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Improvement of diode parameters in Al/n-Si Schottky diodes with Coronene interlayer using variation of the illumination intensity

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ABSTRACT

In present work, Coronene thin films on Si wafer have been deposited by the spin coating method. It has been ultimately produced Al/Coronene/n-Si/In Schottky diode. Current–voltage (*I-V*) measurements have been used to determine the effect of illumination intensity in the Schottky diodes. The barrier height (Φ_B) values increased as ideality factor (n) values decreased with a increase in illumination intensity. The Φ_B values have been found to be 0.697 and 0.755 eV at dark and 100 mW/cm^2, respectively. The n values have been found to be 2.81 and 2.07 at dark and 100 mW/cm^2, respectively. Additionally, the series resistance (R_s) values from modified Norde method and interface state density (N_{ss}) values using current-voltage measurements have been determined. The values of R_s have been found to be 1924 and 5094 Ω at dark and 100 mW/cm^2, respectively. The values of N_{ss} have been found to be 4.76×10^{12} and 3.15×10^{12} eV^{-1} cm^{-2} at dark and 100 mW/cm^2, respectively. The diode parameters are improved by applying the variation of illumination intensity to the formed Schottky diodes.

1. Introduction

Recently, the use of organic molecule layers in Schottky diodes has garnered significant momentum for the optoelectronic and electronic devices since organic materials have cheaper and simpler fabrication process compared with inorganic materials [1–5]. It has been observed that organic materials can be used to form rectifying junctions with inorganic semiconductors and metal [6–8]. A large number of investigations have been carried out on electrical and photovoltaic behavior of organic/inorganic semiconductor device in the different illumination intensity [9–15].

Many efforts have been reported to achieve a modification of the barrier height using an organic semiconducting layer [9–15]. Inorganic-organic contacts such as n-Si/9,10-H_2BaP [10], n-Si/Oxazine (OXZ) [11], n-Si/CoPc [4], n-Si/phenolsulfonphthalein (PSP) [12], n-Si/PTCDA [13], n-Si/DMFC [14], and n-Si/Anthracene [15] have been prepared in literature and then their electrical and photoelectrical properties have been evaluated. Özerden et al. [10] have determined the electrical and photoelectrical properties of the Ag/9,10-dihydrobenzo[a]pyrene-7(8H)-one (9,10-H2BaP)/n-Si contact, and reported that the barrier height of the device was lower than that of Ag/n-Si Schottky diode. Farag et al. [11] have fabricated OXZ organic compound on n-Si substrate by spin coating process and the electrical characterization. They have determined some junction parameters of this structure by the electrical and photoelectrical characterizations such as capacitance–voltage (*C–V*) and current-voltage (*I–V*). Wahab et al. [4] have studied the fabrication and characterization of cobalt phthalocyanine (CoPc)/n-silicon heterojunction diode. The authors have also obtained the ideality factor and barrier height values of the heterojunctions.

Coronene among organic semiconductor compounds is considered a good candidate for organic semiconductor device fabrication such as photovoltaic cell and Schottky diode [16–18]. We have chosen Coronene as organic material for the fabrication organic/inorganic device. Coronene is known with molecular formula $C_{24}H_{12}$. Coronene is the simplest hydrocarbon in which benzene rings completely surround a central aromatic nucleus.

A detailed work on device properties and an understanding of the possible effects of illumination is a major step in the development of the Coronene based photodiodes. The propose of this paper is to characterise the variation of ideality factor, barrier height, series resistance and interface states in Al/Coronene/n-Si structures under dark and illumination and study the effect of Coronene organic film on the electrical characteristics. For this purpose, the photocurrent

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characteristics of the Schottky diode have been studied under dark and 10, 30, 60, and 100 mW/cm^2 illumination intensity. The dependence of illumination intensity of electrical characteristics of the main parameters such as barrier heights, ideality factors, interface state densities and series resistances determined from various techniques has been examined. Moreover, the capacitance-conductance-voltage (*C-G-V*) measurements in the 1 MHz have been made to determine the characteristic parameters of the diode. It is important to determine device parameters of the diode under illumination for its potential application in photosensors.

