

A Photovoltaic Fiber Design for Smart Textiles

Abstract In this paper, the active photovoltaic fibers consisting of nano-layers of polymer-based organic compounds are presented. A flexible solar cell, including a polymer-based anode, two different nano-materials in bulk heterojunction blends as the light absorbing materials, and a semi-transparent cathode to collect the electrons, was formed by coating these materials onto flexible polypropylene (PP) fibers layer by layer, respectively, to produce electricity. Photovoltaic performances of the fibers were analyzed by measuring current versus voltage characteristics under AM1.5 conditions. The maximum value obtained as the short-circuit current density of photovoltaic fibers was 0.27 mA/cm². The fabrication issues and also possible smart textile applications of these photovoltaic fibers were discussed.

Key words polymer-based organic solar cell, photovoltaic fiber, smart textile, smart fiber

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Today, energy is an important requirement for both industrial and daily life, as well as political, economical, and military issues between countries. While the energy demand is constantly increasing every day, existing energy resources are limited and slowly coming to an end. Due to all of these conditions, researchers are directed to develop new energy sources which are abundant, inexpensive, and environmentally friendly. Solar energy, which is limitless, clean, and renewable, can meet these needs of mankind.

The solar cells, which directly convert sunlight into electrical energy, are very interesting structures for energy generation. In particular, polymer-based organic solar cell materials have the advantages of low price and ease of operation in comparison with silicon-based solar cells. Organic semiconductors, such as conductive polymers, dyes, pigments, and liquid crystals, can be manufactured cheaply and used in organic solar cell constructions easily. In the manufacturing process of organic solar cells, thin films are prepared utilizing specific techniques, such as vacuum evaporation, solution processing, printing [1, 2], or nano-fiber formation [3] and electrospinning [4] at room temperatures. Dipping, spin coating, doctor blading, and printing

techniques are mostly utilized for manufacturing organic solar cells based on conjugated polymers [1].

A conventional organic solar cell (Figure 1) consists of a transparent conductive bottom electrode, e.g., indium tin oxide (ITO) (approximately 120 nm), a poly(3,4-ethylenedioxythiophene:poly(styrene sulfonic acid) (PEDOT:PSS) layer facilitating the hole injection and surface smoothness, an organic photoactive layer to absorb the light, and a metal electrode (approximately 100 nm) to collect charges on the top of the device. In addition, it has to be mentioned that all of these conventional solar cell materials are mainly developed on rigid substrates, such as glass, which are heavy, fragile, and inflexible, and which also have problems of storage and transport [5].

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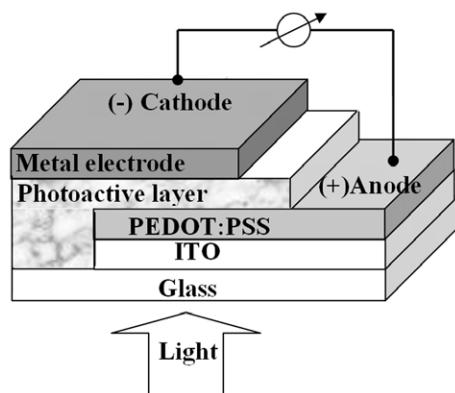


Figure 1 Schematic drawing of a conventional polymer-based organic solar cell on ITO-coated glass-based substrate.

Smart Textiles and Photovoltaic Applications

Both conventional and technical textiles are indispensable products for human daily life with various functions. Research and development activities in the field of textiles are running parallel to the advances in smart materials, which sense all relevant environmental stimuli (electrical, chemical, mechanical, magnetic, optical, etc.) and evaluate, react, or sometimes adapt to those conditions [5]. Smart materials may be in the form of phase-changing materials, chromic materials, shape-memory polymers and alloys, piezo materials, and light-emitting diodes, as well as photovoltaic materials. For example, smart photovoltaic textiles can produce power for electronic devices [6], such as mobile phones, iPods, pocket computers, etc. by collecting sunlight with nano-based materials.

There are limited scientific studies and few commercial applications of wearable solar cells based on inorganic materials [6–11]. In fact, the patching process, which is generally prevailed to develop wearable photovoltaics, may not always meet consumer demands, such as flexibility, comfort, and ease of cleaning. Although, there are some studies about flat textiles integrated with organic solar cells [12, 13], photovoltaic fibers may form energy-harvesting textile structures in any shape and structure. Therefore, some researches have been conducted to develop fiber-based solar cells using inorganic materials, photochemical reactions, etc. [14–17].

In the scientific literature, there are also a few patents, projects [18–20], and research papers [21, 22] about fiber-shaped organic solar cells. To obtain photovoltaic fibers, both polymer and small molecule-based light-absorbing layers were used in previous studies. In one of these stud-

ies, the optical fibers, which are not flexible, were coated with poly(3-hexylthiophene) (P3HT): phenyl-C61-butyric acid methyl ester (P3HT:PCBM)-based photoactive materials. While the light was travelling through the optical fiber and generating hole–electron pairs, the 100 nm top metal electrode (which does not let the light transmit from outside) was used to collect the electrons [21]. In addition, in another study [22] that used small molecule-based materials in an organic active layer of the fiber-shaped solar cell, all layers were deposited onto polyimide coated silica fibers using the thermal evaporation technique in a vacuum. A semitransparent top electrode that let the light enter the device was used and the fibers were rotating during the process in the mentioned study.

