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RESEARCH ARTICLE

Investigation of the Electrical Properties of PAN-GO/p-Si Schottky Diode

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ABSTRACT

In this article, the electrical properties of PAN-GO/p-Si Schottky diode were investigated in the dark at room temperature. Field-emission scanning electron microscopy (FE-SEM) was utilized to study the structure of the PAN:GO interfacial layer. Diode parameters were calculated according to thermionic emission theory. By using the I-V characteristic of the prepared PAN-GO diode, the ideality factor (n), barrier height (Φ_B) and series resistance (R_s) values were evaluated with the I-V method and Norde functions. The barrier height values calculated with the I-V and Norde function were found to be 0.767 eV and 0.761 eV, respectively. The ideality factor was found to be 2.078 from the I-V method. The series resistance value of the diode was calculated as 42 kΩ using Norde functions. Energy-dependence profile of interface state density was determined from the current-voltage characteristics by considering the voltage-dependence of barrier height and ideality factor The interface state density (N_{ss}) values of the PAN-GO/p-Si Schottky diode are $9.5x10^{11}$ $eV^{-1}cm^{-2}$ for 0.35-E_v eV and $1.03x10^{11}$ $eV^{-1}cm^{-2}$ for 0.74-E_v eV. Experimental results approved that the PAN-GO interfacial layer improved the performance of metal-semiconductor Schottky diode in respect of low ideality factor, interface state density, and high barrier height and rectification rate.

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Introduction

Schottky diodes in metal-insulator-semiconductor (MIS) structure have an important place in today's technology, especially in integrated devices. These diodes are commonly used in electronic systems and optoelectronic applications such as solar cells, photo detectors, gas sensors, transistors, and switching circuits (Wang et al., 1998; Kang et al., 2016; Kumar et al., 2017; Aldirmaz et al., 2018; Al-Ahmadi, 2020; Aftab et al., 2021; Zhang et al., 2021; Aldirmaz et al., 2022; Yıldırım et al., 2022). The electrical parameters of diodes in electronic circuits are necessary for the analysis and design of the circuit. The electrical behavior of the Schottky diode is determined by calculating parameters such as the ideality factor, barrier height, series resistance, and saturation current (I_0). To examine the Schottky diode parameters, it is possible to gain information about the diode by analyzing the current-voltage (I-V) properties (Tatar et al., 2009; Güllü & Türüt, 2010; Saloma et al., 2020). With this analysis, it becomes clear how the interface states of the MIS structure and how the transmission mechanism behaves. Using the current-voltage (I-V) data obtained using the forward bias applied to the Schottky diode, many methods have developed such as Norde, Cheng, and thermionic emission theory (Gholami et al., 2009; Gupta et al., 2009; Mahala et al., 2018). The most widely used of these calculation methods is the TE method. The diode parameters

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are calculated using linear region of ln*I*-*V* curve. The series resistance effect in the diode structure is evaluated using all ln*I*-*V* data according to the Norde method (Norde, 1979). This method, which is valid for an ideal Schottky diode, has been generalized by Bohlin (1986) for non-ideal Schottky diode structures.

Graphene, which consists of a two-dimensional hexagonal layer of carbon atoms, is used in various applications in different fields owing to its large surface area. In electrical studies, graphene is an attractive material because it is compatible with thin-film processing. Graphene oxide (GO), a graphene-based material, attracts scientists' attention due to its high specific surface area, thermal properties and high flexibility (Kedambaimoole et al., 2020), which make it a two-dimensional support material to host metallic nanoparticles. GO is water soluble, hydrophilic, chemically stable, and mechanically resistant (Suk et al., 2010). However, unlike graphene, graphene oxide contains structural defects and covalent bond defects and is atomically rough because of this property (Vacchi et al., 2017). It is low cost and abundant because it is obtained from inexpensive graphite. It can be used in biological applications due to its excellent aqueous workability (Sun et al., 2018). This property allows it to form heterojunction devices with various semiconductors. It is also a candidate material for various applications such as gas sensing, cancer therapy, supercapacitors, field effect transistor (FET), solar cells, chemical sensors (Jaworski et al., 2015; Muazim & Hussain, 2017; Tian et al., 2019; Hue et al., 2020; Eswaran et al., 2022; Ferrag et al., 2022; Strimaitis et al., 2022; Lv et al., 2023). Polyacrylonitrile (PAN) polymer is frequently used in the preparation of nanofibers due to its water-resistance properties and can be applied in many fields such as water treatment, filtration, or medical fields (Nataraj et al., 2012). Additionally, PAN is frequently used in the production of carbon nanofibers because it has a high carbon yield (Saufi & Ismail, 2002; Lu et al., 2004). Furthermore, carbon nanofiber mats are easy to use and overcome all major challenges in dispersion, processing and transport compared to other carbon nanomaterials such as carbon nanotubes. Therefore, polyacronitrile polymer was chosen for the preparing Al/PAN-GO/p-Si/Al device structure. In recent years, to improve the performance or quality of MS diodes, metal-insulator-semiconductor (MIS) diodes have been changed by metal-polymer-semiconductor (MPS)-type diodes. It is known that the interface materials such as polymer or doped polymer can be commonly used in optoelectronic and electronic device. PAN-GO has advantages of both PAN and GO materials. The interface layer such as PAN-GO is a significant factor for the high performance of MIS devices. Our aim is to compose MPS type Al/PAN-GO/p-Si diodes instead of MIS type diodes due to easily growing the interfacial organic/polymer layer by spin coating between semiconductor and metal.

