Progress towards efficiency of polymer solar cells

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Received: 27 July 2016, Revised: 28 August 2016 and Accepted: 13 October 2016

DOI: 10.5185/amlett.2017.7005
www.vbripress.com/aml

Abstract

Among all renewable sources, solar energy is the crucial zero emission renewable energy and the amount of solar energy impinging upon earth surface in one hour far exceeds the annual global energy demands. Polymer solar cells research exceeds crystalline silicon solar cells due to being inexpensive, light weight and processable into large area flexible devices. Polymer solar cells also possess high potential for power generation applications in comprehensive non-grid and grid modes. Moreover, the broad installment of polymer solar cells across the globe would certainly help to solve the problems associated with pollution, non-renewable resources, global warming and sustainability. Polymer solar cells being at present the hottest field of interdisciplinary research, there has been remarkable outcome in terms of efficiency of single-junction polymer solar cells, tandem solar cells, polymer-polymer solar cells, triple-junction polymer solar cells and solution-processed polymer solar cells. The present review briefly provides the latest breakthroughs and developments towards the efficiency and commercial aspects of various polymer solar cells. Copyright © 2016 VBRI Press.

Keywords: Polymer solar cells, power conversion efficiency, single-junction polymer solar cells, tandem solar cells, polymer-polymer solar cells, triple-junction polymer solar cells, solution-processed polymer solar cells.

Introduction

The amount of solar energy that impinges upon the earth surface in one hour is far more than the annual global energy demand **[1]**. Among renewables, solar energy is the crucial zero emission renewable energy source. Polymer solar cells research exceeds crystalline silicon solar cells due to being inexpensive, light weight and processable into large area flexible devices **[2]**. Polymer solar cells also possess high potential for power generation applications in comprehensive non-grid and grid modes **[3]**. In comparison to the clean energy sources such as clathrate hydrates and wind energy, the broad installments of polymer solar cells across the globe would rapidly resolve the issues associated with environmental pollution, ever diminishing non-renewable resources, global warming and sustainability **[4-10]**.

Ever since the first major breakthrough discovered by Tang **[11]** that higher power conversion efficiencies (PCEs) of about 1 % can be attained in organic photovoltaic cell (OPVs), there have been spectacular discoveries in polymer solar cells (PSCs) worth reporting as far as materials (both donors and acceptors) development, architecture of polymer solar cells and improvement in polymer solar cells processing **[12]**. Moreover, fabulous researches have happened in efficiency, stability, and processing of polymer solar cells in last decade **[13, 14]**. By stacking two or more complementary single cells the efficiencies of single junction solar cells have been significantly improved in the form of tandem cells **[14]**. PSCs being light weight, flexible and inexpensive can also be produced by an economical low temperature solution processing. The previous decade observed the remarkable developments in bulk heterojunction concept **[15]** in polymer solar cell technology which lead to the enhancement in the single junction cell efficiencies from 4 % in 2005 to efficiencies of 8-9 % till 2012 **[16-21]**. As suggested by Scharber *et al.* **[19]** the efficiencies of the single junction solar cells can be achieved upto 13 % by the optimization of materials having proper band gap (necessarily low band gap), energy levels and carrier mobility. Additionally, estimated theoretical power conversion efficiency (PCE) of 15 % may be achieved by the organic tandem solar cells consisting of two series connected single cells with large complementary solar spectra **[22, 23]**. More importantly, you *et al.* **[24]** have already demonstrated an efficiency of 10.6 % in solution processed tandem solar cell (**Fig. 2**) whereas an OPV multi-junction cell by Heliatek Co. (a German company) has achieved a certified efficiency of 13.2 % **[25]**.

Polymer/organic solar cells are a latest and promising technology compared to silicon **[26]**. The polymer/organic solar cell technology is inexpensive and rapid to set up projects aiming MW /GW with an estimated cost of 0.25 DKK / KWh **[26]**. In addition, the remarkable developments in roll to roll processing of single and tandem cells resulted in the fine setting of 1

GW solar power parks in Denmark and south of Spain. Considering the high energy demand and environmental sustainability, India has also designed an ambitious programme to establish solar energy parks with total output of 300 GW by 2030 [**27**]. The end result has been that by now single polymer solar cells have attained the efficiency above 10 % and triple junction tandem polymer solar cells now are having power conversion efficiency exceeding 11 % [**24, 28-36**] (**Table 1**). A new electron acceptor is challenging fullerenes for efficient polymer solar cells.

