Nickel ohmic contacts of high-concentration P-implanted 4H-SiC

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Abstract: Different-dose phosphorus ion implantation into 4H-SiC followed by high-temperature annealing was investigated. AlN/BN and graphite post-implantation annealing for ion-implanted SiC at 1650 ℃ for 30 min was conducted to electrically activate the implanted P^+ ions. Ni contacts to the P^+-implanted 4H-SiC layers were examined by transmission line model and Hall measurements fabricated on P-implanted (0001). The results indicated that a high-quality ohmic contact and specific contact resistivity of 1.30×10^{-6} $\Omega\cdot cm^2$ was obtained for the P^+-implanted 4H-SiC layers. The ρ_C values of the Ni-based implanted layers decreased with increasing P doping concentrations, and a weaker temperature dependence was observed for different samples in the 200–500 K temperature range.

Key words: ohmic contacts; phosphorus ion implantation; contact resistance; Hall concentration; silicon carbide
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1. Introduction

4H-SiC is one of the most attractive semiconductors for high-power electronic device applications owing to its superior electrical, thermal, chemical and mechanical properties[1,2]. A high-quality ohmic contact with low specific contact resistance on SiC is very important to device performance. The doping of impurities to SiC at high concentrations by conventional diffusion techniques cannot be used for SiC due to the solubility limits of these elements and the small diffusivity of the impurities[3], so ion implantation with a high donor dose into SiC is required to reduce the resistivities of the ohmic contacts. To form selective n^+ regions with a low resistivity in SiC, nitrogen ion (N^+) and phosphorus ion (P^+) implantations are commonly employed. Considering the relatively higher solubility limit of P in SiC (about 10^{20} cm^{-3}) and the lower ionization energy of P donors (27 meV) with respect to nitrogen ion at concentrations above 10^{19} cm^{-3}, high-dose P^+ implantation at an elevated temperature is used to reduce sheet resistance[4−6].

In this article, phosphorus was chosen as an implanted material. To minimize the contact resistance and avoid amorphization of the implanted layers, especially at high flux, selective P^+ implantations were conducted at 500 ℃. The post-implantation activation annealing with an AlN/BN and a graphite cap can bring the implanted phosphorus atoms to silicon sub-lattice sites in the crystal structure, where the atoms become electrically active donors. Through the linear transmission line model (TLM) method, the contact electrical properties of the Ni contacts to the P^+-implanted 4H-SiC layers were examined by measuring the ρ_C and sheet resistance of the implanted SiC layers. As electron concentration affects contact resistance, the electron carrier concentration of the implanted SiC layers were measured as a function of the implant dose using Hall measurements. The temperature dependence of the free-electron concentration for a fixed implant concentration was also studied. To ensure an equipotential surface and prevent possible oxidation during thermal annealing, a layer of Au was sputter-deposited over the nickel silicide contact layer for all the TLM patterns[7].

2. Experiments

In this experiment, commercial Cree n-type 4H-SiC wafers with an 8° off-axis (0001) were used. Boron-doped 6 μm thick p-type epilayers with a doping concentration of 1.1×10^{16} cm^{-3} were grown on the substrates by chemical vapor deposition. Multiple implantation of P^+ was carried out at 500 ℃ to form a 0.7 mm-deep box profile of P atoms at different ion energies from 100 to 80 MeV. The implant concentrations were 4×10^{18}, 5×10^{19} and 1×10^{20} cm^{-3}. To ensure optimal activation of the implanted ions and to reduce lattice damage, the samples were annealed at 1650 ℃ for 30 min in a pure Ar ambient. During annealing the samples were protected in a SiC container with an Ar ambient of 1 atm to avoid thermal decomposition of the SiC surfaces. Subsequently, a surface layer of 0.2 mm was removed by reactive ion etching, resulting in an implanted layer of 0.5 mm. After ion implantation, AlN/BN and graphite annealing caps were formed on the implanted SiC to obtain excellent flatness without macro-step formation, by blocking the out-diffusion of the Si and C atoms on the surface of the implanted SiC during high-temperature annealing[8]. For the electrical measurements, a specific pattern was prepared using a lift-off technique on the 8×8 mm^2 substrates, as shown in Fig. 1[9]. The four square electrodes with a 1 mm^2 area at the corner of the substrate were prepared for the sheet resistance and Hall measurements of the SiC substrates. The four TLM patterns were formed between the two square electrodes with an inter-spacing of 4, 8, 16 and 24 μm. The current–voltage (I–V) characteristics of the TLM contacts were measured using a Keithley 2400 Source-Meter. To avoid leakage current along the sample edges and improve the blocking behavior

