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Parameter analysis for gate metal–oxide–semiconductor structures of ion-implanted 4H silicon carbide metal–semiconductor field-effect transistors

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From the theoretical analysis of the thermionic emission model of current–voltage characteristics, this paper extracts the parameters for the gate Schottky contact of two ion-implanted 4H-SiC metal–semiconductor field-effect transistors (sample A and sample B for three and four times multiple ion-implantation channel region respectively) fabricated in the experiment, including the ideality factor, the series resistance, the zero-field barrier height, the interface oxide capacitance, the interface state density distribution, the neutral level of interface states and the fixed space charge density. The methods to improve the interface of the ion-implanted Schottky contact are given at last.

Keywords: silicon carbide, interface states, ion-implantation, barrier height

PACC: 7155D, 7120C, 7320A, 7850G

1. Introduction

Ion implantation is a key fabrication process for the SiC devices. From the historical developments of the research about the ion-implantation of SiC materials, three periods for this research field can be summarised as follows. (1) Research on the process about the ion-implantation technique of SiC, such as aluminum, boron, nitrogen, phosphorus and their co-implantation or with carbon and so on,[1,2] the effects of the implantation temperature, post implantation annealing temperature, annealing methods and equipments and the surface protect methods on the quality of implanted layer.[3,4] (2) Research on the fabrication of SiC devices using ion-implantation as one process step, such as 4H-SiC trenched and implanted vertical-junction field-effect transistors, high voltage 4H-SiC bipolar junction transistors, high voltage junction barrier Schottky rectifiers and PiN rectifiers.[5,6] (3) Research on the active region of SiC devices by ion-implantation method, such as U-shape metal–oxide–semiconductor field-effect transistors (MOSFETs), lateral reduced surface field MOSFETs, high voltage short-channel vertical double-implanted MOSFETs and triple implanted vertical MOSFETs and so on.[7,8] The last period expands the utilisation of SiC material and more SiC devices with perfect functions can be realized. Ion-implanted metal–semiconductor field-effect transistors (MESFETs) show low cost production process, great low noise performance, higher speed characteristics and keeping planarity without mesa etching due to the creation of the active device region by an ion-implantation technique.[9,10] Ion-implanted channel of MESFETs is more controllable to form thinner and higher doped channel layers than those fabricated with conventional epitaxial growth, so it can improve radio frequency (RF) characteristics of MESFETs. References [11] and [12] reported the fabrication of a 2 μm gate length ion-implanted 4H-SiC MESFETs with the source, the drain and the channel regions made by ion-implantation. Recently, reference [13] reported the fabrication of a 0.5 μm gate 4H SiC MESFETs on semi-insulating substrate using ion-implantation for the channel and contact regions and had the same electrical characteristics as the epitaxial SiC MESFETs.

Ion-implanted MESFETs have metal–oxide–semiconductor (MOS) structures, gate Schottky contacts, which are fabricated on the implantation layers. The interface characteristics for the implanted Schottky contact are different from the conventional

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Schottky diode made on the epitaxial layer. In order to fabricate high performance SiC MESFETs, the interface characteristics about ion-implanted Schottky contacts are strongly desired to be investigated. In this work, the MOS structures of ion-implanted gate Schottky contacts have been analysed in detail. Multiple times ion-implanted 4H-SiC MESFETs (sample A for three times nitrogen ion-implantations and sample B for four) have been fabricated in the experiment. The parameters extraction method about the gate Schottky contacts of two ion-implanted 4H-SiC MESFETs are investigated on the thermionic emission method of current–voltage characteristics of the Schottky gate. The ideality factor n, the series resistance R_S, the zero-field barrier height ϕ_{B0}, the interface state density distribution D_{it}, the interface oxide capacitance C_i, the neutral interface level ϕ_0 and the fixed space charge density Q_{SC} of the ion-implanted gate Schottky contacts have been given. The potential methods to improve the quality of ion-implanted Schottky contacts are discussed at last.

