

## Research Article

# Effects of Organic Solvents for Composite Active Layer of PCDTBT/PC<sub>71</sub>BM on Characteristics of Organic Solar Cell Devices

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Bulk heterojunction (BHJ) structure based active layers of PCDTBT/PC<sub>71</sub>BM were prepared by using different organic solvents for fabrication of organic solar cell (OSC) devices. Mixture of precursor solutions of PCDTBT/PC<sub>71</sub>BM in three different organic solvents was prepared to fabricate composite active layers by spin-coating process: chloroform; chlorobenzene; o-dichlorobenzene. Four different blend ratios (1:3–1:6) of PCDTBT: PC<sub>71</sub>BM were adopted for each organic solvent to clarify the effect on the resulting OSC device characteristics. Surface morphology of the active layers was distinctively affected by the blend ratio of PCDTBT/PC<sub>71</sub>BM in organic solvents. Influence of the blend ratio of PCDTBT/PC<sub>71</sub>BM on the OSC device parameters was discussed. Performance parameters of the resulting OSC devices with different composite active layers were comparatively investigated. Appropriate blend ratio and organic solvent to achieve better OSC device performance were proposed. Furthermore, from the UV-Vis spectrum of each active layer prepared using the PCDTBT/PC<sub>71</sub>BM mixed solution dissolved with different organic solvents, a possibility that the nanophase separation structure inside their active layer could appear was suggested.

## 1. Introduction

The 2007 Nobel Prize for peace was awarded to Al Gore and intergovernmental panel on climate change (IPCC). The IPCC has created an ever-broader informed consensus about the connection between human activities and global warming. Furthermore, the IPCC predicted climate change would significantly impact every aspect of human life in this generation [1]. On replying to the issue, in the 34th G8 Toyako summit, it has been agreed to cut carbon emissions by at least 50 percent by 2050 [2]. To realize that goal, development of new energy sources is inevitable. As for new energy, several candidates have been suggested: wind power; solar energy; biomass energy; geothermal energy. Usage of solar energy would be one of the most promising technologies, because the solar energy has the greatest potential to meet world's growing electricity needs compared to other renewable energy sources. Production of solar cells has grown drastically with

annual growth rate of over 40% in recent years, and the output in 2007 has reached over 3.5 GW, which corresponds to 3.5 nuclear power plants of 100 M kW output [3].

From the beginning of organic solar cell (OSC) having power conversion efficiency (PCE) of ~1% [4], various research works have been devoted to enhance the performance [5–7], which is still lower than the marginal threshold of 10% and quite inferior to those of the Si based counterparts. Nevertheless, OSC attracts more and more attention due to advantages such as light weight, flexibility, and easy and low-cost fabrication process [8–10]. Researchers have adopted many ways to achieve high power conversion efficiency (PCE) in OSCs and to cover a large area at low cost [11]. Among the various polymers used, conjugated small-band-gap polymer-based active layers yielded high PCE of 5–9% [12–15]. However, PCEs greater than 10% are needed for commercial viability [16]. Power conversion efficiency (PCE) of OSC device could be possibly enhanced by several

factors: (1) increase of light absorption area; (2) improvement of charge carrier transport; (3) higher efficiency of exciton generation [17]. To improve performance of OSC devices, bulk heterojunction (BHJ) structure with blended active layer of electron acceptor and electron donor has been studied, where interface area between active bilayer could be drastically enlarged and thereby charge separation efficiency could be improved [18–20]. Organic polymer of poly [N-9''-heptadeca-nyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'-benzo-thiadiazole)] (PCDTBT) with deeper highest occupied molecular (HOMO) level and shallow band gap has been focused as a promising material for electron donor layer in BHJ structure [21]. Increase of light absorption area and open circuit voltage ( $V_{oc}$ ) could be achieved by using the PCDTBT as an electron donor material [21]. The extended red absorption of such materials can lead to improved performance via the harvesting of a greater fraction of the sun's radiation. Solar cells based on PCDTBT : PC<sub>71</sub>BM blend show high PCE of 5.6% [22]. Park et al. reported a PCE of 6.1% for a solar cell with a titanium suboxide as an optical spacer between the PCDTBT : PC<sub>71</sub>BM active layer and the cathode [13]. The addition of two dipolar solvents of dimethyl sulfoxide (DMSO) and dimethyl formamide (DMF) to the 1,2-dichlorobenzene solution of PCDTBT led to an improved PCE of 6–7.1% [23]. Wang et al. reported a PCE of 7.1% for devices prepared by spin-coating 1,2-dichlorobenzene : chlorobenzene solution of PCDTBT : PC<sub>70</sub>BM (3:1) with silver nanoparticles used in the active layer [24]. As for an electron acceptor material, a fullerene material of [6,6]-phenyl-C<sub>71</sub>-butyric acid methyl ester (PC<sub>71</sub>BM) has been proposed due to superior electron transporting property [25].

