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DEPARTMENT OF CHEMICAL ENGINEERING

CONTACT DOPING FOR ORGANIC PHOTOVOLTAICS

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ABSTRACT

To increase efficiency of polymer solar cells, the use of a dopant layer has been utilized. The dopant layer is the interface layer between the ITO (indium tin oxide) and active polymer layer which helps to increase contact. Currently, PEDOT:PSS is the most widely used dopant layer, but it has inherent issues. As a replacement to PEDOT:PSS, sulfonated polyphenylsulfone was explored by comparing the maximum efficiency of cells with different concentrations and levels of sulfonation. The active layer consisted of the donor polymer Poly(3-hexylthiophene) (P3HT) and the acceptor polymer indene C-60 (ICBA). After testing, the average maximum efficiency of no dopant layer was found to be 1.15%; PEDOT:PSS showed an average maximum efficiency of 2.51%; the best sulfonated dopant layer was 0.15 mg/mL with a sulfonation level of 2.33 which produced an average maximum efficiency of 2.96%. The trend of the curve showed that a higher sulfonation level and a lower concentration lead to a higher maximum efficiency. However, low sulfonation levels showed to have a negative effects on the cell and cause the efficiency of the cell to be well below the no dopant layer cell. Based on these results, sulfonated polyphenylsulfone at certain sulfonation levels show promise as a replacement for PEDOT:PSS as a dopant layer.

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Chapter 1 : Introduction

As oil supplies deplete and CO₂ emissions rise, the need for a new energy source is at an all-time high. However, the idea that one energy source will be able to serve all the world's energy needs is not likely. Ultimately, it will be a culmination of energy technologies that solves the problem, and one such technology is organic photovoltaic also referred to as polymer solar cells. This new technology has the potential to be cheaper and more flexible than its silicon counterpart thus giving it a variety of new applications.²

When most think of solar cells, they imagine the cells seen on top of buildings. These cells are silicon based solar cells which have become the major method of capturing the sun's energy and converting it to useable energy. Unlike silicon based solar cells, organic photovoltaics (OPV) use polymers as a means of capturing photons and producing energy. The basic structure of an OPV is shown in Figure 1.⁵

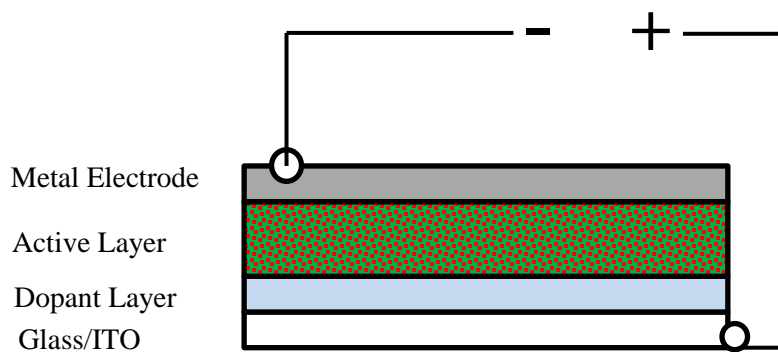


Figure 1. Diagram of a heterojunction organic photovoltaic.

As shown in Figure 1 there are five main layers in a cell: the glass or plastic layer which acts as the base for the cell, the conductive oxide layer most often indium tin oxide (ITO), the dopant layer, polymer active layer which is a mixture of an electron accepting and electron donating polymer, and a metal electrode often aluminum. The basic mechanics of the solar cell begins with a photon being absorbed by the cell. The glass and ITO layer must be clear for the photon to be absorbed by the active layer. The absorbed photon then excites electrons from the highest occupied molecular orbital (HOMO) of the electron donating polymer to the lowest unoccupied molecular orbital (LUMO) of the electron accepting polymer. This is depicted in Figure 2.^{2,9}

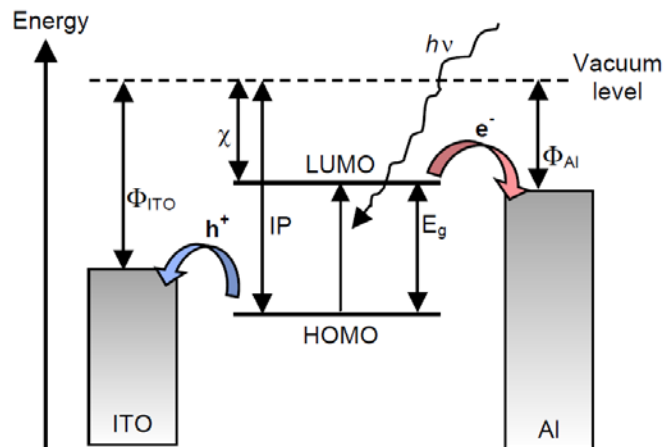


Figure 2. The depiction of a solar cell absorbing light and forming an excitation.²

The excitation of the electrons forms an exciton which is the electron and the positive hole it leaves behind when the electron moves from the HOMO to the LUMO. The electron moves from the acceptor to the anode (aluminum) whereas the positive hole moves through the donor to the cathode (ITO) which ultimately creates the external direct current.²

In a cell, there are multiple characteristics that are measured to calculate efficiency which are the I_{SC} , V_{OC} , and FF. These three items multiplied out gives the maximum power. The I_{SC} or J_{SC} is the maximum current and gives information about charge separation. The V_{OC} is the maximum voltage difference between the two electrodes. FF is the fill factor. The maximum

efficiency is the ratio between the maximum power produced by the cell to the power of the incident light and is the characteristic used to measure performance of the cell.^{4,5}

To maximize the efficiency, the dopant layer is added between the ITO and active layer. The purpose of the dopant layer is to increase contact between the active layer and the ITO by reducing the energy barrier between the two layers. It can also help form a selective contact. The anode is a hole collector whereas the cathode is an electron collector. The dopant layer can be selective and allow electrons to go through while also serving as a method to block holes from going through and vice versa. Currently for polymer solar cells, the dopant layer used is PEDOT:PSS with the structure as shown in Figure 3.⁸

