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Investigation of electrical parameters of Al/GO-PTCDA/p-Si semiconductor structures under different light intensities

[1]Mahmut YUMUK, [2]Şükrü KARATAŞ

[1]Department of Materials Science and Engineering, Kahramanmaras Sutcu Imam University, Kahramanmaraş 46100, Turkey
[2]Department of Physics, Faculty of Sciences and Arts, Kahramanmaraş Sütçü İmam University, 46100-Kahramanmaraş, Turkey

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The current-voltage (*I-V*) characteristics of the Al/GO-PTCDA/*p*-Si metal-oxide-semiconductor (MOS) structure were investigated in dark and under 40 mW/cm^2 light illumination. The electrical parameters such as ideality factor (n), zero-bias barrier height (Φ_{bo}) and series resistance (R_S) of Al/GO-PTCDA/p-Si metal-oxide-semiconductor (MOS) structure obtained from different methods in under dark and illumination conditions at room temperature using forward bias current-voltage (I−V) measurements. Experimental results shows that the photocurrent under illumination intensities is higher than the dark current. The values of R_S obtained from Cheung and Norde functions are also decreased with increasing illumination intensity. The illumination dependent power-voltage curve of the Al/PCDA-GO/p-Si photodiode at 40 mW/cm^2 of Al/PTCDA-GO/*p*-type Si structure were investigated using current–voltage (*I*–*V*) characteristics.

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**Corresponding author:* mahmutymk46@gmail.com

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1. Introduction

Metal–semiconductor (MS), metal-oxide-semiconductor (MOS), or metal-oxide-semiconductor (MOS) electronic semiconductor structures have great importance in the electronic applications. MS structures are frequently used in integrated circuits, in light detectors and solar cells in the electronic industry [1-5]. Si is extensively used in the fabrication of electronic devices such as diodes, integrated circuits, and transistors [1-3]. Thus, due to the technological importance of electronic circuit components which are among the most simple of the graphene-Si contacts [1-7], a full understanding of the nature of their electrical and photovoltaic properties are of great interest.

The organic interfacial metal–semiconductor structures have been comprehensively studied because of their use in a wide range of optoelectronic products and organic/polymer electronic, like organic light-emitting diodes (OLEDs), field effect transistors, photovoltaics (PVs) [6–10].

The metal-semiconductor (MS) photodiodes with graphene oxide (GO) and perylenetetracarboxylic dianhydride (PTCDA) interfacial layers have received a lot of attention recently as they are used in many different applications, especially optoelectronics. Because this GO and PTCDA interfacial layer plays a critical role in controlling current flow between MS.

In this work, our purpose is to experimentally investigate the electrical properties of the Au/GO/n-Si structure under dark and under 40 mW/cm^2 light illumination at room temperature (300 K). The illumination dependence of electrical characteristics of the main parameters such as ideality factors, barrier heights, series resistances and interface state densities obtained from different methods was investigated.

2. Experimental details

In this study, we purchased PTCDA and GO organic semiconductor powder from Fytronix, but chemical solvents for cleaning substrates from Sigma-Aldrich. The Si crystal used in the preparation of photodiodes has a thickness of 525 µm in the [100] direction and a resistive structure of 2-10 Ω-cm. Firstly, the wafer cleaned using the cleaning process to remove contaminants from the semiconductor surfaces. The wafer was dried using nitrogen gas (N2) after the cleaning procedure. With a thermal evaporation apparatus, Al (99.999 percent) metal was evaporated at 10^6 Torr for ohmic contact. After that, the Si wafer was cut into small pieces. The semiconductor wafer front faces were coated PTCDA-GO (1:1) solutions with spin speed of 1000 rpm for 30 s by spin coating method.