In the present work, varieties of organic solar cell devices were fabricated using currently most representative conjugated polymers of PCDTBT and fullerene of PC<sub>71</sub>BM. Precursor mixture solutions of the PCDTBT and PC<sub>71</sub>BM were prepared with various compositions in three different organic solvents: (1) 1 wt% of chloroform; (2) 2 wt% of chlorobenzene; (3) 3 wt% of o-dichlorobenzene. The precursor mixture solutions were then used for spin-coating process to fabricate BHJ structure based OSC devices. Critical surface parameters of the resulting organic active layers were extracted from surface morphology by using atomic force microscopy (AFM). Standard performance parameters were then investigated for the OSC devices having different blend ratio of PCDTBT and PC<sub>71</sub>BM. Effects of the organic solvents on the characteristic of the resulting OSC devices were discussed to suggest an appropriate organic solvent to achieve better performance parameter.

## 2. Experimental Procedure

**2.1. Preparation of Precursor Solutions for Organic Polymer Active Layers.** To prepare a bulk heterojunction of organic polymer active layers for organic solar cell device, electron donor layer was prepared with PCDTBT having relatively deeper HOMO level of 5.45 eV. In case of electron acceptor, representative fullerene material of PC<sub>71</sub>BM with better

electron transport property was used. It has been reported that morphology of the active layer could play an important role in the performance of the resulting OSC device, which could be influenced by organic solvent and blend ratio for active layers [26–28]. To clarify the influence of the organic solvent on the characteristic and/or the OSC device performance, three different organic solvents were utilized to prepare precursor solution mixtures for blended active layer preparation: (1) chloroform of 1 wt%; (2) chlorobenzene of 2 wt%; (3) o-dichlorobenzene of 3 wt%. Different precursor solution mixtures of PCDTBT and PC<sub>71</sub>BM with various blend ratios were prepared using the organic solvents: (1) PCDTBT : PC<sub>71</sub>BM (1:3~1:6) dissolved in 1 wt% of chloroform; (2) PCDTBT : PC<sub>71</sub>BM (1:3~1:6) dissolved in 2 wt% of chlorobenzene; (3) PCDTBT : PC<sub>71</sub>BM (1:3~1:6) dissolved in 3 wt% of o-dichlorobenzene.

**2.2. Organic Thin Film Solar Cell Device Fabrication.** ITO coated glass (Asahi Glass; 25 Ω/□) was used as substrates. ITO as anode electrode was patterned with 1 cm line width by using a hard mask and exposing them in hydrochloride acid (HCl) vapor ambient. The patterned ITO substrates were cleaned with distilled water to remove residual hydrochloride on the surface. Then the substrates were further cleaned ultrasonically prior to organic layer deposition in neutral detergent, acetone, ethanol, and DI water in each 10 min sequence. As hole transporting buffer layer, a conducting π-conjugated polymer of poly (3,4-ethylenedioxythiophene) : poly (styrenesulfonate) [PEDOT : PSS; Heraeus Clevis P AI4083] thin film of 50 nm thickness was deposited by spin-coating technique. Prior to the PEDOT : PSS deposition, the ITO patterned substrates were exposed to UV in vacuum for 10 min to modify its surface into hydrophilic state for better adhesion. The PEDOT : PSS buffer layer was deposited by using the following spin-coating process: (1) rotation with 3000 rpm for 30 s and (2) drying in oven at 120°C for 10 min. Thickness of the PEDOT : PSS layer was 50 nm.

The prepared precursor solutions of PCDTBT : PC<sub>71</sub>BM mixture were used in a spin-coating process to prepare bulk heterojunction structure active layer of the organic solar cell devices: rotation speed of 1000 rpm and rotation time of 60 s. Then the spin-coated active layers were dried in a vacuum oven at 120°C for 10 min, while the samples based on the organic solvent of o-dichlorobenzene were dried in vacuum for one day. Finally, cathode electrode of the organic solar cell device was deposited by thermal evaporation of Al (100 nm) in vacuum. Effective light absorption surface area of the resulting OSC device was 0.3 cm<sup>2</sup>. Figure 1 shows a schematic structure of the resulting OSC device.

