

## The Vision for Polymer Solar Cells is Power Production at Low Cost

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Polymer solar cell (PSC) design requires the implementation of high performance, high reliability, and low-cost equipment. PSCs accomplish the function exactly as another kind of solar cell and as such enter the well-charted commercial realm, with numerous types of solar cells and many potential applications. "Today's world of portable electronics is power-hungry, so existing portable solar cells cannot power a cell phone, music player, or laptop – it is just a back-up or trickle-up power supply, and does not provide 'on-the-go' power, as many would like it to. In fact, being a portable solar cell does not really mean that it can charge the batteries in your gadget while you are on your way to work, as it would take a full day or more of the direct sun onto the solar cell. The vision of PSCs is a low-cost power generation. At present, the role of PSCs lies between the ongoing development of technology and the initial market introduction, and, as a result, sustainable power generation is far from within reach". New applications can be developed as the technology emerges, and new market segments can be added. There are several challenges for this industry, including lower production costs, public awareness and the best infrastructure. Solar energy is a necessity of the day and solar cell research has a promising future all over the world.

**Keywords:** Polymer solar cell, Spin-coating, Organic photovoltaic, Nanoparticles, Batteries.

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### 1. INTRODUCTION

Over the past decades, the use of sustainable energy sources, such as solar energy, has gained tremendous interest due to the increasing demand for energy worldwide. Solar cells which can turn energy from the sun into electricity have produced industry and made large-scale applications, particularly for silicon-based solar cells. Certain forms of solar cells have also emerged at the same time, with thin-film photovoltaic cells being a major hub in recent years. Polymer solar cells (PSCs) were studied among them, largely due to their huge advantages of a lightweight, low-cost, ease of manufacture and mechanical flexibility [1, 2].

In the 21<sup>st</sup> century, the development of emerging sustainable energy as a substitution for conventional fossil energy is highly desirable. The organic photovoltaic (OPV) cells are made of lightweight, versatile and renewable light-harvesting organic/polymer materials as a potential option that can provide an economically viable and environmentally friendly source of energy by simple coating technique and solution printing method. Fig. 1 shows that in a traditional OPV cell, two electrodes, i.e. normally ITO and metal modified with buffer layers, sandwich the light-harvesting layer in which donor and acceptor materials are combined at the molecular level to form bulk heterojunction (BHJ) [3-5]. Solution processing methods, low-cost, low energy budget, and scalable solar cells are terminology linked to organic solar cells and the driving force behind PSC research has been the enormous potential of the material for the high-performance production of low-cost solar cells over many decades. The development started with small area cells that used simple and relatively inexpensive manufacturing techniques such as spin coating, sputtering technique and thermal evaporation [6].

Through a schematic point of view, organic solar

cells turn the incident solar radiation into electrical current, basically by a four-step cycle as seen in Fig. 2. In this view, the donor is called the holes carrying material, making contact with the anode, while the acceptor is the electrons carrying material, which is in contact with the cathode.

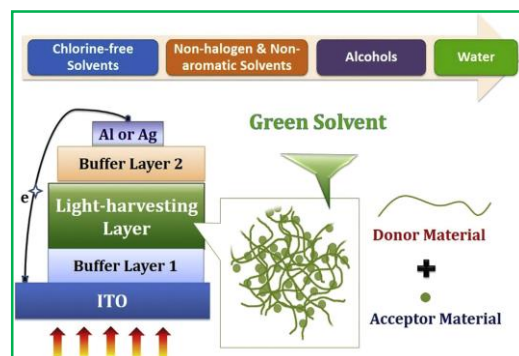
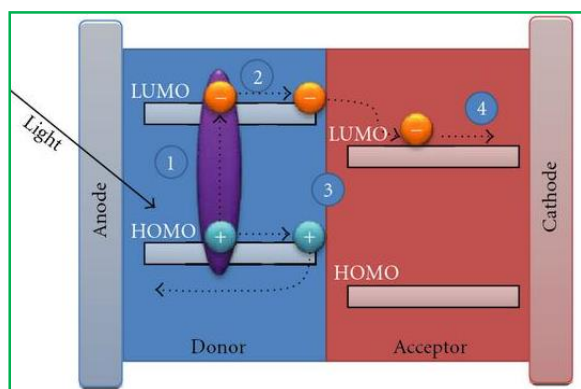


Fig. 1 – Schematic diagram of green-solvent-processable OPV cells and four types of green solvents [6]

