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# **Organic Polymer Solar Cells: The Effects of Device Packaging on Cell Lifetime**

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# Organic Polymer Solar Cells: The Effects of Device Packaging on Cell Lifetime

Spencer Herrick

## *Abstract*

As the earth runs out of nonrenewable energy sources and climate change starts to have drastic effects on the environment, the world is becoming increasingly desperate for cost efficient, renewable energy sources. Organic polymer based solar technology is a cutting edge approach to meeting the world's energy demands. We fabricate single-layer, organic photovoltaics devices that utilize the electrical characteristics of semi-conductive polymers. These solution processable materials are beneficial due to their low material cost, lightweight, and simple fabrication requirements. Our devices utilize multiple photoactive polymers, P3HT and PCPDTBT, to absorb photons over a wide spectral range. We optimized various device characteristics including thickness and thermal anneal, to reach a power conversion efficiency of 3.0% in AM1.5 sunlight, standard illumination. We also investigated the effects of different packaging techniques on cell lifetime.

## *Introduction*

Organic Photovoltaics are a rapidly emerging field in solar technology, which could prove to be an economically viable and environmentally conscious solution to meeting the world's energy needs. Our planet is suffering drastic environmental and climate changes from decades of excessive fossil fuel use [1]. But even with the knowledge that our planet is suffering and that we need to stop saturating our atmosphere with green house gasses, there is no large-scale economic alternative to fossil fuels [2]. There are many emerging renewable technologies that hope to be economically competitive with fossil fuels, but none have reached this goal. Solar has incredible potential to meet our energy needs, as the sun provides 1000 watts per square meter of power on the surface of the earth (at a 48 degree zenith angle). The sun is providing an abundance of energy, and, with the right technology to harness its power, we could fuel much of our planet without having a negative impact on the environment.

Within the field of solar electric technology, there are many different approaches toward reaching competitive cost goals. Figure (1) shows the progress of the different avenues of solar research that have been pursued over the past 35 years. While many of these technologies have shown remarkable increases in efficiency over this time, they all remain too costly to be economically competitive with fossil fuels [3]. Currently, crystalline silicon is the only

commercially viable option, but this is only due to substantial government subsidies. The major problem with silicon is the low absorptivity of the material [4], which creates an inherent material cost that is currently difficult to overcome. This is not the case with organic polymer technology. As Figure (1) shows, there was little research done on this technology until the early 2000's, and since then it has shown increasing efficiency over the past ten years [3]. What makes this technology so promising is its incredibly low potential cost. Once this technology can compete with the efficiency of silicon cells, organic cells may be an economically competitive source of electricity. Organic cells are also lightweight, and flexible [5], meaning that they will be relatively easy to install, as their lightweight will not require any complicated structural support. Their flexibility also has the potential for many novel applications, such as clothing, windows, and automobiles [5].

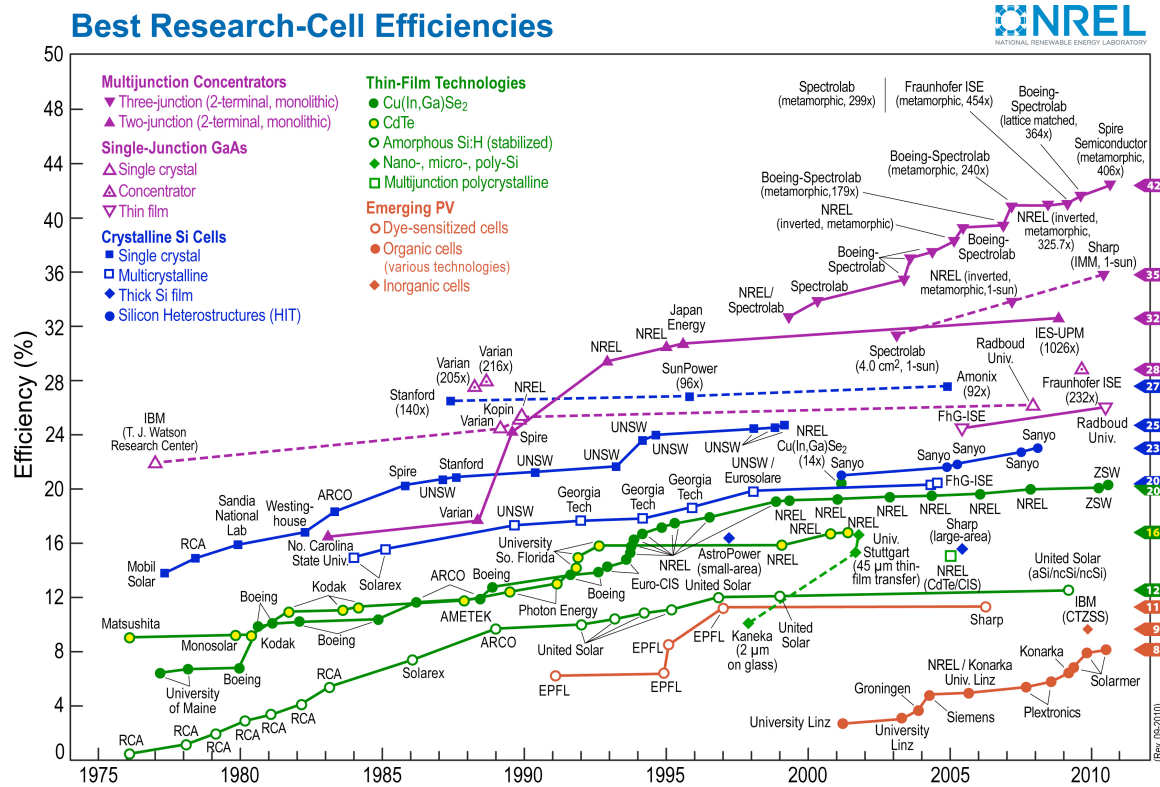


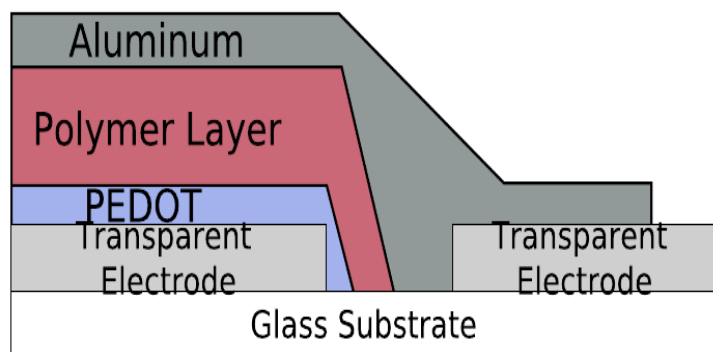
Figure 1. Shows the efficiencies achieved by different solar technologies over the past 35 years [3]

There are two main areas where organic cells need to be improved before they can be commercially viable. The efficiency needs to continue to increase, but also the lifetime of these cells needs to be extended. As it stands, these cells degrade rather quickly; current commercial

devices only last for a couple of years [5]. Once the efficiency is competitive and these cells can last for a reasonable lifespan, then they will be a cost effective, renewable power source.

Organic polymer solar cells are a “down-up” field of research. Whereas most product research starts with meeting requirements and then working to lower cost (“up-down”), organic researches are taking cheap and abundant materials and then working to achieve competitive efficiencies. This unique approach appears to be working, as the efficiency records for organic cells have been steadily increasing, with the current record being over 12% efficient [6]. One of the contributing factors to the low potential cost of these cells is their solution processable, layer-based, construction. Because the layers are added in liquid form, these cells could be printed and rapidly manufactured with a roll-to-roll or inkjet printing process [5].

