Fabrication of a-Si and a-InGaN Photovoltaics by Plasma Sputtering

A Thesis

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Chapter 1: Introduction

Fossil fuels provide 80.6% of the world’s energy but produce unwanted byproducts when burned (“Renewables 2012 global”, 2012). These unwanted products have significant effects on our environment. They can cause pollution, health risks, environmental degradation, and global warming. They have also been the cause of multiple wars and the migration of families. Energy has an impact on the world around us but many choose to ignore it. Though we do not know when, fossil fuel supplies will eventually be depleted. In order to avoid future problems with energy availability, forms of renewable energy must be developed. This has prompted an increase in renewable energy technologies. There are many forms of renewable energy such as wind, hydropower, solar, geothermal, bioenergy, hydrogen, and fuel cells; some are shown in Figure 1. An attractive choice is photovoltaics, which converts sunlight to electrical energy. One of the greatest advantages of solar energy is that it can be generated almost anywhere. As long as sunlight is present, energy can be produced. However, the intensity of the sunlight does affect the amount of energy produced, which means areas with higher solar irradiation are best. The United States and the global community are beginning to research renewable energies extensively and hopefully, this will make possible the necessary change from fossil fuels to renewables.
1.1 Photoelectric Effect, the Sun, and Solar Cells

Photovoltaics work by utilizing a variation of the photoelectric effect, which was discovered by Heinrich Hertz in 1887. It was observed that when light falls on a metal surface (emitter), it can release electrons, which travel to a collector. An electron absorbs energy from incident photons (light). The minimum amount of energy required to release the electron is called the work function of the material (Krane, 1996). The work function is dependent upon the material and many materials values have been determined. The electrons will absorb any frequency photon but only those exceeding the work function will cause the release of electrons. Photovoltaics harness this effect to the fullest by creating a flow of these electrons, which becomes a current. This current can then be removed from the cell and become a source of electrical energy. This phenomenon is explained in Figure 2.
Unlike metal’s work function, semiconducting materials have a band gap, shown in Figure 3. The band gap is the difference in energy between the valence and conduction bands. Band gap energy can be defined as the energy to free an electron from the outer shell. The electron becomes a mobile charge carrier, which is what allows a photovoltaic device to create a current. Without this property, solar cells would not work. There are two possible types of band gaps for semiconducting materials, direct or indirect. Direct is when the momentum of electrons and holes (absence of electrons) is the same in the conduction and valence bands, while indirect means the electron must transfer momentum to the crystal lattice, which causes a loss of energy. The difference between direct and indirect band gaps is shown in Figure 4.

The crystal lattice is the structural arrangement of atoms within a substance. The lattice is composed of repeating unit cells. These unit cells are used to determine
the lattice parameters, a group of lattice constants, by using the lengths of the edges and the angles between them. In the case of a cubic structure, there is only one lattice constant referred to as “a”.

![Diagram of electronic band structure]

**Figure 3** - Demonstrates the internal photoeffect in semiconductors. If the photon energy is equal or greater than the band gap energy, an electron will be excited from the valence to conduction band (cross the forbidden zone) and an electron-hole pair is created. Adapted from (Physical Bog, 2013).

![Diagram of direct and indirect bandgap]

**Figure 4** - The difference between direct and indirect band gap semiconductors. As can be seen, indirect band gaps require greater energy to move an electron between valence and conduction bands. Adapted from (Sun, 2010).
Many types of solar cells have been developed with the most common being single junction silicon. A single junction cell is one that operates at only one band gap. However, single junction cells are subject to the theoretical efficiency limit of a perfect, defect-free single PN junction, which is 33.7%. This is known as the Shockley-Queisser limit, shown in Figure 5 (Liao & Hsu, 2010). However, such real-world cells typically operate with efficiencies ranging from 13% to 17% due to material defects, cell design, and solar reflection. If multiple junctions are added, the cell becomes tandem or multi-junction. Improved efficiencies may be reached by employing such solar cells. Such cells have multiple PN junctions that are tuned to different wavelengths of light, shown in Figure 6. The maximum theoretical efficiency limit of tandem solar cells is 86.8% (Dimroth, Baur, Bett, Meusel & Strobl, 2005). Even when subjected to typical efficiency losses, these cells access more light and create more energy than a single junction cell. The benefits of tandem cells are not only in the efficiency, but in the potential of lower production cost and the reduction of heat loss, due to the multiple available band gaps. However, traditional approaches to fabrication require layers of different band gap materials to compose the cell, which complicates the fabrication process. The usage of multiple materials brings about layer mismatch. Layer mismatch or lattice mismatch occurs when two materials with different lattice constants are deposited on each other, shown in Figure 7. The difference in lattice constant “will cause strained or relaxed growth and can lead to interfacial defects” (Ucer, 2010). This negatively impacts the cell’s optoelectronic properties and conversion capabilities.
Figure 5 - The efficiency versus bandgap curve for a single junction cell. Shows the highest efficiency that can be achieved for a solar cell at a specific bandgap, known as the Shockley-Queisser Limit. Permission by Sbrynes321 (Sbrynes321, 2011).

Figure 6 - A tandem solar cell. Each junction is a complete PN junction of the noted material. These are stacked upon each other in order to capture the maximum amount of solar energy. The highest bandgap goes first so that any extra energy will be used by the next junction. This is what allows for greater capture of light. Adapted from (Weiss, 2010).
1.2 Crystalline Silicon

The most common type of photovoltaic is made of crystalline silicon, which represents 87% of world PV cell market sales in 2011 (“Crystalline silicon photovoltaics”, 2014). One silicon atom has 14 electrons, where the four outermost electrons are valence electrons. These valence electrons can be given to, accepted from, or shared with other atoms. In the case of crystalline silicon, each silicon atom shares its valence electrons in a covalent bond with four other silicon atoms, as is shown in Figure 8. This means crystalline silicon unit cells consist of five silicon atoms. If this solid is extended over and over again, the arrangement becomes a crystal lattice (“Crystalline silicon photovoltaic”, 2013).

Figure 7 - The consequences of layer mismatch between two materials with different lattice constants. The bonding at the interface results in dangling bonds that negatively influence the optical and electronic properties. Adapted from (Schubert, 2004).
The band gap of crystalline silicon is 1.1 electron-volts (eV); however, unlike tunable band gap materials, crystalline silicon cannot change its band gap making it unable to access more of the solar spectrum. Another shortcoming of crystalline silicon is that the band gap is indirect. This means the silicon does not absorb light as well as other semiconducting materials. However, the key reason for silicon’s use is its natural abundance, cell lifetime, maturity of technology, and performance. Industrially produced crystalline silicon solar modules achieve efficiencies ranging from 18% - 24% and lifetimes of 25+ years (“Crystalline silicon photovoltaics”, 2014).

1.3 Amorphous Silicon

Another type of photovoltaic is amorphous silicon or hydrogenated amorphous silicon. Amorphous silicon represents about 3% of the 2011 world market for photovoltaics. Amorphous silicon has the same properties as crystalline silicon but has a different lattice structure. Rather than possessing a structured formation of
crystalline silicon unit cells formed by five silicon atoms each, the silicon atoms can bond with fewer than four other atoms. This means that the amorphous lattice structure has dangling bonds (“Amorphous silicon”, 2014). Dangling bonds are created when a silicon atom does not bind with four other silicon atoms. When this occurs, the dangling bonds need to be passivated by hydrogen atoms. If the dangling bonds are not passivated, they can cause anomalous electrical behavior. However, hydrogenation is associated to the Staebler-Wronski effect of light induced degradation of material. This effect is the increase of defect density as light exposure increases, which causes an increase in recombination current and reduces efficiency (Staebler & Wronski, 1980). This effect is one of the leading reasons amorphous silicon cells are not more widely produced.

There are some benefits of utilizing amorphous silicon. The first is less material is necessary than crystalline silicon. Amorphous silicon cells use approximately 1% of the silicon needed in crystalline cells. This is because it is a direct band gap material. The second is amorphous silicon can be deposited in temperatures as low as 75 degrees Celsius, which allows it to be deposited on more flexible substrates than common crystalline silicon wafers. The current industrial efficiency of thin film amorphous silicon is between 6% - 9% (“Amorphous silicon”, 2014).

1.4 Tunable Band Gap Materials

Tunable band gap materials arise from ternary, quaternary, or higher alloys. Ternary alloys are developed by creating an alloy of three elements with differing
amounts of electrons in the outer shell, in this case a III – V (three – five) compound such as Indium Gallium Nitride (InGaN). Some examples of the III and V column elements are aluminum, boron, indium, and gallium and arsenic, antimony, phosphorus, and nitrogen, respectively. By varying the mix of the elements, one is able to tailor the band gap of the alloy (Rogers, 2006).

This has vast implications in the fields of semiconductors, and specifically for photovoltaics. By tailoring the band gap, one can make a solar cell with a range of band gaps, solely based on the composition of the alloy. Depending on the amount of an element used, the band gap will change. This allows one to choose what band gap to make. An example of such a range is shown in the following section. However, a problem arises with lattice spacing, which is the spacing between the lattice planes within the crystal structure, when using ternary materials. Quaternary or higher compositions have the additional option of tuning the lattice constant of the alloy, which can rectify the issue of lattice mismatch. By introducing a fourth element to the alloy, one can alter the composition of the elements to change band gap and lattice constant. Though this allows greater material engineering, it makes the fabrication process more complex. This allows one to engineer a direct band gap material rather than indirect (Rogers, 2006). The ability to create a direct band gap has major implications in photovoltaics and the potential to greatly increase the efficiency and energy output of solar cells. This is because many of the common solar cell types utilize indirect band gap materials.
1.5 Indium Gallium Nitride

Indium Gallium Nitride (InGaN) is a material composed of III – V elements. Indium and Gallium are Group III elements. This material is a direct band gap, ternary semiconductor. The band gaps of InN and GaN are 0.7 eV and 3.4 eV, respectively. The band gap of the ternary semiconductor InGaN is tunable between these limits (Preuss, 2002). This corresponds to photon wavelengths of 1771 nm and 365 nm, respectively. These wavelengths span the entire visible spectrum and include parts of the ultraviolet and infrared, shown in Figure 9. Control of the band gap is accessed through the composition of the material or doping amount. The effectiveness of a two-layer InGaN cell, with one tuned to 1.7 eV and the other to 1.1 eV, has been shown to reach a theoretical maximum efficiency of 50% (Preuss, 2002). This is already greater than the maximum efficiency of a single junction cell. Also, InGaN is fairly insensitive to optoelectronic defects caused by a lattice mismatch between layers, a common source of efficiency loss. There has been recent study utilizing the quaternary material, Al$_x$In$_y$Ga$_{1-x-y}$N, in order to lower lattice mismatch defects even further (Ghazai, Aziz, Hassan & Hassan, 2012). This property allows a complete tandem cell to be composed solely from In$_x$Ga$_{1-x}$N without significant efficiency loss from layer mismatch. This demonstrates the potential of an InGaN tandem cell with the only problem residing in the fabrication. There are many methods to fabricate solar cells; however, most are expensive or unavailable at Ohio University. We attempted to fabricate a solar cell through a Physical Vapor Deposition (PVD) method.
1.6 Doping of Semiconductors: P-type and N-type

Doping of semiconductors involves the introduction of impurities. These impurities cause a change in the carrier concentration of the semiconducting material and can have an effect on the electrical properties. Silicon is a poor conductor. By introducing impurities, one is able to make p-type or n-type silicon, shown in Figure 10. To do this, one must dope the silicon with acceptor dopants (III elements) or donor dopants (V elements), respectively (Leadley, 2010). P-type materials have holes as the majority carrier. Holes are considered positive (the p in p-type) because of the absence of electrons. In the case of p-type silicon, a hole is created through doping of a Column III element. Since a Column III element has one less electron than silicon, three covalent bonds form and a hole is created. The hole attracts a neighboring electron towards it (since opposites attract). As this electron moves to fill the hole, it
produces another hole in its previous location. This cycle continues and gives the appearance of holes moving as a positive charge within the crystal structure. N-type materials are the exact opposite; they have a majority carrier of electrons. This is made by introducing a Column V element, which has an extra electron in comparison with silicon. When the silicon bonds with the Column V element, four covalent bonds are made and one free electron is present. This free electron will begin to flow when a voltage is applied. This creates a flow of electrons giving a negative charge within the crystal structure (Storr, 2014). For a solar cell to be created one needs to create a PN or PIN junction, which is simply placing a p-type semiconductor on an n-type semiconductor.

![Diagram of pure silicon, n-type silicon, and p-type silicon](image)

**Figure 10** - A. Shows pure silicon with its undoped structure (black dots are valence electrons). B. Shows N-type silicon made through the doping of phosphorous, which adds an electron. C. Shows P-type silicon made through the doping of boron, which creates a hole. Adapted from (Leadley, 2010).