The initial step is the creation of an exciton after a photon is absorbed. The exciton diffuses into the material to reach the donor-acceptor interface where it will be separated. All four of these measures represent possible targets for researchers to increase OPV's performance. The efficiency of absorption, i.e. how much light is absorbed, primarily depends on the organic materials absorption spectrum. However, in collecting as much as incident wavelengths, the architecture of the devices, including their size, does not play a minor role. The exciton's diffusion duration is the element that accounts for second step efficiency. As a result, longer diffusion duration leads to a greater likelihood of the exciton entering the D/A interface, thereby increasing the efficiency of the electron-holes. It is also very evident that the

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D/A boundary morphology is very significant. In fact, the acceptor will have to be very close to the donor, so that the D/A interface is still after the point where the exciton is created. Yes, the third step is the exciton split-up into free charges, and this step relies largely on the donor and acceptor properties, in addition to the fact that overall computer design plays a significant role. The final step, which is the transportation of the free charges through the sample and their accumulation at the electrodes, is the final step and can be considered as fundamental in an OPV device [7-10].



**Fig. 2** – An operative sequence of organic photovoltaic cell scheme

For all the potential, they have shown in the lab, PSCs still need to "get on a roll" like the ones used in printing newspapers so that large sheets of acceptably efficient photovoltaic devices can be produced continuously and economically. PSCs provide various advantages over their conventional silicon-based counterparts, including lower prices, probably lower carbon footprints and a more extended range of applications [11, 12].

Recent research results published by an international team headed by the national institute of standards and technology (NIST) suggest that the "sweet spot" for mass-producing PSCs – a tantalizing possibility for decades – may be much greater than conventional wisdom dictates. The researchers developed polymer-based solar cells with a "power conversion efficiency of more than 9.5 percent in experiments using a high-volume, roll-to-roll processing system, just shy of the required commercial target of 10 percent. That is almost as effective as the spin-coating devices made in the laboratory, a process that produces high-quality films in the laboratory but is economically inefficient because it loses up to 90 percent of the original ink [13].

PSCs have unique features such as lightweight, slim layout, brittle strength and excellent adaptability of scale, shape, and curvature to the actual application. Such techniques are available not only for cost-effective and energy-efficient use of cells but also for aesthetic solutions. As the PSC is manufactured in a roll-to-roll process, the potential for achieving low production costs at high production volumes is significant. The ability for low-cost manufacturing applies not only to the solar cell itself but also to solar cells being further transformed into more refined products. Such refined products could be "self-powered electronic devices" designed for easy incorporation into the production of consumer

or solar-powered end-user goods [14].

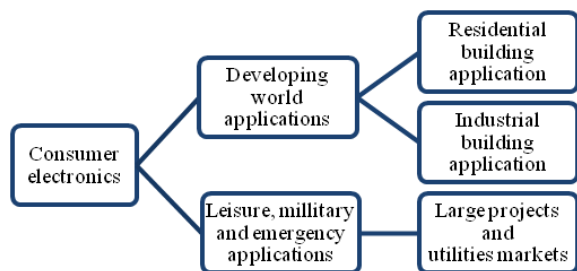
### Polymer solar cells

Frederik Krebs and Torben Damgaard Nielsen from Risø-DTU, Denmark, made a significant contribution to this example. PSCs based primarily on polymers and nanoparticles can be used in a wide range of applications – small electronic devices, off-grid community power generation, or power plant generation – where technology development assists. Building the integration of photovoltaic cells (BIPV) is one of the fields of most importance for use. From an architectural point of view, a great interest is the PSCs because they are very inexpensive, manufactured in materials that are environmentally friendly, thin, light and highly flexible. Compared to traditional silicon-based solar cells, this opens up many more building applications due to the possibility of adapting or integrating solar cells to most forms and materials, e.g. in facades, windows, curtains and roofs, and all of the structures could become solar energy reservoirs.

Plastic solar cells or PSCs are essentially structures consisting of semi-conductive organic compounds. These are similar in function to solar cells based on silicon but they are distinct in material. Although substantial attention has been paid in recent years to PSCs, the technology is still at the research level and, thus, is not available commercially. The PSCs have advanced dramatically in recent years as a promising energy technology for the future and small-area energy conversion efficiencies of up to 6.5 percent (1-10 mm<sup>2</sup>) have been registered. Unfortunately, for the long lifetimes required for commercial maturity, those values have not yet been sustained [15, 16].

