# Reduction of SiO<sub>2</sub>/4H-SiC Interface Defects by H<sub>2</sub>O-Post-Nitridation-Annealing

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### Abstract

The effects of H<sub>2</sub>O-annealing on SiO<sub>2</sub>/SiC interface characteristics after nitridation of thermally-oxidized interface by NO-annealing, were systematically investigated. This combination of annealing processes was found to minimize the interface state density, the near-interfacetrap density, and the fixed charge density, by tuning the annealing time.

### 1. Introduction

4H-SiC is one of the attractive materials for power device applications because of its physical properties. However, the large amount of defects at the SiO<sub>2</sub>/SiC interface limits the MOSFET channel mobility and induce a serious threshold voltage instability. Wide variety of post-oxidation annealing (POA) methods to improve interface quality have been studied. The nitridation of the interface is an effective way to remove interface defects [1] and improve the V<sub>th</sub> stability. H<sub>2</sub>Oannealing also enable us to achieve lower interface state density and higher channel mobility for both 4H-SiC Si-face [2] and C-face [3]. However, the combination of these annealing processes has not been studied well. In this study, we investigate the effect of H<sub>2</sub>O-post-nitridation-annealing on MOS interface properties of SiO<sub>2</sub>/4H-SiC, to clarify the benefit of the combined process over the conventional POA.

## 2. Experimental

4°-off axis 4H-SiC (0001) Si-face wafers covered with ntype epitaxial layer (doping density  $\sim 1 \times 10^{16}$  cm<sup>-3</sup>) were employed as the substrates. These were oxidized in dry-O<sub>2</sub> at 1300°C to grow around 30 nm-thick SiO<sub>2</sub> films. Next, these samples were annealed in NO:N<sub>2</sub>=1:2 ambient for 2 hr to introduce nitrogen to the interface (NO-POA). Some of them were further annealed in H<sub>2</sub>O:O<sub>2</sub>=9:1 ambient at 800°C for 0-8 hours (wet-PNA). Sample preparation procedures are schematically shown in Fig.1. Finally Au as top electrode on SiO<sub>2</sub> was vacuum evaporated to fabricate MOS capacitors.

XPS was performed to investigate the concentration of nitrogen introduced to the interface, after removing the whole oxide film by HF. For the capacitors, interface state density ( $D_{it}$ ) was evaluated by the conductance method, and density of near-interface-traps in oxide was evaluated by photo-CV measurement [4, 5].

#### 3. Results and Discussions

Figure 2 shows N/Si atomic ratio at the interface determined by XPS after removing oxide film. The peak areas of N1s and Si2p core-level spectra, measured with take-off angle of 90°, were employed to estimate the ratio. Though most



Fig.1 Schematics of MOS interface fabricated in this study. After nitridation of the interface by NO-POA, ultrathin SiO<sub>2</sub> (<1nm) was additionally grown in H<sub>2</sub>O+O<sub>2</sub> ambient (wet-PNA).



Fig.2 Wet-PNA time dependence of N concentration on SiC surface, indicated by N/Si atomic ratio deduced from N1s/Si2p (substrate component) XPS intensity ratio.

of the N atoms remain at the interface after wet-PNA for short time, long time annealing (8hr) to cause ~ 3ML regrowth of SiO<sub>2</sub> resulted in a significant decrease of N at the interface. This phenomena is consistent with the reported results of O<sub>2</sub> regrowth [6].

CV characteristics of the MOS capacitor fabricated with 30 min wet-PNA are shown in Fig. 3. Frequency dispersion was negligibly small, indicating low  $D_{it}$  near the conduction band edge.

Figure 4 (a) shows energy distribution of  $D_{it}$  for some samples evaluated by the conductance method. The sample w/o wet-PNA show comparable or even lower  $D_{it}$  with reported in literature [1], which mean the nitridation of the interface sufficiently proceeds with our experimental condition.

It was found that significantly lower  $D_{it}$  was obtained after wet-PNA for 30 min than that of as-nitrided sample. However, longer time of wet-PNA results in deterioration of interface, which is understandable by considering that the interface properties become similar to those formed



Fig.3 1MHz and 1kHz CV charactristics of the sample with wet-PNA for 30 min.



Fig.4 (a) Energy distribution of  $D_{it}$  observed for the samples with wet-PNA for 0 hr (circle) , 30 min (triangle), and 8 hr (diamond). The result for only wet-POA w/o nitridation is also shown for the comparison. (b) Wet-PNA time dependence of  $D_{it}$  at  $E_c$ -E=0.2eV.

only with wet oxidation (without nitridation), by applying the wet-PNA for excess time. Fig.4 (b) shows the wet-PNA time dependence of  $D_{it}$  at the energy level of  $E_C$ -E=0.2eV. Improvement of  $D_{it}$  was clearly observed only for short time annealing, where the regrown thickness of SiO<sub>2</sub> by wet-PNA was estimated within 1 ML considering its growth rate (0.11 nm/hr). It is reasonable to consider that H<sub>2</sub>O-annealing can annihilate some kinds of interface defects that nitrogen does not passivate by NO-POA. Taking account the fact that N concentration at the interface does not change significantly by short time PNA (see Fig. 2), ~1 ML regrowth by wet-PNA would be the best balanced process to take advantages of both nitrogen passivation and H<sub>2</sub>O-annealing effects.

Next, near-interface-trap density with relatively long time constant was evaluated by photo-CV measurement [5]. At first, inversion voltage was applied to the MOS capacitor and trapped electrons near the interface were expelled by photo



Fig.5 Wet-PNA time dependence of NIT areal density estimated by photo-CV measurement. The results for only wet-POA w/o nitridation are also shown for the comparison.



Fig.6 Wet-PNA time dependence of interface fixed charge density estimated by flatband voltage shift.

illumination with energy above bandgap ( $\sim$ 3.4eV). After turning-off the illumination, the hysteresis of CV curve due to charge trapping during the voltage sweep was evaluated. We estimated the areal density of NIT by,

Areal density of NIT (cm<sup>-2</sup>) = 
$$\frac{C_{ox}\Delta V_{hys}}{q}$$
 (1)

where  $C_{OX}$ ,  $\Delta V_{hys}$ , and q are capacitance of oxide film, hysteresis width, and elementary charge, respectively. Wet-PNA time dependence of NIT areal density is shown in Fig. 5. Similar to the result of  $D_{it}$ , the density of NIT reduced efficiently by wet-PNA for short time, although the optimum PNA time to minimize NIT seems a little longer than that to minimize  $D_{it}$ , which indicates that the annihilation of defects within oxide takes longer treatment than the defects at the interface.

Finally, the fixed charge density at the interface was evaluated from the flatband voltage ( $V_{FB}$ ) shift, as shown in Fig. 6. As-nitrided sample before PNA showed a negative  $V_{FB}$ shift due to positive fixed charges. After the short-time wet-PNA,  $V_{FB}$  shifts back to the value to the ideal one by reducing the interface fixed charge density, whereas the PNA for longer time results in the positive  $V_{FB}$  shift.

#### 4. Conclusions

Significant reduction of  $D_{it}$ , as well as NIT was demonstrated on 4H-SiC by short-time wet-PNA at low temperature after interface nitridation by NO. This process is also beneficial to shift the V<sub>FB</sub> closer to the ideal one by reducing fixed charges. The combination of NO-POA and wet-PNA should be one of the most advantageous process in terms of achieving the lowest density of interface defects on 4H-SiC.

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