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Article

PEDOT:PSS Film Preparation and Characterization Using Convective Deposition System Controlled by Arduino Microcontroller for Organic Photovoltaic Application

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Abstract. PEDOT:PSS films are prepared using convective deposition system. The convective deposition system is designed and controlled by a low-cost Arduino microcontroller. The microcontroller shows suitable potential for the system operation with good performance. Then, the system was applied to prepare PEDOT:PSS films and the prepared films are characterized. The prepared films reveal the increase in roughness and thickness for the high-velocity operation which could be occurred due to turbulent flows of PEDOT:PSS molecules. The result causes a decrease in transmittance, resistance, and water contact angle. For organic photovoltaic application, the enhanced power conversion efficiency is observed in corresponding to the increased short-circuit current density due to carrier transport efficiency improvement in organic photovoltaic devices provided by rough surfaces and thick films. The success of organic photovoltaic fabrication confirms the accepting ability of the convective deposition system controlled by Arduino microcontroller for non-vacuum thin film deposition. Thus, it should be considered as a usefulness system for thin-film based device fabrication with a low-cost operation.

Keywords: PEDOT:PSS, convective deposition, Arduino, organic photovoltaics.

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1. Introduction

Arduino is one of the interesting microcontrollers because of flexibility, low-cost, and variety of applications [1]. Arduino shows an efficient performance which can be employed in small machine or system for various application such as a displacement sensor [2], a portable gas sensor [3], an automated calorimeter [4] a carbon dioxide measurement system [5]. Asua *et. al.* developed a displacement sensor using Arduino. The sensor was successfully operated by detecting voltage and frequency. The sensor showed an excellent maximum resolution of 0.2 nm [2]. Yang *et. al.* constructed a portable gas sensor with low-cost using Arduino processing assistance. MQ-4 methane sensor was used as a detector for demonstration. Responsibility was directly proportioned to linear correlation with methane concentrations where it was ranged from 4000 to 110000 ppm. Moreover, it showed the possible detection of methane gas in the case of low concentration (400 ppm). After compared with the analytical detecting technique of gas chromatography, the sensor revealed excellent measurement within a very low absolute error of around 0.69%. The sensor has the performance to examine methane content although low contamination (2.4%) in biogas [3]. Moreno *et. al.* presented an automated calorimeter applied with Arduino to determine the specific heat of soils. The specific heat measurement of soil water and organic matter contents for evaluating the automated calorimeter performance. For soil water content, specific heat measurements of sandy clay loam texture, sandy texture, and sandy clay texture were performed and the specific heats were 945 - 1876 J/kg.K, 736 - 1154 J/kg.K, and 1099 - 2296 J/kg.K, respectively. For organic matter contents, the specific heat of sandy clay soil was measured with value of 1105 - 1793 J/kg.K. The studied exhibited that the automated system has reliability confirmed by comparing the measured results with estimated results from known worldwide equation [4]. Singh *et. al.* presented an application of Arduino for the carbon dioxide measurement system. The system has to measure ability with accepting reliability and validity. They claimed that the measurement system may be useful devices for medical activity [5]. According to the precision of the Arduino microcontroller, it should be interestingly considered for applying in convective deposition system. The convective deposition technique is one of the non-vacuum thin film depositions that can prepare thin films with rapid deposition, low-cost process, and small amount of starting material requirement. Kumnorkaew *et. al.* presented the thin films of aqueous binary suspensions of silica microspheres and polystyrene nanoparticles prepared by convective deposition [6]. Similarly, the convective deposition was also applied to prepare a monolayer of microspheres. The monolayer preparation was performed by moving substrate horizontally paralleled to a fixed blade. Colloidal crystal which was dropped between the substrate and blade was self-assembled by capillary forces to deposit on the substrate. The convective deposition was applied to prepare microlens arrays for light-emitting diodes (LEDs) application. The application showed that photon extraction efficiency was enhanced for InGaN-based LEDs employing microlens arrays with silica microspheres [7]. Moreover, the convective deposition was demonstrated for application in organic photovoltaics (OPVs) and perovskite solar cells (PSCs) [8, 9]. Nevertheless, thin films modified with potential materials should be considered for optoelectronic device developments.