2. Experimental

In the present experiment, Coronene was obtained from Sigma Aldrich and toluene was used as a solvent. the Si wafer grown by Czochralski process has a P-doped, (100) orientation, 20 Ω cm resistivity and 380 µm thickness. To remove the oxide layer, the n-Si surface has been cleaned by the RCA process [19,20]. Indium (In) and Aluminium (Al) metals with 150 nm thickness have been thermally grown by using basket-shaped tungsten filament in evaporation system (Nanovak, 300-2TH1SP) for the ohmic and rectifying contacts, respectively. Coronene thin film has been coated on n-Si by the spin coating process (Laurell spin coater, WS-650-23 model). Finally, the structure of Al/Coronene/n-Si/In Schottky diode has been constructed. The current-voltage (*I-V*) characteristics of diode were performed in dark and under the different light intensity by means of Keithley 4200 semiconductor characterization system. The characteristics of photodiode have been investigated by using solar simulator (Sciencetech (SF-300-B) small collimated beam Solar Simulator, 300 W, Class ABA) in the light intensity range of 10–100 mW/cm^2.

3. Results and discussion

3.1. Current–voltage (I-V) characteristics of Al/Coronene/n-Si/In diode in dark and illumination intensity

A typical set of semilogarithmic *I–V* characteristics of the investigated Al/Coronene/n-Si Schottky diode for dc bias voltages ranging from −2 V to +2 V at dark and various illumination intensity (10–100 mW/cm^2) is shown in Fig. 1. From the figure, the diode shows a good rectification behavior. The rectification ratio of the Coronene/n-Si structure at ± 2 V has been calculated as 6.15. The relevant diode parameters have been calculated according to thermionic emission model before and after illumination. Therefore, the diode characteristics from the *I-V* are analyzed as [21–27]

$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right];\quad I_0 = AA^*T^2\exp\left(-\frac{q\Phi_{B0}}{kT}\right) \tag{1}$$

where Φ_{B0} is the Schottky effective barrier height, I_0 is the saturation current, q is the electronic charge, T is the absolute temperature in Kelvin, n is the ideality factor, A is the contact area, and A^* is the effective Richardson constant (A^*= 112 A K^{-2} cm^{-2} for n-Si [21,22]). It is calculated the n values from the slope and Φ_{B0} values from extrapolated I_0 of the straight-line region higher than $3kT/q$ region of Fig. 1 according to the following equations [28,29]:

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln I}\right) \text{ and } \Phi_{B0} = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_0}\right) \tag{2}$$

The *I–V* measurements have been also carried out to investigate the effect of light on the electrical characteristics of the Al/Coronene/n-Si diode under illumination intensities 10, 30, 60, and 100 mW/cm^2 and in the dark. From the figure, it is observed that the structure has very strong light sensitivity and the reverse bias current of the diode increases with the increasing light intensity. This change of the Al/Coronene/n-Si Schottky diode is a conventional tendency of a photodiode [10,30]. Furthermore, This shows that the resistance of the diode decreases by the illumination [30]. Furthermore, according to Eq. (2) and Fig. 2, the values of Schottky barrier height and the ideality factor have been determined to be Φ_{B0}= 0.697 eV and n= 2.81 at dark and Φ_{B0}= 0.755 eV and n= 2.07 for 100 mW/cm^2, respectively. Furthermore, the n value (n= 2.81) for Coronene/n-Si contact at dark is lower than the value of 3.14 given for new fuchsin/n-Si contact [35] and the value of 3.48 given for Aniline green/n-Si contact [36] but is higher than the value of 2.41 given for Anthracene/n-Si contact [15]. Fig. 2 shows the variation of n and Φ_{B0} with illumination intensity (P). As seen from Fig. 2, while the ideality factor decreases almost linearly, the barrier height increases linearly with the illumination intensity. It is an expected situation under illumination intensity for Schottky barrier

