Nanotechnology and the potential for a renewable solar future

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Energy is a basic requirement for people in the modern world. Sadly, it is only going to become more expensive in the future as the world population increases and oil becomes harder to find. A renewable energy future is essential to mitigate both the rising cost of oil and the damage wrought by carbon dioxide to the Earth and its climate. Solar energy is a highly promising technology capable of supplying a large amount of our total energy needs with very few downsides. Solar cells use nanoscale architecture either as the morphology for the active component or by using nanoscale thin film architecture (or both). At present the majority of commercial solar cells are based on silicon technology. They are rigid panels that use complex and expensive processing methods to manufacture. Adopting new manufacturing methods based on nanoscale self-assembly could launch solar cells into one of the dominant energy-producing technologies over the next few years. In this article I discuss the possibility of mass-produced solar cells based on organic polymer solar cell materials and their potential to made at a fraction of the existing manufacturing costs and in much higher volume.

Introduction

There is a huge drive all around the globe for scientists and industrialists to find new ways of producing abundant clean renewable energy. The spike in the oil price has made many people realize that this vital commodity is becoming harder to extract from the ground and will only ever get more expensive. The effects of pumping carbon dioxide into the atmosphere are—whether people believe it or not (the evidence is convincing enough)—environmentally detrimental, increasing the average global temperature. There are very few examples of rapid paradigm shifts in energy use and in general the transitions tend to be gradual; however, to avoid reaching a climate tipping point by raising global average temperature further we now need to switch to new clean energy sources rapidly. Delay could have dangerous climate implications and, in turn, serious social impacts due to unstable weather patterns giving rise to food and water shortages. In short, we need to change the economy from being fossil fuel-based

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to renewable energy-based; it will take a lot of political impetus to do this. Encouragingly, though, governments are now ramping up investment in energy, and energy security is high on the political agenda, the ultimate goal being energy sustainability. Technology and innovation are going to be crucial in meeting the challenge. By 2050 the amount of energy we currently use is projected to double: the world's population will have increased to over 9 billion (9×10^9); most of those living in the currently low-income nations will have by then many of the electrical conveniences seen as essential to modern living.

The gift of sunlight

We desperately need to find ways to provide energy sustainably, and one of the main ways to do this could be by harnessing the power of the Sun. In a day we get enough sunlight to provide the human race with all of the energy we use in a year. If we could harness this we'd be self-sufficient and no longer need to go looking for oil and gas in extreme and costly environments like the Arctic or build expensive and controversial nuclear plants that the public are increasingly distrustful of especially in the wake of the Fukushima reactor crisis. The yellow square in Figure 1 shows the land area needed for solar panels that would be required to meet the total energy needs of the entire population of the USA, which is roughly 500 million people using 250 kWh/day. The calculation assumes 10% efficient solar energy conversion into electricity. This same area of land (at a latitude of 30° north of the Equator) would provide enough power for a thousand million Europeans (whose average energy consumption is roughly half that of North Americans). It is possible to envisage numerous ways in which the land area could be selected for this endeavour. In the past, the US government has requisitioned areas of desert for military training (during World War 2) and still holds large banks of such land through federal management vehicles or as national parks. The question of energy independence and sustainability would have to compete with the biodiversity concerns of these desert environments. Discussions about the problems already exist: the US Bureau of Land Management has already allowed the building of some large-scale solar farms and the necessary power transmission lines. It would not be sensible, though, to use a single site alone, which would concentrate the risk of a natural disaster affecting a particular nation's total energy supply. Multiple sites would also better serve a dispersed population and fit it well with an integrated network of electricity distribution.

Solar cell production, costs and deployment

In order to fill such a large area with solar cells it will be necessary to increase their global production year on year. The current rate of production is rising fast, with a 10-year compound annual growth rate (CAGR) of 46% and a 5-year CAGR of 56% in 2008.[1] Total global production in 2008 reached nearly 7 GW and recent figures show that this trend is continuing, with the production of 18 GW in 2010.[2] At the same time as production is rising, the overall cost of producing solar cell modules is diminishing, from over \$20/W in the 1980s to a low of \$3/W

1 US Department of Energy, *Solar Technologies Market Report* (2008).
2 Solarbuzz, http://solarbuzz.com/facts-and-figures/market-facts/global-pv-market (last accessed 12th October 2011).

