Characteristics and parameter extraction for NiGe/n-type Ge Schottky diode with variable annealing temperatures*

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Current transport mechanism in Ni-germanide/n-type Ge Schottky diodes is investigated using current–voltage characterisation technique with annealing temperatures from 300 °C to 500 °C. Based on the current transport model, a simple method to extract parameters of the NiGe/Ge diode is presented by using the I–V characteristics. Parameters of NiGe/n-type Ge Schottky diodes fabricated for testing in this paper are as follows: the ideality factor n, the series resistance $R_{\rm s}$, the zero-field barrier height $\phi_{\rm b0}$, the interface state density $D_{\rm it}$, and the interfacial layer capacitance $C_{\rm i}$. It is found that the ideality factor n of the diode increases with the increase of annealing temperature. As the temperature increases, the interface defects from the sputtering damage and the penetration of metallic states into the Ge energy gap are passivated, thus improving the junction quality. However, the undesirable crystallisations of Ni-germanide are observed together with NiGe at a temperature higher than 400 °C. Depositing a very thin (∼1 nm) heavily Ge-doped n^+ Ge intermediate layer can improve the NiGe film morphology significantly.

Keywords: NiGe, Schottky diode, barrier height, parameter extraction

PACC: 7360, 7755, 7320A

1. Introduction

Schottky-barrier diode (SBD) is a conventional semiconductor device in integrate circuits, which has the functions of detecting, rectifying, modulating and mixing.[1−5] Besides, the structure of SBD is also the key components of metal-semiconductor field-effect transistors (MESFET), and static induction transistors (SIT).[6] As the scaling of silicon complementar metal oxide semiconductor (CMOS) devices becomes more and more challenging, both innovative structures and new materials with high carrier mobility are needed to continue improving the device performance. The Schottky-barrier (SB) metal oxide semiconductor field effect transistor (MOSFET), as a promising candidate structure for the 45 nm technology node and beyond, has been extensively studied. Ge or GeSi devices have also received much attention due to their high carrier mobilities and small bandgaps.[7,8] Pure Ge offers mobilities twice higher for electrons and four times higher for holes than Si. Recently, Ge MOSFETs have attracted much attention due to their high low-field carrier mobilities.[9] However, highly Ge-doped pn junction leakage is an issue concerned due to the narrow Ge band gap. Therefore, the germanide/Ge SBD is extensively studied. The practical germanide/Ge SBDs are not ideal devices because of the interface state defects and insulation layer between the germanide and Ge during the device fabrication. Therefore, a simple method is needed to obtain the parameters of the germanide/Ge diodes, including ideality factor n, barrier height $\phi_{\rm b}$, series resistance $R_{\rm s}$, and interface state density $D_{\rm it}$. Many authors have investigated some characteristics of SBDs by using I–V and C–V methods.[8,9] Parameters of SBDs in Refs. [10] and [11] were obtained by assuming the values of the thickness and permittivity of the interfacial layer, and the other unauthentic parameters, as well as by using a complicated extraction method. However, none of them gave a method to calculate the interface oxide capacitance $C_{\rm i}$. In the present paper, the germanide/n-type Ge (100) SBDs are experi-

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mentally investigated with variable annealing temperature. The parameters of Ni-germanide/Ge SBD are extracted from I–V characteristics analysis. Several devices with different thin heavily Ge-doped n^+ Ge intermediate doping layers are also characterised.

2. Device fabrication and experimental results

The Ni-germanide SBD was fabricated on n-type Ge substrate. The n-type Ge (100) wafers with an n-type doping concentration of about 8×10^{15} cm^{-3}, were first wet cleaned using acetone and dilute HF and dried with N_2 before gate growth. Nickel layers were deposited afterwards at room temperature by ion beam sputtering Ni target. Then the electrode contacts are patterned in an area of 10^{-2} cm^2 and the samples were annealed at different temperatures ranging from 300 °C to 500 °C for 5 min. The current–voltage (I–V) measurements were performed with an HP4156B semiconductor parameter analyser, while the capacitance–voltage (C–V) characteristics of the SBDs were measured by using a Keithley 590 C–V analyser.