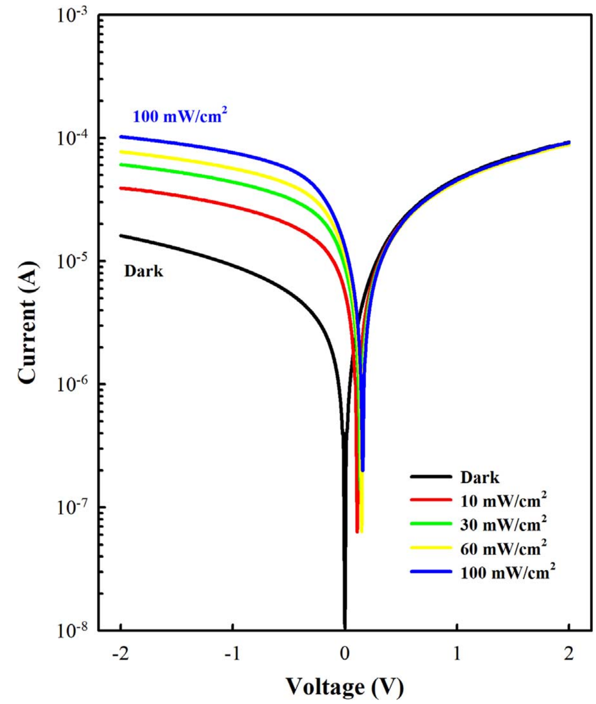

Fig. 1. Semilogarithmic *I–V* curves obtained from the *I–V* data of the Al/Coronene/n–Si diode under dark, 10, 30, 60 and 100 mW/cm^2 illumination intensities.

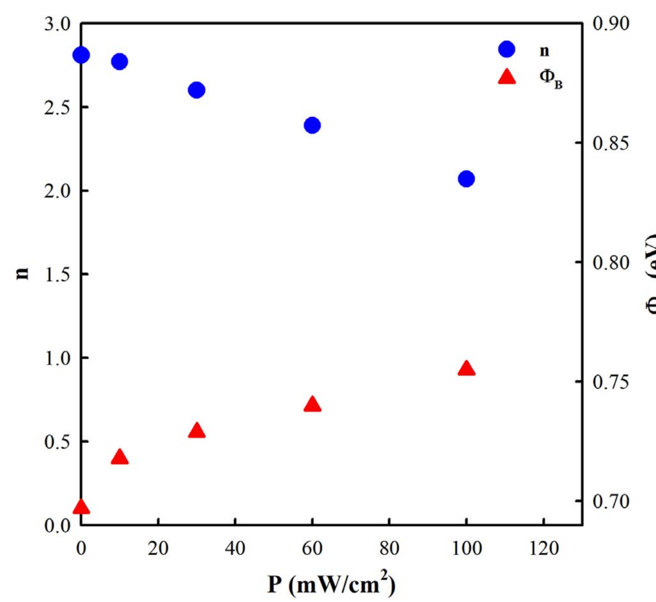

Fig. 2. The illumination intensity dependence of the ideality factor (n) and the Schottky barrier height (Φ_B).

diodes. Similar behavior is seen in the literatüre [10,30,31]. Higher values of the ideality factors are caused possibly by other effects such as of the series resistance effect, the film thickness, and the interface dipoles [4,10,32–34]. The Φ_{B0} value of 0.697 eV determined for the Al/Coronene/n-Si device in dark is remarkably higher than that achieved with conventional Al/n-Si devices, where Φ_{B0} is 0.50 eV [21]. This result was referred to Coronene interlayer modifying the effective barrier height by influencing the space-charge region of the n-Si substrate [34]. Furthermore, the $\boldsymbol{\Phi_{B0}}$ value (Φ_{B0}= 0.697 eV) for Coronene/n-Si contact is lower than the value of 0.80 eV given for new fuchsin/n-Si contact [35] and the value of 0.76 eV given for Aniline green/n-Si contact [36] but is higher than the value of 0.65 eV given for NiPc/n-Si contact [37].