In organic solar cells, the most widely used transparent hole collecting electrode material is ITO. However, besides being an expensive material due to the low availability of indium, ITO requires expensive vacuum deposition techniques and high temperatures to guarantee highly conductive transparent layers. The advantages of the application of transparent flexible plastic substrates are restricted due to the thermal and mechanical damages of the ITO deposition process. There are some ITO-free alternative approaches, such as using carbon nanotube (CNT) layers or different kinds of PEDOT:PSS and its mixtures [23–27], or using a metallic layer [28] to perform as a hole-collecting electrode. Therefore, in order to realize polymer-based solar cells, which are completely flexible, and to substitute the ITO layer, this paper focuses on the highly conductive PEDOT:PSS solution as a polymer anode that is more convenient for textile substrates in terms of flexibility, material cost, and fabrication processes compared with ITO material.

In this study, the structure and properties of the photovoltaic fiber converting sunlight into electricity are described [29]. The sun's rays entered into the photoactive layer of photovoltaic fibre by passing through a semi-transparent cathode which is very thin outer electrode consisting of *ca.* 10 nm of lithium fluoride/aluminum (LiF/Al) layers. The materials and techniques used to fabricate the photovoltaic fibres are explained and experimental results are presented. The maximum short-circuit current density was obtained as 0.27 mA/cm². Here, the advantages of photovoltaic fibers and their main diversities from conventional solar cells are also explained and a possible approach to continuous photovoltaic fiber manufacturing is suggested.

Experimental details

Preparation of Photovoltaic Fiber Structure

Photovoltaic fibers were prepared using the PEDOT:PSS layer, the photoactive layer, and a metal-based electrode (Figure 2) [29]. Firstly, a substrate was prepared using a flexible polypropylene (PP) monofilament (obtained from

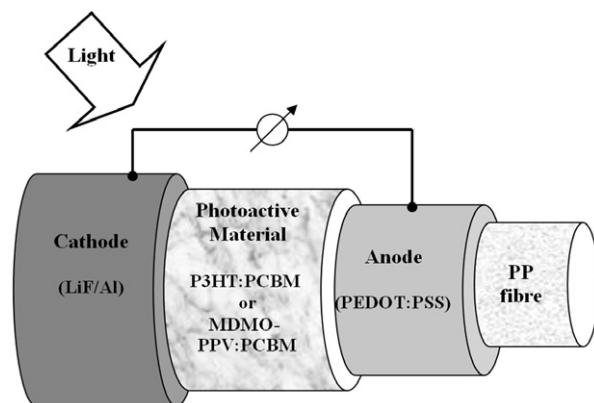


Figure 2 Schematic drawing of a photovoltaic fiber.

SUNJUT, Turkey) with a diameter of 0.59 mm to form the photovoltaic fiber. The non-transparent material and non-conductive monofilament was cut in order to obtain certain length pieces (5 cm long). Then, the fibers were gently cleaned of industrial and environmental contaminants using methanol, iso-propanol, and distilled water, respectively, and dried in nitrogen flow.

In the next step, the solution of highly conductive PEDOT:PSS (Baytron PH 500), which is a doped conjugated poly-

mer with high hole conductivity [30], was prepared as the anode. The chemical structure of PEDOT:PSS is given in Figure 3(a). A PEDOT:PSS mixture was prepared by adding approximately 5% dimethylsulfoxide (DMSO) (Sigma-Aldrich) and approximately 0.1% Triton X-100 (Sigma-Aldrich) to improve conductivity and adhesion to the surface of the PP fiber, respectively, and stirred for 24 hours. Then, the fibers were dip coated with PEDOT:PSS mixture one by one and dried at 50 °C for 3 hours; the samples were stored under the vacuum (in a nitrogen environment) for about 24 hours. Conventional organic solar cells prepared on ITO-coated glass substrates are generally heated after being coated with a PEDOT:PSS layer (>100 °C) to achieve complete drying. However, common textile-based substrates, such as the PP fibers used in this study, are not stable at these temperatures. So, fiber solar cells were processed at lower temperatures. For thermal treatment, a temperature of 50 °C and a longer period of time (3 hours) were enough for complete drying of the PEDOT:PSS solution.