Table 1. Efficiency milestones of various polymer solar cells.

Sl.	Efficiency	Type/novelty	Author	Reference
I	**Single Junction Solar Cells**			
	10.8 %	Aggregation and morphology	Y. Liu et al.	*Nature Commun. 2014* [28]
	10 %	Efficiency and photovoltage	Z. He et al.	*Nature Photon. 2015* [29]
	11.7 %	Hydrocarbon solvents	J. Zhao et al.	*Nature Energy, Jan 2016* [30]
II	**Tandem Solar Cells**			
	10.6 %	Tandem power polymer solar cells	J. You et al.	*Nature Commun. 2013* [24]
	11.3 %	Polymer Homo-Tandem Solar Cells	H. Zhou et al.	*Adv. Mater. 2015* [31]
III	**Polymer-Polymer Solar Cells**			
	6.31 %	Fullerene free polymer solar cells	Y. Lin et al.	*Energy Environ. Sci. 2015* [22]
	7.7 %	All polymer solar cells	Y.-J. Hwang et al.	*Adv. Mater. 2015* [33]
	8.5 %	Non-fullerene polymer solar cells	Y.-J. Hwang et al.	*Adv. Mater. 2016* [34]
IV	**Triple-Junction Polymer Solar Cells**			
	> 11 %	Triple junction polymer solar cell	C.-C. Chen et al.	*Adv. Mater. 2014* [35]
	11.83 %	Solution processed polymer inverted triple junction solar cell	A. R. B. M. Yusoff et al.	*Energy Environ. Sci. 2015* [36]

Single junction polymer solar cells

So far high efficiency single junction polymer solar cells systems have utilized PTB7 family donors with $PC_{71}BM$ acceptors and efficiencies were found below 10% **[18, 37]** which were also below the efficiency of the most efficient tandem cells **[20, 21]**. Liu *et al.* **[28]** have recently shown that the exquisite control of the aggregation results in high performance thick polymer solar cells for three different donor polymers and ten polymer-fullerene combinations which yield polymer solar cell efficiencies higher than the existing state of arts efficiencies of 9.5 % and six combinations show the efficiencies more than 10 % (**Fig. 1 and Table 2**). The cells show temperature dependent aggregation behavior allowing processing of PSCs at moderately elevated temperatures.

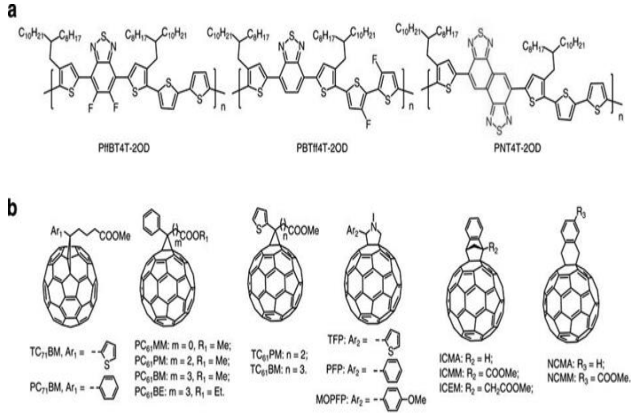

Fig. 1. (a) Chemical structures of donor polymers, and (b) Chemical structures of donor fullerenes [28]. (Copyright © 2014, Nature Communications, Nature Publishing Group).

Table 2. PSC performance of 10 high-efficiency polymer:fullerene material combinations [28]. (Copyright © 2014, Nature Communications, Rights Managed by Nature Publishing Group)

Active layer	V_{OC} (V)	J_{SC}	FF	PCE (%)
PffBT4T-2OD:$TC_{71}BM$	0.77	18.8	0.75	10.8 (10.3)*
PffBT4T-2OD:$PC_{71}BM$	0.77	18.4	0.74	10.5 (10.2)
PffBT4T-2OD:$PC_{61}PM$	0.77	17.7	0.76	10.4 (10.1)
PffBT4T-2OD:ICMA	0.78	16.4	0.77	9.8 (9.4)
PffBT4T-2OD:$TC_{61}PM$	0.75	17.4	0.74	9.7 (9.3)
PffBT4T-2OD:$PC_{61}BM$	0.77	17.1	0.73	9.6 (9.3)
PBTff4T-2OD:$PC_{71}BM$	0.77	18.2	0.74	10.4 (10.0)
PBTff4T-2OD:$TC_{71}BM$	0.76	18.7	0.68	9.7 (9.4)
PBTff4T-2OD:$PC_{61}PM$	0.76	18.6	0.69	9.6 (9.2)
PNT4T-2OD:$PC_{71}BM$	0.76	19.8	0.68	10.1 (9.7)

