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Patternable solution process for fabrication of flexible polymer solar cells using PDMS

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ABSTRACT

PH 500, a highly conducting poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS), is a typical conducting polymer anode material used in organic electric devices. However, it has the disadvantages of low conductivity and poor surface roughness and requires a patterning method for the electrode through including the laser and plasma. In this paper, therefore, the conducting polymer ink for a transparent anode was formulated by adding dimethyl sulfoxide (DMSO) and BYK-333 as the surfactant to enhance the conductivity and surface roughness. The conducting polymer anode was patterned through the application of a new patterning method that used polydimethylsiloxane (PDMS) on a flexible substrate. In addition, a photoactive layer was formed by applying the new patterning method to the conventional brush painting method in which patterning had previously been impossible. The resulting material was compared with the device fabricated by the spin coating method. The fabricated flexible polymer solar cells (PSCs) exhibited short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF) and power conversion efficiency (PCE) values of 4.2 mA/cm², 0.878 V, 26.5% and 0.98%, respectively, which represented an efficiency improvement of 38% over those fabricated by the spin coating method. Meanwhile, the J_{sc} value was increased when the series resistance (R_s) decreased to 150 Ω cm².

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1. Introduction

Polymer solar cells (PSCs) have evolved as a promising and cost effective alternative to silicon-based solar cells [1–7]. Some of the important advantages of PSCs include low cost of fabrication, ease of processing, mechanical flexibility and versatility of chemical structure from advances in organic chemistry. Recently, many studies have been conducted on flexible and lightweight devices using a plastic film substrate instead of a brittle glass substrate. To fabricate the fully plastic PSCs, it is necessary to apply transparent anode using organic-based materials. Indium tin oxide (ITO) is the mostly widely used transparent anode material in optoelectronic devices [8,9]. However, the application of a transparent anode in flexible devices introduces several disadvantages. First, a thin film must be formed through vacuum deposition because it is hard to apply a solution process with an inorganic oxide composite. To increase the conductivity by enhancing the crystallinity of ITO, the annealing temperature of the substrate must be increased to over 300 °C. Hence, there are many restrictions on the glass transition temperature (T_g), substrate size and thickness of the plastic

substrate [10]. In addition, it easily fills off under bending due to its brittle properties [11] and reduces the characteristics of the device by erupting indium with poly(3,4-ethylenedioxythiophene) blended with poly(styrenesulfonate) (PEDOT:PSS, strong acid) (hole transporting material) during the manufacture and the operation of optoelectronic devices [12]. Therefore, other studies have focused on graphene, another inorganic transparent material; thanks to its high conductivity and transparency. However, it has a problem of high sintering temperature (over 1000 °C) at synthesis and is difficult to manufacture in large areas [13]. Therefore, it is necessary to perform a study on the formation of transparent anodes using organic-based materials to fabricate fully plastic PSCs.

A conducting polymer is an organic-based material among various transparent anode materials. It facilitates the solution process and enables the easy and fast fabrication of large-area transparent anodes because there are no constraints in selecting a substrate with low curing temperature [14]. PH 500 (Clevios, Germany), the PEDOT:PSS, which shows highly conducting property among conducting polymers, has high conductivity (ca. 1 S/cm) and transparency. Recently, the conductivity of the electrode fabricated to a flexible substrate by spin-coating the solution, which was formulated by adding 5 wt% of dimethyl sulfoxide (DMSO) has reached about 470 S/cm, which confirmed its potential

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as a transparent anode [15,16]. The conducting polymer anode showed excellent mechanical properties by maintaining the conductivity level even after the bending test at ca.2500 cycles. Even though DMSO improves conductivity by generating a screen effect between PEDOT and PSS [17], it causes phase separation in PEDOT, PSS and solvent, which decreases the surface roughness of the fabricated thin film and thereby reduces the uniformity of the conductivity. Furthermore, the fabrication in a limited manner such as spin coating introduces the disadvantage of an inability for anode patterning. Therefore, it is inappropriate for the fabrication of large-area devices and modules. Hence, several studies have been performed to apply screen printing [18], ink-jet printing [18], slot-die coating [19] and roll-to-roll process [20–23] methods for conducting polymer anode patterning. However, the application of these methods it is difficult in the above processes because of their own viscosity, vapor pressure and concentration of the conducting polymer solution. In the brushing painting method, on the contrary, it is possible to adjust the film thickness and morphology by controlling the brush painting speed regardless of the solution type and concentration [24]. In addition, the brush painting method enables the fabrication of annealing free PSCs efficiently for the mass production of organic devices based on high-speed roll-to-roll systems [25]. Despite its many advantages, the brush painting method has hardly been used because it has been impossible to fabricate modules and large-area devices due to difficulties in the application of the patterning process. Recently, however, we have developed the patterning-enabled brush painting method using a repositionable adhesive in a simple manner. This method has been used to fabricate PSCs that have been patterned with both a hole-collecting layer and a photoactive layer on the ITO-PET film, and the research results have been reported [26]. Consequently, both the hole-collecting layer and the photoactive layer have been successfully patterned. However, it has been impossible to pattern a transparent anode.

In this paper, therefore, PH 500, a highly conducting polymer, was used instead of ITO-PET film and applied as a transparent anode in order to fabricate fully plastic PSCs. Unlike the conventional method in which the conductivity of the conducting polymer is enhanced by adding DMSO, 1 wt% of BYK-333 was added to a conducting polymer ink in order to reduce the surface roughness. After measuring the electrical and optical properties of the formulated conducting polymer ink, the surface morphology was observed using atomic force microscopy (AFM). In addition, a new patterning method was applied using polydimethylsiloxane (PDMS) for conducting polymer anode patterning. Very clear pattern images were obtained using the optical microscope. A photoactive layer was fabricated under the new patterning method using PDMS and its *J*-*V* characteristics and incident photon to current conversion efficiency (IPCE) were compared with those of the conventional device fabricated using spin coating.

