Investigation of Illumination Effects on the Electrical Properties of Au/GO/*p*-InP Heterojunction with a Graphene Oxide Interlayer

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Abstract

In this work, the electrical property of Au/graphene oxide/*p*-InP hetero-structure has been evaluated by *I*–*V* and *C*–*V* measurements in dark and illuminated conditions (visible light). The diode exhibited significant rectifying behavior, thus indicating the heterojunction-type diode. The key electrical parameters of heterojunction diode including ideality factor (*n*), series resistance (*R_s*), shunt resistance (*R_{sh}*), and barrier height (Φ_b) are estimated from *I*–*V* data based on the theory of thermionic emission. The modified Norde and Cheung's methods were utilized to evaluate the electrical parameters and compared the results. The current conduction mechanism at different voltage regions of *I*–*V* has also been investigated. The variation of $1/C^2$ versus voltage signifies linearity at high frequency (1 MHz), indicating that the type of heterojunction can be abrupt. The experimental outcomes of this study revealed that the performance of heterojunction diode in dark is considerably good as compared to the illumination condition with respect to the lower values of Φ_b , *n*, *R_s*, and interface state density (*N_{ss}*).

Keywords Electrical properties · Heterojunction diode · Graphene oxide · *I*–*V* and *C*–*V* techniques · Interface state density · Ideality factor

1 Introduction

Owing to the intriguing properties of III–V semiconductors, in particular, indium phosphide (InP) is a kind of prominent semiconductor material and extensively employed in the development of optoelectronic and microwave devices [1, 2]. It has numerous applications including metal/insulator/semiconductor field effect transistors, photodetectors, solar cells, microwave sources, and amplifiers [3–7]. In addition, InP has great potential for radiation resistance in comparison to other semiconductor materials like GaAs [8] and Si [9], which makes it a promising candidate in telecommunication applications, especially optical generation, switching, and detection components. In the meantime, InP-based Schottky junctions suffer low Schottky barrier height, which will cause a huge leakage current and degenerate the performance of the devices resulting from the high surface state density and other nonstoichiometric defects [10]. The

inserted layer of high conductive oxide material can act as a blockade of inter-diffusion, which can not only decrease the existing surface state density, leakage current, and series resistance, but also improve the shunt resistance and rectification ratio. Meanwhile, the inserted layer isolates metal from the semiconductor and hence hinders the inter-diffusion and reaction among them. Benefiting from these advantages, the metal/insulator/semiconductor (MIS) structure devices have emerged with excellent potential in a wide variety of applications, especially in optoelectronic and high-frequency devices owing to their easy and low-cost processing, better performance, flexibility, and low energy consumption. Therefore, in this regard, the in-depth knowledge of the rectification behavior characteristics of metal/insulator/InP structure would help to accelerate the development of the emerging potential applications.

There are only a few reported studies in open literature on the tuning of the Schottky barrier properties of metal/bulk InP contact by inserting a very thin interfacial layer between the M/S interface by different research groups [11–21]. Lin et al. [16] have prepared the MoS₂/*p*-InP heterojunction diode by chemical vapor deposition. The BH, ideality factor, and *R_s* values extracted from forward bias *J*–*V* characteristics are 0.73 eV, 2.4, and 12.8 Ω respectively.

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Chen et al. [17] reported the Al/MoO₃/p-InP MIS Schottky barrier diode and measured its electrical parameters with temperatures from 310 to 400 K. Reddy et al. [18] demonstrated that effective improvement could be attributed to the modification of Ti/p-type InP interface by inclusion of a polyvinylpyrrolidone (PVP) polymer interlayer. Recently, Acar et al. [21] fabricated the Au/ZnO/p-InP metal/oxide/semiconductor structure by using RF magnetron sputtering technique, and they found the density of interface states of this structure is from 8.18×10^{13} to 1.24×10^{11} eV⁻¹ cm⁻² with a change of frequency.

