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ORIGINAL PAPER

Effect of illumination on electrical parameters of Au/(P3DMTFT)/*n*-GaAs Schottky barrier diodes

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Abstract: Reverse- and forward-bias current–voltage (*I–V*) data of the Au/(P3DMTFT)/*n*-GaAs Schottky barrier diodes (SBDs) were measured in dark and at under various illumination levels (from 50 to 200 W with steps of 25 W) for the purpose of examining the change in electrical parameters such as zero-bias barrier height (Φ_{bo}), ideality factor (n), reverse saturation current (I_o), series resistance (R_s) and shunt resistance (R_{sh}) with illumination. The values of n, Φ_{bo} and I_o were determined using *I–V* data in dark as 1.34, 0.91 eV and 7.25×10^{-12} A, respectively. On the other hand, these parameters were obtained as 1.85, 0.80 eV and 5.11×10^{-10} A, respectively, when the SBD is exposed to 200 W illumination. The values of shunt resistance (R_{sh}) and series resistance (R_s) were determined from Ohm's law and shown as R_i–V plots. Additionally, Cheung's and modified Norde's functions were also utilized for the extraction of R_s in dark and under various illumination levels. The energy density distribution profiles of interface states (N_{ss}) were investigated for various illumination levels. The dependency of the energy density distribution profiles of interface states (N_{ss}) on illumination levels was investigated. Obtained results suggest that these electrical parameters are sensitive to illumination. Moreover, Au/(P3DMTFT)/*n*-GaAs SBDs shows remarkable photovoltaic performance with the values of short-circuit current (I_{sc}) of 1.45×10^{-6} A, open-circuit voltage (V_{oc}) of 0.37 V and fill factor of 0.65 under 200 W illumination.

Keywords: Polymer interlayer; Metal–semiconductor contact; Photodiode; Illumination effects; Interface states

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1. Introduction

Gallium arsenide (GaAs) is a III–V compound semiconductor with a band gap of 1.42 eV. Diodes made of GaAs show 10 times more transition frequency than the diodes made of silicon (Si). Therefore, GaAs is used as a component of many electronic devices and utilized in the production of devices with high performance [1]. GaAs is preferred particularly in high-efficiency metal–semiconductor (MS) Schottky photodiode applications because of properties such as direct band gap, high carrier mobility and high saturated electron velocity [2–6].

Semiconducting conjugated polymers can be used as active materials in the production of MS Schottky barrier diodes (SBDs) and heterojunctions [3, 7–10]. In particular, metal–insulator/polymer–semiconductor (MIS/MPS) type SBDs can be obtained by using polymer at *M/S* interfacial layer [11–13]. Devices with photovoltaic properties are sensitive to light, that is, a Schottky photodiode behavior can be observed when MPS structure with a photo-responsive interlayer is illuminated. When the rectifier/Schottky contact is illuminated, photons with sufficient energy (have a higher energy than the forbidden energy gap) are absorbed and the electron–hole pairs are produced in the depletion region of semiconductor. If an electric field is applied to this structure, electrons are rapidly swept from polymer interlayer, whereas holes are slowly swept, and consequently, there would be an additional current. The photovoltaic properties of MPS-type SBDs can be characterized from the fourth region of current–voltage (*I–V*) characteristics under illumination. The basic photovoltaic parameters include short-circuit current (I_{sc}), fill factor (FF) and open-circuit voltage (V_{oc}). These

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parameters provide information about the device quality and the photovoltaic performance [1, 2, 4, 5, 14, 15].

Among polymers, polythiophene and its derivatives are most impressive conjugated polymers. These materials exhibit good optical properties and environment stability, and there has been enormous interest toward these polymers for their usage in applications such as solar cells, light-emitted diodes and sensors [16–20]. Furthermore, the devices based on polythiophene derivatives are typically sensitive to light and they are highly preferred due to this property for photovoltaic devices [20–23]. Poly (3-substituted thiophene) (P3DMTFT) is a polythiophene derivate, and its molecular structure is given in Fig. 1. P3DMTFT semiconducting conjugated polymer has been considered as one of the most stable semiconducting polymers for various electronic applications [8]. Therefore, the MPS structure, which is obtained by using the P3DMFT interface layer between M and S, needs to be examined.

