Title
Improvement of Photovoltaic Properties of Solar Cells with Organic and Inorganic Films Prepared by Meniscus Coating Technique

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The development of renewable energy technologies has been extensively studied to utilize alternative energy sources cleaner and cheaper than traditional fossil fuels.\textsuperscript{1} Moreover, using fossil fuels include oil, coal, and natural gas are causing an environmental problem, such as air pollution, global warming, and climate change.\textsuperscript{2} Therefore, the renewable energy technologies have become an urgent need to affordable, reliable, sustainable and modern energy from clean sources. Among renewable energy, solar energy is the most abundantly available natural resource on the earth. The irradiation of solar energy on the earth is approximately 175,000 TWh, this is more than 10,000 times of the total energy consumption of human.\textsuperscript{3} There have been several ways to convert solar energy to electrical energy. However, direct conversion of the solar energy to electrical energy in a one-step process can be achieved by using the photovoltaic device. The first time of conversion of solar energy into electricity by photovoltaic effect was observed by Edmond Becquerel in 1839.\textsuperscript{4,5} The first success of a silicon $p$-$n$ junction solar cell with a power conversion efficiency ($PCE$) approximately 6\% was reported by Chapin \textit{et al.} in 1954.\textsuperscript{6} The development of solar cell technologies has been increased to reduce fabrication cost and improve the efficiency of solar cells.

Currently, research of new photovoltaic technologies such as dye-sensitized, organic, quantum dots and perovskite solar cells (PSCs) have been extensively studied. Those solar cells can be fabricated by using only simple printing technique based on solution process. The solution-based coating techniques for solution-processed thin-film solar cells have been
attracted to improve their crystallinity, morphology, and performance of the photovoltaic devices for the sake of reduction of the cost and the time for preparations in large area.\textsuperscript{7-11} Many solutions of coating techniques have been proposed and applied for linear motion of the substrate against the meniscus of the solution with constant velocity such as dip coating,\textsuperscript{12-13} doctor blading,\textsuperscript{14-15} and slot-die coating.\textsuperscript{16-17} Among various solution-based coating techniques to prepare the thin-films, the convective deposition method is one of the promising strategies because of its well-ordered, rapid, low material consumption, easy setup, and scalable fabrication of thin-films for large area.\textsuperscript{18-20}

When considering about coating process of organic bulk heterojunction (BHJ) solar cells, the microphase-separated structure and the molecular orientation of organic semiconductors is very important for the photovoltaic performance. The addition of additives in polymers and fullerenes have been used for optimizing the morphology of BHJ.\textsuperscript{21} The high boiling point solvents are the most generally applied in polymer blends such as 1,8-diiodooctane (DIO)\textsuperscript{22-24}, 1,8-dibromoocotane\textsuperscript{25} and 1,2,4-trichlorobenzene (124-TCB).\textsuperscript{26-27} It is well known that the additive of DIO 3 v\% is the most efficient ratio for optimization the nanoscale morphology of the BHJ based solar cells.\textsuperscript{28-32} The DIO additive can selectively dissolve fullerenes, which aggregates to smaller domains and promote a better donor-acceptor network into smaller domains.\textsuperscript{33-34} However, the addition of DIO into BHJ cannot improve molecular packing and orientation of polymer.\textsuperscript{33} Among the various strategies, one of the best effective techniques to improve the molecular orientation of semiconducting polymer is directional solidification by using a solidifying solvent such as 1,3,5-trichlorobenzene (135-TCB).\textsuperscript{35-38} This technique requires solidifying solvent as supporting reagent for nucleation and orientation of the polymer. The improvement of the molecular orientation of organic semiconductors is very important for the enhancement of optical and electrical properties of organic active layer in organic solar cells. As expected, taking account for the advantageous points of directional solidification and convective deposition; a combination of two coating techniques will create more controllable in terms of nucleation density, directions of solidification, microphase-separated structure, and morphology of the polymer blend films.
For planar PSCs, the development of the electron transport layer is one of the most important keys to improving photovoltaic performance and stability. In conventional planar PSCs, titanium dioxide (TiO$_2$) has been widely used as an effective electron transport layer.\textsuperscript{39-40} However, TiO$_2$ has some drawbacks such as poor conductivity\textsuperscript{41} and low electron mobility.\textsuperscript{42} Those disadvantages resulted in the limitation of the electron extraction from perovskite to TiO$_2$ layer and the limited photovoltaic performance of the devices. Many researchers introduced the methods to improve the electron extraction from perovskite to TiO$_2$ such as doping of TiO$_2$ with Zn$^{2+}$, Y$^{3+}$, Zr$^{4+}$, Mo$^{6+}$, and NH$_4^+$,\textsuperscript{43-45} insertion of interlayer with ZnS, C$_{70}$, In$_2$S$_3$, and SnO$_2$ as bilayer systems,\textsuperscript{39,42,46-47} and loading of nanomaterials onto TiO$_2$ with carbon quantum dots and carbon nanotubes as the composites.\textsuperscript{41,48} Wang et al.\textsuperscript{49} applied CsPbCl$_3$:Mn quantum dots as the down conversion layer onto the front side of the PSCs to improve the performance and the stability of planar PSCs. This method showed significant enhancement of the $EQE$ response in the UV region and improvement of the stability under the UV irradiation of the planar PSCs. While AgInS$_2$ is a I-III-VI$_2$ semiconductor with its band gap in the range from 1.8 eV to 2.2 eV.\textsuperscript{50-51} This material has alternative potentials as the light absorber and the fluorescent materials.\textsuperscript{52-54} It was also found that the annealing of the AgInS$_2$ film at 500 °C in air brought the improvement of charge mobilities up to around 6.0 cm$^2$ V$^{-1}$ s$^{-1}$.\textsuperscript{55-56} Therefore, AgInS$_2$ is one of the expecting materials for the improvement of solar cells through mixing with TiO$_2$ as the electron transport layer followed by the annealing at 500 °C in air. As expected, taking account for the advantageous points of AgInS$_2$ quantum dots in TiO$_2$ as electron transport layer will create more effects on the performance and the stability of the planar PSCs in terms of promoting the electron extraction, enhancing the light harvesting and down conversion.