The basic cell construction can be seen in Figure (2). We built our cells on a base of Indium Tin-oxide (ITO) coated glass. The ITO serves as the anode for the solar cell, and it allows light to pass through it into the active layer. The next layer of the cell is a conductive polymer called PEDOT:PSS (PEDOT), which is added into the cell to improve device performance (though it is not necessary for the operation of the cell). PEDOT has a lower energy level than ITO, so it effectively raises the work function of the ITO and gives the cell a greater electric potential for power creation. The PEDOT also planarizes the ITO anode layer of the cell; this smoothness allows for better electrical contact with the ITO and improves layer uniformity. Because the PEDOT is itself conducting, there is no loss in the internal electric field of the cell by adding in this extra layer, and the field is even increased in strength due to the larger work function of PEDOT compared to ITO. The PEDOT also serves to preserve the ITO, and create an

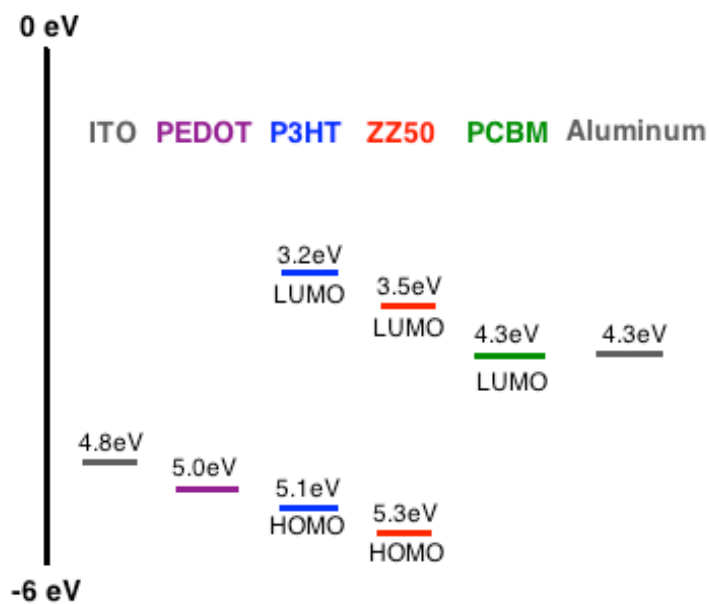


**Figure 2. Layers of the organic solar cell [8]**

oxygen barrier [7]. Once the cell is completed, the oxygen in the ITO could diffuse into the cell, degrading the electrical properties, but the PEDOT will prevent this by sealing the oxygen into the ITO. The active layer of the cell is traditionally a blend of P3HT (poly(3-hexylthiophene)) and PCBM (6,6-phenyl-C61 butyric acid methyl

ester). P3HT is a polymer that absorbs visible light out to wavelengths of 650 nm, and acts as the electron donor [8]. PCBM ( $C_{60}H_{14}O_2$ ) is a modified Bucky Ball, which is a Fullerene derivative [9]. It has a soluble tail attached to the Bucky Ball so that the PCBM can be put into solution and mixed with the P3HT. Both of these molecules are relatively cheap and commercially available [9]. The layered structure of the solar cell means that these various compounds can be easily spun onto the cell to achieve a thin layer, usually on the order of 100 nm. Future manufacturing process should be able to take advantage of this by printing these layers quickly and cheaply [10].

The basic principle that drives the operation of these cells is the action of photons exciting electrons. The purpose of the various polymers and metals is to create a circuit that is driven by this action, and thus create power from photons emitted by the sun. There are several parts to this system that work together to complete the circuitry, and Figure (3) shows an energy level diagram of the various components. The output of the cells is measured between the anode and cathode of the circuit, ITO and Aluminum. These metals have different work functions (energy levels), and this property is a key component to the function of the circuit. The Aluminum has a higher energy



**Figure 3. Energy levels of the solar cell components**

level, so when it comes in to contact with the lower energy ITO, electrons naturally flow from the Aluminum to the ITO. This stops once the metals are in a balanced energy state, but leaves the Aluminum as positively charged due to the absence of electrons and the ITO as negatively charged due to the excess of electrons. This natural flow of electrons is what will produce power from the circuit, but to make

this a continuous process we have to continuously supply electrons to the Aluminum and remove them from the ITO; this is the purpose of the polymer, PCBM, and the photons.

The active layer is a blend of an electron donor and an electron acceptor. In traditional organic solar cells, P3HT is the electron donor and PCBM is the acceptor. When a photon enters the active layer, it excites one of the electrons in the P3HT from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO) in the P3HT. The electron, now in a higher energy state, leaves a hole in its absence. This electron and hole pair is called an exciton, and the electron and hole are still slightly coulombically bound when created in the active layer [8]. The exciton then has a short time to diffuse to a P3HT/PCBM boundary, before decaying back into its unexcited state. Once at the boundary, the exciton is dissociated by the high electron affinity and low energy level of the PCBM [8]. The electrons travel through pathways created by the PCBM to the positively charged Aluminum, and the holes travel through the P3HT to the negatively charged ITO. As these metals return to neutral charge, the work function difference once more causes electrons to flow from the Aluminum to the ITO; the different energy levels can be seen in Figure (3). Photons from the sun continuously enter the active layer and facilitate this cyclic process to continuously generate current [11]. By placing a resistor between the anode and cathode we then get power from the cell.

The active region of the cell has many important properties that determine the layer's ability to produce excitons and then harvest these electrons to make power. These properties are determined by the morphology of the active layer, how the P3HT and PCBM are mixed together and structured (our devices have a bulk heterojunction structure) [11]. The more that these two molecules are mixed, the more surface area will exist between the P3HT and PCBM, which maximizes the number of excitons created from incoming photons. But if the layer is over mixed then there will be not be continuous pathways of P3HT and PCBM for the electrons and holes to travel to the anode and cathode [8]. Creating an optimized device requires the active layer to be mixed to the appropriate degree that maximizes exciton creation, while being able to extract the created pairs. Finding this balance is required for maximum cell performance.

In addition to improved efficiency, the other area where these polymer solar cells require further research is in operational lifetime. Cell performance is compromised over time due to degradation of the active polymer layer. Atmospheric water and oxygen have been shown to contribute to this decay [12], so the packaging needs to seal the cell and protect the polymer from

these molecules. The goal for this experiment was to evaluate our packaging method and analyze how fast our devices decay. Our current packaging procedure consists of two parts, aluminum foil to cover the exposed polymer, and epoxy to seal any remaining areas. We used three experimental groups to evaluate the various components of this packaging method, and we performed extensive testing in an attempt to better understand the decay process.