2. Materials and Measurements

2.1. Materials

The PDMS used in the patterning of the anode and photoactive layer was supplied by Dow Corning (Sylgard 184). The PH 500, used as the conducting polymer for the transparent electrode, was from Clevios. The DMSO and the surfactant BYK-333 used in forming the conducting polymer ink were purchased from Aldrich and BYK-Chemie GmbH, respectively. The chemical structure of BYK-333 is shown in Fig. 1(a). In addition, PC₇₁BM, an acceptor material used in the photoactive layer, was purchased from Nano C. The donor material that was used in the photoactive layer, poly[N-9'-heptadecanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-

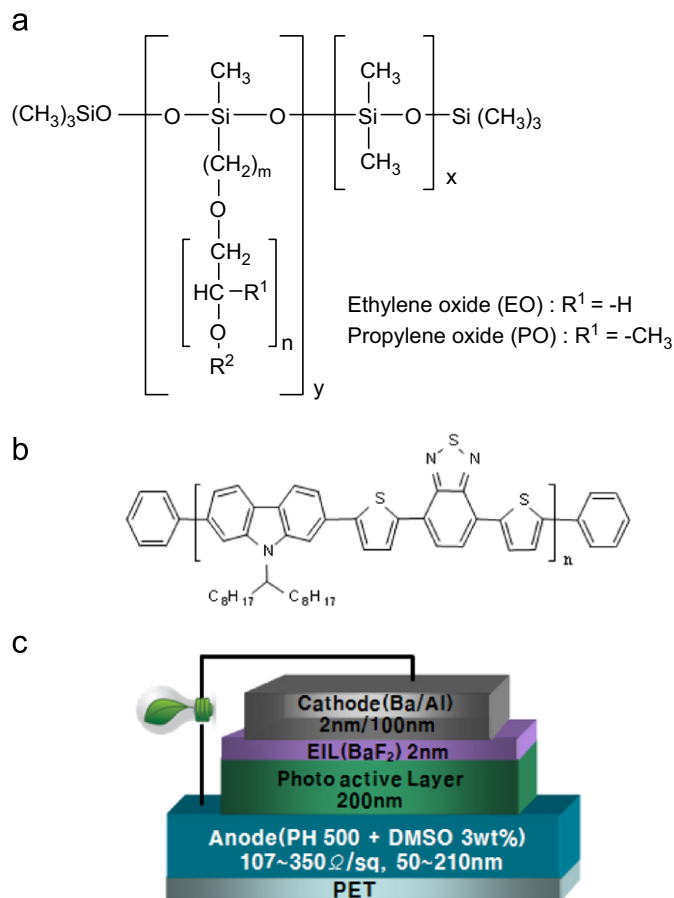


Fig. 1. (a) Chemical structure of BYK-333 and (b) PCDTBT; (c) Structure of flexible PSCs in this study.

2',1',3'-benzothiadiazole)] (PCDTBT), is shown in Fig. 1(b) and was synthesized in accordance with the method mentioned in the literature [27]. The number average molecular weight (*M_n*) of PCDTBT was 34.5 kg/mol, the weight average molecular weight (*M_w*) was 72.4 kg/mol and PDI value was 2.1.

2.2. Measurements

All thin films were fabricated using a GMC2 spin coater (Gensys, Korea), and their thickness was measured using an Alpha-Step 500 surface profiler (KLA-Tencor). The absorbance, transmittance and electrical properties of the thin film were measured using an Agilent 8453 UV-visible spectroscope (HP Agilent) and a 4-point probe station (MST6000C), respectively. In addition, the optoelectronic properties of the fabricated device were characterized with a Keithley 2400 source meter unit (Keithley) and solar simulator (Newport). The thin film morphology of the fabricated device was measured by AFM (PSIA XE-150).

3. Experimental part

3.1. Cleaning of PET film

To clean the PET film (125 μm, SKC), sonication was performed using a detergent (Alconox[®] in deionized water, 10%), acetone, isopropyl alcohol and deionized water in the order listed, for 20 min each. The moisture was removed by blowing thoroughly with N₂ gas. In order to ensure the complete removal of all of the remaining water, the ITO was baked on a hot plate for 10 min at

100 °C. For the hydrophilic treatment of the PET surface, it was cleaned for 10 min in a UVO cleaner.

3.2. Formulation of conducting polymer ink for the transparent anode and film formation

For fabrication of the conducting transparent anode, 1–5 wt% of DMSO was added as an additive to enhance the conductivity of PH 500 as the conducting polymer. The conducting polymer ink was then formulated by adding 1 wt% of the surfactant BYK-333 to enhance adhesion with the PET substrate and uniformity of film and conductivity.

To measure the electrical properties and transmittance according to the film thickness, the conducting polymer ink, which had been filtered with 5 µm polytetrafluoroethylene (PTFE), was spin-coated on the cleaned PET film at 3,000 rpm for 1–4 times, and then annealed at 120 °C for 20 min. The thickness of the thin film, electrical properties and transmittance were measured using the surface profiler, 4-point probe station and UV–visible spectroscopy, respectively, described above.

3.3. Solvent resistance test of the conducting film and photoactive layer

To eliminate the PDMS that was used in the patterning of the anode and active layer, it was rinsed with hexane. To measure the solvent resistance of the conducting film and photoactive layer, both the conducting polymer ink and the photoactive ink were coated on the cleaned PET film at 3000 rpm and 500 rpm, respectively. To remove any residual solvent, it was annealed at 120 °C for one hour and a 160 nm-thick film was obtained. After rinsing the fabricated thin film with hexane, the film absorbance before and after rinsing was measured using UV–visible spectroscopy.

3.4. Fabrication of flexible PSCs by patterning method using PDMS

3.4.1. Patterning method of the conducting polymer anode

The patterning method of the conducting polymer anode is shown in Fig. 2(a). For anode patterning, a perforated pattern metal mask was fabricated out of SUS 304 stainless steel. PDMS was coated on the opposite side of the perforated pattern metal mask using the brush painting method. The mask was then attached to the cleaned

