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Theoretical Investigation of Pinch off Voltage of Box-Like Ion-Implanted 4H-SiC MESFETs*

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Abstract: A precise theoretical calculation off the pinch of voltage of the box-like ion implantation 4H-SiC MESFETs is investigated with the consideration of the effects of the ion-implanted channel and the depth of MESFETs channel. The implant depth profile is simulated using the Monte Carlo simulator TRIM. The effects of parameters such as temperature, acceptor density, and activation rate on channel depth a, pinch off voltage are studied.

Key words: silicon carbide; ion implantation; MESFET; pinch off voltage
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1 Introduction

Silicon carbide (SiC) has outstanding properties such as wide bandgap, high breakdown field, and saturation electron drift velocity, and has been expected to fabricate high-temperature, high-power, and high-speed devices. Because thermal diffusion rates of most dopants are very slow in SiC at normal temperature, ions implantation of dopants has been recognized as a crucial means of selective area doping. A number of experimental[1,2] and theoretical[3~5] investigations have been carried out by various workers to study the effect of ion implantation on SiC device characteristics. An analytical model of an ion-implanted Si-MESFET was reported, with respect of changes of ions profile by thermal annealing, by Chattopadhyay[6], whose samples were implanted one time. However, multiple energy box profile implants are often used in the fabrication of SiC-based devices[7,8]. Furthermore, the nature of silicon is not the same with that of SiC. No nitrogen diffusion is apparent after annealing at ~ 170℃[1]. At present, the Monte Carlo simulation is a vital tool for predicting implantation parameters, such as damages[9] and implantation ranges[10]. The location of peak concentration and the longitudinal straggling of implanted ions can be calculated with the Monte Carlo simulator TRIM. There have not been reports on the characteristics of 4H-SiC MESFETs fabricated on nitrogen multiple implanted channels.

In this article we report a theoretical modeling of the pinch off voltage of the box-like-profile ion implanted 4H-SiC MESFETs. The profile of ion-implantation into SiC is represented approximately by a symmetric Guassian distribution. Poission's equation has been solved to obtain the pinch off

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voltage of SiC MESFETs. The expression of the pinch off voltage and the channel depth are given. We focus on explaining the effect of parameters such as temperature (T), acceptor density (N_a), and activation rate (β) on pinch off voltage (V_P). Such study is expected to have an assistance on the fabrication of multiple ion implanted 4H-SiC MESFETs hereafter.

2 Theory

The structure of MESFETs investigated in this study is shown in Fig. 1. The substrate is highly doped n-type with a lightly doped p-type epitaxial layer. N-wells were formed by multiple nitrogen ions implantation, while n^+ regions for Ohmic contacts were formed by a highly nitrogen ions implantation.

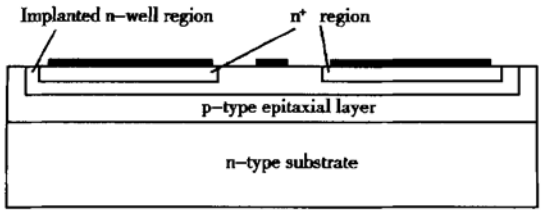

Fig. 1 Schematic structure of the MESFETs

One-dimensional Poisson's equation in the illuminated condition can be written as

$$\frac{d^2\psi}{dx^2} = -\frac{q\rho(x)}{\epsilon_s} \tag{1}$$

where

$$\rho(x) = \sum_{i=1}^{n} \frac{\beta Q_i}{\sqrt{2\pi}\sigma_i}\exp\left[-\left(\frac{x-R_{pi}}{\sqrt{2}\sigma_i}\right)^2\right] - N_a \tag{2}$$