The aim is to produce a new type of Schottky diode using PAN-GO interfacial layer, and to determine the diode parameters by using *I*-*V* measurement. For this, Al/PAN-GO/p-Si/Al was produced using the drop casting technique. *I*-*V* measurement was performed between ±4 V bias range in the dark at room temperature, and n, Φ_B, N_{ss}, and R_s values were calculated.

Materials and Methods

The wafer used for the PAN-GO/p-Si Schottky diode structure has an orientation (100) and a resistivity of 1-20 Ω·cm, and 525 μm thickness. Before preparing the diode structure, a cleaning procedure was applied to remove the inorganic and the organic impurities. using chloroform ($CHCl_3$), acetone (C_3H_6O), and methanol (C_2H_6O) in an ultrasonic cleaner for 5 min, respectively. To remove the oxide layer formed on the wafer, it was kept in HF:H_2O (1:10) solution for 1 min and rinsed with distilled water.

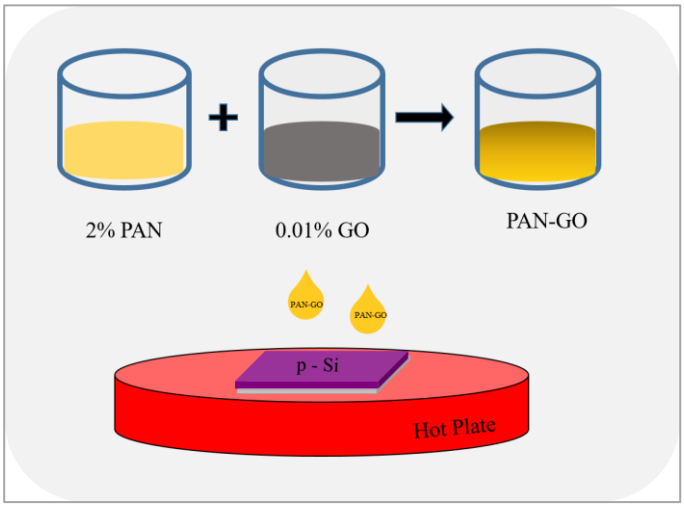

Figure 1. Experimental procedure of coating.

After cleaning, aluminum was deposited on the back of the p-Si to form ohmic contact using a thermal evaporation system under 10^{-6} Torr pressure. For the PAN-GO solution to be used as an interface layer, 2% by weight of PAN in powder form was dissolved in dimethylformamide ($HCON(CH_3)_2$) by stirring on a magnetic stirrer for 24 h. 0.01% by weight GO nanopowder was mixed in dimethylformamide for 3 h with a magnetic stirrer, then homogeneously dispersed in an ultrasonic cleaner for 1 h (Figure 1). These prepared solutions were mixed and the PAN-GO solution became ready. p-Si was placed on the hot plate at 45 °C. The solution was dropped onto the surface, and allowed to dry. Finally, aluminum was deposited by thermal evaporation as a rectifier contact. A schematic representation of the Schottky diode structure prepared as Al/PAN-GO/p-Si/Al is shown in Figure 2. Current-voltage characteristics were measured using a Keithley 4200 Sourcemeter with 0.01 V step ±4 V bias range in the dark at room temperature.