Figure 1 exhibits the reverse- and the forward-voltage–current characteristics of fabricated NiGe/Ge SBDs with annealing temperatures from 300 °C to 500 °C. The typical I–V rectifier characteristics of the SBDs are shown. No current saturation occurs as a result of Schottky-barrier height lowering (SBHL) with electric field increasing when the device works under reverse-biased conditions. The C–V characteristics of NiGe/Ge SBDs with different annealing temperatures from 300 °C to 500 °C are shown under $f = 100$ kHz in Fig. 2 and the inset profile is the plot of $1/C^2$ versus applied voltage as a function of annealing temperature. A constant slope with respect to temperature indicates negligible trapping effects in these devices at various annealing temperatures.

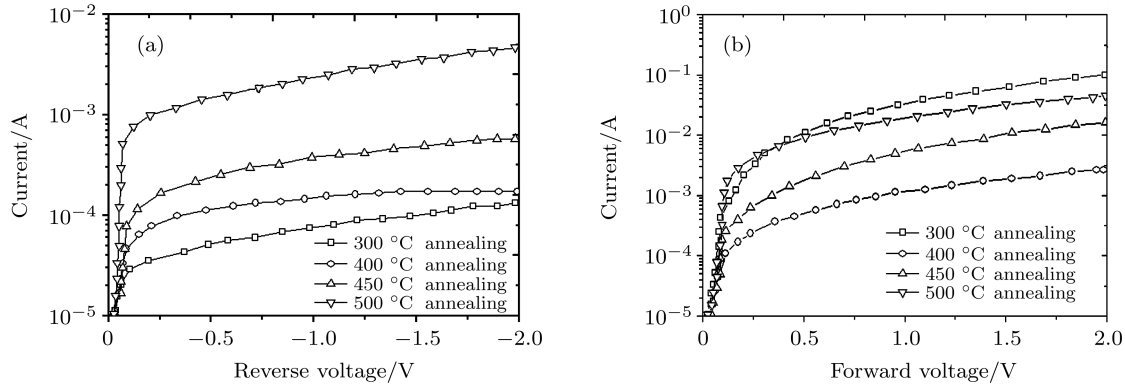


Fig. 1. Reverse (a) and forward (b) I–V characteristics of NiGe/Ge SBDs with different annealing temperatures.

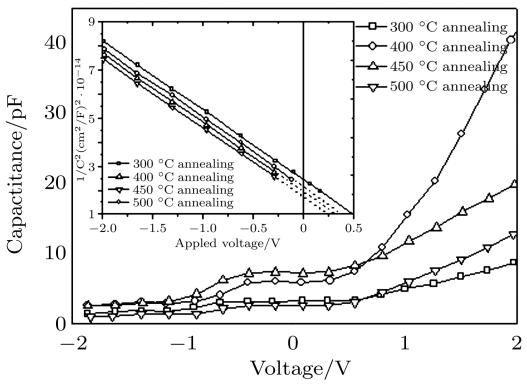


Fig. 2. C–V characteristics of NiGe/Ge SBDs with different annealing temperatures and the inset is the plot of $1/C^2$ versus applied voltage as a function of annealing temperature.

3. Extraction of diode parameters

Using the thermionic emission theory, the current though the NiGe/Ge SBDs can be expressed as follows:

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

where A is the diode area, A^* is the Richardson's constant, ϕ_b is the effective SBH, n is the ideality factor, and other constants have their usual meanings. At a lower forward voltage, n is given by

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

In a quasi-neutral region, the I–V characteristics are affected considerably by the series resistance $R_{\rm s}$, which is composed of the Schottky spreading resistance, ohmic contact resistance, and the resistance contributed by the neutral region of the semiconductor. $R_{\rm s}$ in an SBD is generally nonlinear, and it is a complicated function of the current flow in the device. On the other hand, the current flow is determined from the Schottky-barrier properties that strongly depend on the net voltage applied across the junction. Typical measured forward I–V characteristics are plotted in Fig. 3 and an equivalent circuit model is shown in the inset.

