Ohmic contacts of 4H-SiC on ion-implantation layers

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The ohmic contacts of 4H-SiC are fabricated on nitrogen ion implanted layers made by performing box-like-profile implantation three and four times. Implantation parameters such as the standard deviation σ and the projection range $R_{\rm p}$ are calculated by the Monte Carlo simulator TRIM. Ni/Cr ohmic contacts on Si-face 4H-SiC implantation layers are measured by transfer length methods (TLMs). The results show that the values of sheet resistance $R_{\rm sh}$ are 30 k$\Omega/\Box$ and 4.9 k$\Omega/\Box$ and the values of specific contact resistance $\rho_{\rm c}$ of ohmic contacts are 7.1×10^{-4} $\Omega\cdot{\rm cm}^2$ and 9.5×10^{-5} $\Omega\cdot{\rm cm}^2$ for the implanted layers with implantation performed three and four times respectively.

Keywords: silicon carbide, ion implantation, ohmic contact, sheet resistance

PACC: 7280J, 7630D, 7155D, 7850G

1. Introduction

As a wide-bandgap semiconductor, silicon carbide (SiC) has outstanding properties,[1] such as high thermal conductivity, great breakdown field and high saturation electron drift velocity, so it is expected to be used for fabricating high-temperature,[2] high-power,[3] and high-speed devices.[4] But diffusion processes in SiC require both temperatures to be higher than about 2000 °C and time to be relatively long to accomplish the mass transport needed by device fabrication.[5] The ion-implantation of dopants has been recognized as a crucial means for selective area doping except in situ doping. These years, SiC ions doped by implantation and their effects on devices have been investigated experimentally and theoretically.[6−10] Implantation range (the standard deviation σ and the projection range $R_{\rm p}$ of the implanted ions) damage and defects[11] after high temperature annealing are often simulated by the Monte Carlo method.[12,13] The ion-implantation technique is often used to fabricate SiC devices, such as metal–semiconductor field-transistors (MESFETs),[14] high electron mobility transistors (HEMTs), static induction transistors (SITs) and so on.[15] So ohmic contacts usually need to be formed on the ion-implantation layers; it is desirable to study the characteristics of ohmic contacts on the implanted layer, such as the specific contact resistance $\rho_{\rm c}$, and the sheet resistance $R_{\rm sh}$ of the implanted layer.

Good ohmic contact is extremely important for fully realizing the potential of SiC, and many kinds of ohmic metallizations on SiC have been studied for years, such as Ni,[16,17] Co,[18] Pt,[19] Ti/Ni,[20] Ni/Ta,[21] Ta/Ni/Ta,[22] Ni/Ti,[23] Al/Ti, Al/Ni, Al/Ti/Al, Al/Ni/Al,[24] Au/Ti/Al,[25] Ti/Ni/Al[26] and so on. In order to achieve low specific contact resistance $\rho_{\rm c}$, making the silicide between metals and SiC is needed by using annealing at high temperatures, such as 800,[21] 900,[23] 1000 °C.[26] But, relatively, the ohmic contact on implantation layer has been little studied. It was reported in Ref. [27] that the contact resistance was reduced by using Ge implantation, which shows an alternative in the ion-implantation technique for achieving good ohmic contact.

In the present paper two kinds of multiple ion-implantations (implanting nitrogen ions three and four times) are designed on the P type 4H-SiC epilayer. The profiles of ion-implantations into 4H-SiC are simulated by using the TRIM. The parameters of the implantation and post-annealing conditions are given in detail. The fabrication processes of making the Ni/Cr ohmic contacts on the implanted layers are presented. The specific contact resistance $\rho_{\rm c}$ of the ohmic contact and the sheet resistance $R_{\rm sh}$ of the implanted layer are analysed by linear transfer length methods (TLMs).[28,29] The values of resistivity ρ of the two kinds of implantation layers are calculated. The fab-

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rication processing of ohmic contact in this study is expected to conduce to the fabrication of high quality ohmic contact and to make 4H-SiC MESFETs by using the multiple ion implantation technique in the future.