In recent years, an interesting layered material, graphene oxide (GO), has attracted many researchers' attention in a variety of applications due to its exceptional electrical, mechanical, and optical properties, which makes it one of the potential candidates in emerging electronics and optoelectronics. Currently, graphene/bulk semiconductor-based hybrid heterojunction has emerged in versatile diverse applications, such as solar cells, photodetectors, sensors, and Schottky junctions [22]. To date, many research groups have been devoted to constructing graphene-based hybrid heterostructures to modify or improve their performance with various bulk semiconductors such as GaAs [23], SiC [24, 25], AlGaIn [26, 27], GaN [28–31], Ge [32, 33], and Si [34–39], whereas only a little work [40–42] had been reported on InP. Phan et al. [43] have explored the photoelectrical performance of Al/GO/n-Si/Al Schottky diode and revealed that the photocurrent increases while the light intensity increases, where the nanoscale GO film acts as a semiconductor with high photoconductivity. Kalita et al. [44] analyzed the photovoltaic properties of Au/pr-GO/n-Si Schottky diode in dark and illuminated conditions. The *J*–*V* characteristics of the diode show good rectification and the leakage current is small under reverse bias in dark conditions. Yang et al. [45] have introduced a GO interlayer into Gr/Si solar cells and found that the performance of Gr/GO/Si structure was significantly more stable than that without a GO interlayer, and the maximum power conversion efficiency with GO is about 6.18%. Gullu et al. [42] prepared a Al/GO/n-InP heterojunction, where the MIS structure achieved higher barrier height (0.85 eV) with GO of about 100% compared with the value (0.43 eV) of the MS diode without a GO interlayer. However, there were no reports on heterojunction diode fabrication using graphene oxide (GO) Schottky contact on *p*-type InP with a detailed electrical characterization. Therefore, in this context, a thin graphene oxide film was used as an interlayer at the metal/semiconductor interface and the properties of the heterojunction were investigated under dark and illuminated conditions. It has been discovered that a thin inserted layer in the interface can be wiped out to enhance the interfacial properties and influence the quality and performance of the device. To validate the above arguments, we have fabricated the Au/GO/p-InP heterojunction and determined its electrical and photoelectrical properties. Moreover, the main electrical

parameters under dark and illuminated conditions were also evaluated, compared, and discussed in detail.

2 Experimental details

A cleaned *p*-type (100) InP (Zn-doped, 0.5 Ω cm) with 350-μm thickness (given by the manufacturer) was taken for the fabrication of the device. First, the wafer was treated by trichloroethylene, acetone, and methanol with ultrasound. Then the degreased wafer was dipped in a mixture of H₂SO₄, H₂O₂, and H₂O (5:1:1) for 1 min to clean the surface. After that, the wafer was treated with diluted HF (10%) solution to etch the oxide layer. Subsequently, DI water was used to clean the wafers, which dried under the flow of high-purity N₂ gas and then were immediately transferred into the deposition chamber. Pt film (30 nm, 99.99%) was deposited by electron beam evaporation and annealed at 350 °C for 1 min in N₂ atmosphere to attain good conductive contact. Initially, the graphene oxide powder (purchased from XF Nano) was dissolved in water for 12 h by ultrasonic agitation to achieve the homogeneous GO solution. Then, using the drop casting method, the GO layer was obtained on the front side of the substrate (see in Fig. 1a) and the sample was baked at 50 °C. The thickness of GO was measured by a stylus profiler and the value was about 40 nm, which was obtained from the difference between the average height of the upper surface and the average height of the lower surface, so no repeated measurements were made. The preparation process and the schematic illustration of Au/GO/p-InP heterojunction structure are given in Fig. 1a, b. In addition, AFM was adopted to evaluate the surface quality before and after depositing the GO layer and is depicted in Fig. 2. The images show the continuous GO film, which works as the interlayer between the metal and the semiconductor. Eventually, Au circular dots with 30 ± 1 nm thickness and 0.7 ± 0.0075 mm diameter were deposited through a stainless-steel mask.

The *I*–*V* and *C*–*V* data of Au/GO/p-InP heterojunction were recorded by semiconductor device analyzer (Keysight B1500A) in dark and illuminated conditions. The illumination was carried out by a general commercial lamp with a power density of 30 mW/cm². As well, the capacitance frequency (*C*–*f*) characteristics were also evaluated using a Keysight B1500A device. In addition, SEM was also used to evaluate the surface of the GO/p-InP structure as depicted in Fig. 2c.