### 1.7 PN and PIN Junctions

As stated above, the essential component needed for a photovoltaic is a PN junction. A PN junction is when n-type and p-type semiconducting materials are joined together. Once again, we will use silicon as an example. When this junction is created, some of the free electrons from the n-type side diffuse across the junction towards the holes in the p-type. At the same time, holes from the p-type side diffuse toward the n-type side. As the electrons and holes move to each respective side, they...
create exposed charges on the dopant atom sites that are fixed within the crystal lattice (Honsberg & Bowden, 2014). Positive ion cores are exposed on the n-type side due to absence of free electrons and negative ion cores are exposed on the p-type side due to absence of holes. This will continue until a strong enough voltage difference is formed between the two regions so as to prevent any more charge carriers from crossing over the junction. No free charge carriers can be present within this zone. The p and n-regions close to the junction will be depleted of all charge carriers in comparison to the n and p-type regions further away. This is commonly called the depletion region. The depletion region is what allows the cell to generate electricity. A photon strikes the cell and passes through a thin n-type layer. It enters the depletion region, where it interacts with the atoms present to create electron-hole pairs. Due to the voltage difference across the depletion region, the electrons are swept into the n-layer and the holes into the p-layer. It should be noted that these electron-hole pairs can be generated in all layers, p-type, n-type, and depletion. However, most pairs created in either the p or n-type layers will recombine unlike the depletion region. It is the pairs that do not recombine that contribute to the photocurrent, shown in Figure 11 (Van Zeghbroeck, 2004).

The PIN junction has one large difference from the PN; it increases the size of the depletion region, shown in Figure 12. By expanding the size of the depletion region, there is a larger photo sensitive volume. This increased volume enhances conversion efficiency because as stated before, it is the depletion region’s electron-hole pairs that produce the majority of the photocurrent (Van Zeghbroeck, 2004).
Carrier lifetime is the amount of time it takes for an electron-hole pair to recombine and annihilate each other. When the recombination occurs, energy is released thermally or through photons. The lifetime of the semiconductor is dependent upon the recombination rate, which in turn depends on the concentration of minority
carriers. This process is also called minority carrier recombination for this reason (Honsberg & Bowden, 2014).

1.9 Fabrication of Solar Cells

There are many methods to make solar cells. In this section, I described the most common fabrication process of crystalline silicon wafers and amorphous silicon films, discussed the fabrication method available to us at Ohio University, and explained the components of a complete solar cell.

1.9.1 Crystalline Silicon Wafers

Crystalline silicon wafers are produced by using silicon boules, which are polycrystalline structures with the atomic structure of a single crystal (“How products are,” 2013). The process to create a boule is the Czochralski method, shown in Figure 13. This process requires a seed of crystal silicon to be dipped in melted polycrystalline silicon. The “seed crystal is withdrawn and rotated” to form a boule. The silicon’s impurities remain in the liquid (“How products are,” 2013). The boule is then cut with a circular saw to produce the silicon wafer. This process produces pure silicon wafers but for photovoltaics, a P or N-type wafer is needed. This is done by introducing a dopant such as boron and phosphorous during the Czochralski process.
1.9.2 Plasma – Enhanced Chemical Vapor Deposition (PECVD)

PECVD is the main method of fabricating amorphous silicon cells. The process works by pumping down a chamber to almost vacuum and using a radio-frequency (RF) electric field to ionize an inert gas to create a plasma. This plasma consists of electrons and heavy ions, or parent precursors. In the case of silicon, the precursor would be something like silane (SiH$_4$). The precursor is vaporized and pumped into the chamber. The electron “energies are sufficiently high to excite molecules or break chemical bonds” during inelastic collision with gas molecules (Barron, 2009). The reactive species of the gas molecules, silicon in this case, then form films on the substrate in the chamber, shown in Figure 14 (Barron, 2009).
1.9.3 Physical Vapor Deposition (PVD): Plasma Sputtering

In the Clippinger Laboratories, we possess two PVD machines. These machines utilize sputter deposition, which is a specific type of PVD. Sputtering utilizes energetic ions to bombard a solid or liquid target to cause the ejection of atoms. The ejection occurs from collisions between the energetic ions or recoil atoms with the surface atoms of the target (Depla, Mahieu & Greene, 2010). There are two types of sputter deposition, ion beam sputtering and plasma. Our systems utilize the plasma option. Plasma sputtering is done by applying a high negative voltage to the cathode located by the target so the positively charged ions are attracted toward it (opposites attract). These ions gain a sufficient amount of energy, while moving through the electric field, to initiate sputtering (Depla, Mahieu & Greene, 2010). The atoms ejected from the target are propelled toward a substrate. This substrate will begin to collect the atoms that begin to form a layer of the target material, shown in Figure 15.
Due to the nature of this sputtering technique, the layer tends to be amorphous in structure.

Figure 15 - Schematic of the plasma sputtering deposition process. Shows the energetic ions bombarding the target and the target atoms being ejected and coating the substrate. Adapted from (Heraeus, 2013).

1.9.4 Contacts and Anti-Reflective Coating

The most essential component of the photovoltaic is the PN junction; however, there needs to be a way for the electrons and holes produced in the depletion region to flow out of the cell. This is done by placing metal contacts or a transparent conductive oxide on the cell. A cell needs a front and back contact that allows electrons to enter a circuit. The back contact is a complete layer of metal such as aluminum, which is used for its conductivity. The front contact is a little more difficult. Since sunlight enters from the top of the cell, any metal contact placed there will keep light from entering further into the cell. This lowers the efficiency and active area of the cell. Another type of front contact is a transparent conductive oxide. This can cover the entirety of the front face. As long as most visible light is not absorbed by the oxide, an efficient
reliable contact can be made. Finally, there is an anti-reflective coating that is placed on the front face of the cell. When light enters the cell, it can be absorbed or reflected. An anti-reflective coating allows light to pass through it with minimal absorption and traps the light within. This increases the amount of light entering the cell, which increases efficiency. Though an AR-Coating is beneficial to cell efficiency, we are unable to apply one to our specimens. All of these components (excluding the AR-Coating), shown in Figure 16, are necessary for a complete solar cell to be constructed.

![Diagram of a complete solar cell with all components marked. Also, shows the path of the electron and hole generated. Used with permission of Cyferz (Cyferz, 2007). Some alterations were made.](image)

1.10 Practical Problems of Solar Irradiation

The first problem is that our sun emits electromagnetic energy in a specific band of wavelengths, where 50% is infrared, 40% visible, and about 10% ultraviolet at the top of the atmosphere (Fu, 2003). This affects current photovoltaic cells in that about 55% of the sun’s energy is either below the band gap of the material or carries excess energy ("Crystalline silicon photovoltaic", 2013). Tandem cells are being
pursued because of their capability of accessing a larger amount of the sun’s energy. Another problem is the sun’s angle with the Earth’s surface and interaction with the atmosphere. These two components have effects on the wavelength, or energy, of light hitting the Earth. This is rectified by the use of an air mass (AM) coefficient, which defines the direct optical path length through the Earth’s atmosphere. AM1.5 is the common air mass used in studying solar panels because it represents the overall yearly average of solar irradiance for mid-latitudes, shown in Figure 17 (Gueymard, Myers & Emery, 2002). The use of the AM coefficient allows for cells to be tailored towards the actual solar irradiation they will receive and not the irradiation they would get outside of our atmosphere.
1.11 Project Description

In Professor Kordesch’s laboratory, we have used the physical vapor deposition technique (plasma sputtering) to fabricate single junction cells of a-Si and a-InGaN. Our goal was to create a working single junction a-Si and a-InGaN cell and to develop a technique that would permit precise manipulation of atomic composition.

Science Goals:

1. Analyze the voltage and current measurements under lamp light to determine efficiency and record cell degradation.
2. Create an excitation spectrum for the samples to determine what wavelengths activate the cell.

3. Study surface morphology to better understand the defects present and the cause of cell degradation.

4. Study each individual layer’s composition and structure to determine the continuity of our deposition method.

5. Determine all foreign contaminants present on our samples.

Technical Goals:

1. Develop an efficiency measurement device.

2. Create a process of solar cell fabrication utilizing our sputtering deposition equipment.

3. Determine the feasibility of plasma sputtering in creating solar cells.
Chapter 2: Methods

2.1 Introduction to Equipment

2.1.1 Scanning Electron Microscope (Energy Dispersive X-Rays)

The scanning electron microscope (SEM) was used to analyze the morphology of the top layer of a sample. This was done by an electron beam that traced the surface of the sample. As the beam interacted with the surface, electrons were dislodged and then read by a detector. The amount of dislodged electrons determined the brightness of that region of the sample. The SEM used small fluctuations in voltage, which changed the magnetic field the electron beam moved through so the beam could trace the sample (Atteberry, 2009). The components of the SEM are shown in Figure 18. We used a Hitachi S-4500 and a Hitachi S-2460N, shown in Figure 19. The S-2460N was also equipped with energy dispersive X-ray spectroscopy (EDS), which used the NORAN software package to analyze samples. EDS was used to find the elemental composition of a sample. A detector read the X-ray (photon) excitation caused by the electron beam and the device matched the energy of the excitation with the corresponding element. This was because each element has a unique atomic structure and therefore, characteristic peaks on its X-ray spectrum (Goldstein, Newbury, Joy, & Lyman, 2007). The pictures of the surface morphology were shown on the SEM monitor, while the elemental analysis was shown on the attached computer.
2.1.2 Transmission Electron Microscope

The transmission electron microscope (TEM) was used to study the “topographical, morphological, compositional, and crystalline information” of a sample (Anderson, 2010). The TEM shined an electron beam on the sample; the
device provided a black and white picture, formed by the interaction between the atoms and electrons. The process is shown in Figure 20. The darker section was where the electrons interacted strongly, while the lighter section was where the electrons interacted weakly with the sample (Anderson, 2010). The TEM was used to analyze the different physical characteristics of all the materials we deposited. We used a Jeol JEM-1010, shown in Figure 21, which provided us with an image of the sample on the monitor.

Figure 20 - Schematic of a transmission electron microscope. Permission by Gringer (Gringer, 2009).
2.1.3 Vacuum Furnace

A vacuum furnace was used to anneal materials. The key reason we used a vacuum furnace was that the act of decreasing the pressure to near vacuum removed almost all gaseous contaminants, such as carbon, oxygen, and hydrogen, and prevented them from interacting with the sample. The heat provided can increase bonding strength of materials or cause a phase change (amorphous to crystalline), among other things. In our case, we used the furnace to anneal the sputtered aluminum back contact to our p-type silicon. This transitioned the amorphous/crystalline (was not one or the other) deposited aluminum to crystalline structure, which was required for strong conductivity, as well as to better the contact with the p-type silicon. We used a NEY Mark III-Modular furnace with a Pfeiffer Vacuum, shown in Figure 22.
2.1.4 Monochromator

A monochromator is an optical device that takes light and disperses or diffracts it so a specific wavelength is emitted, shown in Figure 23 (Zbigniew, 2005). We used a Model 585-11 Monochromator Housing device made by EG&G, shown in Figure 24. This device was used to target our cells with specific wavelengths of light. This allowed us to see the wavelength and as a result, the band gap energy the cell activated at. We then compared this with the known band gap energy of our materials to either confirm the same band gap or discuss the reason for differences. We then monitored the voltage at all of the different wavelengths. This gave us measurements of the voltage generated by the cell, which was processed into a curve to see where in the electromagnetic spectrum the cell was most active.
2.1.5 Optical Microscope

An optical microscope uses a beam of light to magnify an image. This allowed us to study the surface of a sample at different magnifications, which illuminated surface stresses, cracks, and contaminants such as oils. The image created by the
microscope was photographed for later comparison and study. This piece of equipment allowed us to compare a strong sample versus a weak one. We were able to see the causes of reduced voltage between samples or within the sample itself (i.e. voltage pockets or sections of a sample corresponding to a specific voltage due to a structural defect). We used a Bausch & Lomb Optical Microscope shown in Figure 25.

![Figure 25 - The optical microscope used in our laboratory.](image)

2.1.6 Basic Voltage and Efficiency Measurement System

Our voltage system was a 300 Watt light bulb with a focusing bowl over it, as shown in Figure 26. This gave us a rough spectrum of light that activated our cells. The system used a docking setup, which formed electric contact with our cells. This loading station could be shifted so the light hits the cell directly and indirectly. We made measurements directly under the light source and away from it. These
measurements were made multiple times to watch for cell degradation and to increase the basic voltage information of the cell.

We built an efficiency measurement system that used a variable resistor to measure for open circuit voltage and short circuit current. This allowed us to create a voltage/current graph and determine the efficiency of each cell. This system had a metal stand with prongs to make contact with the cell. A lamp was stationed above the stand to irradiate the cell. An ammeter, voltmeter, and variable resistor were set up in a circuit so measurements could be made. The circuit is shown in Figure 27 and the complete efficiency system is shown in Figure 28.

Figure 26 - Our basic voltage measurement system with a 300 Watt light bulb and reflective bowl. The docking station can be seen turned toward the light bulb.
Figure 27 - The circuit used to measure the open circuit voltage and short circuit current of our cells. By altering the resistor’s value, these measurements can be determined.

Figure 28 - The efficiency measurement system where the meter on the left reads current, the meter on the right reads voltage, and the unit in between in the variable resistor.
2.1.7 Thickness Measurement System

Dr. Hugh Richardson, from the Chemistry Department, possesses a thickness measurement system that uses spectroscopy. This system, shown in Figure 29, used the interaction of light with a substrate to determine thickness. This was done by sending light through a fiber optic cable and having it shine on the substrate one wants to analyze. The center of the cable was used to shine the light and the outside of the cable was used to capture the refracted light. The captured light was then sent through the cable to a spectrometer (Ocean Optics SD 2000). Based on the light’s interaction with the sample and the refracted light collected, an absorption spectrum would be generated. This was done using the OOI Program, which allowed us to capture the spectrum and input the data into the Grams Spectral Analysis Package. From this program, the absorption peaks were found and converted into wavenumber, which is the inverse wavelength. The data was then processed in Excel to determine the thickness of the sample.

