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Progress in Organic Photovoltaic Fibers Research

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1. Introduction

Energy management including production, distribution and usage of energy is an important issue, which determines internal and external policy and economical situation of countries. For generating electrical energy, use of traditional energy sources in particular fossil based fuels through long ages, caused environmental problems, in recent years. Renewable energy technologies using power of wind, sun, water, etc. can be remedies to hinder negative effects of pollution, emissions of carbon dioxide and irreversible climate change problem, which it caused. Photovoltaic technology, which converts photons of the sun into electrical energy by using semiconductors, is one of the most environmental friendly sources of renewable energy (Dennler et al., 2006a). Solar cells are used in many different fields such as in solar lambs and calculators, on roofs and windows of buildings, satellites and space craft, textile structures (fibers, fabrics and garments) and accessories (bags and suitcases).
In addition, there is an increasing interest in organic electronics from a wide range of science disciplines in which researchers search for novel, efficient and functional materials and structures. Organic materials based optoelectronic devices such as organic photovoltaics (organic solar cells), organic light emitting diodes and organic photo detectors (Curran et al., 2009) are desirable in many applications due to interesting features of organic materials such as cost advantage and flexibility. Production of electrical energy, which is necessary in both industrial and human daily life by converting sunlight using organic solar cells (organic photovoltaic technology) via easy and inexpensive techniques is also very interesting (Günes et al., 2007).
A photovoltaic textile, which is formed by combining a textile structure with a solar cell, and on which carries physical properties of textile and working principle of solar cell together, can generate electricity for powering different electrical devices. Photovoltaic fiber providing more compatibility to textiles in terms of flexibility and lightness owing to its thin and polymer-based structure may be used in a wide variety of applications such as tents, jackets, soldier uniforms and marine fabrics. This review is organized as follows: In the first section, an overview of photovoltaic technology, smart textiles and photovoltaic textiles will be presented. In the second section, a general introduction to organic solar cells and organic semi conductors, features, the working principle, manufacturing techniques, and characterization of organic solar cells as well as polymer based organic solar cells and studies about nanofibers and flexible solar cells will be given. In the third part, recent studies about photovoltaic fiber researches, production methods, and materials used and

application areas will be recounted. Finally, suggestions on future studies and the conclusions will be given.

1.1 Photovoltaic technology

"Photovoltaic" is a marriage of two words: "photo", which means light, and "voltaic", which means electricity. Electrical energy produced by solar cells is one of the most promising sustainable alternative energy and can provide energy demand of the world, in the future (Green, 2005). Today, silicon based solar cells having the highest power conversion efficiency are dominated in the market; however they have still high production costs. Electricity generation by solar cells is still more expensive than that of fossil fuels due to materials and manufacturing processes used in solar cells and installation costs. However, photovoltaic technology, compared to traditional energy production technologies, have interesting features such as using endless and abundant source of sun's energy, direct, environmental friendly and noiseless energy generation without the need of additional generators, customization according to requirements, having low maintenance costs and portable modules producing power ranging between milliwatt to megawatts even in remote areas, which make it unique (Dennler et al., 2006a). A photovoltaic system can convert sun light into electricity on both sunny and cloudy days (European PhotoVoltaic Industry Association (EPIA), 2009). The worldwide cumulative photovoltaic power installed reached about 23GW, in the beginning of 2010 and produces about 25TWh of electricity on a yearly basis (European PhotoVoltaic Industry Association (EPIA), 2010).

The electricity produced by solar cells can be utilized in many applications such as cooling, heating, lighting, charging of batteries and providing power for different electrical devices (Curran et al., 2009). Solar cells using silicon wafers are classified as first generation technology having high areal production costs and moderate efficiency. Thin-film solar cells using Amorphous silicon (a-Si), Cadmium telluride (CdTe) and Copper indium gallium (di)selenide (CIGS) as second generation technology have advantages such as increased size of the unit of manufacturing and reduction in material costs. However, this technology has modest efficiency beside these advantages compared to first generation technology. Therefore, third generation technology concept has been developed to eliminate disadvantages of earlier photovoltaic technologies (Green, 2005). There are two approaches in third generation photovoltaic technology. The first one aims to achieve very high efficiencies and second one tries to achieve cost per watt balance via moderate efficiency at low cost. Therefore, this uses inexpensive semiconductor materials and solutions at low temperature manufacturing processes. The third generation photovoltaics use various technologies and grouped under organic solar cells (Dennler et al., 2006a).

1.2 Smart textiles

Humankind has always been inspired to mimic intelligence of nature to create novel materials and structures with fascinating functions. Over the last decades, in industrial and daily life, paralleling to growth in world population and advancements in science and technology, human requirements have changed and begun to diverge from each other. Therefore, different functional products have emerged according to expectations and requirements of human kind. One of these, intelligent materials, can coordinate their characteristic behavior according to changes of external or internal stimulus (chemical, mechanical, thermal, magnetic, electrical and so on) as in biological systems and have different functions owing to their unique molecular structure (Mattila, 2006; Tani et al., 1998). Intelligent materials and structures can sense and react and more, adapt it and perform a function of changes (Takagi, 1990; Tao, 2001).Intelligent material systems consist of three parts: a sensor, a processor and an actuator. Intelligent materials can provide advancements in many fields of science for energy generation, medical treatments, and engineering applications and so on.

There are also many application areas for interactive textiles, which use intelligent materials such as shape memory alloys or polymers, phase change materials, conductive materials and etc. Intelligent textiles are defined as structures that are capable of sensing external and internal stimuli and respond or adapt to them in a pre-specified way. Knowledge from different scientific fields (biotechnology, microelectronics, nanotechnology and so on) is required for intelligent textile research (Mattila, 2006). Intelligent textiles find uses in many applications ranging from space to healthcare and entertainment.

Power supply by using discrete batteries is an important obstacle towards functionality of intelligent textiles. Besides, flexibility, comfort and durability are other parameters concerned to manufacture consistent products (Coyle & Diamond, 2010). Flexible solar cells (Schubert & Werner, 2006), micro fuel cells (Gunter et al., 2007; enfucell, 2011), power generation by body motion and body heat (Beeby, 2010; Starner, 1996) can be some alternatives to the traditional batteries. Photovoltaic fibers and textiles can overcome this power supply problem since they use the working principle of solar cells.

1.3 Photovoltaic textiles

Small electronic devices such as personal digital assistants, mobile phones, mp3 players, and notebook computers, usually use traditional batteries of which energy is used up in a short time. Integration of flexible solar cells into apparels and fabrics, which cells are positioned in/on the textile, can provide required electrical energy for these portable electronic devices (Schubert & Werner, 2006). Photovoltaic textiles can be formed by integrating solar cells into textile structure or making textile structure itself from photovoltaic materials. Photovoltaic textile research needs cooperation of different sciences consisting of textile, electronics, physics and chemistry. Incorporation of solar cells with fibers and textiles that are flexible can extend the applications of photovoltaics from military and space applications to lighting and providing power for consumer electronics of humankind in daily usage.

Textile based solar cells are also named as photovoltaic textiles, solar textiles, energy harvesting textiles, solar powered textiles in the literature. Photovoltaic textiles, which are high value added intelligent products, and, which have a large application area, can benefit textile industry by increasing its competitiveness with long term development.

Power conversion efficiency and price properties beside the flexibility, weight, comfort, durability and washability properties of the products are also important from a customer point of view. Position of the flexible solar cells on fabric is also important to take efficient irradiation from the light source. Places of needed wires, controllers and batteries, which have to be lightweight under the cloth, are needed to be concerned to develop viable photovoltaic textiles (Schubert & Werner, 2006).

In recent years, there has been an increase in studies about developing photovoltaic fibers which can take charge in different textile and clothing applications. An active photovoltaic fiber, which is produced by using advanced design and suitable materials, and, which consist of adequate smooth layers, efficiency and stability, is capable of forming a flexible fabric by suitable knitting or weaving techniques, or integrating as a yarn into a cloth to generate power for electronic devices by converting sunlight (DeCristofano, 2009)

Fiber based photovoltaics take the advantage of being flexible and lightweight. Integration of photovoltaic fibers into fabrics and clothes is easy to manufacture wearable technology products. Small surface of a fiber also provide large area photoactive surfaces in the case of fabric, so higher power conversion efficiency can be obtained.
Traditional solar cells using silicon based semiconductors are generally rigid and are not suitable to be used with textiles. The thin film solar cells based on inorganic semiconductors can be made flexible and however they are more suitable for patching onto fabrics (Schubert & Werner, 2006).
Inexpensive electricity production can be achieved, when both low-cost and high efficient manufacturing of photovoltaic cells are achieved. A potential alternative approach to conventional rigid solar cells is organic solar cells, which can be coated on both rigid and flexible substrates using easy processing techniques. In addition, the polymer based organic solar cells can be used to produce fully flexible photovoltaic textiles easily, in any scale, from fibers to fabrics and using low-cost methods.

2. Organic photovoltaic technology

2.1 Organic semiconductors

Organic semiconductors, which are generally considered as intrinsic wide band gap semiconductors (band gap>1.4 eV), have many advantages to be used in solar cells. For example, organic semiconductors of which electronic band gap can be engineered by chemical synthesis with low-cost (Günes et al., 2007) have generally high absorption coefficients.
Organic semiconductors consist of different chemical structures (Nunzi, 2002) including polymers, oligomers, dendrimers, dyes, pigments, liquid crystals (Yilmaz Canli et al., 2010) etc. In carbon-based semiconductors, conductivity is obtained by conjugation, which single and double bonds between the carbon atoms alternate (Pope & Swenberg, 1999).
Conjugated organics are challenging materials for solar cells owing to their semiconducting and light absorbing features. As a compound of organic solar cells, organic semiconductors can be processed by thermal evaporation techniques or solution based coating or printing techniques at low temperatures (Deibel & Dyakonov, 2010).

