theoretically calculated values for both (0001) and $(11\bar{2}0)$. The theoretical C density is found by calculating the contribution from the intrinsic surface peak of C in $(11\bar{2}0)$ SiC.[11,17] The intrinsic surface peak is the intensity arising from the ion beam interaction with the first monolayers of atoms. For Si, the sum of the intrinsic surface peak of Si and Si in a thin layer of stoichiometric SiO_2 has been calculated. The carbon intensity for both faces is significantly greater than that expected for an ideal SiC crystal, for both the as-oxidized and NO passivated samples. This may be due to a severely reconstructed interface or, more likely interfacial carbon produced during the oxidation process. The difference between the calculated and measured values of carbon sets a limit on the amount of the excess interfacial carbon to approximately a monolayer of carbon. The measured Si surface intensity for the $(11\bar{2}0)$ face is somewhat higher than that expected for an ideal SiO_2/SiC. On the contrary, for the (0001) samples; the measured Si intensities were lower than the calculated theoretical values. This could be a preliminary indication of a thin layer of nonstoichiometric suboxide (i.e., SiO) existing between the stoichiometric SiO_2 and the SiC substrate.

In conclusion, we have observed that the density of states on dry oxides near the conduction band edge at the $SiO_2/(11\bar{2}0)$ 4H–SiC interface decreases following a postoxidation anneal in NO comparable to that on the (0001) surface. This suggests that the physical natures of defects contributing to the density of interface states near the conduction band on these two crystal faces are similar.

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