Performance improvement of polymer solar cells using SWCNT as a buffer layer and solvent engineering

Mahdi Fasihbeiki[1*], Farhad A. Boroumand[1]

Received: 2016-6-01 Accepted 2016-9-01

Abstract

Single-walled carbon nano tube (SWCNT) is used as a buffer layer to improve the performance of polymer solar cells. The buffer layer is located between the active layer and the cathode electrode in the solar cell structure such as PET/ITO/PEDOT:PSS/MEH-PPV:C60 (1:2)/SWCNT/Al. SWCNTs act as tunnels to help electron collection by cathode electrode, prevent the randomly movement of electrons, leading to the reduction of recombination at the interfaces after dissociation. By implementing this method, the short circuit current (J_{sc}) of fabricated solar cells increases from 20% to 40% depending on the solvent and the open circuit voltage (V_{oc}) reduces slightly. Since the type of solvent has an important effect on the properties of fabricated solar cells, the active layer was spin coated using three different solvents which were Chlorobenzene, 1, 2-Dichlorobenzene and Toluene. The best performance was achieved for the device fabricated using Chlorobenzene. The resulted output powers using Chlorobenzene, 1, 2-Dichlorobenzene and Toluene were 10.04 μW/cm^2, 7.59 μW/cm^2 and 1.74 μW/cm^2 respectively.

Keywords: polymeric solar cells, cathode electrode, buffer layer, active layer, output power

Introduction

Low cost and clean source of energy such as solar energy is highly desirable in order to reduce the environmental pollution associated with the use of fossil fuels [1]. Silicon based solar cells have been utilized as an alternative green source of energy but their cost is still high [2]. Organic solar cells using conjugated organic molecules (COMs) are under intensive research as an alternative to Silicon based devices due to their ease of processing, flexibility, tunable properties and low cost [3]. There is a rapid development in recent years in organic electronics that utilize organic semiconductors due to their unique properties. However, the realization of large-scale organic solar cells is slowed because of their poor environmental stability and charge transport across the photoactive medium [1]. The introduction of carbon nano tubes (CNTs) into the photoactive layers of organic photovoltaic (OPV) cells was intended to mitigate shortcomings of conjugated polymers discussed above [4]. CNTs and conjugated polymers have a similar sp^2 type hybridization and exhibit high electrical conductivity [5]. Apart from electrical and mechanical properties of the CNT, its geometrical structure is favorable to act as a pathway for photo-generated free charge carriers in the medium of bulkheterojunction OPV cells [6].

Due to the good conductivity of metallic SWCNTs [7] and suitable properties reported by Barnes et al. [8] and Hatton et al. [9], herein it is used as a buffer layer between the active layer and the cathode electrode to examine the performance improvement. This method totally differs from the above-mentioned work that pre-functionalized SWCNTs were blended into the photoactive layer and the resulted performance improvement mainly attributed to the extension of excitons dissociation area and fastening charge carriers transfer across the active layer [6]. Also, this method is much more convenient to implement than the work that Boron-doped-CNTs or Nitrogen-doped-CNTs were intermixed with P3HT: PCBM or the B-CNTs/P3HT film was placed next to the hole collecting electrode or the N-CNTs/P3HT film was placed next to the electron collecting electrode [10] because the buffer layer is implemented independently and separately with no need of a common solvent for both SWCNTs and the active layer materials.

In this work after description of the structure, materials and fabrication process of polymer solar cells, the operation is analyzed briefly but documented according to the obtained UV-visible absorption spectrum of C60 and MEH-PPV and energy diagram. Then the effect of SWCNT as buffer layer is investigated comparing the I-V characteristics of the fabricated solar cells, which were produced without and with the buffer layer located between the active layer and the cathode electrode in the solar cell structure such as PET/ITO/PEDOT:PSS/MEH-PPV:C60

[1] Faculty of Electrical Engineering, K.N. Toosi University of Technology, Seyed-Khandan bridge, Shariati Ave., Tehran, Iran. Boroumand@eetd.kntu.ac.ir

(1:2)/SWCNT/Al. To fabricate the active layer, three solvents such as Chlorobenzene, 1,2-Dichlorobenzene and Toluene were used and their effects on the device performances were investigated.

Experimental

The structure of the fabricated solar cells is shown in Figure 1.

Figure 1. The structure of the fabricated solar cells.

The molecular structures of the organic materials used in the fabrication of the solar cells such as SWCNT, C60, Poly[2-Methoxy-5-(2_-Ethyl-Hexyloxy)-1,4-PhenyleneVinylene] (MEH-PPV) and Poly(3,4-EthyleneDioxyThiophene)-Poly(StyreneSulfonate) (PEDOT:PSS) are shown in Figures 2-5.

