Measurement of Light Capture in Solar Cells from Silver- and Tin-Plated Patterned Bus Bars

by

Christine Eve Winiarz

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Submitted to the Department of Mechanical Engineering
on May 11, 2007 in partial fulfillment of the
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as recommended by the Department of Mechanical Engineering

Abstract

Bus bars on solar cells shade silicon from light. When the bus bars are patterned, they can reflect light back onto the silicon using total internal reflection. These patterned bus bars are tin plated and produce 1-2.5% improvement in module efficiency [6]. There is a potential for even greater improvement by using higher reflectivity metal plating on the bus bars. Silver is the most reflective of all metals, but is also very expensive. We tested to see if silver would actually be as reflective as published values and if silver could redirect a substantial amount of light using total internal reflection. We found that silver plating followed the published spectural dependence curve with little deviation, and would reflect 18.4% more light than the published values for tin. Plating 2.24 microns resulted in 94.9% of reflected light undergoing TIR; the most reflected light of any tested material. Finally, given the current cost of silver is $430 per kilogram and the variable cost of a solar cell is $2 per Watt, the maximum allowable thickness we could afford to plate is 44.8 microns. In our testing, plating as little as 0.35 microns produced a very high light capture. The benefit of silver plating patterned bus bars far outweighs the material costs.

Thesis Supervisor: Emanuel Sachs
Title: Fred Fort Flowers and Daniel Fort Flowers Professor of Mechanical Engineering

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Acknowledgments

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I would like to give a special thanks to Professor David Parks in Mechanical Engineering. Professor Parks took the time out of his schedule to discuss my thesis with me and help me understand the mechanics of my project. He also urged me to approach my project from different perspectives and gave me tools to understand. He kept my interest fresh by showing me relationships between my work and current work in the industry. In short, I really appreciated his council throughout the course of this project.

I would also like to thank Tim McClure in the Center for Materials Science and Engineering for his help training and operating the Diffuse Reflectance Accessory. His knowledge of the machinery and lab helped me to understand the experiments and find the diagrams I needed. Thanks to Angie Locknar in the MIT Libraries for her responsiveness and help in finding sources and statistics. When she wasn't sure of an answer, she continued to search until we found the data I was looking for.

I would also like to thank my friends and family for their constant support throughout this project and my term at MIT. To my close 'godzilla' friends, thank you for being with me every step of the way. You are truly some of the best people I have ever known, and I am lucky to be one of you. To my Sigma Kappa sisters, thank you for helping me grow in ways I never thought possible, and thank you for making me a part of something bigger than myself. To my family, thank you for your support, patience, and love. I feel completely blessed to have such wonderful parents, such a caring sister, and such a close-knit family. Thank you all for always being there for me.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

When solar cells are manufactured, their bus bars are plated with tin for soldering purposes. When incident light hits these bus bars, it is reflected away from the solar cell. Prior research by Emanuel Sachs and Jim Serdy proposes the patterning of bus bars to reflect the light back down onto the silicon panel using total internal reflection. The light would hit the bus bar, but reflect at an angle. It would then be redirected back down to the solar cell by the glass. This method allows for the recapture of a significant amount of light, enough to increase the solar cell's efficiency by 2-4% [6]. However, the tin coating is imperfect. The choice of tin as the bus bar coating is of convenience rather than optimization. Silver is the most reflective of all metals, but is also very expensive. This thesis will test if silver plating could be a viable alternative to tin plating on solar panel bus bars. In pursuing this question, we will test the reflectivity of the rolled materials, and measure their angular reflectances. In addition, this thesis will determine if the additional benefit provided by the more reflective metal is worth the additional cost.

Chapter 2

Background

2.1 Anatomy of a Solar Cell

A solar cell is a form of renewable energy that converts light into energy. Silicon is a semi-conducting material, so when photons hit the silicon, they are absorbed and excite the silicon electrons. Only photons at specific wavelengths will be able to excite electrons. The photon must have greater energy than the band gap in the silicon to excite an electron, or it will pass simply pass through the material. If it has too much energy, it will excite an electron but give off heat as well. The photons that can excite electrons in silicon have wavelengths between 350 and 1200 nanometers. A schematic of a solar cell is shown in Figure 2.1.