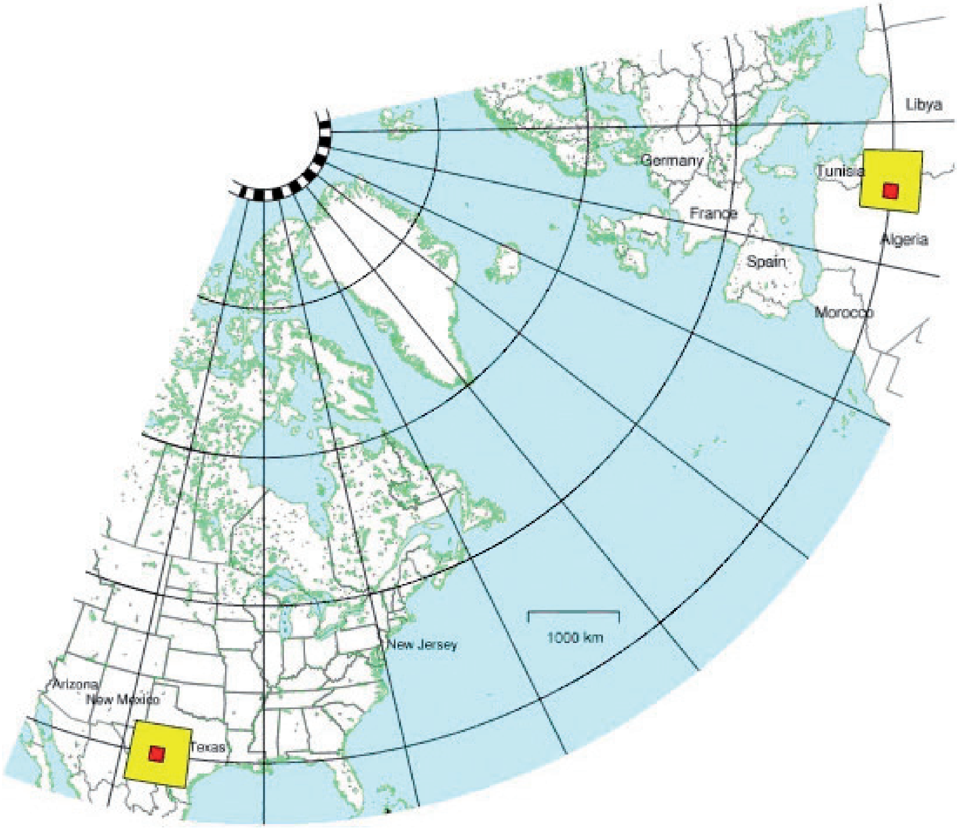

Figure 1. The yellow square 600 km by 600 km is the area required to provide 500 million people with the average American's power consumption of 250 kWh/day. This assumes a power density of 15 W per m^2; the average incident solar flux is 185 W/m^2. The red square is the area needed to provide sufficient energy for the United Kingdom. From D.J.C. Mackay, *Sustainable Energy—Without the Hot Air*. Cambridge: UIT (2009).

in 2003.[3, 4] This reduction in price has currently stalled due to high demand, which is itself a consequence of some of the governmental incentives used to stimulate uptake and adoption of solar cell technology.

One of the main difficulties with any new energy technology is its deployment in the real world. Analysis of the development of existing energy technologies has shown some strong patterns (the laws of energy technology deployment), which most new energy sources follow as they go from an initial exponential growth period through to linear growth, after the energy source has typically become ~1% of the world's energy supply, a point termed materiality. Materiality essentially marks the point at which an energy source is capable of being produced

[3] P. Mints and D. Tomlinson, *Photovoltaic Manufacturer Shipments 2005/2006* (Report #NPS–Supply1). Palo Alto, California: Navigant Consulting Photovoltaic Service Program (2006).

