Interface nitridation of thermally-grown SiO$_2$/4H-SiC by post-oxidation annealing in pure nitrogen gas

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The most engaging interest of silicon carbide (SiC) is that the thermal oxidation for producing silicon dioxide (SiO$_2$) film as a gate insulator in metal-oxide-semiconductor field-effect-transistors (MOSFETs) can be adopted from silicon. However, many defects at SiO$_2$/SiC interfaces may significantly increase channel resistance. Hence, at the present stage, channel mobility of SiC-MOSFETIs is much lower than that of the bulk mobility. Nevertheless, these interface defects can be partially passivated by interface nitridation using post-oxidation annealing (POA) in reactive nitrogen-containing gas, i.e., NO$_x$ [1]. In this work, we proposed an alternative and effective method to perform interface nitridation by POA in pure N$_2$ ambient for 4H-SiC substrates containing thermally grown oxides (SiO$_2$/SiC).

The samples were fabricated on 4H-SiC(0001) substrates with n-type epilayers. After wet cleaning, 15-nm-thick SiO$_2$ layers were thermally grown on the substrates using dry oxidation at 1150°C for 90 min. Then, POA was carried out for 30 min inside pure ambient N$_2$ gas (99.9999%). The annealing temperature was varied from 1300 to 1400°C. The SiO$_2$ layers were completely removed in HF (1%) solution prior to x-ray photoelectron spectroscopy (XPS) to examine the incorporation of nitrogen atoms into SiO$_2$/SiC interfaces.

Figure 1(a) shows N 1s core-level spectra of the samples normalized by the peak signals in Si 2p core-level spectra. We found that the annealing temperature at 1350°C seems to be the fundamental requirement that facilitates interface nitridation by N$_2$-POA as indicated by the N 1s peak at 398 eV. This result coincides well with the formation of atomically thin silicon nitride (SiN) layers on bare 6H-SiC surfaces by N$_2$ annealing at 1350°C reported by Shirasawa et al. [2]. However, the N$_2$-POA at 1300°C was ineffective to cause interface nitridation. Moreover, the N 1s peak intensities taken from the samples with N$_2$-POA at 1400°C increased considerably. As shown by Fig. 1(b), the amount of nitrogen content indicating by intensity ratio between the N-Si bond and the SiC bulk signal ($I_{N_1S}/I_{Si\;2p}$) for the samples with N$_2$-POA at 1400°C is significantly higher than that with the optimal NO-POA at 1250°C [3].

Next, we fabricated SiC-MOS capacitors by depositing Al gate electrodes on the SiO$_2$/SiC samples. Figure 2 represents the energy distribution of interface state density ($D_i$) for the capacitors estimated by the high-low method, and the C−ψ$_i$ method [4] that captures entire traps, including fast traps. It was found that both methods showed a reduced $D_i$ with an increase in N$_2$-POA temperatures. The $D_i$ discrepancy between these two methods represents a certain amount of fast states that were generated at the nitrided SiO$_2$/SiC interfaces treated by N$_2$-POA at 1350 and 1400°C, which is analogous to previous report on NO-POA [5]. Nevertheless, The N$_2$-POA at 1400°C was the most advantageous to eliminate the slow traps, thus improving interface quality.


![Fig. 1 Change in (a) the N 1s core-level spectra and (b) the $I_{N_1S}/I_{Si\;2p}$ ratios obtained from the N$_2$-POA treated SiC samples with various annealing temperatures. The oxides were entirely etched prior to XPS measurement.](image1)

![Fig. 2 Energy distribution of $D_i$ estimated by high-low and C−ψ$_i$ method [4] for samples with and without N$_2$-POA (as-ox.).](image2)