We examined the change in some electrical parameters such as zero-bias barrier height (BH) (Φ_{bo}), ideality factor (n), reverse saturation current (I_o), series resistance (R_s) and shunt resistance (R_{sh}) of the Au/(P3DMTFT)/n-GaAs Schottky barrier diodes (SBDs) with illumination. The reverse- and forward-bias current–voltage (I–V) data of these diodes were measured in dark and under various illumination levels (from 50 to 200 W with steps of 25 W). Also, capacitance–voltage (C–V) measurements were carried out in dark for 500 kHz.

The values of R_s were extracted using I–V data in Cheung's and modified Norde's functions. The energy density distribution profiles of interface states (N_{ss}) of the studied SBD were determined in both dark and under various illumination levels. Finally, our objective is to investigate whether the Au/(P3DMTFT)/n-GaAs SBDs can be used as a photovoltaic device.

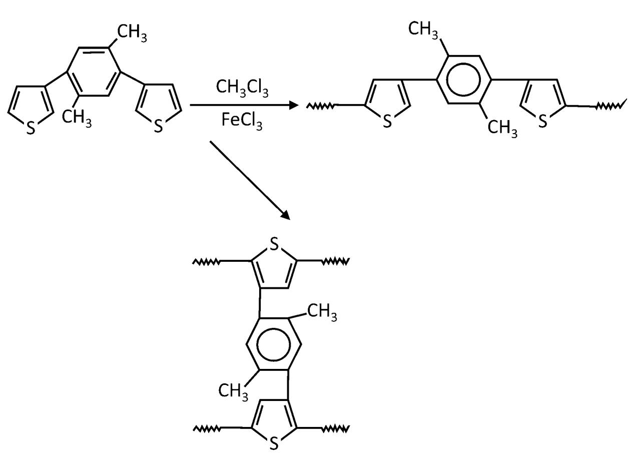

Fig. 1 Molecular structure of the poly (3-substituted thiophene) (P3DMTFT)

2. Experimental process

In the present work, the Au/(P3DMTFT)/n-GaAs SBDs were manufactured by using n-type GaAs wafer with (100) surface orientation, 2–5 $\times$ 10^{17} cm^{-3} doping donor atoms and 450 µm thickness. Wet chemical cleaning procedures were performed before the deposition process. The wafer firstly was dipped into $5H_2SO_4 + H_2O_2 + H_2O$ solution for 1 min., secondly it was dipped into $10H_2O + HCl$ solution, and then, it was rinsed in de-ionized water and dried with dry nitrogen (N_2) gas. After cleaning procedure, the wafer immediately was transferred into the high-vacuum thermal evaporation system, and then, highly pure Au (99.999%) was thermally grown on the back side of the wafer at 10^{-6} Torr so that Au layer with thickness of 1500 Å was achieved. For obtaining ohmic contact, it was annealed at 450 °C in flowing N_2 atmosphere. Later, front side of the wafer was grown with the solution of poly (3-substituted thiophene) (P3DMTFT) through dip coating process. The Au rectifier/Schottky contacts with 1500 Å thickness were thermally grown on the polymer layer at 10^{-6} Torr. The area of circular contacts was 0.018 cm^2. Consequently, fabrication of the Au/(P3DMTFT)/n-GaAs SBDs was completed. Schematic diagrams of these SBDs and measurement system are given in Fig. 2. The manufactured SBDs were on a holder, and the contact was made by silver paste. Also, the electrical contact was made on electrodes by using small thin silver-coated wires with silver paste.

Firstly, I–V measurements were held in the dark. Then, a solar simulator light source (shown in Fig. 2) was used to illuminate the SBDs and the sample was measured under various illumination levels (from 50 to 200 W with steps of 25 W). The intensity of the light was controlled by using research radiometer (Model ILT1700, International Light Technologies, Massachusetts, USA). The photons at different power levels passed through the AM 1.5 filter (appropriate for the wavelengths only between 400 and 700 nm) to reach the surface of the diodes. The forward and reverse bias I–V measurements were carried out by using a source meter (shown in Fig. 2) in dark and under various illumination levels. The forward and reverse bias C–V measurements were performed in dark for 500 kHz by using HP 4192 LF impedance analyzer. All measurements were carried out at room temperature.