3 Results and discussion

The *I*–*V* behavior of the Au/GO/p-InP heterojunction is measured in dark and illuminated conditions, respectively. As shown in Fig. 3, the Au/GO/p-InP heterojunction has exhibited a good rectifying behavior,

Fig. 1 **a** Schematic step-by-step preparation process of the Au/GO/*p*-InP heterojunction structure. **b** Schematic illustration of Au/GO/*p*-InP heterojunction diode

while the ratios of the forward current and reverse current (I_F/I_R) in dark and illuminated conditions are $(9.66 \pm 0.01) \times 10^{-2}$ and $(5.14 \pm 0.01) \times 10^{-3}$ at 3 V, respectively. The measured reverse leakage currents are found to be $(5.6812 \pm 0.0001) \times 10^{-8}$ A at 1 V in the dark and $(4.1393 \pm 0.0001) \times 10^{-7}$ A at 1 V under illuminated conditions, respectively. Based on the TE theory, the current is [46],

$$I = I_0 \exp \left(\frac{q(V - IR_S)}{nk_B T} \right) \left[1 - \exp \left(\frac{-q(V - IR_S)}{k_B T} \right) \right] \quad (1)$$

where V is voltage, IR_S is the voltage drop across the R_S , k_B is Boltzmann's constant (1.3806×10^{-23} J/K), T is absolute temperature in Kelvin, q is the charge of electron (1.602×10^{-19} C), and I_0 is the saturation current.

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

where A is active area, A^* is effective Richardson constant for *p*-InP ($60 \text{ A cm}^{-2} \text{ K}^{-2}$), Φ_b is Schottky barrier height. From Eqs. (1) and (2), the ideality factor and barrier height can be rearranged as

$$n = \frac{q}{kT} \left[\frac{d(V - IR_S)}{d(\ln I)} \right] \quad (3)$$

and

$$\Phi_b = (kT/q) \ln(A^* AT^2/I_0) \quad (4)$$

Fig. 2 Atomic force microscopy images of **a** the etched surface of *p*-InP, **b** surface of the GO thin film on *p*-InP, and **c** SEM image of the etched surface of *p*-InP

Fig. 3 The forward and reverse bias (*I*–*V*) characteristics of Au/GO/*p*-InP heterojunction measured at room temperature in dark and under illumination conditions

To investigate, the $V < 3kT$ regime, in dark and under illumination, the saturation current (I_0) is derived from semilog reverse-bias *I*–*V* plots as shown in Fig. 4. Using Eq. (2), very small saturation current (I_0) values of 5.94×10^{-11} A and 2.44×10^{-10} A can be acquired in dark and under illumination, respectively. The barrier heights of Au/GO/*p*-InP heterojunction could be obtained through the saturation current density (I_0) in dark and under illumination. The ideality factor and barrier height of the Au/GO/*p*-InP heterojunction are estimated to be 1.67 and 0.87 eV in the dark and 1.81 and 0.83 eV in light conditions at room temperature, respectively. A summary of these experimental results is provided in Table 1. It can be observed that the differences in Φ_b obtained in dark and illuminated conditions were due to the device illumination at 30 mW/cm^2 light and extra free charge carriers (electron–hole pairs) occurred in the devices. Now, these carrier movements cause an increase in the current in the reverse region depending on the illumination [47]. Usually, the expected value of the ideal factor should be close to unity, but as seen from Table 1, the obtained ideality factor is greater than 1, thus exhibiting the deviations from the ideal

Fig. 4 Plots of semi-logarithmic $I/[1 - \exp(-qV/kT)]$ versus voltage (V) for the Au/GO/p-InP heterojunction **a** in the dark and **b** under illumination conditions from the reverse bias I – V data at room temperature

Table 1 The measured barrier height, ideality factor, series resistance, and interface state density values of dark and illumination conditions of the Au/graphene oxide (GO)/p-InP heterojunction diode