In the third step, two types of photoactive materials were prepared and coated with a similar way to the nano-coating of PEDOT:PSS. To achieve this, a blend of P3HT (Rieke Specialty Polymers), as the conjugated polymer, and phenyl C61 butyric acid methyl ester (PCBM) (Nano-C) materials were prepared by dissolving P3HT and PCBM with the ratio of 1:0.8 in chlorobenzene. In the meantime, a blend of poly[2-methoxy-5-(3,7-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV) (Merck) and PCBM were

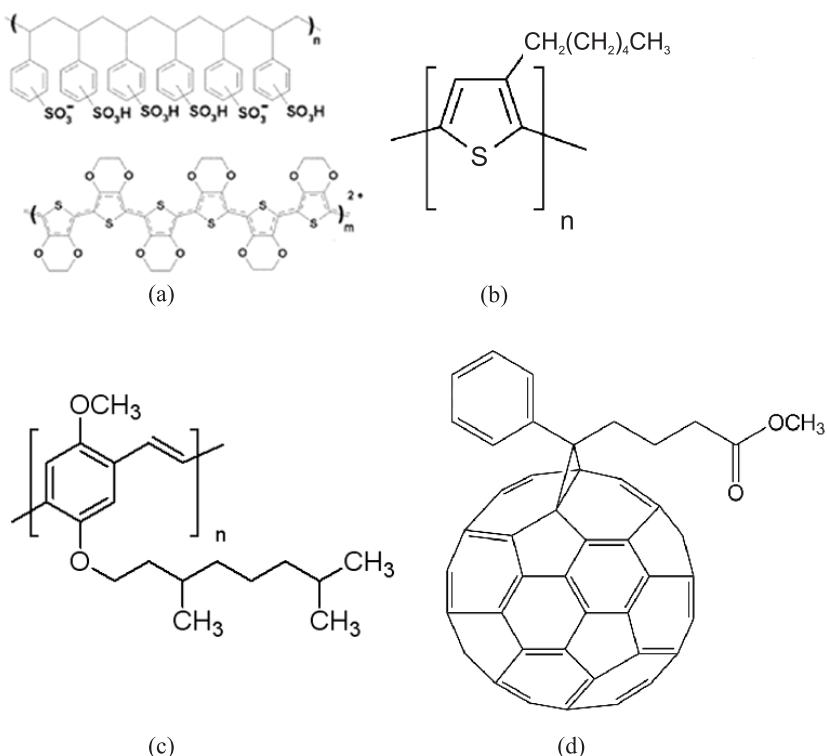


Figure 3 Chemical structures of (a) PEDOT:PSS, (b) P3HT, (c) MDMO-PPV, and (d) PCBM.

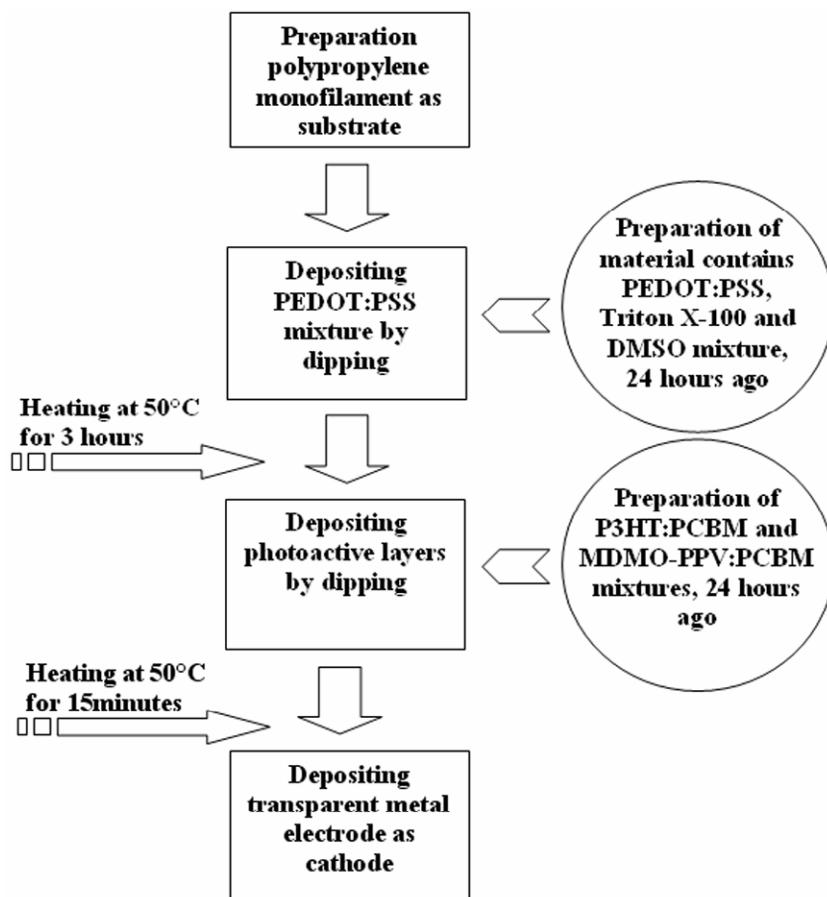


Figure 4 Schematic description of the preparation of a photovoltaic PP fiber.

