

Engineering low-cost energy from plastic photovoltaics

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Optimization of new and existing conjugated polymers for solar cells helps bring inexpensive renewable electricity closer to reality.

Global warming is one of the big issues of our time, and low-cost renewable-energy generation offers hope of reducing the environmental threat. One promising research direction is the use of semiconducting plastics that can turn sunlight into electricity. The efficiency of organic photovoltaic (OPV) devices based on such materials has been making steady improvements in recent years, increasing from <1% in 2001¹ to 6% in 2009.² While this may still be only a third to a quarter of the efficiency achieved by the best silicon solar cells, OPV fabrication methods have more in common with the food-packaging than the semiconductor industry (think crisp packets rather than silicon wafers). The ultimate goal is to produce flexible, mass-produced devices that will generate electricity more cheaply than by burning fossil fuels. Before this can be achieved, it will be necessary to combine improved efficiency, extended lifetime, and inexpensive manufacture in a single fabrication process.

This requires development of new materials and processing techniques as well as a better understanding of how OPVs work. However, while the number of researchers working in this field has increased rapidly in response to government and funding-body priorities, only relatively few groups master device fabrication with >4% efficiency. The problem becomes even more acute for new materials with unknown properties.

Over the last five years, many research groups³ have studied OPVs based on the polymer poly(3-hexylthiophene) (P3HT) and fullerene derivative phenyl-C61-butyric acid methyl ester (PCBM). These materials can form an interpenetrating network of nanoscale domains. When incident light excites an electron-hole pair in the P3HT, the electron hops across to the PCBM because of its different electronic-energy levels. This produces separated charges that can be extracted at the device electrodes to generate electricity. Unfortunately, the low optical absorption of P3HT in the near-IR and poorly matched energy levels result in a fundamental limit to the power efficiency that can be

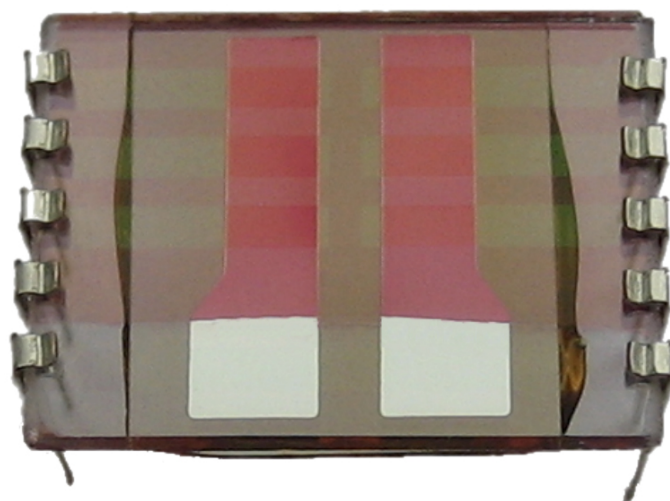


Figure 1. OPV device fabricated at the University of Sheffield. Two vertical aluminum ‘stripes’ define the device cathode. The six horizontal indium tin oxide anode stripes overlap with the cathode stripe, thus defining the active area ($3 \times 1.5 \text{mm}^2$) of each of the individual devices. The white patches at the bottom are areas from which we have deliberately removed the (red) P3HT/PCBM semiconductor thin film to generate a good electrical contact with the cathode. The total size of the device substrate is $15 \times 20 \text{mm}^2$.

obtained from P3HT/PCBM devices. Nevertheless, the amount of existing research on these materials and their commercial availability make them an excellent test system for OPV research.

