

A case of polymer photovoltaics in India

R. P. Singh

Polymer solar cells are light weight, flexible and inexpensive. There has been great progress in three important aspects of polymer solar cells in the last decade, i.e. efficiency, stability and processing. The efficiencies of single-junction solar cells have been improved by stacking two or more complementary single cells in the form of tandem cells. There has been tremendous progress in roll-to-roll processing of single and tandem cells resulting in the setting up 1 GW solar power parks in Denmark and south of Spain. India has an ambitious programme of setting up solar energy power houses up to 300 GW by 2030. However, sub-critical research and development is taking place in the field of polymer solar cells in India. It is high time we decide to pursue intensive polymer photovoltaics in the country.

Following the commentary by Bose¹, I discuss here polymer photovoltaics in India. The progress in polymer photovoltaics has no parallel in any technological growth in the world^{2,3}. Polymer solar cells being light weight, flexible and inexpensive can be produced by cheap low-temperature solution processing. Three important aspects of polymer solar cells, i.e. efficiency, stability and processing have shown tremendous progress.

Tang⁴ reported the first polymer solar cell in 1986 using bilayer structure demonstrating a power conversion efficiency of 1%. The last decade witnessed the impressive development in bulk heterojunction concept⁵⁻⁷ in polymer solar cell technology leading to the increase in single-junction cell efficiency from 4% in 2005 (refs 8 and 9) to state-of-the-art present-day efficiencies of 8–9% (refs 10–15; Figure 1). By optimization of materials with proper band gap (necessarily low band gap), energy levels and carrier mobility, efficiencies up to 10–12% are achievable in single-junction solar cells¹⁶. The organic tandem solar cells comprising two series-connected single cells and covering complementary solar spectra can reach theoretical Power Conversion Efficiency (PCE) of 15% (refs 17 and 18). You *et al.*¹⁹ have demonstrated an efficiency of 10.6% in solution-processed tandem cells (Figure 2). Heliatek Co,

Germany²⁰ has recently demonstrated certified 12% efficiency in a vacuum-processed small-molecule organic triple-junction device with an active area of $>1\text{ cm}^2$.

There has been remarkable progress in the stability of bulk heterojunction solar cells in the last ten years^{2,21-23}. There are various degradation phenomena taking place in polymer solar cells. When the device is illuminated, complex chemical reactions of organic semiconductors with oxygen and moisture have been observed. Similarly, interface is another source of degradation. The diffusion of the electrode materials into an active layer, acidity of the poly(3,4-ethylene-dioxythiophene)–polystyrene-para-sulfonic acid (PEDOT : PSS) layer and change of morphology of active layer are some reasons for the degradation of polymer solar cells. These instabilities can be significantly reduced by appropriate encapsulation. Flexible poly(3-hexyl thiophene) : (6,6)-phenyl-C₆₁-butyric methyl ester) (P3HT : PC₆₁BM), organic photovoltaics (OPV) devices encapsulated with food-quality packaging barrier film have shown a lifetime over 1200 h. Where a higher quality barrier film was used, lifetimes of 4000 h (at 65°C/85% relative humidity) have been achieved. Peters *et al.*²³ recently reported a lifetime of 7 years for poly[9-(1-octyl-nonyl)-9H-carbazole-2,7-diyl]-2,5-thiophenediyl-2,1,3-benzothiadiazole-4,7-diyl-2,5-thiophenediyl]–(6,6)-phenyl-C₆₁ buty-

ric methyl-ester (PCDTBT–PCBM) solar cells. An inter-laboratory outdoor stability study of flexible roll-to-roll coated organic photovoltaic modules (P3HT : PCBM inverted architecture) in different geographical locations from the southern and northern hemispheres has been undertaken²⁴. The most stable modules have demonstrated lifetime of more than 10,000 h and sub-cell analyses revealed stability of up to 17 months.

Development has also taken place in the processing of polymer solar cells resulting in the setting up 1 GW solar power parks in southern Spain and Denmark²⁵.