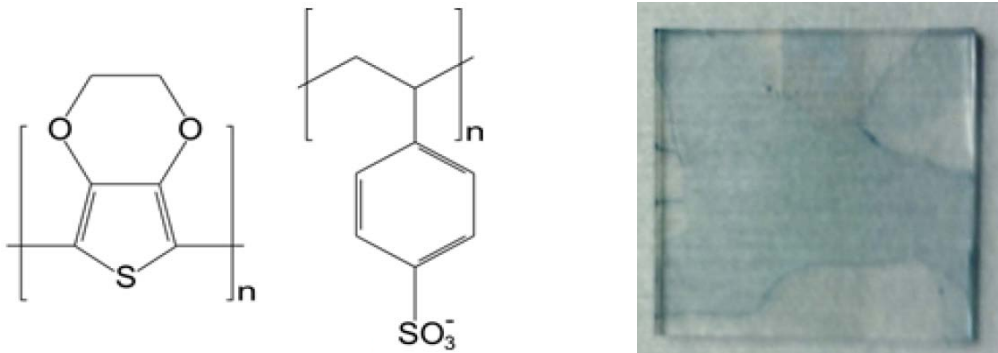


Figure 3. The molecular structure of PEDOT:PSS, and a cell with PEDOT:PSS spincoated on it.

Though PEDOT:PSS helps to increase efficiency in the cell, there are inherent issues with PEDOT:PSS. PEDOT is hygroscopic and will absorb water from the atmosphere which can degrade performance, it is slightly acidic which also can degrade the cell, it is not completely transparent as shown in Figure 3, and it cannot extract electrons efficiently.⁸ Due to the problems arising from PEDOT:PSS, a sulfonated polyphenylsulfone (SPS) dopant layer was explored with the structure shown in Figure 4.

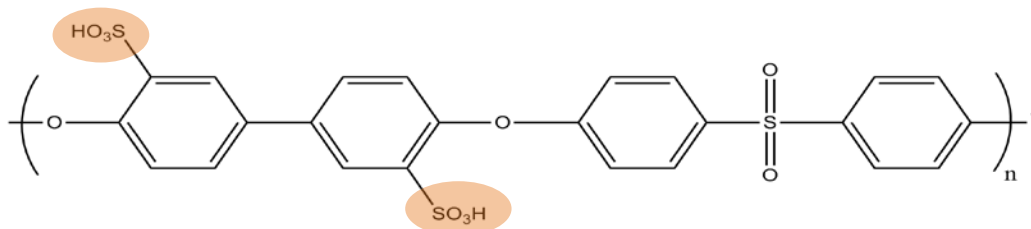


Figure 4. The molecular structure of sulfonated polyphenylsulfone.

The sulfonated layer helps performance by inducing free charges and fills potential between the ITO and active layer to increase electron mobility. From previous works, the sulfonated layer has been found to improve efficiency in comparison to no dopant layer as well as increasing the sulfonation level of the layer increased the maximum efficiency as shown in Figure 5.³

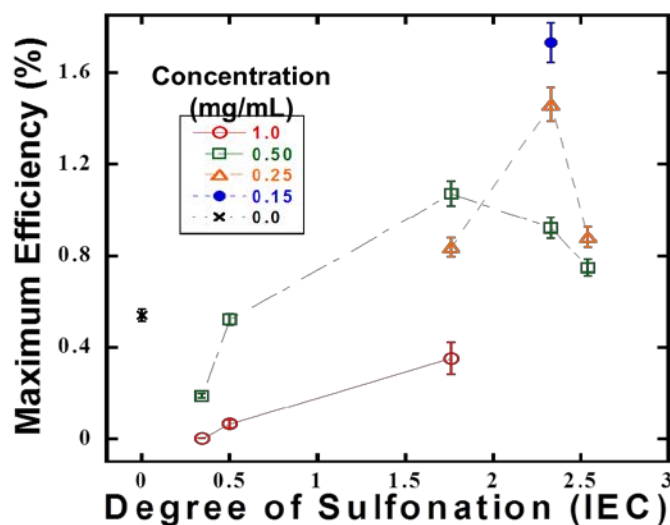


Figure 5. Results of efficiency vs. degree of sulfonation. (Data collected by Patrick Weathers from the University of Florida)

In addition to higher sulfonation level, a lower concentration leads to a better efficiency. In this case, the concentration of the dopant layer refers to mg of SPS to mL of organic solvent. For the solar cell data displayed in Figure 5, the active layer consisted of the donor polymer Poly(3-

hexylthiophene) (P3HT) and the acceptor material [6,6]-phenyl-C-61-butyric acid methyl ester (PCBM). These two polymers are the most represented material in polymer solar cell research. Figure 6 shows the molecular structure of the two polymers.^{7,9}

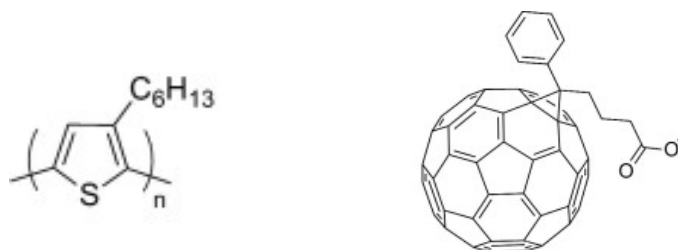


Figure 6. Molecular structure of P3HT and PCBM.

New research has gone into finding a better polymer to increase efficiency. PCBM is soluble in organic solvents, has high electron mobility, and a high electron affinity. The major issue with PCBM is low LUMO energy level and a low absorption of visible light which decreases the cell's ability to absorb photons. The low LUMO energy gives the solar cells a lower V_{OC} due to its relation to the energy difference between the HOMO of the donor polymer and the LUMO of the acceptor molecule. To counteract this problem, a new acceptor polymer is being explored which is indene-C₆₀ (ICBA). ICBA is easily synthesized and soluble in organic solvents. It also has a higher LUMO thus a higher V_{OC} and is less attracted to the ITO than PCBM.^{1,7}

ICBA is made from a Diels-Alder reaction between C₆₀ and indene. Figure 7 shows the reaction mechanism.