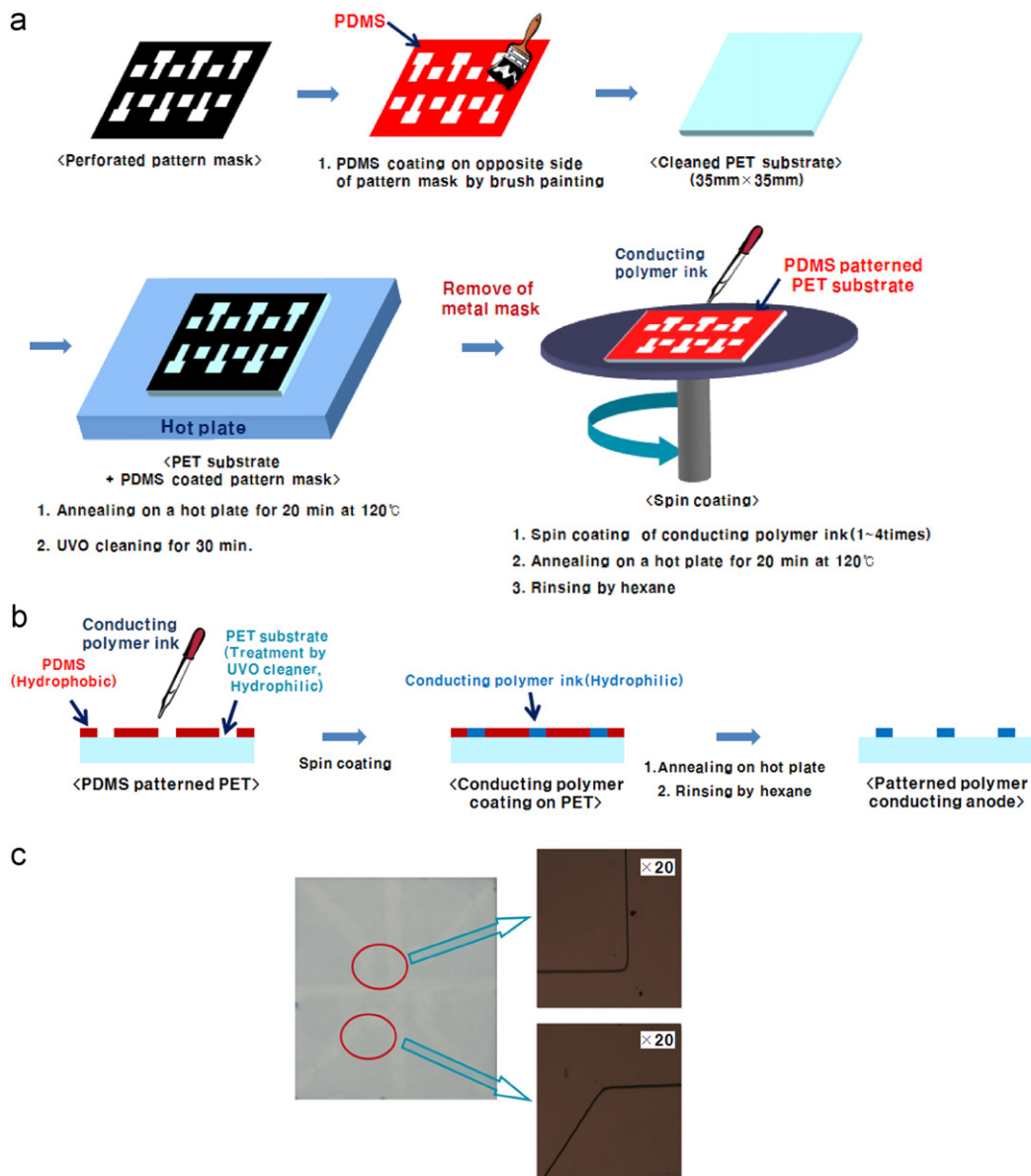


Fig. 2. (a) Patterning method of conducting polymer anode, (b) principle of conducting polymer anode patterning method and (c) clear patterned conducting polymer anode.

PET substrate (35 mm × 35 mm) with the coated side downward. To facilitate transfer of the PDMS coated on the mask into the PET substrate, it was annealed on the hot plate at 120 °C for 20 min and then cleaned for 30 min using the UVO cleaner to render the hydrophobic PET substrate hydrophilic. After removing the mask, we could obtain transcribed PDMS pattern of 1 μm thickness. The conducting polymer ink for the anode, which was blended PH 500, DMSO (3 wt%) and BYK-333 (1 wt%) on the PDMS-patterned PET substrate, was spin-coated at 3000 rpm for 1–4 times and then annealed on the hot plate at 120 °C for 20 min. After eliminating PDMS by rinsing the substrate with hexane, it was annealed on the hot plate at 120 °C for 10 min. Thus, the patterned conducting polymer anode was fabricated.

3.4.2. Patterning method of the photoactive layer

The patterned method of the photoactive layer is shown in Fig. 3. Similar to the anode, a perforated pattern metal mask was prepared out of SUS 304. After coating the PDMS on the opposite side using the brush painting method, it was attached to the anode-patterned PET substrate. To facilitate transfer of the PDMS coated on the mask into the PET substrate, it was annealed on the hot plate at 120 °C for 20 min and then cleaned for 30 min using the UVO cleaner to render the substrate hydrophilic. PCDTBT and the acceptor material PC₇₁BM were blended (0.5 wt% of concentration) in ortho-dichlorobenzene in the ratio of 1:4 and heated at 90 °C for 30 min. The masked substrate was put on the hot plate at 50 °C, and the photoactive ink was coated at 1 cm/s using the brush painting method to produce a 150 nm-thick film. To remove the residual solvent and increase the crystallinity of the polymer, it was annealed at 140 °C for 10 min, after which the residual PDMS was removed by rinsing with hexane and annealed on the hot plate at 120 °C for 10 min for patterning of the photoactive layer. For comparison with the brush painting method, the photoactive ink was coated on the PDMS-patterned substrate and spin-coated at 500 rpm to obtain a 150 nm-thick film. Just like the brush painting method, it was annealed at 140 °C for 10 min to enhance the crystallinity of the polymer and remove any residual PDMS by rinsing with hexane.

3.4.3. Deposition of cathode

To form the cathode on the photoactive layer, BaF₂ (0.1 Å/s, 2 nm), Ba (0.2 Å/s, 2 nm) and Al (5 Å/s, 100 nm) were thermally deposited in sequence in a high vacuum chamber (1 × 10⁻⁶ torr or less). To protect both organic and electrode layers from H₂O

and O₂, respectively, a getter was attached to the inside of the glass cover and encapsulated. The characteristics of the device were evaluated and the structure of the fabricated device is shown in Fig. 1(c).

3.5. Characterization of PSCs

The devices were evaluated at 298 K using a Class A Oriel solar simulator (Oriel 96000 150 W solar simulator) having a xenon lamp that simulates AM 1.5G irradiation (100 mW/cm²) from 400 to 1100 nm. The instrument was calibrated with a monocrystalline Si diode fitted with a KG3 filter to bring spectral mismatch to unity. The calibration standard was calibrated by the National Renewable Energy Laboratory.

