Characteristics of N^+ Implanted Layer of 4H-SiC*

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Abstract: The nitrogen ions implanted layer of p-type 4H-SiC epilayer is investigated. The fabrication processes and measurements of the implanted layer are given in details. The profile of implantation depth is simulated using the Monte Carlo simulator TRIM. Lateral Schottky barrier diodes and transfer length method (TLM) measurement structure are made on nitrogen implanted layers for the testing. The concentration of activated donors N_d is about $3.0\times10^{16}cm^{-3}$. The resulting value for the activation rate in this study is 2 percent. The sheet resistance R_{sh} is 30kΩ/□ and the resistivity $\rho(R_{sh}\times d)$ of the implanted layer is 0.72Ω·cm. The electron mobility calculated is about $300cm^2/(V\cdot s)$ in the N implanted layer.

Key words: silicon carbide; ion implantation; annealing; sheet resistance
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1 Introduction

Silicon carbide (SiC) has been used to fabricate high-temperature, high-power, and high-speed devices for its outstanding properties such as wide bandgap, high breakdown field, and saturation electron drift velocity. Ion implantation of dopants has been crucial for selective area doping because thermal diffusion rates of most dopants are very slow in SiC at the temperature range of 1800~2000℃. A number of experimental[1,2] and theoretical[3~5] investigations have been carried out, in which the effects of ion implantation on characteristics of SiC device are studied. At present, the Monte Carlo simulation is a vital approach for predicting implantation parameters such as damage[6], implantation ranges[7] and so on. The location of peak concentration and the longitudinal straggling of implanted ions can be calculated with the Monte Carlo simulator TRIM. As one of essential part of fabrication process for SiC devices, an optimized procedure of ion implantation (the ion implantation temperature, implantation energies and doses, the annealing temperature and environment etc.) and the characteristics of the implanted layer (the activation rate, the sheet resistance R_{sh}, and the resistivity ρ of the implanted layer, the electron mobility of the implanted layer etc.) are expected.

In this article, the processes of nitrogen ions implanted into p-type 4H-SiC epilayer and the measurements of the implanted layer are presented in details. The profile of ion-implantation into SiC is simulated with TRIM. The characteristics of the implanted layer are analyzed by C-V measurements and the linear TLM (transfer length method)[8,9].

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This study is expected to have an assistance on the fabrication of multiple ion implanted 4H-SiC MESFETs hereafter.

2 Experimental procedures

4H-SiC wafer used in this experiment was purchased from Cree Research Company. The ion implanted layer was made on the p-type epitaxial layer with concentration of $N_a = 6.5\times10^{15}cm^{-3}$ and depth of 1.8μm based on the n-type silicon faced substrate with concentration of $N_d = 7.1\times10^{18} cm^{-3}$. Multiple nitrogen ions were implanted into epilayer at the temperature of 500℃ after the chip had been cleaned. The energies and doses for ion implantation were 55keV and $1.07\times10^{13}cm^{-2}$, 100keV and $1.53\times10^{13}cm^{-2}$, 160keV and $1.95\times10^{13}cm^{-2}$, respectively. In order to reduce the damages of implantation, ions were implanted from high to low energy. After chemically cleaned in BHF (buffer agent of hydrofluoric acid), the sample was annealed at 1450~1480℃ for 30min in pure argon atmosphere. Schottky barrier diodes and standard TLM structures were formed on the ion implanted layer to study the characteristics of the implanted layer. The structures of the TLM pattern used in this study had seven rectangular n^+ regions with the spacings of 4, 8, 12, 16, 20 and 24μm.

3 Result and discussion

The location of peak concentration and the longitudinal straggling of N are calculated with the Monte Carlo simulator TRIM. Figure 1 shows the profiles of ion implantation using the Gaussian model for expressing the ion implantation ranges.

From one-dimensional Poisson's equation, the concentration of donors $N_d(d)$ at the depth d from the surface of 4H-SiC can be expressed as[10]

$$N_d(d) = \frac{C^3}{q\epsilon_s A^2}\left(\frac{dC}{dV}\right)^{-1} \quad (1)$$

where $d = \frac{\epsilon_s}{C}$, C is the capacitance of SBDs, ϵ_s is

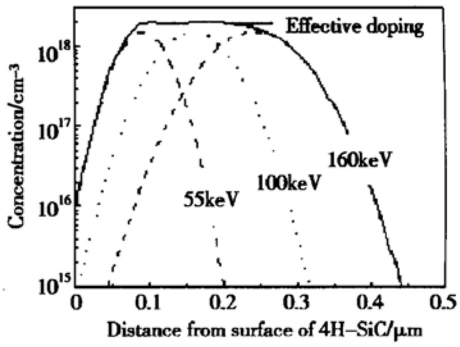

Fig. 1 Simulated ion implantation profiles for N implants into 4H-SiC

the permittivity of 4H-SiC, A is the area of $1.2\times10^{-4}cm^2$ of SBDs in this study. $N_d(d)$ here is the concentration of activated donors of ion implanted layer after high temperature annealing. The measurements of small signal a. c. capacitance as a function of applied voltage (C-V) at 1MHz are carried out. Figure 2 gives the concentration of activated donors $N_d(d)$ versus d calculated from equation (1) and the C-V characteristics of SBDs. The concentration of activated donors $N_d(d)$ of $3.0\times10^{16}cm^{-3}$ can be received.

