Materials Research Express

PAPER

Fabrication of indium tin oxide free bulk heterojunction organic solar cells using inkjet-printed silver grids and PEDOT: PSS

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Keywords: inkjet printing, silver grids, PEDOT:PSS, organic solar cells
Supplementary material for this article is available online

Abstract
In this article, we discuss the inkjet printing of silver nanoparticle ink and PEDOT: PSS (poly(3,4-ethylene dioxythiophene) polystyrene sulfonate) for indium tin oxide-free organic solar cells. We observed that the significant parameters for the printing of silver nanoparticle ink and PEDOT: PSS are waveform parameters voltage and time, substrate temperature, drop spacing and annealing temperature. Organic solar cells were fabricated over grids with three different line spacing (1 mm, 2 mm and 3 mm) and better performance was observed for grids with 2 mm spacing. The figure of limit, which is the ratio between the optical transmission and sheet resistance, was used as a tool to evaluate the performance of the current collecting grid. The figure of limit was high for grids with 2 mm spacing ($21.11 \times 10^{-3} \, \Omega^{-1}$), which confirmed the experimental results.

1. Introduction

Indium tin oxide (ITO) is extensively used as the transparent electrode in organic solar cells because of its higher optical transmission (>90%) and lower sheet resistance ($\sim 10 \, \Omega/\square$) [1, 2]. In an organic solar cell, the major cost is from the transparent electrode ITO. Hence, to replace ITO, researchers tried with high conductivity (HC) poly(3,4-ethylene dioxythiophene: polystyrene sulfonate (PEDOT:PSS) [3, 4], metal grids polymer composite electrode [5–8], silver nanowires [9], carbon nanotubes [10, 11] and graphene [12, 13]. Among all these reported methods, the metal grid/HC PEDOT: PSS was found to be an excellent choice when it comes to flexibility and cost [14, 15]. The idea of metal grids/High conductivity PEDOT:PSS was originally proposed by Aeronauts et al and they used DTR (Diffusion transfer reversal) to fabricate metal grid [16]. Subsequently, Galagan et al fabricated organic solar cells using digital inkjet printing and achieved an efficiency of 1.3% [17]. After that, there were numerous research articles about the inkjet-printed silver grids/HC PEDOT: PSS composite electrodes [18–21]. It was reported in those articles that the important parameters for the working of metal grid/HC PEDOT: PSS was the spacing between the lines and conductivity of the silver grid. Recently Xinlin Li printed ITO nanoparticle water-based ink using an electrohydrodynamic jet printer after reducing the surface tension with a non-ionic surfactant [22]. In electrohydrodynamic printing, the ink drop is released from the nozzle by applying an electrostatic field between the nozzle and the substrate. The electrostatic force should surpass the surface tension of the ink to initiate the jetting of the droplet. Electrohydrodynamic printing is not suitable for printing aqueous solutions such as PEDOT: PSS whose surface tension is high. For aqueous printing solutions with high surface tension drop on demand inkjet printing is the best option. But there are some areas in inkjet printing which were yet to be addressed properly, such as the adhesion of the ink to the base substrate. In inkjet printing, the spreading of ink occurs naturally without any external force and depends mainly on the surface tension of the ink and the surface energy of the substrate [23]. Other factors that influence the spreading of the ink are the movement of the substrate or the print head, the velocity of the ink drop and the gap between the print head and the substrate [24, 25]. Many research articles explain the spreading of ink-based on the contact angle of the ink.
drop with the substrate in the three-phase interface [26, 27]. But the mere measurement of contact angle does not give a clear-cut idea about the spreading behaviour of ink. Hence in this research work, we calculated the surface energy of the substrate using contact angle measurement as a tool and compared it with the surface tension of ink for proper adhesion. Apart from the adhesion of the ink, we also discuss the electro-optical properties of the ITO free organic solar cells. The most important optical property which influences the performance of organic solar cells is the absorption of photons [28]. In ITO free organic solar cells, the absorption of a photon is dependent not only on the material property of the photoactive layer but also on the geometry of the grid. The spacing between the grid should be as large as possible to facilitate the movement of photons towards the photoactive layer. Another important factor is the collection of charge carriers at the respective electrodes. The sheet resistance of the PEDOT: PSS layer should be least to enhance the movement of the charges to the respective electrodes.