Even though PSCs were not available in marketable forms until 2009 when the first low-performance polymer solar panels were introduced by Konarka Technologies [17], various design concepts were developed and some of them were tested. In contrast, PSCs can be used as an add-on or addition in consumer electronics, developed world uses, recreational, military and emergency, residential and industrial construction and eventually large-scale use as shown in Fig. 3.

The fulfillment of the list of application areas is by current advances in power conversion efficiencies (PCEs) "cost and lifespan and, as such, suggests that the first demand for PSCs will be considered to be a power source for small-scale electronic devices, i.e. battery chargers. Compared to existing types of solar cells, flexible solar cells create several application choices because they are potentially inexpensive, versatile, lightweight, semi-transparent, color-variable, and ecologically friendly and provide portable solar energy. In many situations, these technically specific factors represent both market opportunities and risks. Portable solar energy has been a dream since the discovery of solar energy and, admittedly, it has interesting possibilities if the solar cell is economical enough and if the PCE matches the portable application-which is a key point. External limiting factors are the requirements for energy and energy storage, i.e. the available application and battery capacity coupled with the PCE of the solar cell" [18].

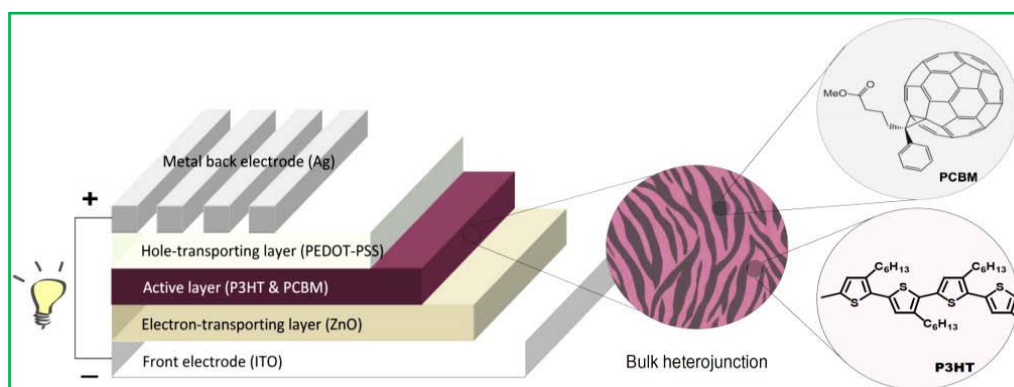


**Fig. 3** – Performance-cost enhancement enables access to new market segments [17]

## 2. THE PROCESS ONE SOLAR CELL

The Process One polymer solar cell is a structure composed of five layers of individual functionality: a transparent front sun-facing electrode, an electron-carrying surface, a photoactive plate, a hole-carrying layer, and finally a metallic back electrode (see Fig. 4). The “heart” of the process one solar cell is the active layer in which the sunlight is absorbed and converted into an electrical current. The active layer is a familiar combination of an electron donor material and an electron acceptor material, the light-absorbing P3HT (poly(3-hexylthiophene) and PCBM (phenyl-C61-butyric acid methyl ester), respectively. The P3HT and PCBM are chosen because it is well researched and serves as a standard blend for any work within PSCs.

“When light falls on the active layer blend, electrons in the light-absorbing donor material P3HT will be photoexcited leaving behind positively charged holes. If the electrons are not physically removed from the site of excitations, they will sooner or later recombine with their counterpart, the positively charged hole. However, as the active layer is an intimate blend, the regions of the P3HT donor – and the PCBM acceptor material are separated only by some nanometers, the charge carrier can thus readily diffuse from the point of excitation to the boundary between the donor – and the acceptor material where charge separation takes place. The blend forms a three-dimensional junction between the donor and acceptor materials, a so-called bulk heterojunction, which is the equivalent of the silicon solar cell’s planar  $p-n$  junction. The interfacial area of the bulk heterojunction is, however, orders of magnitude larger than the planar heterojunction” [19].



