

# Electrical characterization of p-Si/fullerene-C<sub>60</sub> heterojunction photodiode

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Photovoltaic and electronic properties of p-Si/C<sub>60</sub> device have been investigated by current-voltage and capacitance-voltage methods. The ideality factor  $n$  and barrier height  $\phi_B$  values of the p-n junction were found to be 2.92 and 0.83 eV respectively. Current-voltage characteristic of the device indicates a non-ideal behavior due to ideality factor higher than unity. Capacitance-voltage characteristic of the device indicate an abrupt junction behavior. Electrical characterization results confirms that p-Si/C<sub>60</sub> device is an photodiode with the calculated electronic parameters, maximum open circuit voltage  $V_{oc}$  of 150 mV and short-circuit current  $I_{sc}$  of 12.1 nA

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## 1. Introduction

Organic semiconductors raised a considerable interest in the fields of electronic and photonic devices due to a wide range of applications as low-cost, large-area and disposable or throwaway electronics on thin and flexible substrates. In particular organic photodiodes have improved to a level which is sufficient for many applications [1–7]. The electronic and optoelectronic devices require new functional materials with special optical and electrical properties. Such properties are determined by a complex combination of many physical factors as well as the chemical nature of the starting material. Organic semiconducting layers are one of such class of prospective thin layer materials. Their low cost production is very simple using recent high vacuum evaporation and spin coating technology. Organic semiconductor can be functionalized to obtain specific optical and electrical properties. [8–12]. Hence, organic semiconductors have been used to fabricate p-n diode and organic photovoltaic devices [13–14]. C<sub>60</sub> is an organic semiconductor and has the possibility of photovoltaic device application because of its band gap energy being in the range 1.6–1.7 eV [15]. Heterostructure devices such as a:C/C<sub>60</sub>/Si (p-i-n) solar cell structures, C<sub>60</sub>/p-Si solar cells, C<sub>60</sub>/Si heterostructures have showed rectification and photovoltaic effect properties [16–17]. The aim of this study, it is fabricate a photodiode based on fullerene and explain current voltage characteristics under dark and illumination.

## 2. Experimental

p-type Si (100) wafer was used as p-type semiconductor. In order to remove the native oxide on

surface on p-Si, the wafer was etched by HF and then was rinsed in deionised water using an ultrasonic bath for 10–15 min and finally was chemically cleaned according to method based on successive baths of methanol and acetone. Fullerene-C<sub>60</sub> was purchased from Sigma-Aldrich Co. The thin film of C<sub>60</sub> was made by deposition of C<sub>60</sub> on the p-Si coated glass substrate by dip coating technique [18–19]. The film thickness of deposited film was found to be 50 nm. Au contacts were deposited front and back p-Si/C<sub>60</sub> device by vacuum thermal evaporation. Current-voltage (I-V) characteristics of the device under dark and illumination were measured using a KEITHLEY 2400 sourcemeter. Capacitance-voltage measurement of the diode was performed by a HIOKI 3532-50 LCR. The applied voltage was scanned between -2.0 to +2.0 V. The device can be exposed to light coming from a light source to get an intensity of incident power of about 6 mW/cm<sup>2</sup> [19]. Photovoltaic measurements were employed under the light intensity of 6 W/m<sup>2</sup> using a 200W halogen lamp.

## 3. Results and discussion

### 3.1. Current-voltage characteristics of p-Si/C<sub>60</sub> p-n junction diode

Fig. 1 shows the current-voltage (I-V) characteristics of the p-Si/C<sub>60</sub> p-n junction diode under dark and illumination conditions. At low voltages, forward current of the diode exponentially increase with applied voltage and shows a linearity. Whereas at higher voltages, a deviation in I-V characteristic of the diode is observed. For a non-ideal diode, the standard equation of diode can be expressed [20],

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

where  $n$  is the ideality factor,  $I_o$  is the reverse saturation current,  $R_s$  is the series resistance and  $q$  is the electronic charge and  $R_{sh}$  is the shunt resistance. The ideality factor was calculated from the slope of dark forward current-voltage region of Fig. 2 and was found to be 2.40. The ideality factor higher than unity is observed due to the interface state density and series resistance. A drop in applied voltage takes place due to the interface layer and thus, barrier height is dependent on the applied voltage, leading to the ideality factor higher than unity. The series resistance becomes significant for non-linear I-V behavior of the diode. The series resistance can be evaluated using a method developed by Cheung and Cheung and series resistance can be determined using the following relations [21-22],