2. Experimental

Silver grids were inkjet printed with a 60 \( \mu \)m print head. Silver ink purchased from UT dots with a particle size 10 nm and silver concentration 25–60% was used for printing of silver grids. After printing, the grids were annealed at 200 \( ^\circ \)C for two hours. A high conductivity grade PEDOT: PSS (1% wt. in H\(_2\)O) purchased from Sigma Aldrich was inkjet printed over the silver grids with an 80 \( \mu \)m print head. The PEDOT: PSS film was annealed after printing at 120 \( ^\circ \)C for 10 min. The photoactive layer solution was prepared by dissolving P3HT (poly(3-hexylthiophene) and ICBA (Indene C-60 bis adduct) (1:1 weight ratio) in ortho dichlorobenzene and stirring the solution for 12 h at a temperature of 70 \( ^\circ \)C. The photoactive layer was spin-coated over the HC PEDOT: PSS inside the glove box with speed 1000 rpm, acceleration 100 rpm s\(^{-1}\) and time 50 seconds. The electron transport layer calcium and the top electrode aluminium were deposited thermally over the photoactive layer through a shadow mask for a thickness of 5 nm and 80 nm respectively. The devices were then encapsulated with glass and epoxy glue. The active area of the solar cell was 4.5 mm\(^2\). The number of solar cells fabricated for each type of geometry was 16. The mean and standard deviation in the calculation of power conversion efficiency for organic solar cell without grids, grids with 1 mm spacing, grids with 2 mm spacing and grids with 3 mm spacing are 0.88 \( \pm \) 0.12, 3.86 \( \pm \) 0.11, 4.27 \( \pm \) 0.09 and 3.51 \( \pm \) 0.10 respectively.

Adhesion of silver ink on the glass substrate was evaluated using the ASTM D3359-B standard. Grid pattern with six cuts was made over the inkjet-printed silver film in both the horizontal and the vertical direction. An adhesive tape is positioned over the grid pattern and then peeled off slowly. Based on the ink pattern created over the grid, the adhesion of the ink is indicated qualitatively on a scale from 0 B to 5B [29, 30]. The characterization of the inkjet printed silver grid and the organic solar cell was performed in environmental conditions of temperature 25 \( ^\circ \)C and relative humidity 60%. Nordson march AB series plasma treatment with a 13.56 MHz RF generator was used for the plasma treatment of glass substrates. Agilent Atomic force microscope was used to determine the surface roughness of the silver grid, high conductivity PEDOT: PSS, and the active layer in non-contact mode. A field emission scanning electron microscope (Zeiss/ultra 55) with 1 nm SEM imaging resolution was used for the imaging of the inkjet-printed silver ink film (before sintering and after sintering). Nova Solar simulator with a Xenon light source, which emits light of intensity 1000 W m\(^{-2}\) under condition AM 1.5 G, was used for the measurement of the IV characteristics of the solar cell. The optical transmittance of HC PEDOT: PSS with silver grids was measured using Perkin Elmer Lambda 950 UV/Vis spectrophotometer in the wavelength range from 300 nm to 1200 nm. GBX digidrop contact angle meter was used for the measurement of contact angle of water, diiodomethane and PEDOT: PSS on glass. A dektak profilometer was used for the measurement of the thickness of the silver grids. X-ray diffractometer (Philips Xpert) was used for the measurement of the x-ray diffraactogram of the inkjet-printed silver ink on glass. Four probe measurements were used to measure the sheet resistance of the solar cell.

3. Results and discussion

Organic solar cells were fabricated in normal geometry with the silver grid/HC PEDOT: PSS as the anode, P3HT: ICBA as the photoactive layer, calcium as the electron transport layer and aluminium as the cathode. figures 1 (a), (b) shows the geometry of the fabricated organic solar cell and the energy level diagram. The silver grid /HC PEDOT: PSS composite electrode acts both as the hole transport layer and as the anode in ITO free organic solar cells.

Before fabrication, the surface characterization of the substrate was performed by the sessile drop contact angle method using polar solvent water and a nonpolar solvent diiodomethane (DIM) of known surface tensions. The dispersive surface energy of the substrate was calculated using the formula [32].
Where \( g_{sd} \) is the dispersive surface energy glass substrates, \( \theta_{dim} \) is the contact angle of DIM on the glass.

The polar surface energy of the glass substrates was calculated using the formula

\[
\gamma_{sp} = \frac{\gamma_{water}(1 + \cos \theta_{water}) - 2\sqrt{\gamma_{water} \times \gamma_{sd}}}{4} 
\]  

The total surface energy is given by

\[
\gamma = \gamma_{sd} + \gamma_{sp} 
\]  

The derivation of equations (1) and (2) are given in the supporting information.