![Figure 29 - The thickness measurement system. Left: The complete system setup. Middle: The blue cylinder is the source of our light and connects with the blue fiber optics cable. The white box is the Ocean Optics Spectrometer that reads in the refracted light through the fiber optic cable. Right: The loading tray that holds our sample.]

2.1.8 Sputtering Systems

We have two sputtering systems in Clippinger. The first is a commercial system, the Denton Vacuum DV-502A, shown in Figure 30. This system was used to
form the aluminum back contact on the p-type silicon. The second system was custom-built. We made alterations to this system to allow for two sputtering chambers and an arm to shift the sample from one chamber to the other, as shown in Figure 31. In this system, we deposited the n-type material on our p-type silicon substrate. Once this process was completed, we used the arm to move the sample to the other chamber. In this chamber, we deposited Indium Tin Oxide, ITO, which is a transparent conductive oxide. This acted as the front contact of the cell and allowed for proper electron flow. In this system, we completed our fabrication of a solar cell, as described in the introduction.

![Image](image-url)

**Figure 30 -** The commercial sputtering system in our downstairs laboratory. This is where the back contact is applied to our cells.
2.2 Steps for Cell Production

2.2.1 Building the System

In order to fabricate our cells, we refitted our sputtering apparatus. This required the addition of a second chamber, which had its own magnet and cooling system. Also, we attached an arm that allowed our samples to be shifted between the two chambers. The building process required taking apart the system, to add these components, and then resealing the system. If the system had not been resealed correctly, it would have been unable to pump down close to vacuum, which is required for plasma sputtering. Part of the cooling system construction is shown in Figure 32.
2.2.2 Cutting Silicon Pieces from P-type Wafer

The first step in creating our samples was to make a substrate. We used p-type silicon, a key component of our cell. We purchased many p-type silicon wafers online. These wafers were circular, as shown in Figure 33, but this form was not suitable for our needs. We cut these wafers into one inch by one inch squares using a diamond tipped blade. Because the wafers were extremely fragile and chipped easily, the cuts were made with great care. The cutting process is shown in Figure 34.

Figure 33 - P-type Silicon wafers being used as our substrate.
2.2.3 Using Denton Vacuum DV-502A System to Deposit Aluminum

As stated previously, we used the Denton Vacuum DV-502A sputtering system to deposit our aluminum back contact on the square p-type silicon pieces. To do this, we returned the sputtering chamber to atmospheric pressure. Once the correct pressure was reached, the sealed chamber was opened. We then loaded our samples, four at a time, into the chamber on a tray. We closed the lid and pumped the chamber back down to vacuum. It took about two hours for the system to reach the correct pressure. Once finished, we turned on our argon or nitrogen gas pump to put gas into the chamber. We then began to turn up the current or voltage difference within the chamber. This had to be done slowly in order to create and maintain the plasma. Once the plasma was created and the current stabilized, we began deposition. During this whole process, we had to turn our water cooling system on so the magnet did not overheat. We allowed the samples to be deposited on for roughly two hours. Once we reached the desired thickness, we turned the current off and allowed the system to cool down. After this wait period, we brought the system to atmosphere and removed our aluminum/p-type silicon samples.
2.2.4 Vacuum Furnace to Anneal Aluminum/P-type Silicon Together

The aluminum deposited by our sputtering machine was amorphous/crystalline. This means there was no to little structure throughout the layer. Amorphous structures do not allow for good electrical conductivity, which was why we had to change the structure to crystalline. In order to do this, we placed our samples into a vacuum furnace. The furnace heated the samples to 450 degrees Celsius for about 15 minutes. This caused the aluminum’s structure to shift from amorphous to crystalline and form better contact with the p-type silicon. Also, this act removed some gaseous contaminants, such as hydrogen and oxygen, from the sample. Through this process, the electrical conductivity of our back contact increased.

2.2.5 Shifting Sample to Custom-built Sputtering System

Once the annealing of the samples was completed, we moved them to our custom-built sputtering system. This system acted in the same way as the commercial one. We brought the system back to atmosphere and loaded the samples on a tray in the first chamber. We proceeded to pump down the system, which took some time to reach our preferred pressure. Once the system reached vacuum, we introduced the nitrogen gas into the chamber. We applied a voltage difference within the chamber to produce the plasma, which is shown in Figure 35. During this process, the water cooling system was turned on to prevent overheating. Once the plasma was created, the deposition process began.
We made two types of solar cells: n-type amorphous silicon on p-type crystalline silicon and n-type a-InGaN on p-type crystalline silicon. The first deposition was n-type silicon onto the p-type silicon side of our samples. If placed on the aluminum side, we would be unable to create the necessary PN junction. We allowed for this deposition to occur for different time periods to sputter different thicknesses. Our first batch was sputtered for 17 hours. When we reached the proper thickness, we turned the voltage difference to zero and halted the deposition. We then allowed the system to cool down. Once enough rest time was given, we shifted the samples to the second chamber.

The deposition process of a-InGaN was basically the same. However, the a-InGaN sputtering target was more fragile than the amorphous silicon one and had to
be handled with care. Also, we had to clean the system when we switched the sputtering targets. This kept the chambers as devoid of contaminants as possible. We pumped the system to vacuum, inserted the gas, created the plasma, and waited until the desired thickness was deposited. We then shifted the sample to the second chamber.

In the second chamber, we repeated the same acts of pumping down the system, introducing a gas, and creating a plasma. In this chamber, we deposited Indium Tin Oxide, ITO, onto the n-type material we previously deposited. We allowed this to deposit for four hours. The ITO was used as a transparent conductive oxide. This means it encompassed the whole cell without obstructing light from reaching the PN junction. Also, it acted as the front contact of our cell. With this layer deposited, we completed the required components of a solar cell. After letting the system cool down, we brought the chamber back to atmosphere and removed our samples.

For our cells to work, we had to take one more step. We had to cut off the edges of our squares. This was necessary because the ITO wrapped around the edges forming a short. If we tested our cells under light without cutting, we would see zero voltage on the readout. By cutting our samples, we were able to remove the short and began reading the voltage produced by our cell. The completed cell was extremely fragile so cutting them usually caused various shapes to arise. The samples we are analyzing are shown in Figure 36.
2.3 Steps for Cell Analysis

2.3.1 Testing Samples under a Light Source

The first analysis step was to prove that the samples were photovoltaics. This required us to place the samples under a light source and try to measure a voltage. This was done using our voltage measurement system. We loaded the sample into the docking station and measured the cell’s voltage directly under light and away from it. The docking station was a simple construction of a metal tray combined with a metal clip. This allowed proper contact to be made to the back and front contacts of the cell; therefore, we measured the voltage produced by the cell through the connected voltmeter. The system in action is shown in Figure 37. This step was done for each sample multiple times. The process must be repeated every few days to check for cell degradation. All data was compiled into an Excel table for comparison.

Figure 36 - The amorphous silicon on crystalline silicon solar cells we are testing. As can be seen, many shapes arise during the cutting process.
2.3.2 Testing Samples at Specific Wavelengths

We then created an activation spectrum for each cell. This spectrum was simply the wavelength versus voltage. We used the monochromator and looked at the voltage produced at specific wavelengths between 350 nm and 800 nm. We continued to use the docking station to measure the voltage. All monochromator measurements were made in darkness to decrease ambient light interacting with the cell. The process is shown in Figure 38. We recorded the voltage at each wavelength, which enabled us to build a graph showing the wavelength the cell was most active. From this, we found voltage peaks corresponding to the wavelengths of light that most strongly affected our cell. This technique was used on every strong sample (sample showing proper voltage production) because the weak sample’s voltage would not change significantly.
enough for a trend to be seen. If strong discrepancies appeared between samples, further analysis of the composition of the cell was necessary. The data was compiled into an Excel table and then converted into a graph.

![Image](image.png)

Figure 38 - Left: The monochromator in action. The light's wavelength is adjusted and sent out to hit the cell. A voltage is then read by the voltmeter. Right: Shows a close up of the light hitting the cell. This also shows a close up of the docking station we are using.

2.3.3 Efficiency Measurement

Next, we measured the open-circuit voltage and short-circuit current, which are used in calculating efficiency. To do this, we placed each sample onto a metal tray and connected to the front and back contacts. We then turned on the lamp to illuminate the cell. We varied the resistance of the circuit from high (10MΩ) to low (0Ω) to get different voltage and current measurements. When the correct resistance limits were found, we recorded the open-circuit voltage (highest resistance) and short-circuit current (lowest resistance). Measurements were made between these two resistance limits in order to create a current versus voltage graph. All of the data was compiled in Excel for further analysis. The measurement system in action is shown in Figure 39.
2.3.4 Analyzing Basic Surface Structure of Cells under the Optical Microscope

After voltage measurements of the samples were made, the cells were organized into strong and weak. Samples from each group were then studied under an optical microscope. To use the microscope, a sample was placed on a glass tray underneath the magnification lenses. Then, the microscope was turned on and the light shutter opened to illuminate the sample. After focusing the image, we examined the surface of the sample. We took pictures of the front and back sides of the cell at 10X, 20X, 40X, and 60X magnification. This allowed for comparison between samples to determine the cause for strength differences. Also, information about stress, cracks, contaminants, and other surface structure defects became apparent.
2.3.5 Measurement of the cell thickness

Another piece of data, helpful to the understanding of our samples, was the thickness of each layer. This was found by placing a single layer of each material on the loading tray. We turned on the light and placed a filter on it to reduce the intensity. If this was not done, the data would contain a lot of noise and give erroneous numbers. The OOI Program was then opened and a dark measurement was made to zero the scale. After this, a light spectrum was made of the glass substrate to subtract its influence on the material’s spectrum. We then placed the material directly under the light and saved the spectrum created in the program. This spectrum was opened in the Grams Spectral Analysis Package to determine the peaks. In this program, we converted the data from wavelength to wavenumber, removed the noise, and located the peaks. Once accomplished, the data was sent to Excel to calculate the thickness.

2.3.6 SEM and EDS Analysis

Once all other analysis steps were completed, we placed the samples in the SEM and SEM/EDS systems. This required us to bring the chamber to atmosphere, place the sample within the chamber, seal the chamber, pump it down (close to vacuum), and adjust settings to produce a picture of the surface morphology. The SEM can give us magnification as high as 40,000X, much greater than that provided by the optical microscope. This enabled us to see contaminants, stresses, layers, and other defects with greater clarity than the optical microscope. The images were captured and saved by the computer attached to the system. The second system was used to perform an EDS analysis utilizing the NORAN software. This gave us the elemental
composition of the cell. We decided to do this for the completed cell and a single layer of each material deposited on a glass substrate. This gave us the elemental composition of each material we used and the contaminants present in our deposition systems.

2.3.7 TEM analysis

The TEM process was done in a similar manner to the SEM. The main difference was the preparation of the sample for use in the machine. A complete cell cannot be studied in the TEM. In order for a sample to be studied in the TEM, the sample had to be extremely thin. The complete cell was too large, so we were required to deposit a new, single layer of a-Si, aluminum, a-InGaN, and ITO on a glass substrate coated with sugar. This was then placed in water to dissolve the sugar and create thin flakes of each material. We then placed these thin layers on a TEM grid to be analyzed. This showed us the structural morphology of the materials. Pictures were taken by the device and captured on the connected computer.
Chapter 3: Analysis – Electrical

For the analysis of our samples, we studied the voltage the cells produced under a general light source and their degradation over time, the samples’ surface morphology under an optical microscope to explain the degradation, the voltage versus wavelength spectrum of each “strong” cell, the fill factor and efficiency of each cell with reference to commercial cells, and the detailed surface and layer structure of the “strong” and “weak” cells seen through the SEM. This was done for the N-type amorphous silicon and the N-type amorphous Indium Gallium Nitride cells, which were compared. The final objective was to look at each material layer individually. We studied the thickness, surface morphology and elemental composition, and structural morphology through the use of the thickness measurement, SEM/EDS, and TEM systems, respectively. Throughout the process, we addressed the problems we found with our method of analysis and rectified or created a plan to rectify them. Finally, we addressed the limitations of our fabrication method and determined its feasibility.

3.1 Basic Voltage Measurement Data

The basic voltage measurements were made using our 300 Watt bulb and a metal dish to direct the light. These measurements were made for each batch of samples (2 amorphous silicon and 2 amorphous Indium Gallium Nitride). The values are shown in Tables 1, 2, and 3.
<table>
<thead>
<tr>
<th>Amounts of Samples</th>
<th>Cell 1</th>
<th>Cell 2</th>
<th>Cell 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumes (ml)</td>
<td>100</td>
<td>200</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 1. The first batch of porous silicon on crystalline silicon voltage measurements close and away from a 500 W lamp. The values demonstrate cell performance and the indication of voltage measurement due to the placement of metallic contacts. Each batch contains four cells, these are then cut into rectangular pieces. 