3. Results and discussion

When the SBDs with insulator or polymer interlayer are considered, according to thermionic emission (TE) theory ($V \geq kT/q$), the current expression is given as [24]:

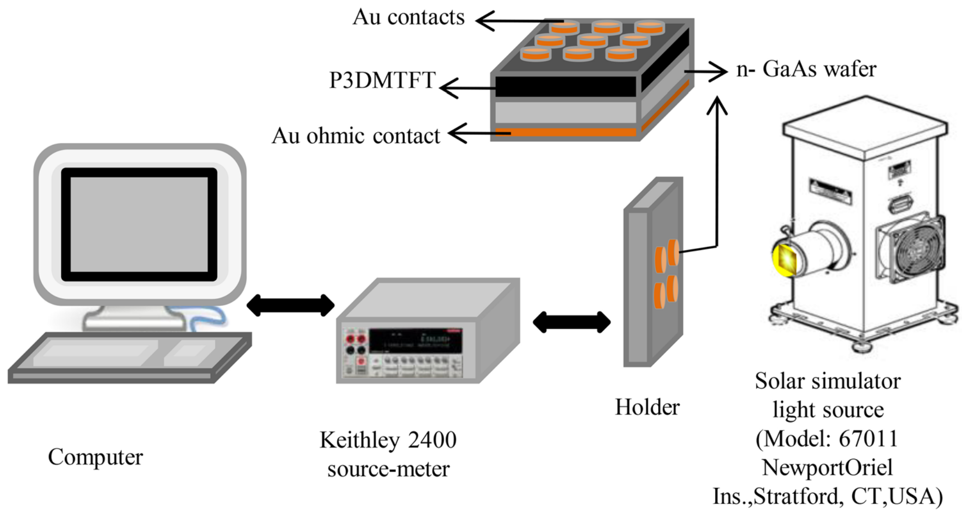

Fig. 2 Schematic diagrams of the Au/(P3DMTFT)/*n*-GaAs SBDs and measurements system

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

where the I_o, IR_s, T, n, and k are, respectively, saturation current, voltage drop across R_s of the diodes, temperature in K, ideality factor and the Boltzmann constant [24]. The value of I_o can be obtained from the forward-bias *I–V* curves' *y*-axis intercept at zero bias and can be written as [24]:

$$I_o = AA^*T^2 \exp\left(-\frac{q\Phi_{bo}}{kT}\right) \quad (2)$$

Here, A is the Schottky contact area and A^* is the effective Richardson constant of *n*-GaAs (= 8.16 A/cm^{2}K^2) [24, 25]. Also, n is an important electrical parameter which can be obtained using the following expression [24]:

$$n = \frac{q}{kT}\frac{dV}{d(\ln(I))} \quad (3)$$

Figure 3 displays the *I–V* curves of the Au/(P3DMTFT)/*n*-GaAs SBDs for both dark and under various illumination levels. For dark and each illumination level, the diodes exhibited a good rectifying behavior and each semilogarithmic *I–V* curve revealed a wide linear region. These regions take place in the bias range of $0.1 \leq V \leq 0.8$ with different slopes, but deviate from linearity at above 0.8 V owing to the effect of R_s and P3DMTFT interlayer [11, 14, 25, 26].

The reverse bias *I–V* characteristics exhibit non-saturating behavior in dark. Such behavior is explained by the presence of P3DMTFT layer at *M/S* interfacial layer and the image force lowering of BH [24, 27]. It is also seen that the reverse bias *I–V* curve in the dark shows unsatisfactory behavior, but the current is saturated with illumination. The values of n, Φ_{bo} and I_o for dark and illumination conditions were obtained by using Eqs. (1)–(3) and are tabulated in

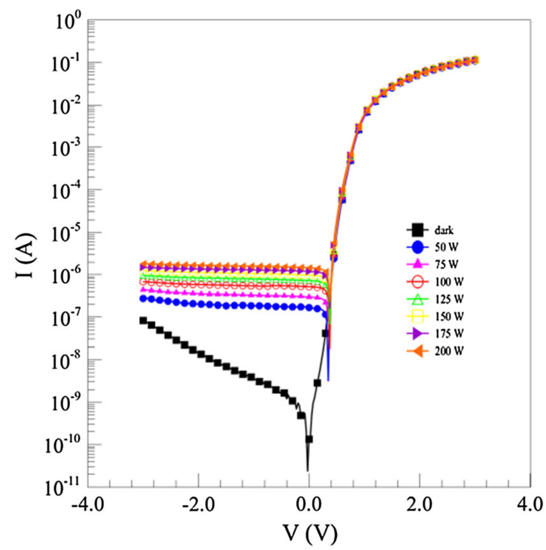

Fig. 3 The *I–V* characteristics of the Au/(P3DMTFT)/*n*-GaAs SBDs in dark and under various illumination levels at room temperature