The surface energy calculation of the glass substrates used is given in table 1.

The surface tension of the silver ink and the HC PEDOT: PSS ink measured using the capillary rise method were 28 mN m\(^{-1}\) and 51 mN m\(^{-1}\) respectively. Since the surface tension of silver ink was lower than the surface energy of the glass substrate (ref. table 1) by a larger margin of 34.5 mN m\(^{-1}\), the adhesion issue is not found in silver ink. The contact angle of the silver ink over the glass substrate in the three-phase interface was 9°. But in the case of PEDOT: PSS adhesion issue is observed as the surface tension of the PEDOT: PSS was less than the surface energy of the substrate only by a smaller margin of 11.49 mN m\(^{-1}\). To improve surface energy, the glass substrate was subjected to oxygen plasma for 120 sec, with the parameter power 740 watts and an oxygen flow rate of 25 mL min\(^{-1}\). After surface treatment, the surface energy was increased from 62.49 mN m\(^{-1}\) to 72.67 mN m\(^{-1}\).

To understand the role of the substrate on the all film growth process, x-ray diffraction was performed. Figure 2(a) shows the x-ray diffractogram of the glass substrate and the silver ink printed over the glass substrate. There is no characteristic peak in the XRD of the glass substrate, which indicates the amorphous nature of glass. However, there is a blunt peak at 23.5°. The broadening of the peak in glass indicates more stacking faults, microstrain and other defects in the crystal structure. The intensity of the peak is reduced when silver ink is printed over glass since pure glass reflects more x-rays. The XRD pattern of silver ink has three characteristic peaks with a larger peak at 37.9°, a smaller peak at 44.14° and the smallest peak at 64.32° corresponding to the planes [111], [200] and [220] of the face-centered cubic silver crystal [33]. The size of the silver nanoparticles calculated using Scherrer formula was 24 nm. Figure 2(b) shows the Raman spectra of silver nanoparticle ink. The Raman spectra exhibit peaks at 1371 cm\(^{-1}\), 1555 cm\(^{-1}\), 2843 cm\(^{-1}\) and 2923 cm\(^{-1}\). The peaks at 1371 and 1555 are due to the antisymmetric and symmetric vibrations of the carboxylate group (COO\(^{-}\)) [34]. The peaks at 2843 cm\(^{-1}\) and 2923 cm\(^{-1}\) are due to symmetric stretching vibrations of the methyl group (–CH\(_3\)) group and the methylene group (–CH\(_2\)) [34]. The weak peak at 651 cm\(^{-1}\) indicates the presence of silver oxide on the ink.
surface. We can understand from the Raman spectra that the sintered silver nanoparticle ink surface has carboxylate groups and the silver film is coordinated by these groups \[34\].

The carboxylate group is electronegative in nature due to the presence of oxygen atom. Glass which is made up of silicon dioxide has hydroxyl groups in its surface. The carboxylate group is connected to the hydroxyl group on the surface of glass through a hydrogen bond. During sintering, the silver carboxylate group decomposes to form silver nanoparticles. Similarly, the water molecules present in the PEDOT: PSS aqueous solution are connected to the hydroxyl group present in the surface of glass through a hydrogen bond, as shown in figure 2(c) \[35\]. Oxygen plasma treatment improves the hydroxyl content in glass. The contact angle of PEDOT: PSS before plasma treatment was 43.89°, as shown in figure 1(c). It was decreased to 14.82° after improvement in hydroxyl content of glass due to plasma treatment as shown in figure 1(d). Figure 2(d) shows the 3d AFM image of glass used for fabrication of organic solar cells. The root mean square roughness of the glass substrate was 5.04 nm.

Figures 3(a) and (b) show the waveform used for printing silver grids and PEDOT: PSS. A bipolar waveform was used for printing both the silver ink and the PEDOT: PSS. The bipolar waveform produces a suction effect on the ligament of the ink drop and resists the formation of satellites \[36\]. The echo time in PEDOT: PSS waveform is set at a higher value than the echo time in silver ink waveform. Since PEDOT: PSS is a viscoelastic fluid, it takes a longer time to pull back the satellite drop to the main drop. The waveform parameters used for printing silver ink and HC PEDOT: PSS is given in table 2.

