Fabrication of MOS Capacitors by Wet Oxidation of p-type 4H-SiC Preamorphized by Nitrogen Ion Implantation

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Abstract. 4H-SiC p-type MOS capacitors fabricated by wet oxidation of SiC preamorphized by nitrogen ion (N^+) implantation have been investigated. The oxidation rate of the SiC layer preamorphized by high-dose N^+ was much larger than that of crystalline SiC, allowing us to reduce the fabrication time of SiC MOS devices. We found that the presence of the surface amorphous SiC layer before the oxidation process did not influence the interface state density in MOS capacitors. Moreover, the shift of the flat-band voltage is not correlated to the amount of nitrogen in the oxide. On the contrary the density of interface states near the valence band edge increased according with the high concentration of the implanted N at the oxide–SiC interface, as in the case of dry oxidation reported by Ciobanu *et al.* The generation of positive charges due to the nitrogen embedded inside the oxide layer was smaller compared with dry oxidation. We discuss the difference between wet and dry oxidation for MOS capacitors fabricated with N^+ implantation.

Introduction

SiC is the only wide band-gap semiconductor whose native thermal oxide is SiO_2. This feature places SiC in an advantageous position for MOS-based power device applications. However, the electrical characteristics of SiC MOSFETs are at present poorer than those predicted from the physical properties of SiC. In particular, on-resistance is one or two orders higher than theoretically predicted value. It has been considered that this high on-resistance is due to the low channel mobility at the inversion layer, attributed to the high interface state density (D_{it}) [1]. It has been reported that wet or pyrogenic oxidation reduces the D_{it} values [2, 3]. As another approach, thermal nitridation of oxide-SiC interfaces in NO or N_2O ambient is reported to be effective in reducing interface states [4]. As an alternate method of nitridation, Ciobanu *et al.* have employed nitrogen ion (N^+) implantation of SiC prior to dry oxidation, by which the D_{it} values for n-type MOS capacitors reduced dramatically, especially at the energy level near the conduction band edge [5]. However, in the case of p-type MOS capacitors, the D_{it} values increased [6]. These facts forecast that the further reduction of interface state density might be achieved if n-type MOS structures are fabricated by wet oxidation of N^+ implantation layer.

Another negative feature of SiC based MOS technology is the low oxidation rate of SiC that requires a high oxidation temperature or/and a long oxidation time to grow a gate oxide layer on SiC. We have reported that the SiC layer pre-amorphized by a high-dose ion-implantation has a high oxidation rate, allowing us the reduction of the fabrication time of SiC MOS devices [7, 8].

In this work, we have fabricated p-type MOS capacitors by wet oxidation on SiC layer preamorphized by a high-dose implantation to examine whether wet oxidation is useful for MOS capacitors fabricated with N^+ implantation, or not. We have also examined the influence of the amorphous phase, produced by ion-implantation, on the electrical characteristic.

Experiments

A p-type 4H-SiC homoepitaxial wafer with 8° off-axis (epilayer thickness = 6 μm, epilayer doping $|N_d - N_a| = 2 \times 10^{15}$ cm^{-3}) was employed for this study. We cut the wafer into four pieces, denoted as sample #1 to #4. An un-implanted sample (#1) was prepared for comparison. Samples #2 and #3 were implanted with energy of 10 keV and doses of 1.5×10^{13} cm^{-2} and with 2.5 keV and 1.0×10^{15} cm^{-2}, respectively. Sample #4 was implanted with 2.5 keV and 5.0×10^{14} cm^{-2}, followed by implantation with 5 keV and 5.0×10^{14} cm^{-2}. The nitrogen depth profiles in the implanted samples were computed by a simulation based on a Pearson IV distribution [9]. Rutherford back scattering spectroscopic measurements (not reported here) were used to evaluate the presence of an amorphous SiC layer in the as-implanted samples. Only the samples #3 and #4 show an amorphous SiC layer respectively up to around 9.5 and 11.5 nm from the surface. We carried out the wet oxidations for samples #1 and #2 at temperature of 1100°C for 8 hours, and the wet oxidation for samples #3 and #4 in two steps: first at 850°C for 30 minutes and then at 1100°C for 6 hours. In the latter process, because the crystalline SiC is hardly oxidized at temperature of 850°C, only the amorphous layers were oxidized in the first step. Taking into account that the thickness of the consumed SiC layers during oxidations is around 28 nm, only the samples #2 and #4 should have N concentrations larger than 10^{17} cm^{-3} at the oxide–SiC interfaces. The preparation condition of these samples, as well as the oxide thicknesses (T_{ox}), the thicknesses of the consumed SiC layer during oxidation (T_{con}), N concentration at the oxide–SiC interface (N_{inter}), and total number of N inside the oxide film (N_{total}), are summarized in Tab. 1.

High-frequency (HF) and Quasi-static (QS) capacitance to voltage (C–V) characteristics at room temperature were measured by use of a simultaneous capture system. HF measurements were carried out at 100 kHz with small amplitude (15 mV). QS characteristics were measured

Sample	E_{impl} (keV)	N_{impl} ($\times 10^{14}$ cm^{-2})	T_{ox}/T_{con} (nm)	N_{inter} (cm^{-3})	N_{total} (cm^{-2})	V_{fb} (V)	N_{eff} ($\times 10^{12}$ cm^{-2})
#1	-	-	64 / 30	~ 0	~ 0	-7.84	1.9
#2	10	0.15	57 /27	2.4×10^{18}	1.4×10^{13}	-14.38	4.6
#3	2.5	10	59 / 28	~ 0	1.0×10^{15}	-7.92	2.1
#4	2.5, 5.0	5.0, 5.0	57 / 27	1.3×10^{17}	1.0×10^{15}	-14.20	4.5