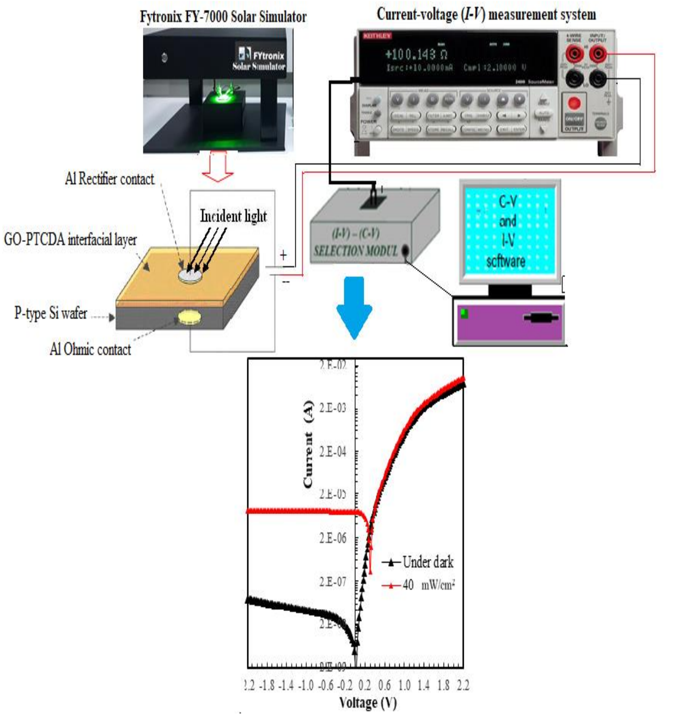

Fig.1. Schematic representation of the Al/GO-PCDA/p- Si structure and *I-V* measurement system

Following these procedures, to make a rectifier Al metal contact with diameter of 1 mm at 10^6 Torr pressure Al (% 99.999) metal was thermally evaporated on the surface of organic layer-semiconductor pieces. The rectifier contact's area of the photodiode was found to be $3.14\text{x}10^{-2}$ cm^2. As conclusion, the cross-section of the Al/ PTCDA-GO/p-type Si/Al semiconductor structure is shown in Fig. 1. The temperature dependent IV measurements were performed by using a Keithley 2400 Source-Meter.

2. Results and discussion

Fig. 2 shows the lnI–V curves of the Al/GO-PTCDA/p-type Si photodiode in dark, room light and in the illumination light of 40 mW cm^{-2} (light power intensities) in the range ± 2.00 V and at 300 K absolute temperature. Thus, the I-V measurements of the Al/PTCDA-GO/p-type Si photodiode structure can be written with the following equation [1-8];

$$I = I_0 \exp\left(\frac{q(V-IR_S)}{nkT}\right)\left[1-\exp\left(\frac{-q(V-IR_S)}{kT}\right)\right] \qquad (1)$$

where, k is Boltzmann constant (eV/K), q is the electronic charge, V is applied voltage, T is temperature, R_S is series resistance, and n is the ideality factor which ideality factor is a known electrical parameter for determining the deviation of *I-V* curves and I_0 is the saturation current density which I_0 can be extracted from the straight line intercept of *I-V* curves in Fig. 2 expressed as follows;

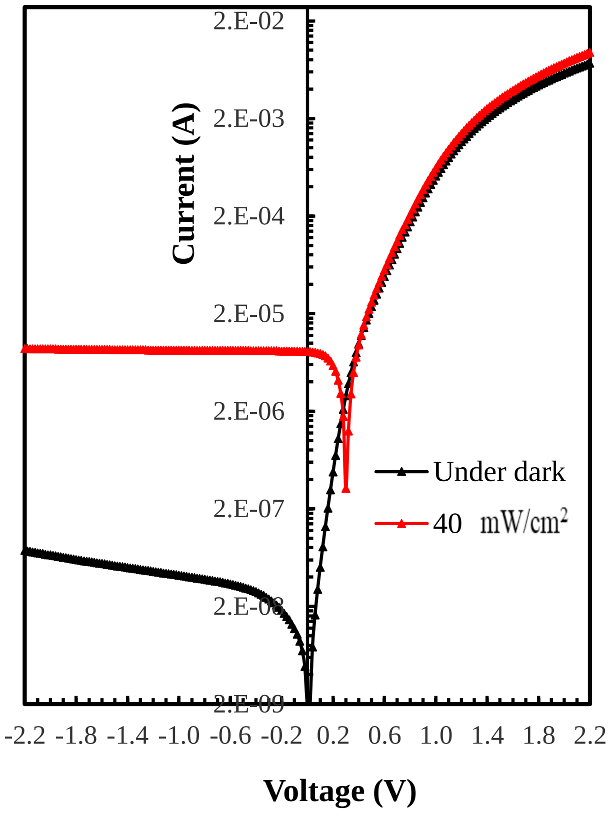

Fig. 2. The current–voltage plots of the Al/GO-PCDA/p-Si structure at room temperature