The geometry of the grids with three different line spacings (1 mm, 2 mm and 3 mm) line and the inkjet-printed silver grid with the microscopic image (inset) is shown in figures 3(c) and (d). The profilometry image of the silver grids is shown in figure 3(e). The width of the inkjet-printed line was 150 μm and the thickness of the grid was 200 nm. Coffee ring which is the accumulation of nanoparticles at the edge of the drop in the form of a dried coffee drop is a major problem in inkjet printing nanoparticle inks \[37\]. The substrate temperature mainly influences the coffee ring formation. Silver ink was printed with a substrate temperature of 25 °C to prevent coffee ring formation. The 3d Zeta image of the coffee ring formation in silver ink is shown in figure 3(f).

The percentage coverage area (the grid area which completely blocks the light) for the three type grids was mathematically calculated using the formula

![Figure 2.](image-url)
Where $AG$ is the area of the grid, $nH$ is the number of lines in the horizontal direction, $W$ is the width of the line and $L$ is the length of the line.

The percentage coverage for the 1 mm, 2 mm and 3 mm spacing grids was found to be 19%, 14% and 12% respectively. The optical transmission of the Glass/silver grid/PEDOT:PSS transparent should be maximum so that many photons are incident on the active layer. If the spacing between the lines is less, the sheet resistance is reduced, but it affects the transmission of light. A trade-off should always be there between the sheet resistance and optical transmission. The criteria for the eligibility of a material as a transparent electrode is given by the figure of limit $F$ which is the ratio between the transmittance and sheet resistance originally proposed by Fraser and Cook [38].

$$F = \frac{T}{R_s}$$

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$$\text{%Coverage} = \frac{AG}{TG} \times 100$$

Where $AG = nH \times W \times L + nV + W \times L - \frac{w \times nH \times nV}{2}$

Table 2. Wave form parameters for inkjet printing of silver and PEDOT: PSS.

| Ink printing ink | Rise time (μs) | Dwell time (μs) | Fall time (μs) | Echo time (μs) | Rise time (μs) | Dwell voltage V | Echo voltage V | Frequency Hz |
|------------------|----------------|----------------|---------------|---------------|----------------|----------------|----------------|-------------|
| Silver ink       | 5.0            | 14.0           | 10.0          | 14.0          | 5.0            | 35             | -25            | 800         |
| PEDOT: PSS       | 4.0            | 21.0           | 5.0           | 42.0          | 5.0            | 44.0           | -45.0          | 800         |

Figure 3. (a) Dual waveform used for inkjet printing of silver nanoparticle ink with the inset image showing a silver ink drop jetting from the print head (b) Dual waveform used for inkjet printing of PEDOT:PSS with the inset image showing a PEDOT:PSS ink drop jetting from the print head (c) geometry of the silver grids and (d) inkjet printed silver grid with inset showing the microscopic image of the grid (e) width and height of the silver grids from profilometer and (f) 3d zeta image of the coffee ring.
Table 3. Calculation of figure of limit for silver grids with different line spacing.

| Geometry of grid          | Transmittance | T\textsuperscript{10} | Rs (Ω/□) | Figure of limit X 10\textsuperscript{-3} Ω\textsuperscript{-1} |
|--------------------------|---------------|------------------------|-----------|-----------------------------------------------------------|
| Silver grid with 3 mm spacing | 0.88          | 0.28                   | 18.12     | 15.45                                                      |
| Silver grid with 2 mm spacing | 0.86          | 0.22                   | 10.42     | 21.11                                                      |
| Silver grid with 1 mm spacing | 0.81          | 0.12                   | 6.50      | 18.46                                                      |

Where T is the optical transmittance and R\textsubscript{s} is the sheet resistance.

\[
T = \frac{I}{I_o} = \exp(-\alpha t)
\]  (7)

Where I\textsubscript{o} is the incident light, I is the transmitted light, \(\alpha\) is the absorption coefficient in cm\textsuperscript{-1} and t is the thickness of the thin film.

\[
R_s = \frac{1}{\sigma t}
\]  (8)

Where \(\sigma\) is the electrical conductivity in Ω\textsuperscript{-1} cm\textsuperscript{-1} and t is the thickness of the thin film in nm.

Substituting equations (6) and (7) in equation (5),

\[
F = \sigma t (\exp(-\alpha t))
\]  (9)

According to equation (9), the figure of limit is a function of thickness with the given \(\sigma\) and \(\alpha\). The maximum value of the thickness is calculated by differentiating equation (9) with respect to t.

\[
t_{\text{max}} = \frac{1}{\alpha}
\]  (10)

Substituting (10) in equation (7),

\[
T = \frac{1}{e} = 0.37
\]  (11)

According to equation (11), The figure of limit is maximum is at transmission of 37%. This value is too less for solar cell applications.

