PAPER *Special Section on Nanomaterials and Nanodevices for Nanoscience and Nanotechnology*

Interface State Density between Direct Nitridation Layer and SiC Estimated from Current Voltage Characteristics of MIS Schottky Diode

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SUMMARY Interface state density was estimated from diode factor n of SiC MIS Schottky diode. The interface state density was the order of 10^{12} cm^{-2}eV^{-1}, and was same order to the value for the sample carefully prepared by oxidation and post oxidation annealing. The interface state density determined from n was consistent to the value calculated from the capacitance voltage curve of SiO_2/nitride/SiC MIS diode by Terman method. High temperature nitridation was effective to reduce the interface state density.

key words: *SiC, nitride, interface, MIS Schottky*

1. Introduction

An advantage of SiC over other wide band gap semiconductor is the silicon dioxide that can be formed on SiC by the conventional oxidation process. The high density of states has been detected at the SiO_2/4H-SiC interface with energy levels near the SiC conduction band edge. These traps are believed to be responsible for low inversion channel mobility in n-channel metal-oxide semiconductor field effect transistors (MOSFETs). The post oxidation annealing in NO or N_2O ambient has been the most common method to reduce the density of interface states [1]. It was reported that the pileup of nitrogen at the interface was held responsible for passivation of interface states [2].

Nitride is another candidate for the insulating layer of SiC MIS devices. Few papers have reported about nitridation of SiC surface. We have tried to form an insulating nitride layer on SiC by direct nitridation [3], [4]. Chai et al reported a Si_3N_4 passivation layer grown on the 4H-SiC (0001) surface by direct atomic source nitridation at various substrate temperatures [5]. Although the direct nitridation seemed to be an attractive method to form insulating layer on SiC, it has been difficult to get the nitride layer thicker than several nm by direct nitridation method [3]–[5].

The plasma-assisted method was used to increase the thickness of nitride layer on SiC. Although plasma assistance was effective to increase the thickness, the thickness of the nitride layer was not enough to evaluate the interface state density by Terman method. In this paper, the current voltage characteristics of the samples were measured to estimate the interface state density at the interface between nitride layer and SiC substrate.

Manuscript received February 27, 2009.
Manuscript revised July 22, 2009.
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DOI: 10.1587/transele.E92.C.1470

2. Experimemtal

The substrate was Si face of 4H-SiC from Cree Research. The resistivity was about 0.1 Ωcm. The surface of the substrate was etched by HF solution before nitridation. Figure 1 shows the nitridation chamber for thermal nitridation. The substrate holder was made from graphite. The substrate holder was heated by inductively coupled RF power of 80 kHz up to 1600°C. The substrate temperature was measured by using an optical thermometer. The reaction gas was a mixture of NH_3(50%) and N_2(50%). Another induction coil was set at 5 cm above the heating coil to excite RF grow discharge for plasma nitridation. The grow discharge was excited by RF power of 13.56 MHz to form plasma nitridation layer on SiC substrate.

Ni was deposited on the back surface and annealed at 1000°C for 5 min to form ohmic contact. Al was used as a gate electrode of Schottky contact. The shape of the gate electrode was a circle of 0.5 mm in diameter. The interfacial layer was thin enough for electrons to be transported though the interfacial by tunneling. In this paper, these diodes were called as MIS Schottky diode.

The nitride layer was characterized by using XPS. Cur-

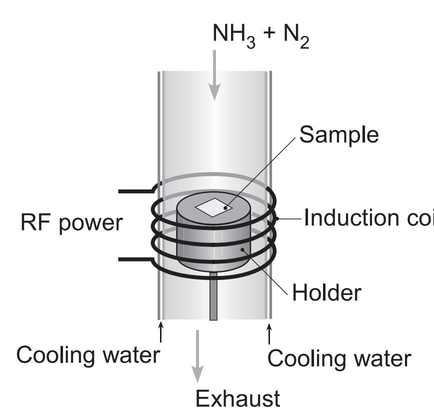

Fig. 1 Schematic representation of nitridatoin chamber. RF coil for exciting grow discharge was set 5 cm above the induction coil.

rent voltage characteristics of SiC MIS Schottky diode were measured to evaluate the interface property between the nitride layer and SiC surface.

