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Design of metal wires-based organic photovoltaic cells

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Abstract

An organic photovoltaic architecture based on conducting polymer and organic compounds deposited concentrically on long metal wires were introduced and designed. The light enters to photovoltaic cells through a semitransparent outer electrode. Preliminary tests on the potential to realize the model in conventional flat devices was carried out. Insertion of a hole collecting layer, poly (ethylene dioxythiophene) doped with polystyrene sulfonic acid (PEDOT:PSS), to between the active layer and the outer electrode, and increasing in the wettability of PEDOT:PSS solutions on polymer-thin films were found to increase in power conversion efficiencies of photovoltaic cells. The power conversion efficiency of 0.11% was obtained from the devices tested, which is reasonably high enough for further development in metal wires-based organic photovoltaic cells.

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1. Introduction

Conducting polymers and other semiconducting organic polymers constitute a specific class of compounds with applications in optoelectronic devices such as polymer solar cells and light-emitting diodes [1-5]. These materials possess several advantages over inorganic semiconductors such as easy processability and compatibility with low-temperature processes, large-scale fabrication, and high throughput. Moreover, the use of these materials paves the way to the development of lightweight and flexible devices. In the field of photovoltaic conversion, the bulk heterojunction principle introduced by Sariciftci *et al.* in 1992 [6], based on the spontaneous phase separation between donor and acceptor materials, has become extremely popular, leading to the development of high-performance devices.

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Recently, a power conversion efficiency (PCE) higher than 5% has been demonstrated using a mixture comprising regioregular poly(3-hexylthiophene) (P3HT) as the donor and [6,6]-phenyl C₆₁-butyric acid methyl ester (PCBM) as the acceptor [7,8]. This value for the PCE is considered to be the lower limit for commercial applications.

Fiber-shaped devices are attractive for many researchers in large-scale electronics [9,10], sensing [11], thermoelectric generation [12], and lighting [13]. Coupled with the commodity scale of fiber and textile technology, fiber-based photovoltaic devices can help realize cost-effective, scalable solar energy harvesting. Some fiber-based photovoltaic cells have been reported in the literature, including silicon devices [14] and dye-sensitized solar cells [15]. Thin-film organic photovoltaic cells based on conducting polymer and organic compounds deposited concentrically on long metal wires or fibers were introduced and designed. Previous attempts at fiber-shaped photovoltaic cells involved polymer-based active layers [16], with light incoupling into the active layers along the fiber axis, limiting the fraction of the organic material generating a photocurrent. Another report also studied in fiber-based organic photovoltaic cells, but small molecules were used in the preparation step [17]. In contrast, we designed a fiber-based polymer photovoltaic cell architecture in which light enters the cell through a semitransparent outer electrode. Preliminary tests on the potential to realize the model in flat form was carried out.

2. Experimental Details

2.1. Cell fabrication

In the preliminary experiment, flat devices were fabricated and tested. A glass substrate was sonicated with acetone and ethanol, respectively. After the dryness and UV-ozone treatment, the first electrode was deposited on glass substrate by thermal evaporation method. A TiO_x layer was prepared by spin-coating of titanium tetraisopropoxide (Wako) in ethanol (Wako) at 2000 rpm. The titanium alkoxide was hydrolyzed to be TiO_x under the atmospheric conditions for 30 min. Active layer of blended P3HT (Aldrich, *M_w* 87,500): PCBM (American Dye Source) (P3HT:PCBM = 1:0.8) in chlorobenzene (Wako) was spin-coated at 1000 rpm. Cells obtained were thermal annealed at 110°C for 4 min. In some cells fabricated, poly (ethylene dioxythiophene) (PEDOT) dissolved in organic solvent (Aldrich, 0.5 wt% dispersion in nitromethane, contains *p*-toluenesulfonate as dopant, tetramethacrylate end-capped solution) or PEDOT doped with polystyrene sulfonic acid (PEDOT:PSS) (Baytron P, H.C. Starck, dispersion in water) was spin-coated at 4,000 rpm onto the substrate and heat treated at 110°C for 4 min. The top electrode was finally deposited by thermal evaporation method.

2.2. Photovoltaic characterizations

Energy conversion efficiency was measured under 1 sun, A.M. 1.5 illumination by using the simulated solar light with CEP 2000 (Bunkoh-Keiki Co., Ltd.). The light intensity of the illumination source was adjusted by using a standard silicon photodiode (BS520, Bunkoh-Keiki Co., Ltd.).

