Fabrication and Characterization of Organic Photovoltaic Cell using Keithley 2400 SMU for efficient solar cell

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Abstract An organic solar cell device or organic photovoltaic cell (OPV) is a class of solar cell that uses conductive organic polymers or small organic molecules for light absorption and charge transport. In this study, we fabricate and characterize an organic photovoltaic cell device and estimated important parameters of the device such as Open Circuit Voltage \( V_{oc} \) of 0.28V, Short-Circuit Current \( I_{sc} \) of \( 4.0 \times 10^{-5} \) A, Maximum Power \( P_{max} \) of \( 2.4 \times 10^{-6} \)W, Fill Factor of 0.214 and the energy conversion efficiency of \( \eta = 0.00239\% \) were tested using Keithley 2400, source meter under A.M 1.5 (1000/m²) illumination from a Newport Class A solar simulator. Also the I-V characteristics for OPV were drawn.

1. Introduction
An organic photovoltaic cell (OPV) or organic solar cell consist of organic materials sandwiched between two electrodes (an anode and a cathode). The anode is a transparent conducting oxide (TCO). Examples are Indium Tin-Oxide (ITO) and Zinc Oxide (ZnO) and graphene. The cathode is a non-transparent material. Examples are Aluminum and Silver. The sandwiched organic materials consist of PEDOT: PSS and P3HT: PCBM. Poly (3, 4-ethylene-dioxylthiophene): poly (styrenesulphonate) [PEDOT: PSS] is a hole transport (electron blocking) layer. P3HT: PCBM is a mixture of P3HT and PCBM in a right proportion. Poly (3-hexylthiophene) [P3HT] is an electron donor and [6, 6]-phenyl C61-butyric acid methyl ester, a fullerene derivative, is an electron acceptor. OPV devices are relatively easy to fabricate, can also be processed on flexible substrates, however they have relatively low conversion efficiencies and offer low stability. Figure 1 below is an example of an organic photovoltaic cell. OPVs were single-layer devices based on a Schottky diode structure, a pristine polymer and two electrodes, resulting in low PCE [1–3]. In 1986, the first OPV was successful reported, which was based on a double-layer structure of p-type copper...
phthalocyanine and n-type perylenediimide derivative by Tang et al. [4]. Heeger et al. 1990s observed the ultrafast photo-induced electron transfer from a conjugated polymer to C60, and the consequent enhancement in charge photogeneration yield opened up the potential of using solution-processed polymers in OPV [5–7]. A bulk heterojunction (BHJ) structure was employed to overcome the primary issue in double-layer OPVs in 1992 [8-9]. In last few decades, so many works have been done on the illumination of the working mechanism of OPVs, the inventory of simple and efficiency processing techniques, the exploration of novel OPV architectures and to increase the device stability, design and synthesis of new materials, which are all working towards improving the PCE of OPVs [10–19]. To date, the highest reported PCEs are in the range of 6.7%–8.94% for small molecule [20–22], 8.4%–10.6% for polymer OPVs [23–25] and 7%–15% for perovskite OPVs [26–28].

In this article, The I-V characteristics of OPV were obtained using a keithley 2400 source meter under A.M 1.5 (100Mw/cm²) illumination from a Newport class A solar simulator (SHESTCO, Abuja) and finally the important parameters such as Fill factor, efficiency, maximum power, short circuit current, and open circuit voltage were executed.

![Figure 1 An Organic Photovoltaic Cell Device](image)

2. **Instrument / Materials Required**

2.1 **Fabrication**
rf Sputtering with ITO target, Vacuum Thermal Evaporator, Spin Coater, Furnace

2.2 **Characterization**
Solar Simulator, Keithley 2400 SMU and Labtracer software.
3. **Procedure**

3.1 **Preparation**

3.1.1 **The Theory of OPV**

![Figure 2 Processes of Operation in an Organic Photovoltaic Cell](image)

The photoactive layers of the organic photovoltaic cell absorb photons (light), causing electrons to move from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO), thereby leading to the generation of excitons (bound electron-hole pairs). The nascent excitons then dissociate into separated charge carriers. This process is facilitated by the presence of an electron acceptor, which accepts the electron while the hole remains on the organic molecule chain. The difference in work functions of the electrodes gives rise to an electric field which drives the separated charge carriers towards the electrodes; i.e., holes diffuse towards the positive large work function $\Phi_{\text{anode}}$ electrode, while the electrons diffuse towards the negative small work function $\Phi_{\text{cathode}}$ electrode without recombination. Charge carrier recombination is one of the major factors that limit the power efficiency of OPVs. The charge carriers are collected at the electrodes. If an electrical circuit is connected to the electrodes, an electrical current flows through it.

In general, for a successful organic photovoltaic cell, five important processes have to be optimized to obtain a high conversion efficiency of solar energy into electrical energy:

- **Absorption of light and generation of excitons:** The absorption spectrum of the photoactive organic layer should match the solar emission spectrum and the layer should be sufficiently thick to absorb most of the incident light.