4. Results and discussion

Table 1 presents the film characteristics according to the formulation of the conductive ink that was used as the transparent anode in the flexible substrate using the solution process. To increase the conductivity of the conducting polymer PH 500, a thin film was fabricated by adding 1–5 wt% of DMSO, a polar solvent with high dielectric constant. In terms of the film's electrical properties, which were measured using the 4-point probe station, sheet resistance decreased while the conductivity increased with increasing DMSO content. In other words, the conductivity of the DMSO, a polar solvent with high dielectric constant, was increased by reducing the Coulombic interaction between the counter ion and the charge carrier through a strong screen effect between positively

Table 1
Electric performance of conducting polymer films.

Conducting polymer ink	Sheet resistance [Ω/sq]	Conductivity [S/cm]	RMS[nm]
PH500+DMSO 1 wt%	1761 ± 30	114 ± 2	0.2
PH500+DMSO 2 wt%	874 ± 35	230 ± 8	0.453
PH500+DMSO 3 wt%			
without BYK-333	399 ± 30	500 ± 40	0.690
with BYK-333	350 ± 5	571 ± 7	0.358
PH500+DMSO 4 wt%	315 ± 28	633 ± 63	1.532
PH500+DMSO 5 wt%	209 ± 25	970 ± 116	3.254

Thickness: 50 nm, Annealing: 20 min at 120 °C.

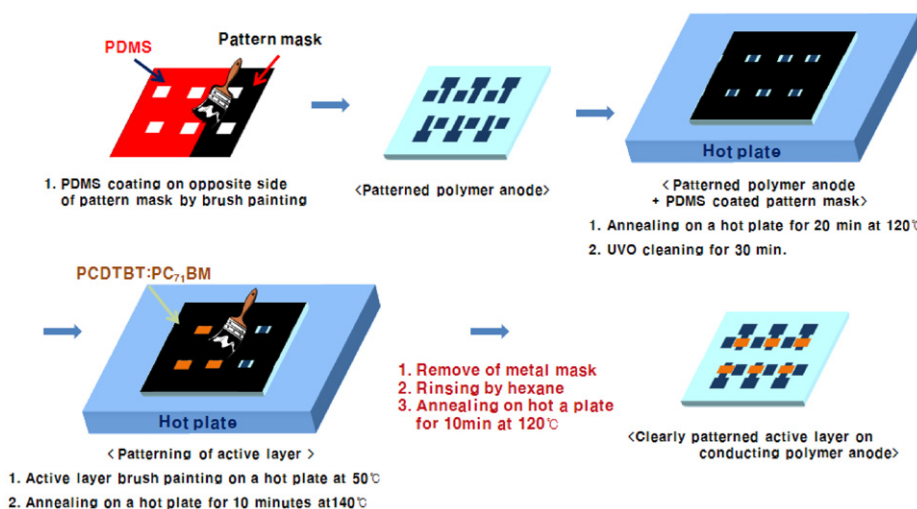


Fig. 3. Patterning method of photo active layer.

charged PEDOT and negatively charged PSS dopant [28]. However, even though the electrical properties increased with increasing DMSO content, the root mean square (RMS) of the film was increased. In other words, the uniformity of the thin film was decreased by spin coating due to the occurrence of phase separation among PEDOT, PSS and DMSO. To improve the film's uniformity, a thin film was fabricated by adding BYK-333, a surfactant that can improve slip, to the conducting polymer ink. BYK-333 is the surfactant of the silicone base material. It includes the hydrophilic group (polyethylene oxide) and hydrophobic group (polypropylene oxide) altogether (Fig. 1(a)). Therefore, the wettability between substrate and the conducting polymer ink was improved. As a result, the surface roughness was reduced. In the case of PH 500 to which 3 wt% of DMSO was added, as shown in Table 1, the conductivity was slightly increased by the addition of 1 wt% of BYK-333. In particular, the film uniformity was significantly increased according the AFM measurement. Fig. 4 shows the

surface morphology, which was observed through the AFM. Fig. 4(a) reveals the surface morphology of the thin film to which 3 wt% of DMSO was added. The DMSO addition produced coagulated particles of PEDOT and PSS. As the DMSO contents were increased, both the sheet resistance and the conductivity improved. As shown in Figs. 4(b) and 4(c), however, many coagulated particles can aggravate the surface morphology, which led to the severe variation that was observed between the sheet resistance and conductivity. As shown in Fig. 4(d), however, when 1 wt% of BYK-333 was added to the sample (PH 500 to which 3 wt% of DMSO was added), a smooth surface was observed on the thin film. In the sample with a DMSO content of 4 wt% or more, however, no improvement was observed in terms of surface roughness and electrical properties, despite the addition of BYK-333. In the sample with 3 wt% of DMSO, the surfactant BYK-333 prevented both PEDOT and PSS from being coagulated by increasing the ink wettability. In addition, BYK-333 played the role of preventing the phase