2.2 Organic solar cells

As a promising renewable energy source, organic photovoltaics have attracted attention during the last decades resulting in significant progress in cell efficiency exceeded 5% (AM1.5, 1000 W/m^2) (Green et al., 2010) in the conventional bulk heterojunction solar cell architecture consisting of a polymer donor and fullerene acceptor blend. Organic solar cells achieving photovoltaic energy conversion by organic semiconductor or conductor are compatible with flexible substrates like textiles for use in novel application areas.
Photovoltaic effect, production of electricity by converting photons of the sunlight, occurs in an organic solar cell by the following steps (Nunzi, 2002): Absorption of photons of the light in the solar cell and exciton (electron-hole pair) creation; separation of charges and carriers generation from exciton dissociation; transport and then collection of charges by respective electrodes (Günes et al., 2007; Nunzi, 2002)
There are some approaches such as using conjugated polymers (Antonradis et al., 1994) and their blends (Granström et al., 1998; Halls et al., 1995; Yu & Heeger, 1995), small molecules (Tang, 1986; Wöhrle & Meissner, 1991) polymer-small molecule bilayers (Jenekhe & Yi, 2000;

Breeze et al., 2002) and their blends (Tang, 1986; Shaheen et al., 2001; Dittmer et al., 2000) or combinations of inorganic-organic materials (O`Reagan & Graetzel, 1991; Greenham et al., 1996; Günes et al., 2008; to develop organic solar cells (Güneş & Sariçiftçi, 2007). Mostly, two concepts are considered in organic solar cell researches: first one, (Krebs, 2009a) which is the most successful is using conjugated polymers (Fig. 1) with fullerene derivatives by solution based techniques and second one is cooperating small molecular materials (as donor and acceptor) by thermal evaporation techniques (Deibel & Dyakonov, 2010).

A conventional organic solar cell (Fig. 2) device is based on the following layer sequence: a semi-transparent conductive bottom electrode (indium tin oxide (ITO)) or a thin metal layer), a poly(3,4-ethylenedioxythiophene:poly(styrene sulfonic acid) (PEDOT:PSS) layer facilitating the hole injection and surface smoothness, an organic photoactive layer (most common poly(3- hexylthiophene):[*6,6*]-*phenyl-C61-butyric acid* methyl ester (P3HT:PCBM)) to absorb the light and a metal electrode (Aluminum, Al and Calcium, Ca) with a low work function to collect charges on the top of the device (Brabec et al., 2001a; Brabec et al., 2001b; Padinger et al., 2003). To form a good contact between the active layer and metal layer, an electron transporting layer (i.e. Lithium Fluoride, LiF) is also used (Brabec et al., 2002).

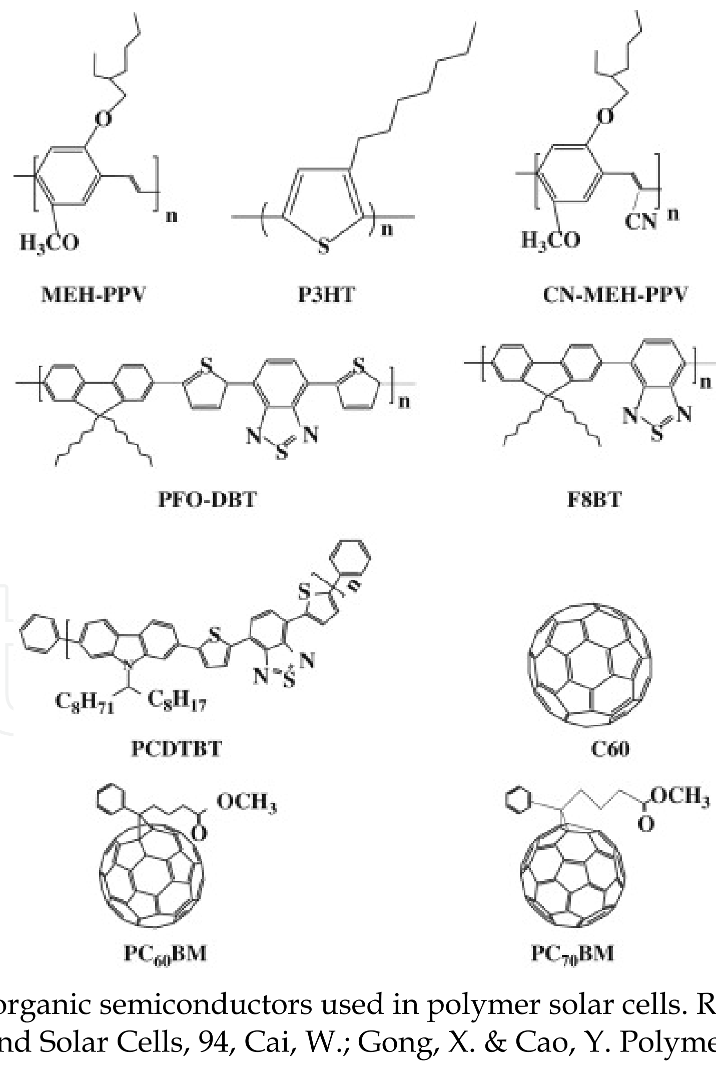

Fig. 1. Example of organic semiconductors used in polymer solar cells. Reprinted from Solar Energy Materials and Solar Cells, 94, Cai, W.; Gong, X. & Cao, Y. Polymer solar cells: Recent development and possible routes for improvement in the performance, 114–127, Copyright (2010), with permission from Elsevier.

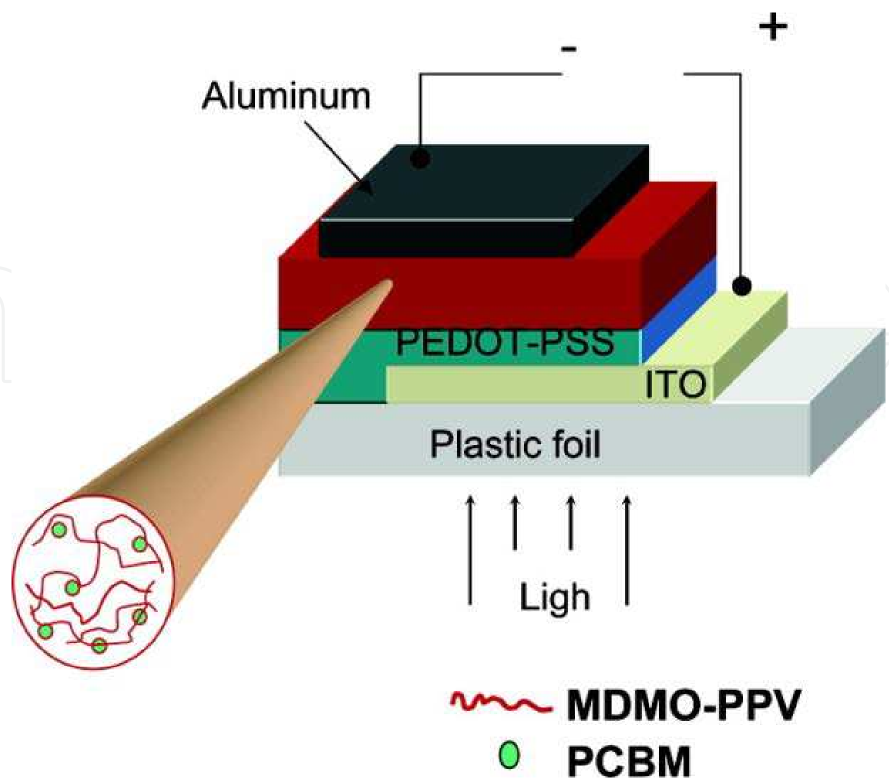

Fig. 2. Bulk heterojunction configuration in organic solar cells (Günes et al., 2007)

ITO is the most commonly used transparent electrode due to its good transparency in the visible range and good electrical conductivity (Zou et al., 2010). However, ITO, which exhibits poor mechanical properties on polymer based substrates, has limited conductivity for fabricating large area solar cells and needs complicated techniques, which tend to increase the cost of the solar cells (Zou et al., 2010). Indium availability is also limited. To alleviate limitations arised from ITO, alternative materials are needed to replace transparent conducting electrode. There are some approaches such as using carbon nanotubes (CNTs) (Rowell et al., 2006; Glatthaar et al., 2005; (Celik) Bedeloglu et al., 2011; Dresselhaus et al., 2001), graphenes (Eda et al., 2008), different conductive polymers (i.e. PEDOT:PSS and its mixtures (Ouyang et al., 2005; Kushto et al., 2005; Huang et al., 2006; Ahlswede et al., 2008; Zhou et al., 2008), metallic grids (Tvingstedt & Inganäs, 2007; Kang et al., 2008), nanowires (Lee et al., 2008) for potential candidates to substitute ITO layer and to perform as hole collecting electrode. In particular, CNTs have a wide variety of application area due to their unique features in terms of thermal, mechanical and electrical properties (Ajayan, 1999; Baughman et al., 2002). A nanotube has a diameter of a few nanometers and from a few nanometers to centimeters in length. Carbon nanotubes can be classified into two groups according to the number of combinations that form their walls: Single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs) (Wang et al., 2009) Recently, CNTs are used in solar cells and can substitute ITO as a transparent electrode in organic solar cells (Rowell et al., 2006; Glatthaar et al., 2005; (Celik) Bedeloglu et al., 2011; Dresselhaus et al., 2001).