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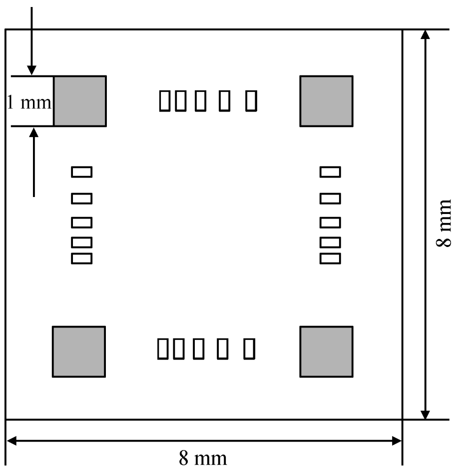

Fig. 1. Schematic illustration of the specific pattern prepared on the 4H-SiC implanted layers.

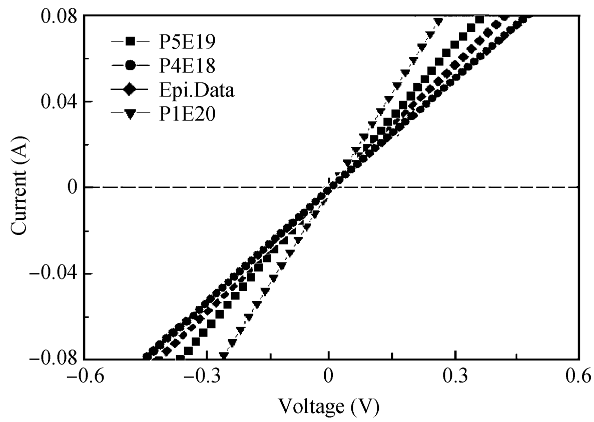

Fig. 2. I–V characteristics of Ni-based contacts on 4H-SiC layers implanted with P ions after rapid thermal annealing in Ar for 10 min.

of the implanted p–n junctions, clover-leaf-shaped mesa structures were prepared by reactive ion etching. Ni ohmic contacts in the van der Pauw arrangement were grown in an electron beam evaporator at a base pressure of 1×10^{-8} mbar and annealed at 550 ℃ for 10 min, followed by 800 ℃ for 3 min in a flow of Ar gas containing 10 vol% H_2 gas. The 4H-SiC samples with 6 μm thick n-type epitaxial layers doped with P at 4 $\times 10^{18}$ cm^{-3} were used for comparison.

3. Results and discussion

3.1. I–V characteristics

The I–V characteristics of the SiC contact layers with various P concentrations after thermal annealing are shown in Fig. 2. The Ni-based contacts show excellent ohmic behavior. When the applied voltage changes from –0.6 to 0.6 V, the I–V curves show linear characteristic and are symmetric with reversal of voltage polarity. So the implanted P concentration, which is an n-type dopant for SiC, extends well beyond the silicide-SiC interface formed by the ohmic contact anneal. For the sample with 1×10^{20} cm^{-3}, it has the lowest ohmic contact resistance of 1.30×10^{-6} $\Omega\cdot$cm^2. Table 1 lists the average values of ρ_C and the sheet resistances of the SiC layers from the TLM measurements. The ρ_C value of the Ni-based layer is about 1.53×10^{-5} $\Omega\cdot$cm^2 for the implanted layers, with a P doping concentration of 4×10^{18} cm^{-3}, which is higher than that for the epitaxial layer with the same P doping concentration and lower than the Ni-based layers[10] for a similar nitrogen concentration of around 10^{18} cm^{-3},while the ρ_C values for the P^+ implanted layers decrease with increasing P doping concentration in the Ni-based contacts. The ρ_C values of the contacts to the implanted and epitaxial layers are determined by Yu's thermionic field emission mechanism[11], so the high ρ_C values of the contacts to the implanted layers may be caused by the high density of dislocation loops following implantation that disrupt lattice periodicity in the implanted SiC layers. This would directly affect the barrier height characteristics and reduce the electron concentration, although these substrates were annealed at high temperatures. The dislocation loop density increases with increasing P doping concentration. Thus the dislocation loop density is highest in the layers implanted at 500 ℃ with a P doping concentration of 1×10^{20} cm^{-3}. Although the highest density of dislocation loops in the implanted SiC layers may influence ρ_C, the height of the barrier decreases rapidly with increasing carrier concentration. So at high concentration, carrier transport takes place via carrier tunneling and barrier height becomes relatively less important. On the other hand, the donor ionization energy for P impurities in 4H-SiC is 27 meV[12], which means that most of the donors are ionized at room temperature for the P-implanted material. Both the decrease in ionization energy for the P donors and the band-gap narrowing due to high donor concentration may explain the decrease in ρ_C and sheet resistance, which is gradually reduced from 280 to about 45 $\Omega/\square$ when the P^+ doping concentration changes from 4×10^{18} to 1×10^{20} cm^{-3}. And at concentrations above 10^{18} cm^{-3}, N atoms apparently start to form electrically inactive precipitates compared to the P atoms, which indicates that N implantation leads to higher resistivity values (2.40×10^{-5} $\Omega\cdot$cm^2) in the samples. So, high-dose P^+ implantation at an elevated temperature is effective in reducing sheet resistances.