**Fig. 4** – The multilayer Process One solar cell comprises the following layers: a transparent front electrode, an electron-transporting layer, an active layer, a hole-transporting layer, and a metal back electrode. The heart of the solar cells is the active layer which is an intimate mixture of an electron donor (P3HT) and an electron acceptor (PCBM) forming bulk heterojunction

## Indium Tin Oxide-Free Flexible PSCs

We should concentrate our efforts on alternative, conductive electrodes to grow ITO-free PSCs. The subsequent topic is performed using various materials for electrodes, including carbon nanotubes, graphene, metal nanowires and nanogrids, conductive polymer, and some other translucent electrodes. The efficiency of the flexible PSCs is accordingly summarized.

In the future, it will be a research trend that is compatible with industrial production, large-scale equipment, and roll-to-roll manufacturing processes, and some groups have already conducted relevant research. Recently, tandem architecture has recorded flexible PSCs with a device area of more than  $10\text{ cm}^2$  and high PCE of 6.5 percent has been obtained [20]. It was also reported that the roll-to-roll process was used to fabricate solar cells for better performance of the devices [21]. The innovative idea, “waterborne PSCs” is being developed and is predicted to become a global major hub in the coming future [22]. Recently, compact and waterproof organic photovoltaics were reported with high efficiency of 7.9 percent, contributing to a further phase in the development of portable solar cells [23]. There are many opportunities for the development of ITO-free flexible PSCs; we agree that the above transparent conductive electrodes will take place step by step from ITO bringing flexible PSCs closer to the practical implementation of large scale.

## 3. RECENT DEVELOPMENTS

PSCs are developing rapidly as new renewable energy sources are required. PSCs are desirable because they can be manufactured using a range of printing methods on plastic substrates. The recent developments in PSCs have increased power conversion efficiency from 3 % to almost 9 %. Such solar cells are produced using solution-processing techniques based on semiconducting polymers and have particular prospects for relatively inexpensive solar energy production due to their content and manufacturing benefits [24].

### 3.1 A Polymer Solar Cell Device Architecture

A traditional PSC is a glass substratum coated with an indium tin oxide (ITO) film that acts as the anode as

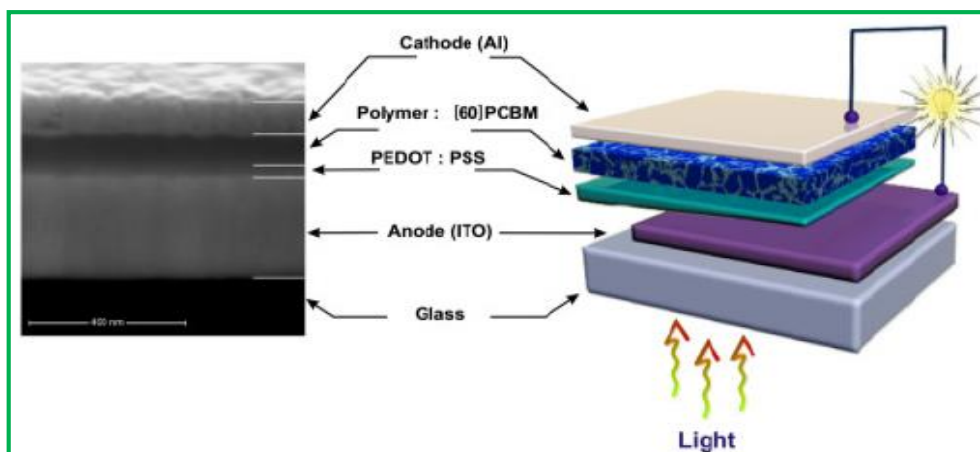


Fig. 5 – Architecture of a PSC [26]

Table 1 – A summary of the recent developments in PSCs [16]

№	PCE (%)	$V_{oc}$ (V)	FF (%)	$J_{sc}$ (mA/cm <sup>2</sup> )	Active materials
1	2.18	~ 0.6	~ 50	~ 7	Hyperbranched CdSe nanoparticle:P3HT
2	2.8	0.76	40	9.1	OC <sub>1</sub> C <sub>10</sub> -PPV:CdSe tetrapods
3	4.76	0.58	65.4	12.5	PTB1:PCBM
4	~ 5	~ 0.6	~ 60	~ 11	P3HT:PCBM
5	5.2	0.62	55	16.2	PCPDTBT:PCBM
6	5.3	0.56	63.3	15	PTB1:P <sub>71</sub> CBM
7	5.4	0.9	50.7	9.5	PSiF-DBT:PCBM
8	6	0.88	66	10.6	PCDTBT:PC <sub>70</sub> BM/TiO <sub>x</sub>
9	6.5	1.24	67	7.8	PCPDTBT:PCBM/TiO <sub>x</sub> /PEDOT:PSS/P3HT:PCBM

shown in Fig. 5. Then ITO is covered by a hole transport layer of a thin film of poly(3, 4-ethylene-dioxythiophene) polystyrene sulfonate (PEDOT:PSS). The active layer is then deposited either by wet processing (doctor blading, spin-coating, ink-jet printing and screen printing) or by evaporation (usually with the small molecule).