In the organic solar cell, the photoactive layer, light absorbing layer, is formed by combination of electron donor (p) and an electron accepting (n) materials (Deibel & Dyakonov, 2010) C_{60}, its derivatives and Perylen pigments are mostly used as electron accepting materials. Also, phtalocyanines, porphyrins, poly(3- hexylthiophene) (P3HT) and poly[2-methoxy-5-(2'-ethyl-hexyloxy)-1,4-phenylene vinylene] (MEH-PPV) are good donors (Nunzi,*2002).* Most of the time, evaporation step is indispensable in the manufacturing of conventional organic photovoltaic devices, but this process tends to increase the cost of the cell. Besides, ITO-PEDOT:PSS interface (de Jong et al., 2000) and Al top electrode (Do et al., 1994) is known to be quite unstable, which limits the lifetime of organic solar cells. Organic solar cells have low charge transport and a mismatch between exciton diffusion length and organic layer thickness. While the efficient absorption of light is provided by organic film based on P3HT:PCBM having a thickness over 250 nm (Liu et al., 2007a), exciton diffusion length of which surpassing causes exciton recombination, is about 10-20 nm in polymer based and in organic semiconductors (Nunzi, 2002). Although, organic solar cells have lower power conversion efficiency (~5%) than inorganic traditional solar cells (for crystalline silicon based solar cells ~25% in laboratory conditions); their cost and processing parameters are favorable (Deibel & Dyakonov, 2010*).*

In order to avoid the limitations of organic semiconductor and to improve the power conversion efficiency of organic solar cells, several approaches such as optical concepts, different device configurations such as inverted layer architecture, multijunction solar cells, novel materials with lower band gap (Park et al., 2009; Chen et al., 2009; Huo et al., 2009; Coffin et al., 2009), wider absorption ranges, higher dielectric constants and higher charge carrier mobility are some approaches are studied in last few years (Deibel & Dyakonov, 2010). Reversing the nature of charge collection in organic solar cells using a less air sensitive high work function metal (Ag, Au) (de Jong et al., 2000; Do et al., 1994; Liu et al., 2007a; Park et al., 2009; Chen et al., 2009; Huo et al., 2009; Coffin et al., 2009; Wong et al., 2006) as hole collecting electrode at the back contact and a metal oxide (TiO_x, ZnO) as hole blocking barrier and electron selective contact at the ITO interface to block the oxidation (Hau et al., 2008) is a beneficial approach to avoid from low power conversion efficiency, which limited absorption in solar spectrum causes. In particular, non-clorinated solvents are more appropriate for high volume manufacturing with low cost. Besides, active layer can be protected by use of metal oxides (i.e. vanadium oxide and cesium carbonate), which are used as buffer layer of inverted polymer solar cells (Li et al., 1997). However, there is still a trade-off between stability and photovoltaic performance in inverted solar cells (Hsieh et al., 2010).

Organic solar cells have many advantages such as potential to be semi-transparent, manufacture on both large or small areas compatible with mass production and low-cost, production possibility with continuous coating and printing processes on lightweight and flexible substrates (for example textiles), ecological and low-temperature production possibilities (Dennler et al., 2006a; Dennler & Sariciftci, *2005*).

Polymer heterojunction organic solar cells have attracted much attention because of their potential applications in large area, flexible and low-cost devices (Park et al., 2009; Yu et al., 1995; Chang et al., 2009; Dridi et al., 2008; Peet et al., 2009; Oey et al., 2006; Yu et al., 2008). Polymer based thin films on flexible and non-flexible substrates can be achieved by various printing techniques (see Fig. 3) (screen printing, inkjet printing, offset printing, flexo printing and so on), solution based coating techniques (dipping, spin coating, doctor blading, spray coating, slot-die coating and so on), and electrospinning (Krebs, 2009a).

Roll to roll, reel to reel, process is suitable for solar cells, which are on long flexible substrates (polymeric substrates and thin metal foils), and, which can be wound on a roll

(Krebs, 2009a). Various coating and printing techniques including knife-over-edge coating and slot die coating can be used for manufacturing flexible solar cells. The most appropriate processes for flexible photovoltaics should be free from Indium, toxic solvents and chemicals, and should have solution based manufacturing steps (coating and printing techniques), which results an environmentally recyclable product (Hoppe & Sariciftci, 2006). The studies about improving polymer solar cells (Günes et al., 2007; Hoppe & Sariciftci, 2006; Bundgaard & Krebs, 2007; Jørgensen et al., 2008; Thompson & Frechet, 2008; Tromholt et al., 2009) include developments in material properties and manufacturing techniques.

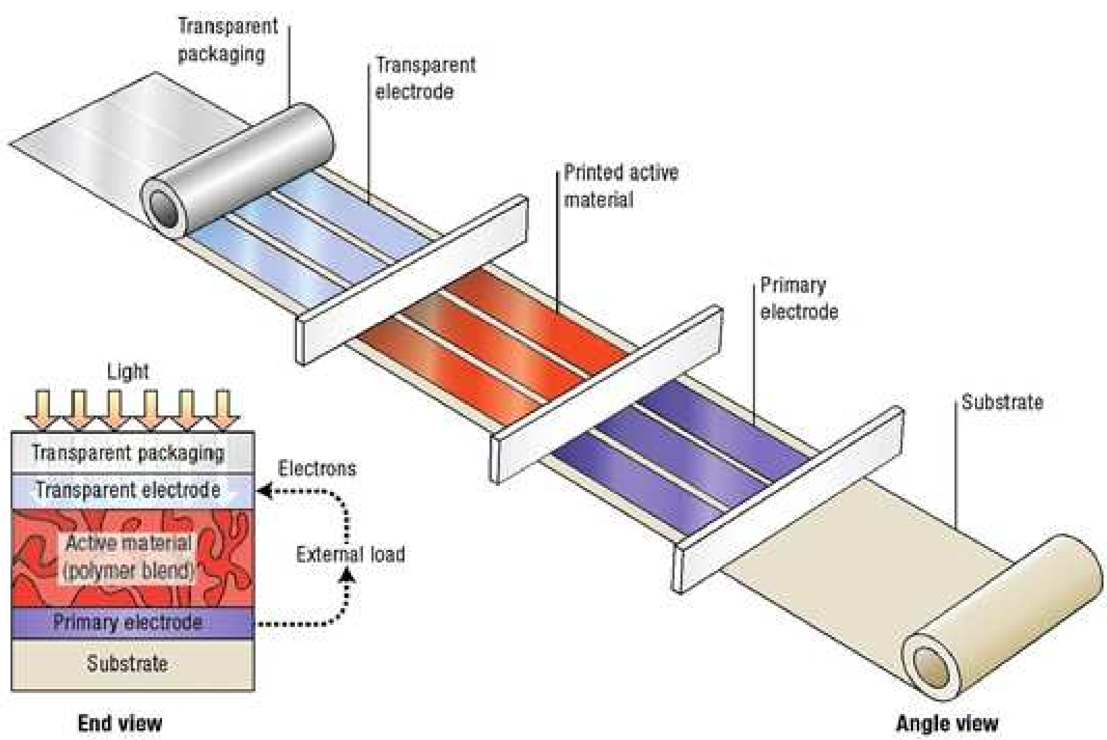

Fig. 3. Schematic description of printing process used for manufacturing of polymer-based photovoltaic cells. Reprinted by permission from Macmillan Publishers Ltd: Nature Photonics, *Gaudiana,* R. & *Brabec,* C. (2008). Organic materials: Fantastic plastic. Vol.2, pp.287- 289, copyright (2008).

2.3 Characterization of organic solar cells

Characterization of organic solar cells performed by measuring efficiencies in the dark and under an illumination intensity of 1000 W/m^2 (global AM1.5 spectrum) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global) (Green et al., 2010). Generally a solar simulator is used as illumination source for simulating AM1.5 conditions. Air Mass (AM) is a measure of how much atmosphere sunlight must travel through to reach the earth's surface. AM1.5 means that the sun is at an angle about 48° (Benanti & Venkataraman, 2006). A graph (Fig. 4) on which shows the current-voltage characteristics in the dark and under an illumination, gives significant information about photovoltaic performance and photoelectrical behavior of the cells (Nunzi, 2002).

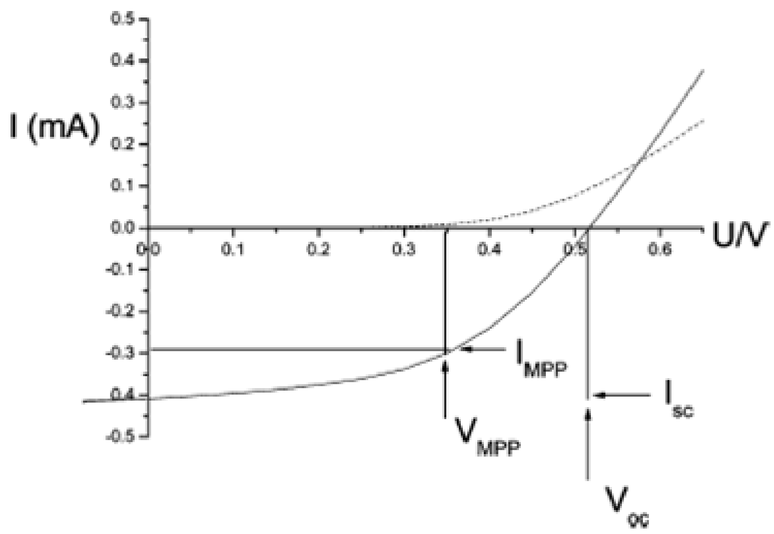

Fig. 4. Current-voltage (I-V) curves of an organic solar cell (dark, - - -; illuminated, -). The characteristic intersections with the abscissa and ordinate are the open circuit voltage (*V*oc) and the short circuit current (*I*sc), respectively. The largest power output (*P*max) is determined by the point where the product of voltage and current is maximized. Division of *P*max by the product of *I*sc and *V*oc yields the fill factor *FF* (Günes et al., 2007).