As has been indicated, all the methods presented above as the effective ways to improve optical and electrical properties, both of organic and inorganic materials to enhance the performance of the organic solar cells and planar PSCs.

In this work, convective deposition technique was applied for preparation of organic and inorganic thin films for two kinds of solar cell, one was organic thin-film solar cell, and another was perovskite type solar cell. For preparation of the active layer of the organic thin-
film solar cells, solidifying reagent was added to the mixture of conducting polymer and fullerene to regulate the nucleation density, directions of solidification, microphase-separated structure, homogeneous distribution, and surface morphology of the bulk heterojunction during the thin-film making process. By taking the convective deposition method, improvement of the photovoltaic parameters ($J_{sc}$, $V_{oc}$, $FF$, and $PCE$) of the organic thin-film solar cells were attained. On the other hand, in order to prepare the electron transporting layer of the perovskite type solar cells by the convective deposition technique, quantum dots (QDs) were added to the solution of titanium tetra(isopropoxide)s as the precursor solution of TiO$_2$ and enhancement of the photocurrent generation both in the uv and the visible regions were observed after the addition of QDs. In other words, the combination of convective deposition technique and solidifying reagents or quantum dots led to the improvement of crystallinity, morphology, extent of contacts between the polymer and fullerene, or between the perovskite and TiO$_2$, and resulted in the enhancement of the photovoltaic performance of the devices.

For organic solar cells, the combination of directional solidification and convective deposition techniques were applied for preparation of polymer:fullerene as active layer for organic photovoltaic (OPV) cells. The polymers and fullerenes in this study composed of poly[N-9’-heptadecanyl-2,7-carbazole-alt-5,5-(4’,7’-di-2-thienyl-2’,1’,3’-benzothiadiazole)] (PCDTBT), Poly[4,8-bis(5-(2-ethylhexyl) thiophen-2-yl)benzo [1,2-b:4,5-b’]dithiophene-2,6-diyl-alt-(4-(2-ethylhexyl)-3-fluorothieno [3,4-b]thiophene-)2-carboxylate-2-6-diyl)] (PTB7-Th), and [6,6]-phenyl C$_{71}$ butyric acid methyl ester (PC$_{71}$BM). The 1,3,5-trichlorobenzene (135-TCB) was used as solidifying solvent.