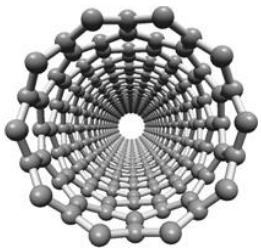

Figure 2. The molecular structure of SWCNT.

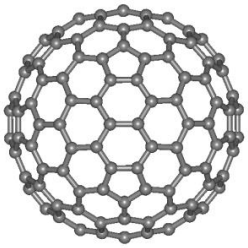

Figure 3. The molecular structure of C60.

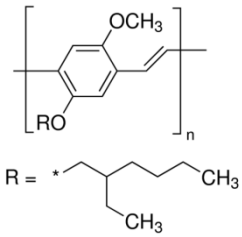

Figure 4. The molecular structure of MEH-PPV.

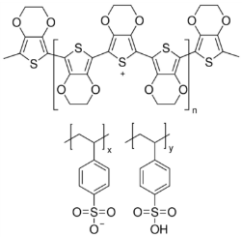

Figure 5. The molecular structure of PEDOT: PSS.

Firstly 12*12mm square shape spice of an Indium Tin Oxide (ITO) Coated PET (Sigma-Aldrich 639303) sheet was cut then the ribbon stick was used to coat the 12*8 mm middle part of ITO Coated PET. Then, the ITO substrate was dipped in a solution of HCl:deionized water (DI) (12% v) for one min to etch the ITO and prevent the short circuit of the cathode electrode with ITO. Subsequently, the substrate was dipped in acetone until ribbon stick separates. Then, etched ITO was cleaned using ultrasonic bath and different solvents. First, it was washed by deionized water and soap at 40°C for 10 min. Then, acetone and methanol were used at 40°C for 5 min, respectively. Finally, the substrate was cleaned by isopropanol at 40°C for almost 2 min. Subsequently the prepared ITO was dried in oven at 80°C for 60 min. Then, PEDOT:PSS (1.3% wt dispersion in H_2O, conductive grade (Sigma-Aldrich 483095)) was spin coated at 3000 rpm for 30 s and then dried in oven at 80°C for 60 min. Also, spin coating was used for active layer deposition which made in the form of bulk heterojunction by mixing the donor and acceptor components (MEH-PPV:C60 (1:2)) in three solvents: Chlorobenzene, 1,2-Dichlorobenzene and Toluene. Then, the spin coated layer was dried in oven at 50°C for 10 min. In the next step, SWCNT layer as a buffer layer was spin coated on the active layer. Although dispersion of SWCNT in used solvents was one of the main problems of this method. To solve this problem, the functional branched of SWCNT was prepared. A suspension containing DiMethylFormamide (DMF) and SWCNT (3% wt) was prepared and stirred for 24 h to obtain a homogenous suspention. Finally, Aluminum (AnalaR BDH Chemicals Ltd Poole England) cathode electrode was coated by the common vacuum thermal evaporation (VTE) method at the pressure of $1.5*10^{-5}$ torr. After fabrication of the devices, the electrical measurements were done by Source Measure Unit (SMU) (Keithley 238).

The fabrication process and measurements were performed at ambient condition without using the glove box or performing device encapsulation.

A Perkin Elmer Lambda EZ201 spectrophotometer was used to record the absorbance spectra of the components.

Results and Discussion

UV-visible absorption spectra of C60 and MEH-PPV, the organic materials used in active layer, are shown in Figure 6. As observed, MEH-PPV exhibits a strong absorption but C60 exhibits a weak absorption in the visible range, which indicates that MEH-PPV is the main light absorber.

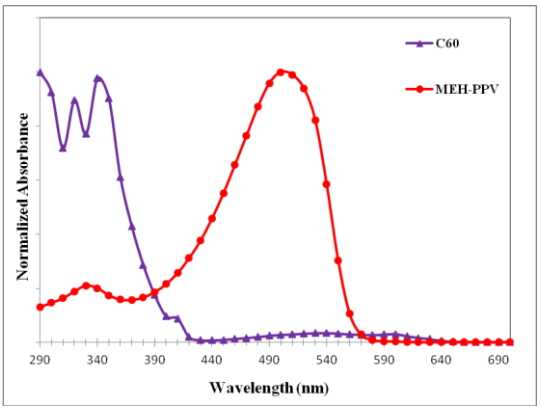

Figure 6. UV-visible absorption spectra of C60 and MEH-PPV

Energy Diagram of the fabricated solar cells is shown in Figure 7. According to this figure, C60 mainly helps in exciton (Electron-Hole pair) dissociation and also the electron transfer to the cathode electrode.