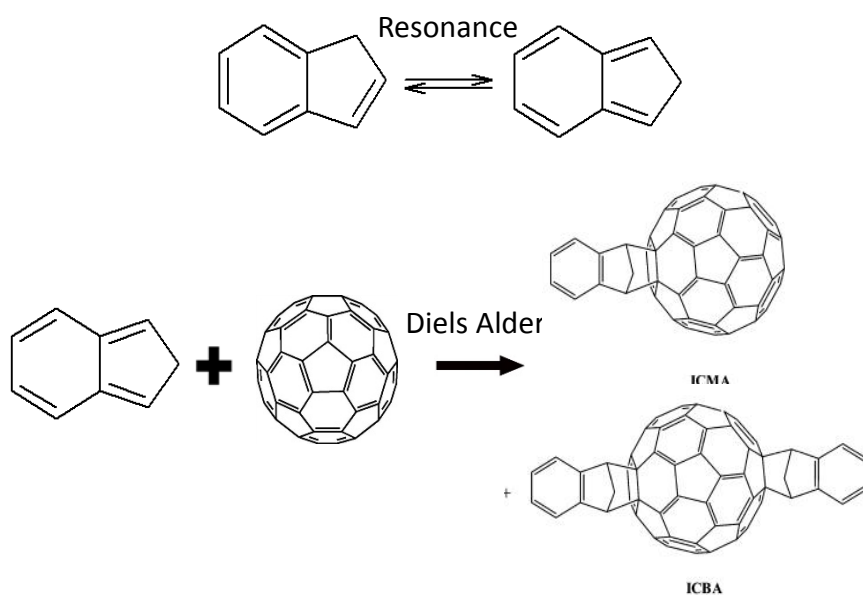


Figure 7. Synthesis of C₆₀ to ICBA.

A Diels Alder reaction is when a conjugated double bond attacks the double bond of an alkene.⁶ In this case, indene attacks the double bonds present in C₆₀. For this synthesis, there are multiple side reactions due to the uncontrolled addition of indene. ICMA is the addition of only one indene, ICBA has two indene additions, and multi-adduct is three or more indenenes. ICBA was the desired product for use in the active layer.¹

It is hypothesized that the sulfonated dopant layer will follow the same trend as shown in Figure 5 when using ICBA instead of PCBM. To test this, the efficiency of polymer solar cells with different levels of sulfonation and concentration of polyphenylsulfone were measured. This showed the relationship between the level of sulfonation with efficiency.

Chapter 2 : Experimental

The experimental section lays out the general practice when synthesizing ICBA, creating solar cells, and testing solar cells. The ICBA was synthesized and used as an electron acceptor in the active layer for the solar cells. The solar cells were made by spin coating various layers on to a glass and ITO layer than tested in a solar simulator.

2.1 Synthesizing ICBA

1.44 g of C_{60} was weighed out and placed in a 500 mL round bottom flask. Indene comes as a liquid (density of 0.992 g/mL) so 4.667 mL was measured out with 60 mL of trichlorobenzene in a graduated cylinder and added to the round bottom flask. A magnetic stir bar was then added and the flask was set aside and covered with aluminum foil.

The next step was to set up the oil bath and condenser as shown in Figure 8.

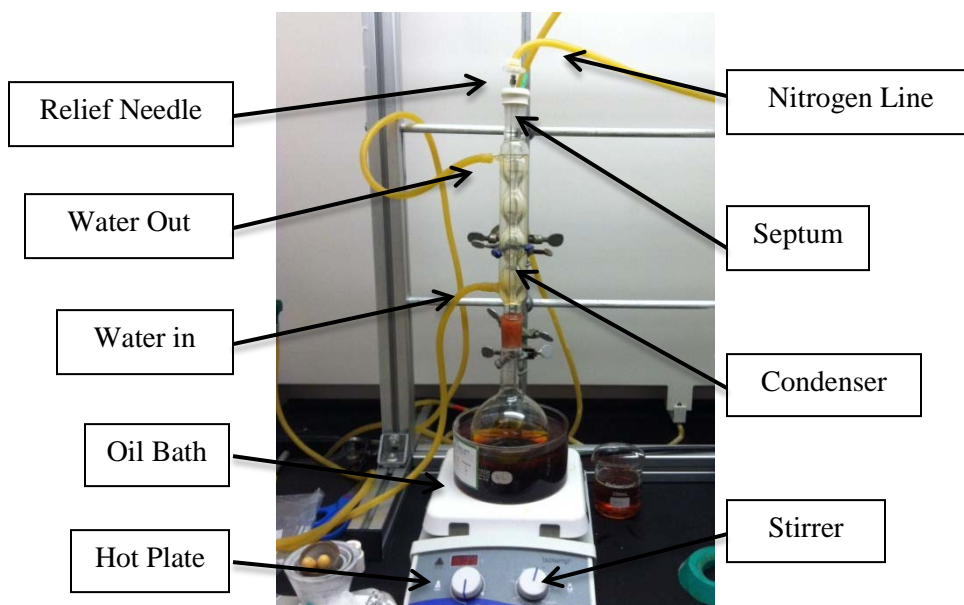


Figure 8. Setup of the hot oil bath with condenser.

The oil bath was prepared by filling the container about half way with oil and placed on the hot plate stirrer. The round bottom flask was placed in the oil bath and stabilized by a ring stand. The condenser was setup and placed into the round bottom flask. A septum was placed on top of the condenser and two relief valves were put in the septum. A needle end was placed through the rubber septum that connected to the nitrogen line. At this point, the reaction was ready to be purged. Ideally, the purge would be overnight and throughout the time the reaction was occurring to prevent oxidation. However due to availability of nitrogen, the system was purged for 1 to 2 hours and the needles removed from the septum. To prevent air from entering, the septum would be taped by electrical tape. Regardless of the availability, the nitrogen purge was allowed to run for an hour before the hot plate was turned on. Once purged, the hot plate was set to 335 °F and a thermocouple was used to monitor the temperature and make sure the oil bath reached 220 °C. The reaction ran for at least 24 hours.