**2.3. Characterization of Organic Active Layers and Organic Solar Cell Devices.** To investigate effect of various blended active layers of PCDTBT : PC<sub>71</sub>BM on performance of the resulting OSC devices, surface morphology of the various PCDTBT : PC<sub>71</sub>BM layers was analyzed by using AFM (Seiko Instruments SPA400-SPI4000). The measured surface parameters were discussed in relation to performance parameters of the resulting solar cell device. Absorption

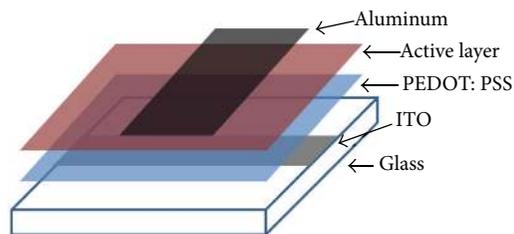


FIGURE 1: Structure of organic solar cell device with heterojunction active layer structure of PCDTBT:PC<sub>71</sub>BM and buffer layer of PEDOT:PSS.

spectra of the blended active layer of PCDTBT and PC<sub>71</sub>BM were investigated by using a UV-Vis spectrometer (Shimadzu UV2450). Standard parameters of the fabricated organic thin film solar cell device were obtained from current density ( $J$ )–applied voltage ( $V$ ) characteristics measured by using an AC meter (Advantest R6441) in a commercial solar simulator: light source from Xenon lamp; air mass filter adjusted for AM1.5; light intensity of 100 mW/cm<sup>2</sup>. All measurements were carried out in atmosphere at room temperature. Open circuit voltage ( $V_{oc}$ ), short circuit current density ( $J_{sc}$ ), fill factor (FF), and power conversion efficiency (PCE) were obtained for the organic solar cell devices, respectively.

### 3. Results and Discussion

Thickness of the active layer plays decisive role in determining the photovoltaic device characteristics. In order to optimize the active layer morphology and blend ratio of PCDTBT:PC<sub>71</sub>BM films and analyze their influence on the device characteristics, OSCs with different blend ratios of 1:3, 1:4, 1:5, and 1:6 were fabricated with various organic solvents. Blend ratios dependant thickness of PCDTBT:PC<sub>71</sub>BM active layer prepared with different solvents of chloroform, chlorobenzene, and o-dichlorobenzene was shown in Figure 2. The thickness of the PCDTBT:PC<sub>71</sub>BM layer gradually decreases while increasing the PC<sub>71</sub>BM acceptor in the case of chlorobenzene and o-dichlorobenzene, whereas it is random for chloroform. We observed that layer thickness varied between 78 and 94 nm with different blend ratios prepared from different solvents. It has been reported that the highest efficiency was obtained based on PCDTBT:PC<sub>71</sub>BM solar cells with thickness of active layers between 70 and 90 nm [29].

Surface morphology of active layer could play an important role for performance improvement of organic thin film solar cell device, which could be influenced by blend ratio of electron donor and acceptor polymer. It has been reported that the surface morphology of the active layer strongly influences the device properties [30, 31]. In addition, thickness and morphology of the polymer active layer could be affected by organic solvent due to appropriate solubility of blended polymer combination. In order to obtain the effect of blend ratios and different solvents on the active layer, AFM analysis was carried out to observe the surface morphology. Although the active layers are prepared with the same spin speed

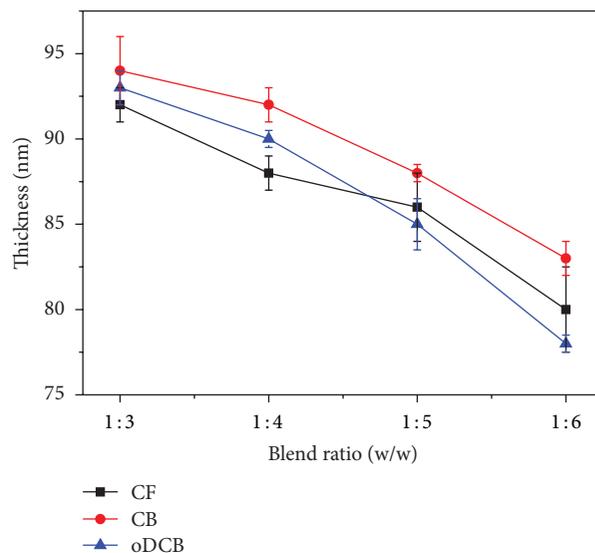


FIGURE 2: Thickness of PCDTBT:PC<sub>71</sub>BM active layer films with different composition prepared in solvents of chloroform (1 wt%), chlorobenzene (2 wt%), and o-dichlorobenzene (3 wt%).

