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Electrical properties of Pt/n-type Ge Schottky contact with PEDOT:PSS interlayer

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The effect of poly (3,4-ethylene dioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) interlayer on the Schottky barrier parameters of Pt/n-type Ge Schottky contacts was investigated. The PEDOT:PSS interlayer in between Pt and n-type Ge influences the space charge region of the Pt/n-type Ge Schottky junction, leading to increase in the barrier height. Due to interface dipoles and lateral barrier inhomogeneities caused by the presence of PEDOT:PSS interlayer, Pt/PEDOT:PSS/n-type Ge Schottky contact showed a deviation from the ideal thermionic emission model of the carrier transport at the metal/semiconductor junction. From the reverse current–voltage (*I–V*) characteristics, the Poole–Frenkel emission and Schottky emission were found to be the dominating carrier conduction mechanisms of Pt/PEDOT:PSS/n-type Ge Schottky contact at lower and higher reverse biases, respectively.

1. Introduction

There has been a renewed interest in Ge as an alternative channel material for high-speed complementary metal–oxide-semiconductor (CMOS) devices due to its higher mobility of both the electrons and holes compared to Si [1,2]. However, Fermi-level pinning (FLP) at the charge neutrality level close to the valence band edge of Ge results in high electron barrier of metal contact to n-type Ge, serving as a major barrier for future Ge-based devices. Until now, considerable efforts have been made to minimize the effects of FLP on metal/Ge interfaces by the insertion of an insulator in between the metal and Ge, such as Al_2O_3 [3], MgO [4], and Ge_3N_4 [5]. Similarly, the introduction of an organic interlayer to the metal/Ge interface is another approach to modulate the Schottky barrier height. For instance, Kumar et al. [6] demonstrated that the presence of a copper phthalocyanine (CuPc) interlayer in a Pt/n-type Ge interface leads to the modification of the effective barrier height of Pt/n-type Ge Schottky contact. Recently, poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) has been considered as a very promising conducting polymer for various applications in electronic devices due to its superior properties such as high conductivity, structural stability, optical transparency, and processability [7]. Despite these features of PEDOT:PSS, the effort in its implementation to Ge-based Schottky contact has been rather scarce. In this work, we fabricate a Pt/n-type Ge Schottky rectifier with a PEDOT:PSS interlayer and demonstrate its electrical properties. In particular, based on the thermionic emission model, Schottky barrier parameters were cross-checked by employing various analysis techniques such as forward *I–V*, *C–V*, Cheung's, and Norde's methods for their consistency and validity. The possible current conduction mechanism of the Schottky contacts modified using PEDOT:PSS interlayers in the reverse bias are also examined.

2. Experimental details

N-type Ge (100) (Sb-doped) wafers with a doping concentration of $2 \times 10^{18}\ cm^{-3}$ were used as a starting material. After removing native oxide using a diluted HF solution, the PEDOT:PSS films were spin-coated at 2000 rpm for 60 s, followed by baking at 150 C for 30 min. From scanning electron microscopy (SEM) examination (not shown here), the thickness of PDEOT:PSS was measured to be 66 nm. Finally, 30-nm-thick Pt electrodes were formed on the top of the PEDOT:PSS thin films by means of Pt sputtering through a metal mask with diameter of 500 μm. For comparison, a Pt Schottky contact without a PEDOT:PSS interlayer was fabricated on an n-type Ge wafer using the same process conditions. The *I–V* characteristics of the Pt/PEDOT:PSS/n-type Ge Schottky contacts were measured at room temperature using a precision semiconductor parameter analyzer (Agilent 4155C).