2. Ion-implanted 4H-SiC MESFETs and Schottky contact structures

The 4H-SiC wafer used in the experiment is silicon-faced P-type epitaxial layer with a concentration of 6.5×10^{15} cm^{-3} and a depth of 1.8 μm based on the N-type substrate with a concentration of 7.1×10^{18} cm^{-3}. Figure 1 shows the structure of ion-implanted 4H-SiC MESFETs, whose N-wells of ion-implanted channel region is formed by multiple times nitrogen ion-implantation. Sample A is three times nitrogen ion-implantations with implanted energies and doses of 55 keV 1.07×10^{13} cm^{-2}, 100 keV 1.53×10^{13} cm^{-2} and 160 keV 1.95×10^{13} cm^{-2} respectively. Sample B is four times implantations with 55 keV 1.07×10^{13} cm^{-2}, 100 keV 1.53×10^{13} cm^{-2}, 160 keV 1.95×10^{13} cm^{-2} and 240 keV 2.34×10^{13} cm^{-2} respectively. The N$^+$ regions for Ohmic contacts are high dose nitrogen implantation with 30 keV and 3.54×10^{14} cm^{-2}. All implantation temperatures are 500 °C. The activation of nitrogen implanted for samples A and B are annealed at 1480 °C and 1650 °C respectively for 30 minutes in pure argon atmosphere. The gate Schottky contacts metal is Ti with a length of 2 μm and the Ohmic contacts metal is annealed Ni/Cr alloy. The source–gate and gate–drain spacings are 2 μm. Figure 2 gives the drain to source current I_{ds} versus the drain to source voltage V_{ds} for two ion-implanted 4H-SiC MESFETs (samples A and B), with the change of gate to source voltage V_{gs}. The pinch-off voltages for samples A and B are about –0.3 and –9.0 V respectively.

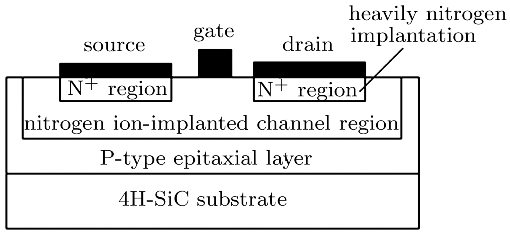

Fig. 1. Schematic cross section of ion-implanted 4H-SiC MESFETs.

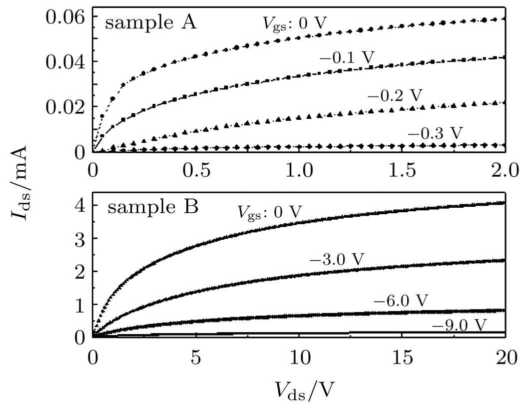

Fig. 2. Current–voltage characteristics of ion-implanted 4H-SiC MESFETs for samples A and B.

Unless specially fabricated, an actual Schottky contact is not an ideal metal–semiconductor type structure but an MOS type.[14] Ion-implanted MESFETs have the implanted channel region whose surface is suffered ion-implantation and high temperature annealing. Therefore, compared with conventional Schottky contact on the epitaxial layer, the native oxide layer between metal and semiconductor before Schottky metal deposition is significant for ion-implanted Schottky contact. The existence of such an interfacial oxide layer converts the Schottky contact to a MOS type and have a strong influence on the diode characteristics, such as a change of the interface state charge with bias will influence the field strength in the interfacial layer, a change of the barrier height will affect the current density of Schottky diode, the series resistance will deviate linearity of forward bias current–voltage characteristics in the semilogarithmic scale. Figure 3 gives the energy band diagram of the

4H-SiC gate Schottky contact with the multiple nitrogen ion-implantation doping channel region on the P-type epitaxial layer, where $q\phi_M$ is the work function of the Schottky metal, $q\phi_B$ is the barrier height, $q\chi$ is the electron affinity of 4H-SiC, $q\Delta\phi_B$ is the image force lowering, $E_F(E_{Fm}, E_{Fn}, E_{Fp})$ is the Fermi level, E_C is the bottom energy of the conduction band, E_V is the top energy of the valence band, qV_n is the potential energy from the Fermi level to the bottom energy of the conduction band, E_g is the bandgap energy for 4H-SiC, D_{it} is the interface state density distribution, ε_i is the dielectric constant of the interfacial oxide layer, δ is the thickness of the interfacial oxide layer, ϕ_0 is the neutral level of interface states, W is the width of the space charge region of the 4H-SiC, Q_{SC} is the fixed space charge density.

