Polymer Solar Cell Construction and Performance

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***Abstract*—Constructing solar cells using organic polymers allows for lower production costs, easier creation, and wider applicability at the expense of durability and efficiency as compared to silicon-based photovoltaic technologies. To demonstrate, polymer solar cells were created and tested in the lab. Several production variables were varied, and resulting efficiencies compared. The most impact step in the process was found to be the thermal annealing of completed cells; efficiencies improved by hundreds of percentage points after the anneal. Other variables were less impact, or suppressed by errors in the construction process.**

I. Motivation

Currently, global energy needs are met with the burning of fossil fuels. Aside from being a finite resource, the CO_2 that results from this combustion is highly detrimental to the environment and, if allowed to continue, a threat to global stability. Solar technologies seek to provide a renewable and emission-less source of energy by absorbing sunlight directly by use of a photovoltaic (PV). Historically, PV devices have used inorganic materials such as silicon to absorb light and generate a current to drive an external circuit [1], [2].

Such devices dominate the market, however they are too costly to compete with fossil fuels [1]. The development of organic, polymer-based solar cells seeks to reduce production cost by using printing and spinning techniques, as well as allow for more flexible materials and potentially a wider applicability of devices [1].

II. Theory

The device converts sunlight into usable energy by utilizing a light-absorbing polymer in each cell. This polymer donates excited electrons to a calcium cathode, which then flows to an ITO anode, generating usable current [1].

Each solar cell is composed of a glass substrate coated with several layers of materials (see Fig. 1). Each cell has an active region and an anode region. The first layer of the active region consists of indium tin oxide (ITO), which acts as the cell's anode. This layer is coated in the polymer PEDOT. The next layer is a blend of polymer (either P3HT or both P3HT and ZZ-50) and PCMB, and is the light-absorbing layer. A final layer of calcium completes the pathway between the active region and the cathode, which is a separate layer of ITO [2].

The glass substrate, ITO, and PEDOT are all transparent, so incident sunlight will travel through the device until it reaches the light-absorbing P3HT/PCBM layer. Light is absorbed in the polymer (either P3HT or a P3HT/ZZ-50 blend), exciting an electron from the polymer's highest occupied molecular orbital (HOMO) to its lowest unoccupied molecular orbital (LUMO). The resulting HOMO hole and LUMO electron form a temporarily-stable exciton, which is free to diffuse through the polymer. If the exciton diffuses to a polymer/PCBM boundary, it will collapse and the electron will fall into the LUMO level of the PCBM. This occurs because PCBM's LUMO is 1eV lower in energy than P3HT's LUMO [2]. If a potential difference is applied across the anode and cathode, the electron will then be pulled through the calcium to the ITO cathode. It will then flow into the PEDOT and complete the circuit [2].

ZZ-50 has a lower band-gap than P3HT. Thus a P3HT/ZZ-50 blend will absorb a wider spectrum of light than pure P3HT, potentially leading to an increase in efficiency .

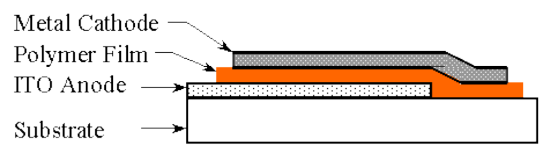

Figure 1: Polymer solar cell strata [4]

III. Methods

Solar cells were built using a pre-built glass substrate with four ITO anode/cathode pairs. Construction consisted of cleaning steps, followed by application of each layer in turn. Cells were then tested and results compared amongst all persons. Each person in our lab group made their own substrate, and an additional two were made by the instructor with no PEDOT layer or cleaning done, for a total of 11.

Cleaning steps consisted of placing substrate in an ultrasonic bath in acetone to remove any organic contaminants, then placed in an ozone oven to further remove contaminants. The ozone can also be absorbed by the substrate, which leads to better wetting of the PEDOT layer. All cleaning was done in a dust-free-area or under nitrogen escort when one was not available. Imperfect nitrogen escort could lead to contamination [4].

PEDOT was then spun onto substrate and annealed. The PEDOT planarizes the ITO surface and improves electron extraction by providing a larger work function than the ITO alone. However, PEDOT is a semiconductor, and can lead to shorts within the cells if it is not wiped from the cathode area [4]. Each person wiped two of their four cells.

Polymer solution consisting of the light-absorbing polymer(s) (either P3HT or the P3HT/ZZ-50 blend) and PCBM was then spun onto the substrate. Two different spin speeds were used, 2k rpm and 4k rpm. Higher speeds generate thinner layers. A via was then wiped roughly 0.5cm around the edge of the substrate, which allowed for electrical contact between the cathode and anode [4].

A final layer of calcium was deposited onto the substrate using vacuum vaporization [4]. This layer acts as part of the cathode; emitting electrons that are then accepted by the ITO. This generates the usable current.