We used a technique proposed by Norde [38] to determine the series resistance (R_s) values of Al/Coronene/n-Si diode from the current-voltage characteristics. Norde's functions can be expressed as [12,14,15,38]:

$$F(V) = \frac{V}{a} - \frac{1}{\beta}\ln\left(\frac{I(V)}{AA^{*}T^{2}}\right) \tag{3}$$

$$\Phi_B = F(V_0) + \frac{V_0}{a} - \frac{1}{\beta} \tag{4}$$

$$R_s = \frac{(a-n)}{\beta I_0} \tag{5}$$

where a is an constant higher than the value of n and β is equal to q/kT. *F(V)-V* plots for Coronene/n-Si structure at dark and different illumination intensity are given in Fig. 3. The Φ_B and R_s values have been calculated from determining the minimum in *F(V)-V* plots of Fig. 3. These values of R_s and Φ_B according to Eqs. (4) and (5) have been calculated and plotted in Fig. 4 at dark and different illumination values.

3.2. Interface state density characteristics of Al/Coronene/n-Si/In diode in dark and illumination intensity

The energy profile of the interface states ($E_c - E_{ss}$) values for n type semiconductor, the density of interface states (N_{ss}), and the effective barrier height (Φ_e) can be calculated from the following equations [21,22,28]

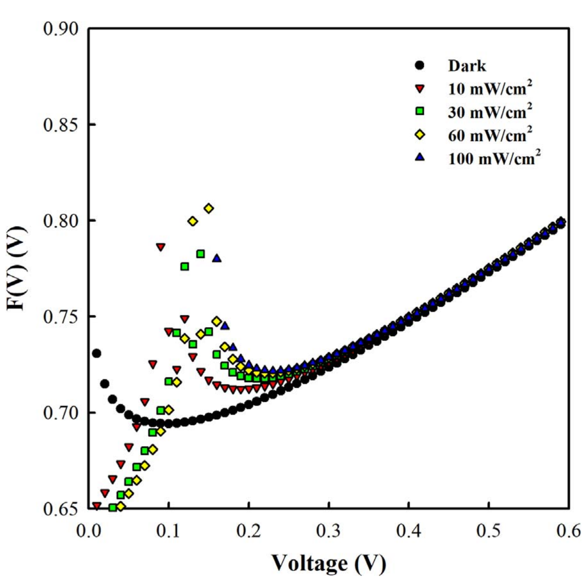

Fig. 3. Plot of *F(V)–V* for Al/Coronene/n–Si diode under dark, 10, 30, 60 and 100 mW/cm^2 illumination intensities.

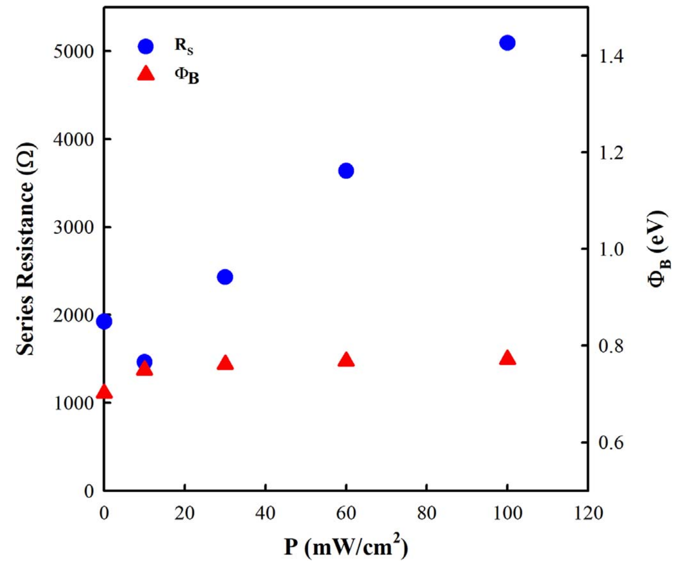

Fig. 4. The illumination intensity dependence of the series resistance (R_s) and the Schottky barrier height (Φ_B) obtained from *F(V)–V* plots.