After 24 hours, the hot plate was shut off and the reaction was allowed to cool to room temperature. 100 mL of pure methanol was added and the flask swirled, so the product could precipitate. The reaction should appear like a dark red brown to an orange brown as shown by Figure 9.

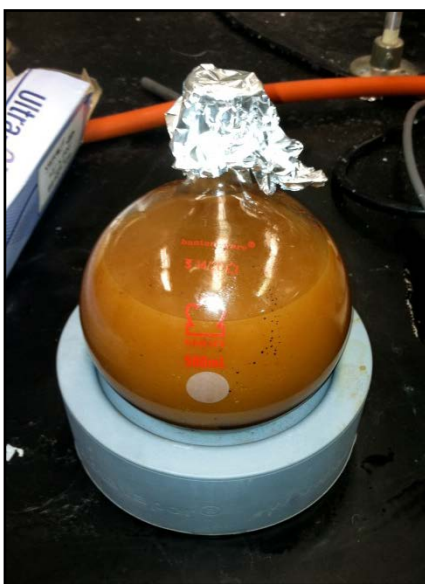


Figure 9. Crude product from the C60 and indene reaction. (Photo taken by Sarah Torhan)

To get out the product, the mixture was vacuum filtered. The Rotovap's vacuum line was used for the filtration process. The vacuum was turned on and lowered to 900 mbar. Pure methanol was poured onto the filter paper then the reaction product was poured onto the filter paper and pulled by vacuum into the flask. The vacuum pressure could be adjusted to as low as 820 mbar. The desired product will be a red/brown solid on the filter paper. The solution should be filtered two or three times, and the filter paper was changed as needed. The product was scraped off the filter paper and placed in a vial as shown in Figure 10.



Figure 10. Filtered product of ICBA synthesis.

The vial was covered with aluminum foil and placed in a vacuum dryer. The vacuum was pulled on the product for 24 hours then the heat was set to 10 and the product was under vacuum for an additional 24 hours.

2.2 Separation of ICBA

The reaction described in section 2.1 created multiple side products such as ICMA and multi-addict C_{60} along with the ICBA. This had to be separated to get the desired ICBA product. This was done through column chromatography.

Silica was added to the flask at approximate ratio of 1:3 of product to silica. The product from section 2.1 was dissolved in 60 mL of chloroform. A small portion of the chloroform mixture was set aside in a vial and diluted further with chloroform. The rest of the solution was taken to the Rotovap and the chloroform was evaporated off. The chromatography column was then set up.

A couple of cotton balls were added to the column then filled two-thirds of the way with silica. The silica was checked to make sure it was packed evenly, tightly, and contained no cracks. The silica product mixture from the Rotovap was added to the column followed by an inch layer of sand. For the mobile phase, a 10% toluene-hexane mixture was used. The stopper at the bottom of the column was opened and mobile phase was added continuously to prevent the column from “running dry”. As shown in Figure 11, the monoadduct (ICMA), bisadduct (ICBA), and multi-adduct products could clearly be identified in the column due to the color difference.

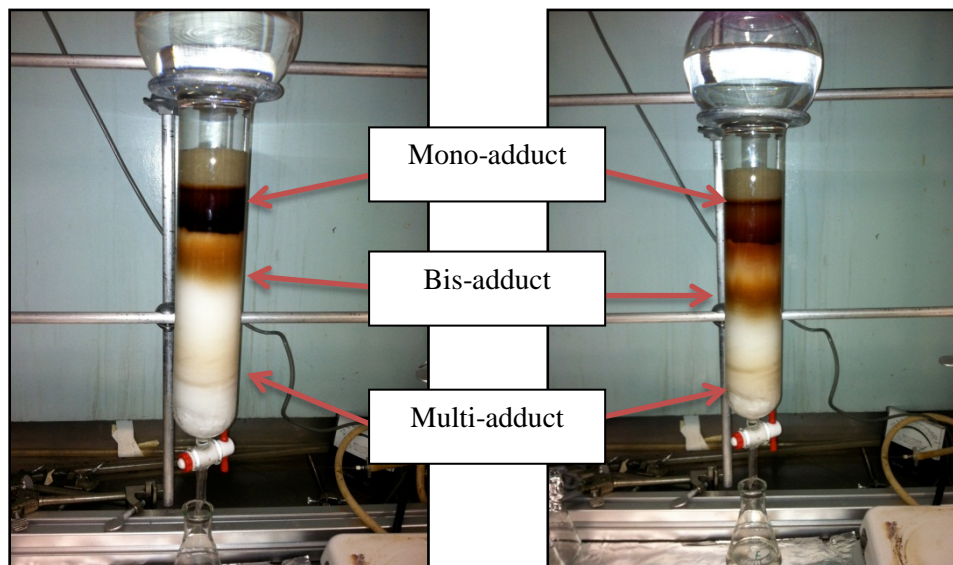


Figure 11. Column chromatography of ICMA, ICBA, and multi-adduct. (Photo taken by Sarah Torhan)

Multi-adduct eluted first followed by bisadduct and monoadduct. This elution order was due to the fact heavier molecules run through the column faster. In the end, the goal was to collect the bisadduct, so larger samples were collected until the bisadduct began to elute.

The composition of each fraction was tested by TLC plates using the same mobile phase as in the column and compared to the diluted solution made before running the column. Pure fractions with the same chemical from the column were combined with one another. The mobile phase was evaporated using the RotoVap. Once a small amount of liquid was left, the solution was transferred to a vial and placed in the RotoVap again. This procedure was repeated for all 3 fractions. The three components were then put in the vacuum oven under vacuum for 24 hours than put under a heat setting of 10 for another 24 hours. Once dried, the ICBA was ready for use and was kept in a typical chest freezer.