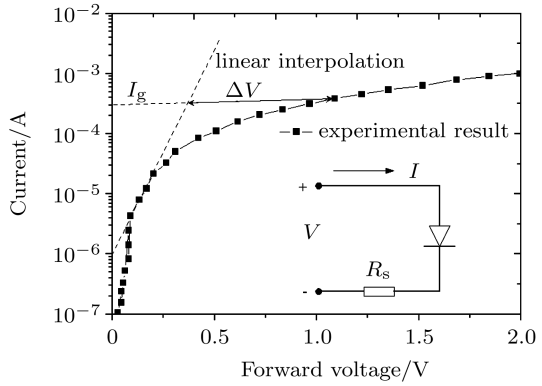


Fig. 3. Series resistance obtained by the conventional method.

In the conventional method, a linear interpolation is made and $R_{\rm s}$ at a given current $I_{\rm g}$ is determined from

$$R_{\rm s} = \frac{\Delta V}{I_{\rm g}}, \tag{3}$$

where ΔV is the voltage drop across the resistance. A new self-consistent method is developed to determine the series resistance of Schottky barrier junctions in the quasi-saturation regime of diode operation. If the forward voltage is larger than the threshold voltage, Eq. (1) can be written as

$$I = AA^*T^2 \exp\left(-\frac{q\phi_{\rm b}}{kT}\right)\left\{\exp\left[\frac{q}{nkT}(V - IR_{\rm s})\right] - 1\right\}, \tag{4}$$

where the $R_{\rm s}$ is given as

$$R_{\rm s} = \left(1 - \frac{\partial \ln I}{\partial V}\frac{nkT}{q}\right) \Big/ \left(\frac{\partial I}{\partial V}\right). \tag{5}$$

On the low reverse voltage condition, it is assumed that the current–voltage characteristic of a NiGe/Ge SBD obeys the thermionic current theory. Then Eq. (1) becomes

$$I = AA^*T^2 \exp\left(-\frac{q\phi_{\rm b}}{kT}\right)\left[\exp\left(\frac{qV}{kT}\right) - 1\right], \tag{6}$$

where

$$\phi_{\rm b} = -\frac{kT}{q}\ln\left(\frac{1\Big/\left[\exp\left(\frac{qV}{kT}\right) - 1\right]}{AA^*T^2}\right) \tag{7}$$

is the barrier height, expressed as[12]

$$\phi_{\rm b} = \phi_{\rm b0} - \lambda E_{\rm m} - \sqrt{\frac{qE_{\rm m}}{4\pi\varepsilon_0\varepsilon_{\rm s}}}, \tag{8}$$

where $\phi_{\rm b0}$ is the zero-field barrier height, λ is a constant with the same dimension as thickness, $\varepsilon_{\rm s}$ is the relativistic permittivity of Ge, and $E_{\rm m}$ is the electric field strength at the NiGe/Ge interface, which can be obtained from

$$E_{\rm m} = \sqrt{\frac{2qN_{\rm D}(V_{\rm bi} - V - kT/q)}{\varepsilon_0\varepsilon_{\rm s}}}. \tag{9}$$

Using Eqs. (7)–(9), $\phi_{\rm b} + \sqrt{qE_{\rm m}/4\pi\varepsilon_0\varepsilon_{\rm s}}$ and $E_{\rm m}$ can have an approximately linear relationship, from which $\phi_{\rm b0}$ and λ can be obtained. Compared with $\lambda E_{\rm m}$, the image force barrier lowering $\sqrt{qE_{\rm m}/4\pi\varepsilon_0\varepsilon_{\rm s}}$ is negligible. Then λ can be written as[13]

$$\lambda = \varepsilon_0\varepsilon_{\rm s}\left(qD_{\rm it} + \frac{\varepsilon_{\rm i}}{\delta}\right)^{-1}, \tag{10}$$

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 state is in equilibrium with the semiconductor, it can also be given as[14]

$$qD_{\rm it} = \frac{\varepsilon_{\rm i}}{\delta}(n-1) - C_{\rm sc}, \tag{11}$$

where $C_{\rm sc} = \sqrt{q\varepsilon_0\varepsilon_{\rm s}N_{\rm D}/2(V_{\rm bi} - V - kT/q)}$ is the space charge capacitance. $C_{\rm i} = \varepsilon_{\rm i}/\delta$ is the interfacial capacitance per unit. Now, the interface layer between the metal and the semiconductor is thought to be a very thin semi-insulated oxide or contamination layer, of which the thickness is on the order of nm.