Cell 1: Close, 100 ml
Cell 2: Close, 200 ml
Cell 3: Close, 300 ml

Close: 102, 110, 87, 92
Away: 74, 74, 87, 92

90, 95, 28, 20
91, 105, 38, 22
123, 88, 54, 32
123, 132, 90, 22
102, 110, 87, 92
110, 122, 87, 92
110, 122, 90, 22
Table 2 - The second batch of amorphous silicon on crystalline silicon wafer measurements close and away from 300 W melt. "Close" means the cell broke during measurement and made multiple pieces.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Wafer Value (Any)</th>
<th>Cell 2</th>
<th>Cell 3</th>
<th>Cell 4</th>
<th>Cell 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
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<tr>
<td>4</td>
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<td>5.4</td>
<td>5.5</td>
</tr>
<tr>
<td>6</td>
<td>6.1</td>
<td>6.2</td>
<td>6.3</td>
<td>6.4</td>
<td>6.5</td>
</tr>
</tbody>
</table>

- 1: Away
- 2: Close
3.1.1 Basic Voltage Measurement Discussion

All of the voltage measurements are in mV. The average voltage of the cells was \(\sim 140\) mV. Also, it is apparent that the voltage of the a-InGaN samples is similar to the first batch of a-Si. They both have a few samples with high voltage, while the rest are either zero or low voltage. The second batch of a-Si samples had the strongest results. This is odd though because each sample was made with the same fabrication process, with the only difference being the n-type material used. The two batches of a-Si should have extremely similar voltage measurements but a discrepancy still appears. This raises the question, why are they different? While the thicknesses of the two samples may differ by miniscule amounts, it would not have such a dramatic effect on performance.

This led us to believe that the difference in voltage values is caused by defects or contaminants present inside of the sample. A speck of dust between our layers could cause a short (cause a voltage of zero), a spot that collects generated charge, essentially killing the electrical properties, a disruption in the interface between the

<table>
<thead>
<tr>
<th>Recording</th>
<th>Voltage (mV)</th>
<th>Batch Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sample Number</td>
<td>1</td>
</tr>
<tr>
<td>1 Close</td>
<td>110</td>
<td>0</td>
</tr>
<tr>
<td>1 Away</td>
<td>100.5</td>
<td>0</td>
</tr>
<tr>
<td>2 Close</td>
<td>127</td>
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<tr>
<td>2 Away</td>
<td>113</td>
<td>0</td>
</tr>
<tr>
<td>3 Close</td>
<td>147</td>
<td>0</td>
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<tr>
<td>3 Away</td>
<td>136</td>
<td>0</td>
</tr>
<tr>
<td>4 Close</td>
<td>134</td>
<td>0</td>
</tr>
<tr>
<td>4 Away</td>
<td>124</td>
<td>0</td>
</tr>
</tbody>
</table>
layers, which can cause stress, and many other negative effects. It was obvious that some foreign contaminant had influenced the voltage of the samples; however, it is interesting that samples cut from the same cell can show such different voltage values. This led us to the idea that these defects cause localized voltage pockets or disruptions. This means that if I had not cut the pieces as I did, the defect would influence the whole cell and not just the cut off cell.

I tested whether this hypothesis was true or not by breaking the samples further. This idea was clearly proven when looking at the voltages of batch 2 a-Si cell 1 sample 1 and cell 2 sample 2 measurements. The first had a voltage measurement of 36 mV and 21 mV, close (directly under light) and away (about 6 inches away). From here on, we compared only the close voltage, though the away voltage shows the same relationship. When this sample was cut into three more pieces, we confirmed the idea of voltage pockets. The three pieces had voltages of 61 mV, 167 mV, and 123 mV, respectively. These three samples had completely different voltage measurements than their parent sample, yet, they also had vastly different voltages from each other. This means that the defects present in these samples were different. The parent sample had large defects present, which dropped the voltage. When it was broken, these defects got spread out between the different samples. The first piece contained either the most or strongest defects, which caused its voltage to be lowest. The other two pieces fared better and contained fewer defects. This allowed them to demonstrate a stronger voltage than their counterpart. The second example of this (cell 2 sample 2) showed the same results. Its originally voltage was 125 mV. When broken, voltages of 124
mV and 160 mV appeared. The same effect had occurred here. The parent sample and the first sample broken from it had the same voltage. This means that the central defect affecting the sample is contained within it. The second sample broken from it showed increased voltage, meaning it was no longer under the influence of the defect and could perform better.

As the measurements were made again and again over the course of a month, another peculiarity appeared. If one looks at the Cell 2 Sample 2 (which will be designated C: 2 S: 2) and C: 4 S: 4 columns of Table 1, the C: 3 S: 1 and C: 3 S: 3 columns of Table 2, and B: 1 S: 1 (B stands for Batch) and B: 2 S: 3 columns of Table 3, the stability of the voltage measurement becomes questionable. These specific samples showed extreme fluctuation of voltage. Samples C: 2 S: 2 and C: 4 S: 4 from Table 1 and C: 3 S: 1 from Table 2 had similar changes. The first had voltage changes from 22 mV to 8 mV to 142 mV to 2 mV, the second had changes from 158 mV to 215 mV to 207 mV to 228 mV to 4 mV, and the third had changes from 60 mV to 131 mV to 118 mV to 35 mV. Both started low, had a substantial increase and then decreased below their initial value. The others demonstrated a gradual increase or decrease. B: 1 S: 1 had a change from 110 mV to 127 mV to 147 mV to 134 mV and B: 2 S: 3 had a change from 184 mV to 192 mV to 183 mV to 211 mV. They both demonstrated an increased voltage over time. The best was seen in C: 3 S: 3 from Table 2, where the voltage decreased from 333 mV to 200 mV to 143 mV to 210 mV to 171 mV to 156 mV. Though there was a spike in the middle, the trend was a fairly stable decrease in voltage. A decrease in voltage is expected in the a-Si samples due to
light degradation, which was explained in the introduction. However, the changes occurred too quickly and were too substantial to be attributed solely to this effect. This brought us back to our idea of voltage pockets.

I hypothesized that depending on where contact was made on the sample, the voltage would change. I further attributed this to the voltage pockets that were confirmed previously. Each sample possessed different regions of voltage and these regions were only accessed when the contact was placed on them. To confirm this, I took a sample shaped as a triangle (C: 1 S: 1 from Table 1) and measured the voltage at each corner. Interestingly, the voltage at each corner was 119 mV, 104 mV, and 89 mV. There was a 30 mV difference between points only 1.6 cm apart! Without a doubt, our fabrication method created voltage pockets within our cells. In Appendix C, I map a complete cell and record the open-circuit voltage and short-circuit current. Whether this was due to contaminants or the method itself though is still unknown. The degradation and stability problems of the cells could be caused by both of these. I determined further analysis was necessary and examined the triangle sample under the optical microscope. The results of which are shown in the Analysis: Imaging – Optical Microscope section.

3.2 Monochromator

Through the use of a monochromator, we were able to create an activation spectrum for each of our samples. This allowed us to determine at what wavelengths the cell is most active at, based on the voltage measurement at each wavelength. Any voltage peaks that arose corresponded to a band gap energy of the sample. For the
analysis, we selected two samples from Batch 1 (a-Si on c-Si), Batch 2 (a-Si on c-Si), and a-InGaN on c-Si and one commercial cell.

3.2.1 Batch 1 Amorphous Silicon Data

The first set we will look at is the first batch of amorphous silicon on crystalline silicon. We manipulated the data and created a graph of voltage versus wavelength. This way the peaks became more obvious, which was shown in Graph 1. As can be seen, there is a large difference in voltage between the two samples. This is solely based on the strength of the sample and no other factor. The activation spectrum simply shows the most active wavelengths for the cell so each sample should demonstrate the same peaks as its counterparts.
3.2.2 Batch 1 Amorphous Silicon Discussion

As can be seen, there are two distinct peaks in this spectrum. The peaks occur around the 675-690 nm and 765-775 nm range. These wavelengths correspond to 1.80-1.84 eV and 1.6-1.62 eV, respectively. For reference, the band gap of crystalline
silicon is around 1.12 eV, which corresponds to a wavelength greater than what was available by our spectrum (~1110 nm). Amorphous silicon’s band gap can vary between 1.60 – 2.1 eV, depending upon the presence of hydrogen. Both of our peaks are within this range, so we can confirm that the presence of these band gaps is acceptable. However, it is interesting to see that our amorphous silicon layer is activating under two different wavelengths. This could mean that within our amorphous layer there is a difference in hydrogen presence, which alters the band gap of that region. This oddity made us question whether or not our monochromator outputs a uniform spectrum. Uniformity requires that the power output at each wavelength is the same and that the peaks correspond to actual peaks and not just increased voltage due to greater amounts of photons striking the sample. We are currently searching for a method to address this possible issue.

3.2.3 Batch 2 Amorphous Silicon Data

The next set of data corresponds to our second batch of amorphous silicon on crystalline silicon samples. We would expect that our peaks would roughly correspond to those in the previous section due to the same fabrication method. There was a slight difference in deposition thickness but this should not have a large influence. Graph 2 shows the activation spectrum.
3.2.4 Batch 2 Amorphous Silicon Discussion

As shown in Graph 2, there are again two peaks in the spectrum. These peaks are located at 685-695 nm and 765-775 nm, which corresponds to 1.78-1.81 eV and 1.6-1.62 eV, respectively. These values are extremely close to the values for our first
batch. The peak between 765-775 nm is exactly the same. The only difference is that this second peak is much stronger than the first in the second batch, while it is the opposite for the first batch. As the second peak is likely related to bulk amorphous silicon with little hydrogen presence, we can claim that our second batch had reduced hydrogen contamination in the samples. However, the presence of hydrogen was still seen by the formation of the first peak. Luckily, the first peaks in both batches were at almost exactly the same wavelength. This means the actual concentration of hydrogen throughout that region of the amorphous silicon was the same. The second batch simply had a larger region of bulk amorphous silicon, while the first had a larger region of hydrogen influenced amorphous silicon.

3.2.5 Amorphous Indium Gallium Nitride Data

With the amorphous silicon samples done, we move to the amorphous indium gallium nitride samples. Graph 3 shows the activation spectrum of the a-InGaN samples.
3.2.6 Amorphous Indium Gallium Nitride Discussion

As shown in Graph 3, the a-InGaN samples show two distinct peaks with a probable third. There were eight a-InGaN samples available for analysis; however, only one of them showed this distinct third peak. The peaks correspond to
wavelengths of 575 nm, 660-665 nm, and 755-760 nm, which corresponds to energies of 2.16 eV, 1.86-1.88 eV, and 1.63-1.64 eV, respectively. The last two peaks were seen in all of the a-InGaN samples, though the clarity is best with the two shown in Graph 3. The presence of multiple peaks related to the InGaN layer is interesting. We cannot adjust the composition of InGaN during deposition. Our sputtering target is set at a specific composition. We would expect that this composition would provide for one band gap, which is directly related to the composition. However, we are seeing multiple band gaps arise from our amorphous indium gallium nitride layer. This means that while our target is a specific composition, the layer itself has a changing composition. Indium and gallium concentrations are not being deposited uniformly, or in the exact concentration of the target. This means that greater indium or gallium concentration may be present at different times during the deposition process. This would allow for the multiple band gaps we are witnessing. Since indium nitride (InN) has a band gap of 0.7 eV and gallium nitride (GaN) has a band gap of 3.4 eV, we can determine that the 2.16 eV band gap we are witnessing is related to a higher concentration of gallium. The other two band gaps correspond to greater and greater indium concentration. Why this occurs remains a question, however, indium is known to be a difficult material to deposit due to its size and properties. It tends to clump together, which makes uniform deposition difficult. Further analysis of the composition our a-InGaN films being deposited is necessary and currently underway.
3.2.7 Commercial Cell Data

Finally, we examine the activation spectrum of a commercial, polycrystalline silicon cell. Graph 4 shows the activation spectrum of a commercial cell.
3.2.8 Commercial Cell Discussion

As shown in Graph 4, there are three distinct peaks for the commercial cell. These peaks correspond to wavelengths of 570 nm, 655 nm, and 755 nm, which correspond to energies of 2.18 eV, 1.89 eV, and 1.64 eV, respectively. These peaks are odd because these band gaps do not correspond to the expected values of a polycrystalline silicon cell. This made us question the identity of our cell. There is some literature on semi-insulating polycrystalline silicon (SIPOS) cells, which showed a band gap of around 2.1 eV. If our cell is some type of SIPOS, then these band gaps would be possible. It again brings into question our monochromator. Could these peaks be pseudo-peaks caused by greater power output at the wavelengths where we are witnessing peaks? All of the samples have a similar peak around the 1.64 eV area and the a-InGaN and commercial cell both show a peak around the 1.89 eV area. The uniformity of light intensity coming from our monochromator needs to be determined. Also, a compositional analysis of the commercial cell would be helpful in determining the reason for the band gap peaks we are observing.

Overall, the monochromator data raised questions about the uniformity of our deposition method and the presence of hydrogen in our system. By attempting to limit these problems, we can determine the cause and validity of the peaks we are seeing. All extra monochromator data is shown in Appendix A.

3.3 Efficiency

Next, we calculated the efficiency of our samples, as well as the commercial cells and panels we possessed. After we built our efficiency measurement system, we
began testing the commercial cells we had as reference. In order to calculate the efficiency, we needed to find the power input and output of our cells. This required us to measure the power output of our lamp. The only necessary measurement for us was the area of the active region or light-collecting region of the device. From this device, we got the power output per area. So to get the power input, we used the following equation:

\[ P_{\text{input}} = P_{\text{density}} \times A_{\text{sample}} \]  

(1)

where \( P_{\text{density}} \) is the power over the known area of our device (2.54 cm\(^2\)) and \( A_{\text{sample}} \) is the area of the sample we are analyzing. As long as all parameters were kept constant (the distance of the light source from the sample), the initial power density calculated would remain constant. This power density was 0.0652 Watts/cm\(^2\), which was measured at 11.5 cm away from the light source and with a water cover. The use of a water cover will be explained later. Using this number, we calculated the power input for each of the samples we analyzed. This gave us the ability to measure the efficiency of the sample using the following equation:

\[ \eta = \frac{P_{\text{max}}}{P_{\text{input}}} \]  

(2)

where \( \eta \) is the efficiency, \( P_{\text{max}} \) is the maximum power produced by the cell, and \( P_{\text{input}} \) is the power the cell receives from the light source, which is calculated in Equation 1.