ψ is the surface potential, x is the direction along which ions are implanted, $\rho(x)$ is the effective carrier concentration at a distance x from surface and also is the impurity concentration in the ion implanted channel of the MESFETs after nitrogen activation by annealing, q is the electronic charge, ϵ_s is permittivity of 4H-SiC, β is the activation rate of ions, $Q(Q_i)$ is the implanted dose, $\sigma(\sigma_i)$ is the implanting straggle parameter, $R_P(R_{pi})$ is the implant range parameter, and N_a is the acceptor concentration. With the boundary conditions $\Phi(h) = 0$ and $E_x(h) = d\Phi/dx(h) = 0$, we get

$$\psi(x) = \sum_{i=1}^{n} \frac{q\beta Q_i}{2\epsilon_s}(x - R_{pi})\left[\mathrm{erf}\left(\frac{x-R_{pi}}{\sqrt{2}\sigma_i}\right) - \mathrm{erf}\left(\frac{W-R_{pi}}{\sqrt{2}\sigma_i}\right)\right] + \frac{q\beta Q_i\sigma_i}{\sqrt{2\pi}\epsilon_s}\left\{\exp\left[-\left(\frac{x-R_{pi}}{\sqrt{2}\sigma_i}\right)^2\right] - \exp\left[-\left(\frac{W-R_{pi}}{\sqrt{2}\sigma_i}\right)^2\right]\right\} - \frac{qN_a}{2\epsilon_s}(x-W)^2 \tag{3}$$

The pinch off voltage is

$$V_P = \frac{\Delta E_F}{q} - \psi(0)\big|_{W=a} = \sum_{i=1}^{n}\left\{\frac{q\beta Q_i R_{pi}}{2\epsilon_s}\left[\mathrm{erf}\left(\frac{h_0-R_{pi}}{\sqrt{2}\sigma_i}\right) - \mathrm{erf}\left(\frac{a-R_{pi}}{\sqrt{2}\sigma_i}\right)\right] + \frac{q\beta Q_i\sigma_i}{\sqrt{2\pi}\epsilon_s}\exp\left[-\left(\frac{a-R_{pi}}{\sqrt{2}\sigma_i}\right)^2\right] - \exp\left[-\left(\frac{h_0-R_{pi}}{\sqrt{2}\sigma_i}\right)^2\right]\right\} + \frac{qN_a}{2\epsilon_s}(a^2 - h_0^2) \tag{4}$$

where W is the thickness of depletion layer under gate, ΔE_F is the Fermi level difference between metal and 4H-SiC, h_0 is the thickness of static depletion layer under gate, and a is the channel depth.

The channel depth (a) can be calculated by the last time implantation. The distance (x_a) from SiC surfaces is the intrinsic point at which

$$qN_a = \frac{q\beta Q_3}{\sqrt{2\pi}\sigma_3}\exp\left[-\left(\frac{x_a-R_{p3}}{\sqrt{2}\sigma_3}\right)^2\right] \tag{5}$$

So we get

$$x_a = R_{p3} + \sigma_3\sqrt{2\ln\frac{\beta Q_3}{\sqrt{2\pi}\sigma_3 N_a}} \tag{6}$$

pn junctions between the buffer (the epitaxial layer) and the channel of MESFETs are abrupt junctions. So the thickness of the depletion layer in the n-region is

$$x_n = \left[\frac{2\epsilon_s N_a}{q(n+N_a)n}(V_D - V_A)\right]^{\frac{1}{2}} \tag{7}$$

where n is the effective carrier concentration, V_D is the build in voltage of pn junction, and V_A is the applied bias voltage. Thus the channel depth is determined by

$$a = x_a - x_n \tag{8}$$

The build in voltage of pn junction[11]

$$V_D = \frac{kT}{q}\ln\left(\frac{nN_a}{n_i^2}\right) \tag{9}$$

where n_i is the intrinsic carrier concentration, and

can be written as[12]

$$n_i(T) = n_i(T_0)\left(\frac{T}{T_0}\right)^{\frac{3}{2}}\exp\left[\frac{E_g(T_0)}{2kT_0} - \frac{E_g(T)}{3kT}\right] \tag{10}$$

Energy gap of 4H-SiC is written as[12,13]

$$E_g(T) = E_g(300) - 3.3\times10^{-4}(T - 300) \tag{11}$$

where $E_g(300) = 3.26\text{eV}$.

3 Simulation results and discussion

In order to obtain simulation results, we designed a triple implanted 4H-SiC MESFETs. Nitrogen ions of n-well region were implanted at energies and doses of 55keV and $1.07\times10^{13}\text{cm}^{-2}$, 100keV and $1.53\times10^{13}\text{cm}^{-2}$, and 160keV and $1.95\times10^{13}\text{cm}^{-2}$. The location of peak concentration and the longitudinal straggling of N were calculated with the Monte Carlo simulator TRIM. Figure 2 shows the ion implantation profiles using the Gaussian model for expressing the ion implantation ranges.