[4] P. Mints, *Photovoltaic Manufacturer Shipments, Capacity, & Competitive Analysis 2008/2009* (Report #NPS–Supply4). Palo Alto, California: Navigant Consulting Photovoltaic Service Program (2009).

as large scale infrastructure using proven technology and manufacturing. These empirical laws are displayed in Figure 2; they show initial rapid growth prior to materiality, after which follows a much slower growth rate. According to these predictions fossil fuels will still account for two thirds of the world's energy supply in 2050, with the obvious and dangerous implication for global warming of the resulting high atmospheric CO_2 concentration. One unchanging feature of fairly recent past energy development eras was the abundance of cheap oil; which may now, as oil becomes ever more expensive, increase the economic argument for accelerating the uptake of solar technology. At the present epoch conventional silicon solar cells are suitably robust and efficient enough for deployment, however they are still too expensive and difficult to produce on a suitably large scale. To overcome these problems new photovoltaic technologies must be able to compete on cost and be able to be produced at scale.

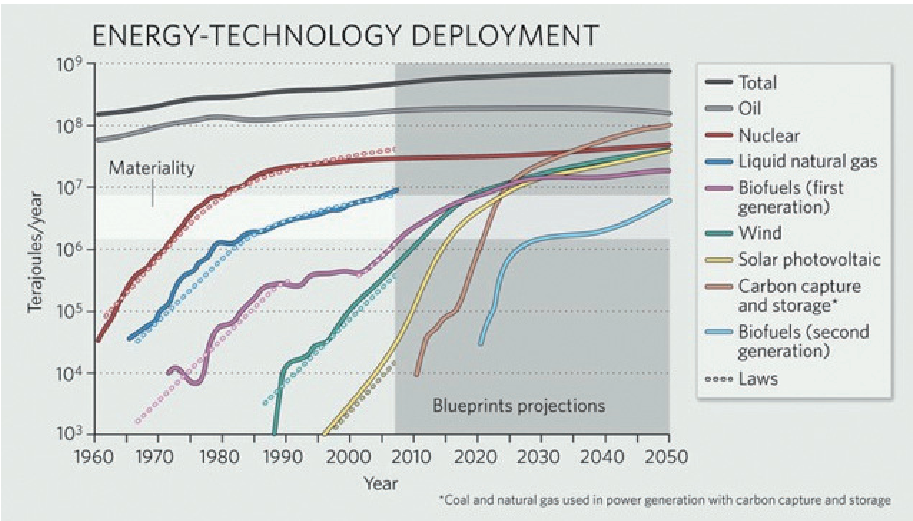

Figure 2. Global production of primary energy sources. When a technology produces 1,000 terajoules a year (equivalent to 500 barrels of oil a day), the technology is deemed to be "available". It can take 30 years to reach "materiality" (1% of the total world energy mix). The graph shows that there are remarkable similarities in the growth and development of any new energy source.[5]

Solar cell efficiency and structure

The wealth of data in Figure 3 can be confusing but is worthy of study as it tracks the efficiencies for numerous photovoltaic technologies and plots the change in efficiency as a function of time. The main take-home message is that a lot of photovoltaic technologies have flatlined or shown very little increase in efficiency in the last ten years of development, with silicon stuck at ~20–28%. Of the two that continue to improve one is the high-end ultraefficient multijunction concentrator whilst the other is organic photovoltaic technology. The former has achieved efficiencies of nearly 43% whilst the latter is around 8%.

[5] G.J. Kramer and M. Haigh, No quick switch to low-carbon energy. *Nature* **462** (2009) 268–269.