Parameter	Under dark conditions	Under light (visible) conditions
From I – V characteristics		
Barrier height, Φ_b (eV)	0.87	0.83
Ideality factor, n	1.67	1.81
Leakage current (A) at 1 V	5.6812×10^{-8}	4.1392×10^{-7}
Saturation current (A) at 0 V	5.9430×10^{-11}	2.4412×10^{-10}
Series resistance, R_s (Ω)	1209	680
Shunt resistance R_{sh} ($M\Omega$)	120	10
From Cheung's method		
$dV/d(\ln I)$ versus I		
Series resistance, R_s (Ω)	367.560	268.701
Ideality factor, n	1.86	1.97
$H(I)$ versus I		
Series resistance, R_s (Ω)	828.996	599.525
Barrier height, Φ_b (eV)	0.93	0.84
From Norde's method		
Barrier height, Φ_b (eV)	0.88	0.84
Series resistance, R_s ($k\Omega$)	2572	1.457
From C – V characteristics		
Diffusion potential V_{do} (V)	0.98	0.86
Barrier height, Φ_b (eV)	1.01	0.88
Surface potential		
Barrier height (eV)	0.83	0.76
Ideality factor (n)	1.82	1.78
Interface state density (N_{ss}) ($eV^{-1}cm^{-2}$)		
	3.3629×10^{16} (0.39 eV– E_v) to 4.0248×10^{15} (0.77 eV– E_v)	3.6584×10^{16} (0.41 eV– E_v) to 2.9443×10^{15} (0.84 eV– E_v)

contact. This may origin from various factors, like different fitting procedures for data analysis, leakage current, series resistance, interface states, as well as the tunneling process [48–51].

Normally, an ideal Schottky diode exhibits low series resistance (R_s) that allows high current through the device, and large shunt resistance (R_{sh}) for small leakage current [46], which has affected the log I – V characteristics of the

diode. In order to evaluate the value of R_s and R_{sh} , a plot of junction resistance (R_j) of the Au/GO/p-InP heterojunction diode was plotted in Fig. 5. The estimated R_s and R_{sh} are 1209 Ω and 120 M Ω under darkness, 680 Ω and 10 M Ω under illumination, respectively. As shown in Table 1, the Au/GO/p-InP heterostructure has low R_s and high R_{sh} , thus indicating that the heterojunction is structure suitable for the potential applications.

As a result of the combined effects, the $\log(I)$ – V plots of Au/GO/p-InP heterojunction deviate at high currents (as shown in Fig. 3). In this context, the estimated value of R_s , Φ_b and n can be deduced using the well-known Cheung's functions [52] as below:

$$dV/d(\ln I) = IR_s + n(k_B T/q) \quad (5)$$

$$H(I) = V - n(k_B T/q) \ln[I/(AA^*T^2)] \quad (6)$$

and $H(I)$ is given by

$$H(I) = IR_s + n\Phi_b \quad (7)$$

Figure 6 describes $dV/d(\ln I)$ and $H(I)$ of the heterojunction in the dark and under illumination, respectively. Using the linear regression line of $dV/d(\ln I)$ – I plot, the parameters R_s and nkT/q can be deduced from the slope and intercept, respectively. From $dV/d(\ln I)$ – V plot, R_s and n were found to be 367 Ω and 1.86 in the dark, 268 Ω and 1.97 under illuminated condition, respectively. From $H(I)$ – V plot, the R_s and Φ_b values are estimated to be 829 Ω , 0.93 eV in the dark and 599 Ω , 0.84 eV under illumination conditions respectively. The estimated values were also presented in Table 1. The experimental results indicate that the R_s values attained by the two equations are well in concurrence with each other,

conforming their consistency and validity. It is also observed from Table 1, that the Φ_b and n deviate considerably with those results from the $\log(I)$ – V measurement. This deviation is due to the employed methods to estimate the Φ_b and n in various regions of $\log(I)$ – V data.