- **Diffusion of excitons to an active interface:** Ideally, all excitons should reach the photoactive interface within the exciton lifetime. Since the excitons diffusion length is about 10nm, only those excitons formed within a distance of 10nm from the interface will contribute to charge separation.

- **Charge Separation:** In most organic solar cells, charges are created by photoinduced electron transfer. In this process an electron is transferred from an electron donor (D) material to an electron acceptor (A) material with the aid of the additional input energy of an absorbed photon.

- **Charge Transport:** After the charge transfer, the electrons and holes are in close proximity and therefore there is a large chemical potential gradient that drives the charge carriers away from the exciton dissociating interface. This should be taken cognizance of during the design of OPVs.
Charge Collection: This is generally accomplished by a transparent conductive oxide (TCO) such as Indium Tin oxide (ITO) or Tin dioxide: Fluorine (SnO$_2$: F) on one side and a metal contact such as Aluminum on the other side. Below is a schematic illustration of the working principle of OPVs.

![Figure 3 Schematic Illustration of the working principle of OPVs](image)

Illumination of a donor material (in red) through a transparent electrode (ITO) results in the formation of an exciton (1). Subsequently, the exciton is transported by diffusion (2) to the interface between the donor material and an acceptor material (in blue). Electron is transferred to the acceptor material (A$^-$), leaving a hole at the donor material (D$^+$) (3). The photogenerated charged carriers are then transported (4) to and collected at opposite electrodes (5). A similar charge generation process can occur when the acceptor is photoexcited instead of the donor.

### 3.1.2 The Keithley Series 2400 Source Measure Unit
A common laboratory method of characterizing the current-voltage characteristics of OPVs is to use a parameter analyzer that employs measurement ports known as Source-Measurement Units (SMUs). In order to measure the current-voltage characteristics of an OPV, the SMU typically is stepped through various voltage limiting levels and the corresponding currents are measured. The Keithley’s Series 2400 Source Meter instruments are widely used for OPV production testing because they enable test engineers to configure a test system using a single instrument that can source and measure both current and voltage.
3.2 Fabrication

The schematic diagram of steps involved in the fabrication of layers of the OPV device is shown below in Figure 5.

![Schematic of Steps Involved in the Fabrication of an OPV Device](image)

Figure 5 Schematic of Steps Involved in the Fabrication of an OPV Device

3.2.1 Cutting and Cleaning of the glass slides

First, the table used was cleaned with ethanol and a clean cloth was placed on it. Then, the glass slide was brought out from its pack and cut into 1cm x 1cm squares. The surface of the glass slides was raised carefully in deionized water. Subsequently the slides were washed thoroughly in Decon-90 and re-rinsed in deionized water before soaking in acetone. They were then placed in an ultrasonic cleaner and cleaned for 10 minutes at room temperature. After cleaning, they were blow-dried using Nitrogen gas from a Nitrogen gun.

3.2.2 Deposition of Indium Tin-oxide by Sputtering and Annealing

Indium Tin-oxide (ITO) was sputtered unto the cleaned glass slides using an Edwards Auto 306 RF magnetron sputtering system that was operated at an initial vacuum pressure of 4.0x10⁻³ Torr and rf power of 40 W. This was done by pressing the ‘cycle’ button to create vacuum in the chamber until a fine pumping is attained. Two cups of nitrogen gas were poured into the sputtering system gas chamber to facilitate the vacuum creation. The sputtering was carried out at room-temperature. Argon, which was the sputtering gas, was introduced into the chamber to excite ions on the ITO target. The rf generator supplied the required power across the target to the substrate in the system, thereby creating the Argon plasma needed for the sputtering process to begin. A nominal thickness of 200nm of ITO was coated onto the glass after about 1 hour, 8 minutes. The thickness was carefully monitored by observing the thickness monitor. Once the desired thickness was attained, the shutter was closed, the rf generator turned off and the sputtering gas supply was closed. Subsequently, the ITO coated glass samples were annealed at 250°C for 1 hour.
3.2.3 Deposition of PEDOT: PSS Thin Film Layer on ITO-coated Glass Substrate

PEDOT: PSS solution was filtered through a 0.2μm mesh size filter into a beaker. The deposition was done using the Laurell spin coater (WS-650HZ Model) as shown in Figure 7, and the conditions that were entered into the program recipe as shown in Table 1. Smearing the glass surface with drops of the polymer solution was achieved using a dynamic dispense mode for 10 seconds with a moderate speed of 200 rpm holding. Thinning of this spread polymer solution on the sample was achieved at a high speed of about 1000 rpm for 40 seconds in the second step as seen in the program recipe. The PEDOT: PSS was first optimized on plane glass slides until 50nm thickness was achieved. Consequently, the ITO-coated samples were then placed on the spin coater chuck and the PEDOT: PSS of 50nm was deposited.
Table 1 Spin Coating Program Recipe

| Sample        | Reagent          | Volume Dispersed | Expected Thickness | Dispense | Step No | Duration (seconds) | Speed (rpm) |
|---------------|------------------|------------------|--------------------|----------|---------|-------------------|-------------|
| ITO glass     | PEDOT: PSS       | 0.4 ml           | 50 nm              | Dynamic  | 1       | 10                | 200         |
|               |                  |                  |                    |          |         | 2                 | 40          | 1000        |