2. Experimental procedure and testing

Ion implantation is a key technique in the state-of-art fabrication processing of semiconductor devices. After a simple calculation, the distribution of the implanted ions can be expressed mathematically by the Gaussian equation as

$$N(x) = \frac{Q}{\sqrt{2\pi}\sigma} \exp\left[-\left(\frac{x - R_{\rm p}}{\sqrt{2}\sigma}\right)^2\right], \qquad (1)$$

which has two parameters, i.e. the projection range $\rho = R_{\rm sh} \times d$ and the standard deviation σ. The area under the impurity distribution is the implanted dose Q, i.e.

$$Q = N_{\rm m}\sigma\sqrt{2\pi}, \qquad (2)$$

where $N_{\rm m}$ is the concentration to be obtained. The projected range $\rho = R_{\rm sh} \times d$ of a given ion is a function of the energy of the ion and of the masses and atomic numbers of both the ion and the target material. The projection range $\rho = R_{\rm sh} \times d$ and the standard deviation σ of the nitrogen ions in 4H-SiC varying with the implantation energy can be calculated by using the TRIM. Their variation approximately follows a linear line as shown in Fig. 1. The implanted energies (performing implantation three and four times) used in the experiment are determined by the implanted range $R_{\rm p}$ and the relation between standard deviation σ and implantation energy can be obtained from Fig. 1. If the concentration $N_{\rm m}$ is known, the implanted dose Q corresponding to the implanted energy can be calculated from expression (2).

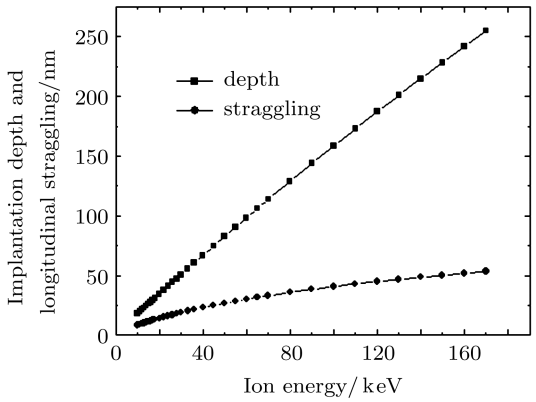


Fig. 1. Projected range and standard deviation calculated by TRIM.

The orientation of the 4H-SiC wafer used in the experiment is 8° off axis ⟨1000⟩ direction, and the concentration of the 1.8 μm thick p-type epitaxial layer is 6.5×10^{15} cm^{-3} based on the n-type silicon faced substrate with a concentration of $7.1\times\times10^{18}$ cm^{-3}. N-wells are formed by nitrogen ions multiply implanted into the epilayer at a temperature of 500 °C after a 450 nm thick SiO_2 layer has been deposited by low-pressure chemical vapour deposition (LPCVD) as shown in the top view (Fig. 2(a)) and the cross section (Fig. 2(b)) separately. The energies and doses with implanting ions three times, received from the analysis above, are 55 keV and 1.07×10^{13} cm^{-2}, 100 keV and 1.53×10^{13} cm^{-2}, 160 keV and 1.95×10^{13} cm^{-2} respectively. The energies and doses with implanting ions four times are 55 keV and 1.07×10^{13} cm^{-2}, 100 keV and 1.53×10^{13} cm^{-2}, 160 keV and 1.95×10^{13} cm^{-2}, 240 keV and 2.34×10^{13} cm^{-2} respectively. Then N^+ regions for ohmic contacts are formed with 30 keV energy and 3.54×10^{14} cm^{-2} high dose nitrogen ion implantation at a temperature of 500 °C after the ohmic contacts have been repatterned. The N-well area is 664×190 μm^2 and the N^+ region is 80×170 μm^2.

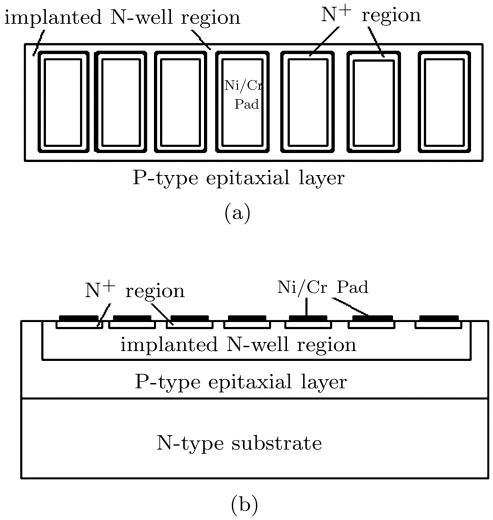


Fig. 2. Top view (a) and cross section (b) of TLM structure fabricated on the implantation layer.