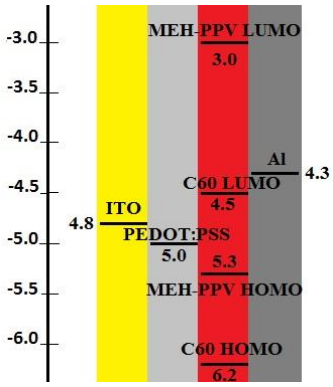

Figure 7. Energy Diagram of the fabricated solar cells

The I-V characteristics of the solar cells fabricated without (red line) and with (black line) buffer layer are shown in figure8. It shows that using SWCNT as the buffer layer increases the J_{sc}. Although, in presence of the buffer layer, the V_{oc} reduces slightly. Thus, the SWCNTs act as tunnels to help electron collection by cathode electrode, prevent the randomly movement of electrons, leading to the reduction of recombination at the interfaces after dissociation [10].

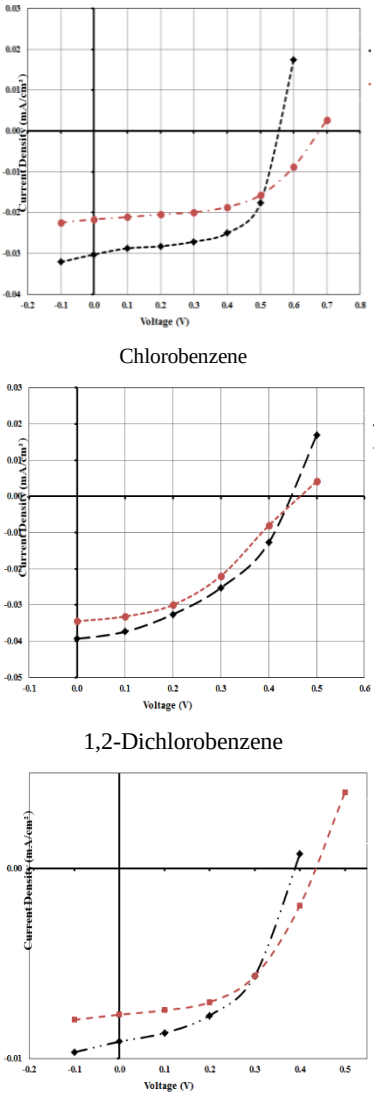

Figure 8. The comparisons of the J-V characteristics of the fabricated solar cells without (red line) and with (black line) the buffer layer.

Furthermore, the effect of active layer solvent on the device performance was investigated for the solar cell containing SWCNT buffer layer and summarized in Table 1.

The results show that the highest V_{oc} relates to Chlorobenzene solvent which is 0.56 V and then 1,2–Dichlorobenzene solvent which is 0.43 V, and the lowest V_{oc} relates to Toluene solvent which is 0.38 V.

The highest J_{sc} is achieved for 1,2–Dichlorobenzene solvent which is $3.94*10^{-2}$ mA/cm^2 and then Chlorobenzene solvent which is $3.03*10^{-2}$ mA/cm^2 and the lowest is achieved for Toluene solvent which is $9.12*10^{-3}$ mA/cm^2 that is less than one third of the other solvents.

The solar cell output power was 10.04 μW/cm^2 for Chlorobenzene, 7.59 μW/cm^2 for 1,2-Dichlorobenzene and 1.74 μW/cm^2 for Toluene as the solvent and the fill factor (FF) of

Chlorobenzene, Toluene and 1,2–Dichlorobenzene solvent were 0.59, 0.50 and 0.44 respectively.
Comparing the output power as one of the most important parameters of solar cells shows that among these three solvents, Chlorobenzene is the best solvent and 1,2-Dichlorobenzene is a weaker solvent and the weakest solvent is Toluene that the output power obviously decreased.

This phenomena is mainly attributed to the better solubility of C60 and MEH-PPV in Chlorobenzene and 1,2-Dichlorobenzene solvents than Toluene solvent. Using these solvents result in the higher intimate and more homogeneous mixture, leading the enhancement of exciton dissociation efficiency and causing better morphology of the active layer after spin coating [11-15].

Table 1. The effect of solvent type on photovoltaic performance of the devices.