2.3 Preparing Active and Dopant Layer Solutions

2.3a Active Layer

A 20 mg/mL mixture of ICBA and P3HT at a 1:1 ratio was created for the active layer. Approximately, 10.0 mg of ICBA and 10.0 mg of P3HT were measured out. 1 mL of chlorobenzene was added to the solution along with a magnetic stir bar. The solution was stirred overnight in the hood.

2.3b Sulfonated Layer

Sulfonated polyphenylsulfone (SPS) solution was made for the sulfonated layer. Approximately 1 to 3 mg of SPS was weighed out and diluted by 0.8 mL of chloroform and 0.2 mL of methanol. The concentration of the solution was calculated. The concentrated solution was used as the stock solution. Samples of the solution were further diluted in two separate vials

to 0.15 mg/mL and 0.25 mg/mL using an 80% chloroform to 20% methanol solvent with each having a total volume of 1mL. Sample calculations to create a 0.25 mg/mL solution are shown below with the assumption of a 2.4 mg/mL stock solution.

$$.25 \frac{mg}{mL} * 1mL * \frac{1 mL}{2.4 mg} = .104 mL \text{ of stock solution}$$

$$1 - .104mL = .896mL \text{ of } 80\% \text{ chloroform} - 20\% \text{ methanol solution}$$

The solutions were made the night before to give the SPS time to dissolve in the solution.

2.4 Solar Cells and Testing

The cells with a glass back and ITO on top were commercially purchased from and used for the solar cell. The cells were washed using soap and a q-tip to remove any dust or dirt particles. The cell was then dried using an air line. Acetone was added to a beaker containing the cell till the liquid was completely covering the cell. The beaker was wrapped with aluminum foil and placed in the Sonicator for 10 minutes. The acetone was then removed and isopropyl alcohol was added to the beaker. The beaker was placed in the Sonicator for another 10 minutes. The cells and beaker were dried, wrapped with aluminum foil, and place in the oven over night.

The cells were taken out of the beaker and placed in the UV cleaner (ITO side up) for 10 minutes. The cells were placed in a four compartment petri dish that was labeled to identify which type of cell was in each compartment. The next following steps varied depending on the type of cell being made.

2.4a Pedot:PSS Cells

The cell was taken from the UV cleaner and immediately placed in a spin coater (still ITO side up). A 3 mL filtered syringe was filled with approximately 250 μ L of PEDOT:PSS. Two drops of PEDOT from the syringe was placed to the side and then approximately three drops were put on top of the slide. The spincoater was set to 1000 RPM for 60 seconds. After the spincoater, the cell was placed on a 165 °C heat plate for 10 minutes. The cell was then brought into the glove box.

2.4b Sulfonated Cells

After the UV cleaner, the cell was brought in the glove box and placed in a spin coater (ITO side up). The spincoater was run for 60 seconds at 1000 RPM with 250 mL of the sulfonated solution (0.15 mg/mL or 0.25 mg/mL) added to the cell.

The cells are kept in the glove box for the remaining procedure due to OPV's sensitivity to oxygen. Once the dopant layer was added, the active layer (P3HT/ICBA solution) was spin coated onto the cell. 0.250 mL was added to the cell and was spin coated for 60 seconds at 1000 RPM. For cells without a dopant layer, the active layer was placed right on top of the ITO. The cells were then placed in the Evaporator, and a 0.750 kÅ layer of aluminum was added to the cells on top of the active layer.

After being removed from the evaporator, THC was used to remove the polymer from one of sides the ITO. Silver paint was brushed on top of the ITO side stripped of the polymer. The cells were then annealed on a hot plate for 10 minutes at 165 °C. Figure 12 shows the finished product. The cells were then ready to be tested by the Solar Simulator which measures the efficiency of the cell.

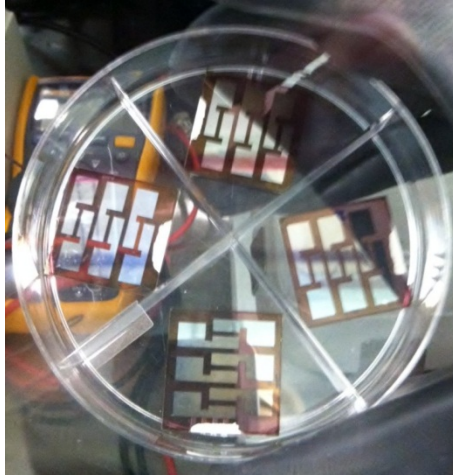


Figure 12. Lab created polymer solar cells using ICBA/P3HT as the active layer.

Chapter 3 : Results and Discussion

An array of cells were made using P3HT/ICBA as the active layer. In these cells the dopant layer was the variable, and different levels of sulfonation for the dopant layer were tested with a dopant concentration of 0.15 mg/mL and 0.25 mg/mL. The level of sulfonation is measured by the IEC number; the higher the level of sulfonation, the higher the IEC number. In the solar simulator, the cell was tested by measuring current vs. voltage in the cell. Figure 13 shows the J-V (current-voltage) curve for three different cells.

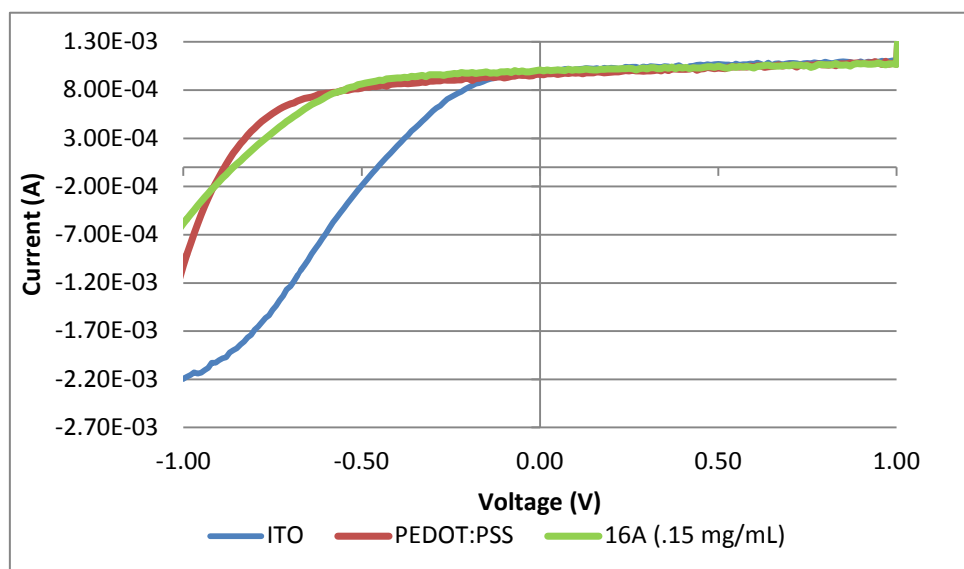


Figure 13 Current vs. voltage for the top efficiency cells.