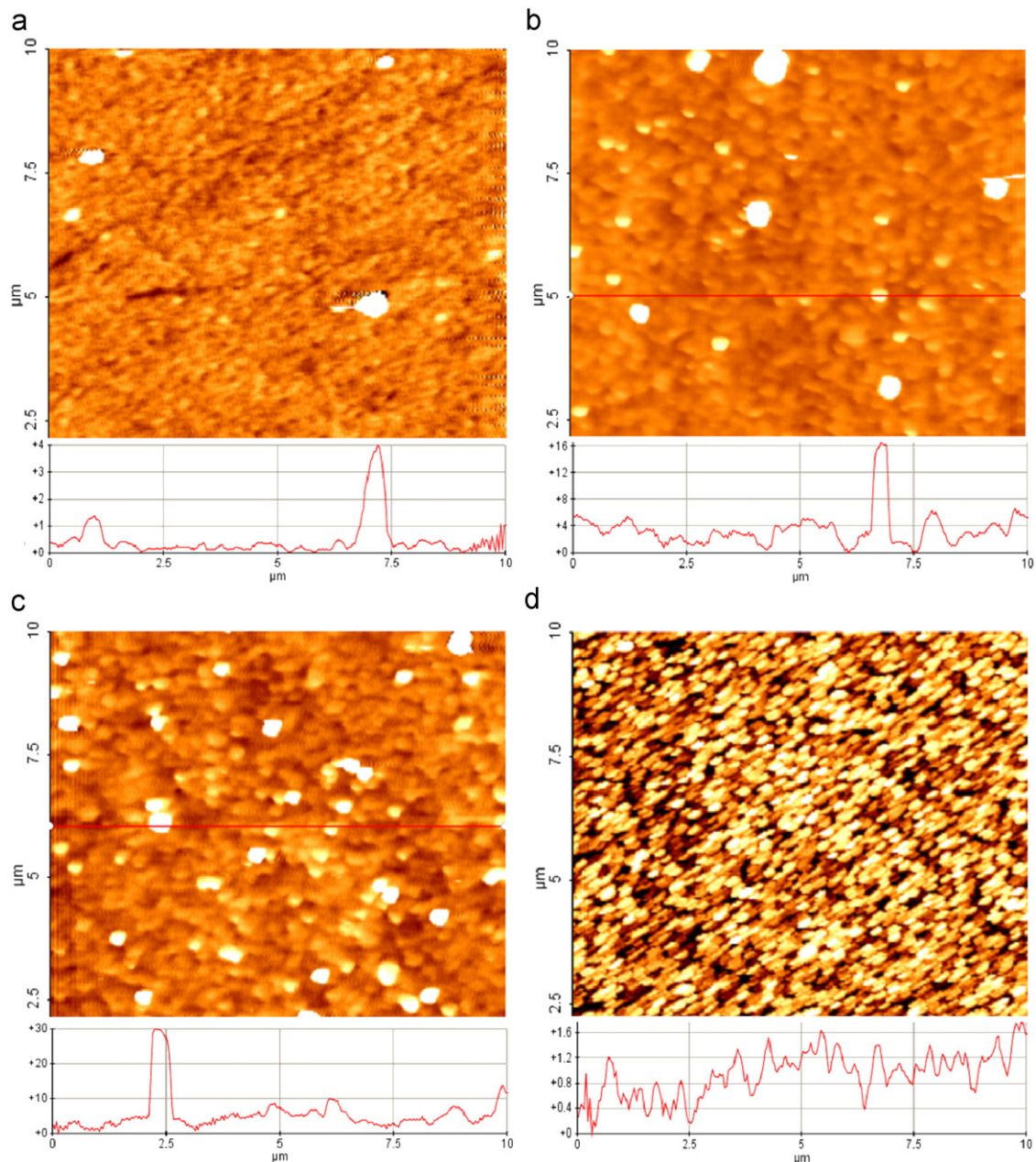


Fig. 4. Surface morphology of conducting polymer anode by AFM: (a) PH 500 + DMSO 3 wt%, (b) PH 500 + DMSO 4 wt%, (c) PH 500 + DMSO 5 wt% and (d) PH 500 + DMSO 3 wt% + BYK-333 1 wt%.

separation of solvent and PEDOT:PSS. As a result, the morphology of the thin film was improved. In fact, the RMS of the film with BYK-333 (0.358 nm) was decreased by 49% compared to that of the film without the surfactant (0.690 nm). With a DMSO content of 4 wt% or more, however, the effect of BYK-333 was not observed as the size and amount of coagulation increased in both PEDOT and PSS.

Fig. 5 shows the film thickness according to the number of coatings, which were conducted at 3000 rpm using a spin coater in order to form a transparent anode on the PET substrate. In terms of the composition of the conducting ink, PH 500 with 3 wt% of DMSO and 1 wt% of BYK-333 was used. As shown in the figure, the thickness increased linearly from 50 up to 210 nm with increasing number of spin coatings. The thickness deviation of the thin film was very uniform with 5–10 nm. The transmittance according to anode thickness is shown in Fig. 6. High transmittance was observed at thicknesses of 50 nm (95% at 550 nm, visible light region) and 100 nm (over 90%). These values were higher than that of ITO glass (ca. 87%). Therefore, when the formulated conducting ink in this paper is applied as a transparent anode, the film thickness can be adjusted by the number of coatings. These results demonstrate the characteristics that could be used in the solution process. In particular, equal uniformity

and high permeability after coating can enhance optical absorption and reduce light scattering.

Fig. 2(a) shows the new PDMS-based patterning process that was used to formulate the conducting polymer ink while Fig. 2(c) shows the fabricated conducting polymer anode. As shown in Fig. 2(b), ink was coated on the PET only by spin coating, even though the formulated conducting polymer ink was sprayed on the front side of the PDMS-patterned PET substrate, because of the characteristics of the PET surface that had been cleaned by PDMS and UVO. The hydrophilic formulated conducting polymer ink was coated onto the UVO-treated hydrophilic PET substrate only, instead of onto the hydrophobic PDMS pattern. The PDMS that had been used to formulate the pattern was rinsed and removed with hexane. As shown in Fig. 2(c), the patterned transparent electrode could be successfully formed on the PET. The Fig. 7 shows the results of the solvent resistance test of the photoactive layer and conducting polymer anode on hexane. Excellent solvent resistance on the hexane was observed with the same UV absorbance both before and after the hexane treatment in both layers.

The patterning method of the photoactive layer is shown in Fig. 3. To facilitate transfer of the PDMS coated on the opposite side of the metal mask in the conducting polymer anode-patterned PET

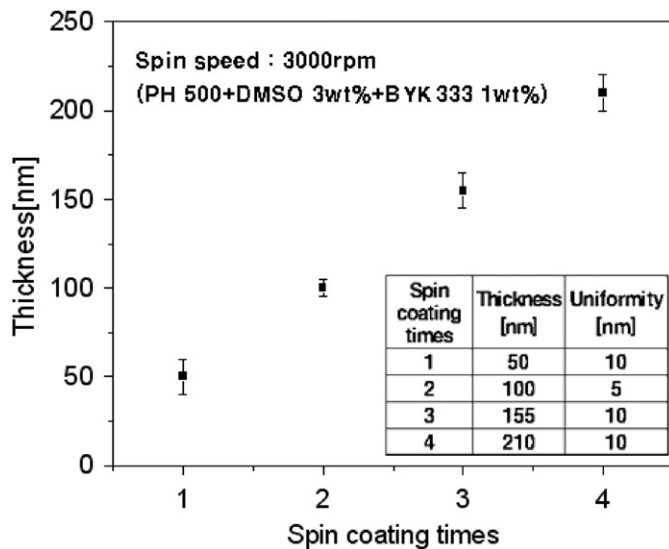


Fig. 5. Thickness of transparent anode by spin coating times.