Current-voltage testing was done on all substrates. The substrates then underwent a thermal anneal at 108°C for ten minutes. This improves performance by inducing spinodal decomposition in the polymer/PCBM layer – the polymer and PCBM phase-separate, creating better highways on which electrons may travel [3]. This method may work too well in some cases, creating highways that act as shorts.

All substrates were tested again after annealing, then a final test of wavelength absorption (measured as optical density) was performed.

IV. Analysis

Tabulated efficiencies before and after thermal annealing are available in Appendix I. Overall results demonstrate a remarkable improvement. Cell A on substrate 3 experienced a 186.6% increase in efficiency and a 69.0% increase to fill factor, while Cell D on substrate 4 experienced an 836.6% increase in efficiency and a 104.5% increase to fill factor after the anneal. This indicates that anneal does indeed lead to beneficial phase separation within the polymer/PCBM layer.

Figure 2 shows the absorption spectra of two of the larger cells, one with purely P3HT and one with a P3HT/ZZ-50 blend. The decrease of the P3HT peak in the blended polymer is expected, as there is proportionally less P3HT in the blend.

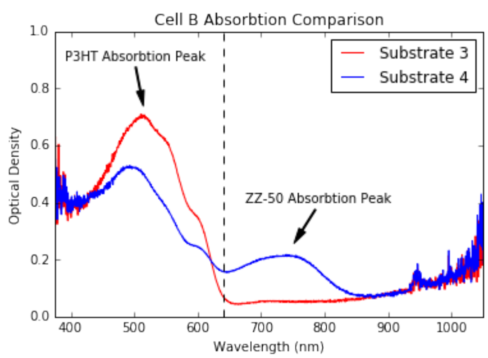

Figure 2: Comparison of polymer blends on absorption

The effect of wiping the PEDOT versus not wiping was minuscule, and in many cases there was almost no difference whatsoever. Higher spin speed should theoretically improve performance, as thinner layers increase the likelihood of an exciton diffusing to a polymer/PCBM boundry and entering the circuit. However, higher spin speed yielded consistent results but did not improve performance (see Fig. 3 and 4).

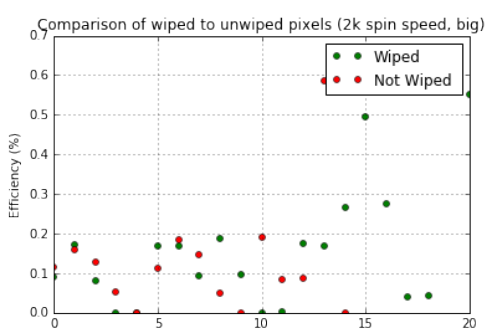

Figure 3: Efficiency comparison for pixels spun at 2k

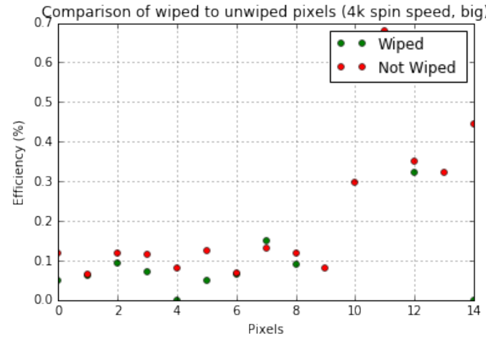

Figure 4: Efficiency comparison for pixels spun at 4k

V. Conclusion

Polymer solar cell technology shows much promise as a cheap and adaptable energy source, however much more work is done to reach consistent efficiencies and drive cost down even further [1], [2]. Construction parameters were varied and found to have minimal impact on cell efficiencies. Thermal annealing of completed cells leads to remarkable improvements to efficiency. Higher spin speed generates more consistent cells, but with no noticeable increase to efficiency. Smaller pixels performed consistently worse than larger pixels, even after anneal. This is most likely due to imperfect wiping or over-wiping of the PEDOT layer or vias, as both were done by inexperienced hands. Though physically it should improve performance, the wiping of PEDOT from cathode area seemed to have no consistent impact, even when selected out from other variables.

References

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[2] Brabec, Christoph J., and James R. Durrant. "Solution-Processed Organic Solar Cells." MRS Bulletin 33 (2008): 670-75. Web. 6 June 2016.

[3] Janssen, Ren A., Jan C. Hummelen, and N. S. Sariciftci. "Polymer-Fullerene Bulk Heterojunction Solar Cells." MRS Bulletin 30 (2005): 33-36. Web. 5 June 2016.