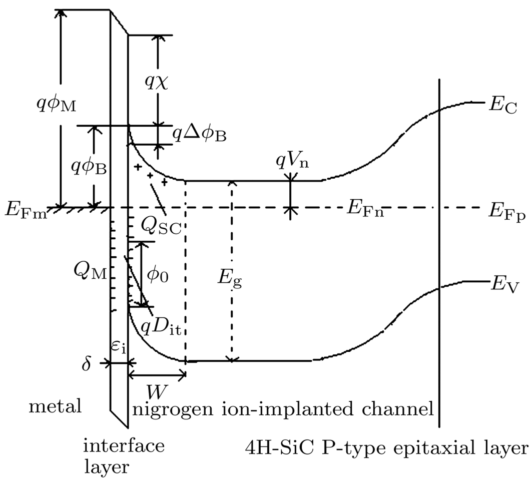

Fig. 3. Energy band diagram of gate Schottky region for ion-implanted 4H-SiC MESFETs.

The thin interfacial native oxide layer between the deposited metal and the semiconductor surface determines the performance and reliability of ion-implanted MESFETs. So it is required to determine the interface properties of the MOS Schottky diode and then improve their quality.

3. Theory for parameter analysis of the MOS structure Schottky gate

3.1. Effective barrier height

Using the thermionic emission theory, we can express the current through the gate Schottky contact of ion-implanted 4H-SiC MESFETs in the form

$$I = AA^*T^2 \exp\left(-\frac{q\phi_B}{kT}\right) \times \left\{\exp\left[\frac{q}{nkT}(V - IR_S)\right] - 1\right\}, \quad (1)$$

where A is the Schottky diode area, A^* is the Richardson's constant, n is the ideality factor, R_S is the series resistance and other constants have their usual meaning. At an ideal forward current–voltage linearity region, the ideality factor is given by

$$n = \frac{q}{kT}\frac{\partial V}{\partial \text{In} I} \quad (2)$$

and the series resistance can be

$$R_S = \left(1 - \frac{\partial \text{In} I}{\partial V}\frac{nkT}{q}\right) \Big/ \left(\frac{\partial I}{\partial V}\right). \quad (3)$$

Figure 4 shows the current–voltage characteristics of the gate Schottky contact of two ion-implanted 4H-SiC MESFETs. From Eqs. (2) and (3), we can obtain the ideality factors 2.9 and 2.4 for samples A and B respectively, and the series resistance 705 and 102 Ω for samples A and B respectively.

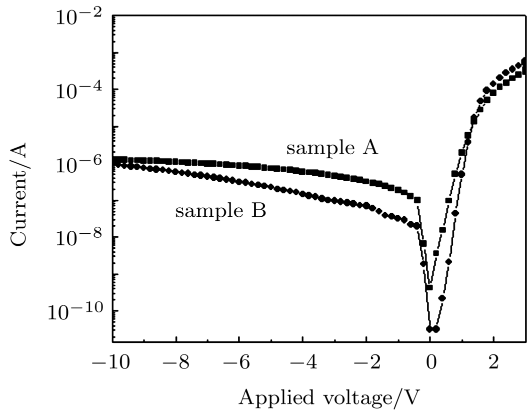

Fig. 4. Current–voltage characteristics of gate Schottky contacts of two ion-implanted 4H-SiC MESFETs.