He *et al.* **[29]** have recently demonstrated highly efficient single junction polymer solar cells with power conversion efficiencies exceeding 10 %. They have fabricated polymer solar cells using newly synthesized narrow-band gap semiconducting polymer PTB7-Th poly [[2, 6′-4, 8-di(5-ethylhexylthienyl) benzo [1, 2-*b*; 3, 3-*b*] dithiophene] [3-fluoro-2[(2-ethylhexyl) carbonyl] thieno [3,4-*b*] thiophenediyl]] and acceptor [6,6]-phenyl-C_{71}-butyric acid methyl ester ($PC_{71}BM$). Electron donor polymer PTB7-Th has narrow band gap of -1.59 eV with absorption onset at 780 nm. It has HOMO of -522 eV. The most efficient polymer solar cell has efficiency of 11 % at relatively low light intensity conditions (0.3 - 0.5 sun illumination) (**Fig. 2**).

Very recently, Zhao *et al.* **[38]** demonstrated a hydrocarbon solvent based processing system which yields higher efficiency single junction PSCs with PCE up to 11.7 %. Here, single junction polymers solar cells based on PFFBT4T-C_9C_{13}:$PC_{71}BM$ has been developed using a hydrocarbon solvent 1,2,4-trimethylbenzene (TMB) and a novel additive named 1-phenylnapthaline (PN).

So far top performance devices have been processed by using halogenated solvents which are considered environmentally hazardous materials. Zhao *et al.* **[30]** recently used hydrocarbon based system which is not only environment friendly but also yields the highest efficiency of 11.7 % in case of single junction polymer solar cells.

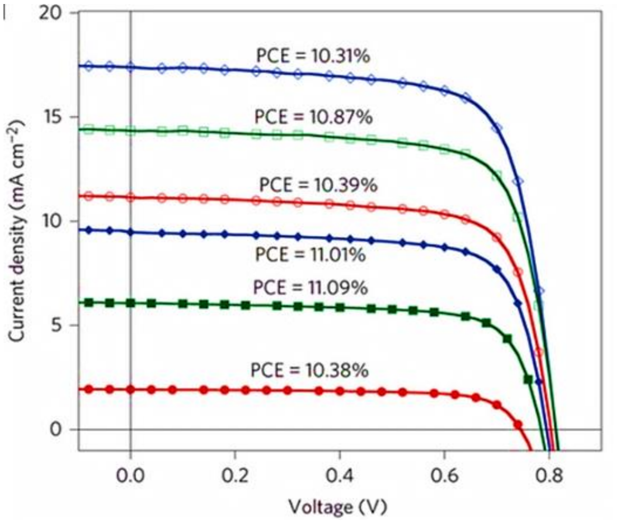

Fig. 2. J–V characteristics of a device with 65 wt % $PC_{71}BM$ in the active layer tested under different illumination conditions (as obtained from standard AM 1.5G, 1,000 W m^{-2} illumination using a set of neutral optical filters) [29] (Nature Photonics, Copyright © 2015, Nature Publishing Group).

Tandem solar cells

The double tandem cells have shown the maximum power conversion efficiency of 10.3 % **[24]**. Multi-junction tandem cells have been fabricated to enhance the power conversion efficiencies recently **[39, 40]**. It has been shown by Chen *et al*. **[35]** that by adopting an efficient design, the triple junction solar cell yields a record power conversion efficiency of 11 % (**Table 3**) which exceeds the record efficiency of a double junction tandem polymer solar cells previously demonstrated by You *et al.* **[24]**. Zhou *et al*. **[31]** have developed all solution processed homo tandem solar cells based on PTB7-Th: $PC_{71}BM$ BHJ blends using a novel interconnecting layer. For fully optimized tandem cells the PCE of 11.3 % has been achieved which is so far the highest efficiency reported for polymer homo tandem solar cells. These results demonstrate that the triple junction solar cell has great potential for use in polymer photovoltaics.

Based on the above discussion, it is apparent that the dramatic developments in polymer conversion efficiencies in single polymer solar cells and triple junction tandem solar cells have taken place mainly due to development of new electron donor with improved properties of better spectral sensitivity, higher hole transport and favorably tuned energy levels matching well with those of fullerene based acceptors.