A well-known modified Norde method was also utilized to evaluate Au/GO/p-InP heterojunction diode for the comparison. From this method, the values of Φ_b and R_s are estimated from $\log(I)$ – V data using modified Norde method [53] as given below:

$$F(V) = V/\gamma - (k_B T/q) \ln[I(V)/(AA^*T^2)] \quad (8)$$

where γ is a (dimensionless) integer greater than the ideality factor (n), and $I(V)$ is the current obtained from the $\log(I)$ – V curve. $F(V)$ – V is plotted using Eq. (8) for the Au/GO/p-InP heterojunction as shown in Fig. 7a and b. The effective Φ_b can be derived by:

$$\Phi_b = F(V_{\min}) + V_{\min}/2 - k_B T/q \quad (9)$$

where $F(V_{\min})$ is the minimum value of $F(V)$ corresponding to the minimum voltage $V_{\min}$, which are attained from the $F(V)$ – V plot (Fig. 7). Similarly, the series resistance R_s is obtained by using the following equation:

$$R_s = [k_B T(r - n)] / (qI_{\min}) \quad (10)$$

where n is the ideality factor, $I_{\min}$ is the current minimum corresponding to the minimum point of $F(V_{\min})$, the estimated values of R_s and Φ_b are 2572 k Ω , 0.88 eV in dark, and 1.457 k Ω , 0.84 eV under illumination for the Au/GO/p-InP heterojunction diode, respectively. These results clearly confirm the similarity of the barrier height (Φ_b) values obtained from Cheung's and Norde methods, as well as high

Fig. 5 The plots of junction resistance R_j versus V for the Au/GO/p-InP heterojunction calculated from I – V data **a** in the dark **b** under illumination conditions at room temperature

Fig. 6 Experimental plots of **a** $dV/d(\ln I)$ versus I , **b** $H(I)$ versus I of the Au/GO/p-InP heterojunction in dark and under illumination condition at room temperature

Fig. 7 $F(V)$ versus V plots for the Au/GO/p-InP heterojunction **a** in the dark, **b** under illumination condition at room temperature

reliability and efficiency of these techniques. Meanwhile, R_s values obtained from the two methods have some discrepancy, because different regions of $\log(I)$ – V data were used in these applied methods. The estimated values of Φ_b and R_s are given in Table 1.

In general, considering the native oxide layer, the current through the Schottky junction can be estimated by [3].

$$I = AA^*T^2 \exp \left(\frac{(-q\Psi_{\text{surf}})}{(kT)} \right) \exp \left(\frac{(-qV_n)}{(nkT)} \right) \quad (11)$$

Besides, if surface potential $\Psi_{\text{surf}}(I_c, V_c)$, V_c are known and $n = 1/\alpha$, the barrier heights Φ_b can be obtained [54]. According to Chattopadhyay's method [54], from Eq. (11), the surface potential (Ψ_{surf}) can be described as

$$\Psi_{\text{surf}} = (kT/q) \ln \left((AA^*T^2)/I \right) - V_n \quad (12)$$

where V_n is the potential difference of Fermi level and valence band maximum, given as $V_n = kT/q \ln(N_v/N_A)$. N_A is the acceptor carrier concentration ($N_A = 2(2\pi m^*kT/h^2)^{3/2}$ with $m^* = 0.078 m_0$, while m_0 is electron effective mass and N_v is the effective density of states in p -InP valence band [55]. Thus, surface potential Ψ_{surf} is deduced by substituting the V_n value in Eq (12). Figure 8 depicts the experimental surface potential Ψ_{surf} of the Au/GO/p-InP heterojunction diode. From the plot, the values of n and Φ_b can be evaluated by the relation $\Phi_b = \Psi_{\text{surf}}(I_c, V_c) + \alpha V_c + V_n$ [54, 56]. The value of α is

$$-\alpha = (d\Psi_{\text{surf}}/dV)_{I_c V_c} \quad (13)$$

As shown in Fig. 8, the critical value of V_c and $\Psi_{\text{surf}}(I_c, V_c)$ for the heterojunction are calculated. The Φ_b and n are calculated using Eqs. (12) and (13) and the values are 0.83 eV, 1.82 in the dark and 0.76 eV, 1.78 under the illumination conditions, respectively.

The C – V measurement is one of the useful tools to attain the key information about the depletion region of the device structure. The characterization of the heterojunction under 1 kHz ~ 1 MHz is described in Fig. 9. It can be clearly observed that the measured capacitance is an intrinsic function of both applied bias and frequency. However, Fig. 9 shows that the capacitance of the Au/GO/ p -InP heterojunction exhibits a slow decline with frequency increment, i.e., it offers higher capacitance at low frequencies ($f=1$ –10 kHz) and lower capacitance at high frequencies ($f=100$ kHz to 1 MHz). This predicated that the interface states have an influence on the variance between the capacitance measured at different frequencies [57].

