

第5章 FPDへの応用

6 Electronics applications of ink jet technologies

1. Introduction

Global need for energy will only increase with time, and in turn, new sources of energy must be created and perfected to meet those needs. With worldwide demand for electricity doubling by 2025 as projected by the United States Department of Energy, so grows the need for cheap sources of electricity¹⁾.

Increasing electricity demands have driven silicon solar panel production up by 20 % for the past 2 decades with sales up to \$9 billion as of 2005. An interesting catch-22 however, is that increasing demand for silicon solar panels has also driven a sharp rise in silicon prices, thereby increasing the cost per unit. To date, electricity from silicon-based solar panels is overall more expensive per kilowatt-hour than current conventional means¹⁾.

Creating ultra-low cost alternatives to silicon based solar cells would ultimately meet the electricity demand as well as offer secondary benefits such as lowering pollution from electricity derived from burning fossil fuels. The use of organic semiconductors for solar energy conversion has sparked interest because of the promising characteristics of specific formulations, their wide availability, and ultra-low cost.

Although opinions abound regarding “ideal” photovoltaic (PV) cell performance, two ideas persist. The first invokes the Power Conversion Efficiency (PCE) model to gauge PV performance. Generally, this formula measures the watts produced per unit area of a solar cell, divided by the watts of incident light under “Standard Test Conditions”. These conditions represent comparison standards that include irradiance, temperature and solar reference spectrum values. The higher the PCE, the better the PV¹⁾.

The second idea regards proper use of the solar spectrum. This spectrum includes wavelengths from ultraviolet (UV), visible, and infrared (IR). Creating a PV that effectively uses as much of the energy from the solar spectrum as possible, the more electricity can be generated from the cell. Although there are materials science obstacles, scientists have worked to combine materials with complimentary absorptive properties into a single PV to increase PCE¹⁾.

Adapting these ideas as a guide to formulating organic materials for use in organic-PV cells has spawned the “4th generation” of PV research in a number of institutions and private companies. Extensive use of organic nanomaterials has enhanced PV performance in ultra-low cost applications, and drives the possibility of wide spread use of organic-PV's in the future¹⁾. There are however, difficulties that must be overcome before mass marketing becomes a reality.

The functional characteristics of organic-PV cells requires much thinner active layers of absorption and excitation materials creating a bottleneck in that only a fraction of light is absorbed. These thinner layers create potential for short circuits between the electrodes. These nanoscopic holes not only decrease the efficiency of the PV, they may completely disable any light conversion. Therefore, developing a low-cost manufacturing method to create Organic-PV cells that improves thin layer deposition will work to improve PCE as materials are devised for more effective spectrum absorption.

With this improvement in mind, we investigated the feasibility of ink jet dispensing bulk heterojunction (BHJ) organic photovoltaic materials to create an organic-PV solar cell. The core of this investigation was to discover whether or not we could reproduce the efficiencies reported in the literature by dispensing similar materials to create an organic-PV cell. At the time of these experiments during 2003 ~ 2004, academic researchers were reporting using fabrication techniques such as spin coating.

For these experiments, we would rely on the drop properties of ink jet based dispensing to create the thin layers characteristic of organic-PV cells. These drop properties include reliable drop volume reproducibility as well as highly accurate drop placement. Our expertise in ink jet based dispensing further governed the direction of each experiment. Ultimately, finding ways to improve organic-PV cell production, by using low-cost manufacturing methods can only improve their acceptance into the wider energy market.

1.1 Solar cell structure and its functioning mechanism

A representation of an organic-PV cell similar to those created during this research is represented in Fig.1. The substrate consists of a plastic film or glass substrate coated with a thin (160 nm) layer of Indium Tin Oxide (ITO) is ink jet printed with poly(3,4-ethylene dioxythiophene)-poly(styrenesulfonate) to a thickness of about 100 nm. This layer facilitates hole conduction and serves to smooth the rough texture of the ITO layer. Surface roughness within the ITO layer is a common cause of short circuits within organic-PV cells for this type of solar cell.

Next, a layer of bulk heterojunction polymer-fullerene blend containing poly(3-hexylthiophene) in its regioregular form as electron donor and a fullerene derivative ([6,6]-Phenyl C61 —

butyric acid methyl ester) as electron acceptor is ink jet deposited to thickness of about 100 nm. Once this layer is complete, a 10 Å layer of LiF evaporated onto the photoactive polymer-fullerene layer to reduce the interface barrier for electron injection. Finally, a 100 nm layer of aluminum is vacuum evaporated onto the LiF layer to create the back electrode, thus completing construction of an organic-PV cell using bulk heterojunction materials.