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

$$H(I) = V - n \frac{kT}{q} \ln \left( \frac{I_o}{AA^* T^2} \right) \quad (4)$$

and

$$H(I) = IR_s + n\phi_B \quad (5)$$

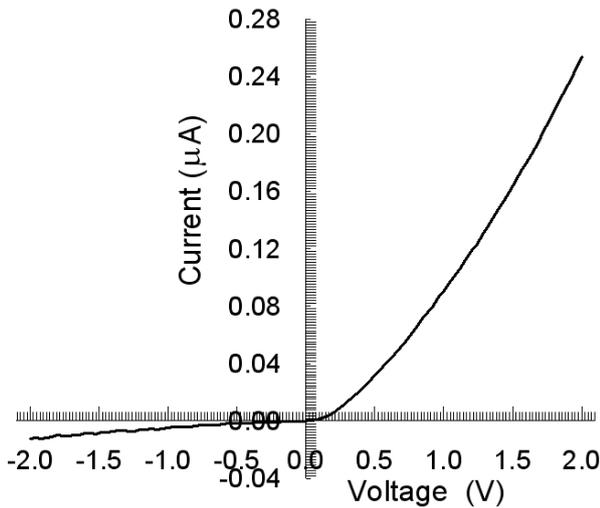


Fig. 1. I-V characteristic of the p-Si/C<sub>60</sub> p-n junction diode under dark condition.

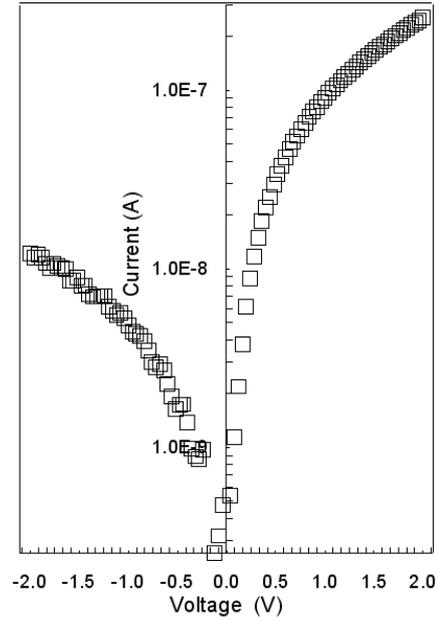


Fig. 2. Plot of  $\ln I - \ln V$  of the p-Si/C<sub>60</sub> p-n junction diode at dark condition.

Figs. 3a and b shows the plots of  $dV/d \ln I - I$  and  $H(I) - I$ . The series resistance  $R_s$  and ideality factor  $n$  values were calculated from Fig. 3a and was found to be  $7.39 \times 10^6 \Omega$  and 2.92, respectively. The  $\phi_B$  and  $R_s$  values were calculated from the  $H(I) - I$  plot and the obtained values are 0.83 and  $7.31 \times 10^6 \Omega$ , respectively.

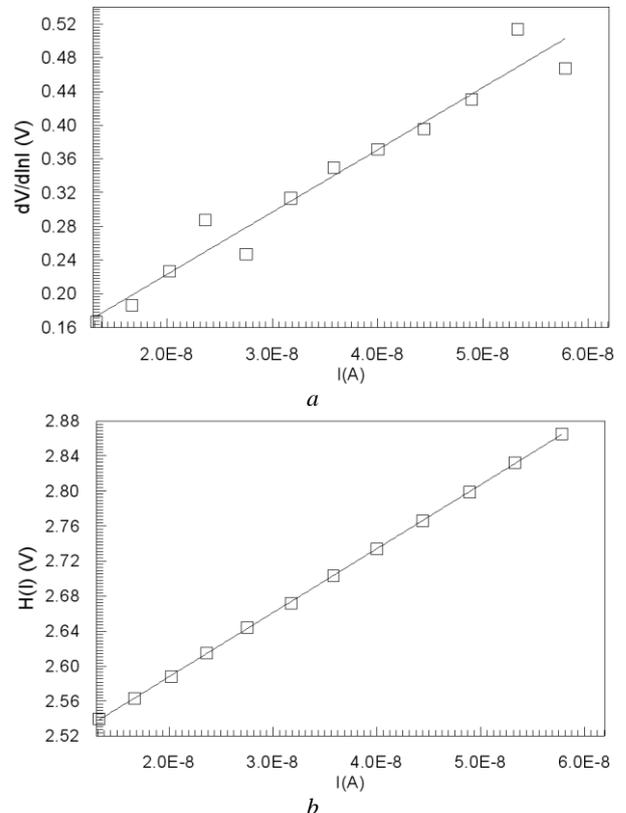


Fig. 3. Plots of  $dV/d \ln(I) - I$  and  $H(I) - I$  of p-Si/C<sub>60</sub> p-n junction diode at dark.