The overall efficiency of a solar cell can be expressed as follows :

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{I_{sc}\ V_{oc}\ FF}{P_{in}} \tag{1}$$

Here, maximum power point is the point on the I-V curve where maximum power (P_{max}) is produced. The photovoltaic power conversion efficiency (η) of a solar cell is defined as the ratio of power output to power input. I_{sc} is the short-circuit current, which flows through the cell when applied voltage is zero, under illumination. Under an external load, current will always be less than max. current value. V_{oc}, the open-circuit voltage is the voltage when no current is flowing, under illumination. When current flows, voltage will be less than max. voltage value. FF, fill factor is the ratio of max. power output to the external the short-circuit current and open-circuit voltage values. FF is given by following formula:

$$FF = \frac{P_{\max}}{I_{sc}\ V_{oc}} = \frac{I_{mpp}\ V_{mpp}}{I_{sc}\ V_{oc}} \tag{2}$$

where I_{mpp} and V_{mpp} represent the current and the voltage at the maximum power point (P_{max}) in the four quadrant, respectively (Nunzi*,2002;* Benanti & Venkataraman*,* 2006).
The incident photon to collected electron (IPCE) or external quantum efficiency (EQE) under monochromatic lightning at a wavelength λ includes losses by reflection and transmission (Benanti & Venkataraman*,* 2006) and gives the ratio of collected charge carriers per incident photons (Dennler et al., 2006a):

$$IPCE = \frac{1240\ I_{sc}}{\lambda\ P_{in}} \tag{3}$$

2.4 Flexible organic solar cells

Solar cells generally developed on rigid substrates like glass and suffer from heavy, fragile and inflexible devices. However, stiff substrates limit usage, storage and transport of photovoltaic devices. Therefore, a big interest from both industrial and academic sides has been observed for research and development of flexible (foldable or rollable) solar cells, recently. Organic solar cells, easy scalable and suitable to roll-to-roll production with low-cost have potential to be used with flexible substrates such as textiles and fibers. Materials used in organic solar cells are also capable of producing lightweight photovoltaics. Polymer based substrates, which are used to replace rigid substrates and which have adequate flexibility are required to have mechanically and chemically stable, while organic solar cell manufacturing processes continue. Optimum substrate should have some features such as resistance to effects of chemical materials, water and air and also, mechanical robustness, low coefficients of thermal expansion, anti-permeability and smooth surface properties and so on.

Polyethylene terephtalate (PET), ITO coated PET, Poly(ethylene naphthalate) (PEN), Polyimide (PI), Kapton and Polyethersulphone (PES) are used as substrates to develop flexible solar cells.

Polyethylene terephtalate (PET) based fibers, which melt about 260ºC show good stability to UV light and most of the chemicals and exhibit good mechanical properties including flexibility and comfort ability both in fiber and fabric form (Mather *&* Wilson*, 2006*). However, PET foils are often used as substrate of the flexible photovoltaics (Breeze, et al., 2002; Aernouts et al., 2004; Winther-Jensen & Krebs, 2006; Krebs, 2009b). Manufacturing of photovoltaics using PET substrates is suitable for reel to reel production, which reduces material and production costs. PET foils are preferable materials for solar cells due to their price, mechanical flexibility and easy availability comparing to other substrates. However, use of PET foils is limited because it melts about 140 ºC (Zimmermann et al., 2007; Krebs, 2009a; Krebs, 2009b). Thermocleavable materials are used for the preparation of very stable solar cells (Liu et al., 2004; Krebs & Spanggaard 2005; Krebs & Norrman, 2007; Krebs, 2008; Bjerring et al., 2008; Krebs et al., 200*8*) but, these materials are required to heat to a temperature of around 200ºC to achieve insolubility, which is a limitation to use of PET foils in conventional methods. However, PET substrates can be used with thermocleavable materials thanks to longer processing time (Krebs, 2009b).

Spin coating and screen printing techniques are used to coat highly conductive PEDOT:PSS dispersions onto flexible PET substrates as anode, which also improves an application of a metallic silver(Ag)-grid deposited between foil and electrode (Aernouts et al., 2004). A silk screen printing procedure (Winther-Jensen & Krebs, 2006) can be applied to develop PEDOT electrode with surface resistances down to 20 Ω^{-1} on flexible PET substrates. Researchers obtained 0.7 V open circuit voltage, 1 mA/cm^2 short circuit current and 0.2%, efficiency under simulated sun light (AM1.5 at 1000 W m^{-2}) with an active area of 4.2 cm^2 based on MEH-PPV:PCBM mixture and Al counter electrode.

In recent years, carbon nanotubes have found a wide variety of applications in photovoltaics. Films of SWNT networks can be printed on PET foils to get flexible transparent conducting electrodes. The well dispersed and stable solutions of SWNTs can be produced as electrode of flexible polymer based solar cells with various methods, which are inexpensive, scalable to large areas, and allows for the transfer of the film to a variety of surfaces. Such a flexible photovoltaic device configuration (Rowell et al., 2006) (see Fig. 5) (PET/SWNTs/PEDOT:PSS/P3HT:PCBM/Al) gave 2.5% efficiency of which efficiency is very close to conventional ITO coated glass based rigid solar cells.

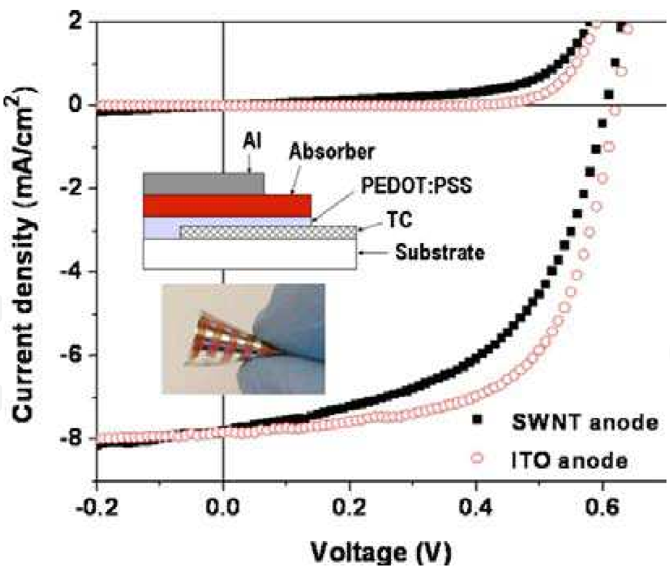

Fig. 5. Current density-voltage characteristics of P3HT:PCBM devices under AM1.5G conditions using ITO on glass (open circles) and flexible SWNTs on PET (solid squares) as the anodes, respectively. Inset: Schematic of device and photograph of the highly flexible cell using SWNTs on PET. Reprinted with permission from Rowell, M.W.; Topinka, M.A.; McGehee, M.D.; Prall, H.J.; Dennler, G.; Sariciftci, N.S.; Hu, L. & Gruner, G. (*2006*). Organic Solar Cells with Carbon Nanotube Network Electrodes. *Applied Physics Letters,* Vol.88, pp. 233506. Copyright 2006, American Institute of Physics.

An inverted layer sequence (see Fig. 6) was used (Zimmermann et al., 2007) in an ITO-free wrap through approach of which device configuration included PET/ AL-Ti/ Absorber (P3HT:PCBM)/ PEDOT:PSS/Au layer sequence. Thermal evaporation, e-beam evaporation and spin coating techniques were used for device fabrication on flexible substrate. Researchers obtained a power conversion efficiency of 1.1% (under 1000W/m^2 AM 1.5) from the device with additional serial circuitry, which employed top illumination by avoiding the use of ITO.

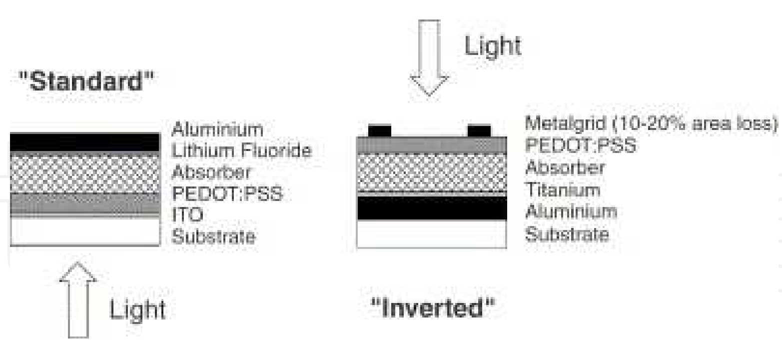

Fig. 6. Comparison of the widely used layer sequence on ITO/PEDOT:PSS electrode (left) and inverted layer sequence (right), where the ITO is replaced by a metal grid for small area devices. Reprinted from Sol. Energy Mater. Sol. Cells, 91, Zimmermann, B.; Glatthaar, M.; Niggemann, M.; Riede, M. K.; Hinsch, A. & Gombert, A., ITO-free wrap through organic solar cells–A module concept for cost- efficient reel-to-reel production., 374- 378, Copyright (2007), with permission from Elsevier.

The commercially available ITO-coated PET foils are used mostly in studies about flexible organic solar cells. PET layer is as polymeric substrate and ITO is the transparent conducting electrode of photovoltaic device.