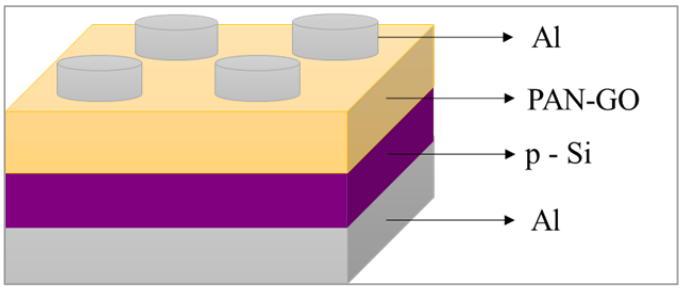

Figure 2. The schematic representation of the Al/PAN-GO/p-Si/Al.

Results and Discussion

SEM images of PAN-GO grown on p-Si substrates are shown in Figure 3. As shown in Figure 3a, the PAN-GO film exhibits a uniformly distribution on p-Si substrate. It is seen in Figure 3b that the film thickness is around 90 nm.

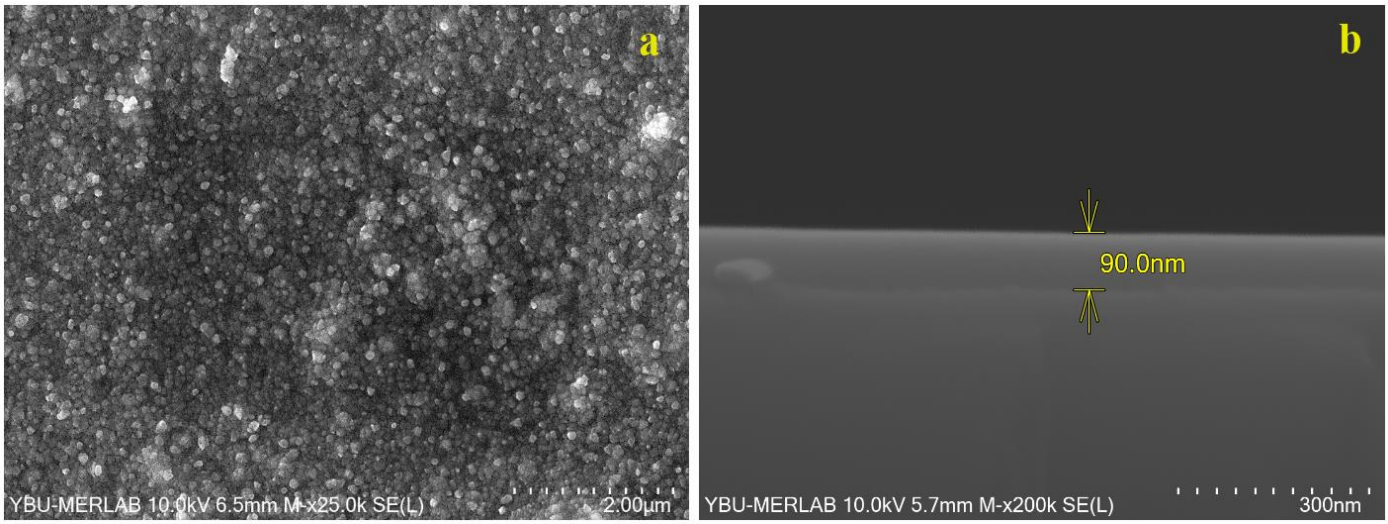

Figure 3. SEM images of (a) surface morphology (b) cross-section of Al/PAN-GO/p-Si/Al diode.

The electrical parameters of the Al/PAN-GO/p-Si/Al diode were calculated using the semi-logarithmic *I-V* graph given in Figure 4. As can be seen in Figure 4, the diode exhibited excellent rectifying behavior with a rectification ratio of 10^6 at ±4 V. Due to this rectifying property of Al/PAN-GO/p-Si/Al diodes, the charge carriers follow the TE theory (Kaplan et al., 2021; Berktaş et al., 2022). Thus, according to TE theory, Al/PAN-GO/p-Si/Al diodes current-voltage equation in reverse and forward bias can be defined by the Eq. (1) and Eq. (2) [Rhoderick & Williams, 1988; Iwai et al., 2013; Kaplan et al., 2021; Şahin et al., 2021; Tezcan et al., 2021].