Table 1: Energy of ion implantation E_{impl}, dose of implantation N_{impl}, oxide thickness and thickness of consumed SiC layer during oxidation T_{ox}/T_{con}, N concentration at the oxide–SiC interface N_{inter}, total number of N inside the oxide film N_{total}, flat-band voltage (V_{fb}), and effective oxide charge density normalized by elementary charge N_{eff}, for samples #1 –#4.
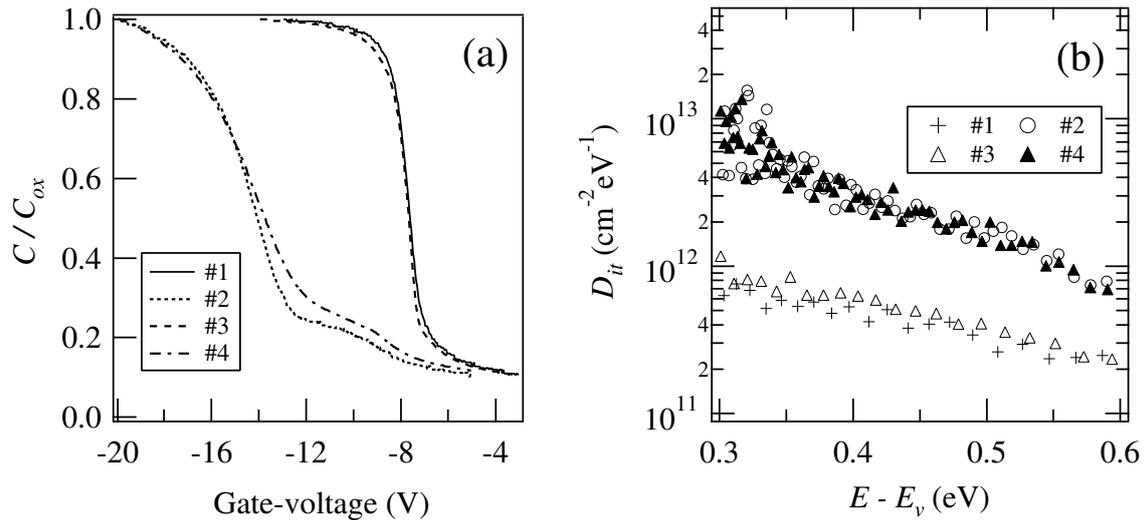
Fig. 1: HF C–V curves (a) and energy distributions of interface states (D_{it}) (b) for 4 samples #1–#4.

with delay time of 0.1 sec using a voltage step of 20 mV. The gate-voltage was swept from accumulation to depletion side. The D_{it} values were estimated by use of Hi-Lo method.

Results and Discussion

Figures 1(a) and (b) show the HF C–V curves and the D_{it} distributions, respectively, for the four samples. The values of flat-band voltage (V_{fb}) and effective oxide charge density normalized by elementary charge (N_{eff}) were evaluated from the C–V curves reported in Fig. 1(a) and are shown in Table 1. As seen in the table, the values of V_{fb} and N_{eff} for sample #1 and #3, and those for sample #2 and #4 are similar to each other. The D_{it} values near the valence band edge for samples #2 and #4 are larger than those for samples #1 and #3. As the values of V_{fb} and N_{eff}, the D_{it} distributions of sample #1 and #3, and those of sample #2 and #4 are almost identical with each other. Therefore, only the nitrogen implanted near the oxide–SiC interface is effective for controlling the interface state density and the presence of amorphous layer does not affect the magnitude of D_{it}. This fact suggests that we can obtain a high-oxidation rate of SiC, i.e. the reduction of the fabrication time of SiC MOS devices, without spoiling the electrical characteristics.

The D_{it} values for wet oxidation increased with increasing the N concentration at the interface, as in the case of dry oxidation [10]. The negative shift of V_{fb} with respect to the theoretical value increases according with the presence of nitrogen at the SiO$_2$–SiC interface, however, there is no evidence of a correlation with the amount of the nitrogen embedded inside the oxide layer. The latter result is supported also by the experimental results obtained from n-type samples [11]. The N implanted samples oxidized in wet ambient show a reduced shift of V_{fb} compared with the dry oxidized ones. We considered that the reason why wet oxidation does not bring about the large shift of V_{fb} is that hydrogen species, such as –H and –OH, in the wet atmosphere deactivate the excess N inside the oxide.

The results summarized in Table 1 indicate that the value of V_{fb} (or N_{eff}) is not proportional to the N concentration embedded in the oxide before oxidation (N_{total}), unlikely in the case of dry oxidation [10]. Moreover, the N_{eff} value hardly changes with the change in N_{total} value. According with the results for n-type reported in Ref. [11], the value of N_{eff} decreases with increasing the N_{total} value. Therefore, these facts suggest that the large negative shift of V_{fb} only seen in the case of p-type is attributed to the states at deep energy level rather than the oxide-fixed trap charges.

Conclusion

4H-SiC p-type MOS capacitors fabricated by wet oxidation of SiC preamorphized by nitrogen ion implantation have been investigated. The presence of the SiC layer preamorphized by high-dose N^+ did not influence the interface state density. As a consequence of the high-dose nitrogen implantation at the SiO_2–SiC interface, though the shift of V_{fb} with respect to the theoretical value was smaller compared with the case of dry oxidation, the density of interface states near the valence band edge increased. By comparing with n-type samples, the large V_{fb} observed in the p-type sample with N^+ implantation can be attributed to the states at deep energy level.

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