In this work, a convective deposition system was designed and constructed. For precision control, Arduino microcontroller was applied to control convection velocity. The system performance was tested by measuring the actual velocity of the system compared with the desired velocity to evaluate the precision. For the valuable application of the convective deposition system, it was used to prepare PEDOT:PSS films for OPV fabrication.

2. Experimental

2.1. Design of Convective Deposition System

The convective deposition system as illustrated in Fig. 1 was designed. Arduino was used to control the stepping motor for moving the substrate. During the substrate is moving on the right-hand side, the solution carrying polymer molecules is coated on the substrate with a glass blade assistance. The Arduino processing operated with basic input commands of velocity and distance as shown in Fig. 2. The velocity and distance were assigned by pulse width moderation (PWD). In an evaluation of the convective deposition system, it was used to prepare PEDOT:PSS films and the films were characterized.

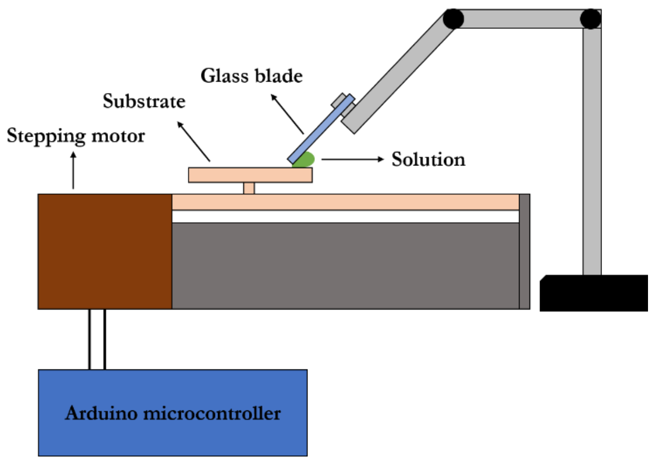

Fig. 1. Schematic structure of convective deposition system.

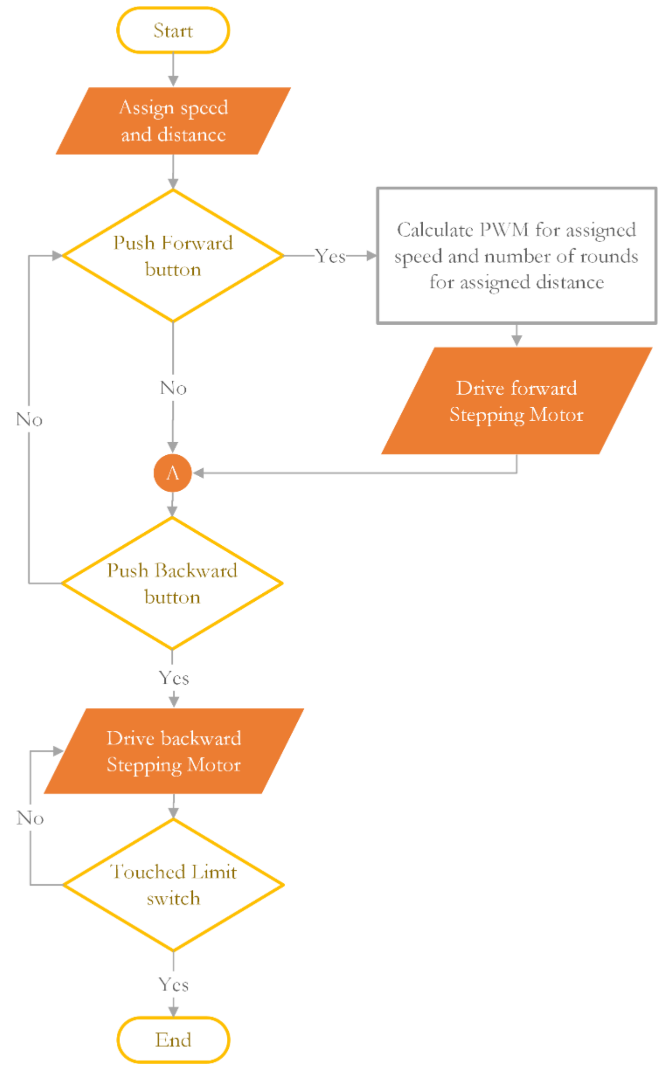

Fig. 2. Flowing chart diagram of Arduino processing.

