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Parameter extraction for a Ti/4H-SiC Schottky diode*

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Based on the MIS model, a simple method to extract parameters of SiC Schottky diodes is presented using the I-V characteristics. The interface oxide capacitance $C_{\rm i}$ is extracted for the first time, as far as we know. Parameters of 4H-SiC Schottky diodes fabricated for testing in this paper are: the ideality factor n, the series resistance $R_{\rm s}$, the zero-field barrier height $\phi_{\rm B0}$, the interface state density $D_{\rm it}$, the interface oxide capacitance $C_{\rm i}$ and the neutral level of interface states ϕ_0.

Keywords: silicon carbide, interface states, Schottky diodes, barrier height
PACC: 7155D, 7120C, 7320A

1. Introduction

The SiC material has been widely investigated[1] and utilized as a promising material for high-temperature and high-power RF applications due to its high thermal conductivity, high breakdown electric field, and highly saturated electron drift velocity. SiC Schottky diodes are a key component of many SiC-based high-power devices, such as metal-semiconductor field-effect transistors, high-voltage rectifiers, and static induction transistors. A simple method is needed to obtain the parameters of SiC Schottky diodes, including ideality factor n, barrier height $\phi_{\rm B}$, specific resister $R_{\rm s}$, interface state density $D_{\rm it}$, interface oxide capacitance $C_{\rm i}$ and neutral interface level ϕ_0. Many authors have investigated some characteristics of Schottky diodes using I-V and C-V methods.[2−4] Parameters of Schottky diodes in Refs.[2] and [3] were obtained by assuming the values of the thickness and permittivity of the interfacial layer. None of them gave a method to calculate the interface oxide capacitance $C_{\rm i}$. The neutral interface level ϕ_0 of SiC Schottky diodes has not been known yet. In this paper, the parameters of SiC Schottky diodes are extracted from I-V characteristic analysis.

2. Device fabrication and experimental results

The 4H-SiC Schottky diodes were fabricated with the epilayer thickness being 10 μm, and N doping concentration being $1.4\times10^{16}{\rm cm}^{-3}$. Circular contacts of Ti/Al (150 nm/300 nm) were deposited by e-beam evaporation and patterned with a diameter of 1000 μm by lift off. The back side ohmic contacts were made of metal Ni (350 nm) deposited after the inductively coupled plasma, etching. The structure of a Schottky barrier diode investigated in this paper is shown in Fig.1. The I-V measurements were performed with an HP4156B semiconductor parameter analyser. Figure 2 exhibits the reverse and forward voltage-current characteristics of 4H-SiC Schottky diodes.

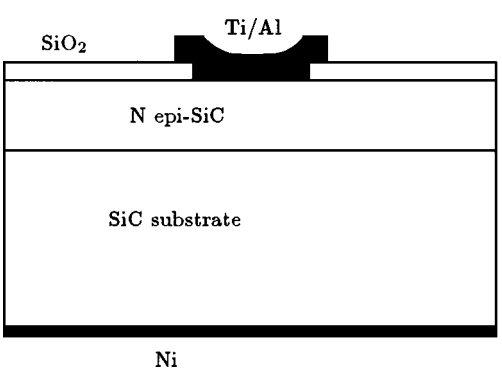


Fig.1. Schematic cross section of Ti/4H-SiC diodes.

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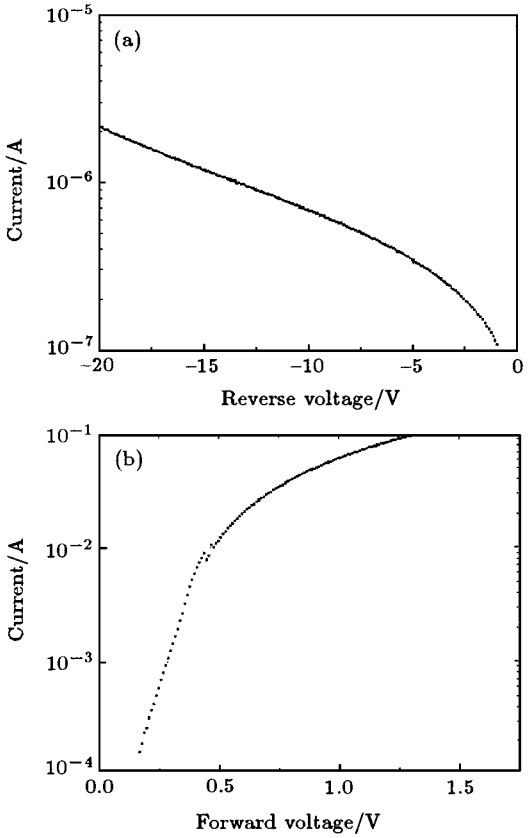


Fig.2. Reverse (a) and forward (b) voltage-current characteristics of 4H-SiC Schottky diodes.