Spin coating is the most popular method in OPV device fabrication in research laboratories. Various printing and coating techniques have been found compatible to fast roll-to-roll processing²⁶. In the past it was confined to single donor–acceptor polymer solar cells. Frederic Krebs and his research team^{27,28} at the Technical University of Denmark have demonstrated for the first time the successful roll-to-roll manufacture of tandem OPV modules, each comprised of a stack of 14 discrete layers which are rapidly printed, coated or deposited on top of another by a machine reminiscent of a printing press (Figure 3). The processing was carried out under simple conditions; it is very fast with single solar cell module being printed onto blank foil each second. The whole processing is cheap

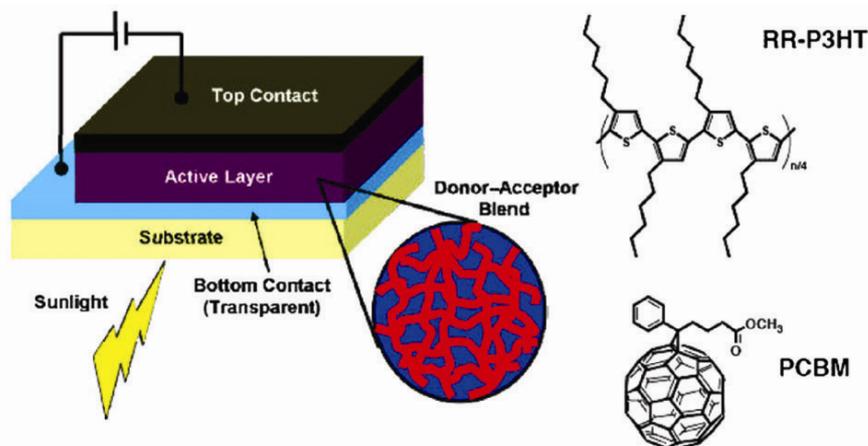


Figure 1. A typical P3HT : PCBM bulk heterojunction polymer solar cell. (Ref. 34; Published with permission from Royal Society of Chemistry.)

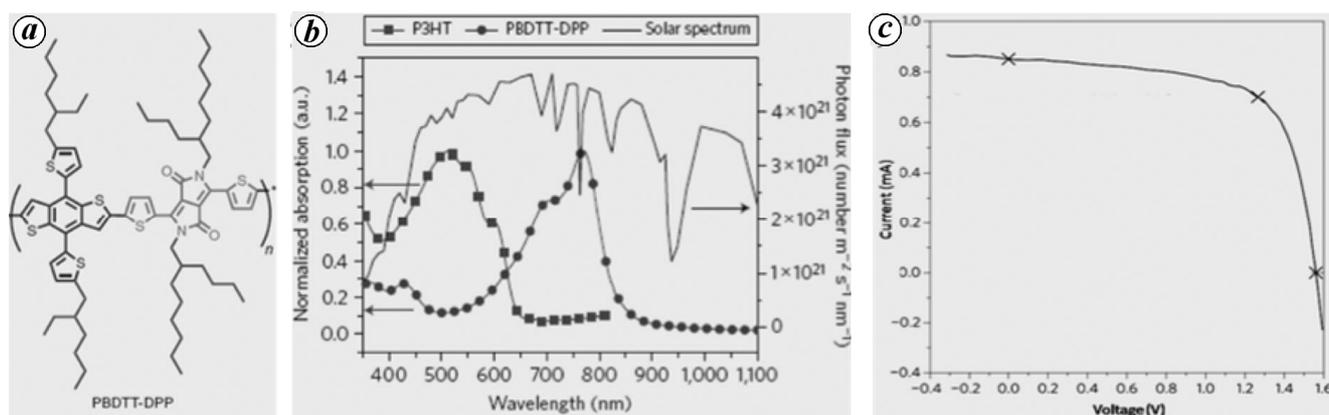


Figure 2. Molecular design and optical properties of HOMO and LUMO for PBDTT-DPP. **a**, Chemical structure of PBDTT-DPP. **b**, UV-visible absorption spectra of PBDTT-DPP and P3HT films and the solar radiation spectrum. **c**, Original *I*-*V* characteristics of the tandem device as measured by National Renewable Energy Laboratory (NREL), Colorado. (Ref. 35; published with permission from Nature Publishing Group.)