2.2. Fabrication of Organic Photovoltaics

For OPV fabrication, patterned SnO_2:In (ITO) substrates were cleaned with detergents (Alconox, distilled water, isopropanol). PEDOT:PSS films were prepared by dropping 20 μL PEDOT:PSS solution on the right-hand side edge of ITO substrate (Fig. 1). Then, the substrate was moved on the right-hand side with different velocity controlled by Arduino. During the substrate movement, PEDOT:PSS solution will be distributed over the substrate due to surface tension between the solution with a glass blade and substrate. The coated PEDOT:PSS films were then heated to form as a hole-transporting layer (HTL). After PEDOT:PSS film preparation, mixtures of PCDTBT:PC_{71}BM solution was convectively coated on the PEDOT:PSS films to form an active layer. Then, the TiO_x solution was coated over the active layer and heated to form an electron transporting layer (ETL). Finally, the Al films were deposited to cover the TiO_x layer using thermal evaporation to form as electrodes. After the fabrication, the OPVs as illustrated in Fig. 3 was moved to measure photovoltaic characteristics under standard irradiation of 100 mW/cm^2 from a solar simulator.

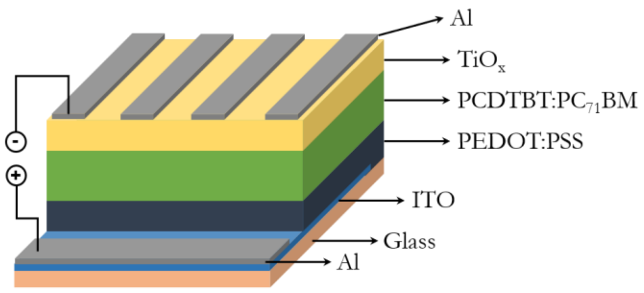

Fig. 3. Schematic structure of OPVs.

3. Results and Discussion

3.1. Test of Convective Deposition System Performance

Actual velocity (v_a) was examined by varying desired velocity (v_d) from 1.50-3.00 mm/s. Then, distance (d) and time (t) were measured and plotted as shown in Fig. 4. The v_a was evaluated from the slope of distance versus time curve as listed in Table 1 and the error of v_a was calculated in comparison to v_d using the relation in the Eq. (1).

$$Error\ (\%) = \frac{|v_a - v_d|}{v_d} \times 100 \tag{1}$$

It is found that v_a value reveals lower than v_d with small errors for all conditions. The error might have occurred because of the limit of stepping motor or screw. However, the small errors could suggest that the convective deposition system has good performance for thin film preparation.

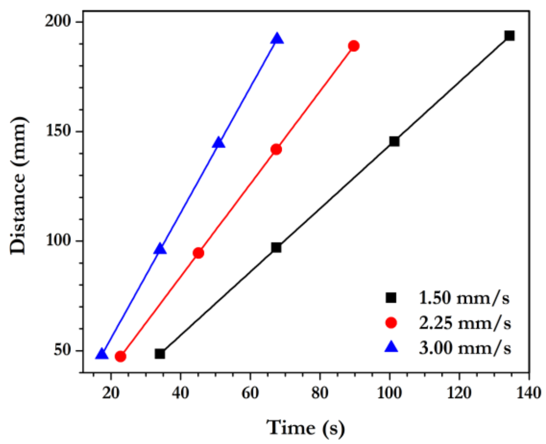

Fig. 4. Distance versus time curves of convective deposition system at different desired velocities.