3. Results and discussion

Fig. 1 shows the *I–V* characteristics of the Pt/n-type Ge Schottky rectifiers with and without PEDOT:PSS interlayers measured at

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room temperature. Both devices exhibited good rectification behavior, implying that thermionic emission theory can be used to assess the electrical parameters of the devices. The ideality factor and barrier height were found to be 1.58 and 0.69 eV for Pt/PEDOT:PSS/n-type Ge Schottky contact, and 1.06 and 0.50 eV for Pt/n-type Ge Schottky contact. The near-unity ideality factor of the Pt/n-type Ge Schottky contact indicates that the diffusion of carrier across a nearly flawless interface of the Schottky contact could be a main contributor to the current flow. On the other hand, Pt/PEDOT:PSS/n-type Ge Schottky contact exhibited an ideality factor deviating from the value of unity. This could be attributed to interface dipoles formed by organic or specific interface structure as well as fabrication-induced defects at the interface [8,9]. Generally, the organic interlayer may cause a significant modification of interface states even though the organic–inorganic interface appears abrupt and unreactive [10,11]. Furthermore, such a relatively high value of ideality factor could be associated with a wide distribution of low Schottky barrier height patches caused by lateral barrier inhomogeneities [12]. The barrier height obtained from the Pt/n-Ge in the present work was lower than those reported in the previous works [5,13]. Such a discrepancy could be associated with relatively high doping concentration of n-Ge substrate (2×10^{18} cm^{-3}) used in this work. Generally, the barrier height decreases with increasing the doping concentration of substrate [14,15]. Namely, the carrier transport in Schottky contacts with substrates having high doping concentration seems to be deviated from the ideal thermionic emission. However, although the doping concentration of the substrates used in the present work was the order of $\sim 10^{18}$ cm^{-3}, the assumption of thermionic emission for the *I–V* characteristics is still justifiable as mentioned in previous works [16–18]. It should be noted that the barrier height of Pt/PEDOT:PSS/n-type Ge Schottky contact is higher than that of Pt/n-type Ge Schottky contacts. This suggests that the PEDOT:PSS interlayer modifies the effective barrier height by influencing the space charge region of the Pt/n-type Ge Schottky junction [19]. Namely, the PEDOT:PSS interlayer produces a substantial shift in the work function of the metal and in the electron affinity of the semiconductor, and in turn confers excess barrier height.

In order to accurately determine Schottky parameters such as barrier height, ideality factor, and series resistance, we employed the plots of Cheung's function *H*(*I*) *vs. I* and *dV/d(lnI) vs. I*, as shown in Fig. 2. From the slope and *y*-axis intercept extracted from the plots of *dV/d*(ln*I*) *vs. I*, the series resistance and ideality factor were calculated to be 168 Ω and 3.2 for Pt/PEDOT:PSS/n-type Ge Schottky contact, and 6.41 Ω and 1.30 for Pt/n-type Ge Schottky contact, respectively. Using the ideality factor determined from the plot of *dV/d(lnI) vs. I*, the $H(I) - I$ plot gives a straight line with the *y*-axis intercept yielding the barrier height. Furthermore, the slope of this plot also provides a second method to determine the series resistance. The series resistance and barrier height evaluated from the plot of *H(I) vs. I* were found to be 159 Ω and 0.68 eV for Pt/PEDOT:PSS/n-type Ge Schottky contact, and 6.3 Ω and 0.48 eV for Pt/n-type Ge Schottky contact, respectively. The series resistances extracted from the plot of *dV/d(lnI) vs. I* were almost identical to those from the plot of *H(I) vs. I*, implying their consistency and validity. It should be noted that the series resistance of Pt/PEDOT:PSS/n-type Ge Schottky contact is much higher than that of Pt/n-type Ge Schottky contact. This implies that the series resistance is a current-limiting factor for Pt/PEDOT:PSS/n-type Ge Schottky contact in comparing the forward current level of both devices shown in Fig. 1. In other words, the voltage drop across series resistance caused by the presence of an organic interlayer is likely to retain forward current conduction in Pt/PEDOT:PSS/n-type Ge Schottky contact, in contrast to Pt/n-type Ge Schottky contact.