### ***Procedure***

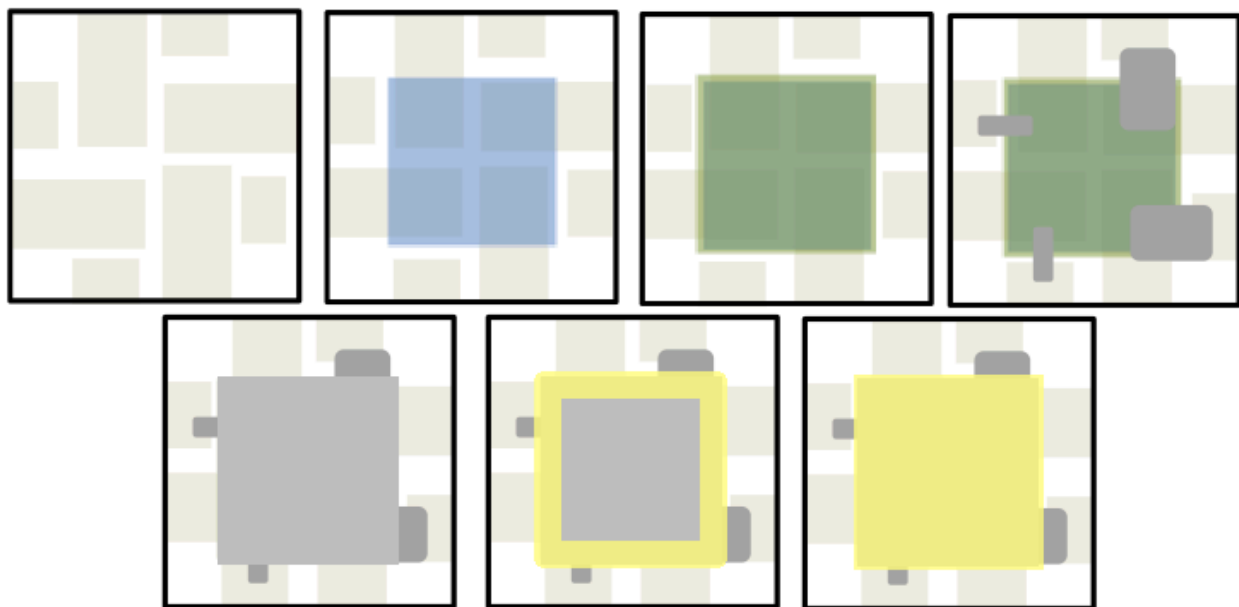
We construct our devices in the Organic Polymer Lab on the Cal Poly campus. The basic part of the lab consist of a dust free environment, chemistry hood, and two nitrogen glove boxes, pictured in Figure (4). To make solar cells, we have to thoroughly clean our ITO coated glass substrates, spin on the PEDOT layer, spin on the active layer, and evaporate on the aluminum cathode layer. This was done over a number of weeks, and afterwards, the cells are repeatedly tested.



**Figure 4. Cal Poly organic polymer lab [7]**

To create the best possible organic solar cell, it is essential that the base of the cell is as clean as possible. The solar cell is built upon a glass substrate that is coated with ITO, Figure (5). All of the layers that make up the cell are coated on top of this substrate, so to ensure that the best possible contacts are made, the surface of the substrate must be completely clear of dust or any other contaminates.





**Figure 5. Built on an ITO coated substrate, the added components are the PEDOT layer, active layer, aluminum electrode, aluminum tape, edge epoxy, or full epoxy [13].**

The first step in cleaning the substrate is to remove any visible contaminants from the ITO coated glass. This step is preformed in the dust free environment and particles are removed from the substrate with a cotton swab. We then attempt to remove any remaining contaminants by treating the substrates in two chemical baths. First, the substrates are submerged in a beaker of Acetone. Acetone is a common laboratory cleaner that is a good solvent for plastics and synthetic fibers, which are often found in laboratory bottles [14]. This beaker is then placed in an ultrasonic bath, which uses high frequency sound waves to agitate the Acetone. The agitation creates bubbles that penetrate the rough areas created by contaminants and scrubs them away [15]. After the bath, the substrates are dried with nitrogen; the inert, pure nitrogen is clean of contaminants, unlike the air in the lab. The chemical cleaning process is then repeated, but the substrates are submerged in isopropyl alcohol. Isopropyl alcohol is a good solvent for removing a variety of non-polar contaminants, and it is a safer alternative to other industrial solvents [16]. The final cleaning step is to treat the substrates with an Ultraviolet Ozone Reactor. This stage is focused on removing any organic contaminants that may still remain on the substrate, as they are disassociated inside the reactor. The UV light creates ozone ( $O_3$ ), which is then blown across the substrates to remove contaminants [7]. The substrates are then declared thoroughly clean and ready for the PEDOT layer to be added.

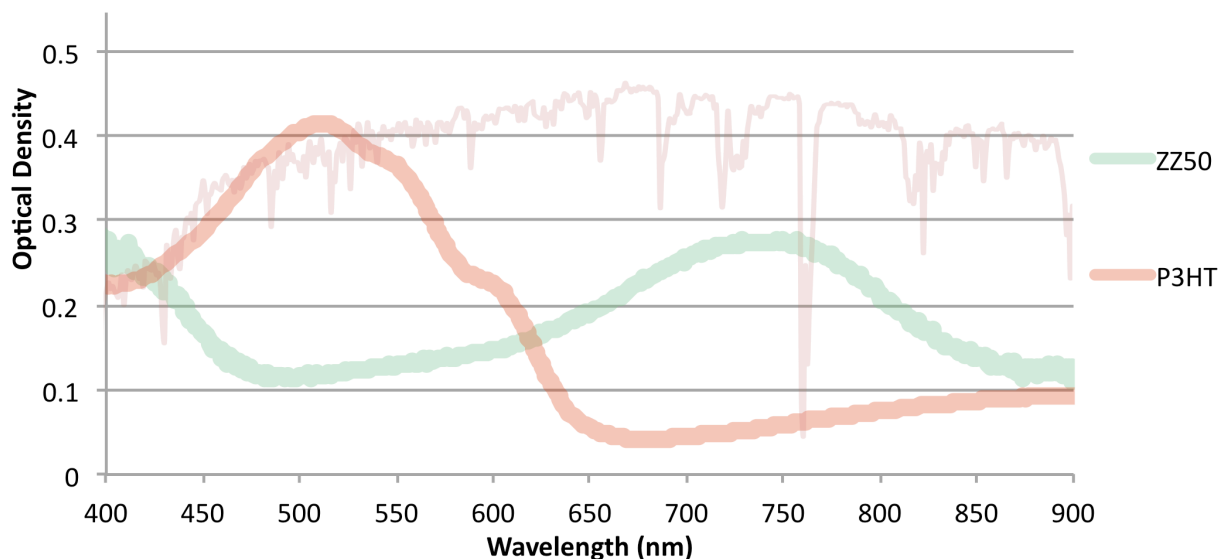
To apply the PEDOT layer, we use a Chemat Technology spin-coater. This coater is located in the dust free zone, so the entire process is preformed with dust free gloves. Once the spin speed is set, we individually transport the substrates from the UV Ozone cleaner into the chuck, which is located within the spin-coater. The chuck holds the substrate in place with eight pins. The PEDOT is then added using a pipette with an attached filter (to remove any solid clumps of PEDOT), making sure all of the active regions of the substrate are coated. A vacuum holds the chuck down as the PEDOT is spun at 5,000 RPM in order to deposit around a 100 nm layer. Once the spinning is complete, we wipe the PEDOT off of the small ITO pads round the edge of the device with deionized water, and use a razor to scratch away any PEDOT that might remain between the large and small ITO pads. If any PEDOT remains connecting the two ITO pads, it will allow current to leak between them and be lost without generating power. The substrates are finally moved to a hotplate, where they are annealed for 15 minuets at 125 degrees Celsius [7]. The anneal hardens and sets the PEDOT, removing any of the water that kept the PEDOT in solution. The substrate can then be easily transported and have new layers added on top of the PEDOT.