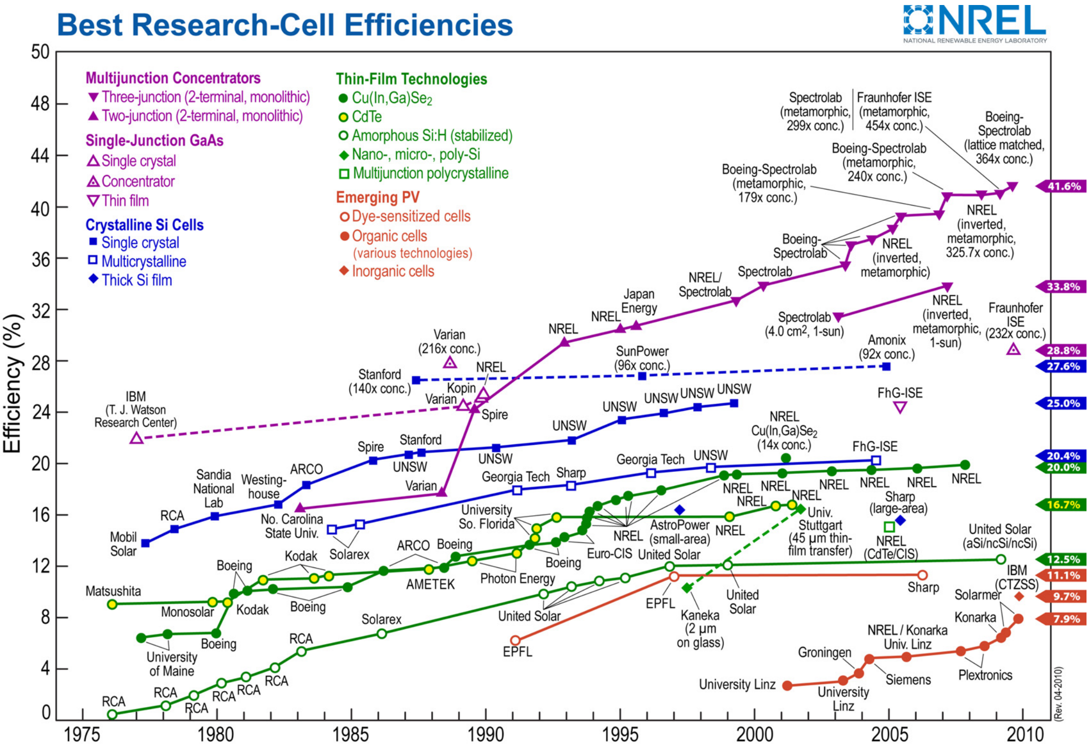

Figure 3. Best research-cell efficiencies for the multitude of different solar cell technologies. Data compiled by Lawrence Kazmerski, National Renewable Energy Laboratory (NREL), Golden, Colorado.

What is the input of nanotechnology into solar technology? Solar cell devices are conventionally made up of a number of layers with a light-absorbing layer sandwiched between two electrode contacts. The solar cells are made of thin films nanometres thick; the interfaces with the contacts themselves are of the order of nanometres. Studying the interfaces between neighbouring layers is important in improving the efficiency and operation of the devices. Solar cells often have nanoscale structure crucial to their performance and, for scientists, studying these buried layered structures is challenging experimentally. Nanoparticle additives can be used to enhance the absorption of light, also surfaces or interfaces can be textured to reduce or enhance reflexion at particular locations within the solar cell.

Self-assembly-guided manufacture of nanoscale structures

One of the main fundamental ways that nanotechnology will really advance the cause of solar cells will be in their manufacture. Currently the inorganic silicon solar cells require expensive fabrication techniques, in which layers of materials are deposited under high vacuum conditions. Inorganic devices tend to be made from silicon, either as a single crystal or in amorphous form; one of the main drawbacks is the energy cost associated with purifying and processing the silicon (Si) into the high quality material necessary for the operation of a solar cell, especially if single-crystalline material is used. The advent of amorphous silicon has, however, allowed much thinner layers of silicon to be used in photovoltaic (PV) devices as the amorphous material is more efficient at absorbing light than single crystal silicon. If the amorphous Si-based cells could be made in a much more continuous process than at present, production costs would drop significantly. This is where the use of self-assembly will really help in solar cell manufacture. Self-assembly is a common process in nature, as illustrated by the way proteins spontaneously develop higher-order structure starting from a linear chain of amino acids or DNA twists into the well known double helix for the storage of genetic information. Self-assembly is achieved by having interactions that preferentially induce a desired orientation, enrichment, degree of order or length scale, or all of these things. If we can design or develop with minimal effort systems that produce nanoscale structures suitable for the harvesting of sunlight into electricity then the total costs of harvest will be massively reduced.

An alternative approach with reduced costs compared to silicon technology is the copper indium gallium diselenide (CIGS) system. Cell layers made from this material can now be deposited via a less complicated ink route that does not require ultrahigh vacuum conditions to create the layer. It has been commercialized by the company *Nanosolar* using a proprietary approach that was able to produce over 115 MW of 11%-efficient panels in 2011.