Additionally, parameters like doping (acceptor) concentration (N_A), diffusion potential (V_{do}), and barrier height Φ_b (C – V) of Au/GO/ p -InP heterojunction were evaluated by C – V method. The depletion capacitance of Au/GO/ p -InP heterojunction is expressed as: [3, 46].

$$1/C^2 = 2(V_{\text{do}} + V)/(q\epsilon_s A^2 N_A) \quad (14)$$

where A is the active area, ϵ_s is the permittivity ($\epsilon_{\text{p-InP}} = 12.4\epsilon_0$). The plot of $1/C^2 - V$ measured at a high frequency of 1 MHz in dark and illuminated condition is shown in Fig. 10. The $1/C^2 - V$ curves should be yielded a straight

Fig. 8 Plots of surface potential (Ψ_{surf}) versus forward voltage (V) of the Au/GO/ p -InP heterojunction at room temperature in the dark and under illumination conditions

Fig. 9 The forward and reverse bias voltage C – V characteristics of the Au/GO/ p -InP heterojunction measured with different frequencies (1 kHz to 1 MHz) at room temperature

line [55]. From $1/C^2 - V$ plot, N_A , V_{do} , and Φ_b (C – V) of the heterojunction are found to be $4.44 \times 10^{18} \text{ cm}^{-3}$, 0.98 V and 1.01 eV in dark, and $3.23 \times 10^{18} \text{ cm}^{-3}$, 0.86 V and 0.88 eV under illumination, respectively. N_A and V_{do} are showing lower values under the illumination condition whereas the same for the dark condition exhibit higher values. The decrease in diffusion potential and the increase in the activation carrier concentration under illumination condition implies an enhancement in the heterojunction performance and exhibits a good control for the optoelectronic applications. Although the Φ_b estimated from C – V data offers higher values than their counterparts derived from I – V data, which could be attributed to the different nature of I – V and C – V measurement techniques [57–60].

Fig. 10 The experimental $1/C^2$ versus V plots of the Au/GO/ p -InP heterojunction at room temperature in the dark and under illumination condition

Further, the interface state density (N_{ss}) is a very prominent parameter in the diode which has a strong impact on the conducting organic/inorganic InP interface. In n case of an adequately thicker interfacial layer, the effective barrier height (Φ_e) and N_{ss} at the interface are stated below:

$$\Phi_e = \Phi_b + (d\Phi_e/dV)V = \Phi_e + \beta V \quad (15)$$

where β is the voltage coefficient. According to Card and Rhoderick [61, 62], N_{ss} versus $E_{ss} - E_v$ for p -type semiconductor barrier diode can be given as the following relation

$$N_{ss} = (\epsilon_i/\delta q)(n(V) - 1) - \epsilon_s/(qw_d) \quad (16)$$

and

$$n(V) = 1 + (\delta/\epsilon_i)(\epsilon_s/W_d + qN_{ss}) \quad (17)$$

where $\epsilon_s = 12.4\epsilon_0$ and $\epsilon_i = 3.8\epsilon_0$ are the permittivity of semiconductor and interfacial layer, respectively. δ is interfacial layer thickness, N_{ss} is interface state density and W_d is depletion layer width which is estimated by $1/C^2 - V$ plot at 1 MHz. The energy (E_{ss}) distribution of N_{ss} with respect to valence band top edge (E_v) at semiconductor surface is presented as below