The TLM is an effective way to analyse the parameters of the ohmic contact and has a circular structure and a linear structure.[30] The structure of the linear TLM pattern used in this study is shown in Figs. 2(a) (the top view) and 2(b) (the cross section).

The interspaces of seven rectangular N^+ regions are 4, 8, 12, 16, 20 and 24 μm. After being chemically cleaned in BHF (buffer agent of hydrofluoric acid), the samples with three and four times ion-implantations are annealed at temperatures up to 1480 °C and 1650 °C respectively by using a ceramic sintering furnace in pure argon atmosphere, lasting 30 min at peak temperature and then naturally cooling while keeping the argon flowing. Finally, the ohmic contacts are patterned through conventional photolithography and lift-off techniques. Ohmic contact windows with an area of 60×150 μm^2 are formed, and Ni/Cr and Au are evaporated in sequence and alloyed at 900 °C for 30 min in a vacuum furnace to realize ohmic contacts.

3. Results and discussion

The activation of ions is dependent on not only annealing temperature but also conditions such as heating, duration and descending time, the container, and the environment gas and so on. Results from atomic force microscopy show that the surface morphology deteriorates as annealing temperature increases.[31] An AIN cap fabricated by pulsed laser deposition was used to protect the SiC surface during high temperature annealing.[32,33] Nitrogen dopants are assumed to occupy C lattice sites in SiC and coimplantation with Si ions is used to increase the electrical activation according the site-competition effect theory. Seshadri received 6.3 percent activation by 1300 °C annealing and nearly complete activation by annealing at temperatures above 1500 °C for nitrogen ion-implantation.[6] As a contrast, an experiment later carried out by Handy indicated that a 15 min implant activation at 1500 °C results in 15 percent nitrogen activation.[7] The activation percentages of N by annealing in a range from 1480 °C to 1650 °C in the experiment are about 10%–20% as expected. So the implanted layers are expected to reach an effective doping concentration of 1.5×10^{17} cm^{-3}.

Figures 3 (a) and 3(b) show the variations of the values of total resistance R_T with implanting ions three and four times between adjacent TLM pads as a function of gap spacing L respectively. In order to reduce the errors, the linear curve shown in Fig. 3 is for the median values from multiple measurements. By assuming that the length of each contact is long enough, the total resistance R_T can be expressed in the form[28]

$$R_T = 2R_C + \frac{R_{sh}L}{W}, \tag{3}$$

where W is the width of the contact, $2R_c$ is the interception of the linear curve on the y axis. The specific contact resistance ρ_c can be given as

$$\rho_c = \frac{(R_cW)^2}{R_{sh}}. \tag{4}$$

Therefore, sheet resistance R_{sh} is W multiplied by the slope dR_T/dL of the linear line in Fig. 3(a) for three times implanting ions or in Fig. 3(b) for four times implanting ions.

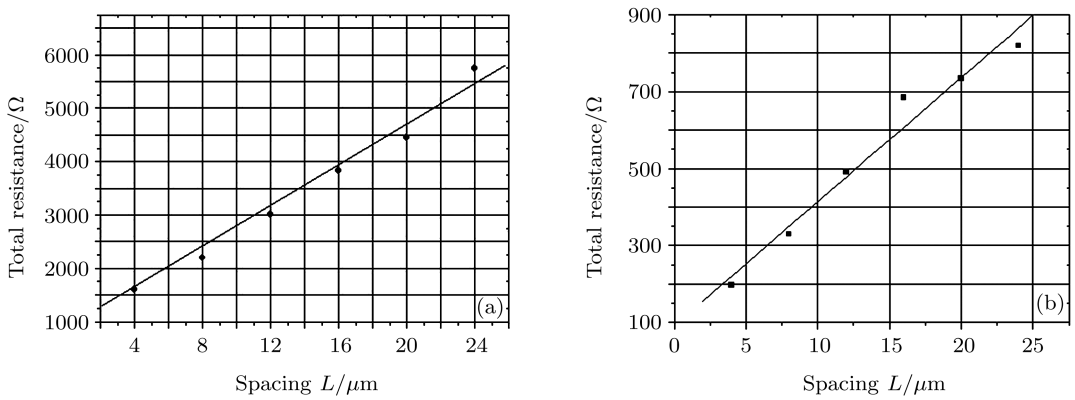


Fig. 3. Values of total resistance for cases of three (a) and four (b) times implanting ions versus gap spacing.