The inherent asymmetry between the work functions of the cathode and anode within the Organic-PV cell creates an electric field. Within this field, holes move toward the ITO layer while electrons move toward the

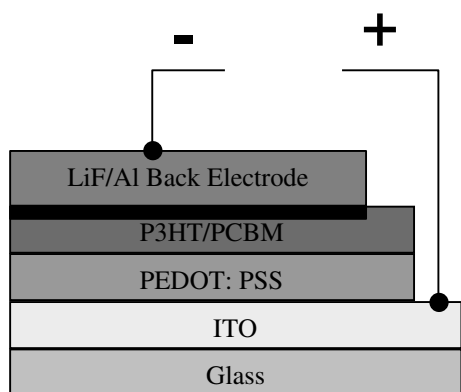


Fig.1
A Typical layered structure of organic solar cell

Continuous Ink Jet Technology

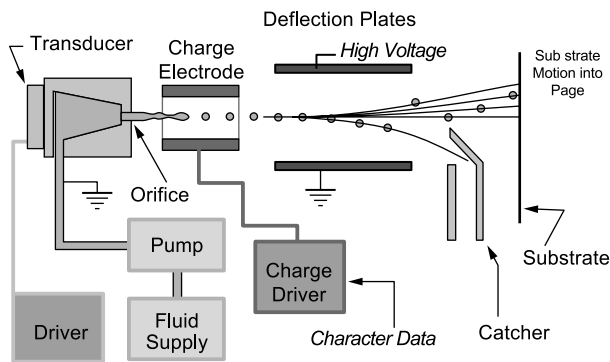


Fig.2
Continuous, Charge & Deflect ink jet system

Demand Ink Jet Technology

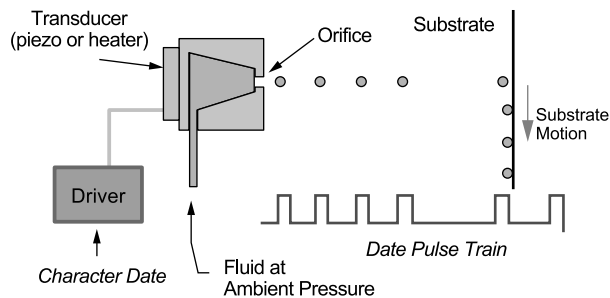


Fig.3
Drop-on-Demand ink jet system

aluminum cathode. When the electrodes are connected externally, a current is generated.

1.2 Background on drop-on-demand ink jet printing

One of the earliest experiments with droplets produced by pressure waves can be traced to Hansell²⁾ in the 1950's. In these experiments, Hansell observed the production of drops from electromechanically induced pressure waves. In this type of system the voltage pulse applied to a piezoelectric material that is directly (in contact with the fluid) or indirectly (affecting the fluid through a second material such as a glass tube) coupled to the fluid induces a volumetric change within the fluid. This type of volumetric change creates pressure/volume transients³⁾ within the fluid that are directional, thereby producing a droplet from an orifice of a specific diameter.

Although numerous methods and ink jet dispensing devices have been created over the years, each can be traced in principle to one of two broad methods. The first, best described as “Continuous, Charge and Deflect”⁴⁾ ink jet dispensing technology is shown in Fig.2. Here, a fluid under pressure is forced from an orifice (50 ~ 80 μm diameter) and breaks up into uniform droplets from amplification of capillary waves.

These waves are commonly induced onto the fluid jet through an electromechanical device.

Each drop is subsequently charged as it leaves the orifice, and pass through a “gate” that is also charged. When the charge on the “gate” is altered, ejected droplets either pass onto their moving target or are deflected into a catcher. This ink jet dispensing approach is most often used for applications requiring high-speed coverage of a large area. Drops created with this method are also larger (typically 500 μm diameter) by comparison to the drop-on-demand ink jet printing method, often twice the diameter of the orifice. One advantage however, is the rate at which droplets can be placed on target. Continuous, charge and deflect systems are capable of generating droplets at rates up to 1 MHz.

The second, more widely used method for ink jet dispensing is the “Drop-on-Demand” (DOD) mode as shown in Fig.3. This approach is well suited for applications requiring smaller droplets (20 ~ 100 μm diameter) and lower frequencies (up to 20 kHz). In DOD mode, a droplet is ejected from the orifice of the device after a voltage is applied to a transducer. Numerous transducers can be used and have included thermal, acoustic, and piezoelectric. In all cases, changes to the transducer in response to an electric pulse create pressure waves within the fluid thereby ejecting a droplet from the orifice. DOD devices produce droplets

nearly matching the diameter of the dispensing device orifice³⁾).

MicroFab Technologies Inc has applied their proprietary ink jet dispensing technology to numerous electronics, optics, and biomedical applications. For each in-house or customer driven project, the inherent accuracy and repeatability of ink jet dispensing and printing was required to achieve results beyond the capability of competing deposition technologies.

Many different technologies have been developed for microelectronics applications. MicroFab's SolderJet[®] technology can dispense molten solder onto targets in a digitally controlled manner. By heating the fluid reservoir and ink jet dispenser, SolderJet[®] printheads have been used to dispense molten solder over large or small substrates. Projects range from creating electrical interconnects, to microelectronics packaging. Numerous projects have benefited from solder dispensing where conventional solder bumping techniques such as screen printing, plating, or wave soldering would be inadequate.