The active polymer layer, aluminum electrode, and aluminum packaging are added to the substrate in the nitrogen environment, where there is little risk of contamination, and cell degradation is limited due to the minimal amount of oxygen present. The substrates were moved to this environment through an antechamber that connects the dust free area with the nitrogen glove box. The chamber is evacuated of air and filled with nitrogen from the glove box, and the process is repeated three times before the antechamber is opened from within the glove box.

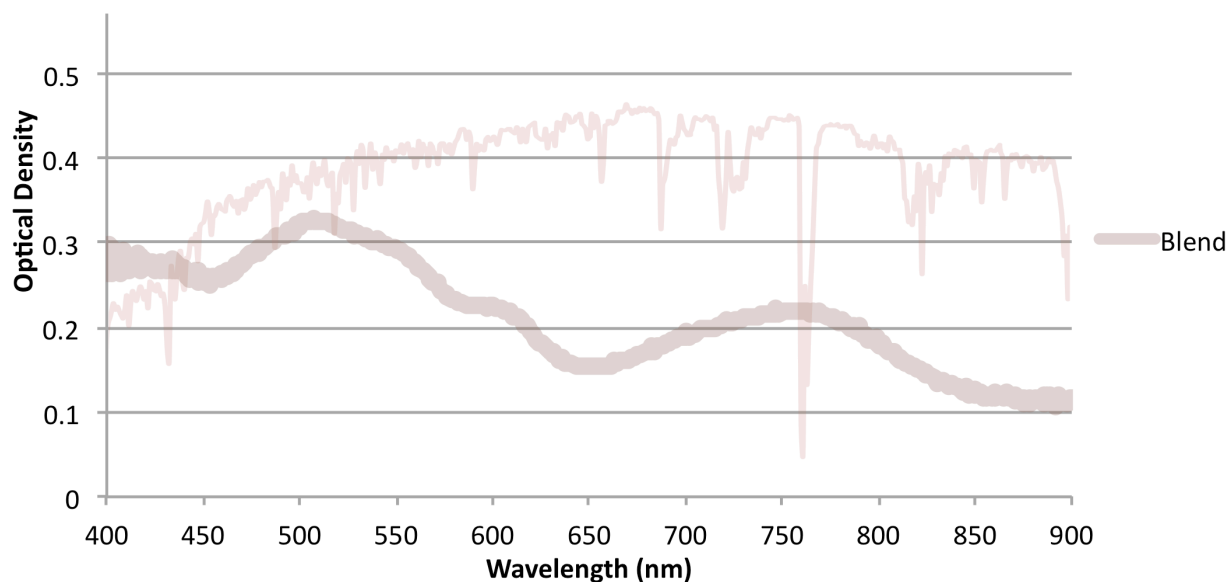
The active polymer/PCBM layer is then added to the substrate. The polymers are measured out, added to chlorobenzene, and heated, so that they are dissolved into liquid solution (in a ratio of 4mg(PCBDBDT):16mg(P3HT):16mg(PCBM) / ml(chlorobenzene)). The polymer blend is then spun onto the substrate the same way that the PEDOT layer was, except the spinner in the glove box is controlled by an external keypad and foot pedal. The substrate is loaded into the chuck and the polymer is carefully added onto the active area of the substrate with a pipette. It is important to remove any bubbles that form on the surface of the substrate, as they cause an uneven final layer, and not to touch the substrate with the pipette when spreading the polymer, as it would scratch the PEDOT layer underneath and compromise cell performance [7]. We then remove the active layer from around the outside of the substrate where it covers the ITO pads.

This is done by dipping a swab in Tetrahydrofuran (THF) and carefully wiping the polymer off of the outside pads. The wiping step is essential, as the cathode layer has to be able to make contact with the ITO pad to complete the electronic circuit.

Our devices utilize a combination of two different active polymers, which are mixed together to create our active layer. The primary polymer, P3HT, has been the standard polymer for solar cell research over the past decade, as it absorbs light in the visible range. We also add in PCPDTBT (poly[2,6-(4,4-bis-(2-ethylhexyl) -4H-cyclopenta [2, 1-b;3,4-b']dithiophene)- alt-4,7-(2,1,3-benzothiadiazole)]), commonly referred to as ZZ50, which is a small band gap semi conductive copolymer synthesized by Zhengguo Zhu on his 50<sup>th</sup> try [17]. It is similar to P3HT except that ZZ50 can absorb into the infrared range of the solar spectrum. The absorption spectrums of P3HT and ZZ50, compared to the output of the sun (In terms of photon flux per wavelength) can be found in Figure (6). Combining these polymers, the mixture will be able to absorb over the range of both P3HT and ZZ50; Figure (7) shows the absorption spectrum of one of our blended devices. Because only one exciton is created per photon, absorption over more of the solar spectrum will maximize the current generated.

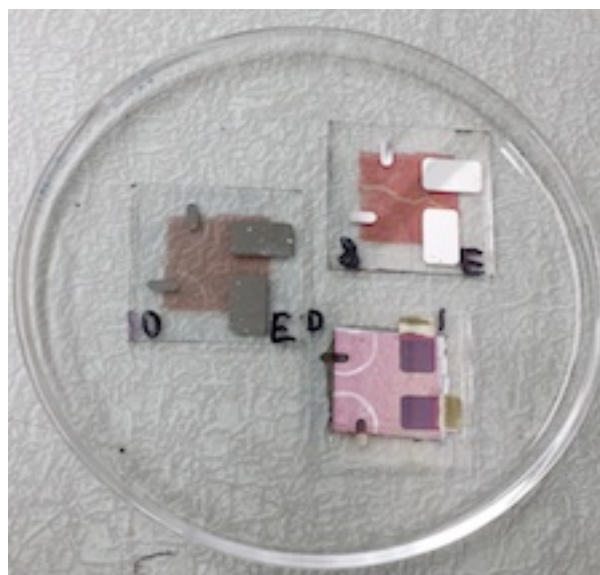


**Figure 6. Absorption spectrum shows ZZ50 in green, P3HT in red, and the sun's output (photons / s·m<sup>2</sup>) in Pink [17].**



**Figure 7. Shows the absorptions of a blended ZZ50 and P3HT device in dark pink and the sun's output (photons / s·m<sup>2</sup>) in pink [17].**

The last layer added to the substrates is the aluminum, cathode layer. It is the final layer of the device and it completes the circuitry of the cell. We add the aluminum using vacuum evaporation to gasify the aluminum and spray it onto the substrate. The aluminum had to be applied to specific places on the substrate in order to lie directly over the polymer layer and the ITO underneath. By gasifying the aluminum and directing it at the substrate through a stencil (mask), we create a very precise, thin layer of aluminum on the cell that is on the order of 100 nm. The mask, or stencil, allows aluminum onto only four specific places on each substrate, creating two small and two large solar cell pixels (the pattern can be seen on the cells in Figure (8) and (5)). Our vacuum evaporator is a powerful piece of equipment that requires two stages of pumping in order to achieve high vacuum. It is essential the chamber be at extremely low pressure so that the aluminum atoms do not react with any Nitrogen molecules while being applied.



**Figure 8. Picture of our completed devices that have two and small and two large pixels**

First, we use a mechanical pump to achieve a vacuum of under 30 microns of mercury, and then we use a diffusion pump decreasing the pressure all the way to  $1.5 \times 10^{-6}$  Torr [7]. Once in high vacuum, we run current through the aluminum to evaporate it. Once the cathode layer is at the desired thickness (about 100 nm) we depressurize the chamber and removed the substrates.