$$E_c - E_{ss} = q(\Phi_e - V), \quad \Phi_e = \Phi_b + \beta V = \Phi_b + \left(1 - \frac{1}{n(V)}\right)V, \tag{6}$$

$$N_{ss} = \frac{1}{q}\left(\frac{\varepsilon_i}{\delta}(n(V) - 1) - \frac{\varepsilon_s}{W_D}\right), \tag{7}$$

where E_c is the conduction band edge, E_{ss} is the energy of the interface states, δ is the interfacial layer thickness ($\delta \cong$ 50.3 nm) (obtained from corrected capacitance-voltage characteristic at 1 MHz and at dark from $C_{il} = \varepsilon_i\varepsilon_0 A/\delta$, C_{il} is the interfacial layer capacitance (C_{il}= 1.66 nF), W_D is the width of space charge region (W_D = 760.26 nm) determined according to $1/C_c^2 - V$ plot, $\varepsilon_i = 3\varepsilon_0$ and $\varepsilon_s = 11.8\varepsilon_0$ are the interfacial layer permittivity and silicon semiconductor permittivity [21], respectively.

The interface state density (N_{ss}) values of Coronene/n-Si diode obtained as a function of voltage are changed to a function of ($E_c - E_{ss}$) according to Eq. (6). The N_{ss} versus $E_c - E_{ss}$ plots of the Coronene/n-Si contact at dark and different illumination intensities are given in Fig. 5. According to Fig. 5, The values of N_{ss} decrease with increasing

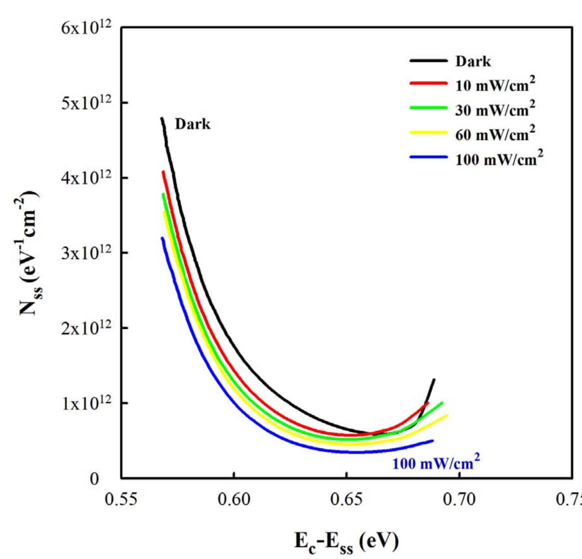

Fig. 5. The interface state density (N_{ss}) vs. energy distribution profile ($E_c - E_{ss}$) plots of the Al/Coronene/n-Si Schottky barrier diode under dark, 10, 30, 60 and 100 mW/cm^2 illumination intensities.

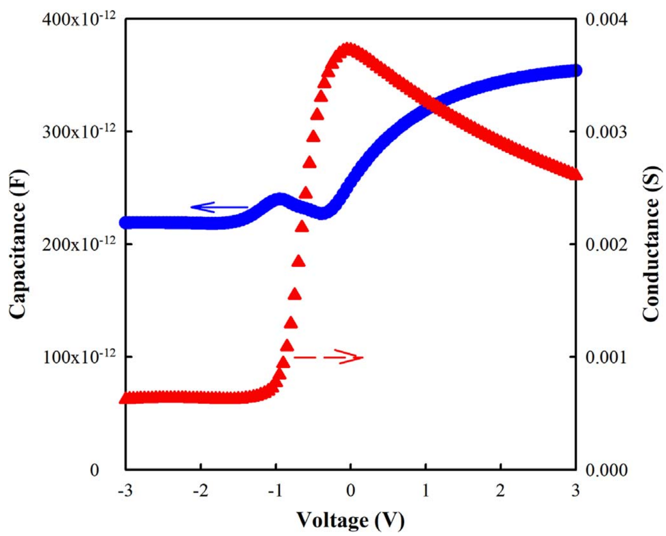

Fig. 6. The measured capacitance-voltage ($C–V$) and conductance-voltage ($G–V$) plots of Al/Coronene/n-Si Schottky barrier diode at 1 MHz.