MicroFab has also ink jet printed special inks laden with resistor material directly onto a circuit board substrate. Resistivity was adjusted by altering the components of the ink. Here, ink jet printed resistors were created between electrical connectors, creating a novel, low-cost method to populate a circuit board with resistors that did not exist before.

Optics has remained another promising field for MicroFab's ink jet dispensing technology. Micro-lenses, waveguides, and other optical components in the micron scale have been created with ink jet dispensing. Ink jet dispensing optical quality polymers has proven useful where non-contact deposition, or ultra-small drop size has been critical. Combinations of Optics Jet[®] and Solder Jet[®] technologies have been projected as ideally suited for Micro Electro-Mechanical Systems (MEMS) packaging (e.g. fabricating an optical switch).

By dispensing a number of different fluids, with myriad fluid properties, MicroFab has positioned itself as an authority in ink jet printing for MEMS, micro-optics and microelectronics applications. MicroFab has extended its dispensing capabilities by creating ink jet printing platforms for research and development.

2. Materials

2.1 Solar cell printing equipment

For these experiments, a MicroFab JetlabII[®] was used as shown in Fig.4 This commercially available platform consists of a substrate mounted to high precision X, Y, Z motion stages under command of the Jetlab[®] program. The Jetlab[®] program controls motion, ink jet dispensing parameters, and dispensing programs. Similar to every JetlabII[®], this platform had a substrate heater with vacuum platen for mounting the printing target, and a pneumatics controller for adjusting the meniscus of the ink jet. The dispensing devices chosen for these experiments was capable of dispensing fluids

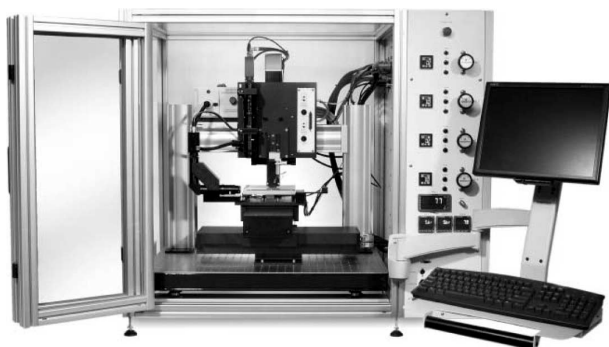


Fig.4
Jetlab[®] ink jet printing platform

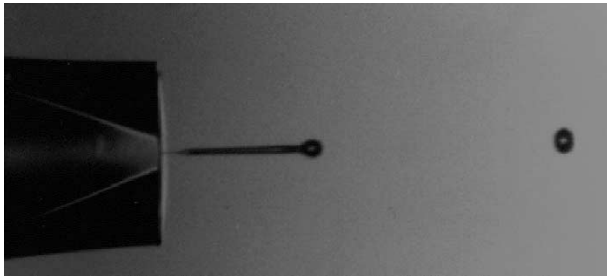


Fig.5
50 μ m drops dispensed from a dropon-demand ink jet device at 2kHz

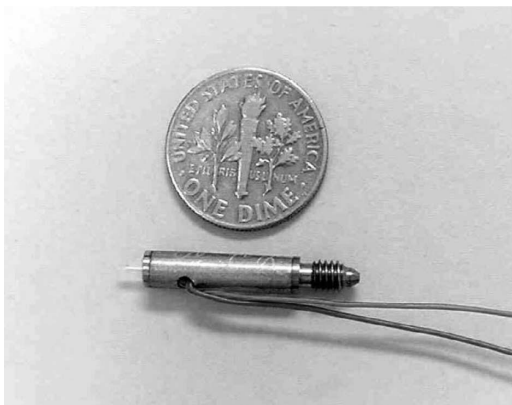


Fig.6
Single-jet, room temperature ink jet device

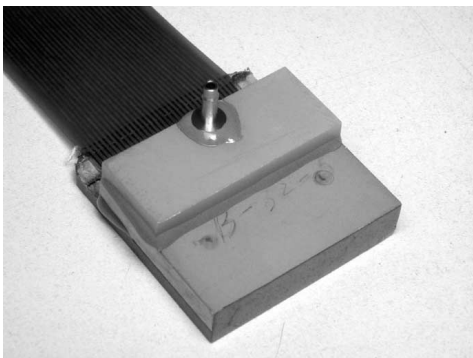


Fig.7
Multi-channel array printhead

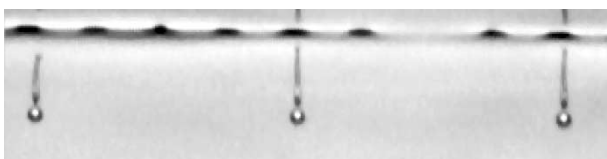


Fig.8
A section of array printhead generating drop-on-demand at 2kHz

of wide ranging rheology and readily appropriate for dispensing BHJ-PV ink.

The printing target was ITO glass substrates placed upon a heating capable platen. The heat source was isolated from the motion stages via thermally insulated standoffs, so as not to alter the accuracy of the motion stages. In this type of printing, the printhead is held in a fixed Z position and the substrate is moved beneath it. This would be in contrast to “gantry” type printing where the substrate is stable on a platen and the printhead moves over the target.