(1000 rpm for 60 s) obvious change in surface morphology could be seen in their AFM images due to various blend ratios and solvents. Figure 3 shows AFM images (2D view) of different active layers of PCDTBT:PC<sub>71</sub>BM prepared with organic solvents of chloroform (1 wt%), chlorobenzene (2 wt%), and o-dichlorobenzene (3 wt%), respectively, where blend ratios of PCDTBT and PC<sub>71</sub>BM were varied from 1:3 to 1:6. As can be seen in these images, PCDTBT:PC<sub>71</sub>BM blend films exhibit large size granular domains with the size of hundreds of nanometers for films prepared from chloroform and chlorobenzene. The size of granular domains increases while increasing the PC<sub>71</sub>BM ratio in the PCDTBT:PC<sub>71</sub>BM active layer. Considering the polymer of PCDTBT presented in this report is amorphous phase, increase of PCBM composition might result in formation of aggregates on the blended active layers, and the aggregate observed for chloroform and chlorobenzene solvent could be thought of as aggregates of PC<sub>71</sub>BM [32]. There was no clear phase separation observed and these types of morphologies with less bicontinuous networks are not suitable for efficient exciton dissociation to the interface of polymer fullerene which was not favorable for charge separation. On the contrary, the PCDTBT:PC<sub>71</sub>BM samples prepared by using another organic solvent of o-dichlorobenzene (Figure 3) reveal no aggregates of PC<sub>71</sub>BM, which could be due to higher solubility of PC<sub>71</sub>BM in o-dichlorobenzene than that in chlorobenzene [23, 33]. When PCDTBT:PC<sub>71</sub>BM films with different ratios were prepared in o-dichlorobenzene, the surface morphology shows remarkable changes as shown in Figure 3. The films contain more elongated fiber-like nanodomains over the entire area. The AFM images of the PCDTBT:PC<sub>71</sub>BM in o-dichlorobenzene indicates well miscibility between PCDTBT and PC<sub>71</sub>BM. With an increase of PC<sub>71</sub>BM content in the films, the domain size of the PC<sub>71</sub>BM aggregates is decreased and phase separation takes place compared to films prepared