3. The I-V characteristics analysis

3.1. Forward characteristics and parameter extraction

Using the thermionic emission theory, the current through the SiC Schottky diode can be expressed in the form

$$I = AA^*T^2\exp\left(-\frac{\phi_{\rm B}}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right)-1\right], \qquad (1)$$

where A is the diode area, A^* is the Richardson's constant, $\phi_{\rm B}$ is the Schottky barrier height, n is the ideality factor, and other constants have their usual meaning. At a low forward voltage, the ideality factor is given by

$$n = \frac{q}{kT}\frac{\partial V}{\partial \ln I}. \qquad (2)$$

If the forward voltage is larger than the threshold voltage, Eq.(1) is written as

$$I = AA^*T^2\exp\left(-\frac{\phi_{\rm B}}{kT}\right)\left\{\exp\left[\frac{q}{nkT}(V-IR_{\rm s})\right]-1\right\}, \qquad (3)$$

where

$$R_{\rm s} = \left(1-\frac{\partial \ln I}{\partial V}\frac{nkT}{q}\right)\Big/\left(\frac{\partial I}{\partial V}\right) \qquad (4)$$

is the series resistance.

3.2. Low reverse voltage characteristics and parameter extraction

On the low reverse voltage condition, we assume that the current-voltage character of a SiC Schottky diode obeys the thermionic current theory. Then Eq.(1) becomes

$$I = AA^*T^2\exp\left(-\frac{q\phi_{\rm B}}{kT}\right)\left[\exp\left(\frac{qV}{kT}\right)-1\right], \qquad (5)$$

where

$$\phi_{\rm B} = -\frac{kT}{q}\ln\left(\frac{I\Big/\left[\exp\left(\frac{qV}{kT}\right)-1\right]}{AA^*T^2}\right) \qquad (6)$$

is the barrier height, expressed as[5]

$$\phi_{\rm B} = \phi_{\rm B0} - \lambda E_{\rm M} - \sqrt{\frac{qE_{\rm M}}{4\pi\varepsilon_0\varepsilon_{\rm s}}}. \qquad (7)$$

Here $\phi_{\rm B0}$ is the zero-field barrier height, λ is a constant with the dimension of thickness, $\varepsilon_{\rm s}$ is the electrical relativistic permittivity of the semiconductor, $E_{\rm M}$ is the electric field strength at the metal/semiconductor interface, which can be obtained by

$$E_{\rm M} = \sqrt{\frac{2qN_{\rm d}(V_{\rm bi}-V-kT/q)}{\varepsilon_0\varepsilon_{\rm s}}}. \qquad (8)$$

Using Eqs.(6)–(8), $\phi_{\rm B}+\sqrt{\frac{qE_{\rm M}}{4\pi\varepsilon_0\varepsilon_{\rm s}}}$ and $E_{\rm M}$ can have the relationship approximately of a line, from which $\phi_{\rm B0}$ and λ can be obtained. Compared with $\lambda E_{\rm M}$, the image force barrier lowering $\sqrt{\frac{qE_{\rm M}}{4\pi\varepsilon_0\varepsilon_{\rm s}}}$ is negligible. Then λ can be written as[6]

$$\lambda = \varepsilon_0\varepsilon_{\rm s}\left(qD_{\rm it}+\frac{\varepsilon_{\rm i}}{\delta}\right)^{-1}, \qquad (9)$$

where $D_{\rm it}$ is the interface state density, and $\varepsilon_{\rm i}$ and δ are the permittivity and the thickness of the interfacial layer respectively. When the interface states are in equilibrium with the semiconductor, they can also be given as[7]

$$qD_{\rm it} = \frac{\varepsilon_{\rm i}}{\delta}(n-1) - C_{\rm sc}, \qquad (10)$$

where

$$C_{\rm sc} = \sqrt{\frac{q\varepsilon_0\varepsilon_{\rm s}N_{\rm D}}{2\left(V_{\rm bi}-V-\frac{kT}{q}\right)}} \qquad (11)$$

is the space charge capacitance. From Eqs.(9)–(11), we can obtain $D_{\rm it}$ and $C_{\rm i}\left(\frac{\varepsilon_{\rm i}}{\delta}\right)$.