Another value of interest was the fill factor, which is a simple value used to characterize a solar cell and determines the maximum power output. The following is the fill factor formula:

\[ FF = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}} \]  

(3)
where $I_{MP}$ is the current at maximum power, $V_{MP}$ is the voltage at maximum power, 
$I_{SC}$ is the short circuit current, and $V_{OC}$ is the open circuit voltage.

### 3.3.1 Commercial Cell Data – With and Without Water Cover

The first measurements we made were on one of the commercial cells we owned. Table 4 shows the important electrical values, Graph 5 shows the current versus voltage curve, and Graph 6 shows the power versus current curve for the commercial cell with and without water cover.

<table>
<thead>
<tr>
<th>Important Values</th>
<th>With Water Cover</th>
<th>Without Water Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power Voltage (V)</td>
<td>0.258</td>
<td>0.248</td>
</tr>
<tr>
<td>Max Power Current (A)</td>
<td>0.06335</td>
<td>0.0797</td>
</tr>
<tr>
<td>Open-Circuit Voltage (V)</td>
<td>0.52325</td>
<td>0.4785</td>
</tr>
<tr>
<td>Short-Circuit Current (A)</td>
<td>0.116</td>
<td>0.1513</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>0.269</td>
<td>0.273</td>
</tr>
<tr>
<td>Max Power Produced (W)</td>
<td>0.0163443</td>
<td>0.0198</td>
</tr>
<tr>
<td>Power In (W)</td>
<td>0.338</td>
<td>0.338</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.0483231941</td>
<td>0.0584</td>
</tr>
<tr>
<td>% Efficiency</td>
<td>4.83</td>
<td>5.84</td>
</tr>
</tbody>
</table>
Graph 5 - The current versus voltage graph of a commercial cell with and without a water cover.

Graph 6 - The power versus current curve of a commercial cell with and without water cover.
3.3.2 Discussion of Commercial Cell Data – With and Without Water Cover

When making these initial measurements, we realized that the voltage took a long time to stabilize. This was due to the heat (infrared) coming from our lamp. To limit this, we placed a small beaker of water between the lamp and the sample. This water cover absorbs the heat from the lamp and allows for stabilized measurements to be made. Looking at Table 4, one can see that the open circuit voltage is higher when the water cover is added (0.4785 V to 0.54325 V); however, there is a significant decrease in short circuit current (0.1513 A to 0.1160 A). This shows that while the water cover adds stability, it decreases current production (though this is current produced by thermal excitation). The fill factor had a slight decrease going from 0.273 and 0.269, while the efficiency decreased when the water cover was added. However, the difference in efficiency must be ignored because the power output of the lamp was measured with a water cover. If the power output was measured without the water cover, it would be greater. This would lead to a difference in power input for the cell with water cover and without. The measurement was made as a reference but it is inappropriate to compare the two. It can be seen that the two curves in Graph 5 show the same trend because of the similarity in fill factor values (measure of the squareness of the graph). The same can be said for Graph 6, where both curves are similar, though the maximum power value for the commercial cell without water cover is higher (due to the heat induced current). Since we expected better values from a commercial cell, we decided to see if there was any parasitic series resistance in our efficiency measurement device.
3.3.3 Commercial Cell Data: Parasitic Series Resistance: Control, .5Ω, 1Ω, and 5Ω

To determine the effect of a parasitic series resistance, we decided to manually add a series resistor to the measurement system and see how this influenced our voltage, current, and subsequent measurements. The resistances added were .5Ω, 1Ω, and 5Ω. To demonstrate this effectively, the measurements were repeated for no resistor and then each resistor was added. There was no water cover during these measurements. In Table 5, one can see the important electrical characteristics as the series resistance is changed. Each different series resistance has a corresponding current versus voltage and power versus current curves in Graphs 7 and 8, respectively.

| Table 5 - The important values of a commercial cell with different parasitic series resistances |
|-----------------------------------------------|-----------------|--------|--------|--------|
| Important Values                              | Control (0 Ohm) | 0.5 Ohm | 1 Ohm  | 5 Ohm  |
| Max Power Voltage (V)                         | 0.2385          | 0.225  | 0.244  | 0.2365 |
| Max Power Current (A)                         | 0.07665         | 0.0722 | 0.05945| 0.02921|
| Open-Circuit Voltage (V)                      | 0.46525         | 0.4715 | 0.478  | 0.463  |
| Short-Circuit Current (A)                     | 0.1452          | 0.1301 | 0.1163 | 0.05855|
| Fill Factor                                   | 0.271           | 0.266  | 0.261  | 0.255  |
| Max Power Produced (W)                        | 0.0183          | 0.0163 | 0.0145 | 0.00691|
| Power In (W)                                  | 0.338           | 0.338  | 0.338  | 0.338  |
| Efficiency                                    | 0.0540          | 0.0482 | 0.0425 | 0.0204 |
| % Efficiency                                  | 5.40            | 4.82   | 4.29   | 2.04   |
Graph 7 - The current versus voltage graph of a commercial cell with different parasitic series resistances added.

Graph 8 - The power versus current curve of a commercial cell with different parasitic series resistances added.
3.3.4 Discussion of Parasitic Series Resistance: Control to .5Ω

Looking at the difference between the control and the .5Ω resistor in Table 5, there is an obvious decrease in fill factor and efficiency, which goes from 0.271 to 0.266 and 5.40% to 4.82%, respectively. It should be noted that these parameters can be compared because they are done under the same condition, which is unknown exact power input. The current versus voltage and power versus current curves look about the same, though the control cell does show an odd bump in both graphs. Where this bump comes from is still unknown. The open circuit voltage increased from 0.46525 V to 0.4715 V but the short circuit current decreased from 0.1452 A to 0.1301 A. To look further into the influence of a parasitic series resistance, we increased the resistor from .5Ω to 1Ω.

3.3.5 Discussion of Parasitic Series Resistance: Control to 1Ω

One can see that the 1Ω curves in Graphs 7 and 8 show similar trends but with a significant change in the area beneath. The control has a greater overall power and higher current. However, we do observe a change in the open circuit voltage from 0.46525 V to 0.478 V and the short circuit current from 0.1452 A to 0.1163 A. This again shows that the voltage increases while the current decreases as a consequence of the series resistance increasing. The fill factor decreases from 0.271 to 0.261 and the efficiency decreased from 5.40% to 4.29%. Both fill factor and efficiency show decreases as series resistance increases. In order to to see how significant the effect can become, we increased the parasitic series resistance to 5Ω.
3.3.6 Discussion of Parasitic Series Resistance: Control to 5Ω

Looking at Graphs 7 and 8, we can determine that adding a parasitic resistor does not effect the current versus voltage and power versus current curves form. However, we again saw an effect on the observed and calculated electrical properties. The open circuit voltage changed from 0.46525 V to 0.463 V and the short circuit current changed from 0.1452 A to 0.05855 A. The current again showed a decrease from the control’s current but the voltage did not follow the usual pattern of increasing. In this case, the open circuit voltage decreased. There are two possible explanations for this decrease. The first is that the parasitic series resistance became so large that it began to impact both voltage and current measurements. The second is that this was a random occurrence. Since this measurement was not repeated multiple times, we cannot determine which explanation is correct. Repeated measurements are necessary. We also saw a significant decrease in the overall power of the cell with the 5Ω resistor added. The fill factor decreased from 0.271 to 0.255 and the efficiency decreased from 5.40% to 2.04%. This confirms, without a doubt, that as the series resistance increases, both fill factor and efficiency decrease. This was the expected result and agrees with literature.

3.3.7 Discussion of Parasitic Series Resistance Overall

Through these measurements, we witnessed the constant decrease of short circuit current of 0.1452 A, 0.1301 A, 0.478 A, and 0.05855 A, fill factor of 0.271, 0.266, 0.261, and 0.255, and efficiency of 5.40%, 4.82%, 4.29%, and 2.04%, which correspond to the added parasitic series resistances of 0Ω, .5Ω, 1Ω, and 5Ω. All of this
is shown in Table 5. With this full understanding of the effects of parasitic series resistance, we decided to measure the efficiency of a known commercial solar panel.

### 3.3.8 Commercial Panel Data

In order to determine the effectiveness of our system, we measured the efficiency of a known commercial panel. The panel was stated to have an efficiency value between 15-17%. These measurements were made with our normal lamp and then with a 300 Watt bulb. These efficiencies are shown in Table 6. Graphs 9 and 10 correspond to the current versus voltage and power versus current curves, respectively. Note the shape of the curves.

<table>
<thead>
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<th>Important Values</th>
<th>Lamp Bulb</th>
<th>300 Watt Bulb</th>
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</thead>
<tbody>
<tr>
<td>Max Power Voltage (V)</td>
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<td>5.225</td>
</tr>
<tr>
<td>Max Power Current (A)</td>
<td>0.022005</td>
<td>0.08695</td>
</tr>
<tr>
<td>Open-Circuit Voltage (V)</td>
<td>5.695</td>
<td>6.045</td>
</tr>
<tr>
<td>Short-Circuit Current (A)</td>
<td>0.0424</td>
<td>0.10445</td>
</tr>
<tr>
<td>Fill Factor</td>
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<td>0.720</td>
</tr>
<tr>
<td>Max Power Produced (W)</td>
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<tr>
<td>Power In (W)</td>
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<td>Efficiency</td>
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<td>% Efficiency</td>
<td>4.35</td>
<td>13.5</td>
</tr>
</tbody>
</table>
Graph 9 - The current versus voltage curve of a commercial panel under the lamp and the 300 Watt bulb.

Graph 10 - The power versus current curve of a commercial panel under the lamp and the 300 Watt bulb.
3.3.9 Discussion of Commercial Panel Data

After using our system, we determined the efficiency to be 4.35%, shown in Table 6, but we were using our normal lamp. We decided to try the measurement again with our 300 Watt bulb, which changed the power density from 0.0652 W/cm\(^2\) to 0.0794 W/cm\(^2\). This increase in power caused an increase in the current produced by the panel, essentially bringing it close to maximum. By changing the light source, we found an efficiency of 13.5%, shown in Table 6. We believe that the efficiency could increase even further with the use of a stronger light source. This result solidified our opinion that our efficiency measurement system is working correctly and without any significant fault. We can also see how strongly changing the light source influenced the properties of the panel. The open circuit voltage went from 5.695 V to 6.045 V and the short circuit current went from 0.0424 A to 0.10445 A. The increase in both values was expected and the current increased significantly by 2.46. The fill factor increased from 0.499 to 0.720, with the latter comparable to expected values for commercial panels. All of this points towards confirmation that our set up is effective and that a stronger lamp may be required to effectively achieve the maximum properties of the cells.

The next point of analysis was the current versus voltage and power versus current graphs of each measurement (regular lamp and 300 Watt bulb). The commercial panel was finally able to give us a correctly shaped current versus voltage graph. The expected current versus voltage shape is a square or rectangle. When the resistance is low, the current should plateau and remain roughly constant until sharply
decreasing as resistance becomes high. This is exactly what we see in Graph 9. Also, these graphs were able to show how changing the light source significantly increased the fill factor of the panel and in turn, the efficiency. The power versus current graphs also showed an interesting result. They had a gradual increase until they peaked and then a sharp decrease, which is shown in Graph 10. This type of curve corresponds perfectly with the expected current versus voltage curve (because the power is directly based on the current and voltage values). It is obvious in both Graphs 9 and 10 that the use of the more powerful 300 Watt bulb had a significant effect on the electrical characteristics of the panel.

With the analysis of the commercial panel complete, we can begin studying our own samples with confidence. We will begin with the first batch of a-Si, continue on to the second batch of a-Si, and end with the a-InGaN. These will then be compared to each other to determine which type has the best performance.

3.3.10 Batch 1 a-Si Efficiency Data

The first of our samples we will study is the Batch 1 of a-Si. In this batch, only one sample showed significant enough results to be used as comparison with the others. The rest of the a-Si cells data is shown in Appendix B. Table 7 shows the voltage and current measurements, as well as the efficiency and fill factor we calculated. Graphs 11 and 12 illustrate the different curves we have been analyzing.
Table 7 - The important values of a Batch 1 a-Si cell.

