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Research paper

Effects of Ta-oxide interlayer on the Schottky barrier parameters of Ni/n-type Ge Schottky barrier diode

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ABSTRACT

The effect of Ta-oxide interlayer on the Schottky barrier parameters of Ni/n-type Ge Schottky barrier diode (SBD) was investigated. The introduction of the Ta-oxide interlayer in-between Ni film and Ge substrate resulted in an increase in the barrier height as against the conventional Ni/n-type Ge SBD. Furthermore, increase in the thickness of the Ta-oxide interlayer led to the increase in barrier height and decrease in ideality factor, which could be associated with the improvement of interface quality of Schottky junction. 5 nm-thick Ta-oxide interlayer was more stoichiometric than 3 nm-thick Ta-oxide one, which was effective in the reduction of interface state density and ideality factor. An investigation of the electric field dependence of the reverse current in the Ni/n-type Ge SBDs with and without Ta-oxide revealed that the Poole-Frenkel emission mechanism dominates the current conduction of both devices in the reverse bias region.

1. Introduction

Germanium (Ge) is a promising candidate as a channel material of future complementary metal-oxide semiconductor (CMOS) due to its inherent property of high carrier mobility of both electrons and holes than Si, which is suitable for the enhancement of device performance [1]. In order to realize high performance Ge-based devices, well controlled electrical contacts are essential. Metal-semiconductor (MS) Schottky contacts are basic device structure in semiconductor technology and have been widely used in semiconductor industry [2]. Due to the technological importance of the Schottky contacts, there have been considerable efforts to fully understand their electrical properties over the past several decades [3]. In general, the interface property of Schottky junction is one of the most important key factors to determine the operation and performance of Schottky devices. Practically, the metal-semiconductor contact is not intimate contacts but it possesses a thin insulating interfacial layer between metal and semiconductor, unless it specially fabricated [4]. The existence of such an interfacial layer converts the MS Schottky device into a metal-insulator-semiconductor (MIS)Schottky device, which gives a significant effect on its Schottky barrier parameters such as barrier height, ideality factor, interface trap density, and series resistance [5,6]. In a recent year, MIS Schottky barrier diodes (SBDs) become more and more important in a great variety of fields of modern semiconductor technology since the thin insulator layer facilitates the modification of Schottky barrier properties [3,7,8]. Until now, there are a vast number of experimental and theoretical studies on electrical characteristics of MIS SBDs [9,10]. They showed that the operation and reliability of MIS SBDs are strongly dependent on the quality and the technological controllability of the thin insulator layer between metal and semiconductor. In particular, MIS structures are preferred to Ge-based Schottky devices since insulator layer allows a modification of the effective barrier height caused by affecting interfacial potential barrier of Schottky junction [11,12]. In other word, by employing thin insulator layer, Schottky barrier properties of Ge-based Schottky devices can be effectively improved. Despite prominent features of MIS structures, however, the detail knowledge about MIS-type Ge Schottky devices remains unclear. Moreover, there are only a few studies focused on the modulation of the electrical characteristics of Ge-based Schottky devices with variable thickness of the insulating layer [13,14]. In this work, we fabricated Ni/n-type Ge SBDs with 3 and 5 nm-thick Ta-oxide interlayer and investigated their electrical properties using the current-voltage (*I-V*) characteristics. Emphasis is placed on investigating the effect of the thickness of Ta-oxide interlayer on Schottky barrier properties of Ni/n-type Ge SBD. It will be shown that the introduction of Ta-oxide interlayer in-between Ni film and Ge

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substrate is effective for the increase in barrier height and a decrease in the interface states. Furthermore, the possible current conduction mechanism of the Schottky contacts modified using Ta-oxide interlayer in the reverse bias will be also examined.

2. Experimental details

Sb-doped n-type Ge (100) wafers with a carrier concentration of 1×10^{18} cm^{-3} were used as a starting material in this work. The wafers were initially cleaned in an ultrasonic bath of acetone and isopropanol for 5 min in each for the removal of contaminants, followed by the removal of the native oxide using buffered oxide etch (BOE) solution. The square patterns with a dimension of 300 μm × 300 μm were defined by means of standard photolithography. Afterward, the patterned wafers were dipped into a BOE solution, and immediately loaded into the E-beam evaporation chamber. The 3-or 5-nm thick Ta-oxide film and 50-nm thick Ni film were sequentially deposited by the E-beam evaporation under a pressure of 1×10^{-6} Torr, followed by patterning using lift-off process. Transmission electron microscope (TEM) measurements (not shown here) revealed that the deposited Ta-oxide films had an amorphous nature. Finally, Al metallization was made on the back side of the Ge substrate as Ohmic contact. For a comparison, the Ni Schottky contact without a Ta-oxide interlayer was fabricated on n-type Ge wafer under the same process conditions. The *I-V* characteristics of the Ni/n-type Ge Schottky diode with and without Ta-oxide interlayer were measured using a semiconductor parameter analyzer (Agilent4155A). X-ray photoemission spectroscopy (XPS; K-alpha, Thermo scientific Inc.) was employed to identify chemical bonding nature of Ta-oxide film. The C1 s peak in the air was fixed to 285.0 eV to set the binding energy scale and the XPS data processing (deconvolution) was performed using CASAXPS software (Version 2.3.16., U.K.).