3.2. Hall measurements

In order to determine the free carrier density, Hall measurements were carried out at room temperature. Figure 3 shows the free-electron concentration versus the implant concentrations of 4×10^{18}, 5×10^{19} and 1×10^{20} cm^{-3}, together with that of the 4H-SiC epitaxial layer with a P doping concentration of 4×10^{18} cm^{-3}. The free-electron concentration tends to increases from 2×10^{18} to 2×10^{19} cm^{-3} with increasing P-doping concentration. The highest electron carrier concentrations are about 2×10^{19} cm^{-3} for the implanted layer, with a P ions concentration of 1×10^{20} cm^{-3}. For the relatively low P ion implant concentrations of 4×10^{18} cm^{-3}, more than 50% of the implanted P atoms act as ionized donors at RT, resulting in the high electron concentration above 2×10^{18} cm^3. In contrast to the activation ratio of 30% for the similar N^+ ions implanted sample, the electrical activation of the implanted P^+ ions is now much higher. So at high-dose implantations, P donors are superior due to their higher electrical activation and give rise to much smaller ρ_C and sheet resistances. The small apparent increase in free-electron concentration at the higher P-donor

Table 1. Specific contact resistivity of Ni-based contacts for P-implanted 4H-SiC layers activated at 1650 ℃.

Sample	Epitaxial layer	N^+ implanted	P^+ implanted concentration		
			4×10^{18} cm^{-3}	5×10^{19} cm^{-3}	1×10^{20} cm^{-3}
ρ_C ($\Omega \cdot cm^2$)	6.47×10^{-6}	2.40×10^{-5}	1.53×10^{-5}	2.67×10^{-6}	1.30×10^{-6}
Sheet resistance (Ω/□)	230	370	280	150	45

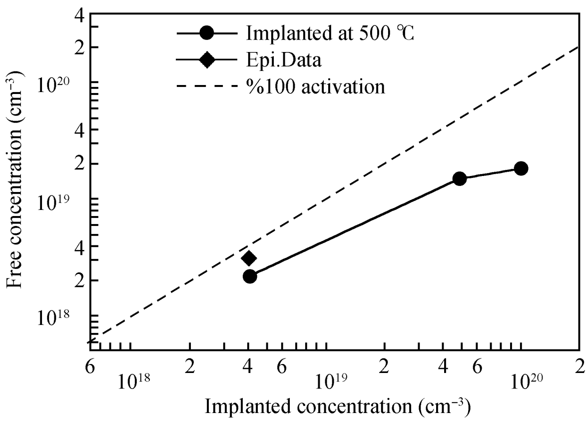

Fig. 3. Free-electron concentration as a function of P-doping concentration.

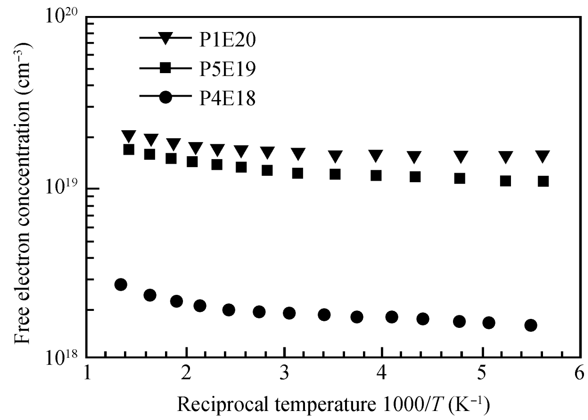

Fig. 5. Temperature dependence of free-electron concentration for P-implanted 4H-SiC.