<table>
<thead>
<tr>
<th>Important Values</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power Voltage (V)</td>
<td>0.06225</td>
</tr>
<tr>
<td>Max Power Current (A)</td>
<td>0.0000006</td>
</tr>
<tr>
<td>Open-Circuit Voltage (V)</td>
<td>0.1315</td>
</tr>
<tr>
<td>Short-Circuit Current (A)</td>
<td>0.0000013</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>0.218</td>
</tr>
<tr>
<td>Max Power Produced (W)</td>
<td>3.74E-08</td>
</tr>
<tr>
<td>Power In (W)</td>
<td>0.00815</td>
</tr>
<tr>
<td>Efficiency</td>
<td>4.58E-06</td>
</tr>
<tr>
<td>% Efficiency</td>
<td>0.000458</td>
</tr>
</tbody>
</table>

Graph 11 - The current versus voltage curve of a Batch 1 a-Si cell.
3.3.11 Discussion of Batch 1 a-Si Efficiency Data

As can be seen, the performance of our sample is much weaker than the commercial cells we have been looking at. The open circuit voltage is not too poor showing 0.1315 V but the short circuit current is extremely low showing 1.3μA. This low current is extremely detrimental to our cell’s overall performance. This is seen significantly in the efficiency measurement of 0.0005%, which is shown in Table 7. The fill factor is 0.218, which is comparable to the commercial cell but in no way reflects the actual strength of the sample. The faults of our sample are even more apparent when looking at Graphs 11 and 12. Graph 11 shows the non-uniformity of the current versus voltage curve. We see this again in the power versus current curve in Graph 12. The power curve shows significant fluctuation, which points to problems in our cell. Both curves are far away from representing the form of the commercial
panel’s curves. The next samples we will examine are from the second batch of a-Si.

3.3.12 Batch 2 a-Si Efficiency Data

Table 8 shows the important electrical characteristics of two of the Batch 2 a-Si cells. We again plotted the current versus voltage curve, Graph 13, and the power versus current curve, Graph 14.

<table>
<thead>
<tr>
<th>Important Values</th>
<th>Batch 2, Group 1</th>
<th>Batch 2, Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power Voltage (V)</td>
<td>0.0945</td>
<td>0.08325</td>
</tr>
<tr>
<td>Max Power Current (A)</td>
<td>0.0000029</td>
<td>0.00000255</td>
</tr>
<tr>
<td>Open-Circuit Voltage (V)</td>
<td>0.1935</td>
<td>0.17</td>
</tr>
<tr>
<td>Short-Circuit Current (A)</td>
<td>0.0000064</td>
<td>0.000005</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>0.221</td>
<td>0.250</td>
</tr>
<tr>
<td>Max Power Produced (W)</td>
<td>2.74E-07</td>
<td>2.12E-07</td>
</tr>
<tr>
<td>Power In (W)</td>
<td>0.0161</td>
<td>0.0156</td>
</tr>
<tr>
<td>Efficiency</td>
<td>1.70E-05</td>
<td>1.36E-05</td>
</tr>
<tr>
<td>% Efficiency</td>
<td>0.00170</td>
<td>0.00136</td>
</tr>
</tbody>
</table>
Graph 13 - The current versus voltage curve of two of the Batch 2 a-Si cells.

Graph 14 - The power versus current curve of two of the Batch 2 a-Si cells.
3.3.13 Discussion of Batch 2 a-Si Efficiency Data and Comparison to Batch 1 a-Si

The open circuit voltage of the cells was 0.1935 V and 0.170 V, which was better than our previous amorphous silicon cell at 0.1315 V. The short circuit current showed an increase as well, from 1.3μA to 6.4μA and 5μA, respectively. The fill factor increased from the first sample’s value of 0.218 to 0.221 and 0.250. There was also an increase in efficiency between the batches going from 0.0005% to 0.00170% and 0.00136%, respectively. This can all be seen by comparing Tables 7 and 8. Though we saw increases in all of the properties, we still have an extremely low current and efficiency. The Batch 2 a-Si graphs demonstrated a much more uniform curve, in both cases, in comparison to the Batch 1 a-Si sample. This is a promising result and speaks to the improvement of our fabrication between depositions. There were no fluctuations in the curves like the ones shown in Graphs 11 and 12, which deems the second batch of a-Si as improved. We will now analyze two a-InGaN samples and compare them with the a-Si. After, we will make conclusions on the effectiveness of our samples.

3.3.14 a-InGaN Efficiency Data

For the analysis of the a-InGaN samples, we will look at the two strongest cells we possessed. Their properties are shown in Table 9. Also, we looked at the current versus voltage, Graph 15, and power versus current curves, Graphs 16.
Table 9 - The important values of two of the a-InGaN cells.

<table>
<thead>
<tr>
<th>Important Values</th>
<th>Batch 1</th>
<th>Batch 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power Voltage (V)</td>
<td>0.0695</td>
<td>0.091</td>
</tr>
<tr>
<td>Max Power Current (A)</td>
<td>0.00000655</td>
<td>0.0000086</td>
</tr>
<tr>
<td>Open-Circuit Voltage (V)</td>
<td>0.1355</td>
<td>0.19575</td>
</tr>
<tr>
<td>Short-Circuit Current (A)</td>
<td>0.0000138</td>
<td>0.0000166</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>0.243</td>
<td>0.241</td>
</tr>
<tr>
<td>Max Power Produced (W)</td>
<td>4.55E-07</td>
<td>7.63E-07</td>
</tr>
<tr>
<td>Power In (W)</td>
<td>0.120</td>
<td>0.160</td>
</tr>
<tr>
<td>Efficiency</td>
<td>3.80E-06</td>
<td>4.89E-06</td>
</tr>
<tr>
<td>% Efficiency</td>
<td>0.000380</td>
<td>0.000489</td>
</tr>
</tbody>
</table>

Graph 15 - The current versus voltage curve of two of the a-InGaN cells.
3.3.15 Discussion of a-InGaN Efficiency Data and Comparison to Batch 1 & 2 a-Si

The open circuit voltage was 0.1355 V and 0.19575 V and the short circuit current was 13.8μA and 16.6μA. The voltages were comparable to our a-Si samples, 0.1315 V, 0.1935 V and 0.170 V. The current found for the a-InGaN was at least double the value of the best a-Si samples, which was 6.4μA. The fill factor was 0.243 and 0.241, which was on par with the Batch 1 and 2 a-Si samples, 0.218, 0.221, and 0.250. We found the efficiency to be 0.00038% and 0.000489%. These efficiencies are an order of magnitude lower than the Batch 2 a-Si samples, 0.00170% and 0.00136%, and roughly equal to the Batch 1 a-Si sample, 0.0005%. These values are seen by comparing Tables 7, 8, and 9. Both of the types of curves, shown in Graphs 15 – 16, resemble the curves shown for the second batch of a-Si, Graphs 13 – 14. They were uniform and did not fluctuate like the first batch of a-Si, Graphs 11 and 12.
3.3.16 Overall Discussion of Our Samples Efficiency Data

The current and efficiency values of our samples were dismal in comparison to the commercial cells. Even the voltage was low, a factor of two less in comparison. This made us question what could have caused these weak electrical properties. The most obvious problem is the low current we measured. This current dictates the efficiency value directly. We believe the cause for low current is that the electrons and holes are not separated fast enough, which gives them time to recombine. Amorphous materials already have limitations in carrier mobility and we believe our fabrication method has intensified this problem. We also believe there are significant defects and traps present in our samples. These defects are either shorting our samples or collecting the charge carriers, essentially limiting the current. We plan to check the validity of this idea by applying a voltage difference to the cell and redoing the measurements. This will force the electron hole pairs to separate and allow our cell to produce the maximum current it is capable of. We hope to see a large improvement. Most of the defects occurring are likely due to exposure to environment and contaminants present between our layers or in our system.

Overall, we saw similar characteristics in all three batches of samples, regardless of materials. This similarity determines that our fabrication method is dictating these values. This led us to believe that the fabrication method is the problem and not the materials. With proper sample preparation and better containment, we believe that we can see significant increases in our electrical properties and efficiency. As we make more batches, we will learn tricks in making a better sample, and correct
any problems with our methods. All of the efficiency data that was not in the analysis is shown in Appendix B. Now that we have analyzed the electrical properties of our samples, it is time to properly characterize them. We looked at each sample in the SEM and examined each individual material with TEM and EDS. This confirmed any obvious defects in our samples, similar to those seen in the optical microscope but with better resolution, and confirmed that the materials we deposited were indeed what we expected them to be.
Chapter 4: Analysis – Imaging

4.1 Optical Microscope Data

As mentioned in Section 3.2 of the Analysis – Electrical chapter, I possessed a triangular cell with different voltages at each corner. I explored the cause of these differences by using an optical microscope. Figure 40 is a compilation of the images I captured when analyzing the cell.

Figure 40 — A. Shows one corner of the sample that had the cleanest coating of aluminum. B and E. Show a second corner that has a defect present on the edge of the sample. C and D. Shows bubbling caused by stresses and scratch marks created during voltage measurements. F. Shows the bubbling effect in the aluminum layer.
4.1.1 Optical Microscope Discussion

In Image A, we can see a fairly even coating of aluminum on the sample. There are a few marks but no glaring defects. Image B, however, shows some obvious defects. One can see that the coating on the edge of the sample has eroded, which makes the aluminum contact non-uniform. Image E shows a close up on the degradation. It is apparent that the aluminum film has been disturbed and a majority of it removed from the sample. There are two possible ways this defect could have occurred. The first is that when cutting the samples, I chipped off some of the edge, which then expanded further after time. The second is the presence of some extreme stress under or within the aluminum back contact. This stress was increased by the interaction of the edges with the atmosphere. This caused further stress, which eventually made a rupture in the aluminum film and thus created the defect. It should be stated that aluminum has a fairly active reaction with oxygen. This reaction may have caused the stresses that expanded into defects. Also, the samples originally had a perfect coating of aluminum so the only way it could degrade is the cutting of the samples, oxidation or interaction with the environment, or foreign elements present between layers. However, most of the defects occurred over time, which makes the last two causes the most probable. Any degradation on the edges is most likely due to cutting. Image C shows the tell-tale bubbling caused by stresses in the aluminum layer. These stresses, when strong enough, cause ruptures in the film. Any bubbling present in the film is detrimental and implicates the last two causes stated previously as the culprit. This is a serious complication in our fabrication method and may force us to
move to a less reactive metal back contact. Unless we can make the aluminum layer near perfect, we will have vastly reduced electrical properties of our cells. Image D gives a better overall look but bubbling and scratch marks are present. The scratch marks are most likely caused during measurements due to the nature of our contact with the cell. In an ideal setting, we will limit the possibility of the scratch marks to reduce human caused defects on the cell. Finally, Image F gives a close look at the bubbling effect mentioned previously. This effect is extremely detrimental to electrical properties and is prone to worsen over time and use. As stated above, this needs to either be eliminated by proper maintenance of the sample or a less reactive material needs to be used. As the interaction with the atmosphere or the presence of contaminants between layers may be the cause for the stresses, both options should be rectified to confirm which has the greatest influence.

The use of the optical microscope helped clarify the presence of defects in the aluminum layer but did little to illuminate any defects in the ITO. These defects will be analyzed through use of the SEM. From this, I learned the necessity of limiting all foreign substances from interacting with the samples. Also, I determined the possible need of a difference back contact material. Both of these can be performed with reasonable ease.

4.2 Scanning Electron Microscope (SEM)

By using the SEM, we studied the surface morphology of our cells with greater resolution than the optical microscope. This was done to examine the ITO, aluminum, and p-type silicon wafer.
4.2.1 SEM – ITO Images

Figure 41 shows some of the SEM images of the ITO side of our cell. These images are of the a-Si, a-InGaN, and annealed a-Si samples. We annealed some of the a-Si samples to see if metal induced crystallization would occur. Since it has been shown that tin will diffuse into a-Si and crystallize it, we decided to explore such a phenomena using ITO.

4.2.2 SEM – ITO Images Discussion

Image A shows the crystal structure of the ITO on the a-Si cell. Its contrast with the crystal structure of the ITO on the a-InGaN cell in Image B is interesting. If one looks at the crystal growth, one can see that the a-Si base shows lateral growth while the a-InGaN base shows vertical growth. This structure is most likely based on the interactions of the ITO with the two different base materials. The ITO deposited on glass was examined to see how the base material influences the crystal structure.
Image C shows a weak a-Si sample’s ITO coating. The crystal structure was still apparent and looks as if it was smudged. This lack of defined structure may have been caused by scratching on the sample or something underneath that region of ITO deposition, which restricted the crystalline growth. The second cause is the more likely of the two, since a scratch would have completely removed most of the ITO.

Image D and E show a once- and twice- annealed a-Si sample’s ITO. In Image D, one can see the crystalline structure losing its definition. This is confirmation that the ITO layer is diffusing into the a-Si layer. Image E shows further diffusion of the ITO layer, as the ITO is much less defined. The crystal structure is almost completely gone and the slight defining lines between crystals have begun melding into each other. This is further confirmed in Image F. One can see that the ITO layer is both diffusing into the a-Si layer and melding together. Also, some cracks are visible in the bottom half of Image F. These cracks are most likely caused by stress occurring within the structure of the sample. The annealing has caused diffusion, which is changing the crystal structure of the surface layers of the sample. This diffusion has caused stress across the surface of the sample, which resulted in ruptures or cracks.

4.2.3 SEM – Aluminum and P-type Silicon Wafer Images

We also examined the aluminum back contact and p-type wafer in the SEM. These images are shown in Figure 42.
4.2.4 SEM – Aluminum and P-type Silicon Wafer Images Discussion

In Figure 42, Image A shows the aluminum back contact of one of our samples. Image B zooms in on the back contact to show the crystal structure of the deposited aluminum. The structure resembles small circular crystals placed next to each other. Image C shows the polycrystalline nature of the p-type silicon wafer. One can see the different crystal pockets throughout the structure of the wafer. Image D zooms in on some of these pockets. This structure shows the polycrystalline nature of the wafer.

4.2.5 SEM – Side View, Complete Cell Images

We then looked at a side-view of both our a-Si and a-InGaN samples. These images are shown in Figures 43 and 44.
Image A, of Figure 43, shows the complete a-Si cell from the side with the back contact on the left and ITO on the right. B, C, and D. Zoom in on the cell so each layer can be seen clearly.