As described the printhead consists of a fluid reservoir and a single nozzle, DOD device, flowingly connected to the reservoir. Fig.5 shows MicroFab's ink jet dispenser producing drops of alcohol at 2 kHz. A similar device used to print the BHJ-PV is shown in Fig.6. These devices are designed to run effectively at low room temperature (up to 100 °C).

MicroFab, also, offers application specific multi-channel array printheads. This type of printhead maintains a plurality of fluid channels terminated at an orifice. Each fluid channel in the array printhead, as shown in Fig.7, is individually addressable. Fig.8 shows an array printhead dispensing alcohol at 2000 drops per second. Currently, these types of array printheads can dispense fluid from 16 channels simultaneously with near identical drop velocity across all channels. MicroFab is continuing work to increase the number of fluid channels for their array printheads.

2.2 Solar cell BHJ materials

There are a number of BHJ materials researchers have tried in order to print organic solar cells. Those commonly used and reported are :

- a. MDMO-PPV (poly (2-methoxy-5-(3',7'-dimethyloctyloxy)-1,4-phenylene vinylene) and [6,6]-PCBM (6,6-phenyl C₆₁-butric acid methyl ester) .
- b. poly (3-hexylthiophene) in its regioregular form as electron donor and fullerene ([6,6]-Phenyl C₆₁ - butyric acid methyl ester) as electron acceptor.
- c. Inorganic-organic hybrid dispersion of Cadmium selenium (CdSe) nanorods in poly (3-hexylthiophene)

in its regioregular form.

3. Methods

3.1 Substrates

For these experiments, each glass substrate was cleaned thoroughly to prevent surface contamination that would endanger thin film quality. Here, each glass substrate was placed in a detergent bath under sonication for at least 30 minutes. After washing, the substrates were rinsed thoroughly in DI water, followed by another sonication step for 15 minutes under filtered isopropyl alcohol (IPA). Each substrate was also cleaned by O₂ plasma treatment prior to printing. O₂ plasma treatment has been found to alter the contact angle of PEDOT on the surface of ITO coated glass substrates, where it is less wetting.

3.2 Printing patterns and strategies

There are many pattern choices available to create thin films on substrates when using ink jet dispensing. Patterns can be as simple as a series of lines, an array, or the more complex array of arrays. For each pattern, consideration must be given to the tendency of the fluid to wet the substrate. Depending on how the fluid wets the substrate, an operator may choose how to allow subsequent dispensed drops to overlap. Overlapping drops, and subsequently overlapping lines of drops can influence the thickness of the printed film. Also, small gaps between drops, or within an array pattern may be overcome by altering the overlaps between dispense cycles.

MicroFab's dispensing equipment used in these experiments can dispense a DOD pattern in two common modes. The first, best described as point-to-point, deposits a droplet at a specific spot on the substrate according to program command. This behavior is best characterized by the stages pausing at each target point, the dispensing device delivering a drop, then the stages move onto the next position for another dispense. This motion between target spots is highly accurate and well suited to similarly demanding applications.

A second drop-on-demand mode printing style is termed print-on-the-fly. Here, the MicroFab print station triggers dispensing onto the substrate, as the motion stages are moving underneath. In this mode, the stage speed and spacing between the drops locations determine the frequency of dispensing. Although the point-to-point mode is more accurate than the print-on-the-fly mode, the print-on-the-fly mode is extremely quick, enabling high throughput without significant penalty in drop placement accuracy.

For each of the experiments described below, dispensing was performed in the print-on-the-fly mode. Both interlaced and non-interlaced printing patterns were tested through these experiments. In a non-interlaced printing scheme, drops are placed sequentially and usually with some degree of overlap between two adjacent drops creating one smooth line. This is repeated across the whole printing area by printing successive lines with some degree of overlap to create one solid area of a thin film.

In an interlaced printing scheme, alternate drops are dispensed within a line, and alternate rows of lines are printed in the first pass of printing. In the second pass, printing begins with

an offset filling the area between the printed drops and printed lines, creating one continuous thin film. The difference comes in the amount of time allowed for the material to spread and dry before the next drop or line is printed. Depending on the solvent and material being printed one scheme may produce better results than the other. A matrix of experiments was generated using print modes and print schemes for a given set of materials as discussed below.

4. Printing experiments and results

Printing experiments basically consisted of varying the dispensed spot pitch (center to center distance between two adjacent spots) for PEDOT, MDMO-PPV and PPV-PCBM while varying the temperature of the substrate. With the exception of PEDOT, all printing experiments were conducted inside a glove box with an inert atmosphere. Moisture and oxygen content within the glove box were maintained below 10 ppm.

In conjunction, a special solution of MDMO-PPV in chlorobenzene (0.05 % by weight of the polymer) was printed for morphological studies of the thin film. Atomic force microscopy and scanning electron microscopy was used to gain a better understanding of the printed film's quality when fullerenes were added.

A brief summary of the printing experiments and their parameters is shown in Table 1. Analysis of the results of each dispensing experiment reveal that at least three critical factors are at work that affect the uniformity of the printed thin films.

