Conduction Mechanism of Se Schottky Contact to n-Type Ge

V. Janardhanam, Yang-Kyu Park, Hyung-Joong Yun, Kwang-Soon Ahn, and Chel-Jong Choi

***Abstract*—The conduction mechanism of Se/n-type-Ge Schottky diodes is investigated using temperature-dependent current–voltage (I–V) characteristics. The presence of microscopic inhomogeneity at the Se/Ge interface could be the primary cause of the differences between the barrier heights measured from the I–V and capacitance–voltage (C–V) characteristics. The position of the quasi-Fermi level suggested the dominance of thermionic emission in the forward bias region. The electric field dependence of the reverse current revealed that Schottky emission, along with the generation mechanism, has dominance over the current conduction in the reverse bias region.**

***Index Terms*—Germanium, Schottky diodes, semiconductor–metal interfaces, thermionic emission.**

I. Introduction

THE CONTINUOUS scaling-down of microelectronic devices to deep-submicrometer dimensions increases the need for fabrication of high-quality rectifying contacts [1]. Ge-based Schottky rectifiers exhibit superior device performance compared to Si-based rectifiers due to the inherent material property of Ge such as high carrier mobility, which is suitable for an enhancement in device speed [2]. Until now, Pt has been widely used in the semiconductor industry for the fabrication of Schottky rectifiers because of its high work function (5.65 eV). However, as considering that rectifying properties of Schottky devices are highly dependent on the metal's work function, Ge-based Schottky contacts fabricated using Se as the Schottky metal, having the highest work function (5.9 eV) of all the chemical elements [3], can be expected to provide superior device performance compared to Pt contacts to Ge. Furthermore, Se is much cheaper than Pt. Namely, Se can be effectively employed to fabricate high-performance and low-cost Schottky devices. However, the fabrication of Se Schottky contact to Ge and the analysis of its electrical properties have not been accomplished to date. This letter investigates the conduction mechanism of Se/n-type-Ge Schottky diodes in forward and reverse bias regions using temperature-dependent current-voltage (I–V) characteristics. It will be shown that the dominant current transport mechanisms in forward and reverse bias regions are driven by thermionic emission and Schottky emission along with a generation mechanism, respectively.

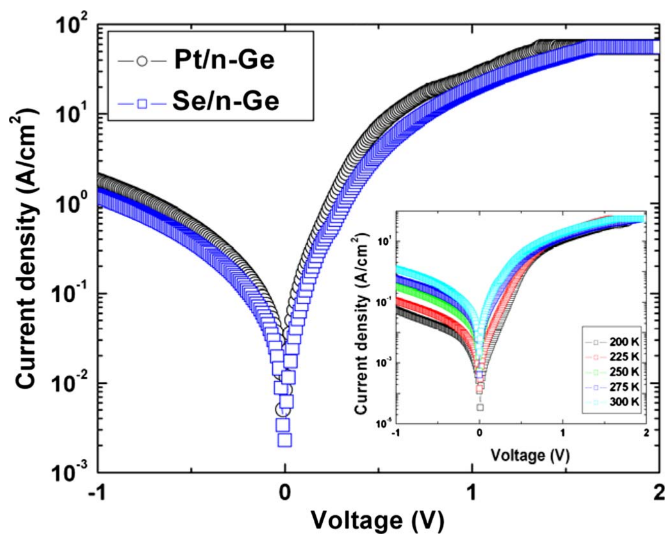

Fig. 1. J–V characteristics of Se and Pt Schottky contacts to n-type Ge at room temperature. The inset shows the temperature-dependent J–V characteristics of a Se/n-type-Ge Schottky diode in the temperature range of 200–300 K.