These were the top efficiency cell for each category: no dopant layer, PEDOT:PSS, and a polysulfonated dopant layer. These curves show the relationship between current and voltage in the cell and are used to calculate other characteristics of the cell such as J_{SC} , V_{OC} , FF, and overall efficiency. The y-intercept is the maximum current which can find the maximum current density (J_{SC}), and the x-intercept is the maximum voltage (V_{OC}). The bend of the curve is the maximum power which is used to calculate the efficiency and FF. From the graph, all three cells

have similar maximum current, but the maximum voltage is significantly less for the non-dopant cell. In addition, the doped cells show a higher FF and overall efficiency. However, the sulfonated layer shows a slightly smaller maximum power compared to the PEDOT:PSS which leads to a lower FF and efficiency. To compare the several variations of the dopant layer and to find the optimum, the characteristics were measured for different levels of sulfonation and concentrations then averaged and plotted together to see if a relationship existed.

Figure 14 and Table 1 show the J_{SC} data based on the level of sulfonation of the dopant layer.

Table 1 JSC data with standard deviation for various dopant layers.

JSC Data								
No Sulfonation			0.15 mg/mL			0.25 mg/mL		
Type	JSC	SD	IEC	JSC	SD	IEC	JSC	SD
ITO	6.13	0.07	0.34	0.76	-	0.34	1.68	0.11
PEDOT	5.81	0.30	1.45	4.81	-	0.5	6.06	0.36
			1.76	6.42	-	1.45	1.72	0.22
			2.33	6.07	0.13	2.33	6.23	0.28
			2.54	6.11	0.10			

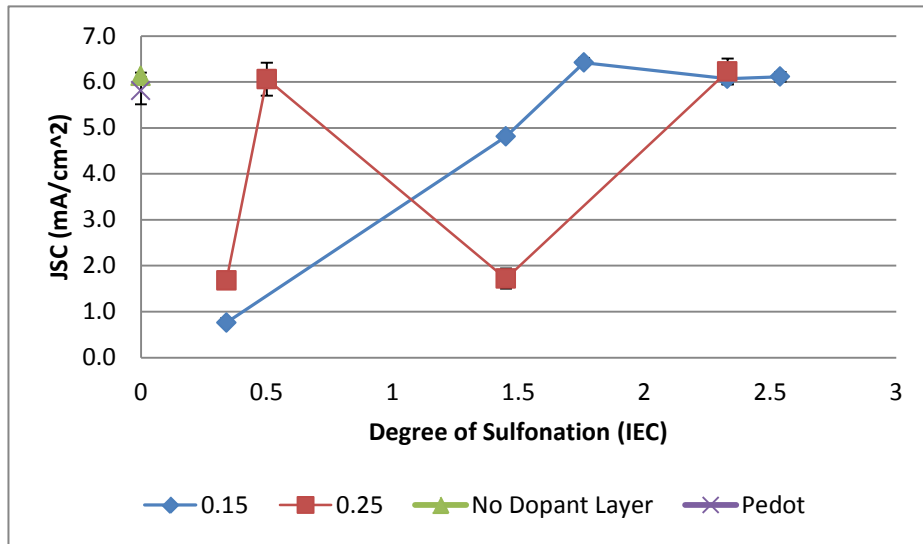


Figure 14. JSC vs. degree of sulfonation

J_{SC} is the short circuit current and determines the maximum cell current. It characterizes how efficiently charges move through the cell. An increase in J_{SC} means an increase in performance. As it can be seen for 0.15 mg/mL, the higher sulfonation leads to an increase in short circuit current then has a dip once a sulfonation level of 1.76 is reached. The maximum current density for 0.15 mg/mL and overall was 6.32 mA/cm² at a 1.76 sulfonation level. In general for a concentration of 0.25 mg/mL, the current density increased with sulfonation level and had a maximum value of 6.23 mA/cm² with an IEC of 2.33. There is a questionable point that exists for 0.25 mg/mL at a sulfonation level of 0.5 due to the large jump in J_{SC} value. Further investigation should be done to confirm if the point is accurate or not. The no dopant layer and PEDOT:PSS dopant layer showed a similar J_{SC} value as the higher sulfonated dopant layer. This suggests the dopant layer has no effect on maximum current density.

A similar plot was made for the V_{OC} for each cell. Table 2 shows the data and Figure 15 graphically represents the data.

Table 2 Voc data with standard deviation for various dopant layers.

Voc Data								
No Sulfonation			0.15 mg/mL			0.25 mg/mL		
Type	V_{OC}	SD	Sulfonation	V_{OC}	SD	Sulfonation	V_{OC}	SD
ITO	-0.445	.021	.34	-0.380	-	.34	-0.13	.01
PEDOT	-0.752	.079	1.45	-0.320	-	.5	-0.49	.007
			1.76	-0.380	-	1.45	-0.21	.015
			2.33	-0.850	.0047	2.33	-0.43	.004
			2.54	-0.855	.005			