4.2.6 SEM – Side View a-Si Images Discussion

Image A, of Figure 43, shows the complete a-Si cell, where the left side is the aluminum back contact, the large dark section is the p-type silicon wafer, then the a-Si layer, and finally the ITO on the right. Some defects are visible in this image but most originate from dust or other contaminants getting on the cell. However, some crack-like defects are visible on the right side of the p-type silicon wafer. These defects either arose during the cutting of the samples or they are caused by stress within the cell. Image B, C, and D all zoom in on the cell to show the layers distinctly. In Image B, a dark line is visible around the middle of the image. This is again visible in Image C and D. This dark line is the interface between the a-Si and the silicon wafer. Images
C and D also show the interface between the a-Si and ITO layers, which is another dark line to the right of the first. Both of these images show the depth of the ITO’s crystal structure. The right side of the cell has obvious crystal shafts stretching from the interface to the surface of the cell. We see similar structures in the a-InGaN’s side-view images in Figure 44.

4.2.7 SEM – Side View a-InGaN Images Discussion

In Figure 44, Image A shows the complete a-InGaN sample. We see the scratch or stress marks in the wafer region of the cell, which is similar to Image A of Figure 43. Images B, C, and D zoom in on the interface between the wafer and the a-
InGan and the interface between the a-InGaN and the ITO. The gray lines are present to help show the location of these interface lines. They are not as defined as those visible in Figure 43 and the reason for this is unclear. We did notice that the a-InGaN sample was more charged up, which contributed to the bright white areas present in the images. However, the layers are noticeable and show that a definite layer of each material is present. The ITO shows its crystal growth in a similar manner to Images C and D of Figure 43, though not as defined. The overall structure is similar to that of the a-Si, which is expected.

**4.2.8 SEM – Defects Images**

Finally, we looked for defects present on our samples. These defects were found on both the ITO and aluminum surfaces. These two sides have the most interaction with the environment and take much abuse during measurements. Some of the defects were caused by our treatment and others were caused by contaminants or issues with our fabrication method. These defects are shown in Figure 45.
4.2.9 SEM – Defects Images Discussion

In Figure 45, Image A shows the edge of one of the samples after cutting. Each layer of the sample is visible. The reason this is a defect is because the cut is not clean. When cutting the samples, the cuts should be as clean as possible so as to avoid stress on the edges of the cell. This has pushed us towards creating a mask to avoid cutting the samples after the deposition stages are complete. Images B and H show the ITO’s crystal structure and how some regions are different than others. The optimal structure would be a uniform, defined crystal structure like those present in Figure 41. However, our deposition method has regions of undefined structure and even spots without any ITO (or so little that the SEM cannot recognize it, the black spots). This issue is one
that needs to be addressed and may require better preparation and cleaning before deposition occurs. Images C and F show some scratches on the ITO surface that were caused during measurements. Also, Image C contains some areas where there is an absence of ITO, which does not resemble the usual scratches visible in Image F. These absences are concerning and need to be avoided in the future by proper cleaning, preparation, and handling of the samples. If these steps do not rectify the issue, further study into the cause of these absences will be necessary. Image D shows the aluminum back contact after it was annealed. During the annealing, the aluminum was under too much stress and ruptures occurred across the surface. These ruptures decrease the electrical properties of the cell by diminishing the conductivity across the back surface. Also, they disrupt the current flow and can cause charge traps beneath the surface, which impede current flow. Image E shows the annealed ITO surface and the presence of ruptures. This was caused by the buildup of stress during the diffusion of the ITO into the a-Si. Image G demonstrates the need for proper cleaning of our p-type silicon wafers. The white blob in the image shows the presence of contaminants on the surface of the wafer. These contaminants can cause shorts, stresses, traps, and other problems with electrical and mechanical properties of the cells. Therefore, they need to be removed to the best of our ability. Finally, Image I shows some scratch marks on the ITO surface and the presence of contaminants. The scratch marks occurred during measurements and are unavoidable due to our setup. The contaminants are caused by exposure to the environment. These contaminants can be reduced by creating an isolated environment for storage and testing.
As can be seen, there are many defects and problems with our samples currently. These defects are the most likely cause of the low current measurements. Most of these problems can be reduced, as stated previously, by proper cleaning, preparing, and handling of the samples. These steps will be addressed when creating new samples in the future. Another solution is the use of a mask so we can avoid the need to cut the samples. By doing this, stress and micro-breaks, throughout the samples, would be avoided. These stresses and micro-fractures could have a detrimental effect on our current values, so they should be treated by the proper steps. These are the easiest methods of attempting to solve the low electrical properties of our cells. If they do not demonstrate a noticeable effect on the electrical properties, further study of the samples will be necessary to determine what else is occurring. This could lead us to determine that our fabrication method is inappropriate for this specific application.

4.3 Transmission Electron Microscope (TEM)

In order to study the morphology, composition, and crystal structure of our samples, we analyzed a thin layer of aluminum, ITO, a-Si, and a-InGaN in the transmission electron microscope. This gave us additional confirmation to the identity of the samples by giving details to the structure and composition.
4.3.1 TEM – Aluminum Layer Images

The first sample we studied was a layer of aluminum on a glass substrate with a sugar coating. The aluminum was dissolved off in water and then placed on a TEM grid to be examined. It was deposited using the commercial sputtering system. The TEM image is shown in Figure 46.

![TEM image of aluminum sample](image_url)

Figure 46 - Shows the TEM analysis of the aluminum layer deposited by the commercial sputtering system.

4.3.2 TEM – Aluminum Layer Images Discussion

Figure 46 shows the TEM image of the aluminum sample. The black sections of the image are individual aluminum crystals. We also studied the electron diffraction pattern using the TEM, which showed the expected pattern for crystalline aluminum. The crystalline nature was expected because aluminum tends to deposited with such a structure. This image along with the EDS of the aluminum sample confirmed that it is indeed to correct element. The EDS did show some points of concern, which are discussed later in this chapter.
4.3.3 TEM – ITO Layer Images

The second sample we looked at was a layer of ITO. It was processed in the same manner as the aluminum. The ITO was deposited using our homebuilt sputtering system. The TEM image is shown in Figure 47.

![TEM image of ITO](image.jpg)

Figure 47 - Shows the TEM image of the ITO layer deposited by our homebuilt sputtering system.

4.3.4 TEM – ITO Layer Images Discussion

Figure 47 shows the TEM image of our ITO. The sample was fairly thick, which is why the image is so dark. Pictures at the edges of the flakes, however, showed the crystalline nature of the ITO. This was what we expected because it mimics the crystal formation we witnessed in the SEM for thicker layers. This means that our deposited ITO is crystalline, which was not confirmed before this measurement. The crystalline structure appears to grow horizontally in these images, similar to the ITO growth on the a-Si samples we observed in the SEM. We are curious about whether the substrate identity effects the growth direction, since the ITO
growth on a-InGaN was vertical. We confirmed the elemental identity of the ITO with our EDS analysis, which is explained later in this chapter.

4.3.5 TEM – a-Si Layer Images

The third sample we looked at was a layer of n-type a-Si. It was processed in the same manner as the aluminum. The a-Si was deposited using our homebuilt sputtering system. The TEM image is shown in Figure 48.

![TEM image of a-Si layer](image)

Figure 48 - The TEM image of the a-Si layer deposited by our homebuilt sputtering system.

4.3.6 TEM – a-Si Layer Images Discussion

Figure 48 shows the TEM image of the a-Si sample. This sample, like the ITO, was a little bit thick; however, we managed to get some strong images at the edges. The sample showed no crystalline structure or growth, which coincides with the fact that this should be amorphous silicon. We did a diffraction pattern measurement on it
and confirmed that no diffraction pattern was made, which implies that the nature of the material is amorphous. An interesting observation was the cracks visible along the edge of the sample. These cracks are directed toward the left into the bulk of the a-Si. We believe these cracks were caused by the breaking of the a-Si when it was dissolved off of the sugar on the glass substrate or when being placed on the TEM grid. These cracks are similar to those present on the side-view of the a-Si cell. This shows the fragile nature of silicon and the necessity for proper handling so as to avoid such cracks or stresses. This reinforces the need to avoid any kind of cutting of the sample so we can avoid stresses or cracks that act as electron-hole recombination sites or shorts in the cell.

4.3.7 TEM – a-InGaN Layer Images

Finally, we looked at a layer of n-type a-InGaN. It was processed in the same manner as the aluminum. The a-InGaN was deposited using our homebuilt sputtering system. The TEM image is shown in Figure 49.

Figure 49 - The TEM image of our n-type a-InGaN layer deposited by our homebuilt system.
4.3.8 TEM – a-InGaN Layer Images Discussion

Figure 49 shows the TEM image of the a-InGaN. The flakes of material showed no defined structure, which is in agreement with its amorphous nature. We performed a diffraction pattern measurement on the sample and only saw the diffraction pattern of the TEM grid, confirming that our substance was amorphous. There are some lines or wrinkles that are visible in the left image of Figure 49. These lines came from our method of removing the a-InGaN off of a glass slide. We did not use the usual sugar method but rather scratched the layer off of a glass sheet, treated it with propanol to make the flakes float, and dipped the TEM grid in it. The act of scratching caused the flakes to wrinkle. These experiments confirmed that the substance was amorphous.

4.4 Energy Dispersive X-Ray Spectroscopy (EDS)

In order to confirm the elemental composition of the different materials we deposited, we used the EDS function of one of the SEM machines. This allows us to determine the presence of contaminants caused by our deposition system, caused by environmental exposure, and the effect of defects on the cell’s surface. Determining each of these characteristics gives us insight into the effectiveness of our fabrication method. To create an effective photovoltaic, we must limit the presence of contaminants to the best of our ability, so we must know what contaminants are present, determine what their origin is, and decide the best method of avoiding the contaminants in the future. We spectrally analyzed single layers of ITO, aluminum, a-Si, a-InGaN, and the ITO side of an a-Si cell.
4.4.1 EDS – Aluminum Layer Image

The first material we examined was a layer of aluminum on a glass substrate and an annealed layer of aluminum on a p-type silicon wafer, Figures 50 and 51. Both of these layers were deposited in our commercial sputtering system and gave us information about the contaminants present within the system.
Figure 5.1 - The spectral analysis of annealed aluminum on the P-type silicon wafer. The second spectrum shows the presence of stainless steel contamination.
4.4.2 EDS – Aluminum Layer Discussion

Figure 50 shows the different elements present on the aluminum on glass sample. At first the high densities of silicon, oxygen, sodium, calcium, and magnesium present on the cell were concerning; however, these elements are used in the fabrication of the glass substrate. Since our layer of aluminum is so thin, the energy dispersive X-rays react with the glass substrate beneath. This is why we see the different elements composing the glass in the spectrum. The presence of potassium is odd but it could be one of the extra additives in the fabrication of glass or a peak that coincides with another of the elements we found. Figure 51 was the aluminum layer deposited on the p-type silicon wafer and annealed. The SEM image of the sample is marked with a 1 for the first spectrum and a 2 for the second. This was done with the point and shoot option of the software. The first spectrum shows the presence of silicon, aluminum, and carbon. The carbon is the only unexpected element present. It may have gotten on the sample through oils on my fingers, when moving the cell, from the graphite blocks within our vacuum furnace, or the tape supporting the sample. The second spectrum is concerning because it shows the presence of stainless steel on the sample. Stainless steel is composed of iron, chromium, and nickel. Its presence on the sample means that the plasma in our commercial system is interacting with the stainless steel walls of the chamber and depositing it upon our sample. This is detrimental and needs to be rectified as soon as possible. A possible solution would be decreasing the intensity of the plasma in the chamber.
4.4.3 EDS – ITO Layer Image

The second material we analyzed was our indium tin oxide layer. This layer was deposited on a glass substrate. The deposition was done by our homebuilt sputtering system. Figures 52 and 53 show two different images of the ITO sample and the elements found at those spots.
Figure 53 - The spectral analysis of a layer of ITO. Shows the different elements present upon the sample.

ITO_Single_Layer.png
4.4.4 EDS – ITO Layer Discussion

Figure 52 showed the presence of elements similar to those in Figure 50. These elements are those composing the glass substrate. Aluminum, which was not associated with glass in the initial discussion, is actually one of the additives used in the fabrication of glass. The nitrogen peak was from the nitrogen gas used to create the plasma in the sputtering chamber. The presence of carbon is probably caused by oils or the tape supporting the sample. We see a high density of indium, which was expected; however, there is no presence of tin on the sample. This is for two reasons. First, tin is right next to indium in the periodic table and therefore has a similar peak, so some of the indium peaks we see are probably tin as well. Second, the sputtering target’s composition of tin is between 5-10%, which would cause the tin content to be less noticeable. Figure 53 shows similar elements as Figure 52 but silicon and calcium are the only elements composing glass that are present. This is most likely due to the thickness of ITO at this spot.