Table 1. Desired velocity (v_d), actual velocity (v_a), and error of the convective deposition system.

v_d (mm/s)	v_a (mm/s)	Error (%)	R^2
1.50	1.44	4.00	0.99998
2.25	2.12	5.78	1.00000
3.00	2.87	4.33	0.99997

3.2. Application of Convective Deposition System for PEDOT:PSS Film Preparation

The convective deposition system was used to prepare PEDOT:PSS films for the possible investigation of thin-film preparation. Three desired velocities of 1.50, 2.25, and 3.00 mm/s are applied to prepare the films. Different topological images are observed as shown in Fig. 5. To investigate the film's thickness and roughness, Fig. 6 shows that thickness increases with proportional to convection velocity. Note that, the thickness at the convection velocity of 2.25 mm/s shows a wide range which might be due to film accumulation as can see from the topological results. However, it can be considered no significant error according to no overlap in the error bar to other conditions. For roughness analysis, it also reveals a direct correlation to the convection velocity similar to the thickness. This result implies that PEDOT:PSS films deposited with the high-velocity operation are formed rough surface and thick film formation which agree to elsewhere reports [10-12]. The behavior occurs because numerous PEDOT:PSS molecules are deposited with turbulent flows during the preparation for high velocity and formed as rough and thick films due to disordered accumulation of PEDOT:PSS molecules on substrates.

Due to the thicker film formation for higher convection velocity, the decrease in optical transmittance spectra is observed as shown in Fig. 7. The average transmittance in the visible region (400-700 nm) is calculated of 93.0%, 85.6%, and 79.6% for the convection velocity of 1.50, 2.25, and 3.00 mm/s, respectively. Moreover, resistant measurement also explores comparative lower value for thicker film formation too (Fig. 8). The results confirm that fast convection velocity can create thick films because numerous PEDOT:PSS molecules are carried and deposited on a substrate.

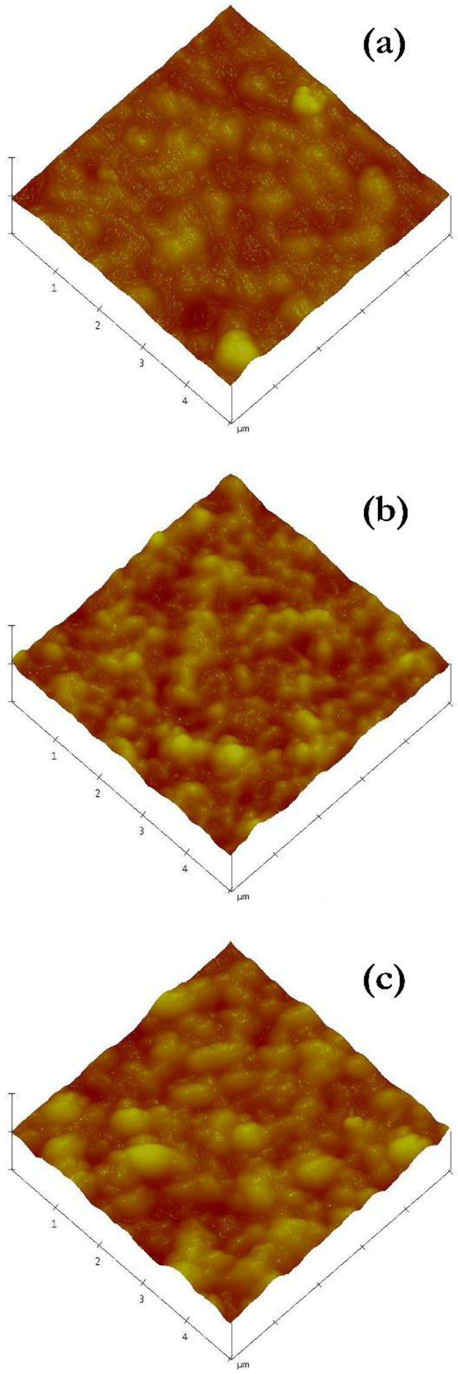

Fig. 5. Topological image of PEDOT:PSS films prepared at convection velocity of (a) 1.50 mm/s, (b) 2.25 mm/s, and (c) 3.00 mm/s.