Researchers (Brabec et al., 1999) performed efficiency and stability studies on large area (6 cm x 6 cm) flexible solar cells based on MDMO-PPV and PCBM materials and compared them with small area devices. Thin films were produced on two different substrates including ITO coated glass substrates and ITO coated PET foils with different active areas. The overall conversion efficiency of the flexible plastic solar cell is calculated with app. 1,2 % and a filling factor FF - 0.35 under monochromatic illumination (488 nm) with 10 mW/cm^2. It is possible to produce organic solar cells on flexible substrates without loosing efficiency, whereas fullerene bulk heterojunctions was still limited by charge transport. Al-Ibrahim et al. (Al-Ibrahim et al., 2005) developed photovoltaic devices based on P3HT and PCBM materials on ITO coated polyester foils with an active cell area of 0.5×0.5 cm^2 with the following photovoltaic device configuration: PET/ITO/PEDOT:PSS/P3HT:PCBM/Al. Device parameters without any special postproduction treatment were obtained as: V_{OC} = 600 mV, I_{SC} = 6.61 mA/cm^2, FF=0.39 and η=1.54% under irradiation with white light (AM1.5, 100mW/cm^2). These results were hopeful for device up-scaling and development of processing technologies for reel to reel production of flexible organic photovoltaic devices.
Different oligothiophene materials are used to develop (Liu et al., 2008) flexible organic photovoltaic devices on ITO-coated PET films. The organic layers (5-formyl-2,2′:5′,2″:5″,2‴-quaterthiophene (4T-CHO), 5-formyl-2,2′:5′, 2″:5″,2‴:5‴,2⁗-quinquethiophene (5T-CHO) and 3,4,9,10-perylenetertracarboxylic dianhydride (PTCDA)) were deposited by vacuum deposition. While the PET-ITO/4T-CHO/PTCDA/Al device showed an open circuit voltage (V_{oc}) of 1.56 V and a photoelectric conversion efficiency of 0.77%, the PET-ITO/5T-CHO/PTCDA/Al device exhibited a V_{oc} of 1.70 V and photoelectric conversion efficiency of 0.84%. Stakhira et al. (2008) fabricated an organic solar cell consisting of an ITO/PEDOT:PSS/ pentacene (Pc)/Al multilayer structure on flexible PET substrate coated with conductive ITO layer. PEDOT:PSS/Pc and Al contact were formed by electron beam deposition technique. The photovoltaic effect was measured with open circuit voltage of ~0.5 V, short circuit current of 0.6 lA and fill factor 0.2. Researchers (Blankenburg et al., 2009) used continuous reel-to-reel (R2R) slot die coating process to develop polymer based solar cells on plastic foils with adjustable coating thicknesses. Transparent conducting and photoactive layers were prepared with good reproducibility and promising power conversion efficiencies (0.5–1% (1.7% as maximum value)).
Krebs et al. (2007) fabricated organic solar cells on ITO coated PET substrates. Active layer consisted of MEH-PPV was coated by screen-printing method and an optional layer of fullerene (C_{60}) and the final Al electrode were applied by vacuum coatings. Thirteen individual solar cells with an active area of 7.2 cm^2 were connected in series. In the simple geometry ITO/MEH-PPV/Al the module gave a V_{oc} of 10.5 V, an I_{sc} of 5 A, a FF of 13% and an efficiency (η) of 0.00001% under AM1.5 illumination with an incident light intensity. A geometry (ITO/MEH-PPV/C_{60}/Al) employing a sublimed layer of C_{60} improved Voc, Isc, FF and η to 3.6V, 178 A, 19% and 0.0002%, respectively. The results of roll-to-roll coated flexible large-area polymer solar-cell modules (eight serially connected stripes), which was performed in 18 different laboratories in Northern America, Europe and Middle East, were presented in another study (Krebs et al., 2009c). In all steps, roll-to-roll processing was employed. A zinc oxide nanoparticle layer, P3HT-PCBM and PEDOT:PSS layers were coated onto ITO coated PET by a modified slot-die coating procedure, respectively. ZnO as buffer layer has high electron mobility compared to titanium oxide (Yip et al., 2008) and so, can be ideal electron selective contact layer in polymer solar cells (Hau et al., 2008). The devices were completed by screen-printing silver paste and lamination of PET protective layer on top. In another study of Krebs (2009c) they prepared polymer solar cell module using all-solution processing on ITO

coated PET substrates. zinc oxide nanoparticles (ZnO-nps) were applied using either knife-over- edge coating or slot-die coating. A mixture of the thermocleavable poly-(3-(2-methylhexan-2-yl)- oxy-carbonyldithiophene)(P3MHOCT) and ZnO-nps was applied by a modified slot-die coating procedure as second layer. The third layer was patterned into stripes and juxtaposed with the ITO layer. The fourth layer comprised screen-printed or slot-die-coated PEDOT:PSS and the fifth and the final layer comprised a screen-printed or slot-die-coated silver electrode. Coating ITO onto the PET substrate by sputtering process in a vacuum, cost of ITO and thermal disadvantage of PET foils (temperatures only up to 140°C) were some implications of the research. Also, efficient inverted polymer solar cell fabricated by roll-to-roll (R2R) process could be obtained in terms of both power conversion efficiency and operational stability. Maximum 1.7% efficiency for the active area of the full module was obtained from eight serially connected cells (Krebs et al., 2009a). They (Krebs et al., 2009b) showed the versatility of the polymer solar cell technology with abstract forms for the active area, a flexible substrate, processing entirely from solution, complete processing in air using commonly available screen printing, and finally, simple mechanical encapsulation using a flexible packaging material and electrical contacting post-production using crimped contacts. Following two different devices were developed:

PET/ITO/ZnO/P3CT/ZnO/PEDOT:PSS/Ag paste/Cold laminated PET with acrylic resin and

PET/ITO/ZnO/P3CT/PCBM/ZnO/PEDOT:PSS/Ag paste/Cold laminated PET with acrylic resin

Poly(ethylene naphthalate) (PEN), has higher glass transition temperature than PET and this provides potential post-treatment of devices (Dennler et al., 2006b). However, shrinkage is seen in the material and so, subsequent processes will be problematic (Krebs, 2009b). PEN substrates (Dennler et al., 2006b) were used to develop flexible solar cells and were coated with ultra-high barrier multilayer coatings (Fig. 7). Shelf lifetime of conjugated polymer:fullerene

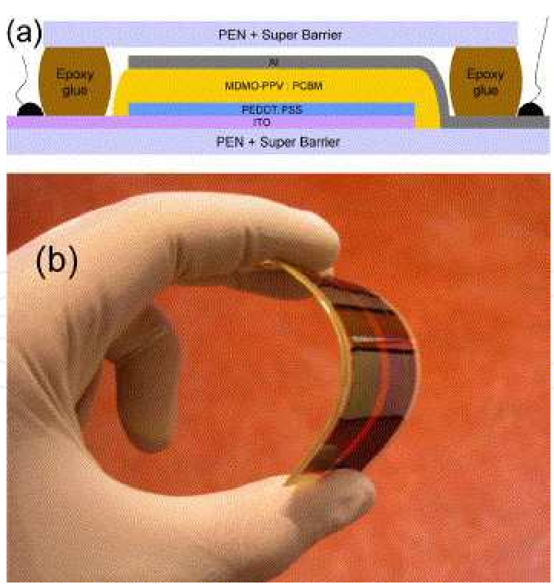

Fig. 7. (a) Cross-sectional view of the conjugated polymer:fullerene solar cells investigated here; (b) picture of a bent device. Reprinted from Thin Solid Films, 511–512, Dennler, G.; Lungenschmied, C.; Neugebauer, H.; Sariciftci, N. S.; Latreche, M.; Czeremuszkin, G. & Wertheimer, M. R., A new encapsulation solution for flexible organic solar cells, *349*–353, Copyright (2006), with permission from Elsevier.

solar cells fabricated on PEN substrates and encapsulated with flexible, transparent PEN-based ultra-high barrier material entirely fabricated by plasma enhanced chemical vapor deposition (PECVD) was studied. ITO bottom electrodes were sputtered through a mask onto flexible substrates and so, good adhesion and ~60 Ω/square sheet resistance was obtained. The complete device provided a shelf lifetime of more than 3000h. Lungenschmied et al. (2007) also studied interconnected organic solar cell modules on flexible ultrahigh barrier foils (Fig. 8). Flexible solar cell modules had 11 cm^2 total active area and reached 0.5% overall powerconversion efficiency under AM1.5 conditions. ITO bottom electrode was structured by deposition through a shadow mask directly onto substrate and a sheet resistance of approximately 60 Ω/square was obtained. PEDOT:PSS and P3HT: PCBM were coated using the doctor blade technique. Al top electrode was thermally evaporated using a shadow mask.

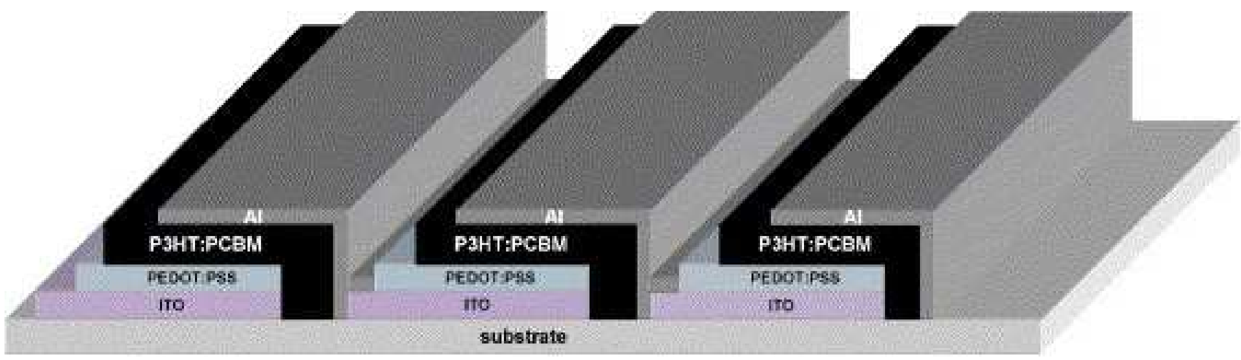

Fig. 8. Serial connection of organic solar cells. Reprinted from Sol. Energy Mater. Sol. Cells, 91, Lungenschmied, C.; Dennler, G.; Neugebauer, H. ; Sariciftci, N. S. ; Glatthaar, M. ; Meyer, T. & Meyer, A., Flexible, long-lived, large-area, organic solar cells, 379–384, Copyright (2007), with permission from Elsevier.

A roll-to-roll process enables fabrication of polymer solar cells with many layers on flexible substrates. Inverted solar cell designs (Krebs, 2009b) can be used on both transparent and non-transparent flexible substrates. Silver nanoparticles on PEN were developed as bottom electrode. ZNO-nps from solution, P3HT-PCBM as active layer and PEDOT:PSS as hole transporting layers were coated, respectively, using slot-die coating. The last electrode was applied by screen printing of a grid structure that allowed for transmission of 80% of the light. The devices were tested under simulated sunlight (1000Wm^{-2}, AM1.5G) and gave 0.3% of power conversion efficiency for the active layer. The illumination of the device is through the top electrode enabling the use of non-transparent substrates. The poor optical transmission in PEDOT:PSS-silver grid electrode caused a decrease in performance.
Polyimide (PI) films, which show high glass transition temperatures, low surface roughnesses, low coefficients of thermal expansion, and high chemical resistance under manufacturing conditions, are suitable for fabrication of flexible electronics. Inverted polymer solar cells were studied on PI substrates (Hsiao et al., 2009). Surface-nickelized polyimide films (NiPI films) as cathodes (back contact electrode) and high-conductivity PEDOT:PSS films as anodes were coated using solution based processes (see Fig. 9). The resulting FF of 0.43 was lower than that of standard devices. However, this ITO-free inverted polymer solar cells exhibited high performance, with the power conversion efficiency reaching 2.4% under AM 1.5 illumination (100$mWcm^{-2}$).