4.4.5 EDS – a-Si Layer Image

We analyzed a layer of our n-type a-Si on a glass substrate. This deposition process was done in the homebuilt sputtering system and the spectral analysis is shown in Figure 54. Since our glass substrates are made of silicon, we had to change our substrate. This required us to remove the a-Si from the glass substrate (pieces that dissolved off of our a-Si film on sugar) and place them onto a brass substrate. A piece of tape was placed on the brass substrate and the a-Si pieces were stuck to it. This allowed us to avoid seeing the silicon from the glass in the spectral analysis.
4.4.6 EDS – a-Si Layer Discussion

As stated above, we changed our substrate to do the analysis on the a-Si sample. Brass is composed of copper and zinc, which we see in the top sample in Figure 54. In the bottom sample, we see some copper but no zinc, which is probably because this was toward the center of the tape whereas the first was toward the edge (meaning better chance of interacting with the brass substrate). The top image also showed some aluminum, which is from the actual stand used to support the sample in the SEM. The presence of carbon is due to the tape being used and is not concerning. However, the silver present in the top image is odd and we believe it to come from the previous use of the brass substrate. Other than these elements, we see the expected oxygen and silicon presence. This confirms that our a-Si is being deposited correctly and without many contaminants.

4.4.7 EDS – a-InGaN Layer Image

The last of the single materials we analyzed was the n-type a-InGaN. This material was deposited by the homebuilt sputtering system and the spectral analysis is shown in Figure 55. The sample was deposited on a glass plate with a greater thickness than usual. Aluminum triangles were placed on each corner for it to be analyzed in the Hall Effect machine. Everything was done the same as our previous samples except these two differences.
4.4.8 EDS – a-InGaN Layer Discussion

The spectral analysis of our a-InGaN layer showed the expected results. We found the presence of aluminum from the corner of the sample and silicon and oxygen from the glass substrate. Due to the thickness of the a-InGaN layer, we did not see the presence of some of the other elements used in fabricating the glass sample. We found
both indium and gallium on the sample. The density of indium was much greater than that of gallium, which is what we expected because the target we are using has higher indium content. There were no unaccounted for elements on this sample.

4.4.9 EDS – a-Si, ITO Side, Complete Cell Image

Finally, we analyzed the ITO side of a complete a-Si cell. We found a defect area on the cell and did a spectral analysis of said area, shown in Figure 56. This allowed us to see how the defect affected the composition of the surface layer.

![Figure 56](image-url)
4.4.10 EDS – a-Si, ITO Side, Complete Cell Discussion

Figure 56 shows a defect on the a-Si sample. The only element of concern present on the sample is carbon, though this was probably caused by oils from human interaction or the tape being used to support the sample. It is quite obvious to see that the defect shows that the ITO, mainly the indium presence, is removed from the sample’s surface. The higher density of silicon at that spot is evidence of the a-Si layer beneath the ITO layer. The oxygen content is fairly uniform with some loss in the defect area. The uniformity is caused by the natural oxide layer that tends to grow on silicon and the oxygen presence of the ITO.

4.4.11 EDS – Conclusion

Looking at all of the single layers of materials deposited by the homebuilt system and comparing them with the aluminum deposited by the commercial system, we determined that the homebuilt system was fairly resistant to depositing any unnecessary elements on the samples. However, the commercial system showed signs of stainless steel contamination, which led us to believe it should not be used for fabrication. The best way to avoid using the commercial system is the addition of a third chamber to our homebuilt system, as well as a built in furnace. This would allow for the complete cell to be fabricated, while decreasing the chances of contamination.
Chapter 5: Conclusions and Future Work

Our fabrication method needs some adjustments, but I believe that most of the issues of low current and efficiency are caused by contaminants and the thickness of the ITO and N-type material. With proper preparation, handling, and treatment of the samples, I believe we can vastly improve the current and efficiency values. Also, depositing thinner layers may assist in increasing the efficiency and current. However, if this adjustment will increase efficiency by three to four orders of magnitude (to reach 1%), is still questionable. There may be some limit to the efficiency we can achieve when utilizing plasma sputtering, as our fabrication technique. We have limits on how well we can control the thickness and the interfaces between layers. Bad interface layers can have negative effects on the electrical properties of the cell and may be strong enough to keep our efficiency below the 1% mark.

We can determine whether the fabrication technique has a natural limit by using proper preparation, handling, and treatment techniques, as well as proper layer thickness. To do this, we would have to build a third chamber in our homebuilt sputtering system, so the sample does not have to be shifted after the aluminum deposition is done. This will keep the sample from the environment during the whole fabrication process. We would also need to properly prepare the p-type silicon wafer by removing most of the natural oxide with an acid bath. A mask would need to be used, during the fabrication process, to avoid the need of cutting the samples with the diamond tipped knife. We could use a complete wafer as the substrate and make cells on different regions of it. By avoiding cutting the sample, we reduce the risk of micro-
fractures and stress being induced within the cell. We would decrease the time of
deposition for the ITO and N-type layers creating thinner layers. All handling of the
samples needs to be done with gloves on and should be done quickly so as to avoid
any environmental contaminants from interacting with the sample. Finally, when
analyzing the electrical properties of the cell, safer contacts need to be made. The
current contacts scratch off the top and bottom layers of the cell. This reduces
uniformity and in turn, results in bad electrical properties. If possible, a sealed
chamber made for testing the sample would be ideal. In conclusion, if these changes
do not result in efficiency over 1%, we can declare our fabrication method as being
limited beneath the 1% mark.
References


Ghazai, A., Aziz, W., Hassan, H., & Hassan, Z. (2012). Quaternary n-
Al$_{0.08}$In$_{0.08}$Ga$_{0.84}$N/p-Si-based solar cell. *Superlattices and Microstructures*, 51(4), 480 - 485.


Appendix A: Monochromator Data

Batch 2 a-Si – Activation Spectrum
Graph A2 – The activation spectrum of two a-InGaN cells.
Appendix B: Efficiency Data

*Commercial Cells – Efficiency, Current vs. Voltage, and Power vs. Current*

<table>
<thead>
<tr>
<th>Important Electrical Values</th>
<th>Normal</th>
<th>Triangle</th>
<th>Normal</th>
<th>Square</th>
<th>Water</th>
<th>Normal &quot;&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power Voltage (V)</td>
<td>0.2465</td>
<td>0.2215</td>
<td>0.2345</td>
<td>0.299</td>
<td>0.2645</td>
<td>0.24875</td>
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<tr>
<td>Max Power Current (A)</td>
<td>0.00243</td>
<td>0.0715</td>
<td>0.07545</td>
<td>0.09545</td>
<td>0.0833</td>
<td>0.06125</td>
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<td>Open-Circuit Voltage (V)</td>
<td>0.4545</td>
<td>0.418</td>
<td>0.4645</td>
<td>0.5275</td>
<td>0.5155</td>
<td>0.5185</td>
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<tr>
<td>Short-Circuit Current (A)</td>
<td>0.00467</td>
<td>0.1381</td>
<td>0.1439</td>
<td>0.1568</td>
<td>0.1548</td>
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<tr>
<td>Fill Factor</td>
<td>0.28221002</td>
<td>0.27473677</td>
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<td>0.34504727</td>
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<td>0.256410499</td>
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<tr>
<td>Max Power Produced (W)</td>
<td>0.000599</td>
<td>0.0158594</td>
<td>0.01793</td>
<td>0.0285955</td>
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<td>0.015235938</td>
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<tr>
<td>Power In (W)</td>
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<td>0.338237657</td>
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<tr>
<td>Efficiency</td>
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<td>0.04188045</td>
<td>0.0523094</td>
<td>0.0972213</td>
<td>0.0667041</td>
<td>0.045045066</td>
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<tr>
<td>% Efficiency</td>
<td>0.17709294</td>
<td>4.18804493</td>
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<td>9.72212971</td>
<td>6.6704134</td>
<td>4.504505756</td>
</tr>
</tbody>
</table>

Graph B1 – The current versus voltage curve of all of the different commercial cells we owned. Two of the cells were measured with a water cover (Water and Normal "") and the rest were without a water cover. Commercial Cell, Water is also in the Normal category. Normal, Triangle, and Square were the three different commercial cells we owned. The ‘ or “ just means that same cell with measurements repeated.
Graph B2 – The power versus current curve of all of the different commercial cells we owned. Two of the cells were measured with a water cover (Water and Normal ") and the rest were without a water cover. Commercial Cell, Water is also in the Normal category. Normal, Triangle, and Square were the three different commercial cells we owned. The ‘ or " just means that same cell with measurements repeated. Note how small the Commercial, Normal curve is in comparison to the others (bottom left corner).

**Batch 1 a-Si – Efficiency, Current vs. Voltage, and Power vs. Current**

<table>
<thead>
<tr>
<th>Important Electrical Characteristics</th>
<th>Group 1</th>
<th>Group 1′</th>
<th>Group 2</th>
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</thead>
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<tr>
<td>Max Power Voltage (V)</td>
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<td>0.00025</td>
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<td>Max Power Current (A)</td>
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<td>0.0000002</td>
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<td>Open-Circuit Voltage (V)</td>
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<tr>
<td>Short-Circuit Current (A)</td>
<td>0.000003</td>
<td>0.000004</td>
<td>0</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>0.177029361</td>
<td>0.215568862</td>
<td>0</td>
</tr>
<tr>
<td>Max Power Produced (W)</td>
<td>0.0000000051</td>
<td>0.0000000072</td>
<td>0.0000000000</td>
</tr>
</tbody>
</table>
Current vs. Voltage

Graph B3 – The current versus voltage curves of some of the Batch 1 a-Si cells.

Power vs. Current

Graph B4 – The power versus current curves of some of the Batch 1 a-Si cells.
Batch 2 a-Si – Efficiency, Current vs. Voltage, and Power vs. Current

<table>
<thead>
<tr>
<th>Short-Circuit Current (A)</th>
<th>Open-Circuit Voltage (V)</th>
<th>Max Power Voltage (V)</th>
<th>Max Power Current (A)</th>
<th>Max Power (W)</th>
</tr>
</thead>
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</tbody>
</table>

**Table B3:** The important electrical characteristics of some of the batch 2 a-Si samples.
Graph B5 – The current versus voltage curves of some of the Batch 2 a-Si cells.

Graph B6 – The power versus current curves of some of the Batch 2 a-Si cells.
a-InGaN Cells – Efficiency, Current vs. Voltage, and Power vs. Current

Table B4 - The important electrical characteristics of some of the a-InGaN cells.

<table>
<thead>
<tr>
<th>Important Electrical Characteristics</th>
<th>Batch 1 #1</th>
<th>Batch 1 #2</th>
<th>Batch 1 #3</th>
<th>Batch 1 #4</th>
<th>Batch 2 #1</th>
<th>Batch 2 #2</th>
<th>Batch 2 #3</th>
<th>Batch 2 #4</th>
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</thead>
<tbody>
<tr>
<td>Max Power Voltage [V]</td>
<td>0.0605</td>
<td>0.067</td>
<td>0.02</td>
<td>0.029</td>
<td>0.0265</td>
<td>0.0935</td>
<td>0.0205</td>
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<tr>
<td>Max Power Current [A]</td>
<td>0.0000006</td>
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<tr>
<td>Open-Circuit Voltage [V]</td>
<td>0.1055</td>
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<tr>
<td>Short-Circuit Current [A]</td>
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<tr>
<td>Fill Factor</td>
<td>0.264673715</td>
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</tr>
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<td>Max Power Produced [W]</td>
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<tr>
<td>Power In [W]</td>
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<td></td>
</tr>
<tr>
<td>Efficiency</td>
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<td>3.02804E-05</td>
<td>9.27497E-06</td>
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</tr>
<tr>
<td>% Efficiency</td>
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<td>0.002319655</td>
<td>3.02804E-05</td>
<td>9.27497E-06</td>
<td>2.72455E-05</td>
<td>0.003391743</td>
<td>8.84264E-08</td>
<td></td>
</tr>
</tbody>
</table>

Current vs. Voltage

- a-InGaN Cell, Batch 1 #1 – a-InGaN Cell, Batch 1 #2 – a-InGaN Cell, Batch 1 #3 – a-InGaN Cell, Batch 1 #4 – a-InGaN Cell, Batch 2 #1
- a-InGaN Cell, Batch 2 #2 – a-InGaN Cell, Batch 2 #3 – a-InGaN Cell, Batch 2 #4

Graph B7 – The current versus voltage curves of some of the a-InGaN cells.

Power vs. Current

- a-InGaN Cell, Batch 1 #1 – a-InGaN Cell, Batch 1 #3 – a-InGaN Cell, Batch 1 #4 – a-InGaN Cell, Batch 2 #1
- a-InGaN Cell, Batch 2 #2 – a-InGaN Cell, Batch 2 #3 – a-InGaN Cell, Batch 2 #4

Graph B8 – The power versus current curves of some of the a-InGaN cells.
Commercial Silicon Diode – Efficiency Table, Current vs. Voltage, and Power vs. Current

Table B5 - The important values of a commercial silicon diode.

<table>
<thead>
<tr>
<th>Important Values</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Max Power Voltage (V)</td>
<td>0.2965</td>
</tr>
<tr>
<td>Max Power Current (A)</td>
<td>0.00001845</td>
</tr>
<tr>
<td>Open-Circuit Voltage (V)</td>
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<tr>
<td>Short-Circuit Current (A)</td>
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<td>Max Power Produced (W)</td>
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<td>Power In (W)</td>
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<tr>
<td>Efficiency</td>
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<tr>
<td>% Efficiency</td>
<td>2.237392638</td>
</tr>
</tbody>
</table>

Graph B9 – The current versus voltage curve of a commercial silicon diode.
Graph B10 – The power versus current curve of a commercial silicon diode.
Figure C1: The voltage and current mapping of Device 2.3 in a HfO_N cell, which shows the voltage and current pockets present on the sample. The top value is the voltage in V and the bottom value is the current in mA.