Table 1. The values of n and Φ_{bo} were found to be 1.34 and 0.91 eV in dark, respectively. The values of n and Φ_{bo} were changed to 1.85 and 0.80 eV under 200 W illumination, respectively. Figure 4 shows illumination dependence of Φ_{bo} and n. It is noted that BH value is decreased with increased illumination level, whereas opposite behavior is observed for n with increased illumination level. A similar phenomenon was observed for many SBDs [5, 12, 15]. Such a change in the values of n and Φ_{bo} with illumination can be a scribed to generation and separation electron–hole pairs and the molecular restructuring and reordering of surface states under various illumination levels [1, 15]. It is well known that the case of n = 1 is associated with ideal diodes [24], whereas n value higher than unity shows that the diode has a MIS structure [24, 28]. The values of n greater than unity can be caused by several factors such

Table 1 Obtained some electrical parameters for the Au/(P3DMTFT)/*n*-GaAs SBDs in dark and under various illumination levels at room temperature

Illumination levels (W)	I_o (A)	n	Φ_{bo} (eV)	R_s (Ω)	R_{sh} (MΩ)	dV/d(ln*I*) − *I*		*H*(*I*) − *I*	
						n	R_s (Ω)	R_s (Ω)	Φ_b (eV)
0	7.25×10^{-12}	1.34	0.91	26.18	35.96	3.59	17.70	16.34	0.64
50	1.17×10^{-11}	1.42	0.90	27.82	10.90	3.52	18.81	17.88	0.64
75	3.00×10^{-11}	1.51	0.87	28.76	6.7	3.52	19.19	17.73	0.64
100	4.68×10^{-11}	1.57	0.86	25.56	4.3	3.36	17.44	16.04	0.65
125	1.16×10^{-10}	1.68	0.83	26.10	3.1	3.36	17.84	16.53	0.65
150	1.62×10^{-10}	1.73	0.82	26.51	2.4	3.44	18.00	16.60	0.64
175	2.47×10^{-10}	1.77	0.81	27.38	2.0	3.60	18.59	17.15	0.63
200	5.11×10^{-10}	1.85	0.80	26.95	1.6	3.57	18.68	17.14	0.63

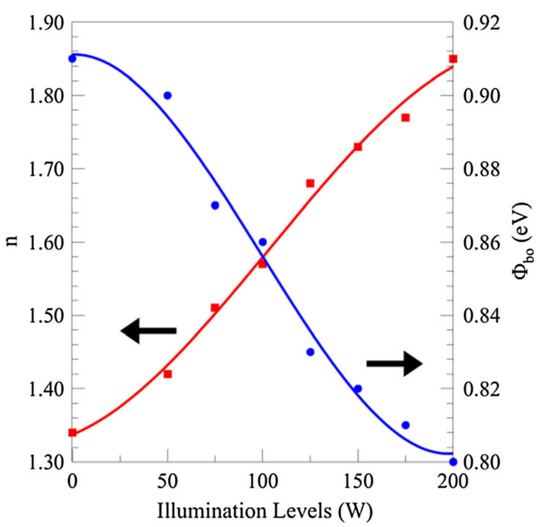

Fig. 4 The variation of the values of Φ_{bo} and n with illumination levels

as the recombination–generation of electron–hole pairs, depletion layer width, distribution of interfacial charges, inhomogeneities of P3DMTFT interlayer at the Au/*n*-GaAs interfacial, N_{ss} and R_s [1, 14, 24, 28, 29]. The value of I_o in dark was determined as 7.25×10^{-12} A, while its value under 200 W illumination was obtained as 5.11×10^{-10} A. This clearly shows that the I_o values increase with increase in illumination level. This situation can be ascribed to the illumination that activates recombination of photo-generated carriers in the interface [12, 15, 30].

To obtain more detailed information on the electrical parameters of SBDs, it is important to examine the effect of R_s on electrical characteristics. There are many methods to investigate the effect of R_s. However, methods developed by Cheung's and Norde's are preferred due to their simplicity of the calculation and the reliability of the results [31–34]. In addition, the values of R_s and R_{sh} can be easily obtained using the Ohm's law (R_i= dV_i/dI_i) as well. The voltage-dependent dispersion of resistivity (R_i) was obtained by using R_i= dV_i/dI_i in dark and under various illumination levels for the Au/(P3DMTFT)/*n*-GaAs SBDs and is shown in Fig. 5.