The combination of directional solidification and convective deposition techniques were demonstrated for preparation of organic thin-film solar cells with PCDTBT and PC$_{71}$BM as the active layer. The coating conditions of the concentration of 135-TCB were ranged from 0 to 500 mg mL$^{-1}$ in dichlorobenzene (DCB) followed by the mixing with PCDTBT:PC$_{71}$BM. The effects of 135-TCB as the solidifier in the polymer blend on the optical property, morphology, hole mobility of the polymer blended films and photovoltaic performance were investigated. The nucleation density and directional solidification of PCDTBT:PC$_{71}$BM films were controlled by the amount of 135-TCB and the coating
direction of convective deposition. This fabrication technique can induce directional crystallization of 135-TCB along the coating direction. From the result of cross-polarized optical microscopic images of PCDTBT:PC71BM thin films prepared by convective deposition with different concentrations of 135-TCB when the concentration of 135-TCB was over 250 mg mL\(^{-1}\), anisotropic thin films with fibrous structures were observed. However, the concentration of 135-TCB more than 100 mg mL\(^{-1}\) might be not appropriate for OPVs fabrication because of the large domain sizes of the fibrous structures and high roughness values of the PCDTBT:PC71BM films. Therefore, the optimum amount of 135-TCB in PCDTBT:PC71BM bulk heterojunction (BHJ) solar cells in this case is 20 mg mL\(^{-1}\). The improvement of the photovoltaic performance by using 135-TCB is presumably ascribed to following three reasons: Firstly, the improvement of the light absorption and the external quantum efficiency spectra, which shifted to a longer wavelength region. That enhanced the generation of photocurrent. Secondly, the improvement of morphology and phase separation of PCDTBT and PC71BM made a formation of good continuous pathway for carrier transportation. Thirdly, the improvement of orientation and mobility of the PCDTBT:PC71BM films, which enhanced the charge collection to the electrode. The highest hole mobility of 1.48 x 10\(^{-4}\) cm\(^2\) V\(^{-1}\) s\(^{-1}\) was obtained when 135-TCB was 20 mg mL\(^{-1}\). The photovoltaic cell with 135-TCB at 20 mg mL\(^{-1}\) showed the highest FF and \(J_{sc}\), brought the highest PCE of 3.89 %. That is a 30% improvement of efficiency as compared to the device without 135-TCB (PCE of 2.99 %).

The effect of binary additives of DIO and 135-TCB on phase separation and molecular orientation of PTB7-Th:PC71BM films for the improvement of the photovoltaic performance were investigated. The solvent additive in this study compose of 135-TCB 30 mg mL\(^{-1}\), DIO 3 v\%, and binary additives of DIO 3 v\% + 135-TCB 30 mg mL\(^{-1}\). It was found that the addition of binary additives into PTB7-Th:PC71BM blend improved the phase separated state of PTB7-Th:PC71BM film into small domain sizes with a homogeneous distribution and a continuous interpenetrating network. The PTB7-Th:PC71BM films with 135-TCB 30 mg mL\(^{-1}\) and binary additives indicated the improvement of the out-of-plane orientation. The improvement of the out-of-plane orientation in PTB7-Th:PC71BM film is
beneficial to the charge transport along the out-of-plane direction of the active layer in OPVs. As a result, the photovoltaic parameters were improved by using DIO 3 v% + 135-TCB 30 mg mL⁻¹ as binary additives. The OPVs with DIO 3 v% + 135-TCB 30 mg mL⁻¹ indicated better diode characteristics with the highest RR of $51.7 \times 10^3$ and lower leakage current, which exhibited lowest $R_s$ and highest $R_p$. The PCE of the device with binary additives was increased up to 7.4% as compared with that of without the additives (PCE of 3.0%) and with DIO 3 v% (PCE of 6.9%).

For perovskite solar cells, convective deposition techniques were applied for preparation of composite films of titanium dioxide (TiO₂) and silver-indium-sulfide (AgInS₂) quantum dots as single layer and dual electron transport layer for the planar perovskite solar cells (PSCs).