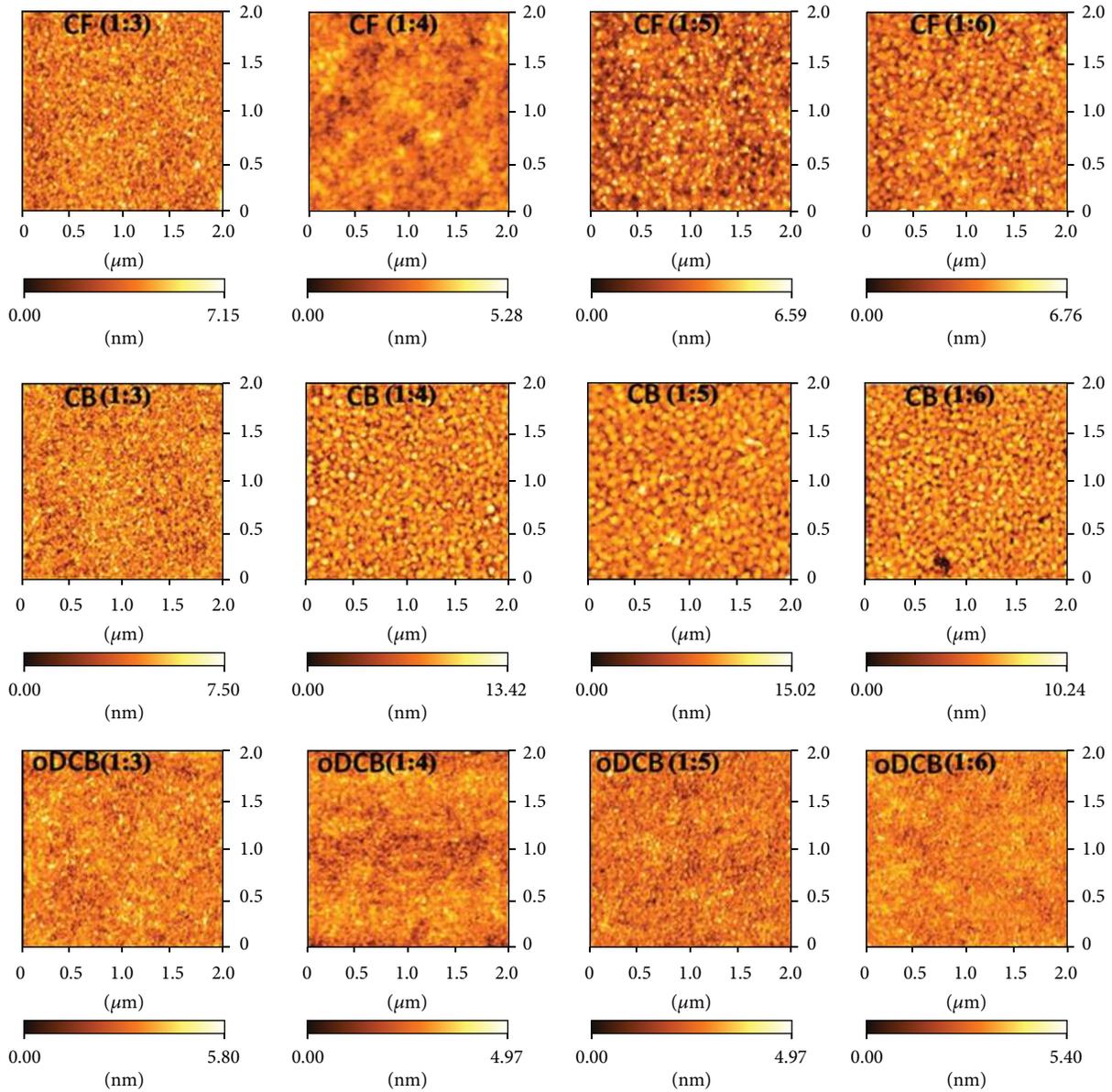


FIGURE 3: AFM images of the PCDTBT:PC<sub>71</sub>BM films prepared by using organic solvents of chloroform (1 wt%), chlorobenzene (2 wt%), and o-dichlorobenzene (3 wt%): blend ratio of PCDTBT and PC<sub>71</sub>BM was varied from 1:3 to 1:6.

with chloroform and chlorobenzene. This can be attributed to low vapor pressure of o-dichlorobenzene (1.2 mm Hg). As it stays long time in thin film before drying, it renders a better mixing ability between PCDTBT and PC<sub>71</sub>BM, leading to the formation of interpenetrating network. Therefore, the large size granular domains remain under control in the films prepared with o-dichlorobenzene than those prepared with chloroform and chlorobenzene, despite increasing the PC<sub>71</sub>BM ratio. In addition, better organization of fiber-like interpenetrating networks of PCDTBT:PC<sub>71</sub>BM restricts overgrowth of large size PC<sub>71</sub>BM aggregates.

Root-mean-square (RMS) roughness of the different PCDTBT:PC<sub>71</sub>BM combinations prepared in different solvents was extracted after the AFM analysis and presented

in Figure 4. RMS surface roughness values measured for 1:3, 1:4, 1:5, and 1:6 PCDTBT:PC<sub>71</sub>BM blend ratios were ~1.02, 0.79, 1.1, and 1.04 nm for chloroform films; ~1.08, 1.98, 2.03, and 1.5 nm for chlorobenzene; ~0.6, 0.74, 0.56, and 0.59 nm for o-dichlorobenzene, respectively. For chloroform films, initially the roughness decreased until 1:4 ratio and increased afterwards, whereas reverse trend was observed for o-dichlorobenzene films. For chlorobenzene films, the roughness increases gradually up to 1:5 ratio and suddenly decreased afterward. The highest roughness for PCDTBT:PC<sub>71</sub>BM blend ratio of (1:5), (1:5), and (1:4) film prepared in chloroform, chlorobenzene, and o-dichlorobenzene was 1.1, 2.03, and 0.74 nm, respectively. It is obvious that the high surface roughness of the film might

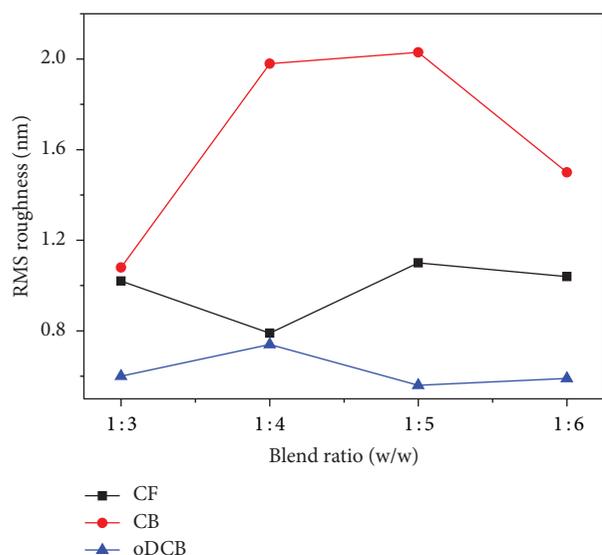


FIGURE 4: Surface roughness values obtained from the AFM images for PCDTBT:PC<sub>71</sub>BM films prepared with organic solvents of chloroform (1 wt%), chlorobenzene (2 wt%), and o-dichlorobenzene (3 wt%).

increase the contact area between the active layer and the contact electrode and thus increase the charge collection. Furthermore, the increased surface roughness may increase internal reflection in the active layer and improve light collection leading to increase in device efficiency [34].