4. Results and discussion

Figure 1 shows the I–V characteristics of the NiGe/Ge Schottky diodes with different annealing temperatures (from 300 °C to 500 °C). From Eqs. (2) and (6), the ideality factor n and the effective barrier height $\phi_{\rm b}$ calculated are plotted in Fig. 4. It is observed from Fig. 4 that the value of n is first increasing and then decreasing with annealing temperature increasing, which is responsible for the NiGe film

morphology changing and crystallisation. Besides, the barrier height increases with temperature increasing. This suggests the appearing of donor states, or the trapping of donor-like interface at the germanide interface. As annealing temperature increases, the donor states are occupied by electrons and interface trap density decreases, thereby increasing the barrier heights. Moreover, the barrier heights seen from the I–V curves are lower than those from the C–V curves as shown in Fig. 4. This is because the voltage measured is larger than the voltage over the NiGe/Ge junction due to the existence of the thin insulator layer between NiGe/Ge and series resistance $R_{\rm s}$.

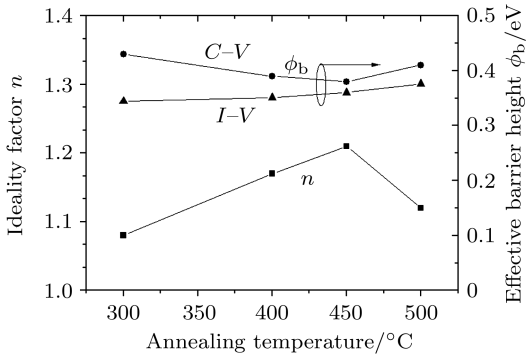


Fig. 4. Curves for n and $\phi_{\rm b}$ of NiGe/Ge SBD versus annealing temperatures.

The resistances extracted from these two methods are plotted as a function of diode current and annealing temperature in Fig. 5. From Eq. (3), the series resistance is calculated from the I–V curves with a fixed current, thus nonlinear series resistances with different currents. The series resistance obtained from Eq. (5) is nonlinear, which is also calculated from the measured I–V curves. Moreover, the series resistance composed of the Schottky external resistance, the ohmic contact resistance and the series resistance in the neutral region, varies with the voltage stress or the current stress, thus it is nonlinear. Above all, the nonlinear nature of $R_{\rm s}$ is evident. Its value calculated by the conventional method is always higher than that obtained from the new approach developed here.

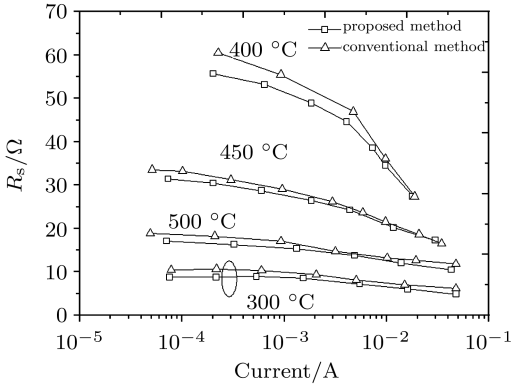


Fig. 5. Comparison between series resistances obtained by two methods in NiGe/Ge SBDs with different annealing temperatures.

The relation between $\phi_{\rm b} + \sqrt{qE_{\rm m}/4\pi\varepsilon_0\varepsilon_{\rm s}}$ and $E_{\rm m}$ as a function of annealing temperature of diode is shown in Fig. 6, indicating that the relationship is approximately linear. From Fig. 6, the slopes and the intercepts of these fitting curves are λ and the zero-field barrier height $\phi_{\rm b0}$, respectively, which are shown in Table 1. As a comparison, the $\phi_{\rm b0}$ obtained by the C–V method is also given in Table 1. Combining Eqs. (10) and (11), $D_{\rm it}$ and $C_{\rm i}(\varepsilon_{\rm i}/\delta)$ can be obtained as shown in Table 1.