3. Results and Discussions

The surface of the sample was characterized by using XPS. Figure 2 shows a typical XPS spectra of the SiC surface nitrided at 1000°C for 60 min with RF power of 15 W. Peaks from oxygen and nitrogen indicated that the surface layer consisted of nitride and oxinitride. The origin of oxygen was not identified, but was supposed to be from residual oxygen, because the background pressure of the reaction chamber was the order of 10^{-3} Torr. The oxidation could not be eliminated from the surface reaction, though the system was carefully purged with pure N_2 for several times.

The cross section of the sample was observed by high-resolution transmission electron microscope (TEM). An amorphous layer was detected on SiC surface. The thickness of the layer was about 2 nm. The results of XPS and TEM measurement indicated that a thin nitride layer or oxinitride layer was formed on SiC surface by direct nitridation.

Figure 3 shows the cross section image of SiC observed by high-resolution TEM. Surface nitride layer was formed at 1400°C for 60 min under plasma assistance. The plasma was excited by RF power of 70 W. Thin amorphous layer was observed at the top of SiC substrate. The figure shows that the thickness of the surface layer was about 2 nm.

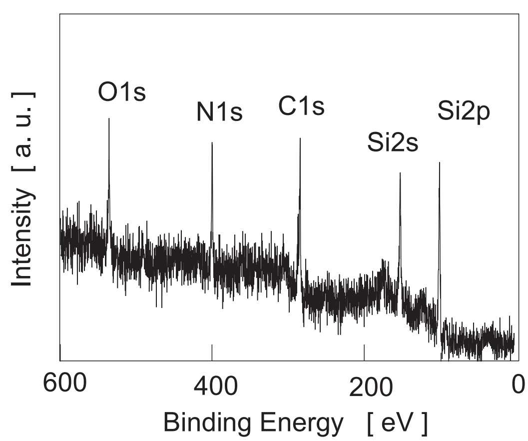

Fig. 2 XPS spectra of SiC surface after nitridation at 1000°C for 60 min. under grow discharge excited with RF power of 15 W.

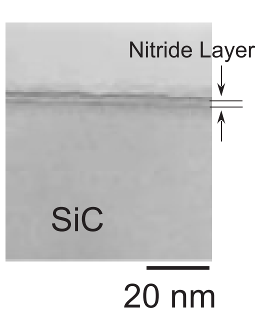

Fig. 3 Cross section TEM image of SiC surface. Nitridation was carried out at 1400°C for 60 min under plasma assistance. The RF power was 70 W.

Figure 4 shows the capacitance voltage curves of the samples with insulating layers formed by direct nitridation. The nitridation was carried out at 1400°C for 60 min with and without plasma assistance. The RF power of 70 W was used to excite grow discharge. The accumulation condition was not observed in the capacitance voltage curves shown in Fig. 4. The capacitance decreased with increasing voltage in the region corresponding to accumulation condition. The leakage current though the nitride layer resulted in this decrease in accumulation capacitance, because the thickness of the nitride layer was several nm and was thin enough for electrons to be transported by tunneling. The curves in Fig. 4 indicated that the samples were not MIS but MIS Schottky diodes.

The difference in depletion capacitance was seemed to be caused from the difference in the donor concentration of substrates.

The thickness of the nitride layer could not be determined from the capacitance voltage curves, because the accumulation capacitance could not be specified form the curves as shown in Fig. 4.

Figure 5 shows the forward current voltage characteristics of the SiC MIS Schottky diodes. Nitridation was carried out at 1400°C for 60 min under plasma assistance. The RF power was 70 W. The diode factor n is related to interface state density D_{it} [6].

Current density J of MIS Schottky diode with thin interfacial layer is,

$$J = J_0 e^{-\beta qV/kT} \left(e^{qV/kT} - 1 \right) \tag{1}$$

where J_0 is reverse saturation current density and V is applied voltage. The factor β is

$$\beta = 1 - \frac{1}{n} \tag{2}$$

where n is diode factor (or ideality factor). When the interfacial layer was thin enough, the diode factor n is related to

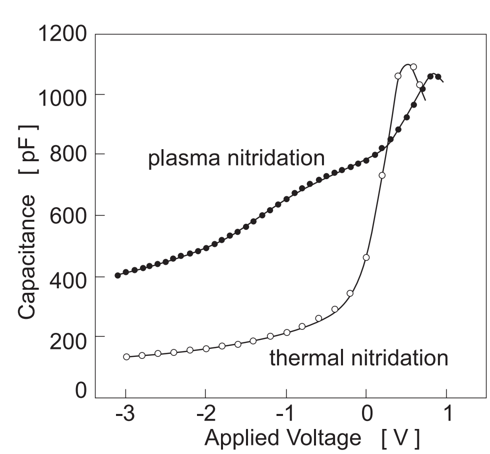

Fig. 4 Capacitance voltage characteristics of SiC MIS Schottky diode at 1 MHz.

