Silicon dioxide/4H-SiC band alignment on Si-face and C-face substrates

Significant effects on SiO$_2$/4H-SiC band alignment induced by the difference of employed crystal face and post-oxidation annealing processes

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[Introduction] To improve the quality of SiO$_2$/4H-SiC interface, several kinds of post-oxidation annealing (POA) process are used. For Si-face 4H-SiC, it is already well known that NO-POA is an effective method to reduce $D_c$. However, after NO-POA, there is a negative shift of threshold voltage. Therefore, as one possible origin of that phenomenon, we reported about the band alignment shift induced by NO-POA [1]. Furthermore, it would be also important to see the crystal face dependence of such influences of POA on the band alignment. In this work, we compared the effect of POA on the band alignment shift of Si-face and C-face. Especially we focused on the effect of Wet-POA as an annealing method of C-face samples because Wet-POA is already confirmed as an effective method for C-face MOS capacitors [2].

[Experiments] N-type 4H-SiC Si-face and C-face wafers with epitaxial layers (N$_D$~1.0×10$^{16}$ cm$^{-3}$) were used as the substrates. After HF cleaning, samples were dry oxidized at 1300°C with 100% and 2% oxygen (diluted with N$_2$) to grow a SiO$_2$ layer for Si-face and C-face substrates, respectively. The thickness of the layer was controlled by the oxidation process. After dry oxidation, NO-POA (1150°C, 33% NO with N$_2$, 0.5–8 h) processes were performed for both substrates and wet-POA (P$_{HF}$: 0.2 atm with N$_2$ as a carrier gas, 800–1000°C) processes were performed for C-face samples. After deposition of the electrodes (top: Au, bottom: Al), we measured C-V characteristic at 1 MHz and $V_{FB}$ was extracted for each sample.

[Results & Discussions] Fig. 1 shows the $T_{ox}$ (CET) dependence of $V_{FB}$ of samples with different POA conditions. The inset shows the C-V curve of C-face MOS capacitor with Wet-POA. The improved interface quality was observed after Wet-POA, especially for the case of 900°C. Also, we confirmed the improved interface quality after NO-POA on both crystal faces. $V_{FB}$ was reasonably extracted since all the samples show nearly ideal curves with small frequency dispersions. From Fig. 1, a larger slope was observed on C-face than on Si-face, which means more fixed oxide charges at the interface. The offset observed by the extrapolation of the slope to CET=0, which gives the value after the removal of the shift due to the fixed charges, shows significant influences of both the employed annealing processes and crystal faces. As we already reported [1], such difference of the offsets is explainable by assuming the formation of a dipole layer at the interface with various strengths. So, we estimated the conduction band offset of the MOS interface ($\Delta E_c$) by measuring the valence band offset from XPS valence band spectra. For some samples, the extracted $\Delta E_c$ was confirmed to be consistent with the value determined from F-N tunneling current. Note that we’ve confirmed from O1s loss spectrum that SiO$_2$ bandgap is not affected by either POAs or crystal faces. Fig. 2 shows the change of $\Delta E_c$ after Wet-POA on C-face. Interestingly, there was a large decrease in $\Delta E_c$ after Wet-POA, even though the origin of this dramatic decrease is not clarified so far. Finally, we compared $\Delta E_c$ after NO-POA on Si-face and C-face, together with the one after Wet-POA on C-face. When we compare the $\Delta E_c$ of the dry oxidized samples, the intrinsic difference of $\Delta E_c$ between NO-POA, NO-POA increased on Si-face but decreased on C-face. Moreover, after Wet-POA on C-face, there was more reduction of $\Delta E_c$. Therefore, we can conclude that the observed large difference of $\Delta E_c$ between Si-face and C-face after POA could be originated from both (i) the intrinsic difference of crystal face and (ii) the difference of the POA effects, especially due to the significant effects of Wet-POA uniquely on C-face.

[Conclusions] There was an intrinsic difference of conduction band offset between the Si-face and C-face 4H-SiC MOS interfaces. Moreover, the effect of POA on the band alignment shift also varied according to the crystal face. On Si-face, there was a large difference of $\Delta E_c$ after NO-POA and increased more with increasing NO-POA duration, whereas the Wet-POA on C-face induced a significant decrease of $\Delta E_c$.