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## Effects of nitridation and annealing on interface properties of thermally oxidized SiO<sub>2</sub>/SiC metal–oxide–semiconductor system

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The effects of N<sub>2</sub>O nitridation and subsequent annealing in different conditions on thermally oxidized *n*-type 6H–silicon carbide (SiC) metal–oxide–semiconductor (MOS) interface properties were investigated. Influence of high-field stress on the MOS system was also studied. The nitrated device annealed in dry or wet O<sub>2</sub> is found to have lower interface-state density compared to the device annealed in N<sub>2</sub> because the reoxidation can reduce nitridation-induced interface damage. Furthermore, significantly less shift of flatband voltage during high-field stress for all nitrated devices indicates much better oxide reliability by replacing strained Si–O bonds with stronger Si–N bonds during nitridation. This is further supported by the fact that annealing of the nitrated device in dry or wet oxygen slightly reduces the robustness of the oxide. In summary, the O<sub>2</sub>-annealing conditions have to be optimized to deliver a proper tradeoff between interface quality and reliability.  
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In recent years, much attention has been paid to exploit SiC's performance in high-power, high-temperature, and high-frequency electronics because of its superior properties such as wide band gap, high breakdown field, saturation drift velocity, and thermal conductivity. One of the most important advantages of SiC over other wide-band gap semiconductors is that SiC can be thermally oxidized to form an insulator SiO<sub>2</sub>. However, oxides grown on SiC with high interface-state density and a large amount of fixed charges, especially for the SiO<sub>2</sub>/*p*-SiC structure, have been reported.<sup>1,2</sup> Nitridation of oxides on SiC significantly affects *p*-type oxides, while the effects on *n*-type oxides are marginal.<sup>3</sup> In this work, the role of annealing of N<sub>2</sub>O-nitrated oxides in different ambients is investigated. Results on the effects of high-field stress on the oxides are also presented.

Si-faced *n*-type 6H–SiC wafers, manufactured by CREE Research, were used in this experiment. The SiC wafers had a 5 μm epitaxial layer grown on heavily doped substrates. The doping level of the epitaxial layer was 4 × 10<sup>15</sup> cm<sup>-3</sup>. The conventional RCA method was employed to clean the wafers. Immediately before oxidation, the wafers were dipped in 1% HF for 60 s and then loaded into an oxidation furnace at 800 °C. After raising to an oxidation temperature of 1100 °C, one sample was oxidized in a wet ambient by bubbling oxygen through de-ionized water at 95 °C for 150 min. After oxidation, the sample was then annealed in N<sub>2</sub> for 30 min (denoted as OX). The oxidation of three other samples was done under the same conditions. They were then nitrated in N<sub>2</sub>O at a flow of 250 ml/min at 1100 °C for 90 min and annealed for 30 min in N<sub>2</sub> (denoted as N2ON), dry O<sub>2</sub> (denoted as N2OD) and wet O<sub>2</sub> (denoted as N2OW), respectively. Aluminum was thermally evaporated and patterned as gate electrode of metal–oxide–semiconductor (MOS) capacitors. No postmetal annealing was performed to avoid masking the defects created during the oxidation

and/or nitridation. High-frequency (HF) capacitance–voltage (*C*–*V*) measurement was carried out using HP4284A at room temperature under dark conditions. SiO<sub>2</sub>/SiC interface properties were studied by HF *C*–*V* measurement after light illumination at deep depletion. The total deep interface states and fixed charges were estimated from a ledge feature occurring on HF *C*–*V* curves and flatband shift. High-field stress (~ 7 MV/cm), with the capacitor biased in accumulation, was used to study the device reliability.

The oxide thickness *t*<sub>ox</sub>, shown in Table I, is calculated from the HF accumulation capacitance as oxide capacitance *C*<sub>ox</sub>. It is seen that the 90 min nitridation adds a small thickness to the oxide grown during wet oxidation. The thickness is increased a bit further during subsequent annealing in wet O<sub>2</sub> while negligible change for dry O<sub>2</sub> annealing is due to lower growth rate in dry O<sub>2</sub>. The nitridation-induced oxide growth is much slower compared to the thickness of wet O<sub>2</sub>-grown oxide since an initial oxide already exists. The self-limiting growth kinetics can usually be explained by nitrogen incorporation into the oxide, which in turn blocks further oxidation of SiC substrates. This observation suggests a shorter time for nitridation at higher temperature so that more nitrogen can be incorporated before the thickness increases too much.