At the low reverse voltage condition, the effective barrier height ϕ_B can be shown as

$$\phi_B = -\frac{kT}{q}\ln\left\{\frac{I}{AA^*T^2[\exp(qV/kT) - 1]}\right\}. \quad (4)$$

Reference [15] gives the effective barrier height ϕ_B with the electric field strength E_M as

$$\phi_B = \phi_{B0} - \lambda E_M - \sqrt{\frac{qE_M}{4\pi\varepsilon_0\varepsilon_s}}, \quad (5)$$

where ϕ_{B0} is the zero-field barrier height, λ is a constant with the dimension of thickness, ε_s is the electrical relativity permittivity of semiconductor, E_M is the electric field strength at the metal–semiconductor interface, which can be obtained by

$$E_{\mathrm{M}} = \sqrt{\frac{2qN_{\mathrm{d}}(V_{\mathrm{bi}} - V - kT/q)}{\varepsilon_0\varepsilon_{\mathrm{s}}}}. \quad (6)$$

Using Eqs. (4)–(6), we find that $\phi_{\mathrm{B}} + \sqrt{qE_{\mathrm{M}}/4\pi\varepsilon_0\varepsilon_{\mathrm{s}}}$ and E_{M} can have the relationship approximately of a line, from which ϕ_{B0} and λ can be obtained. Comparing with λE_{M}, we find that the image force barrier lowering $\sqrt{qE_{\mathrm{M}}/4\pi\varepsilon_0\varepsilon_{\mathrm{s}}}$ is negligible.

Figure 5 exhibits the effective barrier height and the image force lowering $\phi_{\mathrm{B}}+\sqrt{qE_{\mathrm{M}}/4\pi\varepsilon_0\varepsilon_{\mathrm{s}}}$ as a function of the electric field strength E_{M}, from which ϕ_{B0} and λ can be calculated, with the zero-field barrier heights 1.11 and 0.84 eV, the constant values λ 3.6 and 4.0 nm for samples A and B respectively.

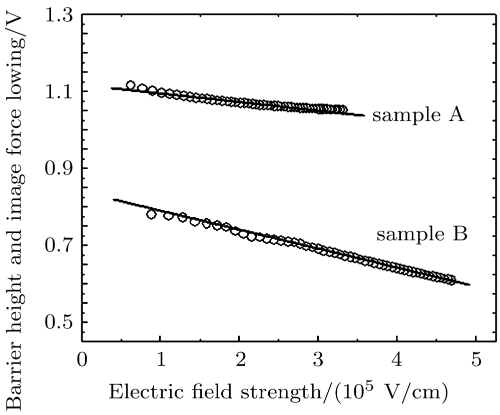

Fig. 5. Characteristics of $\phi_{\mathrm{B}} + \sqrt{qE_{\mathrm{M}}/4\pi\varepsilon_0\varepsilon_{\mathrm{s}}}$ and E_{M}.

3.2. Interface state distribution and oxide layer capacitance

Reference [16] gives the constant λ with the interface state density written as

$$\lambda = \varepsilon_0\varepsilon_{\mathrm{s}}\left(qD_{\mathrm{it}} + \frac{\varepsilon_0\varepsilon_{\mathrm{i}}}{\delta}\right)^{-1}. \quad (7)$$

When the interface states are in equilibrium with the semiconductor, they can also be given as[17]

$$qD_{\mathrm{it}} = \frac{\varepsilon_0\varepsilon_{\mathrm{i}}}{\delta}(n-1) - \sqrt{\frac{q\varepsilon_0\varepsilon_{\mathrm{s}}N_{\mathrm{D}}}{2\left(V_{\mathrm{bi}} - V - \dfrac{kT}{q}\right)}}. \quad (8)$$

So, the capacitance of the interfacial oxide layer C_{i} ($\varepsilon_0\varepsilon_{\mathrm{i}}/\delta$) can be

$$C_{\mathrm{i}} = \frac{\varepsilon_0\varepsilon_{\mathrm{s}}}{n\lambda} + \frac{1}{n}\sqrt{\frac{q\varepsilon_0\varepsilon_{\mathrm{s}}N_{\mathrm{D}}}{2\left(V_{\mathrm{bi}} - \dfrac{kT}{q}\right)}}. \quad (9)$$

With the constant values λ obtained above, the interfacial capacitances 7.52×10^{-7} and 10.24×10^{-7} F/cm^2 for samples A and B respectively can be obtained.