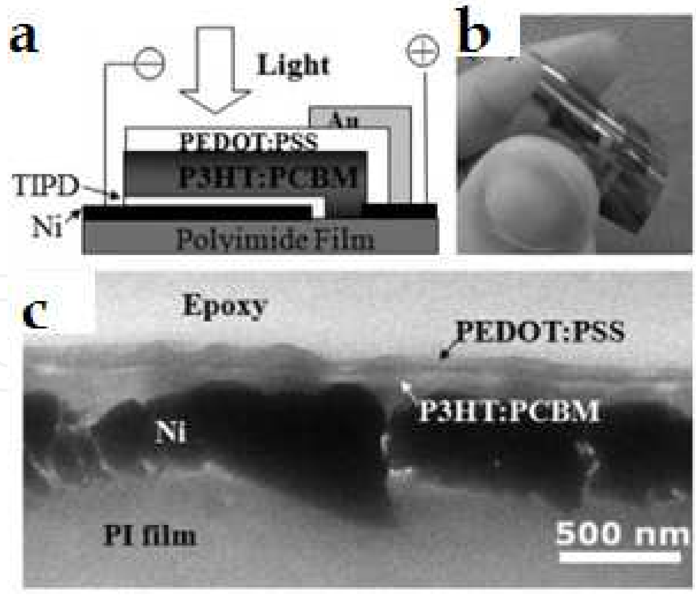

Fig. 9. (a) Architecture of an inverted PSC featuring an inverted sequence on NiPI as the back contact electrode. (b) Optical image of an inverted PSC on NiPI. (c) TEM cross-sectional image of an inverted PSC on NiPI. Scale bars, 500 nm. Reprinted from Org.Electron, 10, Hsiao, Y. S.; Chen, C. P. ; Chao, C. H. & Whang, W. T., All-solution-processed inverted polymer solar cells on granular surface-nickelized polyimide, 551-561, Copyright (2009), with permission from Elsevier.

Kapton®, which was synthesized by polymerizing an aromatic dianhydride with an aromatic diamine, has good chemical and thermal resistance (>400 ºC). Kapton® polyimide films can be used in a variety of electrical and electronic uses such as wire and cable tapes, substrates for printed circuit boards, and magnetic and pressure-sensitive tapes (matweb, 2010). Guillen and Herrero (2003) developed both bottom and top electrodes onto polyimide sheets (Kapton KJ) to be used in applications of lightweight and flexible thin film photovoltaic devices. ITO as the frontal electrical contact and Mo, Cr and Ni layers as the back electrical connections were prepared and then compared with conventional electrodes on glass substrates. ITO deposited polyimide sheets showed similar optical transmittance and higher electrical conductivity than ITO coated glass substrates. Mo, Cr and Ni coated polyimide sheets showed similar structure and electrical conductivity to Mo, Cr and Ni coated glass substrates without bending or adhesion failure.

A commercially available polyimide foil (Kapton), which was overlayed with copper, was used as the substrate of polymer solar cell in a roll-to-roll process that does not involve ITO (Krebs, 2009d). Titanium metal was sputtered onto the kapton/copper layer in the vacuum and both the monolithic substrate and back electrode for the devices were obtained. PEDOT:PSS and the active layer were slot-die coated onto the kapton (25 µm) /Cu/Ti foil, respectively. A front electrode, a protective layer and finally a silver grid was applied by screen printing technique. Vacuum coating step was the current limitation of the device.

Polyethersulphone (PES), which is related to polyetheretherketone and polyetherimide, is used as thermoplastic substrate and has high glass transition temperature (Tg ~223ºC). PES was used as substrate to fabricate small molecule organic solar cells, which have single heterojunction structure, and, which use PEDOT:PSS anodes possessing low sheet resistance (~450 $\Omega/\mathbb{R}$). High conductivity PEDOT:PSS layers were prepatterned using photolithographic technique and spin cast onto fully flexible thermoplastic PES-based substrates having %90 optical transmission. Both organic solar cells, which have plastic and glass based substrates, and, which use a hole transport material, 4,4-bis[*N*-(1-naphthyl)-*N*-phenyl-amino]biphenyl (α-NPD) and C_{60} bilayer structure, exhibited high carrier mobilities and high V_{oc}=0.85V (AM1.5, 97 mW/cm^2) (Kushto et al., 2005).

2.5 Solar cell integrated textiles

Among the photovoltaic technologies, organic solar cells are the most suitable ones to textile structures in terms of favorable features such as flexibility, lightness, cost-effectiveness and usage performance. Studies about photovoltaic textiles consider two main approaches: First, solar cell is formed elsewhere and then, photovoltaic structure is integrated in/onto textiles using various techniques, i.e. patching. Second, solar cell is formed in fiber or textile form. So, it can be used as fiber itself or can form textile structures, which are partly or completely photovoltaic. Shelf lifetime, cost and efficiency of organic solar cells are still important issues for also photovoltaic fibers and textiles to be overcome before commercialization.

Utilizing flexible solar cells with textiles can open many application fields for photovoltaic textiles such as electronic textiles besides powering movable electronic devices. Solar cell integrated bags, jackets and dresses are some of the recent applications of polymer based solar cells. For example, in study of Krebs et al. (2006) incorporation of polymer based organic solar cells into textile structures were performed by two ways: In first one, PET substrate was coated with ITO, MEH-PPV, C_{60} and Al, respectively. Then, device was laminated using PET. In second one, PE layer was laminated onto textile substrate. Then, by applying PEDOT, active material and final electrode, respectively, device was completed. Completed devices were integrated into clothes (Fig. 10).

Fig. 10. An example of patterned polymer solar cells on a PET substrate incorporated into clothing by sewing through the polymer solar cell foil using an ordinary sewing machine. Connections between cells were made with copper wire that could also be sewn into the garment. The solar cells were incorporated into a dress and a belt. Design by Tine Hertz Reprinted from Sol. Energy Mater. Sol. Cells, 90, Krebs F.C.; Biancardo M.; Jensen B.W.; Spanggard H. & Alstrup J., Strategies for incorporation of polymer photovoltaics into garments and textiles, 1058-1067, Copyright (2006), with permission from Elsevier.

2.6 Studies about polymer nanofibers for solar cells

There are several studies about developing conductive polymer nanofibers used to fabricate solar cells. Various methods such as self-assembly (Merlo & Frisbie, 2003), polymerization in nanoporous templates (Martin, 1999), dip-pen nano-lithography (Noy et al., 2002), and electrospinning (Babel et al., 2005; Wutticharoenmongkol et al., 2005; Madhugiri; 2003) techniques are used to produce conductive polymer nanowires and nanofibers. Nanofibers having ultrafine diameters provide some advantages including mechanical performance, very large surface area to volume ration and flexibility to be used in solar cells (Chuangchote et al., 2008a).

Since morphology of the active layer in organic solar cells plays an important role to obtain high power conversion efficiencies, many researchers focus on developing P3HT nanofibers for optimized morphologies (Berson et al., 2007; Li et al., 2008; Moulé & Meerholz, 2008). Nanofibers can be deposited onto both conventional glass-based substrates flexible polymer based substrates, which have low glass transition temperature (Bertho et al., 2009).

A fabrication method (Berson et al., 2007) was presented to produce highly concentrated solutions of P3HT nanofibers and to form highly efficient active layers after mixing these with a molecular acceptor (PCBM), easily. A maximum PCE of 3.6% (AM1.5, 100 mWcm^{-2}) has been achieved without any thermal post-treatment with the optimum composition:75 wt% nanofibers and 25 wt% disorganized P3HT. Manufacturing processes were appropriate to be used with flexible substrates at room temperatures. Bertho et al. (Bertho et al., 2009) demonstrated that the fiber content of the P3HT-fiber:PCBM casting solution can be easily controlled by changing the solution temperature. Optimal solar cell efficiency was obtained when the solution temperature was 45 ºC and the fiber content was 42%. Fiber content in the solution effected the photovoltaic performances of cells.

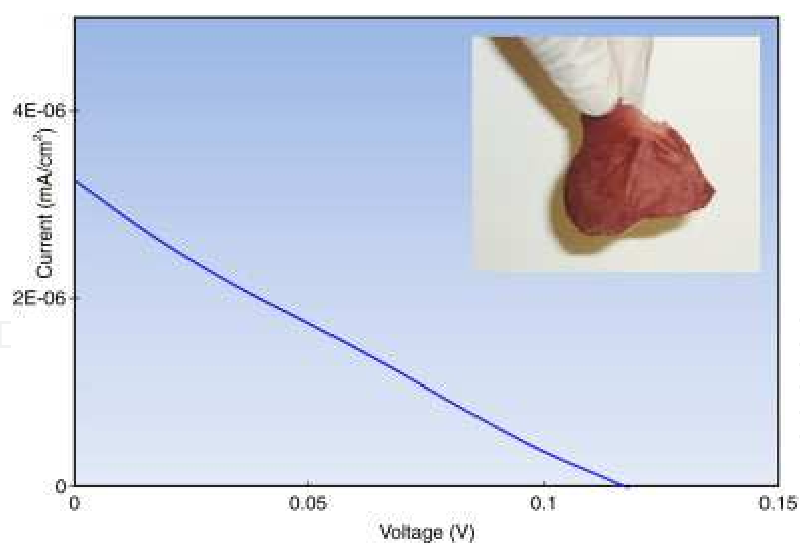

Fig. 11. Jsc–V graph of the P3HT/PCBM based solar cloth measured under 1 Sun conditions. Inset shows a picture of the solar cloth fabricated using electrospinning. Reprinted from *Materials Letters*, 64, Sundarrajan, S.; Murugan, R.; Nair, A. S. & Ramakrishna, S., 2369 -2372., Copyright (2010), with permission from Elsevier.