dissolved with a ratio of 1:4 in chlorobenzene. The chemical structures of P3HT, MDMO-PPV, and PCBM are given in Figure 3(b), (c), and (d), respectively. PEDOT:PSS-coated fibers were coated with the solutions of light-absorbing materials by dipping the fibers one by one in the solution. Then, the samples were stored at 50°C for 15 minutes under vacuum. The conductive top metal electrode was the last layer of the photovoltaic fiber structure. Rectangular masks ($2 \times 8 \text{ mm}^2$) were used during the deposition of metal layers onto the fiber-based solar cells. The fibers were placed in the middle of the holes of the mask and the rest of the holes were covered according to fiber diameter. After the samples were inserted into the evaporation cabin in a glove box (MBraun), transparent metal layers consisting of 0.7 nm LiF and 10 nm Al were deposited on top of the fibers, using the thermal evaporation technique, in a vacuum that is about 5×10^{-6} mbar. The thickness of the metallic layer was controlled and measured by quartz crystal in the cabin of the evaporation machine. The evaporation rate was changed between 0.01–0.2 nm per second. After deposition of the metal layers, before the photoelectrical measurements were carried out in the glove box, small drops of silver

paint were placed onto the electrodes of the photovoltaic fibers in order to develop contacts for better charge conduction. A brief description about the manufacturing procedure of a prototype photovoltaic fiber is given schematically in Figure 4.

Characterization of the Photovoltaic Devices

The electrical performances of photovoltaic fibers were characterized in an inert argon environment inside a glove box system (MBraun). All current–voltage (I – V) characteristics of the photovoltaic devices were measured with a Keithley 236 source measure unit in the dark and under simulated AM1.5 global solar conditions at an intensity of 100 mW cm^{-2} . The solar simulator source (K.H. Steuernagel Lichttechnik GmbH) was calibrated using a standard crystalline silicon diode. Photovoltaic fibers were illuminated through the cathode side. I – V characteristics were measured immediately, the same day, after the photovoltaic fibers were prepared.

Photovoltaic devices are generally characterized by the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}),

and the fill factor (FF). The photovoltaic power conversion efficiency (η) of a solar cell is defined as the ratio between the maximum electrical power (P_{\max}) and the incident optical power and is determined by [1]

$$\eta = \frac{I_{sc} \times V_{oc} \times FF}{P_{in}} \quad (1)$$

In Equation (1), the short-circuit current (I_{sc}) is the maximum current that can run through the cell. The open-circuit voltage (V_{oc}) depends on the highest occupied molecular orbital level of the donor (p-type semiconductor quasi Fermi level) and the lowest unoccupied molecular orbital level of the acceptor (n-type semiconductor quasi Fermi level), linearly. P_{in} is the incident light power density. FF , the fill-factor, is calculated by dividing P_{\max} by the multiplication of I_{sc} and V_{oc} and this can be explained by the following equation [1]:

$$FF = \frac{I_{mpp} \times V_{mpp}}{I_{sc} \times V_{oc}} \quad (2)$$

In the Equation (2), V_{mpp} and I_{mpp} represent, respectively the voltage and the current at the maximum power point (MPP), where the product of the voltage and current is maximized [1].

The ultraviolet-visible absorption spectra of the solid thin films were obtained using a Varian Carry 3G UV-Visible spectrophotometer. The thin films for the measurements were prepared by the spin-coating technique (Spincoater obtained from Specialty Coating Systems Inc. model P6700) on microscope glasses from chlorobenzene solutions containing 10 mg of P3HT and 8 mg of PCBM (in the case of 1:0.8)/ml and 4.5 mg of MDMO-PPV and 18 mg of PCBM (in the case of 1:4)/ml. The absorption spectra for these thin films are given Figure 5.

Both morphology studies and thickness measurement of layers of photovoltaic fibers were performed by scanning electron microscopy (SEM) (LEO Supra 35).

Results and Discussion

Generally, textile-based materials manufactured in fiber or tape forms are colored, not completely transparent. Therefore, these kinds of structures take the light from their outer surface. In this study, considering non-transparent PP monofilament as the substrate of photovoltaic fiber, a semi-transparent top electrode (approximately 10 nm (10 + 0.7 nm)), through which light can be transmitted, was used as cathode. The ITO layer was not used in photovoltaic fiber formation because of the disadvantages of ITO material in terms of brittleness, high cost, and application problems in textiles. The PEDOT:PSS layer, having good conductivity, flexibility, and an easy coating process,

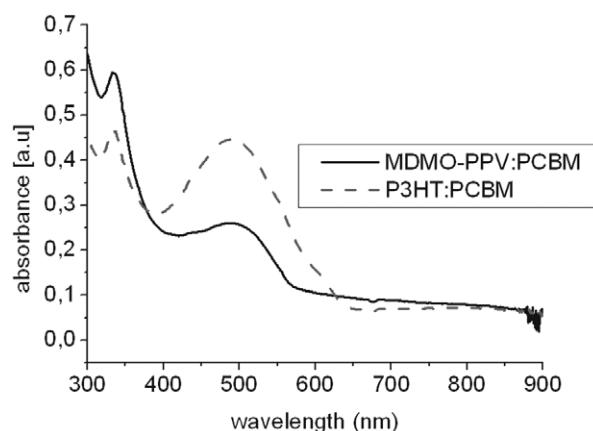


Figure 5 Absorption spectra for solutions of P3HT:PCBM and MDMO-PPV:PCBM in chlorobenzene.

was used successfully to substitute the ITO layer as the anode in this organic photovoltaic fiber formation.