To investigate effect of surface morphology on optical absorbance of active layer of PCDTBT:PC<sub>71</sub>BM, UV-Vis spectra of the active layers prepared by using different organic solvents were investigated. Optical absorbance of organic active layer is directly related to overall performance of the resulting OSC device. Figure 5 shows the UV-vis absorption spectra of PCDTBT:PC<sub>71</sub>BM films prepared from chloroform, chlorobenzene, and o-dichlorobenzene. It is important to note that all these films were spin-coated from the solution with the same rotation speed of 1000 rpm for 60 s. The spectra are not normalized. From Figure 5, the blend layer prepared from chloroform absorbs the less amount of light, whereas layer prepared from chlorobenzene solvent absorbs more light, and o-dichlorobenzene solvent prepared films absorb less amount of light than chlorobenzene solvent, but high absorption takes place at red wavelength region as seen from Figure 5. It is to be noted that the change in film thickness was observed for these solvents. This may be attributed to less viscous nature of the blend solution prepared from chloroform and o-dichlorobenzene; therefore the blend film is thin under the same spin-coating rotation, which causes less light absorption. At the same time, the solution is more viscous when chlorobenzene used as solvent for active layer. Consequently, the film becomes thick and absorbs more light than chloroform and o-dichlorobenzene. It implies that choice of organic solvent and blend ratio of PCDTBT and PC<sub>71</sub>BM could have decisive influence on performance of the resulting OSC device.

The OSC devices were optimized by varying the ratios of the PCDTBT:PC<sub>71</sub>BM and the solvents of blend film.

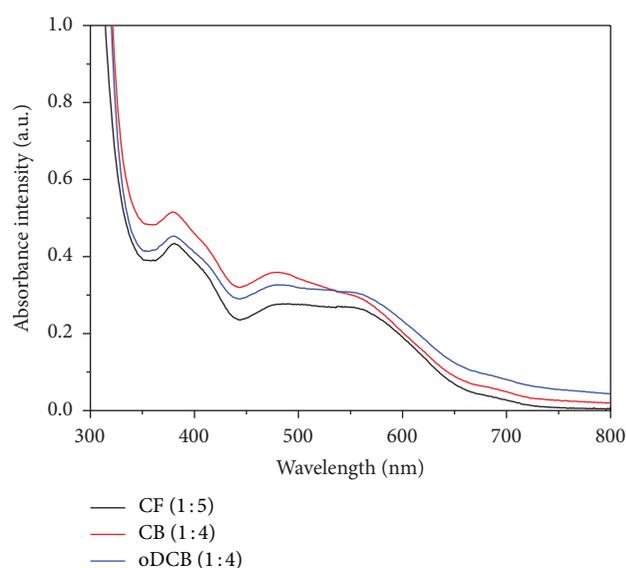


FIGURE 5: Absorption spectra of active layer of PCDTBT:PC<sub>71</sub>BM prepared by using organic solvents of chloroform, chlorobenzene, and o-dichlorobenzene with PCDTBT:PC<sub>71</sub>BM ratios of (1:5), (1:4), and (1:4), respectively.

The photovoltaic parameters obtained for various devices are presented in Table 1. Figure 6 shows the current density ( $J$ )–voltage ( $V$ ) curves under AM 1.5 conditions ( $100 \text{ mW/cm}^2$ ) of PCDTBT:PC<sub>71</sub>BM blend layer prepared from chloroform, chlorobenzene, and o-dichlorobenzene with blend ratio of 1:5, 1:4, and 1:4, respectively.  $V_{oc}$  of all the OSC devices reveals approximately 0.9 V, which corresponds to the difference between the LUMO level of PC<sub>71</sub>BM and the HOMO level of PCDTBT [35]. From the results we observed similar open-circuit voltage ( $V_{oc}$ ) with small random variation with different blend ratios prepared in different solvents of chloroform, chlorobenzene, and o-dichlorobenzene indicating similar characteristics of all solar cells. It is well known that the  $V_{oc}$  is influenced by density of defect states at the interface in solar cells [36]. PCDTBT:PC<sub>71</sub>BM devices with active layer thicknesses between 70 and 90 nm have single state defect trap-assisted centre whereas multilevel recombination centers play major role in  $V_{oc}$  for the layer thickness beyond 110 nm [37]. In our study, blend layer thickness lies between 78 and 93 nm; the change in  $V_{oc}$  may be attributed to possible recombination process via single-defect trap-assisted centers. Moreover, a small reduction in  $V_{oc}$  was observed in other solar cells with increase of PCBM concentration [38, 39]. It might be caused by leakage current, dissociated charge loss at the electrodes due to band bending, and shift of charge transfer state while increasing the PC<sub>71</sub>BM ratio in blend layer [39–41]. Though small variations are seen in  $V_{oc}$ , the  $J_{sc}$ , the FF, and the PCE of the devices vary significantly with blend ratios as seen from Table 1.