Figure 1 shows the HF *C*–*V* curves of all the devices under dark conditions, swept from accumulation to depletion. All nitrated devices show improved flatband voltages relative to the OX device. The nitrated device annealed in dry/wet O<sub>2</sub> shows smaller shift in flatband compared to the N2ON device. The presence of significant interface traps causes such a stretch that the *C*–*V* curve for the N2ON device cannot reach the accumulation capacitance even at 5 V. The flatband shift to the negative direction is mainly caused by real positive fixed charges. The flatband voltage *V*<sub>fb</sub> is determined from the flatband capacitance *C*<sub>fb</sub> as<sup>4</sup>

$$\frac{C_{fb}}{C_{ox}} = \left( 1 + \frac{136\sqrt{T/300}}{t_{ox}\sqrt{N_D}} \right)^{-1}, \quad (1)$$

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TABLE I. Effects of nitridation and dry/wet O<sub>2</sub> annealing on the oxide charge and interface-state density of MOS capacitor on 6H-SiC.

Growth condition	Wet O <sub>2</sub> and N <sub>2</sub> anneal	Wet O <sub>2</sub> , N <sub>2</sub> O nitridation and N <sub>2</sub> anneal	Wet O <sub>2</sub> , N <sub>2</sub> O nitridation and dry O <sub>2</sub> anneal	Wet O <sub>2</sub> , N <sub>2</sub> O nitridation and wet O <sub>2</sub> anneal
$t_{\text{ox}}$ (Å)	393	407	406	410
$C_{\text{fb}}/C_{\text{ox}}$	0.64	0.65	0.65	0.65
$V_{\text{fb}}$ (V)	-3.53	0.56	-0.69	-0.52
$Q_{\text{ox}}$ ( $\times 10^{12}$ cm <sup>-2</sup> )	2.66	-0.49	0.74	0.51
$D_{\text{it}}$ ( $\times 10^{11}$ eV <sup>-1</sup> cm <sup>-2</sup> )	1.82	3.32	1.79	2.50

where  $N_D$  and  $T$  are the donor doping density and temperature (K), respectively. The improved flatband shift for all the nitrided samples indicates reduction of positive fixed charge in the oxide during the N<sub>2</sub>O nitridation. The  $C-V$  curves for N2OD and N2OW devices are closer to the ideal  $C-V$  characteristics because reoxidation can improve the interface quality of nitrided devices. The oxide-charge density is estimated using the following relation:

$$Q_{\text{ox}} = -C_{\text{ox}} \left( \frac{V_{\text{fb}} - \phi_{\text{ms}}}{q} \right), \quad (2)$$

where  $\phi_{\text{ms}}$ , the work function between aluminum and 6H-SiC, is calculated to be 0.031 V for  $n$ -type SiC. The value of  $Q_{\text{ox}}$  of all the devices is indicated in Table I.

The shift in flatband voltage  $\Delta V_{\text{fb}}$  of all samples during high-field stress ( $\sim 7$  MV/cm) is shown in Fig. 2. The positive  $\Delta V_{\text{fb}}$  for N2ON indicates generation of acceptor-type interface states and negative oxide charge. A much smaller  $\Delta V_{\text{fb}}$  for the N2ON device indicates significantly suppressed generation of interface states and oxide traps. From the maximum  $\Delta V_{\text{fb}}$  at 5000 s stress time, and increases of effective

oxide charge,  $Q_{\text{ox}}$  is estimated to be  $4.0 \times 10^{11}$ ,  $-5.4 \times 10^{11}$ ,  $4.2 \times 10^{11}$ , and  $0.9 \times 10^{11}$  cm<sup>-2</sup> for OX, N2ON, N2OD, and N2OW, respectively. The N2OD and N2OW devices exhibit slightly poorer reliability as compared to N2ON because the dry/wet O<sub>2</sub> annealing reduces the nitrogen content and hence strong Si-N bonds in the oxide, and consequently reduces the robustness of the oxides.

The interface-state density  $D_{\text{it}}$  estimated for all the devices is presented in Table I. An increase in  $D_{\text{it}}$  for the N<sub>2</sub>O-nitrided device means deteriorated interface quality of thermally grown oxide on the  $n$ -type SiC substrate due to the fact that nitridation roughens the interface.<sup>3</sup> The interface quality is found to recover after dry/wet O<sub>2</sub> annealing for N2OD and N2OW devices because reoxidation can partially repair the damaged interface.

