Effects of Al ion implantation to 4H-SiC on the specific contact resistance of TiAl-based contact materials

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Abstract

To realize high-performance silicon carbide (SiC) power devices, low-resistance ohmic contacts to p-type SiC must be developed. To reduce the ohmic contact resistance, reduction of the barrier height at metal/SiC interfaces or increase in the doping concentration in the SiC substrates is needed. Since the reduction of barrier height is extremely difficult, the increase in the Al doping concentration in 4H-SiC by an ion-implantation technique was challenged. The Ti/Al and Ni/Ti/Al metals (where a slash “/” sign indicates the deposition sequence) were deposited on the Al ion-implanted SiC substrates. By comparing the experimental and theoretical contact resistances, the current transport mechanism through the metal/SiC interfaces was concluded to be thermionic field emission and the barrier height was determined to be ~0.4 eV. Although the hole concentration increased with increasing the Al doping concentration in 4H-SiC, the barrier height at metal/SiC interfaces increased due to high density of dislocation loops observed in the implanted SiC layers by transmission electron microscopy. The present experiments suggested that the low-resistance ohmic contacts would be formed when a technique to eliminate the crystal defects formed in the 4H-SiC substrates after ion implantation was developed.

Keywords: Ohmic contacts; Specific contact resistance; Ti₃SiC₂; Al ion implantation; 4H-SiC

1. Introduction

Silicon carbide (SiC) is one of the most attractive compound semiconductors for high-power electronic devices. The semiconductor properties of SiC superior to conventional Si are a high thermal conductivity, high electric field breakdown strengths and a high saturation electron velocity. However, doping of carriers to SiC at high concentration by the conventional diffusion techniques cannot be used for SiC due to solubility limits of third elements and small diffusivity of impurities [1], and thus doping carriers by an ion-implantation technique is the only technique to dope heavily with carriers in SiC. Al doping using the hot-implantation technique was reported to be the best technique for p-type SiC [2]. However, the sheet resistance of the SiC layers was high in the range of 5–10 kΩ/□ by this [3]. However, the values of specific contact resistance, ρc, to the implanted p-type SiC were relatively low [4–7]. Thus, a current transport mechanism between metal/implanted SiC interface is not clearly understood. In our previous paper [8], we reported that the lower ρc values of the p-type 4H-SiC layers using Ti/Al and Ni/Ti/Al contacts were due to the formation of Ti₃SiC₂ layers at the interfaces between the as-deposited Ti/Al or Ni/Ti/Al metals and p-type 4H-SiC layers.

In the present experiment, we studied the contact properties of the Ti/Al and Ni/Ti/Al contacts to the p-type SiC layers which were prepared by ion implantation by measuring the sheet resistance and hole carrier concentration of the implanted SiC layers. Also, microstructure of the SiC layers such as lattice defects and their density were observed. Correlating the electrical properties and microstructure, we discussed the effects of the Al ion implantation on the ρc values and proposed a current transport mechanism through the metal/implanted layers.

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2. Experimental procedures

The 4H-SiC wafers with 4μm-thick n-type epitaxial layers with doping concentration of $1.1 \times 10^{16}$ cm$^{-3}$ grown on a n$^+$-type substrate supplied by Cree Research, Inc. were used as the substrates. The wafers were implanted with Al ions on the whole surface at room temperature (RT) or 600 ºC using multiple energies with a dose of $1 \times 10^{13}$ cm$^{-2}$ to form box shape dopant profiles of about 0.4 μm. These wafers were annealed at 1700 ºC for 10 min in Ar atmosphere. Secondary ion mass spectrometry (SIMS) doping profiles of the 4H-SiC samples implanted with the Al ions after annealing are shown in Fig. 1. Two Al concentrations of $1 \times 10^{19}$ and $3 \times 10^{19}$ cm$^{-3}$ were observed for samples implanted at both the low and high temperatures. These four p-type 4H-SiC samples were used in the present experiments as the substrates. Also, the 4H-SiC samples with 4μm-thick p-type epitaxial layers doped with Al at $1 \times 10^{19}$ cm$^{-3}$ (manufactured by Cree Research, Inc.) were used for comparison.

For the electrical measurements, a specific pattern was prepared by a lift-off technique on the $8 \times 8$ mm$^2$ substrates as shown in Fig. 2. The four square electrodes (1 mm$^2$) at the corner of the substrate were prepared for the sheet resistance and hall coefficient measurements of the SiC substrates. For the I–V characteristic measurements, the four TLM (transmission line model) patterns were prepared between the two square electrodes (as shown in the figure) with interspacings between the adjacent electrodes of 1.4, 3, 7, 11, 15, 18 and 25 μm. The $\rho_c$ values were measured by a two-point probe method using the TLM pattern. The sheet resistance and hall coefficients of the substrates were measured by the van der Pauw method.