It seen in Fig. 5 that R_i becomes saturated and take minimum value at sufficiently high forward-bias voltages (≥ 3 V) for both dark and illumination conditions such that the real value of R_s corresponds to these minimum values. The values of R_s (at 3 V) and R_{sh} (at − 3 V) are also given in Table 1. This table clearly shows that the values of both R_s and R_{sh} were affected by illumination.

In Fig. 3, the effect of R_s is evident because of the downward bending of the *I–V* curves ($V > 0.5$ V). To determine the effect of R_s, it was also obtained by using *I–V* data in Cheung's functions which are given below [32]:

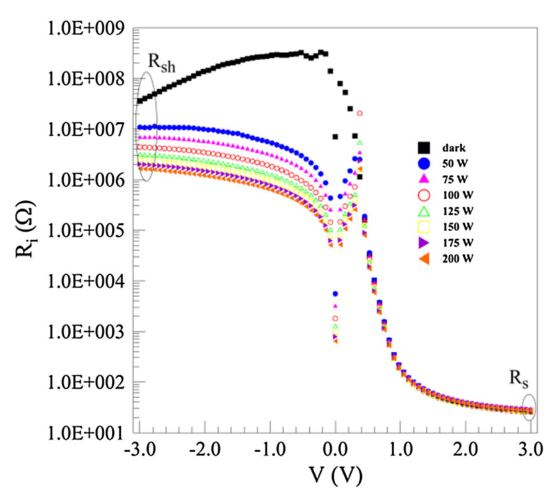

Fig. 5 The R_i–V characteristics of the Au/(P3DMTFT)/*n*-GaAs SBDs in dark and under various illumination levels at room temperature

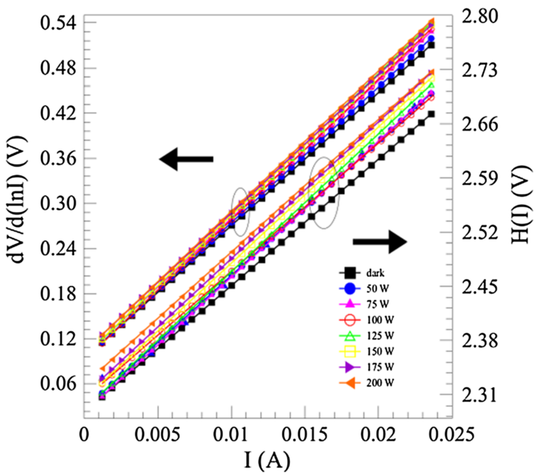

Fig. 6 The $dV/d\ln I - I$ and $H(I) - I$ characteristics of the Au/(P3DMTFT)/n-GaAs SBDs in dark and under various illumination levels at room temperature

$$\frac{dV}{d(\ln I)} = \left(\frac{nkT}{q}\right) + IR_s \tag{4}$$

$$H(I) = V - n\frac{kT}{q}\ln\left(\frac{I}{AA^*T^2}\right) = n\Phi_b + IR_s \tag{5}$$

The plots of $dV/d\ln I$ versus I and $H(I)$ versus I for dark and illumination conditions were drawn by using Eqs. (4) and (5), and are given in Fig. 6. In these plots, a linear region appears and slope of this linear region directly yields R_s whereas y-axis intercept of $dV/d\ln I$ versus I yields n. Later, Φ_b can be obtained using this n value in y-axis intercept of $H(I)$ versus I [32]. The values of these parameters are also shown in Table 2. $dV/d\ln I$ versus I plots revealed R_s as 17.70 Ω and 18.60 Ω for dark and 200 W illumination conditions. Similarly, $H(I)$ versus I plots revealed R_s as 16.34 Ω and 17.14 Ω for dark and 200 W illumination conditions. These results clearly show that R_s values are consistent with each other. Moreover, it is seen in Table 2 that R_s value obtained by Cheung's functions almost do not change with increased illumination level. In this case, it can be said that illumination does not have prominent effect on R_s of Au/(P3DMTFT)/n-GaAs SBDs. It is seen that the values of n and BH calculated from the I–V plots are different from those calculated from Cheung's functions. This is because each method utilizes different regions of I–V data. The values obtained from I to V curves are calculated using the data that correspond to linear region of the plot, whereas those obtained from Cheung's functions are calculated using the data that correspond to downward curvature region of I–V plots. Another reason for this difference is that the value of n depends on the applied bias [5, 12, 14].