The resulting values for sheet resistance R_{sh} of the implanted layer are 30 kΩ/□ (with three times implanting ions) and 4.9 kΩ/□ (with four times implanting ions) respectively. The values of specific contact resistance ρ_c of Ni/Cr/4H-SiC are calculated from expression (4) to be 7.1×10^{-4} $\Omega\cdot cm^2$ (with three times implanting ions) and 9.5×10^{-5} $\Omega\cdot cm^2$ (with four times implanting ions).

The resistivity of the implanted layer is

$$\rho = R_{\rm sh} \times d, \tag{5}$$

where the depth d of N implanted layer is 0.24 μm (for the case of three times implanting ions) and 0.34 μm (for the case of four times implanting ions) obtained from the simulations by the TRIM. So the values of resistivity $\rho(R_{\rm sh} \times d)$ are 0.72 $\Omega \cdot$cm and 0.17 $\Omega \cdot$cm for the implanted layers with implanting ions three times and four times respectively.

Nickel is the metal most commonly used for ohmic contact and can react with SiC to form Ni_2Si.[34] Chromium is used to form ohmic contact which is both ductile and oxidation resistant.[21] The specific contact resistance $\rho_{\rm c}$ for the ohmic contact on a heavily doped semiconductor can be expressed by[35]

$$\rho_{\rm c} = \exp\left(\frac{2\phi_{\rm B}}{\hbar}\sqrt{\frac{\varepsilon_0\varepsilon_{\rm s}m^*}{N_{\rm D}}}\right), \tag{6}$$

where $\phi_{\rm B}$ is the barrier height,[36] $\hbar$ is the reduced Planck constant, ε_0 is the permittivity of free space, $\varepsilon_{\rm s}$ is the electrical relativistic permittivity of the semiconductor, m^* is the effective mass of an electron, and $N_{\rm D}$ is the doping density. The specific contact resistance $\rho_{\rm c}$ is reduced with the increase of doping density $N_{\rm D}$ (see expression (6)).

The specific contact resistance $\rho_{\rm c}$ in this experiment is high compared with the result of Zhang,[37] whose specific contact resistance of Ni/Cr (4:1 at weight) alloy on an N-type 6H-SiC epilayer is 8.4×10^{-5} $\Omega \cdot {\rm cm}^2$, and the doping concentration of the N-type epilayer is 8.0×10^{17} ${\rm cm}^{-3}$, while the ohmic contacts in this work are made on an ion-implanted layer. The high value of the specific contact resistance $\rho_{\rm c}$ results from the low activation efficiency of the N implanted layer and low alloying temperature (900 °C) for ohmic contacts. A higher alloying temperature (also called the annealing temperature for ohmic contacts) assures a significant reaction with SiC, but it is likely to create a graded, highly-defective interface associated with ohmic behaviour. Although lower alloying temperatures have been used in recent years,[21] the alloying temperature often needs to be above 900 °C.[38,39]

The result for four times implanting ions is better than that for three times implanting ions at a higher post-annealing temperature after ion-implantations and one more time implanting. Annealing conditions and implantation times need to be carried out in the future.[40] Under this study, a good quality ohmic contact fabricated on an ion-implanted layer can be expected to be obtained.

4. Conclusions

An array of TLM structures is formed on N-wells created by N ions implanted into a Si faced p-type 4H-SiC epilayer. Instead of mesa isolation by reactive ion etching, the electrical isolation is a PN junction. Each set of the TLM pattern consists of seven rectangular N^+ regions with implanted N ions, and their interspaces are in a range of 4–24 μm. Ni/Cr and Au are evaporated separately and alloyed at 900 °C for 30 min in a vacuum furnace to realize ohmic contacts. The resulting values of sheet resistance $R_{\rm sh}$ are 30 k$\Omega/\Box$ and 4.9 k$\Omega/\Box$ for the implanted layers with three times and four times implanting ions respectively. The values of specific contact resistivity $\rho_{\rm c}$ are 7.1×10^{-4} $\Omega \cdot {\rm cm}^2$ and 9.5×10^{-5} $\Omega \cdot {\rm cm}^2$ for the Ni/Cr/4H-SiC layers with three times and four times implanting ions respectively. The values of resistivity ρ of the implantation layers for three and four times implanting ions are 0.72 $\Omega \cdot$cm and 0.17 $\Omega \cdot$cm respectively. The quality of the implantation layer needs to be improved in order to achieve a low ohmic contact.

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