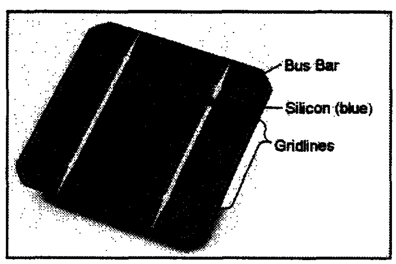

Figure 2.1: Schematic of a Solar Cell

When the electron is excited, or knocked loose from its atom, it flows through the material towards the gridlines. The positive charge created by the missing electron is called a hole, and will flow in the opposite direction of the electron [6]. The majority of solar panels in use today send their electrons to the surface, or in the direction from which the photons came. The gridlines and bus bars are positioned to gather the electrons to use them as energy. Unfortunately, the positioning of the bus bars and gridlines on the top of the cell shades 4-8% of the silicon from light [6]. When light hits these obstructions, it is reflected away from the silicon and decreases the efficiency of the solar cell.

2.2 Optimization and Efficiency

Bus bars are designed to optimize the fill factor, FF, and short circuit current, I_{sc}. The fill factor is the current density at maximum power point [7].

$$FF = \frac{V_{max} * I_{max}}{V_{opencurrent} * I_{shortcircuit}} \tag{2.1}$$

$$Power_{max} = V_{max} * I_{max} \tag{2.2}$$

Increasing the size or width of the bus bar can lead to decreased resistance and increased fill factor which can improve energy output. Unfortunately increasing this size will also decrease energy output by an increase in shading and decrease in current. Bus bars are very carefully optimized for size.

Even with optimized bus bars, commercially sold solar cells are only 14-16% efficient, with the highest attainable levels only at about 30%[6]. The energy conversion efficiency is the percent of power converted from light to electrical energy [5]. Recent research, such as the patterning of bus bars by Emanuel Sachs and James Serdy, works to increase this efficiency.

2.3 Research on Bus Bars

The research on bus bars by Emanuel Sachs and James Serdy describes a pattern of shallow grooves with sidewalls positioned 30° from horizontal [6]. Incident light refracts at the glass layer, contacts the patterned bus bar, and reflects back up towards the surface of the glass. The minimum angle for TIR is approximately 42° with respect to normal, and if the ray is at an angle of greater than or equal to 42°, the light is reflected back down to the solar cell. The groove angle of 30° allows for normally incidental light to contact the surface of the glass at 60° and thus be internally reflected. This patterned design leads to 1-2.5% improvement in module efficiency [6] and could possibly be increased further by using a higher reflectivity metal plating on the bus bars.

The Figures below depict TIR. EVA stands for ethylene-vinyl acetate and is an encapsulant with the same index of refraction as the glass. Figures 2.2 and 2.3 show normally incident light when it contacts the un-patterned and patterned bus bars, and Figures 2.4 and 2.5 depict incident light.

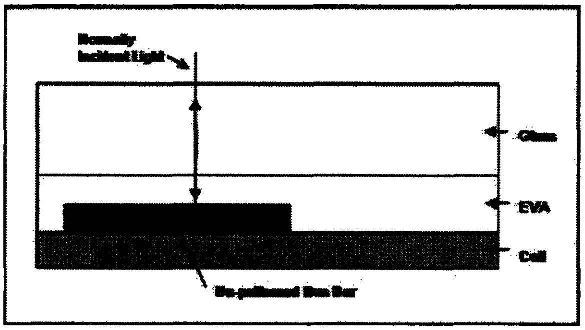

Figure 2.2: Normally incident light reflect off of an un-patterned bus bar.

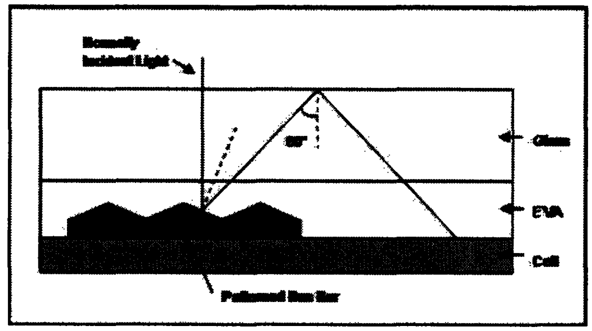

Figure 2.3: Normally incident light redirected to the silicon cell via total internal reflection (angles not to scale)