The first of these major factors is substrate cleanliness. As described earlier, cleaning the substrate prior to printing is a critical preparation step that will ultimately affect the uniformity of the thin film, and in this case potentially alter its electrical performance as a component within a solar cell. We discovered through these experiments that the cleanliness of the substrate clearly affect the degree of wetting of the thin film materials on the surface as well as how the printed material spreads over the substrate when printed as lines, arrays, or an array of arrays.

Substrate temperature was also found to affect the quality of the thin film. The materials in

Table 1
Experimental summary

Print Sample	Ink	Print Mode	Print Speed	Printing in	Substrate	Pitch in	Print	Print
			mm/s	Glove box	temperature, C	X and Y, μm	passes	Date
1	MDMO-PPV	on-postion	N/A	Y	55	100	1	1/14/2004
2	MDMO-PPV	on-postion	N/A	Y	46	100	1	1/14/2004
3	PPV-PCBM	on-fly	2	Y	45	100	1	1/12/2004
4) A	PPV-PCBM	on-fly	2	Y	45	100	2	1/13/2004
4) B	PPV-PCBM	on-fly	2	Y	45	100	1	1/13/2004
5	PPV-PCBM	on-fly	2	Y	45	80	1	1/12/2004
6	PPV-PCBM	on-fly	2	Y	45	100 & 90	1	1/12/2004
Glass Slide # 1	PEDOT	on-fly	10	N	24	1st : 70 ; 2nd : 60	1	11/20/2003
Glass Slide # 2	PEDOT	on-fly	10	N	35	1st : 50 ; 2nd : 60	1	11/20/2003
Glass Slide # 3	PEDOT	on-fly	10	N	29	1st : 60 ; 2nd : 50	1	11/20/2003

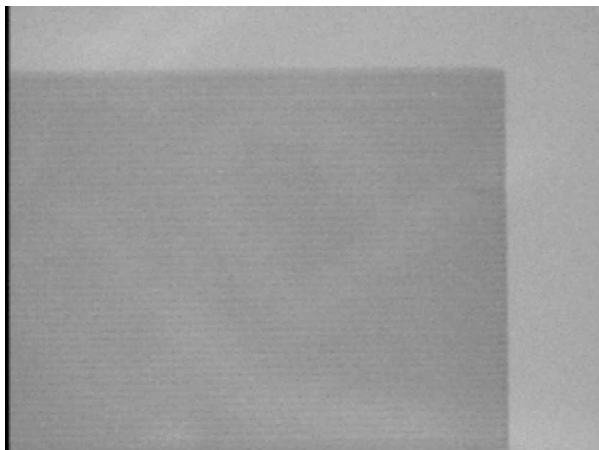


Fig.9
Neat PEDOT (darker area) printed on a clean glass slide at 35°C ; spot pitch of 60µm each in X and Y



Fig.10
A portion of PPV-PCBM film on ITO/glass at 45°C ; spot pitch 110µm each in X and Y

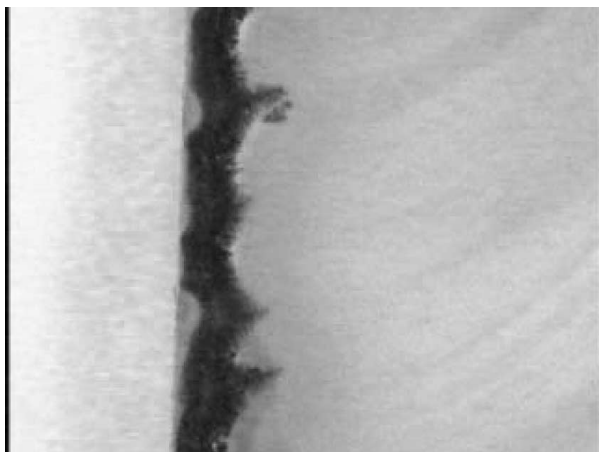


Fig.11
An edge of PPV-PCBM film on ITO/glass at 50°C ; spot pitch 100µm each in X and Y

these experiments often had drying rates that differed from one another. That said, affecting the drying time by altering the temperature of the substrate affected how the thin film spread on the substrate. In experiments where the materials were printed as overlapping lines, arrays or an array of arrays, increasing the temperature affected how the material ultimately rested on the surface. This of course, influenced not only the placement of subsequent lines, or arrays for filling gaps, but also how the overall pattern was laid out on the ITO substrate.

Beyond factors that affected the spreading of materials on the substrate, spot pitch in the X and Y-axis was found to be the third major factor affecting uniformity of the printed thin film. Changing spot pitch in the X and Y coordinates can create an additive affect of materials. The more each pair of spots overlaps, the thicker the film. Repeating this overlap between drops also contributes to the overall increase in thickness of the film throughout the entire printed pattern. Creating overlap by increasing the drop density, and by overlapping lines or arrays within the overall pattern, can greatly influence the film thickness. Here, adjusting the pitch determined the amount of material printed within a given area thereby determining the thickness of the final film. Obviously, smaller pitch between the drops (i.e. greater overlap between drops) translates into a thicker film, and vice versa.