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

where A is the effective diode area, A^* is the effective Richardson constant of 32 Acm^{-2}K^{-2} for p-type Si, respectively. The ideality factor (n) of the Al/GO-PCDA/p-

Si structure are determined from the slope of the linear region of the forward bias *I-V* measurements through the relation;

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

the barrier height (Φ_{bo}) is determined from the saturation current (I_o) and is given by the relation;

$$\Phi_{bo} = \frac{kT}{q}\ln\left(\frac{AA^{*}T^{2}}{I_o}\right) \qquad (4)$$

Using Eq. (3) and Eq. (4) the values of the n, and Φ_{bo} of the Al/GO-PCDA/*p*-Si structure at room temperatures were calculated from the slopes of the linear region of the forward bias ln(*I*)-*V* plots in Fig. 2. The ideality factor and barrier height values were obtained as 6.14 and 0.618 eV; 5.97 and 0.619 eV in dark and under 40 mW/cm^2 light illumination of the Al/GO-PCDA/p-Si structure, respectively. The ideality factors values in this our sdudy is higher than unity (n = 1). This situation can be attributed to the fact that the PTCDA organic interlayer increased the effective barrier height by influencing the space charge region of Si.

Another method to determine the main parameters of metal-semiconductor structures is Cheung method [11]. According to Cheung function is analyzed by following equation;

$$\frac{dV}{d(lnI)} = n\frac{kT}{q} + R_S I \qquad (5)$$

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{I}{AA^{*}T^{2}}\right) = IR_S + n\Phi_{bo} \qquad (6)$$

Experimental *dV/d(ln I)* vs I and *H(I)* vs *I* plots of the of Al/GO-PCDA/*p*-Si structure at room temperature are presented in Fig.3 (a) and Fig. 3 (b), respectively. The slope and intercept of dV/dln(I)-I plots according to Eq. 5 would yield R_S and nkT/q, respectively. The values of idealitry factor and series resistance were found as 6.14 and 154.72 Ω; 5.96 and 136.14 Ω in dark and under 40 mW/cm^2 light illumination of the Al/GO-PCDA/p-Si structure at Fig. 3 (a), respectively. At the same time, the slope and intercept of *H(I)-I* plots according to Eq. 6 would yield Rs and nΦ_{bo}, respectively. The values of Φ_{bo} and R_S were found as 0.614 eV and 183.48 Ω; 0.617 eV and 148.14 Ω in dark and under 40 mW/cm^2 light illumination for the Al/GO-PCDA/*p*-Si structure, respectively. As shown in Figs. 3 (a) and (b) show the plots of H(I) vs I of the of the Al/GO-PCDA/p-Si structure in dark and under light illuminations, respectively. As you can see, this is that series resistance values obtained from Cheung functions are in good agreement with each other. The experimental shoved that the barrier heights and ideality factors have been decreased to be dependent on illumination intensity.