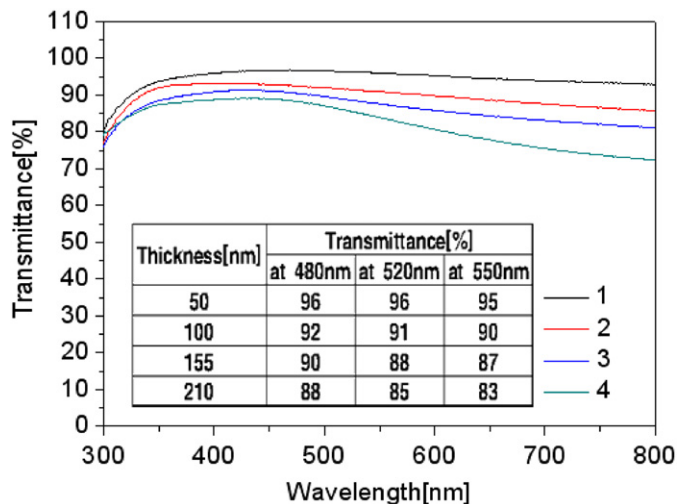


Fig. 6. Transmittance of transparent anode by spin coating times.

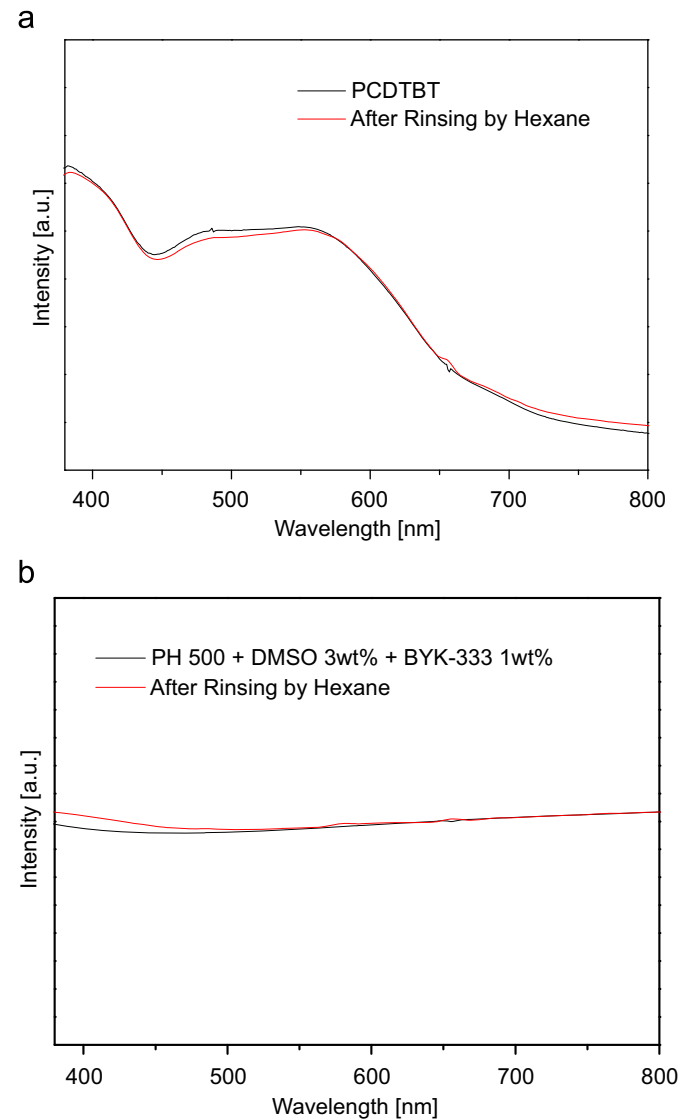


Fig. 7. Solvent resistance test of thin films: (a) Photo active layer, (b) Transparent anode.

substrate, it was annealed on the hot plate at 120 °C for 20 min. In addition, to ensure that the photoactive layer was well coated, it was cleaned 30 min using the UVO cleaner. Unless the PDMS is used, the metal mask is directly masked to the PET substrate, which leads to capillary phenomenon on the coating. The PDMS used in this paper, however, perfectly glued the two layers between the PET substrate and the metal mask, as shown in Fig. 3. This enables the formation of a clean active layer on the anode without any capillary phenomenon. After placing the masked substrate on the hot plate at 50 °C, changes in thickness were observed by changing the brush painting speed (cm/s), as shown in Fig. 8. The layer thickness declined linearly with increasing brush painting speed (cm/s). In other words, the brush painting speed is a critical factor in deciding the layer thickness in the brush painting method. The thickness decreased by about 20% for every speed increase of 0.5 cm/s. Consequently, it was possible to successfully pattern the photoactive layer using the brush painting method. Because the photoactive layer also has strong solvent resistance to hexane, the residual PDMS could be rinsed and removed with hexane.

To form the cathode on the photoactive layer, as shown in Fig. 1(b), BaF₂ (0.1 Å/s, 2 nm), Ba (0.2 Å/s, 2 nm) and Al (5 Å/s, 100 nm) were thermally deposited in sequence in a high vacuum chamber (1×10^{-6} torr or less). BaF₂ was applied as an electron-collecting layer to collect the electrons efficiently through Ohmic contact between the photoactive layer and the cathode. In addition, Ba (−2.7 eV), a low work function material, was used as the cathode. A 100 nm-thick layer of Al was deposited to protect the cathode.

Fig. 9(a) and (b) shows the characteristics of IPCE and current density–voltage (J – V) according to the thickness (50–210 nm) and fabrication method of the conducting polymer anode. The results are summarized in Table 2.

As shown in Table 2, the device III, to which the conducting polymer ink was coated three times, exhibited a sheet resistance and transmittance of 138 Ω/sq and 87%, respectively, which resulted in the highest PCE of 0.98%. The device IV, which was spin-coated four times, had a low sheet resistance of 107 Ω/sq. However, the conductivity of conducting polymer anode was reduced even if the thickness of the film increased due to the low resistivity value of the conducting polymer film. The reduction of the transmittance and conductivity increases the internal resistance of the device. Therefore, the series resistance of the device IV was increased. As a result, PCE was reduced to 0.62%. In contrast, the device with a high transmittance of 95% exhibited a PCE of 0.25% because of the high sheet resistance.