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Appendix I - Tabulated Cell Data

All cells A and D are 'Big' pixels with area 42.0 cm^2. All cells B and C are 'Small' pixels with area 3.75 cm^2. SC Current is really current density, and all efficiencies are in percentages.
On date 5-3-16:

Substrate 1, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.111669	0.28727	-0.147305	0.475
B	0.00719402	0.153059	-0.1	0.075
C	0.00639922	0.143982	-0.106667	0.075
D	0.0923775	0.268633	-0.145643	0.425

Substrate 2, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.184807	0.429292	-0.147597	0.525
B	0.162515	0.436854	-0.127546	0.525
C	0.0	0.241762	-0.192993	0.325
D	0.189107	0.43546	-0.148891	0.525

Substrate 3, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.0970863	0.27193	-0.151208	0.425
B	0.0292774	0.213387	-0.141123	0.175
C	0.0118206	0.218422	-0.129883	0.075
D	0.147965	0.329788	-0.153828	0.525

Substrate 4, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.0507096	0.258994	-0.108439	0.325
B	0.00658298	0.175850	-0.0898443	0.075
C	0.0132477	0.299264	-0.106242	0.075
D	0.0665847	0.260233	-0.108366	0.425

Substrate 5, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.149579	0.305512	-0.185533	0.475
B	0.0159639	0.268911	-0.142476	0.075
C	0.00663073	0.141707	-0.112299	0.075
D	0.125985	0.301864	-0.176762	0.425

Substrate 6, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.0510571	0.26809	-0.105477	0.325
B	66.5055	6443.21	0.0743169	-0.025
C	0.00798377	0.184089	-0.104085	0.075
D			-0.015141	0.025

Substrate 7, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.0918764	0.249020	-0.139813	0.475
B	0.0087554	0.199511	-0.105323	0.075
C			-0.0331574	0.025
D	0.067932	0.235928	-0.138210	0.375

Substrate 8, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.130495	0.315884	-0.1	0.425
B	0.011380	0.0986588	-0.166100	0.125
C	0.00478829	0.0757010	-0.151806	0.075
D	0.119251	0.293057	-0.17234	0.425

Substrate 9, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	9.35171	39257.3	0.00171515	-0.025
B			-0.0125005	0.025
C	0.004844	0.135872	-0.08557	0.075
D	0.080267	0.256707	-0.118489	0.475

Substrate 10, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A			-0.118967	0.025
B	0.141920	0.357316	-0.11	0.625
C	0.130555	0.363828	-0.103345	0.625
D	0.00404560	0.0371717	-0.111944	0.175

Substrate 11, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.175262	0.403204	-0.149030	0.525
B	0.189272	0.40551	-0.160026	0.525
C	0.174023	0.409460	-0.145716	0.525
D	0.169430	0.403422	-0.143994	0.525

On date 5-10-16:

Substrate 1, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.189576	0.272782	-0.294341	0.425
B	0.0299430	0.322665	-0.222718	0.075
C	0.0199770	0.0678167	-0.302990	0.175
D	0.267011	0.357708	-0.358296	0.375

Substrate 2, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.0831390	0.230617	-0.152685	0.425
B	0.371315	0.461988	-0.	0.425
C	0.367426	0.359470	-0.490623	0.375
D	0.494354	0.502726	-0.416476	0.425

Substrate 3, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.276881	0.36038	-0.368779	0.375
B	0.218720	0.285125	-0.3	0.375
C	0.0377750	0.110153	-0.352730	0.175
D	0.0867454	0.240869	-0.1	0.425

Substrate 4, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.597044	0.488832	-0.51728	0.425
B	0.266811	0.276095	-0.535221	0.325
C	0.310520	0.267206	-0.557807	0.375
D	0.635668	0.476964	-0.505036	0.475

Substrate 5, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.323454	0.365324	-0.374988	0.425
B	0.0280653	0.0911378	-0.316742	0.175
C	0.0387338	0.206014	-0.270741	0.125
D	0.298501	0.352697	-0.358449	0.425

Substrate 6, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.585305	0.441585	-0.502280	0.475
B	61.5955	30219.1	0.0146757	-0.025
C	0.344667	0.438865	-0.5	0.275
D			-0.280843	0.025

Substrate 7, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.735859	0.495570	-0.562688	0.475
B	0.	0.24344	-0.5	0.325
C	0.0174401	0.0617482	-0.406713	0.125
D	0.	0.472757	-0.	0.475

Substrate 8, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.351157	0.411918	-0.361055	0.425
B	0.0407659	0.0902348	-0.361421	0.225
C	0.0391579	0.151285	-0.372722	0.125
D	0.322918	0.384880	-0.	0.425

Substrate 9, Spun at 4k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A			-0.0520828	0.025
B			-0.345123	0.025
C	0.431349	0.979750	-0.352211	0.225
D	0.444927	0.431525	-0.390716	0.475

Substrate 10, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.0409208	0.144084	-0.40896	0.125
B	0.659238	0.531973	-0.	0.475
C	0.525109	0.50712	-0.3	0.475
D	0.0446435	0.0912820	-0.391257	0.225

Substrate 11, Spun at 2k:

	Efficiency	Fill Factor	SC Current	OC Voltage
A	0.565824	0.555219	-0.43161	0.425
B	0.591275	0.557580	-0.449123	0.425
C	0.531221	0.556712	-0.404137	0.425
D	0.550371	0.556633	-0.418764	0.425