After all the layers have been added, we treat our devices with a thermal anneal. We subjected this run of devices to 105 degrees Celsius for 30 minutes on a hotplate, because the procedure drastically increases device performance. The improvement comes from a mechanism called spinodal decomposition. The active polymer layer is a mix of the electron donor polymer and electron acceptor PCBM. We had these two components thoroughly mixed, which creates a large surface area between them. This surface area produces many excitons but these electrons and holes also need to travel to the anode and cathode through pathways created by the P3HT and PCBM. If the polymer and PCBM are over mixed, than there are plenty of electrons created but they cannot be harvested for power. By heating the polymer, we induce spinodal decomposition, which causes the polymer to crystallize and create better pathways to the anode and cathode, allowing for better electron extraction.

We experimented with three packaging techniques to seal our devices. We must package our devices in order to remove them from the nitrogen environment, which is necessary for further testing that utilizes other equipment outside the glove box. We want to extend our cell lifetimes as long as possible in order to properly test them without their properties quickly changing and deteriorating. Our current packaging method consists of aluminum tape and epoxy, and this experiment was aimed to determine how effective these components are. The first step of applying the aluminum tape over the center of the substrate took place within the spinning glove box, so there was minimum exposure to the atmosphere. Once the tape was applied, the substrates were then transported of the nitrogen environment to the chemistry hood. Here, the epoxy was applied to the cells in three experimental groups (the placement can be seen in Figure (5)). The epoxy cross-links as it cures, creating a ridged barrier against atmospheric molecules [18]. Four of the substrates were left with foil only, another four had epoxy applied around the edge of the foil, and the final four had the foil completely covered in epoxy. By varying the amount of epoxy, we hoped the lifetime results would indicate which parts of our packaging procedure is most effective.

To gather our results, we repeatedly tested the cells over several weeks to measure their decay. To test the efficiency of the cells we loaded each substrate into a covered test jig. Inside the jig, the substrate was held between six pins with the active layer facing down. Once loaded, the cover was placed on the jig and locked into place. We did the test with a dark cover that did not allow any light into the cells, and with a cover attached to a light source that supplied a known intensity of about 18 (W/m<sup>2</sup>) light. Using a Labview® program, we swept a range of voltages (-1.0 to 1.0 volts in increments of 0.05) across the cell and measured the current produced for each pixel. This voltage and current data allows us to calculate the efficiency of our solar cells. We also tested External and Internal Quantum Efficiency (a measure for determining the percentage of photons that a cell converts into electrons as a function of wavelength) of three devices over this time period. This test was done by exposing the cells to light produced by a monochromator, which uses a diffraction grating to produce specific wavelengths of light. The monochromator swept through wavelengths between 350 and 900 nanometers, and the current produced by the cell at each wavelength was recorded by our Labview program. We also ran the test with a four-diode, which has known EQE absorption characteristics. By comparing the diode and the solar cell, we can determine the external quantum efficiency of the device and analysis the device decay per wavelength.

## ***Results***

In order to characterize device performance, we subjected our cells to a JV-test, where we sweep through the cells with a range of voltages (from -1 to 1 volts) and recorded the current that is produced; the resulting plot of these two variables is referred to as a J-V curve, pictured in Figure (9). The solar cell produces energy in the regime between the open circuit voltage ( $V_{oc}$ ) and the short circuit current ( $J_{sc}$ ) points on the J-V curve (Figure 10)). Within this voltage range the cell produces power, by Equation 1; this section of the curve can be more clearly seen in

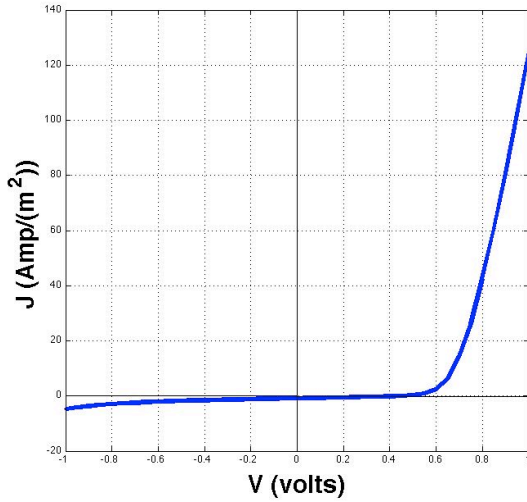
$$P(power) = J(current) \times V(voltage) \quad (1)$$

Figure (10). With this JV information we are able to compute the current density, given by Equation 2, and the efficiency of each cell.

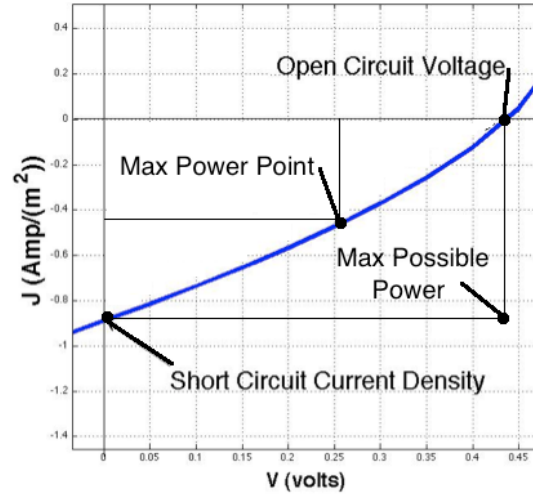
$$\frac{I(Current)}{Area} \quad (2)$$

$$(Area_{small} = 3.75 \times 10^{-6} m, Area_{big} = 42 \times 10^{-6} m)$$

It is important to report these values in terms of current density, so that results between different research labs can be universally compared without knowing the size of each of the cells that were fabricated.



**Figure 9. Typical J-V curve for an organic cell**

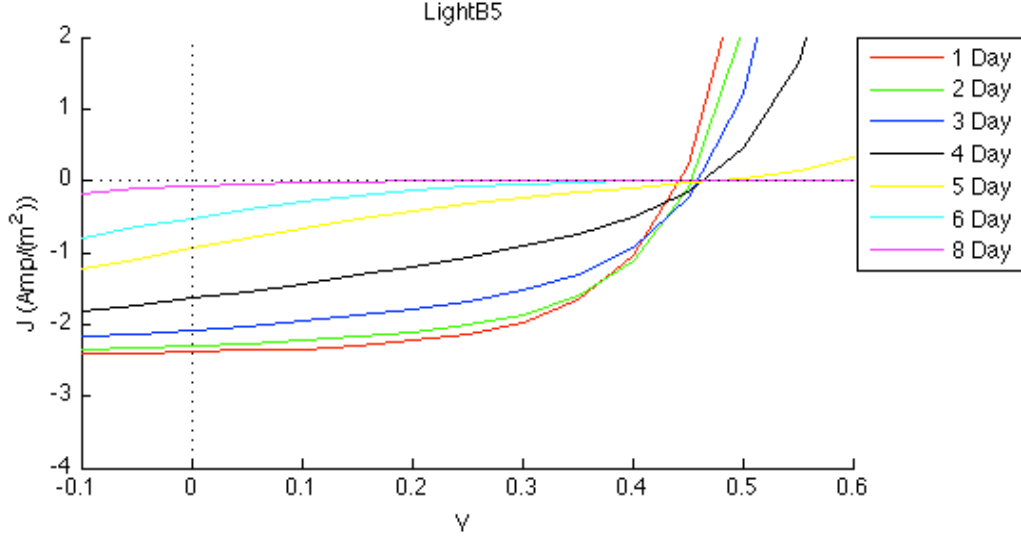


**Figure 10. Output power portion of the J-V curve**

We repeatedly performed this JV-test over the course of a week while the cells decayed. As the cells produced less and less current, the shape of the JV curve changed and the power production (area under the curve) became smaller and smaller. The area under the curve can decrease due to two different mechanisms. As the short circuit current density ( $J_{sc}$ ) goes to zero it drags the curve, eventually becoming a flat line that equates to no power production. The other way that the area can decrease is due to a loss in fill factor ( $ff$ ). Fill factor is the ratio between the max power point ( $P_{max}$ ) on the JV curve (see Figure (10)) and the maximum possible power based on the  $V_{oc}$  and  $J_{sc}$ , Equation 3. If the fill factor decrease without a loss in short circuit