R_s was also calculated using the modified Norde's functions. Bohlin proposed a modified version of the Norde's functions to determine R_s and BH. The modified Norde's functions are expressed as [33, 34]:

$$F(V) = \frac{V}{\gamma} - \frac{kT}{q}\ln\left(\frac{I(V)}{AA^*T^2}\right) \tag{6}$$

$$\Phi_b = F(V_{min}) + \frac{V_{min}}{\gamma} - \frac{kT}{q} \tag{7}$$

$$R_s = \frac{kT(\gamma - n)}{qI_{min}} \tag{8}$$

Here, $F(V_{min})$, I_{min} and V_{min} are, respectively, the minimum value of F–V curve, the minimum current corresponding to $F(V_{min})$ and the minimum applied voltage corresponding to $F(V_{min})$ [24, 33]. γ is an arbitrary constant greater than the value of n. Figure 7 shows $F(V)$ versus V curves of Au/(P3DMTFT)/n-GaAs SBDs in dark and various illumination levels for the case of $\gamma = 2$. The values of I_{min}, V_{min} and F_{min} were determined from these curves for dark and illumination conditions and are given in Table 2. In addition, the values of BH and R_s were calculated by using Eqs. (7) and (8) and are given in Table 2.

As can be seen in Table 2, R_s is decreased with increased illumination level. The values of R_s obtained from the modified Norde's functions are greater than the values of R_s found using the Cheung's functions. This can be explained as follows; the Cheung's functions are applied

Table 2 Some electrical parameters obtained from Norde functions for the Au/(P3DMTFT)/n-GaAs SBDs in dark and under various illumination levels at room temperature

Illumination levels (W)	F_{min} (V, γ = 2)	V_{min} (V)	I_{min} ($\times 10^{-5}$ A)	R_s (Ω)	Φ_b (eV)
0	0.79	0.54	2.47	689.58	0.91
50	0.79	0.54	2.41	622.69	0.89
75	0.79	0.54	2.81	449.89	0.87
100	0.78	0.54	3.01	369.51	0.85
125	0.78	0.54	3.51	235.57	0.83
150	0.78	0.54	3.67	189.89	0.82
175	0.78	0.54	4.27	139.33	0.81
200	0.77	0.52	3.00	129.25	0.80

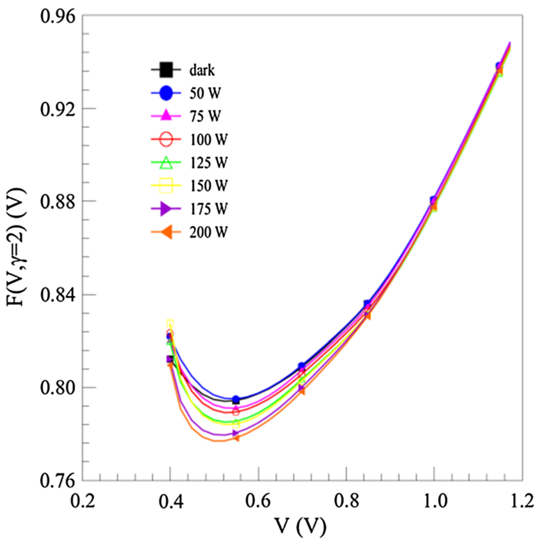

Fig. 7 The Norde functions of the Au/(P3DMTFT)/*n*-GaAs SBDs in dark and under various illumination levels at room temperature

to nonlinear region of the *I*–*V* plots, whereas the modified Norde's functions are applied to the whole forward-bias region of *I*–*V* plots [6, 32–34].

The values of interface states, N_{ss}, can be calculated by using forward-bias *I*–*V* data taking into account the bias dependence of the *n* and BH using the following equation [35–37]:

$$N_{ss} = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n-1) - \frac{\varepsilon_s}{W_D}\right] \tag{9a}$$

Here, δ, ε_i, ε_s and W_D are, respectively, thickness of interfacial layer, permittivity of the interfacial layer, permittivity of semiconductor (ε_s= 11.8ε_o and ε_o= 8.85 × 10^{-14} F/cm) [24, 25] and depletion layer width [25]. The values of W_D were calculated using *C*–*V* characteristics in dark at 500 kHz, and it was assumed that W_D is almost independent of the illumination in the reverse bias region because in this region the effects of surface states (N_{ss}) and R_s can be neglected.