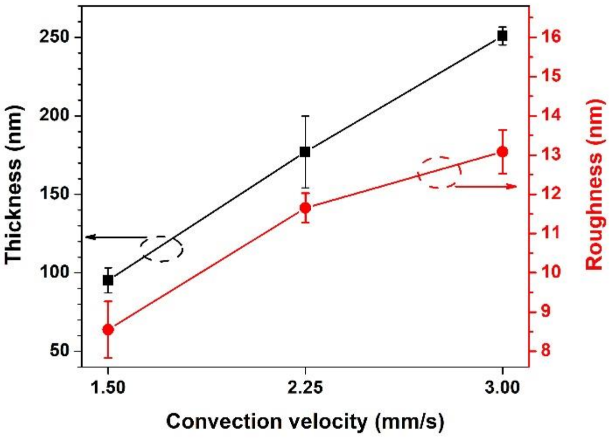

Fig. 6. Relation of thickness and roughness of PEDOT:PSS films prepared at different convection velocities.

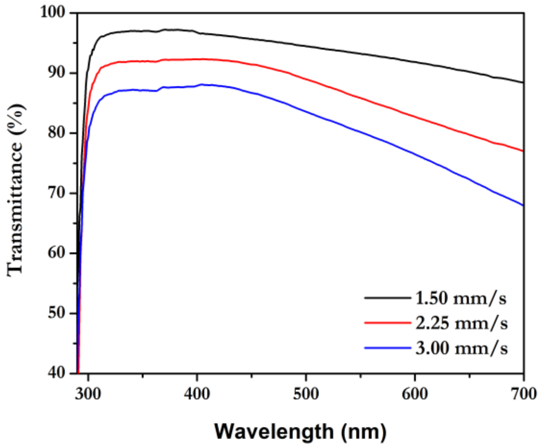

Fig. 7. Transmittance of PEDOT:PSS films prepared at different velocities.

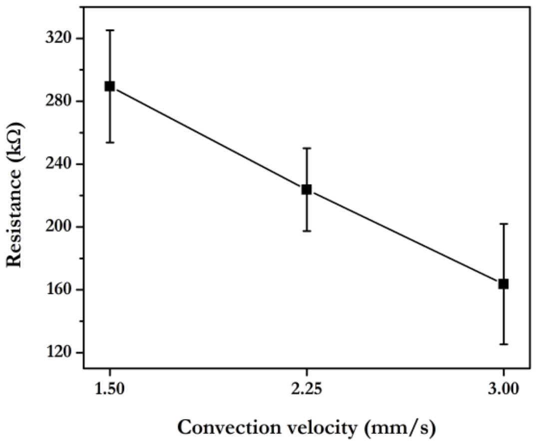

Fig. 8. Resistance of PEDOT:PSS films prepared at different velocities.

For surface effect investigation of PEDOT:PSS films, contact angle measurement is performed using a drop of water. The contact angle slightly decreases for increasing convection velocity (higher surface roughness) as shown in Fig. 9. The decreased contact angle occurs because water fast interacts with film surfaces due to high surface roughness. It can be described that rough films provide high surface areas for better interaction. However, the contact angle shows similar time-dependent decreasing trends for all films which referred to hydrophilic behavior of all PEDOT:PSS films.

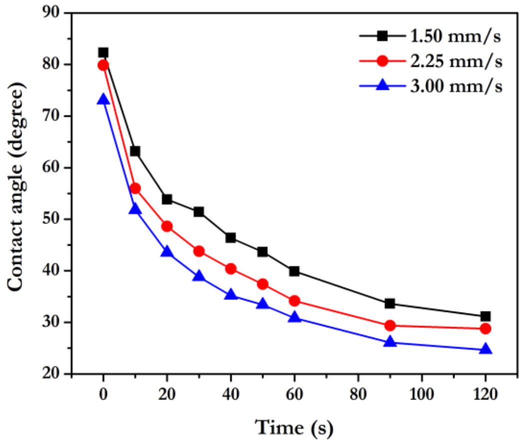

Fig. 9. Contact angle of PEDOT:PSS films prepared with different velocity.