Among the polyolefins, PP is one of the most interesting thermoplastic materials due to its beneficial properties, such as low price and balanced properties and the ability to be recycled. However, poor bondability due to the low surface energy of PP has limited the widespread use of these materials. Therefore, surface modification of these polymers is required. Various surface treatments are used to improve the adhesion of coatings to PP surfaces [31]. Among these methods, using Triton X-100, which is a water-soluble, liquid, and non-ionic surfactant, can be a simple and effective way to improve the wettability of polymer surfaces. In our study, the PP monofilament became highly hydrophilic and was coated with polymeric anode when exposed to a PEDOT:PSS mixture consisting of Triton X-100 mixture for about 5 seconds.

To achieve a highly efficient photovoltaic device, solar radiation needs to be efficiently absorbed. In this type of solar cell the absorption of light causes electron hole pairs, which are split into free carriers at the interface between the donor and the acceptor material. Ultraviolet-visible absorption spectra for thin films of P3HT:PCBM (in 1:0.8 wt/wt ratio) and MDMO-PPV:PCBM (in 1:4 wt/wt ratio) are given in Figure 5. As can be seen from here, the absorption band in the visible range is because of the band-gap absorption of the polymer, while the increase of the absorption for wavelengths shorter than 400 nm is a superposition of the absorption of the polymer and PCBM. As the thickness is the same for both films on the glass, it can be concluded that P3HT:PCBM-based thin film showed better absorption than that of MDMO-PPV:PCBM within the visible range of wavelength (400–700 nm). However, this was reversed below 400 nm due to the fact that the MDMO-PPV:PCBM

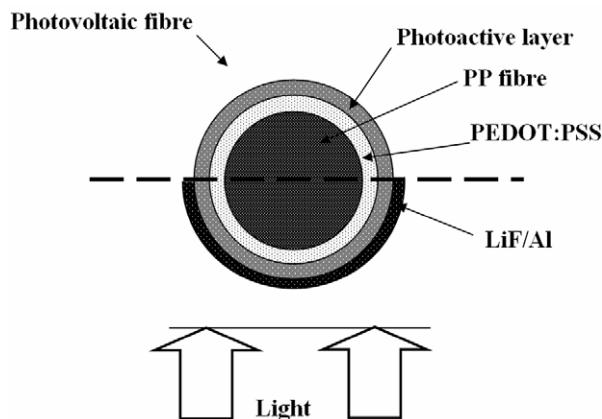
Table 1 Photoelectrical characteristics of photovoltaic fibres having different photoactive layers (MDMO-PPV:PCBM and P3HT:PCBM).

Type of photoactive material	V_{oc} (mV)	I_{sc} (mA/cm ²)	FF (%)	η (%) * 10 ⁻³
P3HT:PCBM	360	0.11	24.5	10
MDMO-PPV:PCBM	300	0.27	26.0	21

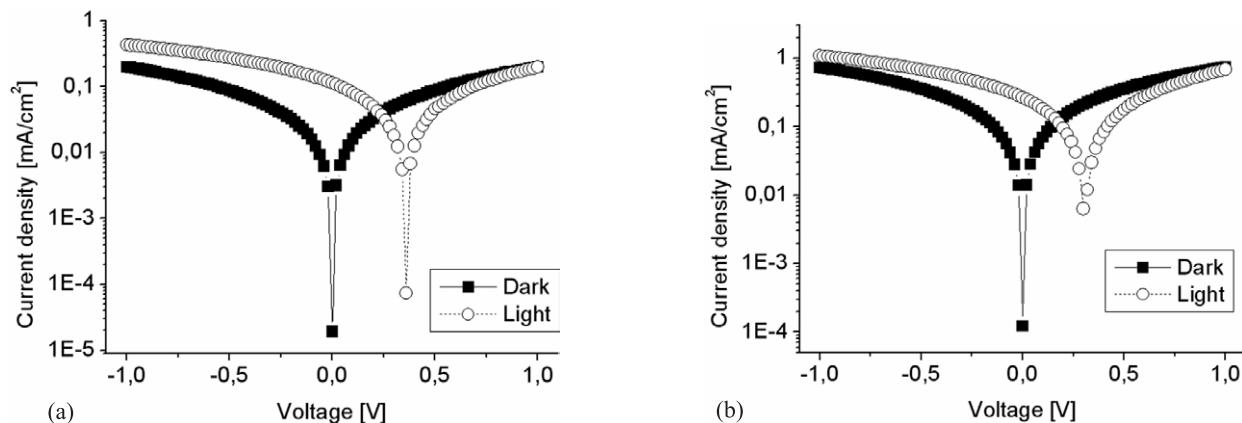
solution contains a higher concentration of PCBM, which has higher absorption below 400 nm.