We prepared two contact metals of Ti/Al and Ni/Ti/Al by an evaporation technique, where a slash “/” sign means the deposition sequence. The thicknesses of the Ti/Al and Ni/Ti/Al layers were 50 nm/190 nm and 35 nm/50 nm/300 nm, respectively. The Ni, Ti, Al layers with high purities were deposited sequentially on the substrates in a high-vacuum chamber with base pressure below $6.7 \times 10^{-6}$ Pa. The pressure during deposition was lower than $1.3 \times 10^{-4}$ Pa. The Ni and Ti were evaporated using electron beam and the Al was evaporated by a resistance heater. The Ti/Al and Ni/Ti/Al metals were annealed at 1000 and 800 ºC, respectively, in an ultra-high vacuum chamber where the vacuum pressure was below $1.3 \times 10^{-7}$ Pa and the TiAl-based contacts for the p-type 4H-SiC were prepared. Microstructure of the contacts and substrates was analyzed using X-ray diffraction method and a transmission electron microscope (TEM).

3. Results and discussion

3.1. Electrical properties of 4H-SiC substrates implanted with Al ions

Prior to investigate the effects of the Al ion implantation on the contact resistivity of TiAl-based contacts for p-type 4H-SiC-implanted layers, the electrical properties of the Al ion-implanted layers were investigated. Fig. 3(a) shows sheet resistances of the SiC layers with various carrier concentrations and together with those of the p-type 4H-SiC epitaxial layers (for comparison) as a function of Al doping concentration. The values of the sheet resistance

Fig. 1. SIMS doping profiles obtained after annealing on the 4H-SiC layers implanted at (a) room temperature (RT) and (b) 600 ºC.

Fig. 2. Schematic illustration of the specific electrode pattern prepared on the 4H-SiC implanted or epitaxial layers with an area of $8 \times 8$ mm$^2$. Four square electrodes (1 mm$^2$) deposited on each corner of the layers for sheet resistance and Hall coefficient measurements. For I–V characteristic measurements, the four TLM (transmission line model) patterns were deposited between the adjacent square electrodes. The TLM pattern consists of multiple rectangular electrodes with the interspacings of 1.4, 3, 7, 11, 15, 18 and 25 μm.
are about 12–17 kΩ/□ for the implanted layers with the Al doping concentration of 1 × 10¹⁹ cm⁻³, which are 30 times higher than that of the epitaxial layers with the same Al doping concentration (430–500 Ω/□), as shown in Fig. 3(a). The sheet resistances of the implanted layers tend to decrease with increasing Al doping concentration. The implantation temperature did not significantly influence on the sheet resistances.

The hole carrier concentrations are about 5 × 10¹⁷ cm⁻³ for the implanted layers with the Al doping concentration of 1 × 10¹⁹ cm⁻³, and the activation efficiency was about one order of magnitude smaller than that of the epitaxial layer with the same Al doping concentration (2–3 × 10¹⁸ cm⁻³), as shown in Fig. 3(b). This indicates that most of the implanted Al ions were not electrically activated to provide high hole carriers, i.e., lower activation of the implanted Al ions. The hole concentration of the implanted layers tend to increase with increasing Al doping concentration. The reduction of sheet resistance is due to increase of the hole concentration. The implantation temperature did not have a strong influence on the hole carrier concentration.

The Al ion implantation to the 4H-SiC substrates would give damage in the implanted layers, although these substrates were annealed at high temperatures. Fig. 4 shows cross-sectional TEM images of the implanted layers. All the implanted layers show many dark spot contrasts which are not observed in n-type 4H SiC substrates below the implanted layers. The thickness of the implanted layers is about 400 nm, which is consistent with the SIMS results of Fig. 1. The many dark spot contrasts correspond dislocation loops and other lattice defects were not observed in all the implanted layers. Their density increases significantly with increasing Al doping concentration and with decreasing the implantation temperature. Thus, the dislocation loop density is the highest in the layers implanted at RT with the Al doping concentration of 3 × 10¹⁹ cm⁻³ (Fig. 4(d)). The formation of the dislocation loops results in the high sheet resistance and low hole concentration in the implanted layers. However, such an increase of the dislocation loop density with increase in the Al doping concentration and decrease in the implantation temperature did not have a strong influence on the sheet resistance and the hole concentrations in the implanted layers.