$$E_{ss} - E_v = (\Phi_e - V)q \quad (18)$$

where V is a voltage drop across the depletion layer. Thus, the N_{ss} can be calculated using Eq. (16) combined with Eqs. (15) and (18). The values of N_{ss} exponentially decays with an increase in $E_{ss} - E_v$ for heterojunction in the dark and under the illumination conditions is nicely described through Fig. 11. Also, in Fig. 11, a prominent enhancement of N_{ss} has been observed at the middle of the forbidden energy band gap to valence band maximum. As observed in Fig. 11, N_{ss} varied in the range of $3.3629 \times 10^{16} \text{ eV}^{-1} \text{ cm}^{-2}$ in (0.39 eV- E_v) to $4.0248 \times 10^{15} \text{ eV}^{-1} \text{ cm}^{-2}$ in (0.77 eV- E_v) in the dark, and $3.6584 \times 10^{16} \text{ eV}^{-1} \text{ cm}^{-2}$ in (0.41 eV- E_v) eV to $2.9443 \times 10^{15} \text{ eV}^{-1} \text{ cm}^{-2}$ in (0.84 eV- E_v) under the illumination condition, respectively, for the Au/GO/ p -InP heterojunction diode. A monotonic increase in N_{ss} with respect to voltage lowering is clearly observable. This type of behavior of interface states (N_{ss}) can be elucidated by charge and discharge of N_{ss} under illumination impact [63].

At the same time, to explore the predominant current transport mechanism of Au/GO/ p -InP heterojunction, a log-log I - V plot is depicted in Fig. 12. The plot can be sub-divided into three distinct regions (namely as region I, II, III) based on bias voltage. At region I (lower forward voltage $V < 0.08 \text{ V}$), a linear dependency of the current on the applied bias ($I \sim V$) is observed, indicating the transport mechanism obeys the Ohm's law (ohmic-type behavior) [64]. At region II (moderately high voltage, i.e., $0.15 \text{ V} < V < 0.40 \text{ V}$), the exponential increment of current ($I \sim \exp(\alpha V)$) suggests that the charge conduction

Fig. 11 Energy density distribution of the surface states obtained from forward bias I - V data for Au/GO/ p -InP heterojunction in dark and under illumination conditions at room temperature

Fig. 12 The forward bias $\log(I)$ versus $\log(V)$ plots of the Au/GO/ p -InP heterojunction diode at room temperature in dark and under illumination conditions

mechanism is dominated by the space-charge-limited current (SCLC) with a discrete trapping level [65]. Eventually, in the region III (at high-voltage region, i.e., $0.80 \text{ V} < V < 2.30 \text{ V}$), the slope of the plot is inclined to decrease because the device approaches towards the trap-filling limit [66]. The term 'trap-filling' significantly influences the conduction process of semiconductors. The experimental outcomes revealed that the studied heterostructure exhibits a clear diversion from ohmic-type of conduction at lower voltage range (region I) to SCLC at higher voltage range (regions II and III) under dark and

illuminated conditions, respectively. This behavior is in good agreement with published reports by various research groups working on different organic hybrid heterostructure devices [67, 68].

4 Conclusions

In this study, the Au/GO/*p*-InP heterojunction is fabricated and the electrical as well as photoelectrical properties are investigated. The ideality factor (n) and the barrier height (Φ_b) values of the Au/GO/*p*-InP heterojunction were found to be 1.67 and 0.87 eV in the dark and 1.81 and 0.83 eV in illumination conditions, respectively. The obtained R_s values from three distinct methods (log(I)– V , Cheung's and Norde) exhibited a certain level of discrepancy, which could be possibly due to the fact that these methods were applied at different voltage regions of the log(I)– V data range. The Φ_b and n values deduced from $\Psi_{\text{surf}}-V$ plot are found to be 0.83 eV, 1.82 in the dark and 0.76 eV, 1.78 under illumination conditions, respectively. The interface state density is one order of magnitude lower for the Au/GO/*p*-InP heterojunction under illumination conditions compared to the same in dark conditions. The detailed analysis of log I –log V characteristics elucidates that at lower voltage range (region I) the dominant conduction mechanism is ohmic-type behavior, whereas the behavior goes through the space-charge-limited-current (SCLC) conduction mechanism occupied at higher voltage range (i.e., region II and III) in dark and illuminated conditions. The results unveiled that the heterostructure performance in dark was substantially good compared to the same under the light (visible light) condition with respect to the lesser values of I_0 , n , N_{ss} , and R_s . The experimental consequences suggested that the Au/GO/*p*-InP heterostructure has promising characteristics to become an emerging candidate for the future photodiode applications.

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