Solvent	V_{OC} (V)	J_{SC} (mA/cm^2)	V_m (V)	J_m (mA/cm^2)	P_m (μW/cm^2)	FF
Chlorobenzene	0.56	-3.03*10^{-2}	0.40	-2.51*10^{-2}	10.04	0.59
1,2-Dichlorobenzene	0.43	-3.94*10^{-2}	0.30	-2.53*10^{-2}	7.59	0.44
Toluene	0.38	-9.12*10^{-3}	0.27	-6.47*10^{-3}	1.74	0.50

Conclusion

In summary, the effect of SWCNT as buffer layer on the performance of polymer solar cells was investigated. Using SWCNT buffer layer, the J_{sc} improved because the SWCNTs act as tunnels to help electron collection by cathode electrode, prevent the randomly movement of electrons, leading to the reduction of recombination at the interfaces after dissociation.
The effect of active layer solvents including Chlorobenzene, 1,2-Dichlorobenzene and Toluene on the devices performance was studied. The results showed that Chlorobenzene is the best solvent and 1,2-Dichlorobenzene is a weaker solvent and the weakest solvent is Toluene that the output power obviously decreased. This was mainly attributed to the better solubility of C60 and MEH-PPV in Chlorobenzene and 1,2-Dichlorobenzene solvents than Toluene solvent which results in the higher intimate and more homogeneous mixture, leading the enhancement of exciton dissociation efficiency and causing better morphology of the active layer after spin coating.

Acknowledgments

Authors are grateful to K.N. Toosi University of Technology, Tehran, Iran for the support of this work. The useful comments of the reviewers are also appreciated.

References

[1] B. Ratier, J.-M. Nunzi, M. Aldissi, T.M. Kraft, E. Buncel, Organic solar cell materials and active layer designs-improvements with carbon nanotubes: a review. Poly. Int. 61(3), 342, 2012
[2] G. Keru, P.G. Ndungu, V.O. Nyamori, A review on carbon nanotube/polymer composites for organic solar cells. Int. J. Energy Res. 38(13), 1635, 2014
[3] M. Giulianini, E.R. Waclawik, J.M. Bell, M. Scarselli, P. Castrucci, M. De Crescenzi, N. Motta, Microscopic and spectroscopic investigation of poly(3-hexylthiophene) interaction with carbon nanotubes. Polymers 3(3), 1433, 2011
[4] A. Ltaief, A. Bouazizi, J. Davenas, Charge transport in carbon nanotubes-polymer composite photovoltaic cells. Materials 2(3), 710, 2009
[5] N.A. Nismy, K. Jayawardena, A. Adikaari, S.R.P. Silva, Photoluminescence quenching in carbon nanotube polymer/fullerene films: carbon nanotubes as exciton dissociation centres in organic photovoltaics. Adv. Mater. 23(33), 3796, 2011
[6] J. Yan, T. Ni, F. Zou, L. Zhang, D. Yang, S. Yang, B. Zou, Towards optimization of functionalized single-walled carbon nanotubes adhering with poly(3-hexylthiophene) for highly efficient polymer solar cells. Diam. Relat. Mater. 41, 79, 2014
[7] C.H. See, A.T. Harris, A review of carbon nanotube synthesis via fluidized-bed chemical vapor deposition. Ind. Eng. Chem. Res. 46, 997, 2007
[8] T.M. Barnes, J.D. Bergeson, R.C. Tenent, B.A. Larsen, G. Teeter, K.M. Jones, J.L. Blackburn, J. van de Lagemaat, Carbon nanotube network electrodes enabling efficient organic solar cells without a hole transport layer. Appl. Phys. Lett. 96, 243309, 2010
[9] R.A. Hatton, A.J. Miller, S.R.P. Silva, Carbon nanotubes: A multi-functional material for organic optoelectronics. J. Mater. Chem. 18, 1183, 2008
[10] Godfrey Keru, Patrick G. Ndungu, Vincent O. Nyamori, Genene T. Mola, Charge extracting

[11] buffer layers in bulkheterojunction organic solar cell. J. Mater. Sci: Mater. Electron 26, 9891, 2015
[12] S.E. Shaheen, C.J. Brabec, N.S. Sariciftci, F. Padinger, T. Fromherz, J.C. Hummelen, 2.5% efficient organic plastic solar cells. Appl. Phys. Lett. 78, 841, 2001
[13] H. Hoppe, T. Glatzel, M. Niggemann, W. Schwinger, F. Schaeffler, A. Hinsch, M. Lux-Steiner, N.S. Sariciftci, Efficiency limiting morphological factors of MDMO-PPV:PCBM plastic solar cells. Thin Solid Films 511-512, 587, 2006
[14] J. Liu, T.F. Guo, Y. Shi, Y. Yang, Solvation induced morphological effects on the polymer/metal contacts. Journal of Applied Physics 89, 3668, 2001
[15] J. Liu, Y. Shi, Y. Yang, Solvation-induced morphology effects on the performance of polymer-based photovoltaic devices. Advanced Functional Materials 11, 420, 2001
[16] J. Liu, Y. Shi, L. Ma, Y. Yang, Device performance and polymer morphology in polymer light emitting diodes: the control of device electrical properties and metal/polymer contact. Journal of Applied Physics 88, 605, 2000