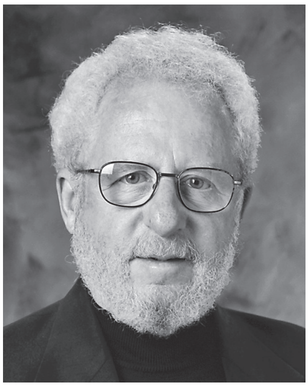
Chapter 23

Low-cost ‘plastic’ solar cells: a dream becoming a reality

Alan Heeger



Alan Heeger was born in 1936 in Sioux City, Iowa, USA. He enrolled in studies of physics and mathematics at the University of Nebraska and obtained his PhD at the University of California in Berkeley in 1961. In 2000 he received the Nobel Prize in Chemistry ‘for the discovery and development of conductive polymers’. Together with Alan G. MacDiarmid at the University of Pennsylvania, Heeger discovered that plastic can be made electrically conductive. He subsequently helped to develop conductive polymer research into a field of great importance for chemists as well as physicists. As Professor of Physics and Professor of Materials at the University of California at Santa Barbara, Alan Heeger remains active in these research areas. His current research focuses on low-cost plastic solar cells made from semiconducting polymers.

The problem

It is clear to all of us that we have an energy problem. Luckily, the power from the sun is available to help solve this energy problem.

We installed solar cells on the roof of our house a year ago. It is a wonderful technology: when the sun comes up in the morning my electric meter runs backwards! My electric bill (i.e., my monthly cost of electricity) has dropped to zero. The problem is, however, that the purchase cost (including installation) was much too high. Depending on the details of how the cost of energy increases in the coming years, more than ten years will be required for the savings to repay the installation cost.

There are two problems that we must solve to enable widespread use of photovoltaic solar cell technology. The first is the cost. The second is that we need to produce a lot of area. At noon on a sunny day, we receive one kilowatt per square metre of energy from the sun. This corresponds to sufficient energy received on Earth in one hour to satisfy all of the energy needs for the planet for one year! Thus, the ability to produce low-cost, efficient solar modules in areas sufficiently large to enable significant energy production is a major opportunity.

The solution: 'plastic' solar cells

An exciting new technology that can produce low-cost solar cells in large quantities uses 'photovoltaic inks'. These inks are organic semiconducting polymers which are in solution with common solvents. Different absorption and transmission associated with the different molecular structures are the reason for different colours of the inks. The unique quality of these coloured liquids is that they have electronic functionality and can be used for printing.

Printing technology was invented by Gutenberg in 1545, more than four hundred and fifty years ago. If printing technology could be used for the fabrication of solar cells, then we could produce low-cost, high efficiency solar cells in large quantities. Indeed, the principles of this old mature technology can be adapted to print solar cells roll-to-roll like newspapers. The potential impact of such printed 'plastic' solar cells on the market for solar technology could be tremendous.

The demonstration sample of a plastic solar cell, shown in Figure 1, has been fabricated by a company called Konarka Technologies. The name of the company stems from a temple dedicated to the Indian Sun God. Initially, this product will be quite expensive, and will therefore only be used by people who can afford it. Possible points of initial use are battery chargers and boats. However, once plastic solar cells are available with high efficiency and printed in large quantities, they will become much more affordable. They could then be given to poor families all over

Fig. 1. Solar module, printed on a roll-to-roll tool similar to a printing tool. Its advantages over standard solar cells are flexibility, light weight, low cost, and potential for mass production. (*Source:* A. Heeger)

the world. The access to energy from the sun could then change the lives of millions of people.

The technology: how to create plastic solar cells

The technology to print plastic solar cells originated from a discovery made in our laboratory at UC Santa Barbara in 1992. We were interested in the potential interaction between our semiconducting polymers with the famous fullerene molecules. We had no concept of solar cells; these initial experiments were motivated purely by curiosity. We discovered that following the absorption of a photon an electron transfer reaction (from polymer to fullerene) occurs on a remarkably short time scale. The rate of this photo-induced electron transfer is two orders of magnitude faster than the first step in photosynthesis. This ultra-fast electron transfer reaction implies that we separate charge (create mobile charge carriers) with a quantum efficiency that approaches unity: every absorbed photon yields a pair of separated charges! This high efficiency of charge separation and mobile carrier generation provides the scientific foundation for creating a technology to produce high efficiency solar cells.