The effect of AgInS₂ quantum dots in TiO₂ as the electron transport layer of the planar PSCs for the improvement of the photovoltaic performance and the stability were investigated. It was observed that the average value of the root mean square of the surface roughness of the electron transport layer was slightly reduced by the addition of AgInS₂ into TiO₂. The electron mobility of the electron transport layer was enhanced from $1.34 \times 10^{-5}$ cm² V⁻¹ s⁻¹ to $2.05 \times 10^{-5}$ cm² V⁻¹ s⁻¹ after the addition of AgInS₂. The external quantum efficiency (EQE) of the device with TiO₂:AgInS₂ was improved in the region from 300 nm to 750 nm as compared with that of the device without AgInS₂. This result was separately caused by following two factors: one was the efficient light harvesting by AgInS₂ in the region from 300 nm to 450 nm, and another was the improvement of the charge transfer from perovskite layer to TiO₂ through AgInS₂ in the region from 450 nm to 750 nm. The power conversion efficiency of the device was increased from 11.9% to 13.8% by the addition of AgInS₂ at 0.8 mg mL⁻¹ into TiO₂. Storage of the PSCs with or without AgInS₂ with encapsulation in air resulted in long stability for 200 days in terms of the PCEs, which were kept relatively 111% and 92% as compared with the initial values, respectively. Addition of AgInS₂ into TiO₂ brought the improvement of the durability against the photodegradation.
The TiO$_2$/TiO$_2$:AgInS$_2$ QDs as the dual electron transport layers of the planar heterojunction PSCs was prepared for the improvement of the photovoltaic performance and the stability of the devices. From the results in Chapter 4, the best performance of the device with TiO$_2$:AgInS$_2$ QDs under reverse scan showed the lower FF, RR, and $R_p$ than the device with pristine TiO$_2$. Therefore, in Chapter 5 the TiO$_2$/TiO$_2$:AgInS$_2$ QDs as the dual electron transport layers was used for the improvement of the device performance and diode characteristics. It was demonstrated that the addition of AgInS$_2$ into TiO$_2$ indicated a reduction of pinholes at the interspace of the grains of the TiO$_2$. The PL intensity of the perovskite film deposited on TiO$_2$/TiO$_2$:AgInS$_2$ QDs was quenched by the addition of AgInS$_2$ QDs into TiO$_2$. Those results of quenching were probably caused by the improved efficiencies of electron transfer and extraction from the perovskite layer to the electron transport layer. Moreover, a rectification ratio ($RR$) of the planar PSCs were improved by using TiO$_2$/TiO$_2$:AgInS$_2$ QDs as dual electron transport layers. As a result, fill factor (FF) and power conversion efficiency ($PCE$) of the device with TiO$_2$/TiO$_2$:AgInS$_2$ QDs (1.6 mg mL$^{-1}$) increased up to 0.77 and 17.5% as compared with FF (0.73) and $PCE$ (16.3%) of the device with TiO$_2$ single layer. The device with TiO$_2$/TiO$_2$:AgInS$_2$ QDs as dual electron transport layers showed the improvement of the external quantum efficiency in the wavelength region from 300 nm to 750 nm as compared with that of the device with TiO$_2$ single layer. This result probably caused by the enhancement of light harvesting by AgInS$_2$ QDs and the enhancement of the charge transfer from the perovskite layer to the dual electron transport layers. The long-term stability of the PSC with the dual electron transport layers was confirmed when 1.6 mg mL$^{-1}$ of AgInS$_2$ was added, which was followed by the encapsulation and improvement of the retained $PCE$ after the storage of the device in air for 15 days from 11% to 34% was also observed. As has been indicated, the TiO$_2$/TiO$_2$:AgInS$_2$ QDs as dual electron transport layers not only brought the improvement of photovoltaic performance but also the durability against the photodegradation.

As has been indicated, the combination of directional solidification and convective deposition techniques for preparation of organic thin-film solar cells and preparation of inorganic composite thin-films with TiO$_2$ precursor and QDs by convective deposition
techniques were investigated in this work. Throughout this work, it was found that the combination of directional solidification and convective deposition techniques was effective for improving both optical properties and electrical properties of the active layer. The directional crystallization of solidifying reagent was regulated along with the coating direction. The nucleation density was also controlled by changing the amount of solidifying reagent in the bulk heterojunction films. While in the case of inorganic composite thin films, homogeneous distribution of QDs with uniform thickness, and good physical contact with FTO substrates were realized by taking convective deposition method. Addition of QDs reduced the surface roughness, enhanced the electron mobility and improved the efficiency of the electron extraction from the active layer of perovskite through the electron transport layer. Furthermore, the long-term stability of the devices was confirmed when QDs was added by the convective deposition, which was followed by the encapsulation and improvement of the retained PCE after the storage of the device in air. This result implies that the addition of QDs into the electron transport layers not only brought the improvement of photovoltaic performance but also the durability against the photodegradation. Therefore, the convective deposition technique can be effective method for preparation of organic and inorganic thin-films for solar cells for improvement of optical property, electrical property, and long-term stability of semiconducting materials.

References


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