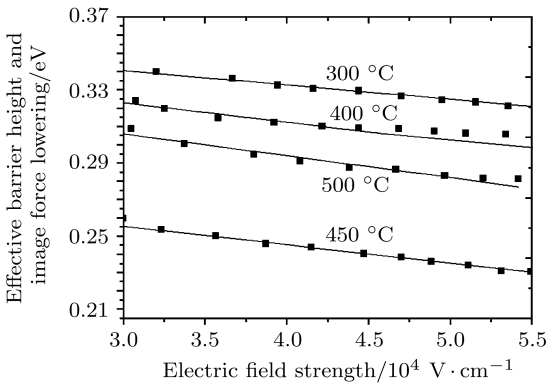


Fig. 6. Measured and fitting curves for $\phi_{\rm b} + \sqrt{qE_{\rm m}/4\pi\varepsilon_0\varepsilon_{\rm s}}$ versus $E_{\rm m}$.

Table 1. $\phi_{\rm b0}$, λ, $C_{\rm i}$ and $D_{\rm it}$ in NiGe/Ge SBDs with annealing temperatures from 300 °C to 500 °C.

parameters	temperature			
	300 °C	400 °C	450 °C	500 °C
$\phi_{\rm b0}$/eV	0.458	0.360	0.351	0.444
λ/nm	1.72	1.83	1.81	2.25
$C_{\rm i}$/F·cm^{-2}	1.786×10^{-6}	1.312×10^{-6}	1.201×10^{-6}	1.419×10^{-6}
$D_{\rm it}$/cm^{-2}·eV^{-1}	2.33×10^{11}	1.48×10^{11}	1.11×10^{11}	4.56×10^{10}

From the extracted parameters it follows that the interface state density of NiGe/Ge junctions is decreasing while the ideality factor n and the effective barrier height are increasing with annealing temperature increasing. The reduction of the interface state density is due to the fact that the interface defects are passivated with annealing temperature increasing. However, the undesirable crystallisation of Ni-germanide was observed together with NiGe at annealing temperatures higher than 400 °C, which results in the degrading of Ni-germanide quality and the increasing of n and $\phi_{\rm b}$. The x-ray diffraction (XRD) spectra show that the Ni-germanide is formed and the crystallisation peak (at $2\theta = 34.6°$) corresponding to the (111) phase is observed in each sample. However, the crystallisation peaks of the (121) and (002) phases are observed only in the samples at annealing temperatures higher than 400 °C. It is found that adding a very thin heavily Ge-doped n^+ Ge intermediate layer can improve the Ni-germanide film morphology significantly, because the n^+ Ge may suppress the crystallisation of NiGe during its growth. However, the thickness and the doping density of the n^+ intermediate layer need to be controlled strictly because the NiGe/Ge diode maybe lose the rectifying characteristics and turns into the ohmic contact with higher thickness or doping density.

Several NiGe/Ge SBDs with different thicknesses of intermediate n^+ Ge were characterised, with the doping density of n^+ Ge fixed at 1×10^{18} cm^{-3}. The barrier height and the diode ideality factor n obtained from the current–voltage characteristics are plotted in Fig. 7, at room temperature. With the thickness of intermediate layer increasing, the value of n is decreasing at $t_{\rm s} < 1$ nm and then increasing over 1 nm, while the barrier height is always decreasing in the range of interest. Due to the thin n^+ Ge layer, the tunneling currents from the field-enhanced emission exceeds the thermionic emission current at $t_{\rm s} = 1$ nm. When $t_{\rm s} = 1.5$ nm, these NiGe/Ge diodes lose their rectifying functions and exhibit nearly ohmic characteristics.