However, our materials, cast from solution into thin films, are very disordered. The analogy would be tangled cooked spaghetti in a bowl rather than rigid straight spaghetti in a box. Because of this disorder, the charges that are separated by photo-induced charge transfer will not travel very far before they recombine. In order to collect these charges, we had to invent a new kind of material comprising charge-separating junctions between two materials – so-called heterojunctions between the donor and the acceptor. Because of the short recombination length, the heterojunction cannot simply be a bi-layer, as is often the case in the semiconductor world. We had to create a nano-morphology with interpenetrating networks of the two components on a length scale of a few nanometres, roughly a hundred angstroms (1 angstrom is equal to 0.1 nanometre). A conceptual sketch of this nano-morphology is shown in Figure 2 a.

As demonstrated in Figure 2 b, this remarkable nano-structure can already be constructed. How was it formed? The answer is simple, but elegant: we were able to achieve this structure through controlled phase separation of two incompatible components both of which are soluble in the same solvent. When cast as films from solution, the phases of the two components separate as the solvent quickly evaporates. After separation, the two components self-assemble into the material depicted in Figure 2. This so-called bulk heterojunction material has charge-separating junctions everywhere. Each component forms a network that can deliver charges to the electrodes.

By using this bulk heterojunction concept, we can collect photo-generated charge carriers. You might wonder how the electrons know which way to go (for example up and not down). Again this is a simple problem. All one needs to do is to break the symmetry by using two different metals for the electrodes. We were able to control the morphology of the heterojunction material, and are now able to efficiently collect the photo-generated charge carriers. With the specific materials shown in Figure 2, a power conversion efficiency of 5 % can be achieved.

The best solar cells fabricated from inorganic semiconductors are triple junction devices that yield power conversion efficiencies in excess of 40 %, but because of the high processing costs, these are prohibitively expensive. They can be used in space applications, but not for the kinds of applications we are discussing here. The question is what we can expect to achieve using low-cost plastic solar cells.

Improving the efficiency of plastic solar cells

The particular material shown in Figure 2, which resulted in solar cells with 5 % efficiency, has an absorption spectrum poorly matched to the solar spectrum: the band gap is too large, missing more than half of the solar spectrum (see Fig. 3).

Obviously, there is an opportunity to improve the efficiency of solar energy absorption by doing the proper science. Synthesizing new macromolecules with electronic structures that yield absorption spectra better matched to the solar spectrum could eventually improve the performance of our solar cells by at least a factor of two (see Fig. 4).

Figure 4 a depicts such a different molecular structure with a smaller energy gap: the absorption spectrum of the polymers now extends beyond red into the near infrared (see Fig. 4 b). Improved performance is achieved through the use of