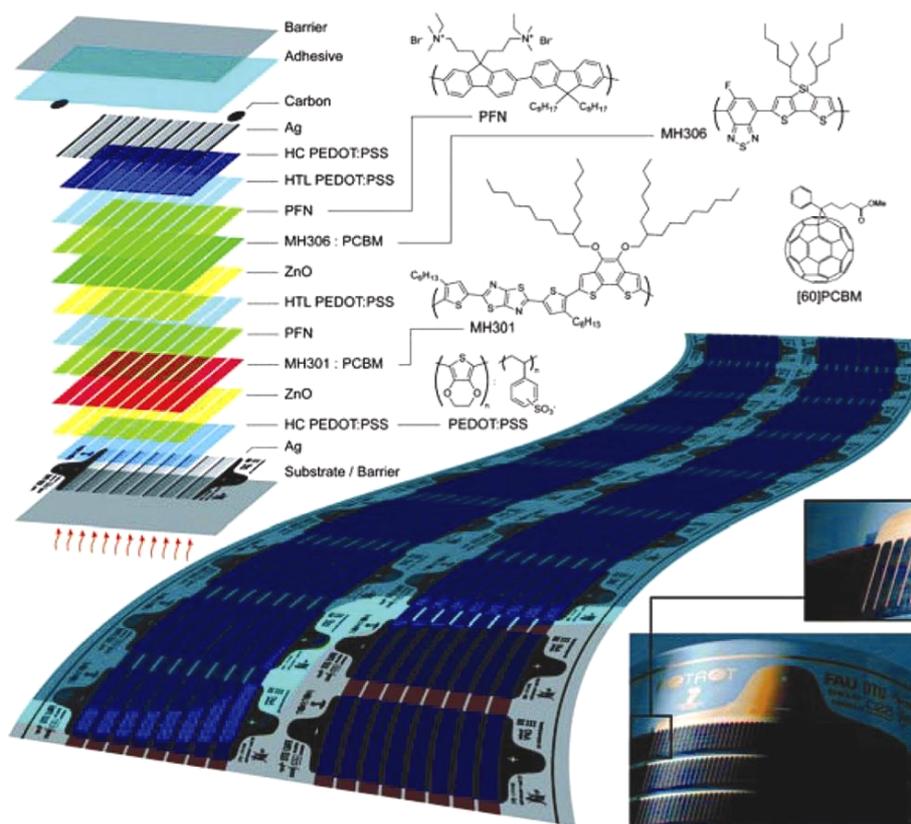


Figure 3. The complete 14-layer tandem stack (top left) along with structural formulae and names for different materials involved (top right). The outline of the printed web is shown (middle) along with an actual photograph of a module (bottom right). In the close-up photograph, the differently coloured active materials (red colour from MH301, green colour from MH306 and blue colour from PEDOT:PSS) are seen representing the wide band gap and low band gap semiconductor junctions and the hole transport layer. (Ref. 28; published with permission from Royal Society of Chemistry.)

and completely scalable with high technical yield.

Commercially available module shows power conversion efficiencies in the range

1.5–2.5%. Recently, efficiencies more than 3% have been achieved²⁹. Using barrier film encapsulation protection enabled an outdoor lifetime of more 10,000 h for

flexible devices based on P3HT and indium tin oxide (ITO) electrodes, and also good stability outside for ITO-free devices²⁷. It is expected that these

parameters will be improved with availability of tandem devices.

The first national workshop on polymer solar cells³⁰ was organized at Indian Institute of Science Education and Research (IISER), Pune in April 2012. Sub-critical research has been carried out in this field in India. A 4 GW power plant (Sambhar Ultra-Mega Green Solar Project) based on silicon solar cells is being built near Jaipur³¹. The mission document targets that installed solar capacity would be increased to 20 GW by 2020, 100 GW by 2030 and 200 GW by 2050 (ref. 32).

Polymer solar cells made of organic materials instead of silicon is a new and promising technology³³. It is inexpensive and quick to set up and project Mega Watt aims to make polymer solar cells totally independent of public subsidies and allow the energy from polymer solar cells to be sold at 0.25 DKK/kWh (ref. 33).

The Danish project³³ to make polymer solar cells more profitable to allow power generation from polymer solar cells to compete on market terms and traditional coal-fired plants as well as establishment of solar energy parks warrant extensive research and development in this field in India.