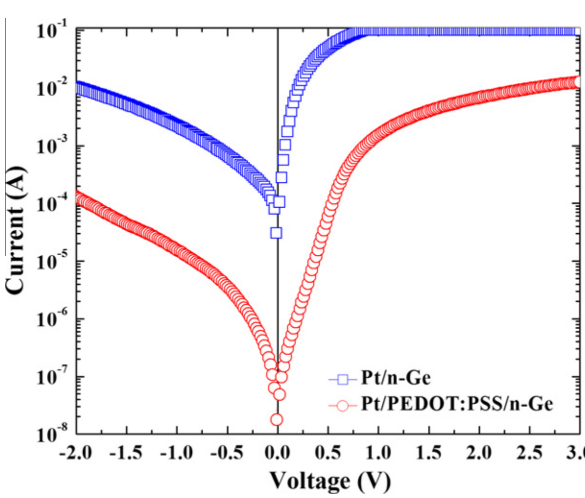

Fig. 1. *I–V* characteristics of Pt/n-type Ge and Pt/PEDOT:PSS/n-type Ge Schottky contacts measured at room temperature.

Fig. 3 presents a plot of the Norde function *F*(*V*) *vs. V* of the Pt/n-type Ge Schottky contacts with and without a PEDOT:PSS interlayer. The barrier height and series resistance, extracted from the Norde plot, were found to be 0.46 eV and 6.05 Ω for the Pt/n-type Ge Schottky contact, and 0.74 eV and 327 Ω for Pt/PEDOT:PSS/n-type Ge Schottky contact, respectively. As shown in Table 1, the Pt/n-type Ge Schottky contact shows reasonably good agreement among the values of barrier height and series resistance obtained from the forward bias *I–V* characteristics, the Cheung function, and the Norde function. On the other hand, there is a relatively large discrepancy in the Pt/PEDOT:PSS/n-type Ge Schottky contact between the values of barrier height and series resistance measured from the Norde function and other methods. Such a large discrepancy could be associated with a deviation from the ideal thermionic emission caused by the presence of the PEDOT:PSS interlayer. Norde's model may not be a suitable method for the rectifying junctions with high ideality factor, which are not compatible with the pure thermionic emission theory. Therefore, the values of barrier height and series resistance calculated from Norde functions can be much higher than those from other methods especially for a non-ideal rectifying structure such as Pt/PEDOT:PSS/n-type Ge Schottky contact [20].

Based on the Poole–Frenkel and Schottky emission models, the dependency of the reverse current (I_R) of Pt/n-type Ge and Pt/PEDOT:PSS/n-type Ge Schottky contacts on the reverse bias (V_R) was investigated using the plot of $\ln(I_R)$ *vs.* $V_R^{1/2}$, as shown in Fig. 4. The theoretical value of field-lowering coefficients for Poole–Frenkel (S_{PF}) and Schottky emissions (S_{SC}) were calculated to be 2.40×10^{-5} and 1.20×10^{-5} eV m$^{1/2}$ V$^{-1/2}$ for Pt/n-type Ge Schottky contact, and 4.38×10^{-5} and 2.19×10^{-5} eV m$^{1/2}$ V$^{-1/2}$ for Pt/PEDOT:PSS/n-type Ge Schottky contact, respectively. For the Pt/n-type Ge Schottky contact, the slope determined from the fit to the data was 1.36×10^{-5} eV m$^{1/2}$ V$^{-1/2}$ which is 0.43 times the theoretical value of S_{PF} and 0.13 times the theoretical S_{SC} and is closely matched to the theoretical slope of the Schottky emission. Hence, the dominant charge conduction mechanism for Pt/n-Ge Schottky contact is assumed to be Schottky emission. For Pt/PEDOT:PSS/n-type Ge Schottky contact, this is characterized by two distinct regions. This indicates the presence of two different conduction mechanisms in the reverse bias region. The plot exhibits linearity with a slope of 4.6×10^{-5} eV m$^{1/2}$ V$^{-1/2}$ in the lower bias region (region I), and the slope of the fitted line in the plot is found to be 2.19×10^{-5} eV m$^{1/2}$ V$^{-1/2}$ in higher bias region (region II). A comparison of the experimental and theoretical slopes revealed that the experimental slope obtained in the lower bias region was closer to the Poole–Frenkel field lowering coefficient being