The best optimized device for PCDTBT:PC<sub>71</sub>BM with ratio of 1:5 prepared from chloroform as solvent demonstrated the  $V_{oc}$  of 0.90 V, the  $J_{sc}$  of  $5.09 \text{ mA/cm}^2$ , the FF of 0.56, and the PCE of 2.55%. The device with 1:4 blend ratio prepared using chlorobenzene as solvent exhibits best

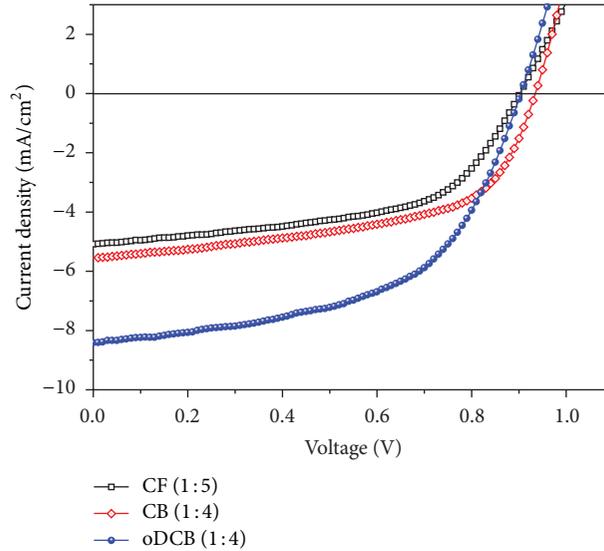


FIGURE 6: Current density ( $J$ )-voltage ( $V$ ) characteristics of ITO/PEDOT:PSS/PCDTBT:PC<sub>71</sub>BM/Al devices with an active layer prepared by using organic solvents of chloroform (D/A; 1:5), chlorobenzene (D/A; 1:4), and o-dichlorobenzene (D/A; 1:4).

performance with the  $V_{oc}$  of 0.93 V,  $J_{sc}$  of 5.55 mA/cm<sup>2</sup>, FF of 0.56, and PCE of 2.91%. For chloroform solvent films the  $J_{sc}$  varied from 4.39 to 5.78 mA/cm<sup>2</sup> when the ratio was increased from 1:3 to 1:4. Further increasing the PC<sub>71</sub>BM concentration  $J_{sc}$  drops suddenly. For chlorobenzene solvent films random variation of  $J_{sc}$  was observed with increasing PC<sub>71</sub>BM amount. This can be attributed to poor active layer morphology with large size domains and no interpenetrating networks, which limits charge carrier transport, resulting in lower  $J_{sc}$ . One of the effective ways to improve light absorption is increasing the active layer thickness and thus increasing the  $J_{sc}$ . However, the device efficiency is dramatically decreased with increasing active layer thickness due to the increased charge recombination in these cells [42]. The device with 1:4 ratio prepared from o-dichlorobenzene as solvent demonstrates the best performance with the  $V_{oc}$  of 0.90 V, the  $J_{sc}$  of 8.41 mA/cm<sup>2</sup>, the FF of 0.55, and the PCE of 4.15%. Relatively higher boiling point of o-dichlorobenzene could possibly be effective to control the nanoscale morphology of blended PCDTBT:PC<sub>71</sub>BM. Effective formation of those interfaces might result in such higher PCE. The same trend of  $J_{sc}$  variations in chloroform solvent film was observed too for o-dichlorobenzene solvent film. The  $J_{sc}$  values for chloroform and chlorobenzene solvent films are low when compared with o-dichlorobenzene films due to absence of nanoscale interpenetrating network in the active layer.

The highest  $J_{sc}$  (8.41 mA/cm<sup>2</sup>) and the PCE (4.15%) were observed (Figure 6 and Table 1) for the PCDTBT:PC<sub>71</sub>BM (1:4) blend film prepared from o-dichlorobenzene solvent, and this implies that the nanoscale fiber-like phase separation morphology (Figure 3) forms effective individual pathways for holes and electrons, which enhance the charge collection efficiency. From Table 1, it is clear that the  $J_{sc}$  values continuously decrease when increasing PC<sub>71</sub>BM concentration in the blend layer. It indicates that concentration of PC<sub>71</sub>BM in the blend film has strong impact on  $J_{sc}$  and FF, which leads to

lower PCE [43]. Regarding the results presented in this study, the blend ratios of (1:5) and (1:4), (1:4) would be preferable for the organic solvents of chloroform, chlorobenzene, and o-dichlorobenzene, respectively. Maximum PCE value observed in the present study is moderate, when compared with highest reported values [44] and this can be improved by further optimization of the devices via adding transport layers, mixture of solvents, and solvent additives.