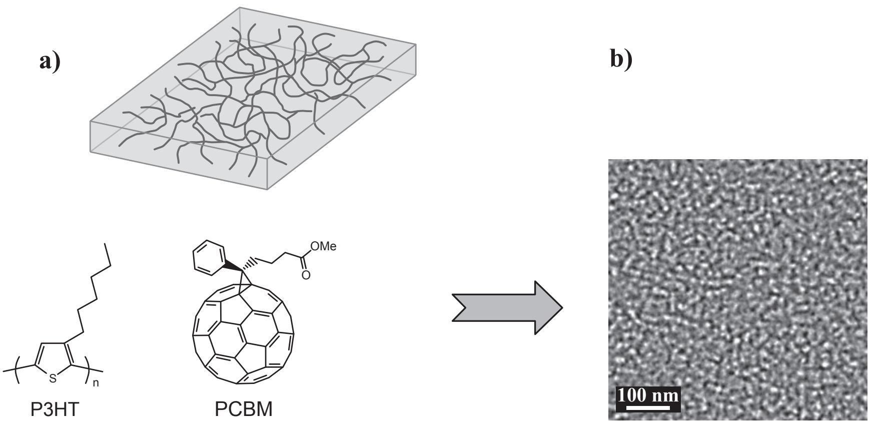


Fig. 2. Illustration of the nano-morphology with ubiquitous charge-separating junctions – so-called bulk heterojunction material. a) Conceptual sketch. The black material is an interconnected network of the fullerene (PCBM) and the white material is an interconnected network of a semiconducting polymer (P3HT). Each of the two components is fully interconnected. b) Electron micrograph. The small white bar on the bottom left represents 100 nanometre. (*Source:* Kim *et al.,* 2007; Ma *et al.,* 2007).

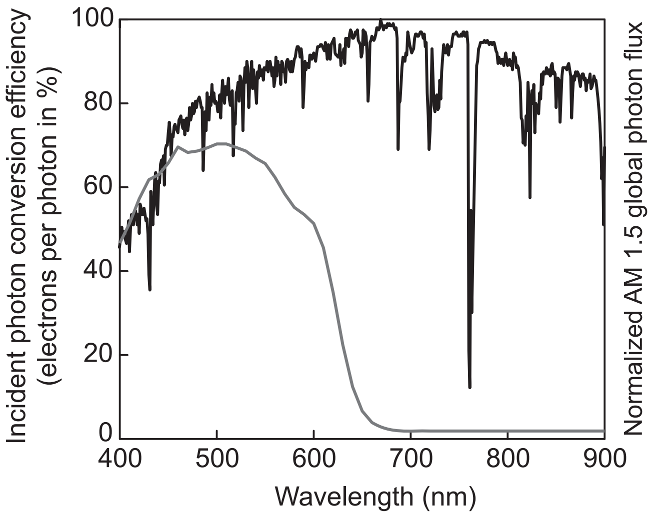


Fig. 3. The solar emission spectrum as received on Earth at twelve noon on a sunny day (fluctuating black line) is not well matched by the absorption spectrum of P3HT (see Fig. 2) solar cells (smooth grey line). (*Source:* Peet *et al.,* 2007).

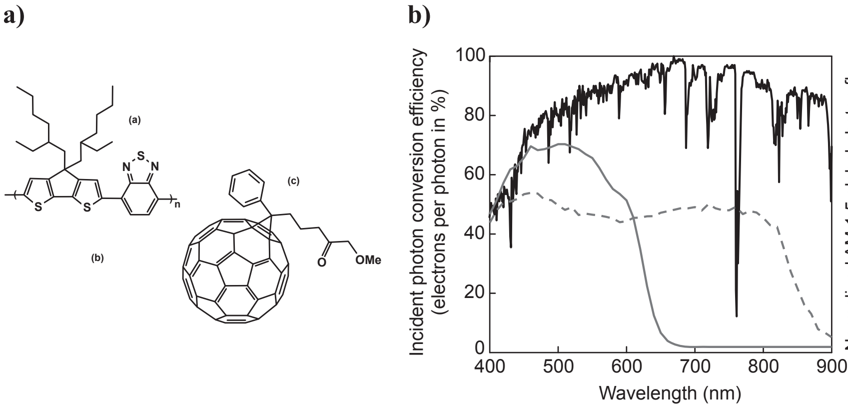


Fig. 4. a) Semiconducting polymers with smaller band gaps matching the solar spectrum better than the original polymers used. b) The improved conversion efficiency is shown (dashed line), particularly at wavelengths beyond 650 nm. Wavelengths above 750 nm belong to the infrared spectrum. (*Source:* adapted from Peet *et al.,* 2007)

processing additives (Lee *et al.,* 2007; Peet *et al.,* 2007). While these polymers still do not absorb far enough into the infrared, future synthesis of new molecules with absorption spectra that are even better matched to the solar spectrum will lead to even higher efficiencies.