3. Results and discussion

Fig. 1 shows the room temperature *I-V* characteristics of the Ni/n-type Ge SBDs with and without the Ta-oxide interlayer. All the devices exhibited relatively good rectifying behavior. The introduction of Ta-oxide interlayer led to the decrease in reverse leakage current. Moreover, reverse leakage current decreased with increasing the thickness of Ta-oxide interlayer. This implies the modulation of Schottky barrier height of Ni/n-type Ge Schottky contact caused by presence of Ta-oxide interlayer. Based on the thermionic emission theory, the Schottky barrier parameters of Ni/n-type Ge SBDs with and without the Ta-oxide interlayer were quantitatively evaluated. When a Schottky contact with

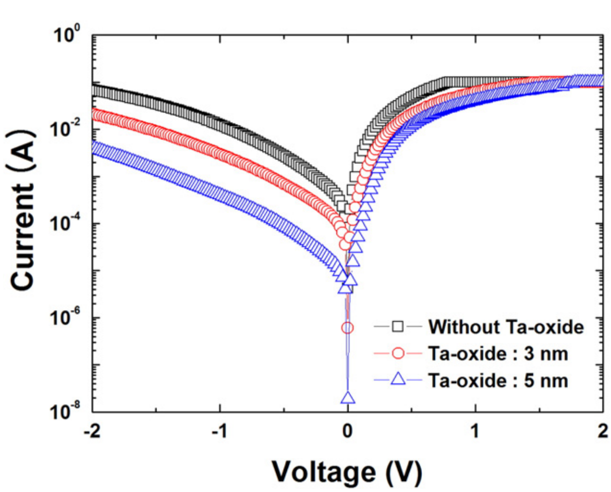

Fig. 1. *I-V* characteristics of the Ni/n-type Ge SBDs with and without the Ta-oxide interlayer measured at room temperature.

series resistance and an interfacial layer is considered with respect to forward bias voltages of V > 3kT/q, we assumed that the net current is due to thermionic emission current that can be described as [9]:

$$I = I_o \exp\left[\frac{q(V-IR_S)}{nkT}\right]\left\{1-\exp\left[\frac{q(V-IR_S)}{kT}\right]\right\} \tag{1}$$

where I is the measured current, V is the applied voltage across the junction, R_S is the series resistance, q is the electronic charge, k is the Boltzmann's constant, T is the absolute temperature is kelvin, n is the ideality factor, and I_0 is the saturation current derived from the straight line intercept of the plot of ln (I) versus V at $V = 0$ given by

$$I_0 = AA^*T^2 \exp\left(\frac{q\Phi_{b0}}{kT}\right) \tag{2}$$

where A is the device area, A^* is the Richardson constant (140 A cm^{-2} K^{-2} 2 for n-type Ge was assumed in this study), Φ_{b0} is the barrier height determined from I_0 using

$$\Phi_{b0} = \frac{kT}{q} \ln\left(\frac{AA^{**}T^2}{I_0}\right). \tag{3}$$

The ideality factor n was determined from the slope of the linear region of the forward bias ln(I)–V plot, and measures the conformity of the diode due to pure thermionic emission, which can be expressed by

$$n = \frac{q}{kT}\left(\frac{dV}{d(\ln I)}\right). \tag{4}$$

The values of barrier height and ideality factor extracted using the forward bias ln(I)–V plot were summarized in Table 1. It is clear that the ideality factor and barrier height were strongly affected by the presence of Ta-oxide interlayer. The barrier height and ideality factor for the Ni/n-type Ge SBD were obtained as 0.46 eV and 1.57, respectively. The barrier height of the Ni/n-type Ge SBD was lower than those reported previously [15,16], associated with the high doping concentration of the Ge substrate used in this work. On the other hand, the barrier height and ideality factor of the Ni/n-type Ge Schottky SBD with 3 nm-thick Ta-oxide interlayer were 0.50 eV and 1.52, respectively and those of the SBD with 5 nm-thick Ta-oxide interlayer were 0.56 eV and 1.15, respectively. Namely, the barrier height of Ni/Ta-oxide/n-type Ge Schottky SBDs was higher than that of conventional Ni/n-type Ge Schottky SBD. This implies that Ta-oxide interlayer influenced the interfacial potential barrier of the Ni/n-type Ge Schottky junction, resulting in a modification of the effective barrier height. Furthermore, barrier height increased with increasing the thickness of Ta-oxide interlayer as reflected in the decrease in reverse leakage current. Such an increase in barrier height could be attributed to the amendment of the interface states that control the barrier height, which will be discussed later. For all devices, the ideality factors were greater than unity, implying their deviation from the ideal thermionic emission. This could be due to the potential drop in the interface layer, the presence of excess current and the recombination current through the interfacial states between the semiconductor and interlayer [17]. Also, the possible reasons include various effects such as in homogeneities of the interlayer, series

Table 1
Schottky barrier parameters measured using various methods (barrier height, ideality factor, and series resistance) of Ni/n-type Ge SBDs with and without Ta-oxide interlayer.

Sample	Barrier height (eV)			Ideality factor (n)		Series resistance (Ω)	
	I-V	H(*I*)	Norde	*I-V*	dV/d(ln*I*)	H(*I*)	dV/d(ln*I*)
Without Ta-oxide	0.46	0.48	0.47	1.57	3.25	4.1	4.5
Ta-oxide: 3 nm	0.50	0.64	0.52	1.52	2.48	9.8	11.1
Ta-oxide: 5 nm	0.56	0.65	0.60	1.15	2.35	15.3	14.9