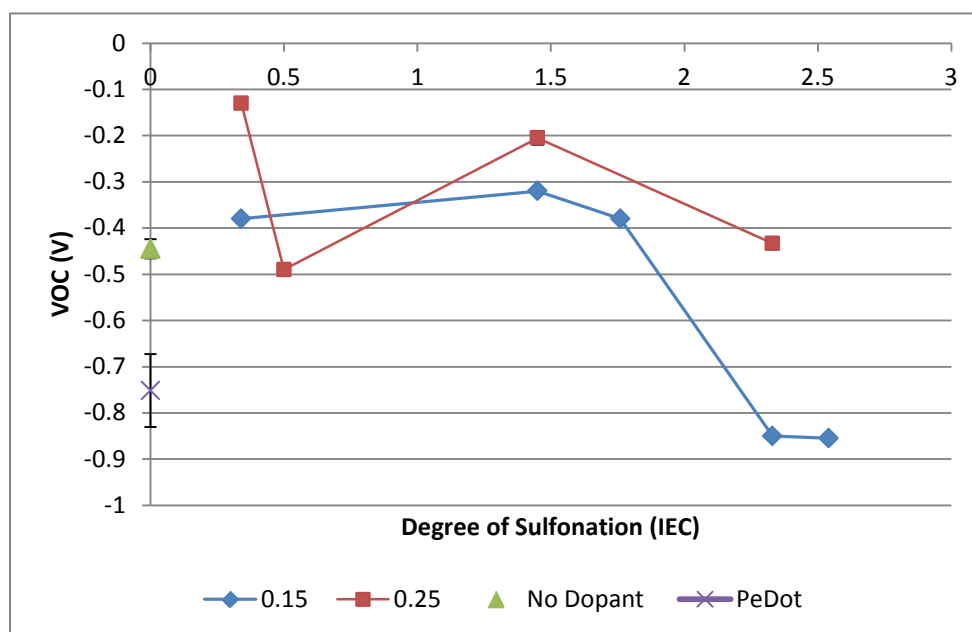


Figure 15 V_{OC} vs. degree of sulfonation

V_{OC} is the maximum voltage in the cell or the point when the charge buildup maximizes at each electrode. A method of increasing the V_{OC} is to increase the gap between the HOMO of the donor polymer and the LUMO of the acceptor polymer. Compared to P3HT/PCBM, ICBA has a higher V_{OC} due to ICBA having a higher LUMO orbital. As seen in Figure 15, the higher sulfonation leads to a larger negative V_{OC} value for 0.15 mg/mL. In addition, 0.25 mg/mL shows a similar relationship assuming the point with an IEC of .5 is an outlier. The graph also shows a lower concentration of dopant layer improves the V_{OC}. The no dopant cell and low sulfonation cells showed a significant decrease in V_{OC}. The no dopant cell had a V_{OC} of -0.445 V, PEDOT had a V_{OC} of -0.752 V, and the highest V_{OC} for the sulfonated cells was -0.855V.

Another important characteristic of OPVs is the fill factor. Table 3 shows the data for the fill factor for different dopant layers and Figure 16 shows the data graphically.

Table 3 Fill factor data with standard deviation for various dopant layers.

FF Data								
No Sulfonation			0.15			0.25		
Type	FF	SD	IEC	FF	SD	IEC	FF	SD
ITO	0.380	.014	0.34	0.161	-	0.34	0.268	.002
PEDOT	0.543	.030	1.45	0.267	-	0.5	0.494	.011
			1.76	0.337	-	1.45	0.211	.003
			2.33	0.488	.007	2.33	0.436	.032
			2.54	0.497	.006			

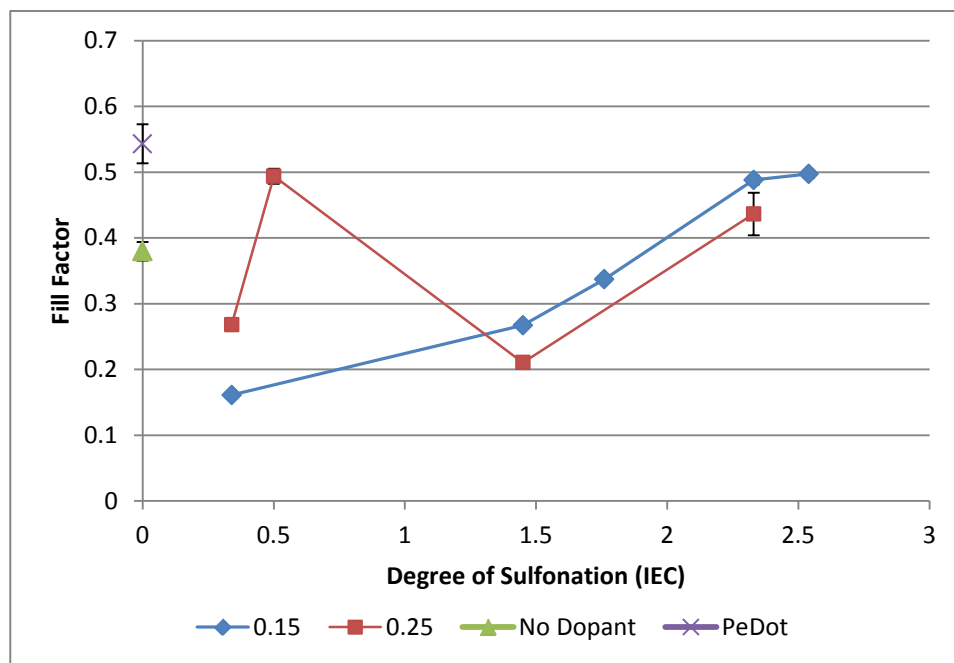


Figure 16. Fill factor vs. degree of sulfonation

The fill factor is measured by the ratio of maximum power to the open circuit voltage times short circuit current and gives insight on the resistance within the cell. An increase in fill factor is associated to a higher efficiency.⁴ From Figure 16, an increase in sulfonation shows an increase in the fill factor for 0.15 mg/mL. In addition, the graph showed 0.25 mg/mL had a dip in the fill factor at a sulfonation level of 1.45 from a sulfonation of 0.34 then showed an increase when the sulfonation level reached 2.33. The fill factor for no dopant layer was approximately less by 0.1

than the highest fill factor for the sulfonated dopant layer and 0.117 less than PEDOT:PSS. The PEDOT:PSS showed a 0.046 increase in fill factor over the sulfonated dopant layer. This suggests a dopant layer increases the fill factor of the cell, but SPS as the dopant layer may have no or negative effect on the fill factor.