At the end, cathode (Ca and/or Al) is chosen to suit the acceptor energy levels (fullerene derivative). Let us recap once again the operational mechanism: the absorption of a photon by the active layer and the formation of an exciton (hole-electron bound by Colombian force), the separation of the exciton in electron (electron polaron) and hole (hole polaron), and the transition of charges through the phases of the active layer to the cathode and anode by the acceptor and donor.

In this respect, to improve the efficiency of solar cells, the bicontinuous interpenetrating network morphology required optimization. Therefore, multiple characterization techniques must be used to test the film morphology. In the next section, we will discuss the key characterization techniques used to evaluate the active composite layer and what kind of information we can obtain from such experiments [25].

The new developments taking place in the field of “PSCs as the potential competitor to the traditional silicon-based solar cells in the past decades. The most promising PSCs are based primarily on the structure of the BHJ, which comprises a bicontinuous nanoscale interpenetrating network of a conjugated polymer and a fullerene blend. The PCEs of BHJ PSCs have now exceeded 11 %. In this review, we present an overview of recent emerging developments of narrow bandgap

conjugated polymers for PSCs. We concentrate on a few essential acceptors that are used for highly efficient PSCs in the donor-acceptor form of conjugated polymers. We have also reviewed the emerged donor- $\pi$ -acceptor (D- $\pi$ -A) side chains polymers”. This describes the band gaps and energy levels as well as the efficiency of conjugated polymers in photovoltaics [27].

Production is very easy in PSCs. The PCE of 6 % from single active layer PSCs was reported recently. The best performances of PSCs are summarized in Table 1. Among others, polymer-fullerene solar cells show substantial high performance [28].

#### 4. CONCLUSIONS AND OUTLOOK

This paper reviewed the recent development of PSCs and discussed possible routes for improvement in their efficiency.

We began by applying basic operating principles and materials to PSCs. Organic solar cells make good promises when developing low-cost photovoltaic alternatives. Formal and systematic research is needed in the field in order to make successful use of the expected benefits of organic solar cells. Most scientists believe there is the best way to achieve greater absorption and higher open-circuit voltage, as well as a better charge transfer environment. For the optimization of solar cell efficiency, a controllable interpenetration network in the films is also necessary. High performance and high stability of PSCs can also be accomplished through the construction of new structures to improve the absorption and controllable local order of materials.

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## Перспективи полімерних сонячних елементів – це виробництво енергії за низькою вартістю

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Конструкція полімерних сонячних елементів (PSCs) вимагає високої продуктивності, високої надійності та недорогого обладнання. PSCs виконують свою функцію так само, як і інший вид сонячних елементів, і входять у загальновизнану комерційну сферу з численними типами сонячних елементів та багатьма потенційними застосуваннями. «Сьогоднішній світ портативної електроніки енергодефіцитний, тому існуючі портативні сонячні елементи не можуть живити мобільний телефон, музичний плеєр або ноутбук – це лише резервне джерело живлення, і воно не забезпечує необхідну потужність в реальному часі як багато хто хотів би. Насправді, портативний сонячний елемент не означає, що він може заряджати батарею у вашому гаджеті, поки ви їдете на роботу, оскільки це займе цілий день або більше прямої дії сонця на сонячну батарею. Перспективи PSCs – це дороге виробництво електроенергії. В даний час роль PSCs лежить між постійним розвитком технологій та початковим введенням на ринок, і, як результат, стійка генерація енергії є по-за межами досяжності». З появою технологій можна розробляти нові додатки та додавати нові сегменти ринку. Перед цією галуззю стоїть кілька проблем, серед яких нижчі виробничі витрати, обізнаність громадськості та найкраща інфраструктура. Сонячна енергія – це необхідність дня, і дослідження сонячних елементів мають перспективне майбутнє у всьому світі.

**Ключові слова:** Полімерні сонячні елементи, Spin-coating, Органічні фотоелектричні елементи, Наночастинки, Батареї.