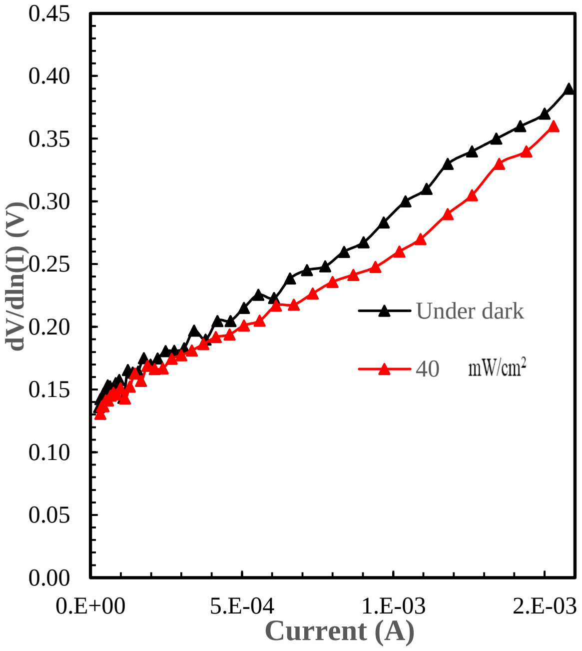

Fig. 3 (a). *dV/d(ln I)* vs I plots of the of Al/GO-PCDA/*p*-Si structure

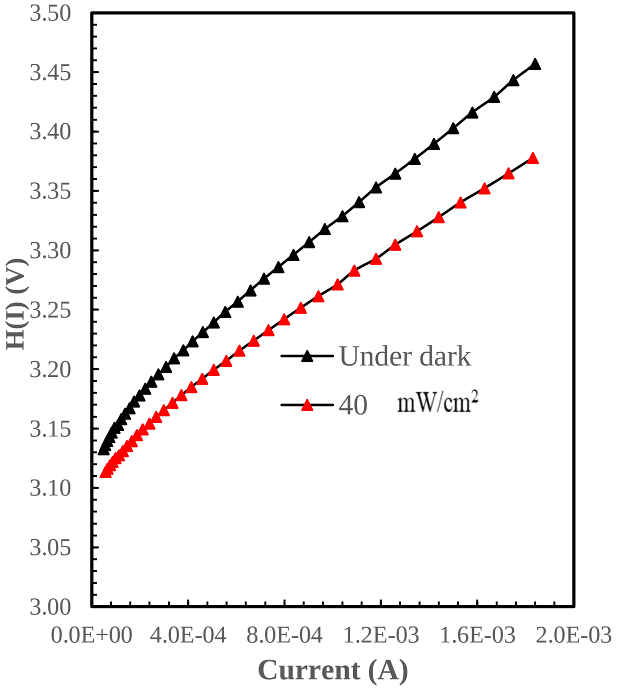

Fig. 3 (b). *H(I)* vs *I* plots of the of Al/GO-PCDA/*p*-Si structure

As you can see, ideality factor values obtained from Cheung functions are higher than the values obtained from *I–V* curve. This difference situation at the main electrical properties can be attributed to the approximation differences between the thermionic emission theory and Cheung methods.

Norde [12] proposed an alternative method to determine value of the series resistance on I–V curves. Because, while Cheung functions are only applied to the non-linear region of the forward bias *I–V* measurements, Norde function is applied to the full forward bias *I–V* measurements of the metal semiconductor structures. Norde's [12] functions Φ_{bo} and R_S are defined as in the following equations;

$$F(V) = \frac{V}{\gamma} - \frac{kT}{q}\ln\left(\frac{I(V)}{AA^{*}T^{2}}\right) \tag{7}$$

$$\Phi_b = F(V_0) + \frac{V_o}{\gamma} - \frac{kT}{q} \tag{8}$$

$$R_S = \frac{\gamma - n}{I_0}\frac{kT}{q} \tag{9}$$

where γ is an constant higher than the ideality factor, $F(V_0)$ is the minimum point of $F(V)$ vs V plot, V_0 and I are the corresponding bias voltage and current values, respectively. $F(V)$- V curves in dark and under 40 mW/cm^2 light illumination of the Al/GO-PCDA/*p*-Si structure at room temperature is shown in Fig. 4.