### 3.2. Specific contact resistances of TiAl-based contacts on the 4H-SiC layers implanted with Al ions

The Ti/Al and Ni/Ti/Al contacts deposited on the implanted layers were annealed at 1000 and 800 °C, respectively. The Ti₃SiC₂ layers were observed to form on the implanted layers through reaction between the contact metals and implanted 4H-SiC as observed in our previous experiments [8]. The TiAl-based contacts showed ohmic behavior for all the implanted layers, except the 4H-SiC layers implanted at RT with the Al doping concentration of 3 × 10¹⁹ cm⁻³. The ρc values of the TiAl-based layers for the implanted and epitaxial SiC layers are shown in Fig. 5. The ρc values of the Ti/Al contact are about 8–20 × 10⁻⁴ Ω cm² for the implanted layers with the Al doping concentration of 1 × 10¹⁹ cm⁻³, which are higher than that for the epitaxial layers with the same Al doping concentration (2.5 × 10⁻⁴ Ω cm²), as shown in Fig. 5(a). The ρc values of the Ni/Ti/Al contacts are similar to those of the Ti/Al contacts (Fig. 5(b)). The ρc values for the implanted layers decrease with increasing Al doping concentration in the Ti/Al contacts, while the Al doping concentrations do not have a strong influence on the ρc values in the Ni/Ti/Al contacts. The ρc values of the Ti/Al contacts to the SiC implanted at RT with the Al doping concentration of 3 × 10¹⁹ cm⁻³ significantly increase (Fig. 5(a)), and no ohmic behavior was obtained for the Ni/Ti/Al contacts. This suggests that although the hole concentration is high enough to provide low ρc values, the highest density of dislocation loops in the implanted SiC layers may influence the ρc values.
In order to understand the current transport mechanism through the metal/SiC substrates, the experimental $\rho_c$ values were compared with the theoretical $\rho_c$ values which were calculated using Yu’s thermionic field emission theory [9] as a function of carrier concentrations of p-type 4H-SiC layers with various barrier heights ranging from 0.3 to 0.6 eV. The measured $\rho_c$ values are plotted on the theoretical $\rho_c$ curves in Fig. 6. When we calculated the $\rho_c$ values, we assumed that the value of effective hole mass equals free electron mass, and the dielectric constant and activation energy of Al in the SiC of 9.96 mV and 190 meV, respectively. The measured $\rho_c$ values for the implanted and epitaxial layers fall on the theoretical curve with the barrier height of 0.4 eV in both the Ti/Al and Ni/Ti/Al contacts, except the Ti/Al contacts to the layers implanted at RT with the Al doping concentration of $3 \times 10^{19}$ cm$^{-3}$. This indicates that the $\rho_c$ values of the contacts to the implanted and epitaxial layers were determined by the Yu’s thermionic field emission mechanism. The high $\rho_c$ values of the contacts to the implanted layers may be explained by the high density of dislocation loops in the implanted SiC layers would reduce significantly the hole concentration. Also, note that although hole concentration in the layers implanted at RT with the Al doping concentration of $3 \times 10^{19}$ cm$^{-3}$ is high enough to provide low $\rho_c$ values, the highest density of dislocation loops in the implanted layers would increase the barrier height at metal/SiC interfaces and thus increase the $\rho_c$ values. In addition, the Ni/Ti/Al contacts did not provide ohmic behavior. These may be explained by the highest density of dislocation loops in the implanted SiC layers would increase the barrier height values of the TiAl-based contacts to the p-type 4H-SiC, rather than by the highest density of dislocation loops would reduce the hole concentration. The high-resolution TEM observation at the interface between the contacts and the implanted layers is in progress.

4. Summary

Sheet resistances of the 4H-SiC layers implanted with Al ions were found to be about 30 times higher than that of the p-type epitaxial 4H-SiC layers with the same Al doping concentration. The higher sheet resistance of the implanted layers was explained by lower hole concentration than those of the epitaxial layers, i.e., lower activation of the implanted Al ions. The sheet resistances and hole carrier concentrations of the implanted layers decreased and increased, respectively, with increasing Al doping concentrations. Many dislocation loops were observed in the implanted layers. The dislocation loop density increased.
with increasing the Al doping concentration. The density was the highest in the 4H-SiC layers implanted at RT with the Al doping concentration of $3 \times 10^{19}$ cm$^{-3}$.

The Ti$_3$SiC$_2$ layers were found to form by reaction between the Ti/Al and Ni/Ti/Al metals and 4H-SiC-implanted layers. These contacts provided ohmic behavior to the implanted SiC layers, except the 4H-SiC layers implanted at RT with the Al doping concentration of $3 \times 10^{19}$ cm$^{-3}$ with the highest density of the dislocation loops. The $\rho_c$ values of the contacts to the 4H-SiC-implanted layers were higher than that to the 4H-SiC epitaxial layers with the same Al doping concentrations. This was simply explained by lower hole carrier concentration in the implanted layers than in the epitaxial layers. The $\rho_c$ values to the 4H-SiC layers implanted at RT with the Al doping concentration of $3 \times 10^{19}$ cm$^{-3}$ (with the highest density of dislocation loops) were significantly higher than those to the other implanted layers, although the hole concentration was high enough to provide low $\rho_c$ values. This suggests that the highest density of dislocation loops in the implanted layers influenced the barrier height at metal/SiC interfaces.
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