$$I = I_0 exp\left(\frac{qV}{nkT}\right)\left[1 - exp\left(-\frac{qV}{kT}\right)\right] \quad (1)$$

where,

$$I_0 = AA^*T^2 exp\left[-\frac{q\Phi_B}{kT}\right] \quad (2)$$

where, q is the charge of electron; k is the Boltzmann constant; T is the absolute temperature in Kelvin; A is the diode area; A^* is the Richardson constant (32 A/cm^{2}K^2) for p-Si (Yuksel et al., 2013; Luongo et al., 2018; Çaldıran, 2021). The I_0 value is used to determine the Φ_B of the Schottky diode, and the I_0 value is determined from the point where intercept the axis at V=0 in the ln*I-V* graph. The Φ_B and n are given in Eq. (3) and Eq. (4).

$$\Phi_B = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_0}\right) \quad (3)$$

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

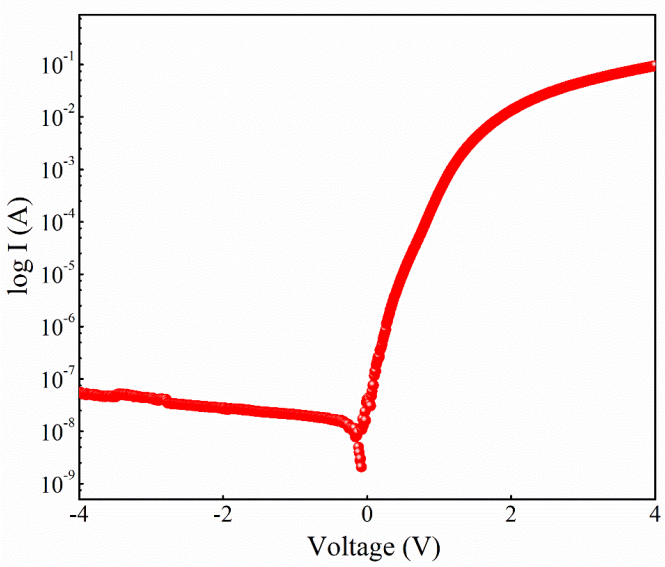

Figure 4. Current-voltage characteristics of Al/PAN-GO/p-Si/Al Schottky diode in dark at room temperature.

As can be seen from Figure 4, in the dark, characteristics of the produced Al/PAN-GO/p-Si/Al Schottky diode showed good rectification behavior. Using Eq. (3) and Eq. (4), n, Φ_B, and I_0 values were calculated and given in Table 1. n and Φ_B values were found as 2.078 and 0.767 eV, respectively. The value of n greater than 1 can be attributed to the inhomogeneity of the interface states, the presence of a thin interface natural oxide layer between the metal and the semiconductor, the series resistance, and the barrier at the metal-semiconductor interface (Batır et al., 2018; Koca et al., 2021). Akin et al. (2022) have been introduced the electrical parameters of Al/p-Si and Al/Al_2O_3:PVP/p-Si Schottky diodes. They reported that the barrier height values are 0.638 eV and 0.735 eV for Al/p-Si and Al/Al_2O_3:PVP/p-Si diode, respectively. Hosseini et al. (2022) have been introduced the electrical parameters of Al/p-Si and Al/CdS-PVP/p-Si Schottky diodes. They reported that the barrier height values are 0.59 eV and 0.69 eV for Al/p-Si and Al/CdS-PVP/p-Si diode, respectively. When these values are compared with the barrier height of 0.767 eV calculated for the Al/PAN-GO/p-Si MPS diode, PAN-GO interfacial layer modified the value of barrier height.

The series resistance and barrier height values were evaluated using the Norde method. These functions are defined by considering voltages greater than 3kT/q. In this method, metal-semiconductor contacts are assumed to be ideal. It is possible to calculate Φ_B and R_s values for non-ideal situations using the Bohlin's modified Norde method (Missoum et al., 2016; Nawar et al., 2020; Çaldıran, 2021). The modified Norde function is defined by Eq. (5);

$$F(V) = \frac{V}{\gamma} - \frac{kT}{q}\ln\left[\frac{I(V)}{AA^*T^2}\right] \quad (5)$$

Where, I(V) is the current; γ is the first integer greater than n. The Φ_B of the Schottky diode can be determined using the plot of $F(V)$-V and Eq. (6).

$$\Phi_B = F(V_{min}) + \frac{V_{min}}{\gamma} - \frac{kT}{q} \quad (6)$$

where, $F(V_{min})$ is the minimum value of $F(V)$ and V_{min} is the minimum voltage the of the $F(V)$-V curve. The series resistance (R_s) of the Schottky diode is determined using Eq. (7). I_{min} and V_{min} values are at the minimum point of the $F(V)$-V plot.

$$R_s = \frac{(\gamma - n)kT}{qI_{min}} \quad (7)$$

The graph of $F(V)$-V for the Al/PAN-GO/p-Si/Al Schottky diode is shown in Figure 5. The R_s and Φ_B values calculated according to the Norde method are shown in Table 1. The R_s and Φ_B values are 42 kΩ and 0.761 eV, respectively.