Table 3. Performance of Triple junction tandem cells (adopted from ref. 35).

Configuration	V_{OC} [V]	J_{SC}[mA cm^{-2}]	FF	PCE [%]
Triple-junction	2.28	7.63	66.39	11.55

Polymer-polymer solar cells

Somehow or other the development of electron acceptor materials has lagged behind that of donor materials. Fullerenes derivatives have been predominantly used as acceptors because of their high electron mobility, affinity as well as their isotropic charge transport **[41]**. In past three years, hectic efforts have been dedicated to develop non fullerene acceptors **[42-44]**. The power conversion efficiency has been obtained upto 4-5.9 % using fullerene free acceptors by several scientific groups **[45-47]**.

Lin *et al*. **[32, 47]** have designed and synthesized a novel electron acceptor (ITIC) comprising a fused ring core which is end-capped with INCN units (**Fig. 3**).

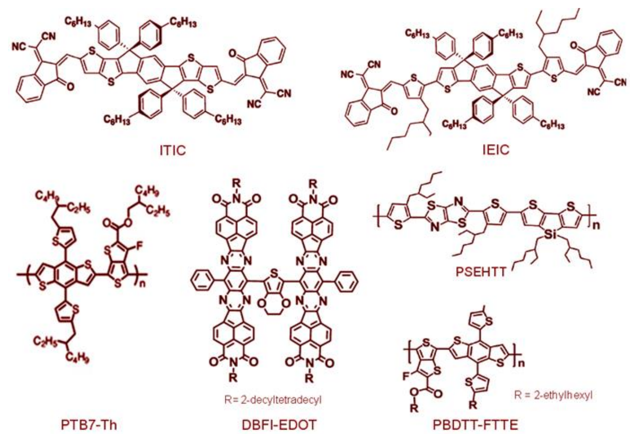

Fig. 3. Chemical structures of compounds ITIC, IEIC, PTB7-TH, DBFI-EDOT, PSEHTT and PBDTT-FTTE. [32, 47, 48].

ITIC shows a strong and broad absorption in visible and NIR regions **[48]**. Its energy levels matched with low bandgap donor polymer such as PTB7-Th. The polymer solar cells based on PTB7-Th: ITIC exhibited power conversion efficiencies of upto 6.8 % which is a record for fullerene free polymer solar cells **[32, 49]** (**Tables 4 and 5**). Hwang *et al*. **[33]** developed all polymer blend solar cells with record PCE of 7.7 %. However, very recently Hwang *et al.* **[34]** successfully demonstrated fullerene free and processing additive free polymer solar cells with PCE of 8.5 % by using a ternary blend DBFI-EDOT:PSEHTT:PBDTT-FTTE.

Table 4. Device data of PSC based on PTB7-TH:ITIC (AM 1.5 G, 100 mW cm^{-2} illumination) (adopted from ref. 47).

Donor:acceptor (w/w)	V_{OC} [V]	J_{SC} [mAcm^{-2}]	FF	PCE [%]
PTB7-TH:ITIC (1:1.3)	0.81	14.21	0.591	6.80

The power conversion efficiencies (PCEs) of polymer:NF (non-fullerene) acceptor based PSCs also known as fullerene free PSCs are still lower than the state of the art PCEs of polymer: PC71BM based PSCs. However, a new class of PSCs have been developed by using PBDB-T:ITIC which exhibited outstanding PCEs up to 11.21 % with excellent thermal stability [50]. An efficiency (PCE) of 10.78 % was certified based on PBDB-T:ITIC. Thus, these results clearly confirm that fullerene free PSCs have high potential for advancing PSC technology for practical applications. It also opens new avenues for fundamental study of organic/polymer photovoltaics [**50**].

Table 5. The device parameters of PSCs based on PTB7-TH:IEIC under illumination of AM 1.5G, 100 mW cm^{-2} (the average values for 20 devices in the brackets) [32]. (Energy & Environmental Science, Copyright © 2014, Royal Society of Chemistry).