According to the interfacial layer model, $\phi_{\rm B0}$ can be expressed as[8]

$$\phi_{\rm B0} = \gamma(\phi_{\rm M} - \chi) + (1-\gamma)\left(\frac{E_{\rm g}}{q} - \phi_0\right), \qquad (12)$$

where

$$\gamma = 1/(1 + q\delta D_{\rm it}/\varepsilon_{\rm i}), \qquad (13)$$

$\phi_{\rm M}$ is the work function of the metal, χ is the electron affinity, $E_{\rm g}$ is the band-gap energy of the 4H-SiC material, and ϕ_0 is the neutral level of the interface states measured from the top of the valence band $E_{\rm v}$.

3.3. Calculated results

Figure 2 shows the I-V characteristics of Schottky diodes. From Eqs.(2) and (4), we can obtain the ideality factor n=1.4 and the series resistance $R_{\rm s}$=6.1Ω (48 mΩcm^2). $\phi_{\rm B} + \sqrt{\frac{qE_{\rm M}}{4\pi\varepsilon_0\varepsilon_{\rm s}}}$ as a function of $E_{\rm M}$ is shown in the Fig.3, from which $\phi_{\rm B0}$ and λ can be calculated by using Eq.(12). We have $\phi_{\rm B0}$=0.75 eV, λ=2.83 nm.

By combining Eqs.(9)–(11), $D_{\rm it}$=5.2×10^{12}cm^{-2} eV^{-1} and $C_{\rm i}\left(\frac{\varepsilon_{\rm i}}{\delta}\right)$=2.2×10^{-6}F/cm^2 can be obtained.

Substituting the values of parameters obtained above in Eqs.(12) and (13), the neutral level of the interface states ϕ_0=0.75 from $E_{\rm v}$.

The ideality factor n is large, this comes from the interface states,[7] residual defects[9] and surface roughening[10,11] of the Schottky barrier diode. The surface of the 4H-SiC diode in this work was not smoothed so as to reduce the interface state density. A proper, etching condition can produce extremely smooth surface,[12] which will make the ideality factor n close to unity.[13]

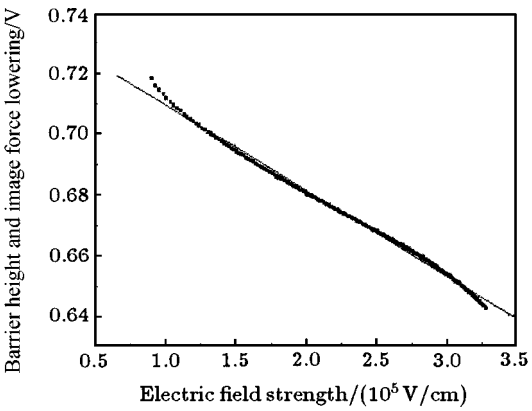


Fig.3. Characteristics of $\phi_{\rm B} + \sqrt{\frac{qE_{\rm M}}{4\pi\varepsilon_0\varepsilon_{\rm s}}}$ and $E_{\rm M}$.

4. Conclusions

Parameters, such as ideality factor, barrier height, specific resister, interface states and neutral interface level of SiC Schottky diodes have been studied using the thermionic emission theory, assuming the semiconductor is in equilibrium. For extracting the parameters, we have fabricated 4H-SiC diodes. The results obtained are: ideality factor n=1.4, series resistance $R_{\rm s}$=6.1Ω, zero-field barrier height $\phi_{\rm B0}$=0.75 eV, interface state density $D_{\rm it}$=5.2×10^{12}cm^{-2}eV^{-1}, interface oxide capacitance $C_{\rm i}\left(\frac{\varepsilon_{\rm i}}{\delta}\right)$=2.2×10^{-6}F/cm^2, and the neutral level of the interface states ϕ_0=0.7 eV.

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