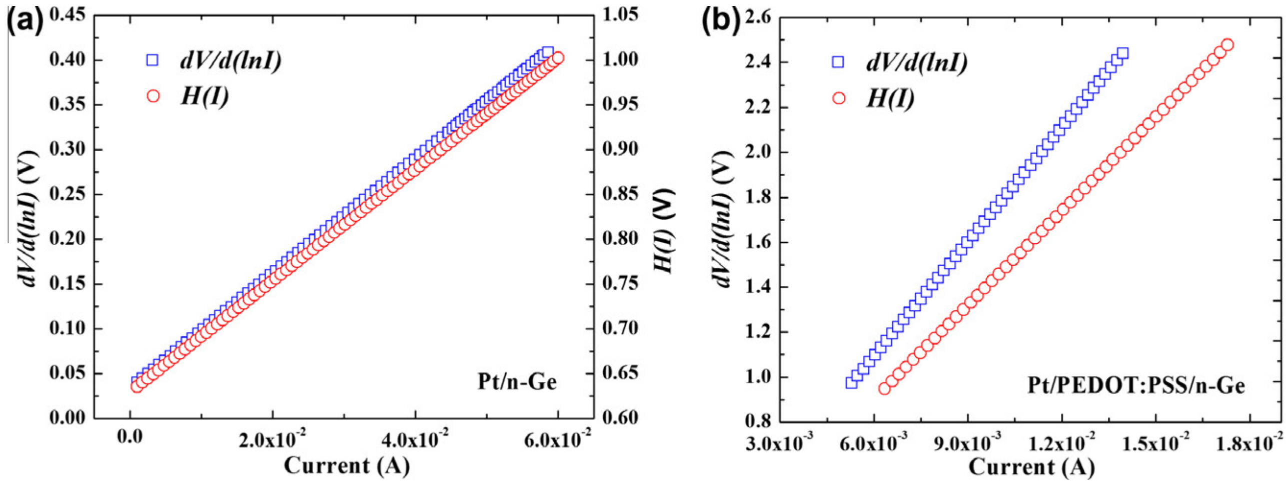

Fig. 2. $dV/d(\ln I)$ *vs. I* and $H(I)$ *vs. I* plots obtained from the forward *I–V* characteristics of the Pt/n-type Ge and Pt/PEDOT:PSS/n-type Ge Schottky contacts.

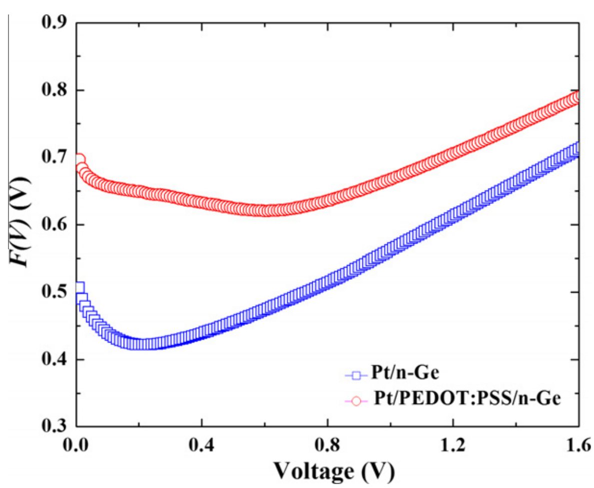

Fig. 3. Norde plot of the Pt/n-type Ge and Pt/PEDOT:PSSS/n-type Ge Schottky contact obtained from the forward *I–V* characteristics.