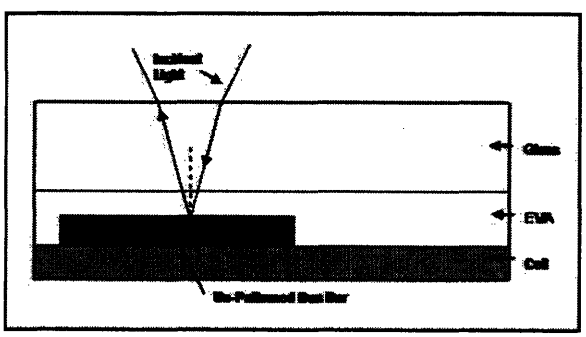

Figure 2.4: Incident light reflect off of an un-patterned bus bar

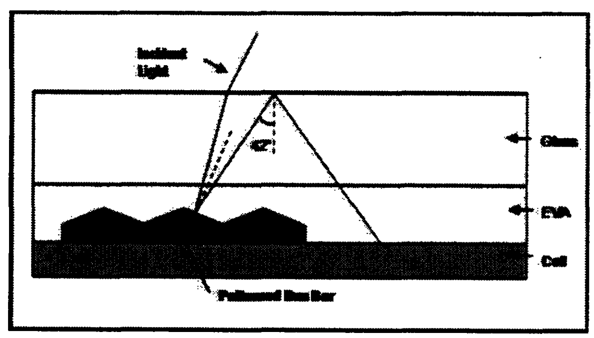

Figure 2.5: Incident light redirected to the silicon cell via total internal reflection (angles not to scale)

Chapter 3

Experimental Procedure

3.1 Metallic Reflectivity

The reason that tin is used to coat the copper bus bars is because of its soldering properties. It is not the most reflective metal, and, in the range of wavelengths applicable to excite silicon electrons, it only has a published reflectivity of 81.2% to 83.0% [3]. Silver is the most reflective of all metals and can reflect 86% to 99% of light [3] in the given wavelengths. In this experiment, an opaque film of silver is applied to the copper bus bar to measure reflectivity.

3.2 Electroplating 101

Electroplating is the process of coving an object with a thin layer of material by electro-chemical deposition [4]. Using an electric current, positive metal ions move from the anode through a liquid solution and deposit onto the cathode. The cathode is the negatively charged work piece being plated, and the anode is the metallic source of the plate, in our case a piece of silver. The plating solution is made up of metallic salts which are dissolved in distilled water [4].

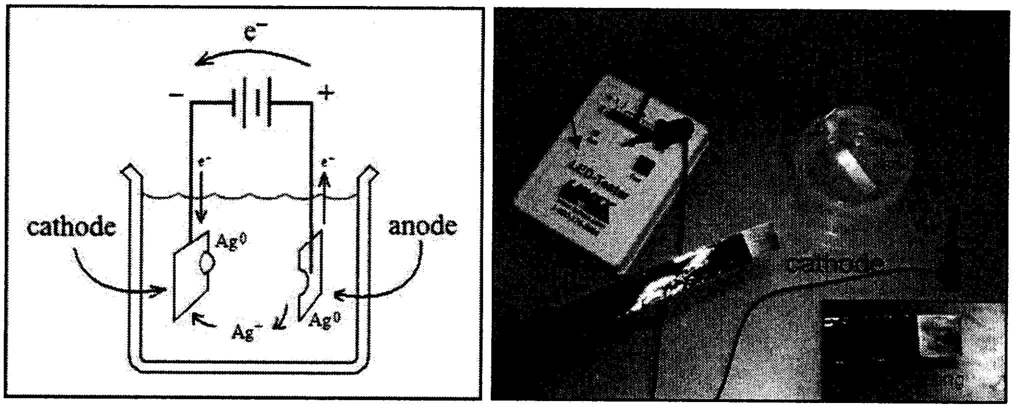

Figure 3.1: Chemical diagram[1] and experimental setup of silver electroplating

The process of electroplating involves setting up the experiment in the display above. Attach the silver anode to the positive lead of the rectifier, and the work piece to the negative lead [4]. Turn on the rectifier long enough to achieve the desired plate.