G Haacke\footnote{[39]} introduced a power term in multiples of 10 for equation (5) so that the maximum figure of limit is at a transmittance of 90%.

\[
F = \sigma t (\exp(-10\alpha t))
\]  (12)

The figure of limit for the silver grid with three different line spacings was calculated and the values are shown in table 3. The figure of limit is high for grids with 2 mm spacing.

For good transparent conductors, the figure of limit would be invariably high. Suppose width of line and spacing between the line are reduced, so that a lesser number of charge carriers are collected at the electrode. Consequently, the figure of limit will also reduce. This is because when we decrease the width of the line, the sheet resistance of the transparent conductor will increase as there is an inverse relation between sheet resistance and the width of the line.

\[
R_s = \frac{\rho L}{Wt}
\]  (13)

Where R\textsubscript{s} is the sheet resistance in Ω/□, \(\rho\) is the resistivity in Ω m, W is the width of the line in \(\mu\)m and t is the thickness of the line in nm. Also, when we decrease the spacing between the lines, optical transmittance will be reduced.

From table 4, the optical transmittance, sheet resistance and the figure of limit for grids with 3 mm spacing are 0.88, 18.12 Ω/□ and 15.45 \(\times\) 10\textsuperscript{-3} Ω\textsuperscript{-1} respectively. Suppose the optical transmittance is reduced to 86% and the sheet resistance is increased to 20 Ω/□ by decreasing the width of the line, the new figure of limit would be a lower value (11 \(\times\) 10\textsuperscript{-3} Ω\textsuperscript{-1}).

The most important factor which influences the performance of the silver grid is the adhesion of the ink to the substrate. According to ASTM D3359, adhesion tape results are classified in a scale of 0 B to 5 B. The relationship between the adhesion class and time at a constant temperature (120 °C) is shown in table 4. During the initial stages, the ink is almost utterly removed after the tape test, which is equal to class 0B. After 40 min, around 25% of the ink is removed from the surface which is equal to adhesion class 2B. After 1 h 20 min, a tiny part of ink is removed which is equal to adhesion class 4B. After two hours the adhesion level is almost equal to adhesion class 5B. The results of the adhesion tape test conducted on the silver nanoparticle ink printed over glass substrate are shown in figures 4(a)–(e) respectively. The FESEM image of the inkjet printed silver...
During sintering, the silver nanoparticles melt and fuse to form a conductive pattern as shown in figure 4(g). PEDOT: PSS was printed over the silver grid three times to cover the entire area of the silver grid. The thickness of the HC PEDOT: PSS after printing three layers and annealing was in the range of 280 to 300 nm. The sheet resistance of the HC PEDOT: PSS printed over silver grids with 1 mm, 2 mm and 3 mm spacing were 6.5 Ω, 10.4 Ω, and 18.1 Ω, respectively.

2d and 3d AFM images of the silver grids, silver grids/HC PEDOT: PSS composite electrode and silver grids/HC PEDOT: PSS/BHJ are shown in figures 5(a)–(f) respectively. The root mean square roughness of the silver grids was 85.7 nm. When the HC PEDOT: PSS was inkjet printed over the silver grids, the surface roughness was reduced to 12.7 nm. The root surface roughness value was 12.7 nm ± 2 nm over the entire surface of the HC PEDOT: PSS. This clearly showed that the HC PEDOT: PSS fully covered the silver grids. The root mean square value of the active layer P3HT: ICBA, which was spin-coated over the HC PEDOT: PSS was 24.3 nm. The higher roughness value of the P3HT: ICBA was due to the crystallization of P3HT after annealing at 150 °C.

The UV–vis transmittance curve of PEDOT: PSS printed over glass and PEDOT: PSS printed over silver grids is shown in figure 6(a). The transmittance of glass at 550 nm is 91%. The transmittance value is reduced to 70% after printing PEDOT: PSS. It is further reduced when printed over grids because of the shadowing effects of the grid.