Plastic or polymer solar cell films can be deposited from solution by low-cost, roll-to-roll printing techniques, resulting in significant overall savings in fabrication energy and time. Importantly, they do not require the use of high-vacuum technology to deposit layer upon layer in the way that most inorganic approaches do (i.e., classical semiconductor processing[6]). Roll-to-roll manufacture is where a substrate film is put on a roll and goes through a series of processes similar to the way newspapers are printed and taken off a roll at the end. Figure 4 shows a laboratory-scale pilot plant capable of making organic solar cells using the roll-to-roll approach, in which all the processing and manufacturing steps are performed one after another and the finished solar cell is taken off on a roll at the end of the process.

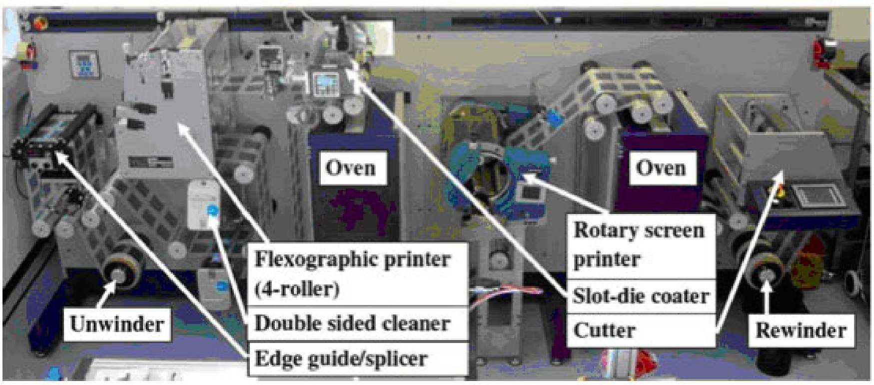

Figure 4. Roll-to-roll printing of organic polymer cells, showing that all the processing is carried out in a continuous, linear sequence.[7]

[6] A.G. Mamalis, A. Markopoulos and D.E. Manolakos, Micro and nanoprocessing techniques and applications. *Nanotechnol. Perceptions* **1** (2005) 31–52.

[7] F.C. Krebs, J. Fyenbo and M. Jørgensen, Product integration of compact roll-to-roll processed polymer solar cell modules: methods and manufacture using flexographic printing, slot-die coating and rotary screen printing. *Journal of Materials Chemistry* **20** (2010) 8994–9001.

There are currently commercial companies using this type of technology, such as *Konarka*, which currently holds the record for an organic polymer solar cell at 8.3% efficiency—nor are the polymer solar cells the author and his team are making at the moment anywhere near 100% efficient, but to get round this problem we just need to produce larger areas—and that's one of the advantages in favour of polymer solar cells as the processing for such a cell is minimal. To increase usage further, however, the technology needs to be made more efficient. Polymer solar cells are currently 7–9% efficient under laboratory conditions but actual devices in the field would need to be stable and maintain these or even higher overall efficiency values for long intervals. If it is possible to make a polymer solar cell in the same manner as cling film and other commodity plastic sheets are made, they could be produced on a very large scale and instead of producing a few square km a year one could feasibly produce the hundreds of square km required to fill the yellow square shown earlier, in Figure 1. There are problems when comparing the costs per watt of polymer solar cells and established silicon photovoltaic modules. Primarily this is because there is not just one established manufacturing route for polymer solar cells. However some cost comparisons show that for a 10% efficiency polymer solar cell the cost per watt could be a third that of a conventional silicon solar cell, 0.8 cents per watt versus 2.3 cents per watt.[8] The life cycle of a polymer solar cell should be at least ten years and the energy payback time (EPBT, the time to recoup the energy used in manufacture in years) should be as short as is possible. Silicon PV cells have EPBT values from 1–4 years and polymer solar cells have half a year up to two years, depending on the manufacturing process.