II. Experimental Procedure

Our experiments started with Sb-doped n-type-Ge (100) wafers with a doping concentration of 2×10^{18} cm^{-3}. After removing native oxide, 100-nm-thick Se films as Schottky metal were thermally evaporated from a stainless steel effusion cell under a base pressure of 1×10^{-6} torr at room temperature. Al metallization was done on the back surface of the Ge substrate as ohmic contacts. The Schottky contacts were defined with an area of 300×300 μm^2 using lift-off lithography. For comparison, 30-nm-thick Pt Schottky contacts were made on n-type-Ge wafers using the same process conditions. I–V and capacitance-voltage (C–V) measurements were accomplished using a precision semiconductor parameter analyzer (Agilent 4156C) and a precision LCR meter (Agilent 4284A), respectively. The microstructures of the Se/Ge interface were characterized using transmission electron microscopy.

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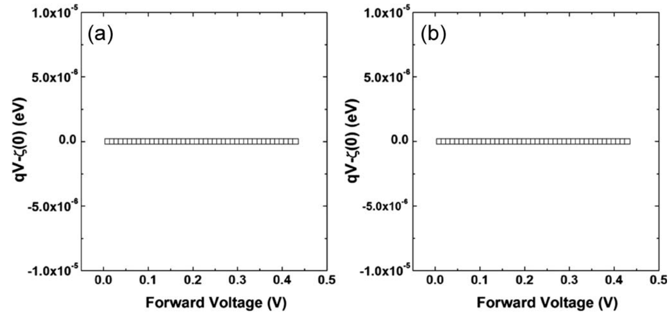

Fig. 2. Differences between the quasi-Fermi levels in the bulk qV and at the interface $\zeta(0)$ as a function of the forward bias at (a) 200 and (b) 300 K.

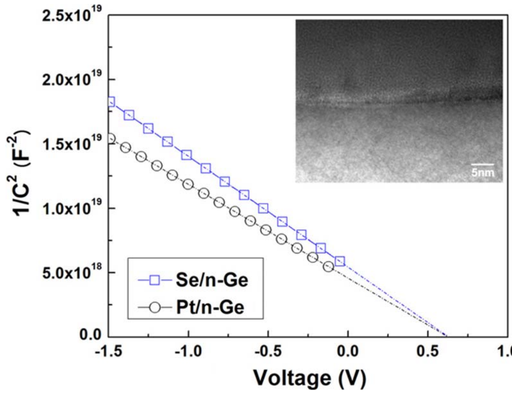

Fig. 3. Reverse bias $1/C^2-V$ characteristics of Se/n-type-Ge and Pt/n-type-Ge Schottky diodes at room temperature. The inset shows a high-resolution electron microscopy image taken from the Se/Ge interface.

III. Results and Discussion

Fig. 1 shows the current-density–voltage (J–V) characteristics of the Se and Pt Schottky contacts to n-type Ge at room temperature. The barrier heights and ideality factors were calculated to be 0.55 eV and 1.3, respectively, for the Se/n-type-Ge Schottky contact, and 0.51 eV and 1.1, respectively, for the Pt/n-type-Ge Schottky contact. The ideality factor was obtained in the range of 0.01–0.1 V. It was reported that Ge shows strong Fermi-level pinning at the charge neutrality level [4]–[6]. Nevertheless, the barrier height of the Se/n-type-Ge Schottky contact was higher than that of the Pt/n-type-Ge structure. This could be attributed in part to a higher work function for Se than Pt and to Fermi-level depinning caused by either the Se–Ge reaction or the Se passivation of the Ge surface. In fact, X-ray photoemission spectroscopy results (not shown here) demonstrated that the Ge $3d$ peak in the Se/Ge interface was shifted by $\sim$0.7 eV toward the higher energy side, as compared to the Ge $3d$ peak in the Ge substrate. This indicates Se–Ge interfacial reaction occurring during Se deposition. The details for the Se/Ge interface structure will be published elsewhere. In particular, the barrier heights obtained for both Schottky contacts in our experiments were lower than those reported in previous works [4]–[7]. This might be associated with the relatively high doping concentration of the Ge substrate used in our fabrication. Generally, barrier height decreases with an increase in the doping concentration of the substrate [8], [9]. For previous works on Pt/n-type-Ge Schottky contacts, the barrier heights were found to be 0.63–0.64 eV whose doping concentrations were in the range of $6 \times 10^{15} - 1 \times 10^{17}$ cm^{-3}[4]–[7]. Furthermore, the J–V characteristics of the Se/n-type-Ge Schottky diode measured at the temperature range of 200–300 K (the inset of Fig. 1) revealed the temperature dependence of the current transport across the Se/Ge interface. In other words, as the temperature increases, more and more electrons have sufficient energy to overcome the Schottky barrier. Namely, the increase in the current under forward bias with increasing temperature indicates that thermionic emission is the dominant mechanism for carrier transport in forward bias. In addition, the reverse currents do not saturate but increase with increasing reverse bias for a temperature of 200–300 K. The carrier generation in the depletion layer and the image force lowering of the barrier height often dominate the reverse characteristics of Schottky diodes because reverse bias increases the electric field in the junction. From the Arrhenius plot of the reverse current at 0.5-V bias (not shown here), an activation energy was calculated to be 0.37 eV, which is close to half the band gap (0.33) of Ge. This indicates that reverse I–V characteristics are indeed dominated by a generation mechanism [10].