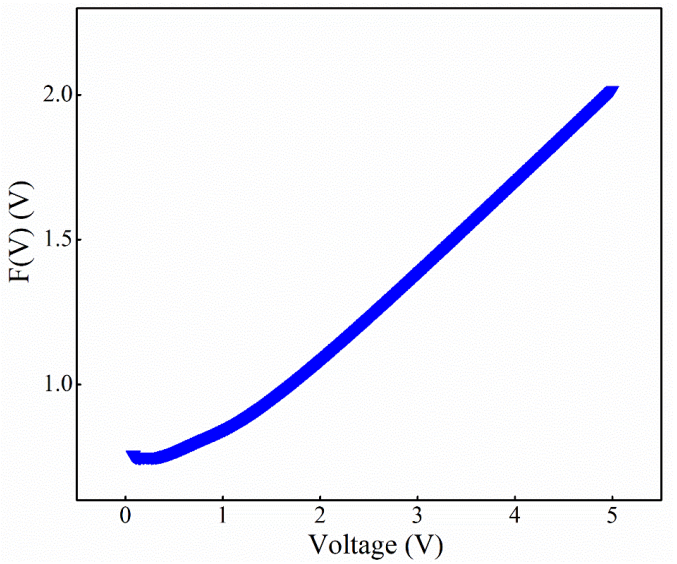

Figure 5. Plot of $F(V)$–V for Al/PAN-GO/p-Si/Al diode.

The R_s values obtained by the Norde method in MPS type Schottky diodes are in the order of kΩ (Akin et al., 2022; Altındal et al., 2022; Hosseini et al., 2022). The reason for this is that the method allows to calculate the series resistance at low voltages. On the contrary, in diodes, the series resistance region is formed at high voltages.

Table 1. Characteristic parameters of Al/PAN-GO/p-Si/Al diode obtained from I-V measurements.

I-V			Norde	
I_0 x 10^{-8} (A)	n	Φ_B (eV)	Φ_B (eV)	R_s (kΩ)
1.646	2.078	0.767	0.761	42

Voltage dependent capacitance characteristic of Al/PAN-GO/p-Si/Al diode at 1 MHz is given in Figure 6. Using the maximum accumulation capacitance value of 5.97x10^{-10} F and the geometric thickness of the PAN-GO thin film layer determined from SEM image, the dielectric constant value of PAN-GO was evaluated with Eq. (8).

$$C_i = \frac{\varepsilon_0 \varepsilon_x}{d_i} A \quad (8)$$

where, C_i is the maximum capacitance value in the accumulation region of the C-V measurement of the diode; ε_x is the dielectric constant of the PAN-GO thin film layer; ε_0 is the dielectric constant of vacuum (8.85x10^{-12} F/m); and A is the rectifier contact area. The dielectric constant value of PAN-GO was calculated as 1.4.

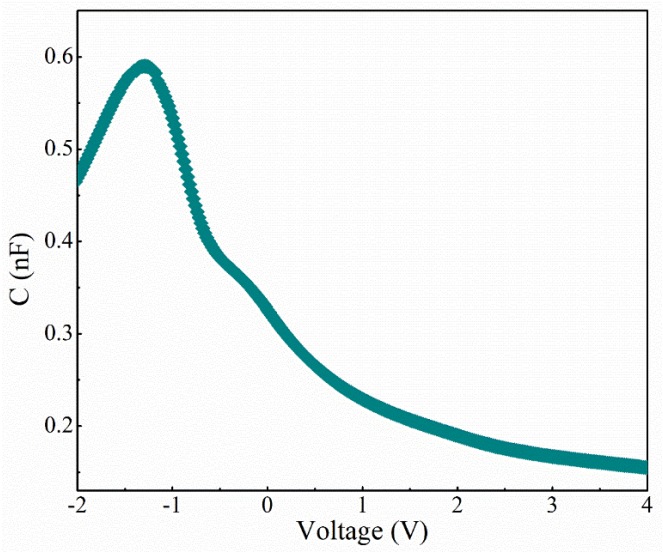

Figure 6. Plot of *C-V* for Al/PAN-GO/p-Si/Al diode.