Active areas for photovoltaic fibers were between 4 and 10 mm². When we consider the photovoltaic fiber structures, it was assumed that they may be used as a kind of textile surface for clothes or coverings and so half of the fiber was illuminated and considered for characterization. In experiments, the photoactive layer on the PP fiber absorbed the light at different angles due to its circular cross section (Figure 6). The current density versus voltage characteristics of the photovoltaic fibers consisting of P3HT:PCBM and MDMO-PPV:PCBM blends are given in Table 1 and demonstrated in Figures 7 and 8. As can be seen from Table 1, the highest values of the photovoltaic parameters are obtained with an open-circuit voltage of 360 mV, a short-circuit current density of 0.11 mA/cm², a fill factor of 24.5%, and a power conversion efficiency of 0.010% from P3HT:PCBM-based photovoltaic fibers. In addition, the MDMO-PPV:PCBM-based photovoltaic fiber gives an open-circuit voltage of 300 mV, a short-circuit current density of 0.27 mA/cm², a fill factor of 26%, and a power conversion efficiency of 0.021%. As can be seen from these results, the power conversion efficiency of the MDMO-PPV:PCBM-based photovoltaic fiber was higher than the P3HT:PCBM-based photovoltaic fiber.

The semi-logarithmic I - V curves in Figure 7 demonstrate the current density versus voltage behavior of photovoltaic

**Figure 6** Schematic demonstration of measurement for photovoltaic characteristics of photovoltaic fibers.

fibers in the dark and under simulated light. In addition, the characteristics of photovoltaic fibers, including open-circuit voltage, short-circuit current density, current, and voltage at the maximum power point under an illumination of 100 mW/cm² (under AM 1.5G conditions), for both devices are shown in linear I - V curves in Figure 8. As can be

**Figure 7** I - V curves of (a) P3HT:PCBM and (b) MDMO-PPV:PCBM-based photovoltaic fibers, lighting through the cathode direction.

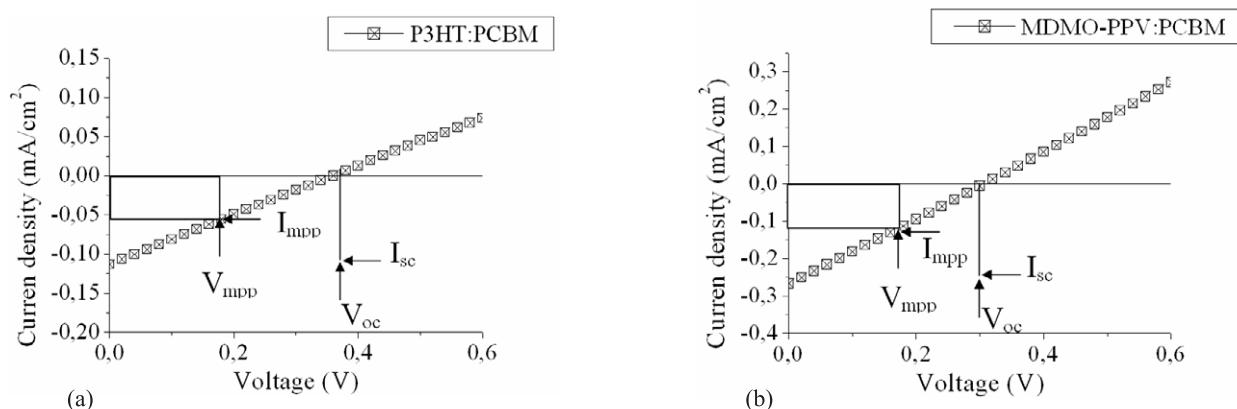


Figure 8 Linear I - V curves demonstrating I_{sc} , V_{oc} , I_{mpp} , and V_{mpp} of P3HT:PCBM- (a) and MDMO-PPV:PCBM- (b) based photovoltaic fibers.

seen from Figure 8, for the P3HT:PCBM-based photovoltaic fiber the maximum power (P_{max}) was obtained as ~ 0.11 W, when values of voltage (V_{mpp}) and current (I_{mpp}) at the maximum power point were 0.18 V and 0.06 mA/cm². In addition, for the MDMO-PPV:PCBM-based photovoltaic fiber, the maximum power was obtained as ~ 0.21 W, when the values of voltage and current at the maximum power point were 0.16 V and 0.13 mA/cm², respectively. The characteristic intersections with the abscissa and ordinate are the open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}), respectively. The maximum power output (P_{max}) is determined by the point where the product of the voltage and current is highest. The maximum power output was obtained higher with the MDMO-PPV:PCBM-based photovoltaic fiber, and a higher power conversion efficiency was also obtained.

The surface photo of the photovoltaic fiber after being coated with the light-absorbing layer is shown in Figure 9. The top view of the PP fiber was taken with 300x magnification. SEM photographs of the photovoltaic fibers are given in Figures 10(a) and (b). SEM analysis shows that the layers of the photovoltaic fibers were more clearly visible with 50000x magnification. The thicknesses of the layers can be also seen from photographs, showing a bright interface line between the polymer anode and the photoactive layer. The metal electrode layer is too thin (~ 10 nm) to be seen on the fiber surface of these images. The film thicknesses of the PEDOT:PSS in P3HT:PCBM and the MDMO-PPV:PCBM-based solar cells are approximately 366 nm and 458 nm, respectively. Generally, the short-circuit current density decreases slightly with increasing thickness of the PEDOT:PSS [32] in solar cells. In this study, thickness measurements of the PEDOT:PSS layer demonstrate that PEDOT:PSS layers are much thicker in both types of devices. An optimization of this layer can increase the