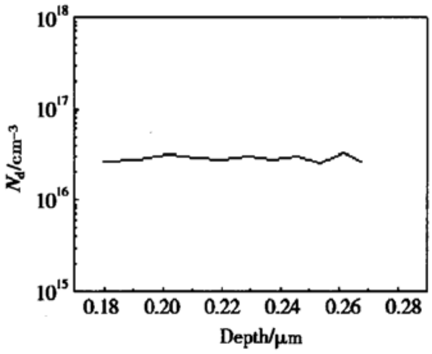

Fig. 2 Concentration of activated donors $N_d(d)$ versus the depth d

The concentration of implanted ions at this range as shown in Fig. 1 is $1.5\times10^{18}cm^{-3}$. So the activation rate is 2 percent. A lower value suggests that a higher implantation temperature above 500℃ and a higher annealing temperature above 1500℃[1,2] are in demand to receive a significant activation rate. High temperatures (600[4], 700[2], and 1000℃[11]) are used to prevent amorgphization[1,11].

The highest temperature of our implantation device is 500℃. In the same annealing time, the activation rate of the implanted nitrogen ions rises with increasing annealing temperature from the experiment carried by Capano[12]. But the changes become flat when the annealing temperature is higher than 1700℃. Seshadri[1] received 6.3 percent of activation by annealing at 1300℃ and near complete activation by annealing at temperatures above 1500℃ for nitrogen. As a contrast an experiment carried out later by Rao[13] indicated that a 15min implant activation at 1500℃ resulted in 3 percent of nitrogen activation.

The heat treatment of post implantation also has the purpose to reduce defects caused by the implantation[14]. However, a high annealing temperature would cause a lot of large black spots[15]. So short time annealing techniques such as flash lamp annealing[16] and rapid isothermal annealing (RIA)[17] are needed because they could reach 2000℃ for about 20ms, and could obtain higher electrical activation rate and further defect removal, compared with the traditional furnace annealing.

In order to reduce the surface roughening[18] and the loss of dopants under the high annealing temperature, a SiC-coated graphite crucible[15] is used to contain the annealing sample and a dummy SiC wafer[3] is placed on the sample. Handy[2] used AlN encapsulant layer to prevent the SiC surface damage during the high temperature annealing. Here we place a semi-insulating (SI) SiC wafer on the implanted SiC surface during annealing (so-called face-to-face technique).

Thus it can be seen, the activation of ions depends on not only the annealing temperature but also the conditions such as the implantation temperature, the rising and descending time, and the environmental conditions etc.

Figure 3 shows the variations of the total resistance R_T between adjacent TLM pads as a function of gap spacing L. In order to reduce the errors, the linear curve shown in Fig. 3 is from the median value of multiple measurements. By assuming that the length of each contact is long enough, the total resistance R_T can be expressed in the form[19]

$$R_T = 2R_c + \frac{R_{sh}L}{W} \tag{2}$$

where W is the width of the contacts, $2R_c$ is the y-interception of the linear curve. The specific contact resistancesc ρ_c can be given as

$$\rho_c = \frac{(R_cW)^2}{R_{sh}} \tag{3}$$

Therefore, sheet resistance R_{sh} is W multiplied by the slope dR_T/dL of the linear curve shown in Fig. 3. The resulting value for sheet resistance R_{sh} of the implanted layer is 30kΩ/□.

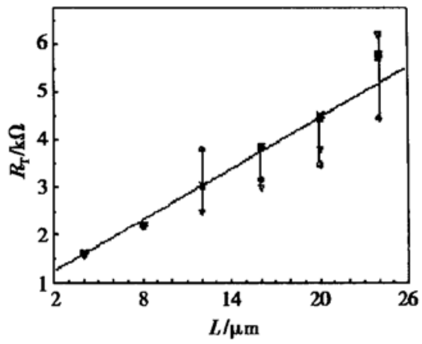

Fig. 3　TLM total resistance versus gap spacing

The depth d of N implanted layer is 0.24μm simulated by TRIM. So the resistivity ρ of the implanted layer is 0.72Ω·cm. From C-V measurements above, the effective carrier concentration is about (2～3)×$10^{16}cm^{-3}$ with incomplete ionization effect[20,21] at 300K, the electron mobility of $300cm^2/(V\cdot s)$ in N implanted layer is received.

4 Conclusion

This paper presents the design considerations of ion implantation, the fabrication procedures of implantation, and the characteristics of implanted layer. Schottky barrier diodes and an array of TLM structures are formed on the ion implanted layer of p-type 4H-SiC epilayer. C-V and TLM measurements show that the resulting value for the activation rate is 2 percent, the sheet resistance R_{sh} of the implanted layer is 30kΩ/□, the resistivity ρ of the implanted layer is 0.72Ω · cm, and the electron mobility in N implanted layer is $300cm^2/(V \cdot s)$.

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4H-SiC N 离子注入层的特性*

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摘要: 研究了在 4H-SiC p 型外延层上用 N 离子注入制备 n 型层的方法及其特性, 注入层的浓度分布用蒙特卡罗分析软件 TRIM 进行了模拟. 为了测试注入层的特性, 制备了横向肖特基二极管和 TLM (transfer length method) 结构. 测得的 N 激活浓度为 $3.0\times10^{16}cm^{-3}$, 计算出激活率为 0.02. 注入层方块电阻为 30kΩ/□, 电阻率为 0.72Ω·cm, 并计算出电子迁移率为 $300cm^2/(V\cdot s)$.

关键词: SiC; 离子注入; 退火; 方块电阻

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