PTB7-TH:IEIC (w/w)	V_{OC} (V)	J_{SC} (mAcm^{-2})	FF	PCE (%)
1 : 1a	0.91(0.907 ± 0.002)	11.55(11.32 ± 0.20)	0.42(0.415 ± 0.003)	4.41(4.26 ± 0.12)
1 : 1.5a	0.93(0.923 ± 0.003)	12.24(11.75 ± 0.38)	0.46(0.456 ± 0.002)	5.24(5.03 ± 0.17)
1 : 2a	0.94(0.935 ± 0.003)	11.15(10.86 ± 0.23)	0.47(0.466 ± 0.002)	4.93(4.73 ± 0.16)
1 : 2.5a	0.94(0.938 ± 0.001)	9.84(9.65 ± 0.15)	0.47(0.462 ± 0.005)	4.35(4.18 ± 0.10)
1 : 1.5b	0.97(0.967 ± 0.002)	13.55(13.05 ± 0.35)	0.48(0.473 ± 0.004)	6.31(6.08 ± 0.20)

*a*The cathode interlayer is calcium.
*b*The cathode interlayer is PDIN.

Triple-junction polymer solar cells

Chen *et al*. **[35]** have demonstrated an efficient design of triple junction solar cells using three materials with different energy gaps as electron donors blended with fullerene derivatives. The selected materials have bandgaps in order of 1.9, 1.58 and 1.4 eV. A highly efficient triple junction solar cell was fabricated having PCE of 11 %. Recently, Yusoff *et al*. **[36]** have developed a high efficiency solution processed polymer inverted triple junction solar cell exhibiting record PCE of 11.83%.

The above developments in the low bandgap polymers, triple junction polymer solar cells and fullerene free acceptors will move the frontiers of polymer solar cells as far as efficiency, stability and solution based processing of polymer solar cells to new heights in coming years. The research developments towards the degradation and stability of polymeric materials **[50-60]**, particularly to those significant in polymer solar cells are also in high demand.

Commercial aspects of solar photovoltaics

A report by Allied Market Research **[61]** predicts compound annual growth rate (CAGR) of 29.5 % between 2014-2020 for organic electronics. Organic photovoltaics (OPV) will be tertiary market driver. After organic displays, organic system components will compose the second largest system of organic electronics market, generating approximately 20 % revenue by 2020.

Chinese thin film giant Hanergy and the German organic electronic specialist Heliatek have opted for BIPV (building integrated photovoltaics) on their HQ facades to demonstrate the capability of this technology to harvest solar energy in less than optimum conditions **[62]**. The one GW solar energy parks based on polymer solar cells have been established in Denmark and South of Spain **[63]**. In India, a 4 GW power plant (Sambhar Ultra-Mega Green Solar Project, near Jaipur) based on silicon solar cells are being built in Rajasthan. The mission document targets that installed solar capacity would be hiked to 20 GW by 2020, 100 GW by 2030 and 200 GW by 2050 **[12, 27]**. Polymer photovoltaics need its inclusion in 100 GW solar energy power projects by 2022 in India **[12, 64]**.

Massachusetts, a small state in USA had near 3 MW solar power capacities in 2007. In 2015, this state has 700 MW installed photovoltaic capacity **[65]**. In 2015, China planned to install 15-18 GW of solar power alone which is double the total solar deployment in USA according to Bloomberger New Energy Finance (BNEF) **[66]**. In next 15 years, China is aiming to have more low carbon electricity (including hydro and nuclear) than entire capacity of US power grid. Apple, a major US based company has agreed to install two large solar farms in China. By 2020, China, which now has more solar capacity than any other country, plans to triple it and photovoltaics is going to play an important role in their endeavors **[66, 67]**.

For the first time, in year 2015, the world invested more in photovoltaic cells than in coal- and gas-fired power generation combined [**67**]. Interestingly, new solar installations in USA are expected to be ~16 GW-dc in 2016 which is more than double when compared to 2015 (~7.5 GW-dc) **[67]**.

Conclusion

Being a zero emission and abundant source of energy, soon the solar power generated electricity would contribute more than any other newer source to US grid system. India and China, the two most populous nations of the world are aiming for big installations and have already invested in huge infrastructure pertaining to solar photovoltaics. With the far ever growing demands for clean energy, high efficiency polymer solar cells have huge business potential in the coming years due to being inexpensive, light weight and processable into large area flexible devices which makes them most favourable for power generation applications in grid and non-grid approach, thus cutting carbon footprint. With the current pace of ongoing research on polymer photovoltaiccs, we are very near to achieve most desirable 15 % efficiency and envision achieving a milestone of 20 % PCE. Furthermore, light weight easy-to-install large fittings of polymer solar cells would unquestionably solve the problems associated with pollution, non-renewable resources, global warming and sustainability by replacing systems which are heavy, time consuming and emitting harmful gases.

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