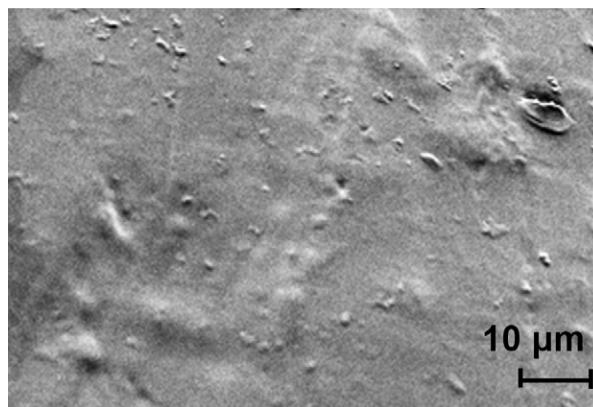


Figure 9 Surface of the photovoltaic fiber after coating a photoactive layer (P3HT:PCBM).

short-circuit current density, resulting an improvement in power conversion efficiency. In addition, a PEDOT:PSS layer as a buffer layer between the bottom electrode and the light-absorbing layer reduces the risk of short circuiting in the case of thin (less than 100 nm) blend layers. The thickness of the photoactive layers in P3HT:PCBM and MDMO-PPV:PCBM-based solar cells were approximately 302 nm and 313 nm, respectively (see Figure 10). In organic solar cells, the external quantum efficiency of the devices depends on the absorption and charge carrier mobility. The optimal layer thickness for many material combinations is too small to absorb all photons within the absorption bands. A thick film can absorb more light compared with a thinner film. On the other hand, the film thickness is limited by a low-charge carrier. As the film thickness

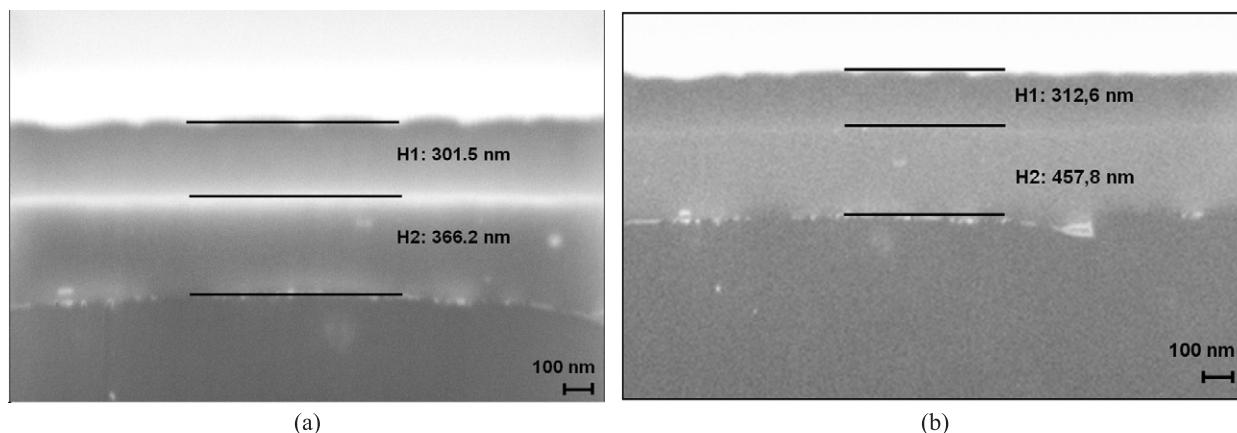


Figure 10 SEM pictures of PP photovoltaic fibers (a) H1: P3HT:PCBM H2: PEDOT:PSS and (b) MDMO-PPV:PCBM, H2: PEDOT:PSS.

increases, the electrical field and the number of charge carriers decrease and so, a decrease in the external quantum efficiency of the devices is observed. Short-circuit current density is inversely proportional to the thickness of the photo-active layer. Therefore, due to limited charge, transport higher currents cannot be obtained in general [33, 34]. As can be seen from Figures 7, 8, and 10 and Table 1, the thickness of the active layer plays an important role in determining the electrical characteristics of the device. Lower electrical results (Table 1, Figures 7 and 8) are probably due to the thickness of the light-absorbing layers. The optimum thickness is required to provide both maximum light absorption and maximum charge collection, at the same time. Thus, optimizing the thickness of the photo-active layer in photovoltaic fibers provides the possibility to increase the power conversion efficiency of a polymer-based

solar cell. The thickness of the layers for optimal photovoltaic fibers can be controlled by solution concentration and dipping time.

In conventional solar cells, since the LiF/Al cathode is ca.100 nm, light cannot enter into the device through the top electrode. Therefore, an ITO-coated glass layer having a transmission of 90% is used at the bottom (ITO as anode) of this kind of solar cell. However, in order to produce a flexible textile structure, a transparent and a flexible outer electrode of about 10 nm (40% of transmission) was utilized in this study, although transmission was lower than that with ITO. By using these flexible layers, PP fiber-based organic solar cells can be curled and crimped without losing any photovoltaic performance from their structure.