$$ff = \frac{P_{max}}{J_{sc} \times V_{oc}} \quad (3)$$

current, the shape of the JV-curve will change, and behave more as a linear function connecting the  $V_{oc}$  and  $J_{sc}$ , rather than the swooping curve displayed by an optimized cell. This change in shape results in a decrease in area, so cell performance degrades. As our cells decayed, we were interested to see if there was a larger contribution from the loss in  $J_{sc}$  or fill factor. The curve decay over the testing period can be found in Figure (11). We see that both causes contributed to the decay, and neither dominates the process.



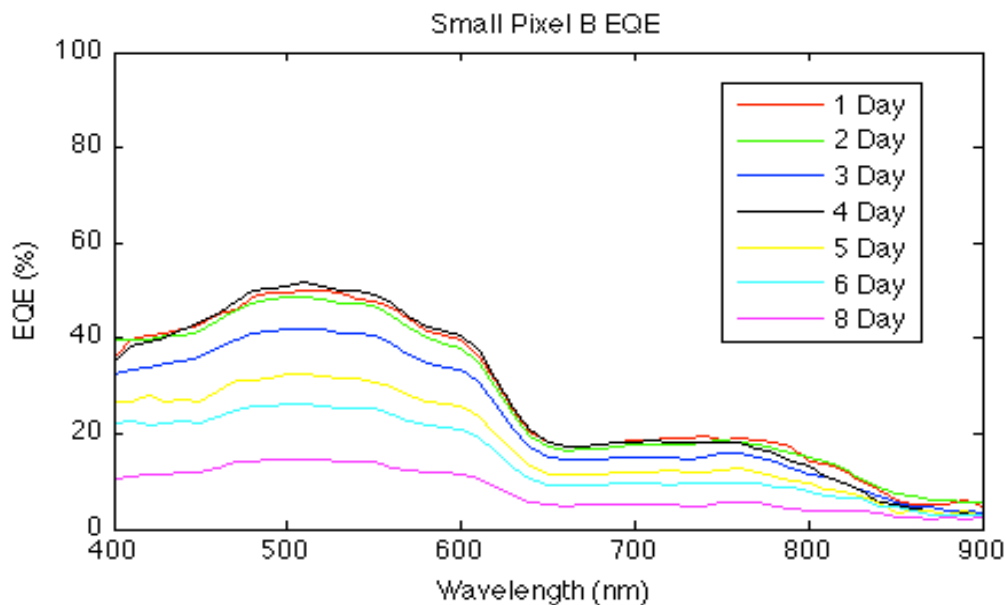
**Figure 11. Decay of the JV-curve for one pixel during the testing. The behavior is characteristic of all the device pixels.**

External and Internal Quantum Efficiencies (EQE and IQE) are a measure for determining the percentage of photons that a cell converts into electrons as a function of wavelength. To calculate the EQE of one of our solar cell pixels ( $EQE_{pixel}$ ), we use a monochromator to expose the pixel to narrow ranges of wavelengths, and measure the current that is produced. In order to determine the number of photons that are hitting the pixel, we subject a diode to the same testing procedure and measure the current it produces. The diode has a known EQE, so the current it produces tells us the number of photons being produced by the monochromator. By combining the measured currents, the diode EQE, and the respective surface areas ( $A_{diode}$  and  $A_{pixel}$ ), we can calculate the EQE of the pixel, Equation 4. The EQE is the percentage of photons

$$EQE_{pixel} = \left( \frac{I_{pixel}}{A_{pixel}} \right) \frac{EQE_{diode}}{\left( \frac{I_{diode}}{A_{diode}} \right)} \quad (4)$$

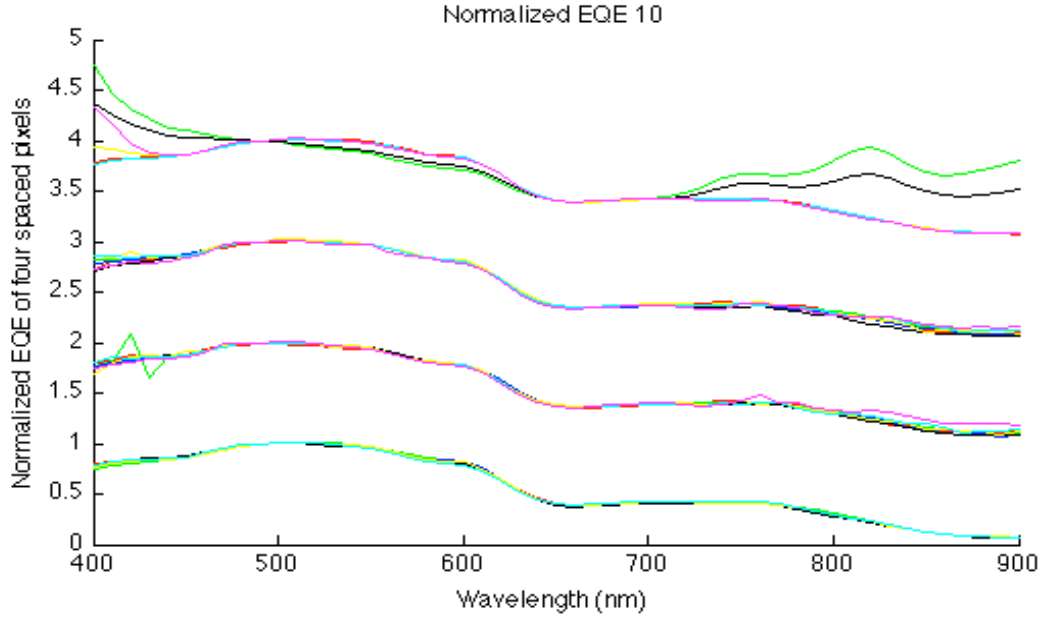
incident on the device, which were converted into electrons. Figure (12) shows the EQE for one of our pixels as it decayed over the course of a week.





**Figure 12. The EQE decay of a small solar pixel over a week (not the same pixel as displayed in Figure 11).**

The EQE results decayed along with the JV-cure, with the percentages dropping over the course of eight days (with the exception of Day 4, which indicates the level of error in our measurements). In order to examine any wavelength dependence of the decay, the curves had to be normalized, so their relative shapes could be compared. Figure (13) shows all four pixels from a fully packaged substrate, including the pixel from Figure (12), but with the data divided by the EQE percentage at 500 nm. This creates plots that are relative to the same point and the behavior changes over time; the four pixel plots are also staggered for visual ease. The figure shows that there was little change in the shape of the curve as the device decayed, which indicates that the cell degradation is not wavelength dependent. The result gives us an interesting insight into how the polymer is degrading, as whatever the mechanism for the loss of current may be, it appears to affect all the absorbed wavelengths equally. The result is especially interesting considering that there are two different polymers within the active layer, and they are responding to the degradation in the same way despite their different chemical structures. We believe this may have to do with the relatively similar work functions of the two polymers, as the energy level is often an indicator of chemical stability [19].