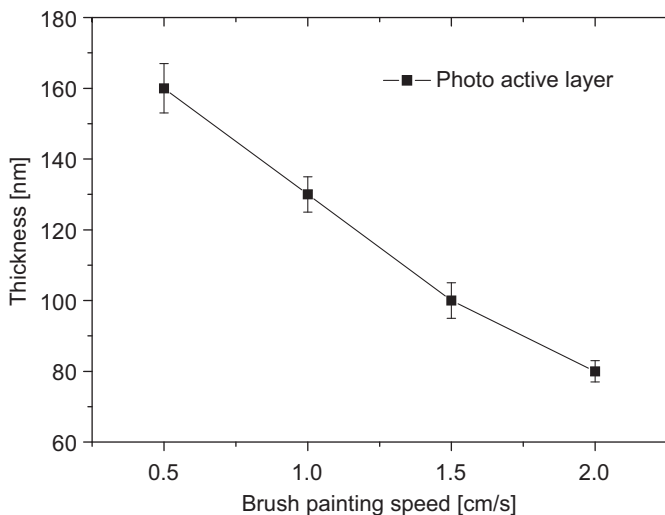


Fig. 8. Thickness of photo active layer by brush painting speed.

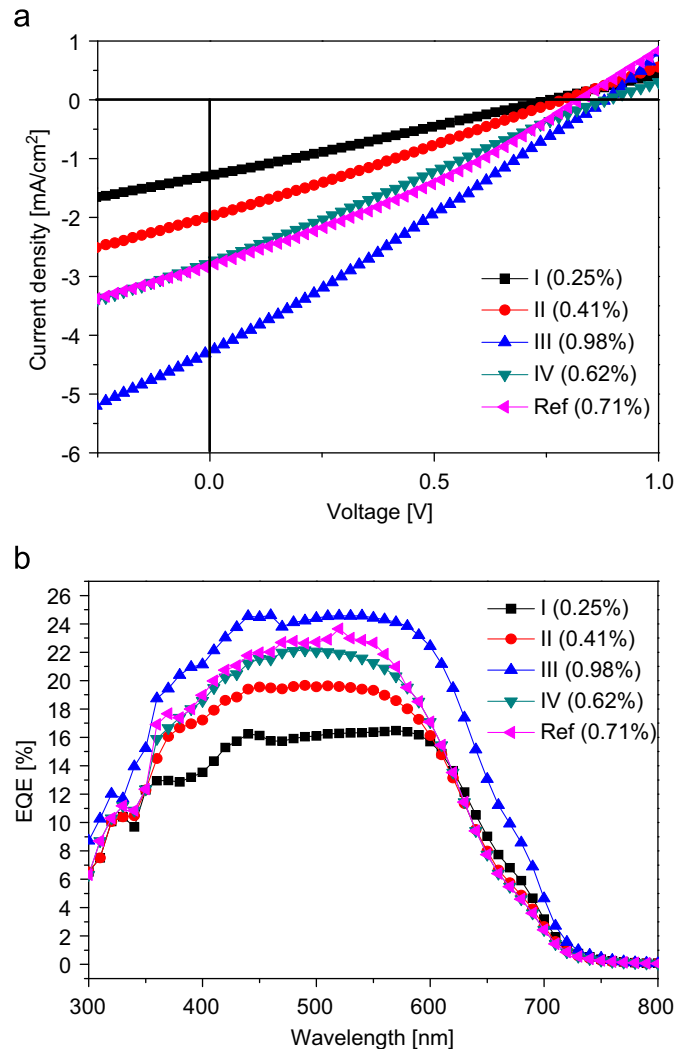


Fig. 9. (a) J – V characteristics of flexible PSCs with different fabrication method and thickness of conducting polymer anode under 100 mW/cm² illumination. (b) IPCE spectra of flexible PSCs with different fabrication method and thickness of conducting polymer anode.

In terms of the series resistance (R_s) of these devices, the device III had the lowest at 150 Ω cm², which was attributed to the low sheet resistance and the high transmittance resulting from the thickness of the optimized conducting polymer anode. This gave the highest short-circuit current density (J_{sc}) and open-circuit voltage (V_{oc}) values of 4.2 mA/cm² and 0.878 V, respectively. In addition, the shunt resistance (R_{sh}) of the devices ranged from 288 to 602 Ωcm², whereas there was almost no change in fill factor (FF). R_{sh} refers to the charge recombination at a photoactive layer and metal interface. It also affects the FF values. As shown in Table 2, however, the FF values of the devices were almost the same (26–27%). In other words, the charge recombination in the photoactive layer and metal interface of the devices I to IV was almost the same, and a uniform film was obtained when a photoactive layer was formed using the brush painting method. These results confirmed that the variation in the R_{sh} values was caused by the difference in transmittance, conductivity and the sheet resistance of conducting polymer anode.

On the other hand, the device (Ref.) in which the photoactive layers were fabricated by a spin coating method was less efficient than the device III with J_{sc} , V_{oc} , FF and PCE values of 2.8 mA/cm², 0.818 V, 31.3% and 0.71%, respectively. The AFM images of the films formed by brushing painting (Fig. 10(a)) and spin coating

Table 2
Characteristics of devices.

Spin coating times/thickness	Sheet resistance [Ω/sq]	Conductivity [S/cm]	Transmittance [%, at 550 nm]	J_{sc} [mA/cm^2]	V_{oc} [V]	FF [%]	PCE [%]	Series resistance [$R_s, \Omega\text{cm}^2$]	Shunt resistance [$R_{sh}, \Omega\text{cm}^2$]
I 1/50 nm	350	571	95	1.3	0.757	26.1	0.25	596	602
II 2/100 nm	203	491	90	2.0	0.777	27	0.41	395	550
III 3/155 nm	138	464	87	4.2	0.878	26.5	0.98	150	288
IV 4/210 nm	107	441	83	2.7	0.878	26	0.62	380	366
R 3/155 nm	138	464	87	2.8	0.818	31.3	0.71	210	404

R: Photo active layer was fabricated by spin coating.