The dominance of the current transport mechanism can be investigated by estimating the position of the quasi-Fermi level at the interface. Generally, two processes are involved in the emission of electrons from the semiconductor into the metal, governing the I–V characteristics of the Schottky system. Wittmer [11] proposed that the dominant process is the diffusion of electrons through the depletion layer. In this case, the quasi-Fermi level decreases across the depletion layer and coincides with the metal Fermi level at the interface. According to Bethe [12], the quasi-Fermi level remains flat in the depletion region without the coincidence of the metal Fermi level at the interface when the thermionic emission of electrons dominates the current transport. Fig. 2 shows the position of the quasi-Fermi level in a Se/n-type-Ge Schottky contact as a function of the forward bias at 200 and 300 K. Based on the method suggested by Wittmer [11], the difference between the quasi-Fermi levels in the bulk $\zeta(x) = qV$ and at the interface $\zeta(0)$ was calculated. It is clear that the quasi-Fermi level is essentially flat throughout the depletion region. Thus, the dominant conduction mechanism in a Se/n-type-Ge Schottky system is the thermionic emission of electrons over the barrier.

Fig. 3 shows the $1/C^2-V$ plot of the Se/n-type-Ge and Pt/n-type-Ge Schottky diodes measured at a frequency of 1 MHz at room temperature. For both diodes, a built-in potential of 0.62 eV was extracted from the intercept on the x-axis from which a barrier height of 0.68 eV was derived. From the slopes of the fitted lines, the doping concentrations were calculated to be 1.2×10^{18} and 1.5×10^{18} cm^{-3} for the Se/n-type-Ge and Pt/n-type-Ge Schottky diodes, respectively. These values were comparable to the specified doping concentration of a Ge substrate provided by the manufacturer. It should be noted that the barrier height obtained from the C–V measurement is higher than that from the I–V measurement. Generally, the underestimation of the barrier height from the I–V method could be associated with the spatial inhomogeneity of the barrier height having low and high Schottky barrier height patches along the 2-D Se/Ge interface. The current in the I–V measurement is dominated by the current that flows through the region of low Schottky barrier height. On the other hand, the C–V method yields the average Schottky barrier height for the entire diode [13]. Hence, the barrier height determined

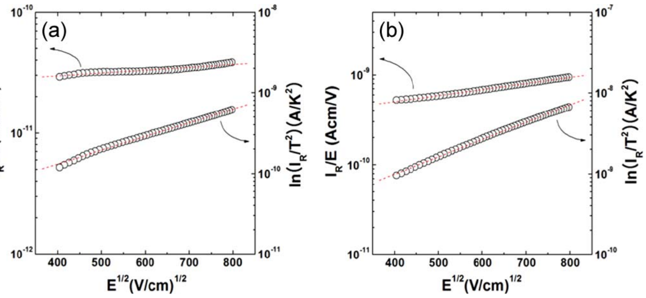

Fig. 4. Electric field dependence of the Se/n-type-Ge Schottky diode in reverse bias at (a) 200 and (b) 300 K. The plots of I_R/E versus $E^{1/2}$ and I_R/T^2 versus $E^{1/2}$ represent the Poole–Frenkel emission and the Schottky emission, respectively.