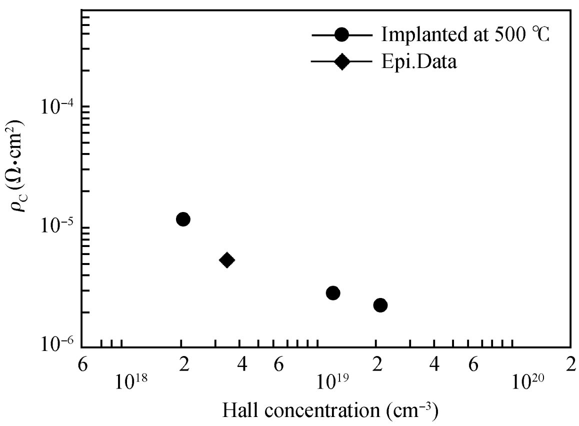

Fig. 4. Specific contact resistance for P-implanted 4H-SiC as a function of Hall carrier concentration.

concentration is attributed partly to higher compensation generated by implantation-induced defects which trap donor electrons[13]. The compensation should increase with the increase in implant dose. Compared with the data of the 4H-SiC epitaxial layer with a P doping concentration of 4×10^{18} cm^{-3}, the free-electron concentration tends to decreases because of dislocation loops caused by ion implantation.

The values of ρ_C for P-implanted 4H-SiC as a function of Hall carrier concentration are shown in Fig. 4. ρ_C for P-implanted samples decrease with Hall carrier concentration. According to the above analysis, the reduction in ρ_C is mainly due to the increase in electron concentration. And the results are in agreement with the TLM data shown in Table 1. It is noted that although electron concentration in the layers implanted at 500 ℃ with a P doping concentration of 4×10^{18} cm^{-3} is high enough to provide low ρ_C values, the higher density of dislocation loops in the implanted layers will increase the barrier height at the nickel/SiC interfaces and reduce the electron concentration, thus there is a slight increase in the ρ_C values compared with the epitaxial layer with the same P doping concentration.

The temperature dependence of free-electron concentration for the samples with P-donor concentrations from 4×10^{18} to 1×10^{20} cm^{-3} are shown in Fig. 5. All samples were annealed with a graphite cap. The free-electron density is almost constant in the wide temperature range of 200–500 K, which is consistent with the results in Ref. [12]. The curve for the P-implanted sample at a concentration of 1×10^{20} cm^{-3} runs almost parallel at half the free-electron concentration (2×10^{19}). Three different P ion implanted samples show weak temperature dependence. So theoretically most of the implanted P atoms work as ionized donors at RT for P-implanted material, and there is a very small influence on sheet resistance by temperature at lower temperatures. The flat curves of the samples indicate that a high concentration of electron states is not occupied in the impurity band, and that all these samples are degenerated semiconductors[14]. As a consequence, the concentration of compensation, which traps the donor electrons, has to be much higher than the concentration of the starting material.

4. Conclusions

The electrical properties of Ni contacts to P^+-implanted 4H-SiC layers were investigated by measuring the ρ_C and sheet resistance of the implanted SiC layers. Annealing with AlN/BN and graphite caps was conducted to eliminate crystal defects. These contacts provided ohmic behavior to the implanted SiC layers, and a specific contact resistivity of 1.30×10^{-6} $\Omega \cdot cm^2$ was obtained for the P^+-implanted 4H-SiC layers. The dependence of electron density on P doping concentration and implant activation temperature was studied for the P-implanted 4H-SiC layers. The free-electron concentration tends to increases with increasing P-doping concentration. The increasing number of electron carriers with increasing P concentration may play a key role in determining the ohmic behavior of the Ni contacts to the P^+-implanted 4H-SiC, although the highest density of dislocation loops in the implanted layers influences the barrier height at the Ni/SiC interfaces. So high-dose P^+ implantation at an elevated temperature is effective in forming better ohmic contacts on SiC.

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