Figs.9 through 12 show the quality of films obtained initially. Figs.9 and 10 show fairly uniform films of



Fig.12
A portion of PPV-PCBM film on ITO/glass at 45°C ; spot pitch 80µm each in X and Y

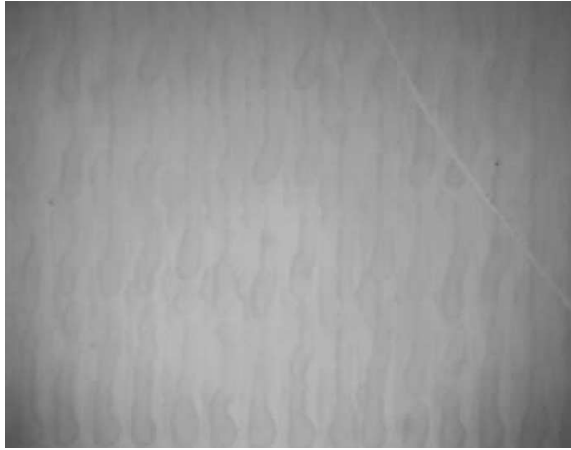


Fig.13
PEDOT on glass at room temperature

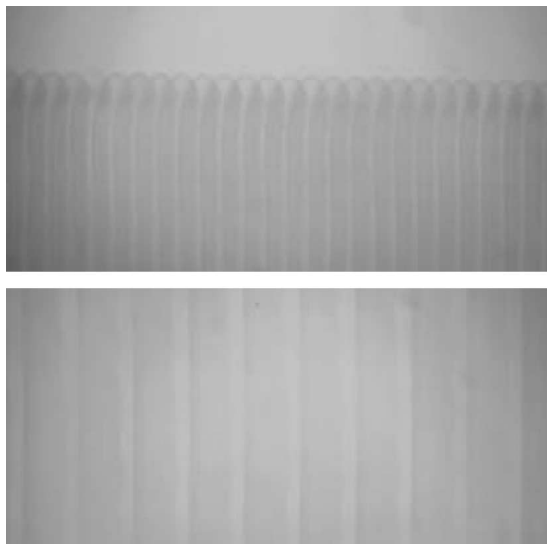


Fig.14
Printed PEDOT at 50°C. Above: note excellent edge alignment. Below (zoom) : note line-to-line coverage

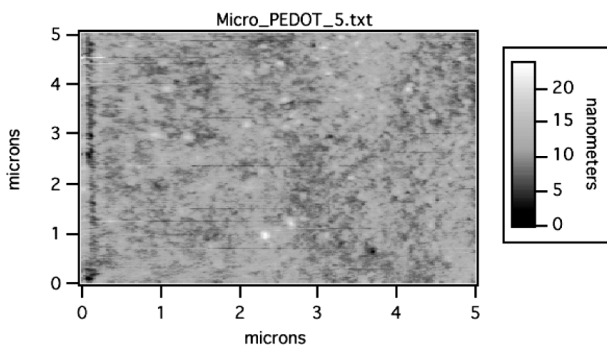


Fig.15
AFM image of PEDOT layer on ITO/glass ; surface roughness (rms) is 1.7nm

PEDOT and PPV-PCBM respectively but Figs.11 and 12 show the aggregation of PCBM at the edge and in the bulk of the film, respectively.

4.1 PEDOT

PEDOT (1.3 % solids) acquired from Sigma-Aldrich Chemical Company was mixed in dilutions ranging from 1 : 0.5 to 1 : 1.33 of PEDOT to DI water. For, initial printing tests a 1 : 0.75 solution was used. The optimum dilution was found to be 1 : 1.33 of PEDOT to DI water for printing onto ITO at 50 °C with an 82 μm spot pitch. By varying the rise and fall time, dwell time, and voltage settings an optimized waveform was discovered. A target velocity of 3 m/s was sought for a given PEDOT solution.

4.1.1 PEDOT printing

Having discovered an optimized waveform, PEDOT was printed on both plain glass substrates and ITO coated 25 mm square glass substrates. Fig.13 shows printed PEDOT film on glass at room temperature. It does show that it is thicker and non-uniform at the edges where lines overlap.

4.1.2 PEDOT on glass

After dispensing onto cleaned glass, the samples were examined using a DekTak profilometer to acquire data regarding surface uniformity. Scans indicated that PEDOT on glass showed a distinct row pattern as indicated by a series of peaks and troughs (data not shown). To minimize this effect, the substrate was heated and a series of tests were conducted to find the optimum temperature to stabilize the PEDOT fluid boundary after it was dispensed onto the glass. Ultimately, heating the substrate to 50 °C proved effective.