1. Bose, D. N., *Curr. Sci.*, 2014, **107**(1), 20–21.
2. Dou, L., You, J., Hong, Z., Xu, Z., Li, G., Street, R. A. and Yang, Y., *Adv. Mater.*, 2013, **25**, 6642–6671.
3. Darling, S. B. and You, F., *RSC Adv.*, 2013, **3**, 17633–17648.
4. Tang, C. W., *Appl. Phys. Lett.*, 1986, **48**, 183–185.
5. Sariciftci, N. S., Smilowitz, L., Heeger, A. J. and Wudl, F., *Science*, 1992, **258**, 1474–1476.
6. Morita, S., Zakhidov, A. A. and Yashino, K., *Solid State Commun.*, 1992, **82**, 249–252.
7. Heeger, A. J., *Adv. Mater.*, 2014, **26**, 10–28.
8. Li, G. *et al.*, *Nature Mater.*, 2005, **4**, 864–868.
9. Ma, W., Yang, C., Gong, X., Lee, K. and Heeger, A. J., *Adv. Funct. Mater.*, 2005, **15**, 1617–1620.
10. He, Z. C., Zhong, C. M., Su, S. J., Xu, M., Wu, H. B. and Cao, Y., *Nature Photonics*, 2012, **3**, 649–653.
11. Chen, H. Y. *et al.*, *Nature Photonics*, 2009, **3**, 649–653.
12. Liang, Y. Y. *et al.*, *Adv. Mater.*, 2010, **22**, E135–E138.
13. Scharber, M. C., Wuhlbacher, D., Kope, D., Denk, M., Waldauf, C., Heeger, A. J. and Brabec, C. J., *Adv. Mater.*, 2006, **18**, 789–794.
14. Singh, R. P. and Kushwaha, O. S., *Macromol. Sympo.*, 2013, **327**, 128–149.
15. Singh, R. P. and Kushwaha, O. S., *J. Mater. Educ.*, 2013, **35**(3–4), 79–120.
16. Scharber, M. C., Wuhlbacher, D., Koppe, M., Denk, P., Waldauf, C., Heeger, A. J. and Brabec, C. J., *Adv. Mater.*, 2006, **18**, 789–794.
17. You, J., Dou, L., Hong, Z., Li, G. and Yang, Y., *Prog. Polym. Sci.*, 2013, **38**, 1909–1928.
18. Dennler, G., Scharber, M. C., Ameri, T., Denk, P., Farberich, K., Waldauf, C. and Brabec, C., *Adv. Mater.*, 2008, **20**, 579–583.
19. You, J. *et al.*, *Nature Commun.*, 2013, **4**, 1446/1–10.
20. <http://www.heliatek.com>
21. Jorgensen, M., Norrman, K. and Krebs, F. C., *Sol. Energy Mater. Sol. Cells*, 2008, **92**, 686–714.
22. Jorgensen, M., Norrman, K., Gevorgyan, S. A., Tromholt, T., Andreasen, B. and Krebs, F. C., *Adv. Mater.*, 2012, **24**, 580–612.
23. Peters, C. H., Sachs-Quintana, I. T., Kastrop, T. P., Beaupre, S., Leclerc, M. and McGehee, M. D., *Adv. Energy Mater.*, 2011, **1**, 491–494.
24. Gevorgyan, S. A. *et al.*, *Sol. Energy Mater. Sol. Cells*, 2013, **116**, 187–196.
25. Krebs, F. C., Espinosa, N., Hosel, M., Sondergaard, R. R. and Jorgensen, M., *Adv. Mater.*, 2014, **26**, 29–39.
26. Sondergaard, R. R., Hosel, M. and Krebs, F. C., *J. Polym. Sci. Part. B, Polym. Phys.*, 2013, **51**, 16–34.
27. Bergius, W., *Chemistry World*, 19 June 2014.
28. Anderson, T. R. *et al.*, *Energy Environ. Sci.*, 2014, **7**, 2925–2933.
29. Carle, J. E., Helgesen, M., Madsen, M. V., Bandgaard, E. and Krebs, F. C., *J. Mater. Chem. C*, 2014, **2**, 1290–1297.
30. www.iiserpune.ac.in/nwpsc (accessed on 21–22 April 2012).
31. Sanjay Kumar, *Nature*, doi: 10.1038/nature.2014.14647
32. Jayaraman, K., *Nature*, doi: 10.1038/news.2009.774
33. <http://dailyfusion.net/2014/polmyer-solar-cells-profitable-28005/>
34. Li, G., Shrotria, V., Yao, Y., Huang, J. and Yang, Y., *J. Mater. Chem.*, 2007, **70**, 3126–3140.
35. Dou, L. *et al.*, *Nat. Photon.*, 2012, **6**, 180–185.

R. P. Singh is in the Indian Institute of Science Education and Research, Pune 411 008, India.
e-mail: singh.prakash.ram@gmail.com