The discrepancy between the devices with heavily doped intermediate layer and without heavily doped interfacial layer, shown in Fig. 7, occurs primarily as a result of excessive tunneling currents in reduced-barrier devices. A qualitative understanding of this phenomenon can be obtained from Fig. 8 where the ratio of tunneling current to thermionic emission current is plotted versus intermediate layer thickness $t_{\rm s}$. With $t_{\rm s} = 1$ nm, the minimum of the electron potential appears within the intermediate layer and therefore enhances the field emission.

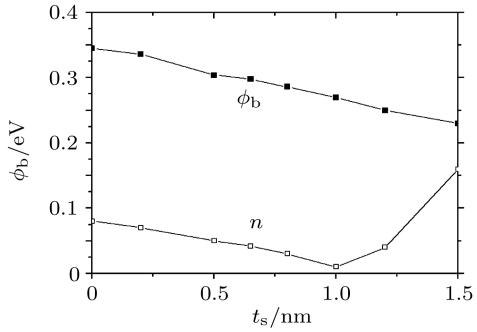


Fig. 7. NiGe/Ge Schottky diode parameters versus intermediate doping thickness.

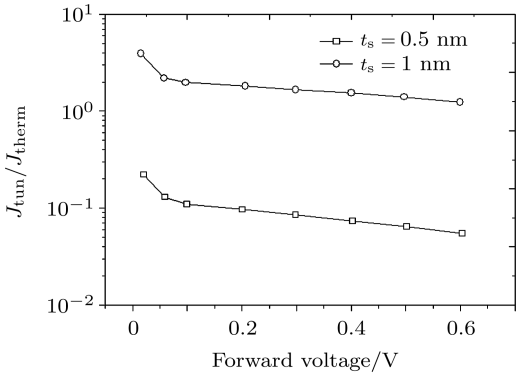


Fig. 8. Ratio of tunneling current to thermionic emission current with variable intermediate doping thickness at $T = 300$ K for the NiGe/Ge Schottky diodes.

In a device with $t_{\rm s} = 1.5$ nm, the current–voltage characteristics are symmetrical and linear around the origin, and, therefore, these devices exhibit nearly ohmic characteristics. The specific contact resistance Rc obtaind from

$$R_{\rm c} = \left(\frac{\partial J}{\partial V}\right)^{-1}\Bigg|_{V=0} \tag{12}$$

is shown in Fig. 9 as a function of temperature. The values of the effective barrier height for thermionic

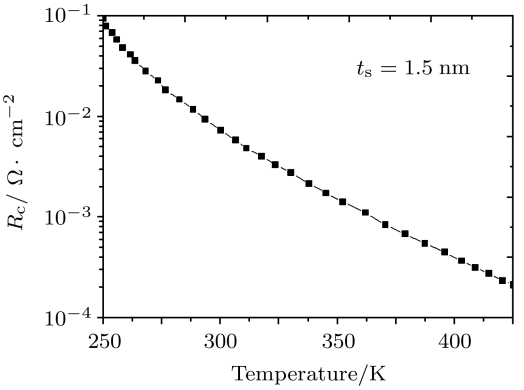


Fig. 9. Specific contact resistance as a function of the temperature with $t_{\rm s} = 1.5$ nm.

emission $\phi_{\rm b}$ in these contacts are calculated to be approximately 0.4 eV, and the mode of current flow turns dominant because of tunneling effect at all temperatures. The room-temperature contact resistance calculated from the thermionic-field-emission model for the same doping parameter is 0.007 $\Omega/{\rm cm}^2$.

5. Conclusion

Ni germanide Schottky barrier diodes are fabricated with annealing temperatures ranging from 300 to 500 °C. The electrical characteristics of NiGe/n-type Ge are investigated, and the Schottky diodes with typical I–V rectifier characteristics are obtained. Parameters, such as ideality factor, barrier height, series resistance, interface state and the interface oxide capacitance of the NiGe/Ge diode are extracted based on the thermionic emission theory, on the assumption that the semiconductor is in equilibrium. Depositing a very thin (∼1 nm) heavily Ge-doped n^+ Ge intermediate layer can improve the NiGe film morphology significantly and reduce the barrier height. The results obtained will be helpful for fabricating the Ge-based Schottky barrier FET. The physical characterisation of the Ge device will be further discussed in future.

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