4.1.3 PEDOT on ITO

Different pitches and dispensing patterns were explored at 50 °C to find the optimum set of dispensing parameters. The optimum pitch was found to be 82 μm in both X and Y direction of printing. After many experiments, an array of arrays print recipe was selected where a PEDOT was dispensed in alternating rows through the pattern and alternating drop locations with-

in the pattern. The second array was printed similarly offset by the radius of the printed drop. At temperature of 50 °C, this pattern offered the most uniform PEDOT coating on ITO glass substrate as analyzed by AFM and shown in Fig.14. Fig.15 shows the quality of a PEDOT film right after printing and annealing at 200 °C for 5 minutes.

4.2 P3HT on PEDOT

After a PEDOT layer was successfully printed the photoactive polymer-fullerene layer would follow it. The electron-donating component of the BHJ material system is P3HT.

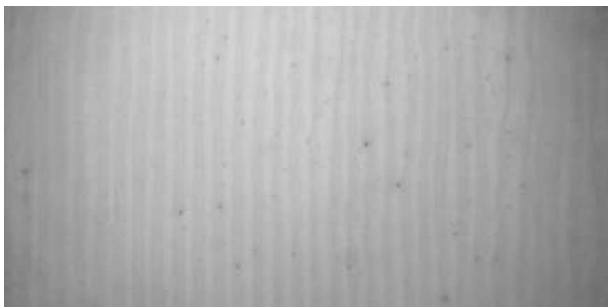


Fig.16
A portion of P3HT layer onto glass at 25 °C



Fig.17
A portion of P3HT layer at 25 °C onto PEDOT layer

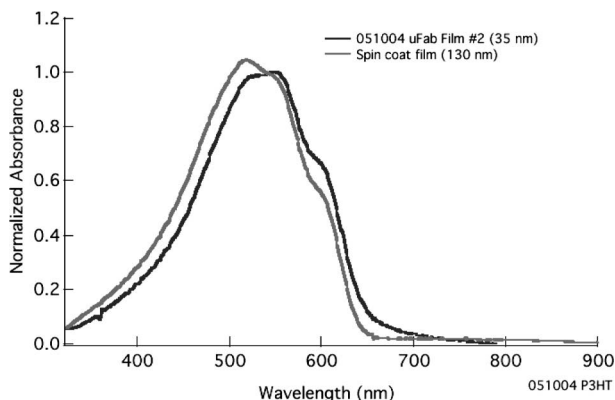


Fig.18
Comparison of absorption spectra of thin films of P3HT made by ink jet printing and spin coating

When combined with an electron acceptor like PCBM, a photovoltaic layer is created. Because purified P3HT was a scarce material, a small sample was prepared and examined for jetting and printing characteristics (Fig.16). After finding the optimum waveform, P3HT was printed onto prepared PEDOT layers on ITO glass substrates as shown in Fig.17. P3HT behaves similarly as PEDOT in that it aggregates at the edges of drops and printed lines. Favorably however, P3HT also stabilizes when dispensed onto a heated substrate. After testing a range of temperatures and printing patterns, 60 °C was chosen with an interlaced dispensing pattern. Fig.18 shows normalized absorption spectra of P3HT films produced by ink jet printing and spin coating. They are clearly comparable.

The desired thickness of the PEDOT layer for the organic-PV cells produced in these experiments was approximately 100 nm. Initial printing efforts created coarse films ultimately measuring within the range of 500 ~ 800 nm. More effort was given to optimize and correct for this overage through printing techniques and alterations to the PEDOT solution. These adjustments included diluting the PEDOT at a 1 : 1 ratio with DI water and varying the spot pitch. A spot pitch within ranges of 70 ~ 90 μm (single value) appeared optimum for thin film quality, however the film was too thin (average 50 nm) and surface roughness was more than desired.

In the final remaining experiments, the research effort was focused on optimizing the printed layers of PEDOT and the P3HT : C₆₀ polymer-fullerene blend. Unfortunately, the lead-time to obtain PCBM was far beyond the time available to complete this research to create a functional solar cell. PEDOT and the P3HT :