The next step is to create multi-layer systems. This is possible with the same printing technology, i.e., by processing multi-layers from solution in successive depositions of electronic inks. Multiple layers will further increase the performance of the solar cells. This is because of the simple fact that if two batteries – regular batteries or solar batteries – with voltages V_1 and V_2 are connected in series ('tandem cells'), then the voltage will be the sum of the two ($V_1 + V_2$). By connecting batteries in series, we can increase the open circuit voltage, and can take better advantage of the energy delivered in the solar spectrum.

Figure 5 shows that these multi-layer structures can in fact be fabricated. Despite the fact that the depicted films were cast from solution, the interfaces are very well defined – a result that gives us confidence in the success of our approach. By fabricating tandem cells, we have been able to show the expected increase in voltage. So far, we have been able to demonstrate power conversion efficiencies as high as 6.5% (Kim *et al.,* 2007).

While 6.5% represents important progress, it is not high enough. Fortunately, there are many opportunities to further improve the efficiency. A slightly different architecture (Kim *et al.,* 2006) enables us to better harvest the incoming photons and thereby improve efficiency by an additional 25–50%, approaching conversion efficiencies as high as 8–9%. (This architecture adds an 'optical spacer' layer between

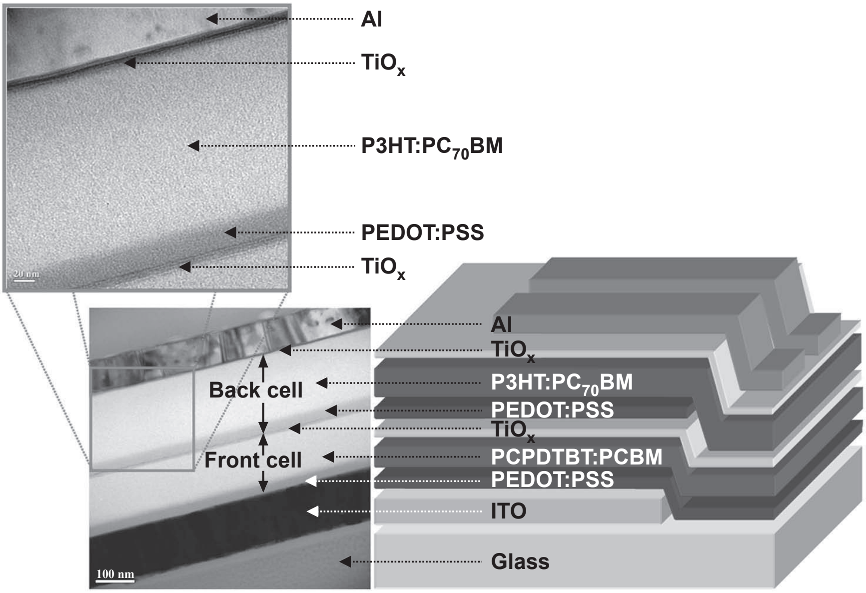


Fig. 5. Multi-layer structure of plastic solar cells connected in series (tandem cells). The images on the left are electron micrographs of cross-sections cut through multilayer structure, sliced down like a meat cutter in a delicatessen, turned over and then imaged by electron microscopy. (*Source:* Kim *et al.,* 2007)

the active bulk heterojunction layer and the metal electrode.) Also, we can expect more than a 50 % efficiency improvement by creating molecular structures where the energy gap is even better matched to the solar spectrum than our current molecules (see Figs. 3 and 4). It must be emphasized that although we have made some improvements in the charge collection efficiency, we are still collecting only approximately half of the photo-generated carriers. In addition, we foresee optimizing the nano-scale morphology to further improve the charge collection efficiency. By precisely tuning the molecular structure, there is an opportunity to optimize the electrochemistry of semiconducting polymers, and thus to increase the open circuit voltage. It has been demonstrated that in this way power conversion efficiency can be improved by another 50 %. The tandem cell configuration offers something between 50 % improvement and a doubling of conversion efficiency (Kim *et al.,* 2007).