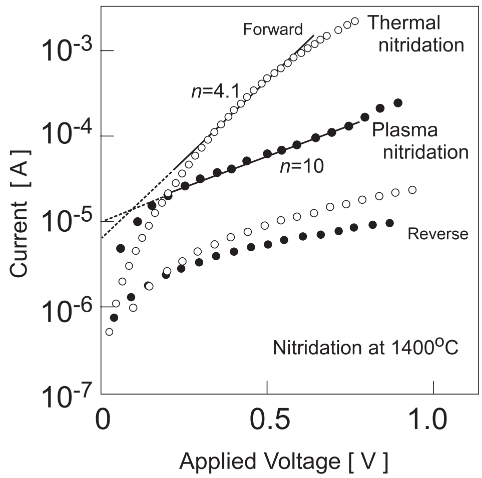

Fig. 5 Forward current voltage characteristics of SiC MIS Schottky diode.

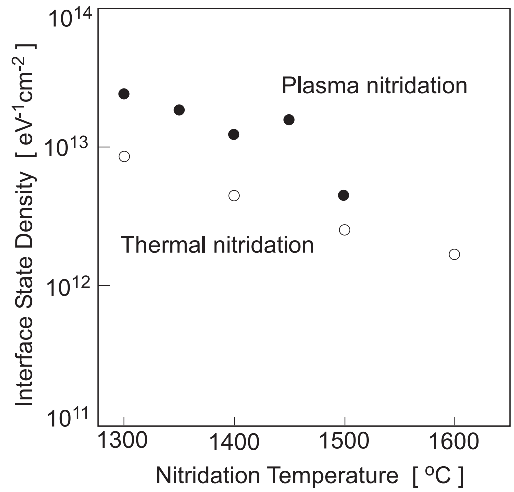

Fig. 6 Interface state density determined from diode factor n.

Table 1 Device parameters of SiC MIS Schottky diodes.

Nitridation	T_{sub}[°C]	n	J_0 [A/m^2]
Thermal	1300	7.1	1.2×10^2
	1400	4.1	3.2×10^1
	1500	2.8	1.6×10^0
	1600	2.1	1.9×10^0
Plasma	1300	18	2.6×10^2
	1350	14	5.2×10^0
	1400	10	5.1×10^1
	1450	12	1.3×10^1
	1500	4.1	6.6×10^{-2}

interface state density as,

$$\frac{1}{n} = \frac{\epsilon_i}{\epsilon_i + q^2\delta D_{it}} \tag{3}$$

where ϵ_i and δ are permittivity and thickness of interfacial layer.

Table 1 lists diode factor n and reverse saturation current density J_0. The large value of n indicated the high interface state density. The reverse saturation current density was determined by extrapolating the linear line of log J vs. V curve around V = 0.4 V, where the diode factor n was determined. This seemed to result in overestimation of J_0, as shown in Fig. 5.

The interface state density D_{it} was estimated from diode factor n obtained from current voltage characteristics of SiC MIS Schottky diode using Eq. (3). The permittivity of such a thin layer may be well approximated by the free-space value [6]. This approximation may lead to an underestimation of interface state density. To avoid this underestimation, the permittivity of interface layer was assumed to be 7.5, which is the value of amorphous Si_3N_4.

Figure 6 shows the relation between interface state density and nitridation temperature. The interface state density was estimated from diode factor n. The value of 2 nm was used as the thickness of the interfacial insulating layer, because the cross section TEM observation indicated that the thickness of the interface layer was about 2 nm. Some samples might have thicker interface layer than 2 nm, and this might result in overestimation of the interface state density.