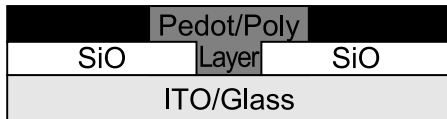


Fig.19
Cross-section of layered (partial) PV structure

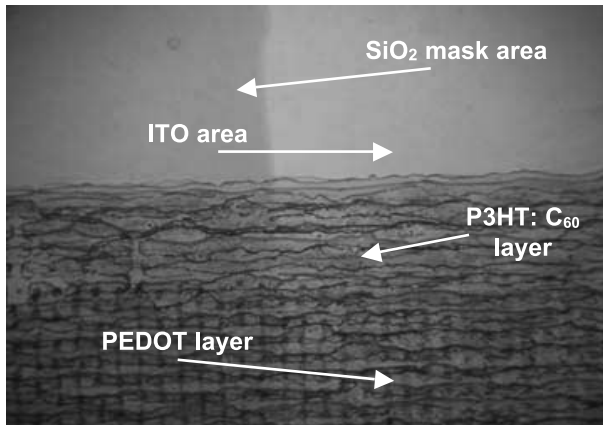


Fig.20
A section of printed device

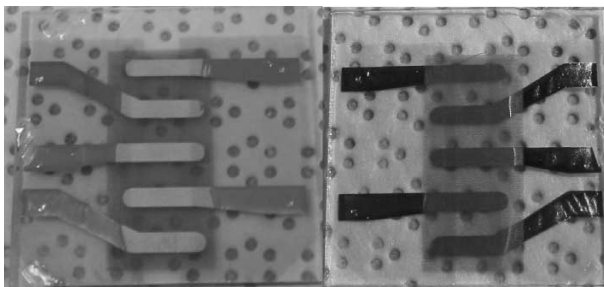


Fig.21
Top and bottom of a completed photovoltaic device on ITO/glass

C_{60} polymer-fullerene blend were printed onto patterned substrates of ITO glass substrates in order to better understand the surface interactions (e.g., drying rate, spreading, etc.,) as well as optimizing the dispensing parameters for these materials.

Once these parameters were optimized, PEDOT and the P3HT : C_{60} polymer-fullerene blend were printed in the correct pattern to create functional Organic-PV cells.

4.3 Solar cell device printing

Each Organic-PV cell was printed onto a 25 mm square ITO glass substrate. The patterning of the device area was performed by depositing SiO insulating layers onto the ITO to define a center stripe 3 mm wide. Fig.19 shows a cross-sectional drawing of the patterned device. PEDOT was then printed over the center stripe in a 5×20 mm rectangle. Polymer-fullerene (P3HT : C_{60}) blend was subsequently printed over the PEDOT layer.

Device fabrication was completed through collaboration with the National Renewable Energy Laboratory (NREL) of Golden, CO. NREL applied the aluminum cathode to the solar cell through an evaporation process onto the printed layers of PEDOT and the P3HT : C_{60} polymer-fullerene blend. This cathode defined a device area of 0.45 cm^2 . Organic-PV cell testing and characterization were also performed at NREL with direct feedback to MicroFab. Devices were characterized for their J-V properties under AM1.5 simulated solar illumination. Fig.20 shows a top view of different

overlapping layers of the device after printing but without the Al cathode. Fig.21 shows the top and bottom of the completed solar cell device with the cathode as back electrode.

5. Results & Conclusion

Devices tested at NREL exhibited a measurable photo-voltage of 360 mV and a photocurrent of 0.005 mA/cm^2 . We attribute the responsibility for the low voltage and current values to the fullerene C_{60} . This material readily crystallizes when in thin film form and disrupts uniformity throughout the film. Certain sub-optimized parameters within dispensing recipes may have contributed to the non-uniformity as well. However this can be corrected with more study.

We expect that substituting PCBM in place of fullerene C_{60} will significantly improve

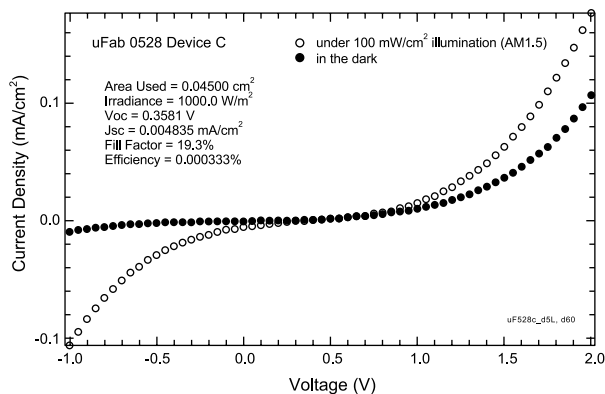


Fig.22
NREL test results for a printed solar cell. Efficiency is rated at 0.0003 %

organic-PV cell performance in combination to improvements in film printing. Other optimizations worth considering include experimenting with the solvents used, testing a wider range of substrate temperatures, and possibly incorporating surfactants in the dispensing solution to enhance the wetting properties of the dispensed droplets when they impact the substrate. Fig.22 shows the result of J-V characterization under AM1.5 simulated solar illumination.

Selecting fullerene C₆₀ as a component of the bulk heterojunction organic-PV cell material was not ideal for these experiments. The fullerene derivative PCBM however would have been preferred. Difficulty with

securing a steady supply combined with the relative long lead time for production and scarcity at the time of these experiments eliminated this material as a candidate. Initially, fullerene C₆₀ was quite difficult to disperse within the P3HT solution. This dispersion problem also manifested as settling out of solution once printing experiments began. Maintaining fullerene C₆₀ in a dispersed phase in the P3HT solution, however easily, would still not be preferred over using PCBM.

Fullerene C₆₀ caused undesirable aggregation along the edges of lines or arrays of printed droplets. This aggregation was only slightly remedied by continually overprinting to prevent holes, however the crystallization at the edges remained.

Our collaborators at NREL concurred that had PCBM been readily available at the time of the experiments as a substitute for fullerene C₆₀, a higher efficiency organic-PV cell would have been possible. We strongly believe future research using PCBM will yield more promising results. Efficiency improvements offered by using PCBM as the electron acceptor in place of fullerene C₆₀ can be expected to be many orders of magnitude greater. This increase will undoubtedly come from using the preferred material and optimized thin film printing processes.

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