illumination intensity in the vary from E_c−0.568 to E_c−0.690 eV. The values of N_{ss} were obtained to vary from 4.76 × 10^{12} eV^{-1} cm^{-2} to 1.32 × 10^{12} eV^{-1} cm^{-2} for E_c−0.568 eV at dark and 3.15 × 10^{12} eV^{-1} cm^{-2} to 5.04 × 10^{11} eV^{-1} cm^{-2} for E_c−0.690 eV at 100 mW/cm^2, respectively. It can be deduced that the carriers'excitations had decreased the trap effects at the interface [39]. The decrease in the value of N_{ss} with the increasing the intensity of illumination may also be explained by discharge and charge of interface states under the effect of illumination [40].

3.3. Capacitance-conductance–voltage characteristics of Al/Coronene/n-Si/In diode in dark

Fig. 6 shows the measured capacitance-voltage ($C_m - V$) and conductance-voltage ($G_m - V$) characteristics under forward and reverse-bias voltages for Coronene/n-Si diode at room temperature and 1 MHz. According to Fig. 6, The capacitance values increase while the values of conductance decrease with increasing positive voltage and depend on some parameters such as interfacial layer, series resistance, and interface state density δ, N_{ss}, and R_s. Also, the measured capacitance-voltage curve shows a peak at − 1 V. This observed peak is due to the interface states and series resistance [41]. If the ($G_m - V$) and ($C_m - V$) characteristics are evaluated at a sufficiently high frequency (1 MHz), the effects of N_{ss} are removed, In this case, the charges of interface state cannot follow an ac signal [41]. Eventually, it is said that the interface states are in equilibrium with the semiconductor.

The series resistance (R_s) seems a valuable parameter which causes the electrical characteristics of the devices to be non-ideal [41]. The technique is used to obtain the value of R_s proposed by Nicollian and Goetzberger [42]. This technique has been used for the Al/Coronene/n-Si diode. The values of R_s, corrected equivalent capacitance (C_c) and parallel conductance (G_c) from −3 V to 3 V have been obtained from the following relations [22,41,42]:

$$R_s = \frac{G_m}{G_m^2 + (\omega C_m)^2}, \tag{8}$$

$$C_c = \frac{(G_m^2 + \omega^2 C_m^2)C_m}{a^2 + \omega^2 C_m^2}, \quad G_c = \frac{(G_m^2 + \omega^2 C_m^2)a}{a^2 + \omega^2 C_m^2}$$

$$a = G_m - (G_m^2 + \omega^2 C_m^2)R_s, \tag{9}$$

$$N_{ss} = \frac{2(G_{c,\max}/\omega)}{qA}[(G_{c,\max}/\omega C_{il})^2 + (1 - C_c/C_{il})^2]^{-1} \tag{10}$$

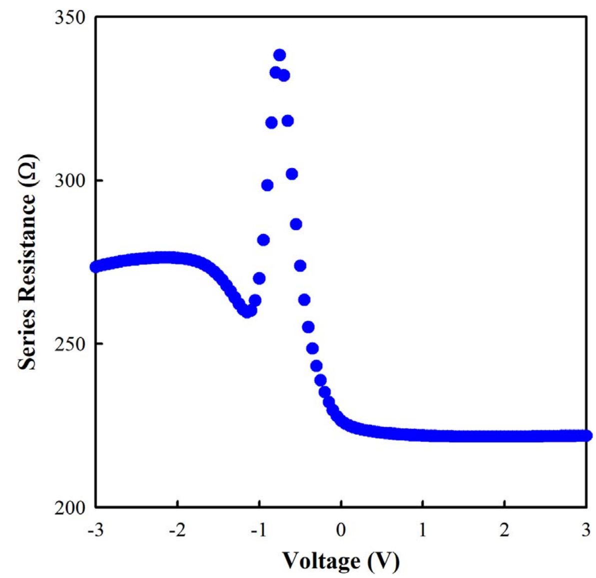

Fig. 7. The determined $R_s - V$ plots of the Al/Coronene/n-Si Schottky barrier diode at 1 MHz.

where $G_{c,\max}$ is the top value of the G_c–V plot and C_c is the diode capacitance corresponding to $G_{c,\max}$. The R_s values versus voltage of Coronene/n-Si diode at 1 MHz in accumulation region are plotted in Fig. 7. The R_s value obtained at 3 V in accumulation region is 220 Ω for Coronene/n-Si diode. This value of R_s is used to obtain the corrected capacitance (C_c) and conductance (G_c) characteristics.