After the manufacturing of the PP monofilament, the processes given in Figure 11 are suggested for achieving the

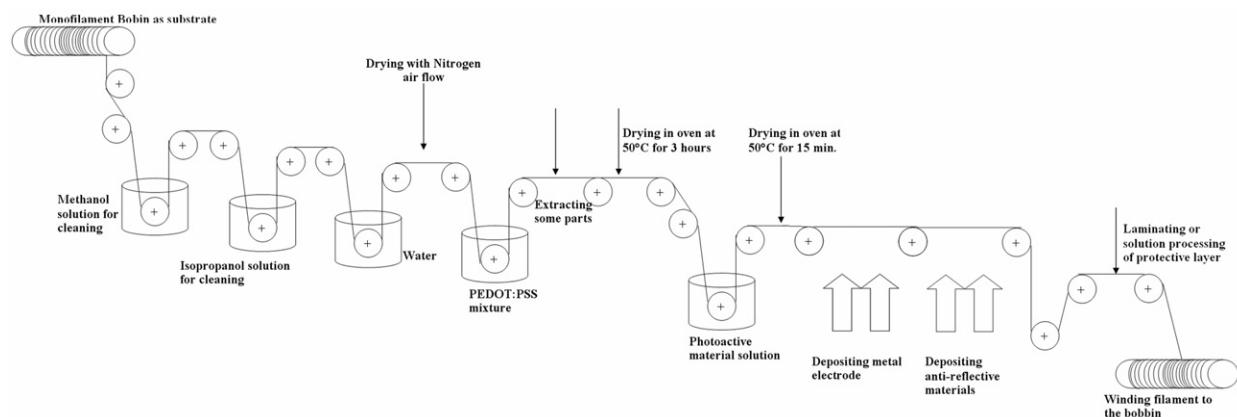


Figure 11 Possible manufacturing processes for photovoltaic fiber.

photovoltaic effect on the fibers. This schematic drawing, showing possible photovoltaic fiber production processes in the industrial scale, demonstrates the liquid solution and drying treatments that are already used in textile finishing processes. Therefore, when a polymer-based organic photovoltaic fiber is produced with high efficiency in the future, the adaptation of fabrication stages into commercialization will not be so troublesome.

In the manufacturing scheme, there are also anti-reflective and protective layer coating steps that will be considered in our future studies. A protective layer will save the organic material from moisture and oxygen. The anti-reflective layer in solar cells can obstruct the reflection of light and also contribute to the device performance. This is an important point that should be overcome in the case of large-scale production of photovoltaic fibers. The manufactured photovoltaic fibers may be also utilized in the manufacture of yarn by spinning and then, a fabric by weaving or knitting processes. While the bobbins are being prepared from photovoltaic fibers for subsequent textile manufacturing processes (spinning, knitting, or weaving), the mechanical forces involved in the weaving, knitting, and cleaning steps may possibly damage the coating layers of the photovoltaic fibers. These delicate structures can be protected by using special layers and techniques to develop usable textile products.

To enhance the power conversion efficiency of the photovoltaic fiber, existing materials and techniques need to be improved. In particular, the optical band gap of the polymers used as the active layer in organic solar cells is very important. Generally, the best bulk heterojunction devices based on widely studied P3HT:PCBM materials are active for wavelengths between 350 and 650 nm (Figure 5). Polymers with narrow band gaps can absorb more light at longer wavelengths, such as infra-red or near-infra-red, and consequently enhance the device efficiency. Low band gap polymers (<1.8 eV) can be an alternative for better power efficiency in the future, if they are sufficiently flexible and efficient for textile applications [35, 36].

Conclusions

In this study, the development of photovoltaic PP fibers using two different kinds of polymer-based photoactive materials was reported. The approach is especially beneficial for photovoltaic textiles, when non-transparent materials are used as substrates of the photovoltaic devices. This study showed that the highly conductive PEDOT:PSS solution and the semi-transparent metallic layer can be used successfully as the anode and cathode of the organic solar cells, respectively, in the case of flexible devices. The maximum open-circuit voltage values for these fibers were obtained as 360 mV and 300 mV for P3HT:PCBM and MDMO-PPV:PCBM-based devices, respectively. In addition, the organic photo-

voltaic fiber based on MDMO-PPV:PCBM yielded the maximum short-circuit current density with 0.27 mA/cm². Although these flexible and cylindrical-shaped devices produced modest power conversion efficiencies due to the materials and modified preparation techniques of solar cells, using a flexible PP fiber as a substrate and a semi-transparent metal layer as the cathode shows promise for future wearable photovoltaic textile applications. For further optimization of the commercial-scale production that enhances the optimized power conversion efficiency of the photovoltaic fibers, some alternatives are to reduce the thickness of the light-absorbing layer and the PEDOT:PSS layer, to use low band-gap materials, infrared light activated materials which would generate power at night, ultraviolet (UV) light selective materials, and to apply anti-reflective and protective nano-coatings. After optimization, this photovoltaic fiber design can be produced in the industry with techniques similar to the textile manufacturing steps and may be used to manufacture smart textiles.

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