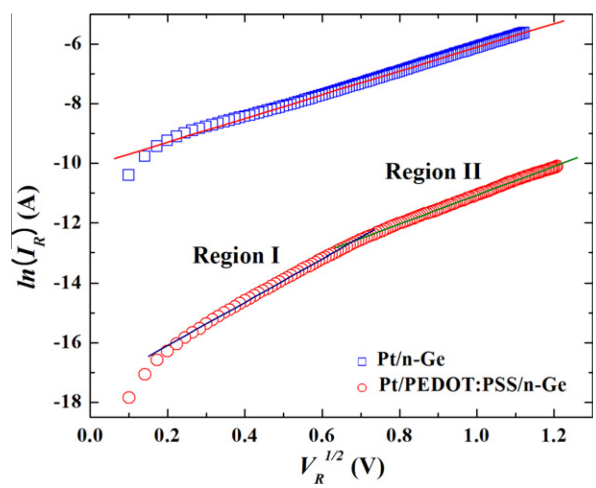

Fig. 4. Plot of $\ln(I_R)$ *vs.* $V_R^{1/2}$ of the Pt//n-type Ge and Pt/PEDOT:PSS/n-type Ge Schottky contacts.

0.05 and 1.1 times theoretical values of S_{PF} and S_{SC}, respectively. Since, the experimental value obtained for lower bias region was close the theoretical value of Poole–Frenkel field lowering coefficient, the leakage current was found to be dominated by Poole–Frenkel emission. While the experimental slope in the higher bias region was closer to the Schottky field lowering coefficient being 0.5 times the theoretical values of S_{PF} and the experimental value exactly matched the theoretical value in the case of S_{SC}, respectively. From the comparison of theoretical field-lowering coefficients with the slope determined from the two regions, it is evident that the slope in the higher bias region is closer to the Schottky field-lowering coefficient, while the slope is closer to the Poole–Frenkel field-lowering coefficient in the lower bias region. This suggests that the Schottky emission is dominant in the higher bias region, where current conduction occurs through the contact interface rather than from the bulk material due to the non-uniformity and sub-atomic structure of the organic layer [21]. The Poole–Frenkel conduction mechanism in the lower bias region could be explained by the wide distribution of traps in the band gap of active organic material employed here. The traps may be associated with defects and/or impurities in the chemical structure of organic material. The high density of structural defects or trap levels leads to the enhancement in the trapping/detrapping performance of the charge carriers [22].

4. Conclusions

We investigated the electrical properties and reverse leakage mechanisms of Pt/n-type Ge Schottky contact with a PEDOT:PSS interlayer. The presence of the PEDOT:PSS interlayer was effective for modifying the interfacial potential barrier of Pt/n-type Ge Schottky contact, allowing for increased barrier height. Non-ideal rectifying behavior of Pt/PEDOT:PSS/n-type Ge Schottky contact was a

Table 1
Values of Schottky barrier height, ideality factor and series resistance obtained from different methods.

Sample	Barrier height (eV)			Ideality factor (n)		Series resistance (Ω)		
	I–V	*H*(*I*)	Norde	*I–V*	*dV*/dln(*I*)	*H*(*I*)	*dV*/dln(*I*)	Norde
Pt/n-Ge	0.50	0.48	0.46	1.06	1.30	6.32	6.41	6.05
Pt/PEDOT:PSS/n-Ge	0.69	0.68	0.74	1.58	3.20	159	168	327

manifestation of the significant modification of the interface states and a wide distribution of low Schottky barrier height patches caused by the PEDOT:PSS interlayer. The current conduction through the contact interface caused by the non-uniformity and sub-atomic structure of the PEDOT:PSS interlayer could be responsible for the transition of the reverse leakage conduction mechanism of Pt/PEDOT:PSS/n-type Ge Schottky contact from Poole–Frenkel emission to Schottky emission at a higher bias range.

Acknowledgements

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