A particularly attractive future method of making polymer solar cells based on a continuous process is for there to be minimal input from the manufacturing process itself. In some of my own recent work we examined the structure and vertical profile of an organic solar cell layer made of two components (a polymer and the C_{60} form of carbon commonly called buckminsterfullerene) dissolved in a solvent. These are mixed together and spread onto a glass substrate already coated with a transparent conducting electrode composed of indium tin oxide. As the solvent evaporates away the two principal components nanostructure themselves into a structure useful as a working solar cell.[9] Also, one material is enriched at the surface and the other partly segregates at the bottom interface, which creates a gradient for the efficient collection of electric charge—the polymer is at the anode and the C_{60} is at the cathode interface. The structuring is intrinsic to the drying process and not externally imposed by the manufacturing, and that's given our best devices—without any need for post-processing. A process where you just apply a solution of two materials to a substrate and let it dry to produce a nanoscale interpenetrating network could become an ideal mass-manufacturing process. It involves very little manufacturing input into actually making a working solar cell. The scope for input from the nanoscientist is in the design and optimization of the precursor components to yield the material structure and morphology to maximize the collection of light and extraction of charges to the cell electrodes.

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[8] N. Espinosa, M. Hösel, D. Angmo and F.C. Krebs, Solar cells with one day payback for the factories of the future. *Energy and Environmental Science* **5** (2012) 5117–5132.

[9] P.A. Staniec, A.J. Parnell, A.D.F. Dunbar, H. Yi, A.J. Pearson, T. Wang, P.E. Hopkinson, C. Kinane, R.M. Dalgliesh, A.M. Donald, A.J. Ryan, A. Iraqi, R.A.L. Jones and D.G. Lidzey, The nanoscale morphology of a PCDTBT:PCBM photovoltaic blend. *Advanced Energy Materials* **1** (2011) 499–504.

Work is ongoing to improve organic solar cell devices so that they collect more light, as some of the polymers currently in use don't absorb the entire solar spectrum. We're also looking at the fundamental mechanisms of how the sunlight entering the solar cell creates an excited molecular state that is then transformed into a positive and a negative electric charge—we need to improve the collection of these charges. *These are the two key things*: absorbing more sunlight from the solar spectrum more efficiently; and collecting the charges created in the device more efficiently. There is a roadmap[10] for solar cells as there is for most new technologies, and 10% efficiency is seen as commercially viable in terms of manufacturing polymer solar cells. We're not that far away, given that polymer solar cells are still in their infancy compared to other solar cell types (Figure 3). The first devices made 10 years ago were basically a sandwich; one layer of material at the bottom and another on top, with an interface between the two where sunlight causes the creation of excited states, which are then transferred into separate positive and negative charges. In these early devices the amount of interface was very low and consequently the efficiency was only about 0.15%; currently we're not too far from 10% and there are all sorts of ways in which we can collect more light using better optics or concentrate the light onto the cells, which could also improve their efficiency. It's an interesting time because there are so many people working on polymer solar cells. Scientists are coming into this field with completely new ways of thinking, and it may not be that far in the future when large areas of these cheap solar cells will be deployed in the right places, the obvious ones being those with no existing land usage like crops. That way they won't compete with the other aspects of our population needs, like feeding people. That can be a problem for other technologies like bio-ethanol—the competing need to feed the population—and deserts seem the obvious place to site large scale solar "farms". They also tend to have cloud-free skies! If in the next 10 years we can get from 0.15% to over 8%, large scale deployment seems inevitable. Mass-producing optimized organic photovoltaic solar cells based on the bulk heterojunction approach[11] will nevertheless require a deeper understanding of the effects of processing on the overall device nanomorphology.

Conclusions

History has shown that it is not always the most technologically elegant solution that wins out, a relatively recent example being the battle between the high quality Betamax and the lower quality VHS video formats; lower economic costs made VHS the winner. In the competition between the present multitude of solar technologies competing for mass adoption, and whether silicon, dye-sensitized or polymer solar cells ultimately become the most widely adopted, it will all ultimately depend on the overall cost including those of the raw materials, manufacture, installation and decommissioning.

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[10] OPV's with efficiencies of ~10% *"OE–A Roadmap for Organic and Printed Electronics"*, 3rd edn (2009). Available at: http://www.vdma.org/wps/portal/Home/en/Branchen/O/OEA/Projects_and_Initiatives/OEA_Projects_StK_20110706_Brochure2011?WCM_GLOBAL_CONTEXT=/vdma/Home/en/Branchen/O/OEA/Projects_and_Initiatives/OEA_Projects_StK_20110706_Brochure2011

[11] G. Dennler, M.C. Scharber and C.J. Brabec, Polymer-fullerene bulk-heterojunction solar cells. *Advanced Materials* **21** (2009) 1323–1338.