The relation between measured *C* and *V* for MS structures with and without an interfacial layer can be expressed as [24, 25].

$$\frac{1}{C^2} = \frac{2}{q\varepsilon_s\varepsilon_o N_D A^2}\left(V_{bi} - \frac{kT}{q} - V_R\right) \tag{9a}$$

Here, V_R is the reverse bias voltage, V_{bi} is the built-in voltage, and *A* is the diode area. Both *C*–*V* plot and reverse bias C^{-2}–*V* plot of the Au/(P3DMTFT)/*n*-GaAs SBDs in dark for 500 kHz are given in Fig. (8a). The thickness of P3DTFT interfacial layer was estimated from the measured interfacial layer capacitance (C_i= $\varepsilon_i\varepsilon_o A/\delta$) as 24.5 nm. As can be clearly seen in Fig. 8(a), C^{-2}–*V* plot is considerably linear in wide range of bias voltage. Thus, the values of V_{bi} and the concentration of donor atoms (N_D= 2/($q\varepsilon_s\varepsilon_o A^2$tanθ)) were calculated from the intercept and slope of C^{-2}–*V* plot as 0.831 V and 1.58 × 10^{17} cm^{-3}, respectively. Thus, the value of W_D(= $(2\varepsilon_s V_D/qN_D)^{1/2}$) was estimated as 0.89 × 10^{-5} cm.

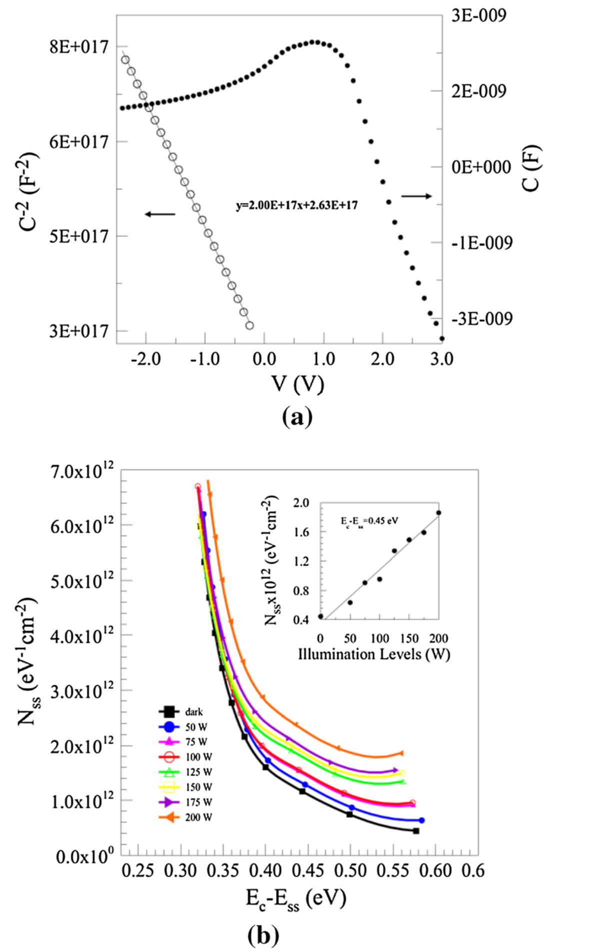

Fig. 8 (**a**) The *C*–*V* and reverse bias C^{-2}–*V* plots of the Au/(P3DMTFT)/*n*-GaAs SBDs for 500 kHz in dark. (**b**) The energy distribution profiles of N_{ss} and the exchange of interface states with illumination level for the Au/(P3DMTFT)/*n*-GaAs SBDs in dark and under various illumination levels at room temperature

In an *n*-type semiconductor, the energy of surface states (E_{ss}) with respect to the bottom of the conduction band (E_c) at surface of the semiconductor can be expressed as follows [36]:

$$E_c - E_{ss} = q(\Phi_e - V) \tag{10}$$

where the term of Φ_e is the effective BH [36]. The energy distribution profiles of N_{ss} versus ($E_c - E_{ss}$) plots were drawn in dark and under various illumination levels and are shown in Fig. 8(b). For various illumination levels, in Fig. 8(b), the values of N_{ss} increase almost exponentially from the near of mid-gap (E_g) toward the bottom of E_c [14, 38]. In addition, the values of N_{ss} increase with increase in illumination level between (E_c-0.35) and (E_c-0.55) eV, particularly it is seen at ($E_c - E_{ss}$= 0.45) eV.