The current-voltage characteristics of the organic solar cell with silver grid/HC PEDOT: PSS composite electrode is shown in figure 6(b) and the best power conversion efficiencies values for the three type of grids are given in table 5. There is not much variation in the open circuit voltage of all the three geometries. The open circuit voltage [40] is the difference in energy level between the LUMO of the acceptor and the HOMO of the donor $\Delta E_{\text{DA}} = E_{\text{LUMO}} - E_{\text{HOMO}}$. The result clearly shows that the open circuit voltage is a property of the material and it does not depend on the structure of the grid. The short circuit density of the grids with 2 mm spacing is high (8.47 mACm$^{-2}$) because more spacing between the grid lines and the charge collection capability of the grids [41]. In the case of grids with 3 mm spacing, the current collecting capability of the grid is less because

Table 4. Classification of adhesion tape results according to ASTM D 3359.

| Figure | Condition | Classification | Percentage of area removed % |
|--------|------------|----------------|-----------------------------|
| 4(a)   | Sintering at 120 °C for 5 min. | 0B | More than 65 |
| 4(b)   | Sintering at 120 °C for 20 min. | 1B | 35–65 |
| 4(c)   | Sintering at 120 °C for 40 min. | 2B | 15–35 |
| 4(d)   | Sintering at 120 °C for 1 h | 3B | 5–15 |
| 4(e)   | Sintering at 120 °C for 1 h 20 min. | 4B | <5 |
the generated charge carrier must travel a long distance before reaching the grid [41]. In the case of grids with 1 mm spacing, the spacing between the lines is less, so only a minimum number of photons can pass through the grid. The fill factor increases with a greater number of lines per unit area. This is mainly due to the reduction in sheet resistance with a higher number of lines in the grid.

The optical transmission of the Glass/ silver grid/ HC PEDOT: PSS transparent should be maximum so that many photons are incident on the active layer. If the spacing between the lines is less, the sheet resistance is reduced, but it affects the transmission of light. A trade-off should always be there between the sheet resistance and optical transmission.

The PCE values shown in table 5 are higher than the similar works about ITO free organic solar cells. In previous works, mostly PCBM was used as the electron acceptor along with the electron donor P3HT. In this work, we have used ICBA as the electron acceptor, which resulted in higher open circuit voltage as shown in figure. Another specialty about this work is the printing of the silver grids and the HC PEDOT: PSS with a single nozzle print head. In other research works, a printer with multiple nozzle print head such as dimatix was mostly used. With a single nozzle printhead of diameter 80 μm, we printed PEDOT: PSS with higher drop volume, so that the underneath silver grids are fully covered with PEDOT: PSS. Also, we have not performed embedding of

Figure 5. (a) 2d AFM image of the silver grid (b) 3d AFM image of the silver grid (c) 2d AFM image of PEDOT: PSS inkjet printed over silver grids (d) 3d AFM image of PEDOT: PSS inkjet printed over silver grids (e) 2d AFM images of P3HT: ICBA spin coated over PEDOT: PSS and (f) 3d AFM images of P3HT: ICBA spin coated over PEDOT: PSS.
the silver grids into the glass substrate, as in some other works in the literature [42]. Embedding of the grids could further improve the power conversion efficiency of the inkjet-printed ITO free organic solar cells. But it increases the cost of production as well as the number of manufacturing steps.

4. Conclusions

Bulk heterojunction organic solar cells with P3HT as donor and fullerene PCBM as acceptor were fabricated over silver grids/PEDOT: PSS composite electrode. The glass substrate was treated with oxygen plasma before printing to improve surface energy and a dual waveform is used in inkjet printing to prevent satellite drops. Adhesion test performed on the inkjet printed silver ink on glass substrates showed better adhesion after sintering the inkjet printed silver ink at a temperature of 120 °C for 80 min. The factors which influence the performance of the inkjet printed grids are adhesion of the ink to the base substrate, uniformity of the printed grid, width of the grid, height of the grid, spacing between the grid, sintering of the inkjet printed grid and the control of coffee ring formation. The performance of grids with 2 mm spacing is better than grids with 1 mm and 2 mm spacing due to the high figure of limit for transparent conductors. This indicates that the charge transport and charge collection are better in grids with 2 mm line spacing. From this research work, we can understand that silver grids/HCPEDOT: PSS composite electrode is a better alternative for indium tin oxide in the near future.

Acknowledgments

The authors would like to acknowledge the National Center for Photovoltaic Research and Education (NCPRE) (project code RD/0116-MNRE000-004-EXP), IITB-Monash research academy, Department of science and technology, (DST) and Indian ministry of human resource development (MHRD) for the funding received. The authors are also thankful to the Department of Metallurgical Engineering and Materials Science (MEMS) at the Indian Institute of Technology Bombay (IIT Bombay), Mumbai, for providing various facilities for device fabrication and characterization.
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