3.2.4 Deposition of P3HT: PSS Thin Film Layer on PEDOT: PSS/ITO-coated Glass Substrate

1 wt% concentration of ratio 1:1 blend of P3HT: PCBM was prepared by mixing 11.11 mg/ml of P3HT and 11.11 mg/ml of PCBM together. The mixture was stirred for 12 hours at a temperature of 50°C. The solution of P3HT: PCBM was first optimized on plane glass for a thickness of 100 nm before spin coating it on the PEDOT: PSS/ITO-coated glass substrate using 1500 rpm for 45 minutes.

3.2.5 Deposition of Aluminium Thin film by Thermal Vacuum Evaporation

Finally, an aluminium cathode layer was deposited on the spin coated samples by thermal vacuum evaporation. This was done by inserting a pure aluminium rod (99.9%) of about 15 mm length and 1 mm radius, which was striated, on a tungsten filament in the evaporation chamber of the Edwards Auto 306 Thermal Evaporator as shown in Figure 8. This was melted in a high vacuum (2.0 x 10⁻⁵ Torr) environment. Rate of deposition and thickness was controlled using the Infinicon Thin film controller. The aluminium was then evaporated and coated through a shadow mask on top of the P3HT: PCBM as shown in the diagram below so as to obtain the cathode back contact. This was then taken for I-V characterization. Figure 9 shows a diagrammatic view of the OPV device fabricated showing the supposed thickness of its layers.

Figure 8 Edwards Auto 306 Thermal Evaporator System
4 I-V Measurement

The OPV was connected in the reverse biased direction to the Keithley 2400 SMU as shown in the diagram below in Figure 10.

The experiment was verified to ensure all connections were right before the source measure unit was switched on. With the aid of a computer software (Labtracer software), the experiment was programmed to source the voltage from 0 - 0.7 V with a step-size of 0.05 V. The current was then measured.

5 Results and Discussion

The I-V characteristics were plotted as shown below in Figure 11. From Figure.11, we can clearly see that the Open Circuit Voltage, \( V_{oc} \), (which is the voltage applied when the current applied or current density of the OPV is zero) is 0.28 Volts. The Short Circuit Current, \( I_{sc} \), which is the current when the applied voltage is zero, is obtained as 4.00 \( \times \) 10\(^{-5}\) Amps. Maximum Power, \( P_{max} \), which is the product of maximum current (\( I_{max} \)) and the maximum voltage (\( V_{max} \)) can be obtained from the given result data (Current – voltage data) by first obtaining the power values for each given current – voltage datum, since power = current x voltage. This was then plotted against the given voltage as shown below in Figure 12 to obtain the maximum power, \( P_{max} \) and subsequently, the corresponding \( V_{max} \) was obtained, as well as the \( I_{max} \).
Figure 11: Graph of Current versus Voltage for the OPV device Characterization

Figure 12 a: Graph of Power versus Voltage of the OPV Device
Reversing the axis of the graphical plot so it can be clear to read the $P_{max}$ and corresponding $V_{max}$, you have the plot below.
From Figure 12b, the maximum Power of the OPV device is $2.4 \times 10^{-6}$ Watts. $V_{\text{max}}$ is 0.125 Volts, thus $I_{\text{max}}$ will be

$$I_{\text{max}} = \frac{P_{\text{max}}}{V_{\text{max}}} = \frac{2.4 \times 10^{-6}}{0.125} = 1.92 \times 10^{-5} \text{ Amps}.$$  

The fill factor (FF), energy conversion efficiency ($\eta$) [29-30] are

$$\text{Fill Factor of the organic solar cell} (FF) = \frac{P_{\text{max}}}{V_{\text{oc}} \times I_{\text{sc}}} = \frac{2.4 \times 10^{-6}}{0.28 \times 4 \times 10^{-3}} = 0.214$$

The surface area of solar cell $A_c$ is $1 \times 1 \text{ cm}^2 = 1 \text{ cm}^2 = 1 \times 10^{-4} \text{ m}^2$ with conversion efficiency of

$$\eta = \frac{V_{\text{oc}} \times I_{\text{sc}} \times FF}{E \times A_c} \times 100 = \frac{0.28 \times 4 \times 10^{-5} \times 0.214}{1000 \times 1 \times 10^{-4}} \times 100 = 0.00239\%$$

6. Conclusion

In this work, we fabricated and characterized OPV and important parameters were estimated. Based on the measured current - voltage characteristics of OPV, the module was used to build OPV with open circuit voltage of 0.28 V and short circuit current of $4.0 \times 10^{-5}$A. Also, the Fill Factor 0.214, which is a measure of how good and effective a solar cell is as it tends to 1.0 was calculated, and it revealed that our fabricated OPV device is a fairly good one. Also the efficiency of 0.00239% achieved.
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