Over the last year, we have invested significant effort into understanding and optimizing P3HT/PCBM thin-film device fabrication. Wide-ranging improvements have enabled us to produce consistently high-performing OPVs. In particular, we have optimized device efficiency by varying film thickness and exploring the effect of varying the relative ratio of P3HT and PCBM in the composite film. The P3HT/PCBM films are cast from solution, and so we looked at the type of

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solvent used for casting. We investigated different techniques to 'grow' a nanoscale-network-like structure of efficient charge-transporting pathways within the film, such as thermal annealing at various temperatures, and the use of a plasticizing solvent vapor to promote crystallization of the P3HT molecules. The latter technique increases hole mobility within the film and also extends the device sensitivity to red light.

We found P3HT 'nanofibrils' (self-assembled bundles of polymer chains) within the P3HT/PCBM films, which are associated with improved device efficiency. These nanofibrils grow over a period of hours in P3HT/PCBM solutions. Their presence suggests that optimized devices are best fabricated from 'aged' solutions. We also found that the thin layer of the high-workfunction conducting polymer PEDOT:PSS—poly(3,4)ethylenedioxythiophene / polystyrenesulfone—that is coated onto the indium tin oxide anode to improve hole extraction from the P3HT/PCBM film is not air stable at high humidity. As the polymer is applied using a water-based solution, this is a counter-intuitive result. This has been recognized previously,⁴ but it is not widely reported in the literature. Other key findings were that the type and grade of PCBM did not affect performance significantly, but the polymer's impurity content had a large effect. In addition, developing a robust encapsulation system for these laboratory-scale devices has made measurements significantly easier and also allowed us to demonstrate the use of OPVs as x-ray detectors⁵ with possible applications in large-area medical imaging.

Our work has led to the catalog spin-out company 'Ossila,' to supply a small but growing range of components to the organic-electronics research community. Ossila provides the metal-evaporation shadow masks used to define the OPV cathode stripes as well as newly developed glass substrates with pre-patterned ITO thin film, used as the OPV anode contact (see Figure 1). We hope that Ossila will help others benefit from the efficiencies we have achieved.

Of course, there is still plenty of engineering left to be done, such as moving to flexible substrates and encapsulation systems, and exploring production techniques and vacuum-free cathode-deposition methods. Having a fully optimised P3HT/PCBM platform allows us to do this effectively and focus on more efficient materials. Indeed, recent reports² of OPVs with efficiencies greater than 6% suggest that using plastics to produce significant quantities of low-carbon power will increasingly become a commercial reality. Our most important result, however, has been to produce devices with 4.5% peak and 4.3% average efficiency. We can now screen new polymers more rapidly and with confidence in the accuracy of our results, and focus on the science rather than device engineering. We are collaborating with

chemists at the Universities of Sheffield and Manchester (UK) to test new plastics, including carbazole-based polymers and block copolymers.

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References

1. T. Fromherz, F. Padinger, D. Gebeyehu, C. Brabec, J. C. Hummelen, and N. S. Sariciftci, *Comparison of photovoltaic devices containing various blends of polymer and fullerene derivatives*, **Sol. Energy Mater. Sol. Cells** **63**, pp. 61–68, 2000.
2. S. H. Park, A. Roy, S. Beaupré, S. Cho, N. Coates, J. S. Moon, D. Moses, M. Leclerc, K. Lee, and A. J. Heeger, *Bulk heterojunction solar cells with internal quantum efficiency approaching 100%*, **Nat. Photon.** **3**, pp. 297–303, 2009.
3. B. C. Thompson and J. M. J. Fréchet, *Polymer-fullerene composite solar cells*, **Angew. Chem. Int'l Ed.** **47**, pp. 58–77, 2008.
4. K. Kawano, R. Pacios, D. Poplavskyy, J. Nelson, D. D. C. Bradley, and J. R. Durrant, *Degradation of organic solar cells due to air exposure*, **Sol. Energy Mater. Sol. Cells** **90**, pp. 3520–3530, 2006.
5. J. W. Kingsley, A. J. Pearson, L. Harris, S. J. Weston, and D. G. Lidzey, *Detecting 6MV x-rays using an organic photovoltaic device*, **Org. Electron.** **10**, pp. 1170–1173, 2009.