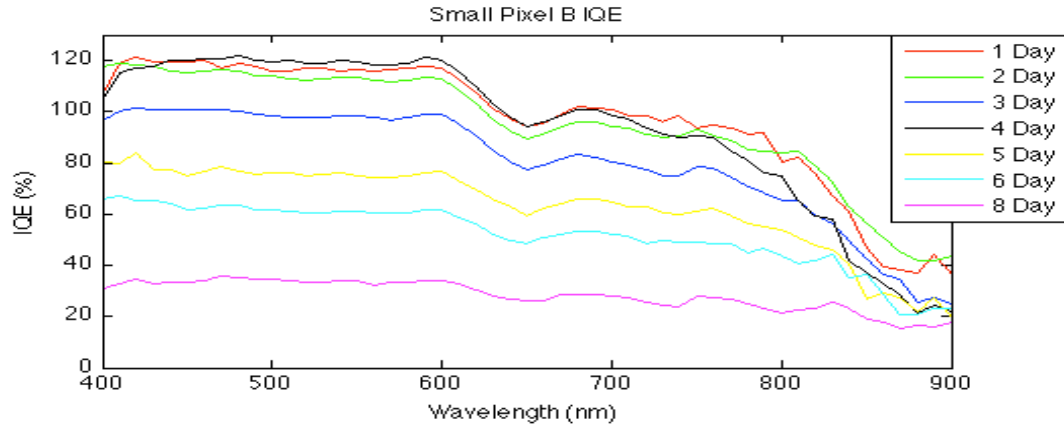


**Figure 13. The normalized EQE of four pixels shows little change over time. The results for each pixel are vertically staggered for ease of viewing.**

Internal Quantum Efficiency (IQE) is similar to EQE, but is a measure of the percentage of absorbed photons converted into electrons, as opposed to the incident photons measured by the EQE. Calculating the IQE requires the EQE be combined with the optical density ( $\alpha(\lambda)$ ) of the device, a wavelength dependent measure of absorbance, which we test separately. Equation 5 gives the IQE based on the EQE, optical density, and the reflectivity of the rear electrode (R)

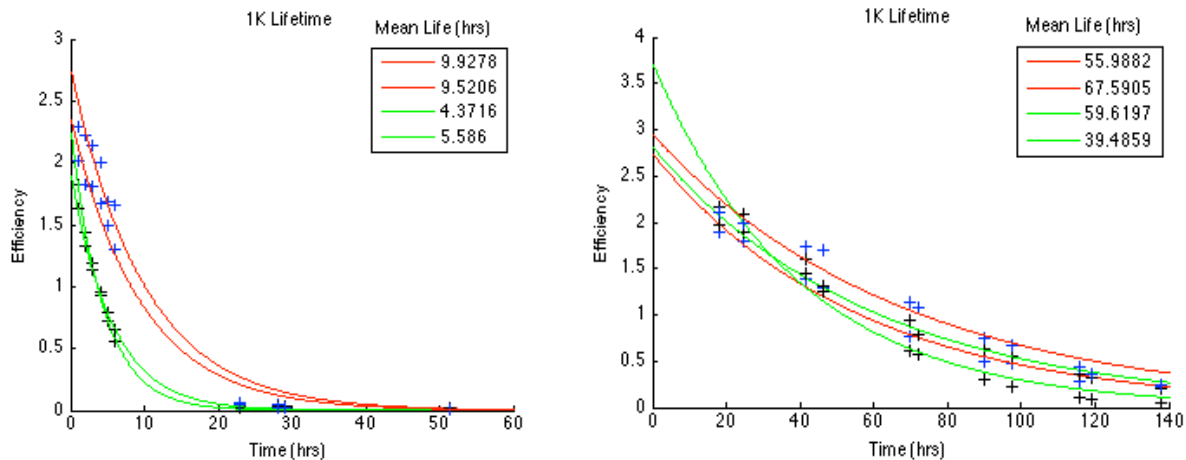
$$IQE(\lambda)_{pixel} = \frac{EQE(\lambda)_{pixel}}{(1 - 10^{-\alpha(1+R)})} \quad (5)$$

(ignoring thin film interference effects). The reflectivity must be accounted for because if the photons are not absorbed on their first pass through the polymer, they are likely to rebound off the metal of the rear electrode and pass through the polymer a second time. Figure (14) shows the IQE for one pixel as it decayed. The behavior is similar to that of the EQE, except the data is less consistent and appears noisier. Our measure of IQE is dependent on many experimental variables, and is not highly accurate. The error is evident in the first few days of testing, where percentages of over one hundred are reported for the IQE, and in the Day 4 data that rises unexpectedly. While the data is unreliable, it is consistent with itself and shows the degradation as a function of wavelength.



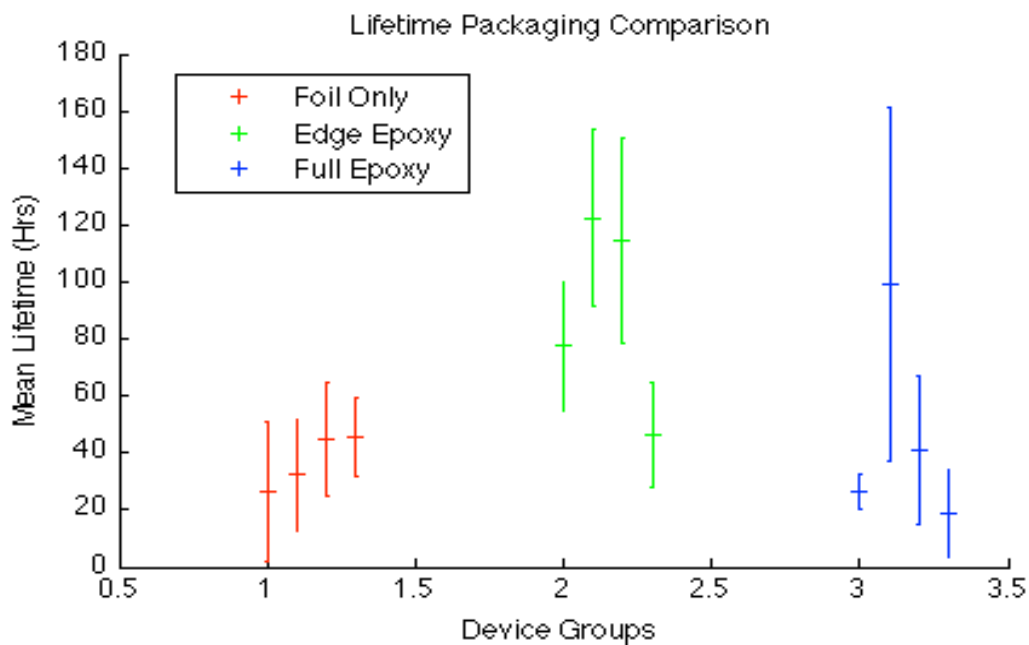
**Figure 14. The IQE decay of a small solar pixel over a week (same pixel as seen in Figure 12).**

The main intent for this experiment was to determine the how effective the various components of our packaging procedure are at extending cell lifetime. In our first device run, we compared the lifetimes of fully packaged devices and unpackaged devices (where the polymer was completely exposed to the atmosphere) to get a baseline measure for our cell lifetimes. Figure (15) shows how the efficiency decayed for two devices that were fabricated in the same way, with the same components. The results show that the packaging greatly increased the mean lifetime of the pixels (the time for the efficiency to drop to  $(1/e) \approx 0.37$  if its initial value). Of the three packaged substrates in the experimental group, all three showed improvement over their unpackaged counterparts, but the amount of improvement was drastically varied between even individual pixels. The lifetime increase ranged from a factor of 6 to a factor of 12, despite all of the devices being packaged in the same manor.