Fig. 8 illustrates the corrected capacitance (C_c) and conductance (G_c) curves corresponding to voltage for Al/Coronene/n-Si diode at 1 MHz and at room temperature. It is clearly seen that the $G_c - V$ curve illustrates a peak. The peak occurs the depletion region of the diode and its existence approves the existence of interface states [41]. The N_{ss} value from Eq. (10) is evaluated from the peak value. A single-frequency approximation method proposed by Hill and Coleman [43] is used to calculate the N_{ss} value of Al/Coronene/n-Si diode. From Hill and Coleman technique, the N_{ss} value of our diode was determined to be 1.18 × 10^{12} eV^{-1} cm^{-2}.

Fig. 9 represents the reverse-bias $1/C_c^2 - V$ curve determined from $C_c - V$ data of Fig. 8 for Al/Coronene/n-Si diode. The $1/C_c^2 - V$ curve for Al/Coronene/n-Si diode has a good linearity.

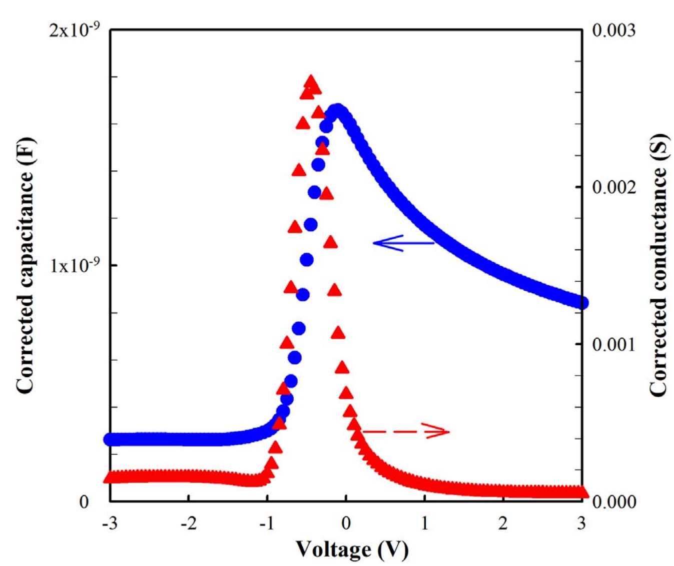

Fig. 8. The corrected capacitance (C_c) and conductance (G_c) characteristics versus voltage at 1 MHz for Al/Coronene/n-Si Schottky barrier diode.

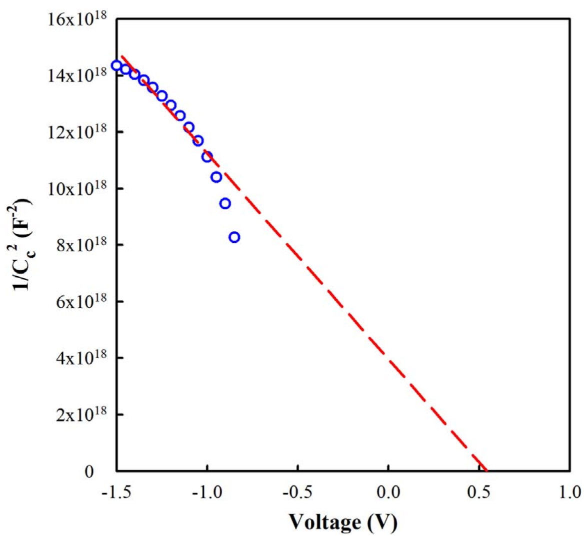

Fig. 9. $1/C_c^2 - V$ characteristic for the Al/Coronene/n-Si Schottky barrier diode at 1 MHz.