### 3.2. The capacitance-voltage characteristic of p-Si/C<sub>60</sub> diode

The curve of  $C^{-2}$ - $V$  of p-Si/C<sub>60</sub> diode is shown in Fig. 4. Figure shows a linearity, suggesting the junction is abrupt. The junction capacitance for an abrupt junction can be expressed by the following relation,

$$C = \left( \frac{\epsilon_0 \epsilon_s}{2qN_a} \right)^{1/2} \frac{qN_a A}{(V_d - V)^{1/2}} \quad (6)$$

where  $V_d$  is the diffusion potential,  $\epsilon_s$  is the dielectric constant of the p-Si, which is 11.8, and  $N_a$  is the doping concentration. Fig. 4 shows the plot of  $C^{-2}$ - $V$  for the diode. The doping concentration  $N_a$  and diffusion potential  $V_d$  values were determined from slope and intercept of Fig. 4 and were found to be  $8.31 \times 10^{15} \text{ cm}^{-3}$  and 0.48 V, respectively.

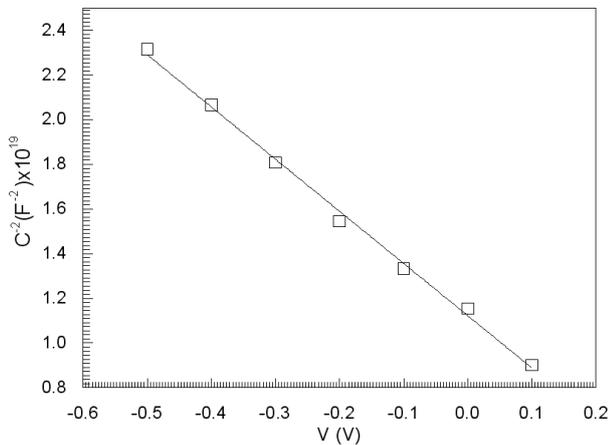


Fig. 4. Plot of  $C^{-2}$ - $V$  of p-Si/C<sub>60</sub> p-n junction diode.

### 3.3. Photovoltaic properties of p-Si/C<sub>60</sub> p-n junction diode

Fig. 5 shows the current-voltage (I-V) characteristic of the p-Si/C<sub>60</sub> p-n junction diode under light illumination condition. The photocurrent characteristics shown in Fig. 5, is clear indication of field dependent photogeneration. Filling factor, FF of the device seems to low due to larger series resistance ( $7.35 \times 10^6 \Omega$ ) of the device. The current in reverse direction is strongly increased by illumination. This suggests that the carrier charges are effectively generated in the junction by illumination and this effect is due to electron-hole pair generation. The organic semiconductor C<sub>60</sub> absorbs light and gives charge separation near the interface of the diode and in turn, the reverse current increases the efficient substantially. The current at a given voltage for the p-Si/C<sub>60</sub> junction diode under illumination is higher than that of under dark. This indicates that the light illumination increases production of electron-hole pairs. The increase in charge production is dependent on the difference in the electron affinities

between p-Si and C<sub>60</sub> semiconductors. The device shows a photovoltaic behavior with a maximum open circuit voltage  $V_{oc}$  of 150 mV and short-circuit current  $I_{sc}$  of 12.1 nA. The  $V_{oc}$  (150 mV) value of the C<sub>60</sub>/p-Si device studied under  $6 \text{ W/m}^2$  illumination is higher than that of C<sub>60</sub>/p-Si (14 mV) and a:C/C<sub>60</sub>/p-Si (90 mV) devices under  $100 \text{ mW/cm}^2$  illumination [16-17]. The C<sub>60</sub>/p-Si structure shows rectification and photovoltaic effect. This suggests that the C<sub>60</sub>/p-Si photovoltaic device can be operated as a heterojunction photodiode. Because solar cells are designed of course to minimize energy losses, whereas photodiodes are routinely designed to achieve a spectral response or a rapid time response [23].

