SiO_2/SiC 界面の高温 N_2 アニールで競合的に生じる SiC 窒化とエッチング

Considerations on competition between SiC surface nitridation and etching at SiO_2/SiC interface induced by high-temperature N_2 annealing

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[Motivation]

SiC-based MOSFET nowadays are suffering from a high interface state density (D_{it}) at the SiC/SiO_2 interface, which may result in a low channel mobility. Nitridation by NO gas has been demonstrated as an effective method to reduce the D_{it}[1]. Besides, high-temperature annealing in N_2 of SiO_2/SiC stack can also introduce nitrogen at SiC surface by partially replacing the topmost carbon atoms[2]. An important difference from standardized-NO-annealing process would be the controllability of oxygen partial pressure in the annealing ambient, resulting in the change of balance among surface nitridation, oxidation and surface etching. The knowledge on such balance is lacking currently but critical for the optimization of nitridation process. Here we investigated the relationship between the two kinds of interface reactions: surface nitridation and etching for various N_2 annealing conditions, to search for the opportunities to introduce higher density of nitrogen to the interface.

[Experimental]

4°-off n-type 4H-SiC(0001) substrates were oxidized in dry O_2 at 1300℃ after RCA cleaning and 5%HF etching, growing around 6nm or 30nm thermally grown SiO_2 on SiC. Post-oxidation annealing (POA) was done at 1350℃ in N_2(containing around 0.002%atm residual O_2), N_2/0.01%O_2 or N_2/0.3%H_2 ambient from 2min to 4hr. Then SiO_2 was fully removed using 5%HF etching for 10min, after which XPS measurement with Mg-Kα source was done with a 90° take-off angle. Relative concentration ratios were estimated with the peak area of Si 2p3/2, O 1s and N 1s. Surface root mean squares (RMS) of SiC were acquired by scanning different positions with AFM.

[Results and Discussions]

Fig. 1 shows the average RMS on SiC surface ($\overline{\mathrm{RMS}}_{\mathrm{SiC}}$, average of the RMS from several positions on each sample) dependence of POA duration with 6nm thermally grown SiO_2 before POA, while Fig. 2 shows the relative concentration ratios (normalized by Si) of N (N/Si) and O (O/Si) for the samples with around 6nm SiO_2 coverage before POA. Quick saturation of N/Si is observed for N_2/0.3%H_2. The low saturation N/Si value for N_2/0.01%O_2 can be explained as the result of excess oxidation over the nitridation reaction, as indicated by the higher O/Si. Fig. 3 shows relationship between nitridation rate ($= (\mathrm{N/Si}(t) - \mathrm{N/Si}_{\mathrm{as-oxidized}})/t$, t is the POA duration) and the SiC roughening rate ($= \left|\overline{\mathrm{RMS}}_{\mathrm{SiC}}(t) - \overline{\mathrm{RMS}}_{\mathrm{SiC}}^{\mathrm{as-oxidized}}\right|/t$). Considering the surface roughening is related to etching, we speculate the etching at SiC/SiO_2 interface breaks the related Si bonds and removes the topmost atoms so that N can be inserted. The control of oxygen partial pressure is important for the nitridation efficiency. Besides, the choice of SiO_2 thickness is critical, as both early-stage nitridation and roughening rate of 6nm SiO_2 are higher than those of 30nm SiO_2, with the higher roughening rate probably due to easier out-diffusion of gas products.

[Conclusions]

We found that lower O_2 partial pressure or thinner SiO_2 is significantly advantageous for nitridation reaction of 4H-SiC in N_2 ambient, but both inevitably result in a gradual emergence of surface roughness, due to surface etching. This is understandable by considering nitridation reaction requires removal of topmost atoms.

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References [1] J. Rozen et al. J. Appl. Phys. **105**, 124506 (2009). [2] K. Murata et al. Appl. Phys. Express **13** 095506 (2020).

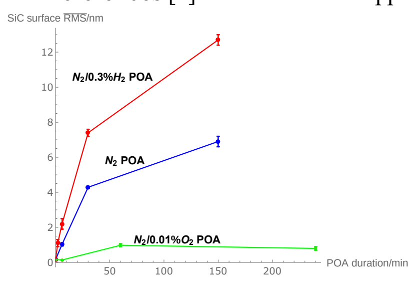

Fig.1 RMS dependence on POA durations for 6nm SiO_2 coverage before POA. Error bar comes from the statistic deviation from positions.

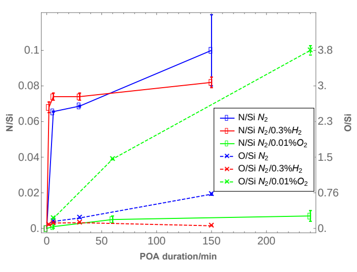

Fig.2 N/Si and O/Si for 6nm SiO_2 coverage before POA. Error bar comes from the ambiguity of peak area after background removals.

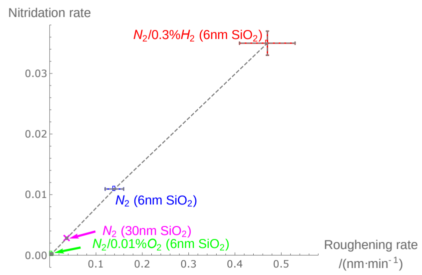

Fig.3 Relationship between early-stage nitridation rate and SiC roughening rate. The SiO_2 thickness before POA is indicated in the bracket near each data.