Electrospinning technique (Chuangchote et al., 2008b) is also used to prepare photoactive layers of polymer-based organic solar cells without thermal post-treatment step. Electrospun MEH-PPV nanofibers were obtained after polyvinylpyrrolidone (PVP) was removed from

as-spun MEH-PPV/PVP fibers. A ribbon-like structure aligned with wrinkled surface in fiber direction was gained. Bulk heterojunction organic solar cells were manufactured by using the electrospun MEH-PPV nanofibers with a suitable acceptor. Chuangchote et al. produced ultrafine MEH-PPV/PVP composite fibers (average diameters ranged from 43 nm to 1.7 mm) by electrospinning of blended polymer solutions in mixed solvent of chlorobenzene and methanol under the various conditions.
Recently, a photovoltaic fabric (Sundarrajan et al., 2010) based on P3HT and PCBM materials were developed. The non-woven organic solar cloth was formed by co-electrospinning of two materials: the core-shell nanofibers as the core and PVP as the shell. The efficiency of the fiber-based solar cloth was obtained as 8.7×10^{-8} due to processing conditions and thickness of structure (Fig. 11-12). However, this is an novel and improvable approach to develop photovoltaic fabrics for smart textiles.

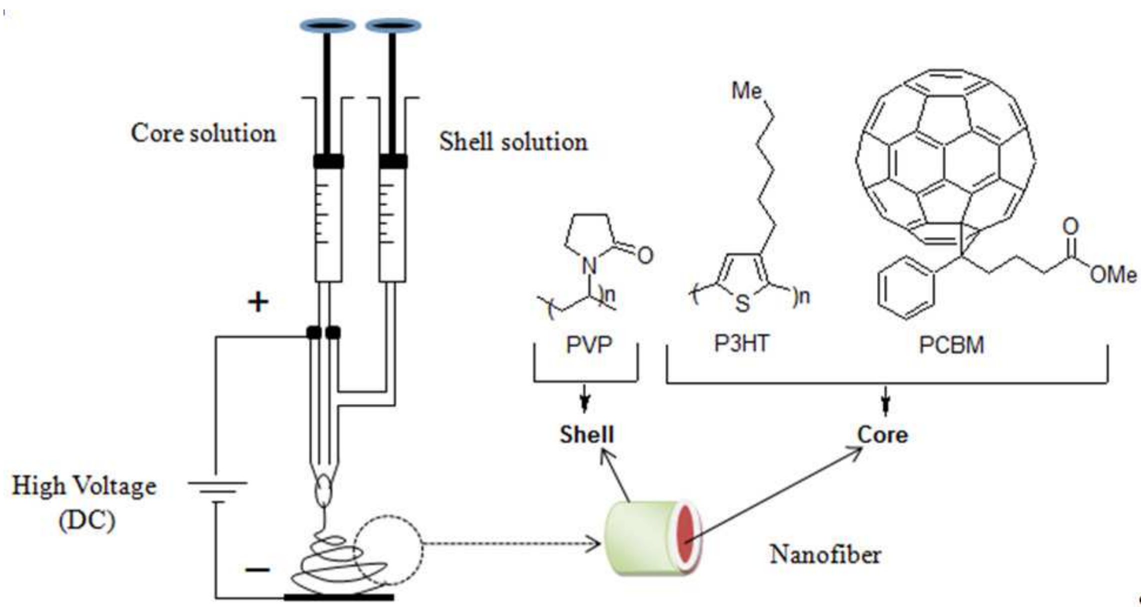

Fig. 12. Schematic diagram of core-shell electrospinning set-up used in this study: direct current voltage at 18 KV, the flow rate of P3HT/PCBM in chloroform/toluene (3:1 ratio, as core) and PVP in chloroform/ethanol (1:1 ratio, shell) was set at 1.3 mL/h and 0.8 mL/h, Respectively. Reprinted from *Materials Letters*, 64, Sundarrajan, S.; Murugan, R.; Nair, A. S. & Ramakrishna, S., 2369 -2372., Copyright (2010), with permission from Elsevier

3. Organic photovoltaic fibers

In recent years, attention on fibrous and flexible optoelectronic structures is increased in both scientific and industrial areas in terms of lightweight, low-cost and large scale production possibilities. Photovoltaic fibers, cost effective and scalable way of solar energy harvesting, work with the principle of solar cell, which produces electricity by converting photons of the sun. Although solar cells made from silicon and other inorganic materials are far more efficient for powering devices than organic solar cells, they are still too expensive to be used in widespread and longterm applications. In studies of fiber-based solar cells, which are incorporated in textiles, organic semiconductors that are naturally flexible and light-weight, are ideal candidates compared to conventional inorganic semiconductors.

For developing optimum photovoltaic textile, choice of the fiber type, which determines UV resistance and maximum processing temperature for photovoltaics and textile production methods (Mather & Wilson, 2006) need to be considered.

In recent years, there are several studies about photovoltaic fibers based on polycrystalline silicon (Kuraseko et al., 2006), dye sensitized solar cells (Fan et al., 2008; Ramier et al., 2008; Toivola et al., 2009) and organic solar cells (Bedeloglu et al., 2009, 2010a, 2010b, 2010c, 2011; Curran et al., 2006; Curran et al., 2008; Curran et al., 2009; Lee et al., 2009; Liu et al., 2007a; Liu et al., 2007b; O'Connor et al., 2008; Zhou et al., 2009; Zou et al., 2010). Protection of liquid electrolyte in DSSCs is problematic causing leakage and loss of performance. However, solid type DSSCs suffer from cracking due to low elongation and bending properties. The organic solar cells based fibers still suffer from low power conversion efficiency and stability. However, organic materials are very suitable to develop flexible photovoltaic fibers with low-cost and in large scale (Bedeloglu et al., 2009; DeCristofano, 2008).

The fiber geometry due to circular cross-section and cylindrical structure brings advantages in real usage conditions. Contrast to planar solar cells, absorption and current generation results in a greater power generation, which can be kept constant during illumination owing to its symmetric structure. A photovoltaic fiber has very thin coatings (about a few hundred nanometers). Therefore, a photovoltaic fabric made from this fiber will be much lighter than that of other thin film technologies or laminated fabric (Li et al., 2010a).

Organic photovoltaic fibers have been produced in different thicknesses and lengths, using different techniques and materials in previous studies. In order to develop fiber based solar cells, mainly solution based coating techniques were applied to develop polymer based electrodes and light absorbing layers. However, deposition techniques in a vacuum were used to develop a photovoltaic fiber formation, too.

Current studies about fiber shaped organic photovoltaics used different substrate materials such as optical fibers (Do et al., 1994), polyimide coated silica fibers (O'Connor et al., 2008), PP fibers and tapes (Bedeloglu et al., 2009, 2010a, 2010b, 2010c, 2011) and stainless steel wires (Lee et al., 2009).

In order to fabricate photovoltaic fiber with low-cost and high production rate, an approach is using a drawing a metal or metalized polymer based fiber core through a melt containing a blend of photosensitive polymer. A conductor can also be applied parallel to the axis of the photoactive fiber core (Shtein & Forrest, 2008).

In optical fiber concept, photovoltaic fiber takes the light and transmitted down the fiber by working as an optical can. The fiber shaped photovoltaics approach can reduce the disadvantage of organic solar cells, which is trade-off between exciton diffusion length and the photoactive film thickness in conjugated polymers based solar cells, by forming the solar cell around the fiber (Li et al., 2010b).

3.1 Device structures

Organic solar cell materials are generally coated around the fibers concentrically in an order in photovoltaic fibers, as in planar solar cells. The Substrate, active layer and conductive electrodes do their own duties. Recent studies about photovoltaic fibers can be classified in two groups: First one is interested with photovoltaic fibers that were illuminated from outside as in photovoltaic textiles, second one is the study of illuminated from inside the photovoltaic fiber (Zou et al., 2010).

For the outside illuminated photovoltaic fibers, different device sequences and manufacturing techniques were used. A fiber-shaped, ITO-free organic solar cell using small molecular organic compounds was demonstrated by Shtein and co-workers (O'Connor et al., 2008). Light was entered the cell through a semitransparent outer electrode in the fiber-based photovoltaic cell. Concentric thin films of Mg/Mg:Au/Au/CuPc/C_{60}/Alq_3/Mg:Ag/Ag were deposited onto rotated polyimide coated silica fibers having 0.48 mm diameter by thermal evaporation technique in a vacuum (see Fig. 13). The cell exhibited 0.5% power conversion efficiency, which was much less dependent on variations in illumination angle. However, coated fiber length was limited by the experimental deposition chamber geometry.

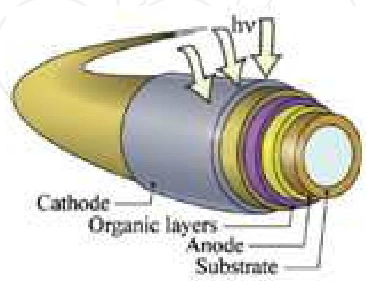

Fig. 13. A flexible polyimide coated silica fiber substrate device, with the layers deposited concentrically around the fiber workers. Reprinted with permission from O'Connor, B.; Pipe, K. P. & Shtein, M. (2008). Fiber based organic photovoltaic devices. *Appl. Phys. Lett.*, vol. 92, pp. 193306-1–193306-3. Copyright 2008, American Institute of Physics.