**Figure 15. The efficiency decay curves and mean lifetime measures of an unpackaged device on the left and a packaged device on the right.**

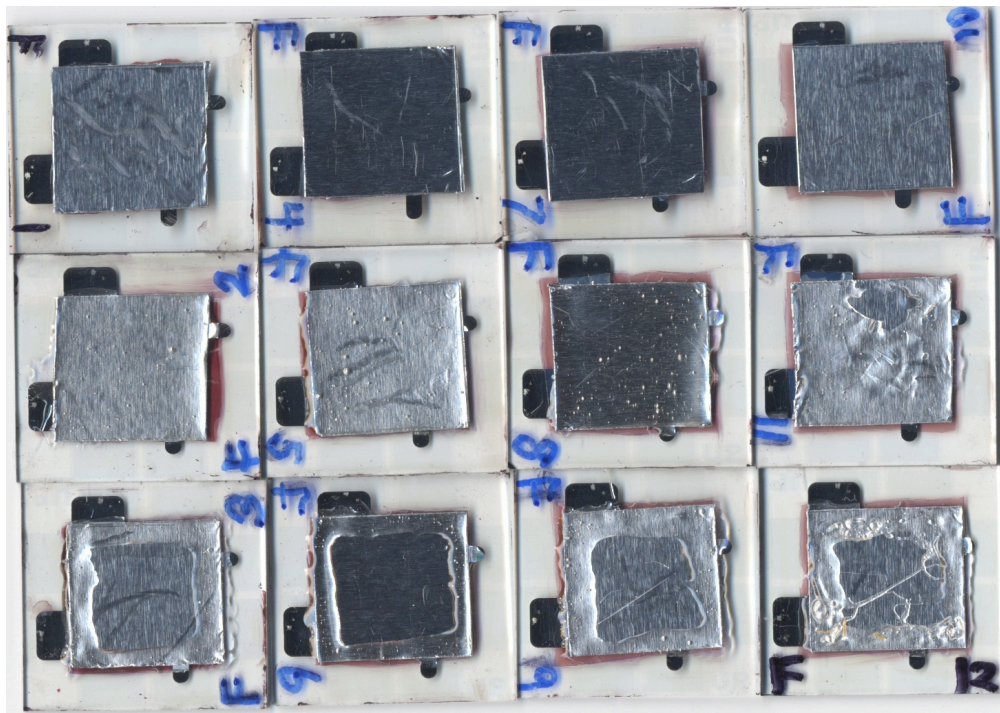
In order to better understand the properties our packaging technique, we fabricated another device run, but with a more specific breakdown of packaging components. We used the same aluminum tape method for all three experimental groups, but one group was left with tape only, one had epoxy applied to the edge only, and the last had the foil entirely covered in epoxy. Figure (16) shows the mean lifetime results from these three different experiment groups; each data point is a substrate given by the average and standard deviation of its four pixels. The edge only packaging (green) produced longer lifetimes than the foil only devices (red), but the results from the fully packaged group (blue) were inconclusive. The fully packaged group had a large range of lifetimes, but was on average more comparable to the foil only group than the edge epoxy group. As there is no apparent reason that more epoxy would result in a worse seal around the device, we conclude that the execution of placing the epoxy is more critical for lifetime performance than the packaging method itself. Different lab members applied the epoxy to the different groups, which likely caused the variance in lifetime performance, rather than the amount of epoxy used.



**Figure 16. The mean lifetime results for each of the packaged substrates.**

We believe that the physical characteristics of the hand-applied epoxy contributed to determining cell lifetime, and we examined the individual devices in order to determine any patterns. Figure (17) shows a high-resolution scan of the cells we fabricated and the placement of

the epoxy is visible. From the examination, it is clear that the packaging varies drastically between devices and individual pixels. In addition it is clear that the cells are inconsistent in terms of how far the polymer layer extends, as this is also wiped by hand. If the polymer extends out beyond the epoxy, this may be allowing atmospheric molecules into the cell, independent of the packaging method used. We made several attempts to quantify the physical characteristics of the packaging, but we were unable to find any correlation to lifetime performance, and we could not find a rigorous method of evaluation. Even if we were able to effectively quantify the packaging characteristics, it still may have been impossible to compare the effects between pixels on a single device. Because all four pixels on a substrate could potentially be affected by a packaging defect it is not immediately adjacent too, there is no clear way to describe the differences between pixels on the same device. There could also be many other factors determining lifetime, as this is a complex physical system, and our attempt to quantify the quality of individual packages may be unrealistic.



**Figure 17. A scan of the 12 experimental devices that shows the foil only group in the top row, the fully covered epoxy group in the second row, and the edge epoxy group in the bottom row.**

## ***Conclusion***

Organic polymer solar cells are a promising solution to meeting the world's growing electrical power demands, while using a renewable energy source and operating without producing carbon emissions. This technology needs extensive further research into increasing the lifetime and efficiency of these solar cells before they will be viable commercially. In our lab, we focus on creating the most efficient devices with the components and equipment at our disposal and experimenting with novel device compounds and structures. For our most recent device run, we investigated variations on the cell packaging techniques. We were unable to determine conclusively what components of our packaging method contribute most to extending cell lifetime, but we were able to show that our packaging method results in longer lifetimes compared to unpackaged cells. It was also evident that the cell decay is not wavelength dependent, revealed in our external quantum efficiency testing. This suggests that our two active polymers degrade in a similar manner, despite their different chemical compositions; hopefully, this means that improved packaging methods will also increase the lifetimes of both polymers. In this device run we also achieved a lab record in terms of device efficiency in 1000 (W/m<sup>2</sup>) solar spectrum conditions, with a pixel reaching a light conversion efficiency of 3.0%. This is a promising result and future research focused along optimizing the polymer/PCBM ratio and thermal anneal parameters may yield even higher efficiencies.

Future research at Cal Poly will likely investigate new polymers and materials to change device structure and performance. We are currently looking into the effects of adding quantum dots to our blended devices, which absorb photons at higher energy levels and reduce their energy so that they can be absorbed by our polymers, thus increasing the spectral range of the device. We are also investigating the use of zinc oxide nanorods to replace PCBM as our electron carrier. With the enhanced conductive pathways from the rods providing easier charge extraction, we could theoretically increase device thickness for better absorbance with less recombination losses. It would also be interesting to continue researching packaging, manufacturing, and printing processes that will eventually be required to mass-produce these cells. Any semiautomatic fabrication procedures invented would also improve the efficiency of organic polymer research, and eliminate human variance in these hand made devices. There are many interesting avenues for research in this field, and hopefully the results will usher in a new era of renewable energy technology.

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