The energy E of the interface state density distribution D_{it} with respect to the bottom of the conduction band E_{C} can be shown as[18]

$$E_{\mathrm{C}} - E = q\phi_{\mathrm{B}} - qV, \quad (10)$$

where V is the applied voltage. The density distribution of the interface states in equilibrium with the semiconductor can be calculated from Eq. (8) as shown in Fig. 6.

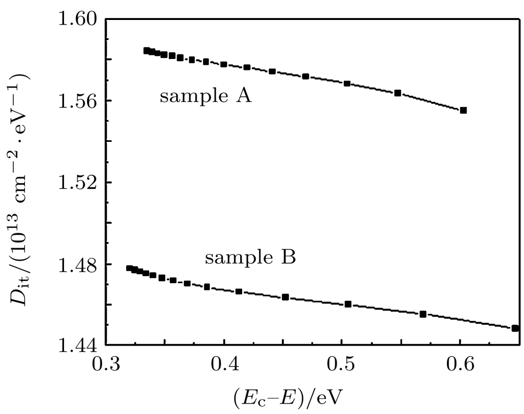

Fig. 6. Interface state density distribution for samples A and B.

According to the interfacial layer model, ϕ_{B0} can be expressed as[19]

$$\phi_{\mathrm{B0}} = \gamma(\phi_{\mathrm{m}} - \chi) + (1-\gamma)\left(\frac{E_{\mathrm{g}}}{q} - \phi_0\right), \quad (11)$$

where

$$\gamma = 1\Big/\left(1 + \frac{q\delta D_{\mathrm{it}}}{\varepsilon_{\mathrm{i}}}\right). \quad (12)$$

So, the neutral levels ϕ_0 of the interface states from the top of the valence band E_{V} are 2.10 and 2.46 eV for samples A and B respectively.

3.3. Fixed charge density

Only considering the work function of Schottky metal ϕ_{M} and the electron affinity χ, we find that the ideality barrier height for metal–semiconductor contact without the interfacial layer is

$$q\phi_{\mathrm{Bi}} = q\phi_{\mathrm{M}} - q\chi. \quad (13)$$

Then, the fixed space charge density can be[20]

$$Q_{\mathrm{SC}} = \frac{2\varepsilon_0\varepsilon_{\mathrm{i}}\Delta\phi_{\mathrm{B0}}}{\delta}. \quad (14)$$

For samples A and B, the fixed space charge density are 2.71×10^{12} and 2.46×10^{12} C/cm^2 for samples A and B respectively.

4. Discussion

The ideality factors n for ion-implanted gate Schottky contact in the experiment are bigger, what may come from the larger interface states,[17] residual defects[21] and surface roughening[22,23] of the Schottky barrier diodes. The higher interface state density comes from the ion-implanted surface of the 4H-SiC Schottky region, which is not smoothed in this work.[24,25] The series resistance is larger than conventional Schottky diodes from the lower value of the activation rate of the ion-implantations.

A higher implantation temperature above 500 °C,[22] rapid thermal annealing and a higher annealing temperature above 1650 °C[26,27] are in demand to receive a significant activation rate. In order to improve the surface quality of the ion-implanted layer, a protect cap should be used during the annealing period in the future.[28,29]

5. Conclusions

Ion-implanted 4H-SiC MESFETs have the gate Schottky contact made on an implanted layer, whose interfacial layer between metal and semiconductor will strongly influence the device characteristics, such as the ideality factor, Schottky barrier height and interface states density. Using the thermionic emission theory of the current–voltage characteristics of Schottky contacts, we have analysed the parameters for gate Schottky diodes of ion-implanted 4H-SiC MESFETs with the channel region fabricated by multiple ion-implantations (sample A for three times and sample B for four times) in the experiment. The ideality factor, the series resistance, the zero-field barrier height, the interfacial oxide capacitance, the interface state density distribution, the neutral interface level and the fixed space charge density of gate Schottky diodes of two ion-implanted 4H-SiC MESFETs have been presented. The interface quality between the metal and semiconductor surface should be improved during the fabrication of the implanted channel region. The potential methods for improving the implanted surface in the future have been given lastly.

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