Some parameters of Schottky diodes such as ideality factor and barrier height are effective in determining N_{ss} (Okutan et al., 2005; Akin et al., 2022; Karataş & Yumuk, 2022; Sevgili et al., 2022). The relationship between N_{ss} and n for a p-type semiconductor are expressed by Rhoderick (1988) as Eq. (9).

$$N_{ss}(V) = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta_i}(n(V)-1) - \frac{\varepsilon_s}{W_D}\right] \quad (9)$$

In Eq. (9), ε_s and ε_i are the dielectric constant of the semiconductor and interface, respectively. The thin film layer thickness is δ_i and the depletion zone width is W_D. In a p-type semiconductor, the relationship of the valence band limit energy (E_v) of the semiconductor with the energy of the interface state density (E_{ss}) is expressed as Eq. (10):

$$E_{ss}-E_v = q(\Phi_e - V); \Phi_e = \Phi_{B0} + \beta V = \Phi_{B0} + \left(1 - \frac{1}{n(V)}\right)V \quad (10)$$

where, Φ_e is the effective barrier height and q is the electron charge.

Figure 7 shows the N_{ss} profile of the Al/PAN-GO/p-Si/Al diode derived from the forward bias *I–V*. The N_{ss} values of the diode are $9.5\text{x}10^{11}$ $eV^{-1}cm^{-2}$ for 0.35-E_v eV and $1.03\text{x}10^{11}$ $eV^{-1}cm^{-2}$ for 0.74-E_v eV. Figure 7 demonstrates a decrease in N_{ss} attributable to the discharge and charge of the interface states due to increasing voltage.

Both Akin et al. (2022) and Hosseini et al. (2022) determined the interfacial state density distribution in the energy band gap at the order of 10^{13} $eV^{-1}cm^{-2}$. Compared to their N_{ss} value, the obtained value of 10^{11} $eV^{-1}cm^{-2}$ for the interfacial state density distribution of Al/PAN-GO/p-Si MPS diode is better.

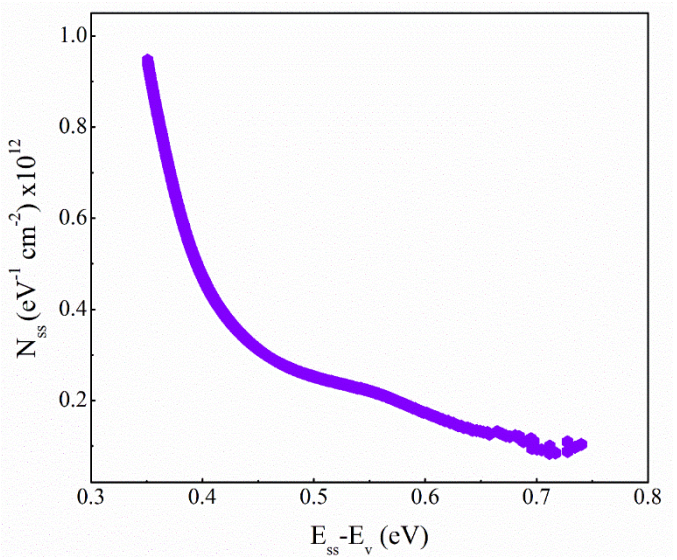

Figure 7. The energy-dependent distribution of the N_{ss} obtained from the forward-bias *I-V* data for the Al/PAN-GO/p-Si/Al diode.

Conclusion

In the presented article, the Al/PAN-GO/p-Si Schottky diode was prepared by a drop casting method. The *I–V* measurement of Al/PAN-GO/p-Si diode was performed in dark at 300 K. The morphology of the prepared diode was examined by SEM. Because of SEM measurement, the thickness of the PAN-GO film was calculated as 90 nm. A good rectification behavior with low reverse leakage current is achieved for the Al/PAN-GO/p-Si Schottky diode. The diode parameters such as the ideality factor, barrier height and series resistance are calculated for the prepared diode by *I-V* and Norde method. The effects of N_{ss} on *I–V* measurements were also examined. The energy-dependent profiles of N_{ss} was obtained from the I-V method. The N_{ss} of the diode has ranged from $29.5\text{x}10^{11}$ $eV^{-1}cm^{-2}$ for 0.35-E_v eV and $1.03\text{x}10^{11}$ $eV^{-1}cm^{-2}$ for 0.74-E_v eV. The experimental observations show that the thermionic emission is the dominant conduction mechanism in the forward bias region of the Al/PAN-GO/p-Si Schottky diode.

Conflict of Interest

The authors declare that they have no conflict of interest.

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