3. Results and Discussion

3.1. Design of photovoltaic cell structure

Fig. 1(a) shows the designed cell architecture of metal wires-based organic photovoltaic cells. Several types of metal wires are commercially available, such as aluminum (Al), titanium (Ti), copper (Cu), *etc.* Fig. 1(b) shows examples of commercially available Ti wires and tubes in different sizes. Most layers in

Fig. 1(a), including TiO_x , P3HT:PCBM active layer, PEDOT:PSS, and protective layer can be deposited on metal wires by solution-based process via solution dipping method, which is considered to be cheap and simple. Only ITO layer cannot be easily prepared to be high electrical conductivity electrode by one-step solution-based process. Evaporation of ITO on fabricated cells or use alternating materials instead of ITO may be a good way for this problem.

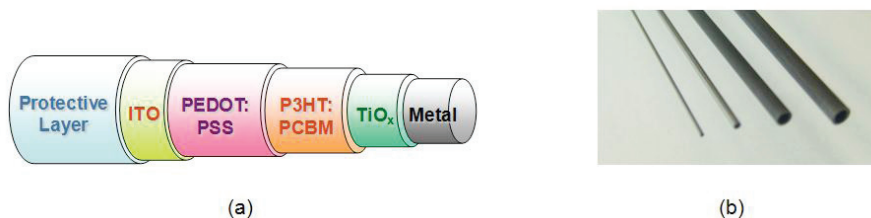


Fig. 1. (a) Designed cell architectures for metal wires-based organic photovoltaic cells. (b) Commercially available Ti wires and tubes (Nittokukan, Japan) in different sizes.

3.2. Preliminary test on flat devices

Instead of ITO, a semitransparent metal was interested to use as an outer electrode. Considered in the step of cell fabrication, structure in Fig. 1(a) is inversed layer of normal-flat organic photovoltaic cells which reported in the literature [7,8]. That is why the first reported of fiber-based organic photovoltaic cells introduced light incoupling into the active layers along the fiber axis, not the outer layer [16].

The structure of inverted cells in fiber form was modified to uncomplicated one for the preliminary test as shown in Fig. 2. The same order of this structure in a conventional flat device as shown in Fig. 3(a) was prepared and tested. Photovoltaic test results are shown in Table 1. Shorting problem was found from the test, because during the photovoltaic test, electrical grips could break out the layer of fabricated cells, hence the direct contact of anode and cathode occurred.



Fig. 2. Modified-uncomplicated fiber-based photovoltaic cells.

Al-half coated on glass substrate was used as an electrode instead as shown in Fig. 3(b). Low conversion efficiency (0.001%) with very low J_{sc} and V_{oc} was achieved from this structure as shown in Table 1. To increase the conversion efficiency, a hole collecting layer should be inserted between P3HT:PCBM active layer and Au electrode. Conventional use of hole collecting layer in organic photovoltaic is PEDOT:PSS [7,8]. However, conventional PEDOT:PSS dissolved in water has very low wettability on the polymer-coated substrate as compared with that on the glass substrate. PEDOT dissolved in organic solvent which has more wettability on the polymer-coated substrate was used to fabricate the flat cells as shown in Fig. 3(c). Photovoltaic characterization (Table 1) shows that cells with PEDOT showed 1 order-higher in conversion efficiency (from 0.001 to 0.017%), due to increasing J_{sc} , V_{oc} , and FF .