The FF, J_{SC} , and V_{OC} are all characteristics used to calculate the maximum efficiency of the cell which was the main factor used to compare performance. Table 4 shows the maximum efficiency data and Figure 17 is a graph of the data.

Table 4 Maximum efficiency with standard deviation for various dopant layers.

Maximum Efficiency								
No Sulfonation			0.15			0.25		
Type	Eff	SD	IEC	Eff	SD	IEC	Eff	SD
ITO	1.15	.085	0.34	0.039	-	0.34	0.061	.009
PEDOT	2.51	.113	1.45	0.424	-	0.5	1.51	.046
			1.76	0.848	-	1.45	0.077	.015
			2.33	2.96	.007	2.33	1.31	.110
			2.54	2.89	.006			

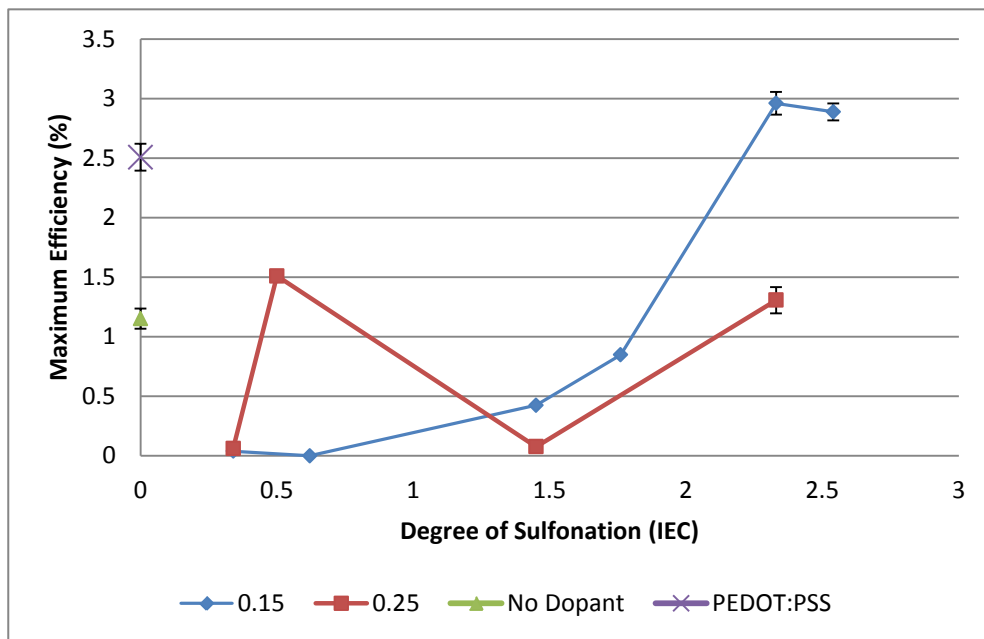


Figure 17 Maximum efficiency in regards to degree of sulfonation.

As mentioned earlier, the point that correlates with 0.25 mg/mL of dopant with an IEC number of 0.5 is a questionable point. When compared to Figure 5, the 0.15 mg/mL follows the general trend of the graph when sulfonation level is increased. 0.25 mg/mL does not follow the trend from Figure 5 which further suggests the point may be an outlier. For 0.15 mg/mL, the increased sulfonation level increased efficiency till an IEC value of 2.33. For 0.25 mg/mL, an increase in sulfonation increased efficiency with a probable outlier at an IEC value of 0.5. From Patrick Weather's data shown in Figure 5, decreasing concentration of the dopant layer increased efficiency. Using ICBA, the same relationship was shown with 0.15 mg/mL having a better efficiency than 0.25 mg/mL. This decrease is primarily due to the lower V_{OC} and FF shown in the higher concentrated dopant layer. The best efficiency was 2.96% shown by a dopant sulfonation level of 2.33 at a concentration of 0.15 mg/mL. This was shown to be higher than the PEDOT:PSS which showed an efficiency of 2.51% and no dopant layer which was 1.15%. In addition, the data showed that having a lower sulfonation level hurt the performance of the solar cell and was less effective than having no dopant layer at all.

Chapter 4 : Conclusion

Polymer solar cells show great promise for the future. However, the efficiency must be increased to make them a viable energy source. After testing, the average maximum efficiency of no dopant layer was found to be 1.15%; PEDOT:PSS showed an average maximum efficiency of 2.51%; the best sulfonated dopant layer was 0.15 mg/mL with a sulfonation level of 2.33 which produced an average maximum efficiency of 2.96%. From these results, it was concluded the sulfonated dopant layer could be a replacement for PEDOT:PSS as a dopant layer, at the right concentration and sulfonation level. At a high enough sulfonation level, it achieves similar efficiency as using a PEDOT:PSS layer. However, the lower sulfonation levels actually had a negative impact on the efficiency of the cell and had a worst performance than no dopant layer. The trends seen in Patrick Weather's data were replicated for ICBA in which the higher the IEC, the higher the efficiency. In addition, ICBA showed a lower V_{OC} than using PCBM which explains the increased efficiency of the cells. Further analysis must be done to confirm the trends in the data due to some outliers and high standard deviations. Higher concentrations of dopant layer and a larger variety of sulfonation level should be explored to find the optimal dopant layer.

Chapter 5 : Future Work

A limited number of concentration and sulfonation levels were tested. Further testing on different concentrations and sulfonation levels of the dopant layer must be continued to explore the relationship between efficiency and sulfonation. More specifically, a max IEC level of 2.54 was tested in this lab. Higher IEC levels along with IEC levels around 2.33 (optimum found in this study) should be tested to see their effects on efficiency and to find the optimum sulfonation level. In addition, there should be further research into why low sulfonation causes the cell to perform worse than using no dopant layer. All this research will lead to a better understanding of the role of sulfonation and the dopant layer as a whole in the performance of the cell.

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