TABLE I
THEORETICALLY CALCULATED SLOPES AND THE SLOPES OBTAINED FROM THE FITS FOR POOLE–FRENKEL AND SCHOTTKY EMISSIONS AT 200 AND 300 K

Temperature (K)	Poole-Frenkel emission $(V/cm)^{-1/2}$		Schottky emission $(V/cm)^{-1/2}$	
	Calculated	From the fit	Calculated	From the fit
200	0.0110	0.0002	0.0055	0.0017
300	0.0073	0.0006	0.0036	0.0021

from the I–V measurement is significantly lower than the weighted arithmetic average of Schottky barrier heights extracted from the C–V measurement. Namely, the discrepancy between the Schottky barrier heights measured from the I–V and C–V techniques seems to be a strong fingerprint for the existence of the spatially inhomogeneous Schottky barrier in the Se/Ge interface. This is supported by the deviation of the ideality factor from unity, as obtained from the I–V characteristics of the Se/n-Ge structure. Furthermore, as shown in the inset of Fig. 3, the atomically nonuniform interface caused by local reaction between Se and Ge could be one of the main causes of the inhomogeneous Schottky barrier.

In order to investigate the dependence of the reverse current (I_R) of Se/n-type-Ge Schottky contacts on the electric field (E), both Poole–Frenkel and Schottky emission models were considered. In Poole–Frenkel emission, the carrier transport occurs through trap states by applying an electric field, whereas in Schottky emission, the carrier absorbs the thermal energy and then emits over the potential barrier at the interface [14]. Fig. 4 shows the plots of the Poole–Frenkel emission and the Schottky emission at 200 and 300 K. The contribution of the reverse current by Poole–Frenkel and Schottky emissions was presented in previously published works [10]. The theoretically calculated slopes and the slopes obtained from the fits for both the Poole–Frenkel and Schottky emissions for different temperatures are presented in Table I. At 200 K, the experimental values are 0.018 times the theoretical value of the Poole–Frenkel lowering coefficient and 0.31 times the theoretical value of the Schottky barrier lowering coefficient. At 300 K, the experimental values are 0.08 times the theoretical value of the Poole–Frenkel lowering coefficient and 0.58 times the theoretical value of the Schottky barrier lowering coefficient. Namely, for both temperatures, the slopes determined from the data fit are closer to the theoretical values of the Schottky lowering coefficients than those of the Poole–Frenkel lowering coefficients. In other words, the results are more consistent for Schottky emissions at both temperatures of 200 and 300 K. Thus, based on the electric field dependence of the reverse current combined with the Arrhenius plot of the reverse current, carrier conduction in the reverse bias region is dominated by a mechanism involving Schottky barrier lowering along with a generation mechanism.

IV. CONCLUSION

A Se/n-type-Ge Schottky rectifier was fabricated, and its conduction mechanism using temperature-dependent I–V characteristics has been investigated. The relatively large discrepancy between the barrier heights measured by the I–V and C–V methods could be attributed to the inhomogeneity of the barrier height. The quasi-Fermi level was essentially flat throughout the depletion region under a forward bias, implying that thermionic emission dominated the current conduction mechanism in the forward bias region. From the electric field dependence of the reverse current and the Arrhenius plot of the reverse current, the primary process involved in the leakage current could be associated with Schottky emission along with the generation mechanism.

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