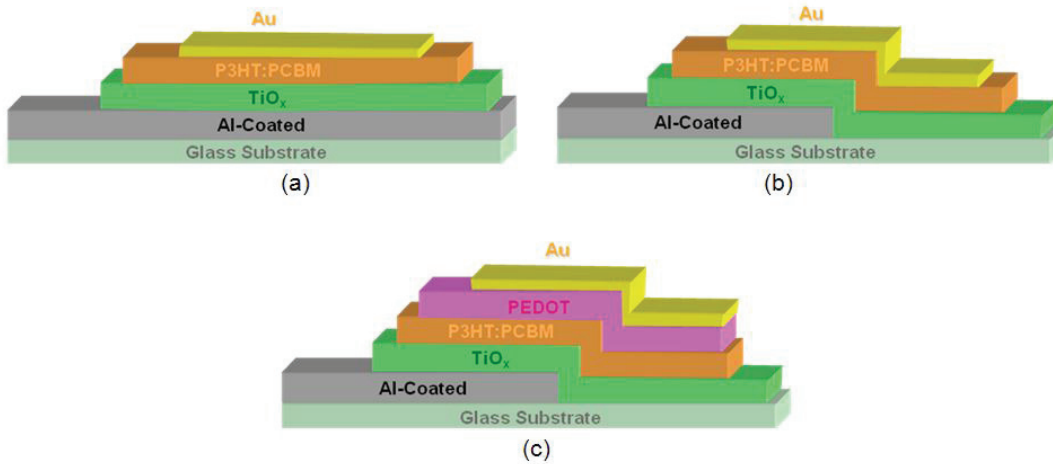


Fig. 3. Structure of conventional flat devices for preliminary photovoltaic tests.

Table 1. Photovoltaic properties of cells investigated at different cell structures [cell names (a)-(c) corresponds to Fig. 3].

Cell structure	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
(a) Al (fully coated) / TiO _x / P3HT:PCBM / Au	-	-	-	-
(b) Al (half coated) / TiO _x / P3HT:PCBM / Au	0.028	0.16	0.33	0.001
(c) Al / TiO _x / P3HT:PCBM / PEDOT / Au	0.072	0.52	0.46	0.017

It was reported previously that mixing of PEDOT:PSS solutions in water with ethanol can enhance the wettability of solutions on organic substrate [18]. In order to study on that point, PEDOT:PSS solutions in water were mixed with ethanol at various mixing ratios in the range of 100:0 to 25:75. The wettability of PEDOT:PSS solutions was found to increase with increasing content of ethanol. However, it was not enough to use these solutions to fabricate uniformly coated PEDOT:PSS film.

PEDOT:PSS solutions have to be fabricated on the polymer-coated substrate which is an organic material. Mixing of PEDOT:PSS solutions in mixed water and ethanol with organic solvent, such as chlorobenzene, which was used to fabricate active layer, may be a good way for improvement in wettability of resulting solutions. Therefore, 10 and 50 μ L chlorobenzene were added to 200 μ L PEDOT:PSS solution in mixed water and ethanol (prepared from the ratio of PEDOT:PSS solution in water to ethanol of 25:75). It was found that the wettability of solutions increased with increasing content of chlorobenzene. At addition of chlorobenzene of 50 μ L, the best wettability was obtained. Therefore, this condition was used to prepare PEDOT:PSS layer for conventional flat devices. The photovoltaic properties of the devices are shown in Table 2. It was found that the conversion efficiency could be enhanced in one order (from 0.017 to 0.110%) by modified solutions of PEDOT:PSS with increasing J_{sc} , V_{oc} , and FF . The efficiency of 0.110% is reasonably high enough for further development in actual metal wires-based organic photovoltaic cells. The optimization of power conversion efficiency, fabrication of ITO, and alternating the form of devices from conventional flat to wires-based cells are needed for next step of study.

Table 2. Photovoltaic properties of cells investigated at different types of PEDOT-based solutions used.

PEDOT solution	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
PEDOT in organic solvent	0.072	0.52	0.46	0.017
PEDOT:PSS in water mixed with methanol and chlorobenzene	0.085	0.89	0.68	0.110

4. Conclusion

An organic photovoltaic architecture based on conducting polymer and organic compounds deposited concentrically on long metal wires or fibers were introduced and designed. The light entered to the cell through a semitransparent outer electrode, which completely different from previously reported works. Preliminary tests on the potential to realize the model in conventional flat devices were carried out. Insertion of hole transporting layer, PEDOT:PSS, to between an active layer and the outer electrode, and increasing in the wettability of PEDOT:PSS solutions on polymer-thin films were found to increase in conversion efficiencies due to increasing J_{sc} , V_{oc} , and FF . The efficiency of 0.11% was obtained from the continual flat devices tested, which is reasonably high enough for further development in real metal wires-based organic photovoltaic cells. The optimization of power conversion efficiency, fabrication of ITO, and alternating the form of devices from conventional flat to wires-based cells are needed for further study. If it is really applicable, reducing in the size of the devices to nanoscale is very interesting to carry out.

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