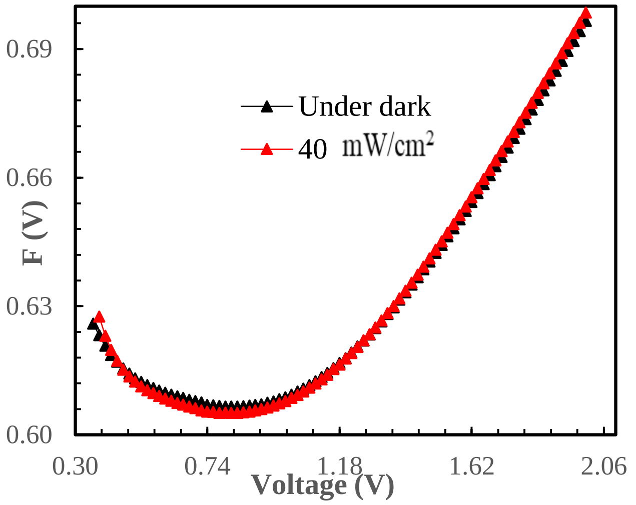

Fig. 4. The F(V)-V plots of Al/GO-PCDA/p-Si structure in dark and under 40 mW/cm^2 light illumination.

In Fig.4, the values of Φ_{bo} and R_S were obtained using Eq. (8) and Eq. (9). Thus, values of Φ_{bo} and R_S were found as 0.878 eV and 299.48 Ω; 0.886 eV and 235.23 Ω for Al/GO-PCDA/p-Si structure in dark and under 40 mW/cm^2 light illumination, respectively. As can be seen, the barrier height and series resistance values obtained from the Norde method are higher than the values obtained from the Cheung method. As mentioned above, this situation clearly shows that Norde's method are applied to the all forward bias regions of the *I–V* curve, while Cheung functions are only extended to the nonlinear region of the forward bias *I–V* curve.

At a given potential the product of voltage and current equals the power delivered by a solar cell [13, 14]. So, maximum power can be determined by following equation;

$$P_{max} = V_{max} x I_{max} \tag{10}$$

where P_m is maximum power, V_m is the maximum voltage and Im is the maximum current for illumination light intensity values. The electric power-voltage (*P-V*) curves depending on different light illumination intensity for Al/PTCDA-GO/*p*-type Si photodiode structure is shown in Fig. 5 under 40 mW/cm^2 light illumination.

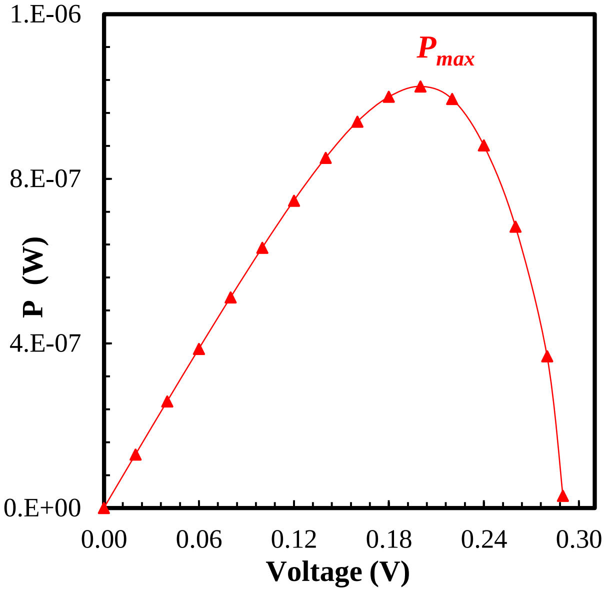

Fig. 5. Power-voltage curve of the Al/PCDA-GO/p-Si photodiode at 40 mW/cm^2

As seen in Fig.5, firstly, the electric power grows as the bias voltage is increased until it achieves its maximum power, after which it declines until it hits zero values when the applied voltage is increased further. It is clearly seen that P_{max} increases with increasing illumination intensity. The P_{max} value was found as 1.02x10^{-6} W under 40 mW/cm^2 light illumination.

4. Conclusions

In this study, the basic electrical properties of the Al/p-Si structures with GO-PTCDA interface were investigated. The basic parameters such as ideality factors (n), barrier heights (Φ_{bo}), series resistance were extracted from *I-V* measurements and discussed in details by thermionic emission theory in dark and under 40 mW cm^{-2} (light power intensities) in the range of ± 2.0 V and at room temperature. The photovoltaic power parameter (P_{max}) value was found as 1.02x10^{-6} W under 40 mW/cm^2 light illumination.

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