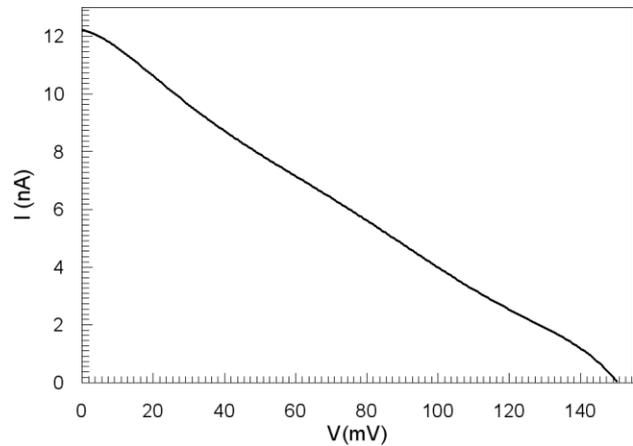


Fig. 5. I-V curve of p-Si/C<sub>60</sub> p-n junction diode under illumination condition.

## 4. Conclusions

Electrical properties of p-Si/C<sub>60</sub> p-n junction diode have been investigated by current-voltage and capacitance-voltage methods. Consequently, p-Si/C<sub>60</sub> device is a photodiode with the calculated electronic parameters, maximum open circuit voltage  $V_{oc}$  of 150 mV and short-circuits current  $I_{sc}$  of 12.1 nA

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## References

- [1] C. W. Tang, Appl. Phys. Lett. **48**, 183 (1986).
- [2] H. Hoppe, N. S. Sariciftci, J. Mater. Res. **19**, 1924 (2004).
- [3] J. Rostalski, D. Meissner, Sol. Energy Mater. Sol. Cells **63**, 37 (2000).

- [4] D. Gebeyehu, B. Maennig, J. Drechsel, K. Leo, M. Pfeiffer, *Sol. Energy Mater. Sol. Cells* **79**, 81 (2003).
- [5] D. Wöhrle et al., *J. Mater. Chem.* **5**, 1819 (1995).
- [6] P. Peumans, A. Yakimov, S. R. Forrest, *J. Appl. Phys.* **93**, 3693 (2003).
- [7] P. Schilinsky, C. Waldauf, J. Hauch, C. J. Brabec, *Thin Solid Films* **451**, 105 (2004).
- [8] D. Whorle, D. Meissner, *Adv. Mater.* **2**, 129 (1991).
- [9] J. B. Whitlock, P. Panayotatos, G. D. Sharma, G. R. Birds, *Opt. Eng.* **32**, 1921 (1993).
- [10] S. Karg, M. Meier, W. Riess, *J. Appl. Phys.* **82**, 1951 (1997).
- [11] H. Bottcher, *J. Prakt. Chem.* **334**, 14 (1992).
- [12] J. Simon, J. J. Andre, *Molecular Semiconductors*, Springer-Verlag, Berlin, 1985.
- [13] S. Gunster, S. Siebentritt, D. Meissner, *Mol. Cryst. Liq. Cryst.* **230**, 351 (1993).
- [14] K. Takahashi, S. I. Nakatani, T. Matsuda, H. Nambu, T. Kormura, K. Murata, *Chem. Lett.* **11**, 2001 (1994).
- [15] A. Khan, M. Yamaguchi, N. Kojima, *Solid State Electronics* **44**, 1471 (2000).
- [16] K. L. Narayanan, M. Yamaguchi, *Solar Energy Materials and Solar Cells*, **75**, 345 (2003).
- [17] D. J. Fu, Y. Y. Lei, J. C. Li, M. S. Ye, H.X. Guo, Y. G. Peng, X. J. Fan, *Applied Physics A Materials Science and Processing*, **67**, 441 (1998).
- [18] F. Yakuphanoglu, *J. Phys. Chem. C.* **111**(3), 1505 (2007).
- [19] F. Yakuphanoglu, *Solar Energy Materials and Solar Cells*, accepted paper (2007).
- [20] J. Nelson, *The physics of Solar cells*, Imperial College Press, UK, 2003.
- [21] S. K. Cheung, N. W. Cheung, *Appl. Phys. Lett.* **49**, 85 (1986).
- [22] Ş. Karataş, A. Türüt, *Nuclear Instruments and Methods in Physics Research A* **566**, 584 (2006).
- [23] R. F. Pierret, *Semiconductor Device Fundamentals*, Addison-Wesley Publishing Company, New York (1996).

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