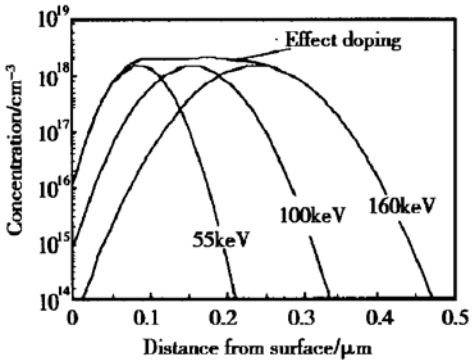

Fig. 2 Simulated ion implantation profiles for N implants into 4H-SiC

The activation of N by annealing in the range of 1400~ 1500℃ is about 10%~ 20%[1,2]. The implanting profile shown in Fig. 2 is expected to result in an effective doping concentration of $1.5\times10^{17}\text{cm}^{-3}$.

Figure 3 shows that the theoretical calculated pinch off voltage of the multiple ion implanted 4H-SiC MESFETs changes with the acceptor density. The activation rate here is 0.1 and temperature is 300K. While the channel depth decreases with increasing acceptor density of the epitaxial layer, the absolute value of the pinch off voltage decreases with increasing values of acceptor density of the epitaxial layer.

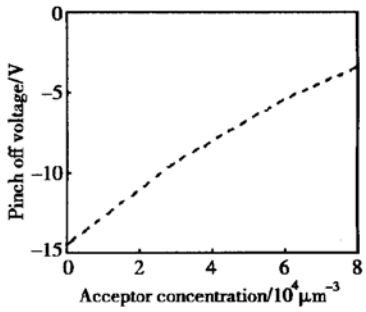

Fig. 3 Pinch off voltage versus acceptor density of the epitaxial layer

Figure 4 shows the pinch off voltage versus activation rate at three different temperature (300, 500, 700K), with $N_a = 6.5\times10^{15}\text{cm}^{-3}$ of the epitaxial layer. We only received one curve in Fig. 4 because the change of the pinch off voltage is small with increasing temperature (Fig. 5). Since the increase in activation rate increases the channel depth, the absolute value of the pinch-off voltage increases with the increase of activation rate.

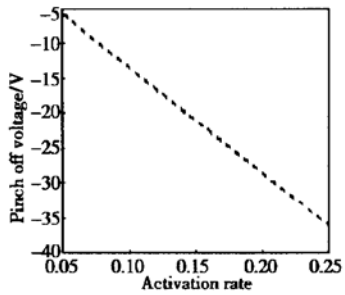

Fig. 4 Pinch off voltage versus activation rate

Considering the temperature dependent parameters, we got the curves of the pinch off voltage versus temperature in Fig. 5, which has the same values of the activation rate and temperature in Fig. 3. With the increase of temperature, the channel depth increases and the absolute value of the pinch off voltage increases too.

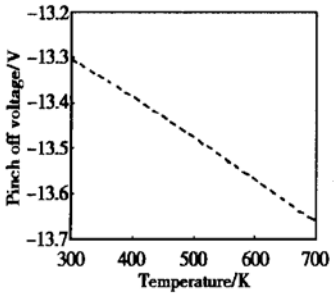

Fig. 5 Pinch off voltage versus temperature

4 Conclusion

An analytical model of the pinch off voltage of the multiple ion implanted 4H-MESFETs is given. The model is based on the Gaussian model for expressing the ion implantation ranges and the Monte Carlo simulator TRIM for calculating the implant depth profile. The effects of parameters such as temperature, acceptor density, and activation rate on the pinch off voltage are studied.

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离子注入 4H-SiC MESFET 器件的夹断电压*

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摘要: 考虑离子注入沟道和沟道深度的影响, 提出了精确的离子注入 4H-SiC MESFET 器件夹断电压的理论计算方法. 注入浓度由蒙特卡罗模拟软件 TRIM 提取计算. 研究了温度、外延层受主浓度、注入离子激活率对夹断电压的影响.

关键词: 碳化硅; 离子注入; MESFET; 夹断电压

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