The interface state density decreased with increasing nitridation temperature. The XPS measurement showed that the atomic concentration of nitrogen increased with increasing nitridation temperature. This indicates that the thickness of the interfacial layer increased with increasing nitridation temperature, and that the value of interface state density at high nitridation temperature might be overestimated because the thickness of the interfacial layer might be thicker than 2 nm.

The plasma assisted nitridation resulted in increase of interface state density as compared to thermal nitridation without plasma assistance. The SiC surface seemed to be damaged by charged particles during plasma assisted nitridation.

In order to discuss the validity of the above estimation, SiO_2 layer was deposited on nitride layer to form MIS capacitor with insulating layer of enough thickness to estimate the interface state density by Terman method. Figure 7 shows the capacitance voltage curve of SiO_2/nitride/SiC MIS diode. The interfacial nitride layer was formed at 1400°C for 60 min with RF power of 70 W. The SiO_2 layer was deposited by CVD method at 750°C using tetraethylorthosilicate (TEOS) as a source material.

Interface state density was estimated from this curve by Terman method. Figure 8 shows the interface state density determined from Fig. 7.

The barrier height of MIS Schottky diode was about 0.6 eV and the diode factor n was estimated from the linear region of current voltage plot, where the applied voltage was around 0.4 V. This means that the interface state density determined from diode factor was the value around the energy level of 0.2 eV below the conduction band edge. As shown in Fig. 8, the value of interface state density was about 10^{13} eV^{-1}cm^{-2} at about 0.2 eV below conduction band edge, and was almost same to the value determined from current

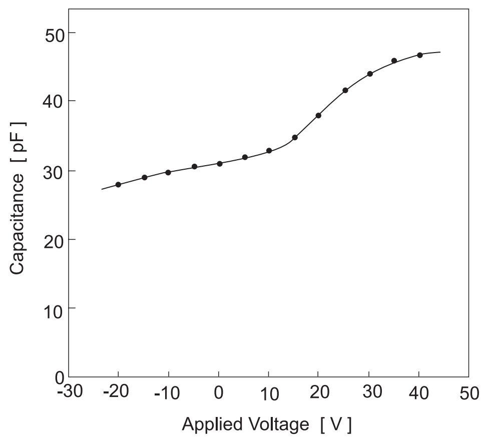

Fig. 7 Capacitance voltage characteristics of SiO_2/nitride/SiC MIS diode.

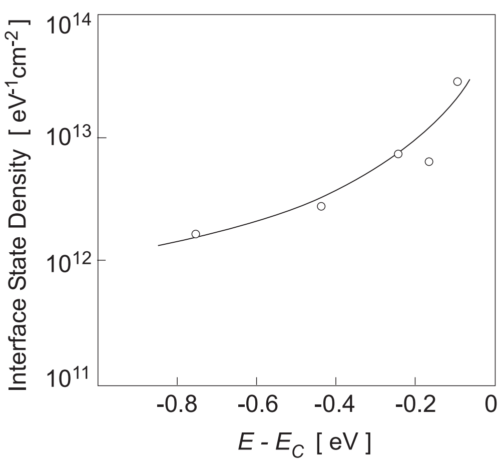

Fig. 8 Capacitance voltage characteristics of SiC MIS Schottky diode.

voltage curve. This means that it is possible to estimate the value of the interface state density from current voltage characteristics.

The most common method to reduce the density of near interface traps is the use of oxidation and post oxidation annealing in NO or N_2O ambient. These process resulted in the interface state density of 10^{12} $eV^{-1}cm^{-2}$, or less, at about 0.2 eV below conduction band edge [7]. The values shown in Fig. 6 indicated that the direct nitridation might be one of the promising methods to obtain high quality interface between SiC and insulating layer.

4. Conclusion

Interface state density was estimated from current voltage characteristics of SiC MIS Schottky diode. The value was consistent to that determined from capacitance voltage curve of SiO_2/nitride/SiC MIS diode by Terman method. The interface state density was the order of 10^{12} cm^{-2} eV^{-1}, and was same order to the value for the sample carefully prepared by oxidation and post oxidation annealing. The direct nitridation is one of the promising methods to obtain high quality interface between SiC and insulating layer.

Acknowledgment

The authors with to thank Mr. Yoshiki Ishida for carrying out the measurements and discussions.

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