For a our sample, the depletion layer capacitance (C) is determined the following relation [21,22,44]:

$$C^{-2} = \frac{2(V_{bi} + V)}{A^2\varepsilon_s\varepsilon_0 qN_D}, \tag{11}$$

$$\frac{\partial(1/C^2)}{\partial V} = \frac{2}{A^2\varepsilon_s\varepsilon_0 qN_D}, \tag{12}$$

where A is the area of device, V_{bi} is the built-in voltage at zero bias, N_D is the carrier concentration, ε_s is the permittivity of the semiconductor ($\varepsilon_S = 11.8\varepsilon_0$ for Si) and ε_0 is the vacuum permittivity ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m) [21].

The barrier height values have been determined from the following equations [21,22,44]:

$$\Phi_b(C - V) = V_{bi} + E_F - \Delta\Phi_b, \tag{13}$$

$$\Delta\Phi_b = \left(\frac{qE_m}{4\pi\varepsilon_s\varepsilon_0}\right)^{1/2}; \quad E_m = \left(\frac{2qV_{bi}N_D}{\varepsilon_s\varepsilon_0}\right) \tag{14}$$

$$E_F = \frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right); \quad N_C = 4.82x10^{15}T^{3/2}\left(\frac{m_e^*}{m_0}\right)^{3/2} \tag{15}$$

$$W_D = \sqrt{\frac{2\varepsilon_s}{qN_D}V_D}; \quad E_{\max} = \frac{2V_{bi}}{W_D} \tag{16}$$

where E_m is the maximum electric field, N_C is the state density of the conduction band, W_D is the width of space charge layer, E_F is the energy difference between the bulk Fermi level and conduction band edge and $\Delta\Phi_b$ is the lowering of image force. It is obtained that the V_{bi} from the extrapolation of $1/C_c^2 - V$ curve to the voltage axis. From Eq. (13)–(16), the V_{bi}, N_D, E_F, $\Delta\Phi_b$, W_D, $E_{\max}$ and $\Phi_b(C - V)$ values were calculated as 0.715 V, 1.812×10^{15} cm^{-3}, 0.250 eV, 0.022 eV, 7.18×10^{-5} cm, 1.99×10^4 V/cm and 0.942 eV. The capacitance-voltage (C–V) characteristic for Coronene/n-Si structure has given a barrier height value higher than those determined from the current-voltage (I–V) characteristic. Compared to the barrier heights calculated for Schottky diodes, the flat band barrier height value calculated from C-V characteristic was always higher than the zero-bias barrier height value from I-V characteristic in the literature [15]. Furthermore, this difference is considered small relative to the possible effects of the Coronene layer or of the charges existing at the Al and the n-Si interface [15].

4. Conclusion

Al/Coronene/n-Si structure was obtained by depositing the Coronene layer using spin coating method on n-Si substrate. Electronic and photovoltaic effect of the Coronene/n–Si (organic/inorganic semiconductor) structures have been investigated by current-voltage (I-V) measurements. All of these experimental results confirmed that the use of a Coronene organic semiconductor thin film between metal and semiconductor leads to improvements in the diode performance. For instance, the n values have been determined as 2.81 and 2.07 at dark and 100 mW/cm^2 for Coronene/n-Si diode, respectively. The Φ_B values have been determined as 0.697 and 0.755 eV at dark and 100 mW/cm^2 for Coronene/n-Si diode, respectively. The N_{ss} values have been determined as 4.76×10^{12} and 3.15×10^{12} eV^{-1} cm^{-2} at dark and 100 mW/cm^2 for Coronene/n-Si diode. The photovoltaic measurement has been showed that the Coronene/n–Si structure is precision to light intensity. The I–V characteristic of the device shows photovoltaic cell, under light situations and can be used as a solar cell and a photo-diode in optoelectronic applications.

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