Bedeloglu et al. developed flexible photovoltaic devices (Bedeloglu et al., 2009, 2010a, 2010b, 2010c, 2011) to manufacture textile based photovoltaic tape and fiber by modifying planar organic solar cell sequence. The non-transparent and non-conductive polymeric materials (PP tapes and fibers) were used as substrate and dip coating and thermal evaporation technique were used to coat active layer and top electrode, respectively. Devices gave moderate efficiencies in photovoltaic tape (PP/Ag/PEDOT:PSS/P3HT:PCBM/LiF/Al) and in photovoltaic fiber (PP/PEDOT:PSS/P3HT:PCBM/LiF/Al) (see Fig. 14). Light entered the photovoltaic structure from the outer semi-transparent cathode (10 nm LiF/Al). Obtained structures that were very flexible and lightweight were hopeful for further studies using textile fibers.

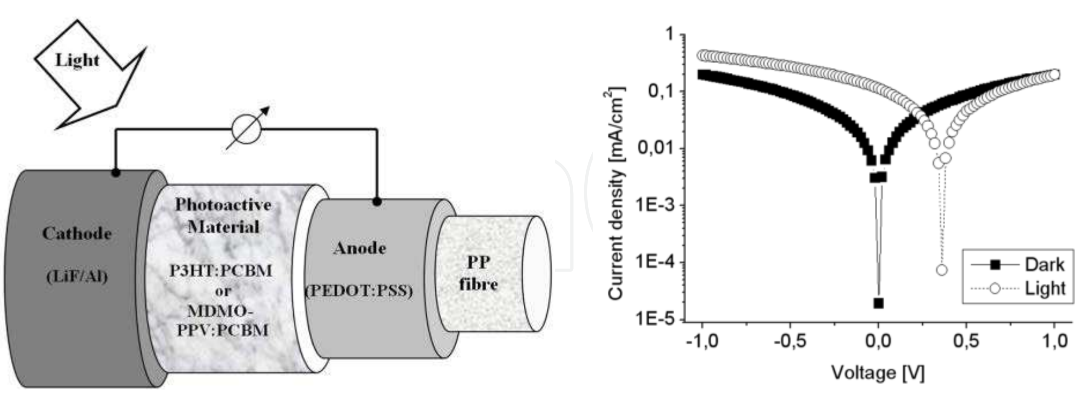

Fig. 14. Schematic drawing of a photovoltaic fiber and I–V curves of P3HT:PCBM -based photovoltaic fibers, lighting through the cathode direction. The final, definitive version of this paper has been published in < Textile Research Journal>, 80/11/July/2010 by <<SAGE Publications Ltd.>>/<<SAGE Publications, Inc.>>, All rights reserved. ©.

Flexible photovoltaic wires based on organic materials can also be produced to be used in a broad range of applications including smart textiles (Lee et al., 2009). In the study, a stainless steel wire used as primary electrode was coated with TiO_x, P3HT and $PC_{61}BM$, PEDOT:PSS materials as electron transport layer, active layer and hole transport layer, respectively (Fig. 15). Another wire as secondary electrode was wrapped around the coated primary wire with a rotating stage similar to commercial wire winding operations. In the best cell, the short circuit current density was 11.9 mA/cm^2 resulting 3.87% power conversion efficiency.

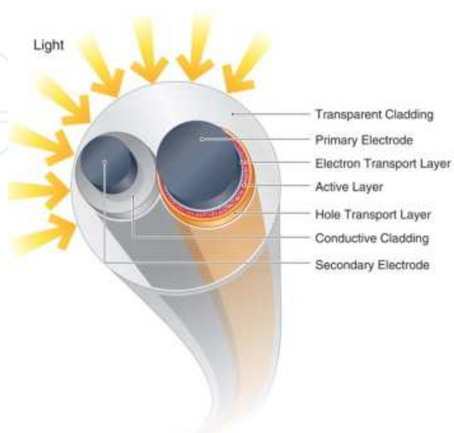

Fig. 15. Schematic of a complete fiber showing the potential for shadowing by the secondary electrode. From Lee, M. R.; Eckert, R. D. ; Forberich, K. ; Dennler, G.; Brabec, C. J. & Gaudiana, R. A. (2009). Solar power wires based on organic photovoltaic materials. *Science*, Vol. 324, pp. 232–235. Reprinted with permission from AAAS.

Many researchers considered photovoltaic fiber design for different function from an optical perspective to capture or trap more light. An optical design was investigated (Curran et al., 2006) to increase the efficiency of photovoltaic device by directing the incident light into the photoactive layer using optical fibers. Prepared fibers are worked up into bundle to confine the light in the device. Polymer based organic solar cell materials are used to develop an optical fiber-based waveguide design (Liu et al., 2007a). P3HT:PCBM is commonly used composite material to form active layer. Carroll and co-workers added top electrode (Al) to only one side of the fiber and tested the photovoltaic fibers under standard illumination at the cleaved end of the fibers. Optical loss into the fiber based solar cell increased as the fiber diameter decreased (See Fig. 16) and increasing efficiency was obtained by the smaller diameter photovoltaic fibers. In their other study (Liu et al., 2007b), performances of the photovoltaic fibers were compared as a function of incident angle of illumination (varied from 0º – 45º) on the cleaved face of the fiber. 1/3 of the circumference was coated with thick outer electrode (LiF/Al) due to fibers having small diameter. Photovoltaic performance of the devices was dependent on fiber diameter and the angle of the incidence light onto the cleaved fiber face.

Using an optical fiber having 400 µm in diameter, microconcentrator cell (Curran et al., 2008) was fabricated to develop an efficient method of light capturing for the optical concentration by using a mathematical based model to pinpoint how to concentrate light within the microconcentrator cell. Behaviour of light between the fiber entrance and active semiconductor layer was investigated. The fiber-based photovoltaic cell, which was a solar collector that utilized internal reflector to confine light into an organic absorber, collected nearly 80% of the incoming photons as current, at ~3 kOhms.cm (Zhou et al., 2009). Li et al. (2010) developed a mathematical model that was also supported by experimental results, for light transmission, absorption and loss in fiber-based organic solar cells using ray tracing and optical path iteration. A patent was developed about photovoltaic devices having fiber structure and their applications (Curran et al., 2009). A tube-based photovoltaic structure was developed to capture optical energy effectively within the absorbing layer without reflective losses at the front and rear surfaces of the devices (Li et al., 2010b). That architecture was enabled that the absorption range of a given polymer (P3HT:PCBM) can be broaden by producing power from band edge absorption.

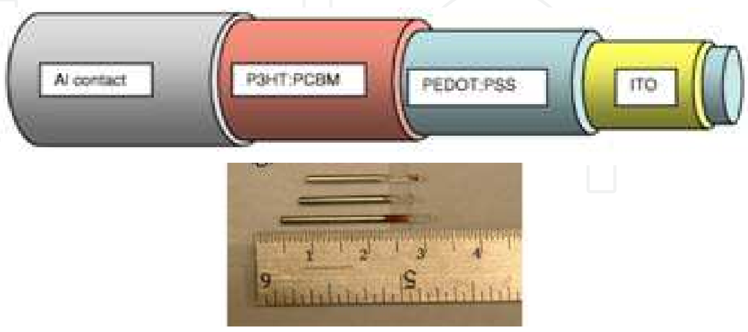

Fig. 16. (a) Schematic diagram showing the device structure (we note that a 0.5nm LiF layer is added below the metal contact but not shown), and (g) optical micrographs of the finished fibers. Reprinted with permission from Liu, J. W.; Namboothiry, M. A. G. & Carroll, D. L. (2007). Fiber-based architectures for organic photovoltaics. *Appl. Phys. Lett.*, Vol. 90, pp. 063501-1–063501-3. Copyright 2007, American Institute of Physics.

4. Conclusions

Polymer solar cells carry various advantages, which are suitable to flexible and fiber-shaped solar cells. However, optimum thickness for photovoltaic coatings and adequate smoothness for the surface of each layer (substrate, photoactive layer and electrodes) are required to obtain higher power conversion efficiencies and to prevent the short-circuiting in the conventional and flexible devices. Suitable coating techniques and materials for developing photovoltaic effect on flexible polymer based textile fibers are also needed not to damage photovoltaic fiber formation in continuous or discontinuous process stages. Many studies still continue for improving stability and efficiency of photovoltaic devices.

Flexible solar cells can expand the applications of photovoltaics into different areas such as textiles, membranes and so on. Photovoltaic fibers can form different textile structures and also can be embedded into fabrics forming many architectural formations for powering portable electronic devices in remote areas. However, optimal photovoltaic fiber architecture and the suitable manufacturing processes to produce it are still in development stage. More studies are required to design and perform for a working photovoltaic fiber.

A viable photovoltaic fiber that is efficient and have resistance to traditional textile manufacturing processes, which are formed from some consecutive dry and wet applications, and, which damage to textile structure, will open new application fields to concepts of smart textiles and smart fabrics.

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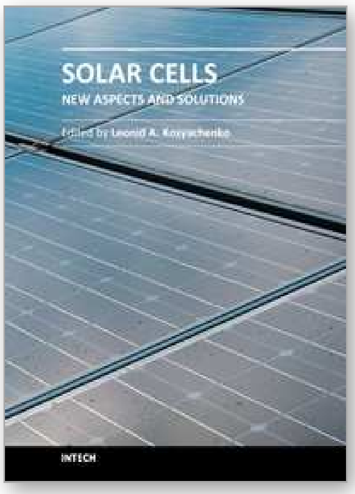

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The fourth book of the four-volume edition of 'Solar cells' consists chapters that are general in nature and not related specifically to the so-called photovoltaic generations, novel scientific ideas and technical solutions, which has not properly approved. General issues of the efficiency of solar cell and through hydrogen production in photoelectrochemical solar cell are discussed. Considerable attention is paid to the quantum-size effects in solar cells both in general and on specific examples of super-lattices, quantum dots, etc. New materials, such as cuprous oxide as an active material for solar cells, AlSb for use as an absorber layer in p-i-n junction solar cells, InGaAsN as a promising material for multi-junction tandem solar cells, InP in solar cells with MIS structures are discussed. Several chapters are devoted to the analysis of both status and perspective of organic photovoltaics such as polymer/fullerene solar cells, poly(p-phenylene-vinylene) derivatives, photovoltaic textiles, photovoltaic fibers, etc.

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