#### 4. Summary and Conclusions

In summary, varieties of OSC devices were fabricated based on representative blended organic polymer active layers of PCDTBT:PC<sub>71</sub>BM in combination with a conducting  $\pi$ -conjugated polymer of PEDOT:PSS as hole transporting buffer layer. The blended active layers of PCDTBT:PC<sub>71</sub>BM were prepared by spin-coating technique, with different blend ratios of 1:3 to 1:6 being adopted for three different organic solvents of chloroform (1 wt%), chlorobenzene (2 wt%), and o-dichlorobenzene (3 wt%), respectively. Surface morphology of the blended active layers was investigated by AFM, through which surface roughness parameters were studied in relation to blend ratio and organic solvent. It was confirmed that the blend ratio and organic solvent influenced directly the surface morphology of the blended active layers, which in turn could be decisive to performance parameters ( $J_{sc}$ ,  $V_{oc}$ , FF) of the resulting OSC devices. Formation of fine nanoscale morphology structure of blended PCDTBT:PC<sub>71</sub>BM could be influenced by the combination of organic solvent and blend ratio. O-dichlorobenzene (3 wt%) was proved to be the most appropriate choice among the three different organic solvents presented in this study to achieve better OSC performance. The device with (1:4) blend ratio prepared from o-dichlorobenzene as solvent demonstrates the best performance with the  $V_{oc}$  of 0.90 V, the  $J_{sc}$  of 8.41 mA/cm<sup>2</sup>, the FF of 0.55, and the PCE of 4.15%. Effective formation

TABLE 1: Photovoltaic parameters of the OSC devices with different solvents and different PCDTBT : PC<sub>71</sub>BM blend ratios.

| Solvents          | Blend ratio | Thickness (nm) | $J_{sc}$ (mA/cm <sup>2</sup> ) | $V_{oc}$ (V) | FF   | $\eta$ (%) |
|-------------------|-------------|----------------|--------------------------------|--------------|------|------------|
| Chloroform        | 1 : 3       | 92             | 4.39                           | 0.90         | 0.48 | 1.89       |
|                   | 1 : 4       | 88             | 5.78                           | 0.91         | 0.47 | 2.49       |
|                   | 1 : 5       | 86             | 5.09                           | 0.90         | 0.56 | 2.55       |
|                   | 1 : 6       | 80             | 3.55                           | 0.91         | 0.55 | 1.77       |
| Chlorobenzene     | 1 : 3       | 94             | 5.94                           | 0.91         | 0.43 | 2.33       |
|                   | 1 : 4       | 92             | 5.55                           | 0.93         | 0.56 | 2.91       |
|                   | 1 : 5       | 88             | 5.72                           | 0.89         | 0.55 | 2.79       |
|                   | 1 : 6       | 83             | 4.92                           | 0.91         | 0.56 | 2.53       |
| O-dichlorobenzene | 1 : 3       | 93             | 7.60                           | 0.89         | 0.53 | 3.60       |
|                   | 1 : 4       | 90             | 8.41                           | 0.90         | 0.55 | 4.15       |
|                   | 1 : 5       | 85             | 7.36                           | 0.89         | 0.55 | 3.56       |
|                   | 1 : 6       | 78             | 7.19                           | 0.87         | 0.55 | 3.45       |

of fiber-like nanostructure in the active layer might result in higher PCE ( $\eta = 4.15\%$ ) for the case of PCDTBT : PC<sub>71</sub>BM blend prepared from o-dichlorobenzene.

### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

### Authors' Contribution

Paik-Kyun Shin and Palanisamy Kumar contributed equally to this work.

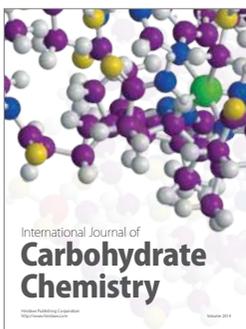
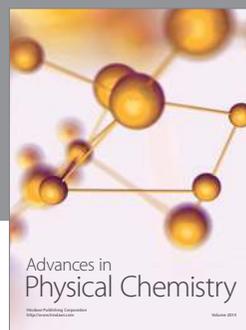
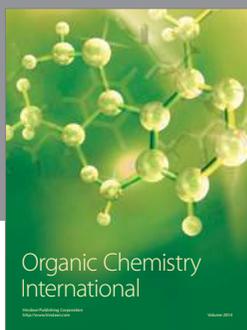
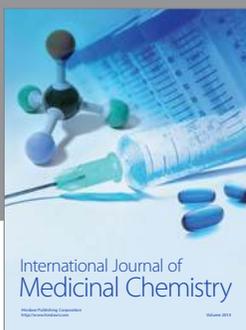
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