When the increments for these independent potential improvements are added up, then we could potentially achieve power conversion efficiency in excess of 25 % – an efficiency approaching that achieved by existing inorganic solar cells. Each of these separate efficiency improvements have been successfully implemented already. However, realizing all of these improvements at the same time is difficult.

Combining independent improvements is the main challenge we will continue to work on in our laboratories. We are confident that we will reach efficiencies that will enable a major impact on the future solar cell technology, and thus on our future energy system.

The lifetime of plastic solar cells

One of the questions that people often ask me is whether this ‘plastic stuff’ will have sufficiently long lifetime in outdoor applications to be actually useful. Although we have been able to make plastic solar cells less sensitive to oxygen or water vapour, they do need barrier films as protective layers. Thanks to the already achieved reduction in sensitivity of the solar cells, inexpensive barrier films such as those used for food packaging can be applied. By depositing, for example, a very thin layer of titanium oxide (a very common material), overall sensitivity of the cells to oxygen or water vapour has been reduced by a factor of 100. We hope that this reduction in sensitivity to oxygen and water will be sufficient to yield the long lifetimes that are required.

Progress on the lifetime issues continues to be promising. The efficiency of plastic solar modules that were on the rooftop for testing over a year (see Fig. 6 a) did not decrease; in fact a slight increase was recorded. In the course of November, the efficiency started to fall and people got a little worried. However, it turned out that the temperature coefficient of the efficiency is opposite to that of silicon. When winter came, the efficiency decreased slightly, but it came up again in spring (Hauch *et al.*, 2008). This different temperature coefficient of the efficiency is an advantage, since solar cells increase in temperature when sitting in the heat of the sun. The initial data provide evidence that the lifetime of our solar cells may be sufficient for large-scale applications. Of course, accelerated lifetime testing must continue to provide information on the longer time degradation.

Clearly, plastic solar cells have a very promising future as they are lightweight, portable, and can be produced quickly in large quantities. In addition, their flexibility makes plastic solar cells useful not only for standard areas such as rooftops (see Fig. 6 b), but also for a vast number of new applications such as tent and umbrella surfaces, backpacks, or sails. In terms of efficiency of plastic solar cells, improvement efforts have produced some impressive figures of merit. If you evaluate plastic and standard solar cells in terms of watts per gram, plastic solar cells are already more than competitive.

Our goal is to achieve a roll-to-roll manufacturing of low-cost plastic solar cells. With such a production, plastic solar cells could become a very important contribution on our path towards a renewable energy system.

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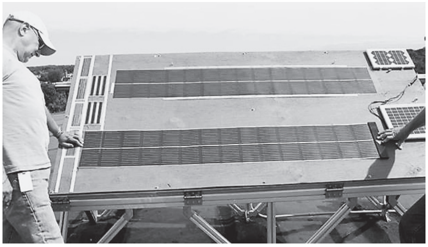

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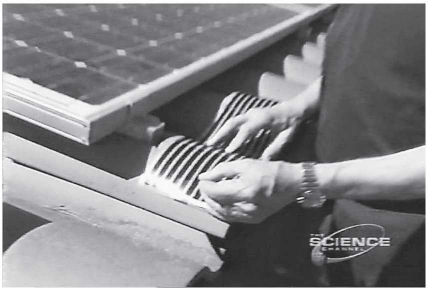

Fig. 6. a) Plastic solar cell testing in progress on the rooftop of Konarka Technologies, and b) the author on his own rooftop placing a plastic solar cell next to a conventional silicon solar cell. Although silicon solar cells work well, they have the disadvantage of being heavy and expensive. In contrast, plastic solar cells are lightweight, flexible and potentially produced at very low costs. Building them directly into the roofing tiles is an exciting opportunity. **(***Sources:* a) Konarka Technologies, Inc., b) Discovery Channel science)

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