In conclusion, results are presented on the effects of dry and wet O<sub>2</sub> annealings on the interface properties of nitrided oxides on  $n$ -type SiC. The results show that nitridation deteriorates the interface quality, while subsequent O<sub>2</sub> annealing (especially in dry O<sub>2</sub>) can repair the interface. The reliability of the O<sub>2</sub>-annealed nitrided oxides is slightly reduced due to

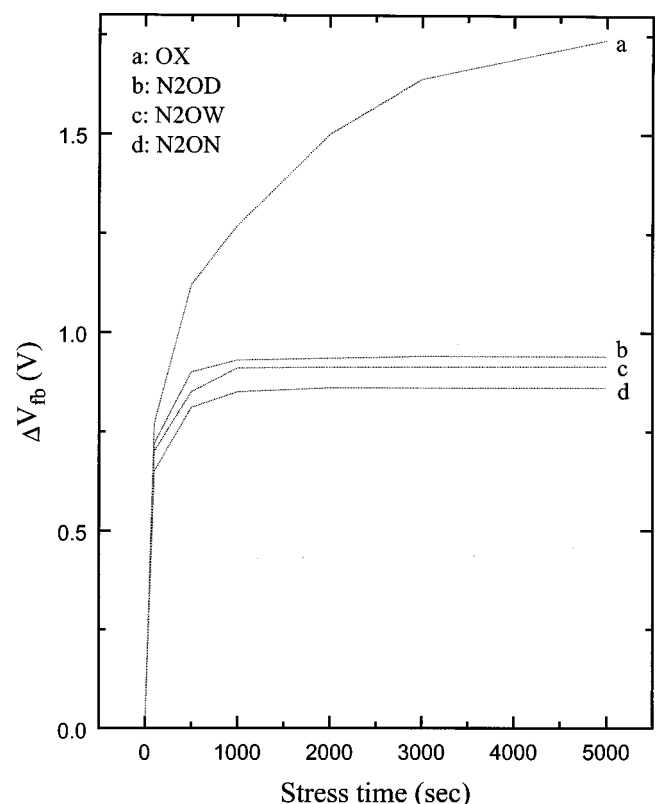
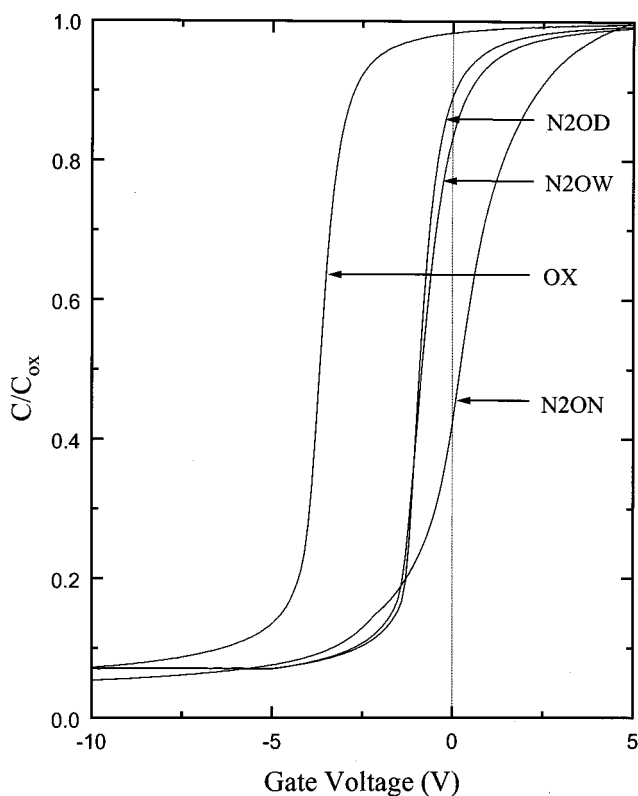
FIG. 1. High-frequency  $C-V$  measurements of MOS capacitors on SiC.

FIG. 2. Flatband voltage shifts under high-field stress at room temperature.

a decrease of nitrogen content during annealing. Therefore, an optimal condition is required for O<sub>2</sub> annealing to provide a good compromise between interface quality and reliability.

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