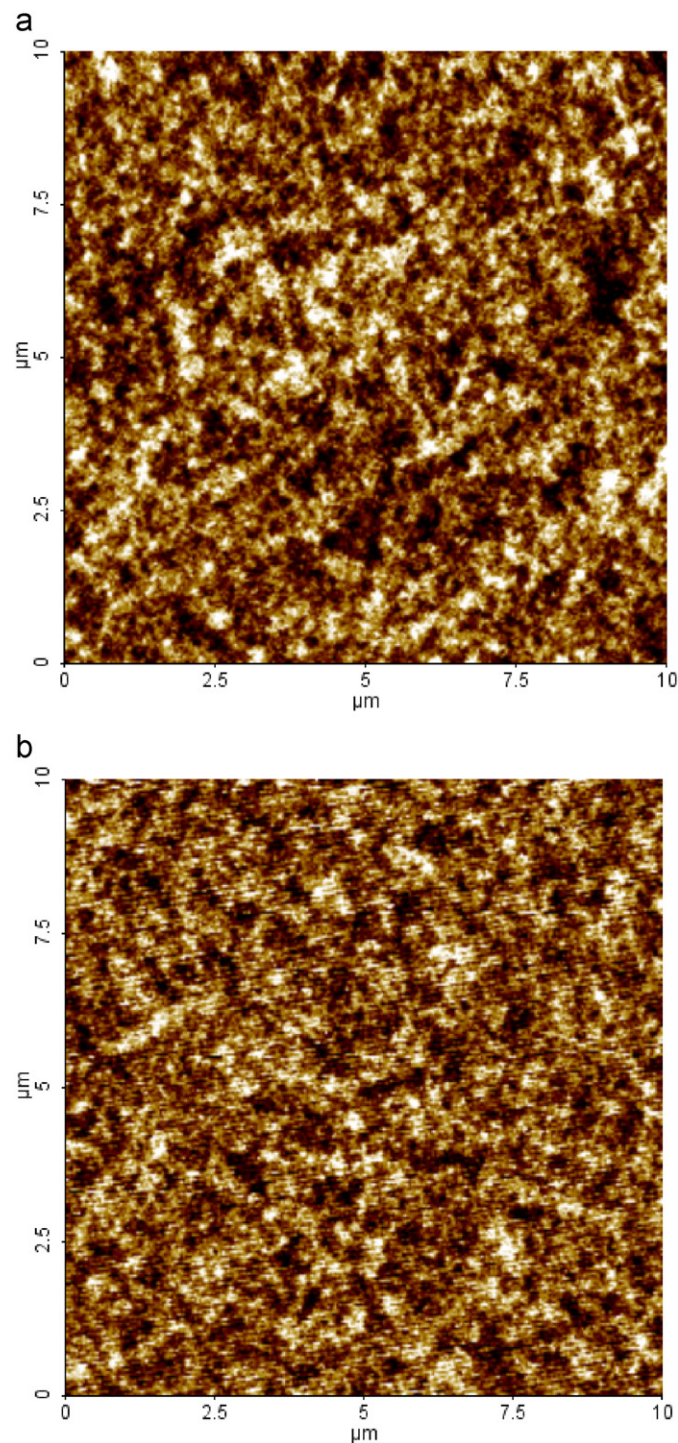


Fig. 10. AFM image of active layers (a) active layer coated by the brush painting method (RMS:0.27 nm) (b) active layer coated by spin coating method (RMS: 0.15 nm).

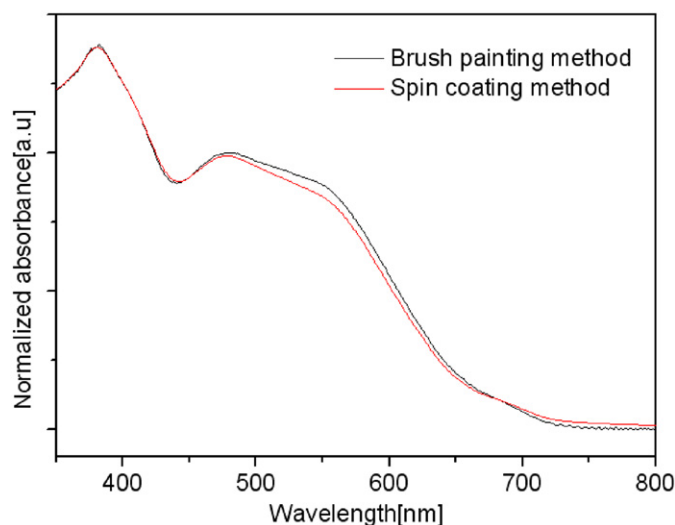


Fig. 11. UV-vis absorption spectra of photoactive layers prepared by spin coating and brush painting method.

(Fig. 10(b)) are shown in Fig. 10. The films thus formed had RMS values of 0.27 nm and 0.15 nm, respectively. These results confirmed the effect of the brushing process had an impact on the enhanced in enhancing the ordering of the polymers. As shown in Fig. 11, the λ_{max} value was slightly red-shifted and the absorbance was increased because of the improved degree of ordering. In other words, the brushing process was more effective than the spin coating process in this enhancement through the improvement of shear stress among the polymer chains. In a Newtonian-type polymer solution, shear stress (τ) is in proportion to velocity gradient (Δv) and viscosity (ν) ($\tau = \Delta v \times \nu$). In the case of spin coating, the Δv of the polymer solution and air boundary is 0, so that shear stress (τ) becomes '0' [29]. In the case of brush painting, on the other hand, even shear stress was observed in all of the polymer solution sections, due to the effective contact between the brush and polymer solution ($\Delta v = \text{constant}$) [30]. Therefore, when the brushing process was used, it was easier to form a channel through which the holes and electrons in the photoactive layer can move. Compared to the spin coating method, R_s decreased from 210 to 150 Ωcm^2 , and J_{sc} increased from 2.7 to 4.2 mA/cm^2 . However, R_{sh} declined from 404 to 288 Ωcm^2 due to the decrease in the charge recombination of the photoactive photo-active layer and metal interface due to the rougher surface. As a result, FF decreased from 31.3 to 26.5%. Consequently, PCE was improved by 38% from 0.71 to 0.98% [31].

5. Conclusion

In this study, flexible PSCs were successfully fabricated by a patterning process of anode and photoactive layers using PDMS

and using a formulation of conducting polymer ink to act as the transparent anode. In terms of the non-uniform conductivity and surface roughness observed in the PH 500 and DMSO system, a very even surface morphology was obtained and the conductivity was improved by adding BYK-333 surfactant. In addition, the device fabricated using the brush painting method exhibited a PCE of 0.98% and a high efficiency that was improved by 38% compared to that of the device that adopted the spin coating method.

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