Table 3 The photovoltaic parameters of the Au/(P3DMTFT)/*n*-GaAs SBDs under various illumination levels at room temperature

Illumination levels (W)	V_{oc} (V)	I_{sc} (A)	V_m (V)	I_m (A)	FF
50	0.34	-1.68×10^{-7}	0.27	-1.34×10^{-7}	0.63
75	0.37	-2.98×10^{-7}	0.27	-2.48×10^{-7}	0.64
100	0.37	-5.18×10^{-7}	0.29	-4.20×10^{-7}	0.65
125	0.37	-7.26×10^{-7}	0.29	-5.87×10^{-7}	0.65
150	0.37	-9.69×10^{-7}	0.29	-8.00×10^{-7}	0.65
175	0.37	-1.19×10^{-6}	0.29	-9.60×10^{-7}	0.65
200	0.37	-1.45×10^{-6}	0.29	-1.17×10^{-6}	0.65

The fourth region in the *I–V* characteristics is photovoltaic region for a photodiode [2]. The value of V_{oc} is obtained from the point where the curve of *I–V* intersects the voltage axis at this region. The value of I_{sc} is obtained from the point where the curve of *I–V* intersects the current axis at same region. The value of I_m and V_m is within the largest rectangle that can be drawn between the *I–V* curve and coordinates of the in the fourth region. The value of V_m is the point at which this rectangle intersects its voltage axis, whereas the value of I_m is the point at which this rectangle intersects its current axis. The value of FF is ($V_m \times I_m$) divided by ($V_{oc} \times I_{sc}$) [2, 3, 6, 15]. The *I–V* characteristics of the Au/(P3DMTFT)/*n*-GaAs SBDs were drawn in the region of fourth quadrant to explore photovoltaic parameters and are given in Fig. 9. The obtained photovoltaic parameters of the Au/(P3DMTFT)/*n*-GaAs SBDs for various illumination levels are shown in Table 3.

As can be seen in Fig. 9 and Table 3, the values of V_{oc}, I_{sc} and FF increase with increase in illumination level. The experimental values of V_{oc}, I_{sc} and FF are determined as 0.34 V, 1.68×10^{-7} A and 0.63 for 50 W illumination, while the values of these parameters are 0.37 V, 1.45×10^{-6} and 0.65 for 200 W illumination, respectively. This clearly shows that the fabricated Au/*n*-GaAs with poly (3-substituted thiophene) (P3DMTFT) interfacial polymer layer is quite sensitive to illumination and exhibits photovoltaic behavior.

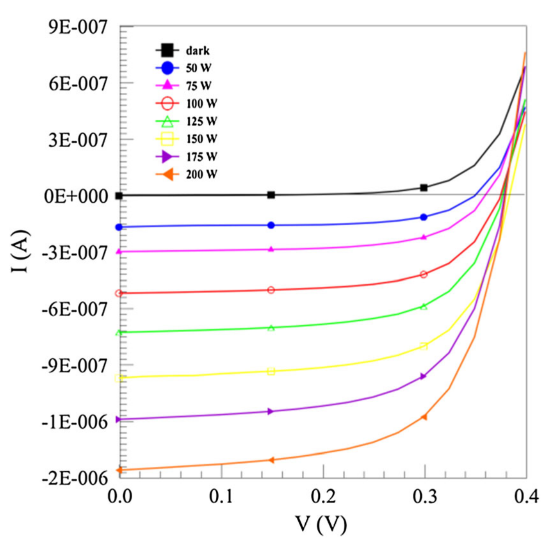

Fig. 9 The fourth quarter of *I–V* characteristics of the Au/(P3DMTFT)/*n*-GaAs SBDs under various illumination levels at room temperature

4. Conclusion

The electrical parameters such as *n*, Φ_{bo}, R_s and N_{ss} of the Au/(P3DMTFT)/*n*-GaAs SBDs were investigated by using *I–V* measurements in dark and under various illumination levels. The value of Φ_{bo} was found to decrease with increase in illumination level, while the value of *n* increases. The values of R_s were calculated using Ohm's law, Cheung's functions and modified Norde's functions. The energy density distribution profiles of N_{ss} were investigated in dark and under various illumination levels. It was observed that the values of N_{ss} were affected by illumination. Obtained results indicate that these electrical parameters are sensitive to illumination and the Au/(P3DMTFT)/*n*-GaAs SBDs exhibit photovoltaic behavior. It is clear that the Au/(P3DMTFT)/*n*-GaAs SBDs are promising for contemporary optoelectronic applications.

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