3.3. Organic Photovoltaic Application

The prepared PEDOT:PSS films were then transferred to use as HTL for OPV fabrication, current density (J) versus voltage (V) curves were measured as shown in Fig. 10. Photovoltaic parameters were calculated using Eq. (2)-(3) [13, 14] as listed in Table 2.

$$PCE = \frac{J_{SC}V_{OC}FF}{P_{in}} \quad (2)$$

$$FF = \frac{J_{max}V_{max}}{J_{SC}V_{OC}} \quad (3)$$

where PCE is power conversion efficiency, J_{sc} is short-circuit current density, V_{oc} is open-circuit voltage, FF is fill factor, P_{in} is power of incident simulated sunlight, J_{max} and V_{max} are current density and voltage at the maximal measured power, respectively. It is found that J_{sc} and PCE increase for increasing of convection velocity, while as V_{oc} and FF are not much change. For higher convection velocity, rough surface and thick film formation are believed as the important factor for PCE enhancement. The rough surface can offer high surface areas to increase the pathway for charge carrier transports in OPVs. Thick films can reduce recombination by improving carrier transport efficiency. It can be explained that the long pathway of thick films may offer fast carrier transfer after carrier separation from the PEDOT:PSS-PCDTBT:$PC_{71}BM$ junction. The fast carrier transfer could improve carrier transport efficiency and reduce recombination at the same time. The results confirm that the convective deposition system controlled by Arduino is a successful operation to prepare thin films for OPV application.

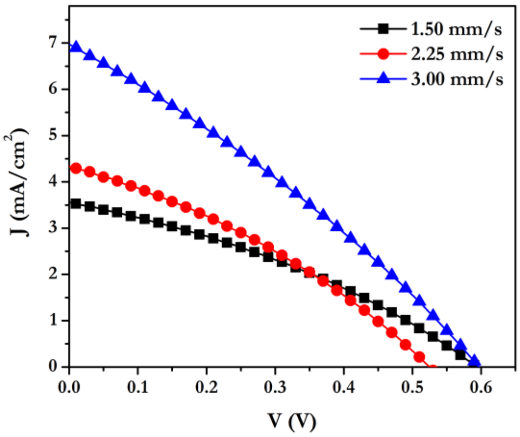

Fig. 10. J-V curves of OPVs fabricated with PEDOT:PSS at different velocities.

Table 2. Photovoltaic parameters of OPVs fabricated with PEDOT:PSS films at different velocities.

Velocity (mm/s)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	PCE (%)
1.50	3.56±0.03	0.59±0.01	0.34±0.01	0.71±0.01
2.25	4.33±0.02	0.52±0.01	0.34±0.01	0.75±0.02
3.00	6.97±0.45	0.59±0.01	0.30±0.01	1.24±0.10

4. Conclusion

Convective deposition system, non-vacuum thin film deposition, was designed and controlled by a low-cost Arduino microcontroller. The microcontroller shows suitable potential for operating the system with good performance. The system can be operated in velocity ranges of 1.50 – 3.00 mm/s with low errors. The convective deposition system is used to prepare PEDOT:PSS films for thin-film preparing examination. The prepared PEDOT:PSS films revealed the increase in roughness and thickness for a high-velocity operation which could be occurred due to turbulent flows of PEDOT:PSS molecules during the deposition. The result causes a decrease in transmittance, resistance, and water contact angle. For organic photovoltaic application, the enhanced power conversion efficiency is observed in corresponding to the increased short-circuit current density provided by high surface areas and long pathway of rough surfaces and thick films, respectively, which causes carrier transport efficiency improvement in OPV devices. The success of organic photovoltaic fabrication confirms the accepting ability of the convective deposition system controlled by Arduino microcontroller for non-vacuum thin film deposition. Therefore, it should be considered as a usefulness system for thin-film based device fabrication with a low-cost operation.

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