3.2.1 Verifying Plating Results

For this experiment, we used Technic Inc 1025 Silver Electrolyte Solution, Semi-Bright, as our solution and a Lumex LED-Tester as our 10 $\frac{mA}{cm^2}$ current source. In order to plate a specific thickness onto our Alfa Aesar 0.127 mm thick Copper Foil, we needed to calculate and verify the thickness plated per unit time.

Below is the derivation of how to calculate the amount plated per unit time. Equation 3.5 gives us the expression for volume plated per unit time, and Equation 3.6 gives us thickness plated per unit time.

$$Q[C] = i[A] * t[s] \tag{3.1}$$

Charge [Coulombs] is equal to the current [Amps] multiplied by time [seconds]

$$Q[C] = F[\frac{C}{mol}] * n[mols] \tag{3.2}$$

Charge [Coulombs] is equal to Faraday's Constant: 69,485.4 $[\frac{Coulombs}{mols}]$, multiplied by number of electrons

$$F * n = i * t \tag{3.3}$$

Combining Equations 3.1 and 3.2

$$\frac{V[cm^3]}{mol} * F[\frac{C}{mol}] * n = \frac{V[cm^3]}{mol} * i[A] * t[s] \tag{3.4}$$

Multiplying Molar Volume by both sides

$$\frac{V[cm^3]}{t[s]} = \frac{i[A]}{F[\frac{C}{mol}]} * \frac{Vol[cm^3]}{mol} \tag{3.5}$$

Volume plated per unit time is equal to the current over Faraday's Constant, times the molar volume

$$\frac{x[cm]}{t[s]} = \frac{i[A]}{F[\frac{C}{mol}]} * \frac{Vol[cm^3]}{mol} \tag{3.6}$$

If we use current per unit area instead of current, we can find the thickness plated per unit time

Substituting values for our experiment into Equation 3.6 above, we are able to determine the thickness plated per unit time of our experiment.

$$\frac{x[cm]}{t[s]} = \frac{10[mA]}{69,485.4[\frac{C}{mol}]} * \frac{10.28[cm^3]}{mol} \tag{3.7}$$

$$\frac{x[cm]}{t[s]} = 1.06467 * 10^{-6}[\frac{cm}{s}] \tag{3.8}$$

By painting wax on part of the copper strip, We were able to very carefully and accurately isolate a 1 cm by 1 cm square section. We silver plated this copper area for 900 seconds and used Equation 3.8 to calculate the thickness of plate to be $9.58 * 10^{-4}[cm]$. Taking this thickness and multiplying it times the total exposed area of $2cm^2$, We calculated the total volume of silver plated onto the copper would be $1.916 * 10^{-3}[cm^3]$. Silver has a density of $10.49[\frac{g}{cm^3}]$, which means the total calculated mass transfer was $2.010 * 10^{-2}[g]$.

Measuring the weight on an Explorer Ohaus Corporation Digital Scale before and after the plating yielded the results below in Table 3.1.

Table 3.1: Weight of Cathode Before and After plating

Initial Weight [g]	Final Weight [g]
1.2202	1.2344
1.2202	1.2331
1.2197	1.2327
1.2198	1.2325
1.2199	1.2322
1.21998 ± 0.000205	1.23298 ± 0.000858

In Table 3.2, we compare our measured mass transfer results with our calculated estimates. From this data, we can determine that the plating efficiency is approximately between 60 and 70%.

Table 3.2: Measured vs. Calculated Mass Transfer

Measured Mass Transfer	0.013 ± 0.001063 [g]
Calculated Mass Transfer	0.020103 [g]
Plating Efficiency	59.4% to 70.0%

3.3 Patterning the Bus Bars

After verifying our electroplating, we are able to plate ribbons of the size and shape of a bus bar. We also use off-the-shelf ribbon with silver and tin plating already on it. In order to redirect the light back to the solar cell, we must pattern the surface. Prior work created a rolling mandrel with symmetric triangular grooves and an included angle of 124° [6]. The pre-made silver ribbon used in testing is Ulbrich Precision Flat Wire Silver Plated Copper Lot #AA 70194. The pre-made tin ribbon used is Ulbrich Precision Flat Wire Tin Plated Copper Ribbon Lot #AA 51607. The solder on the ribbon is actually only 96.5% tin and has a 3.5% silver component.

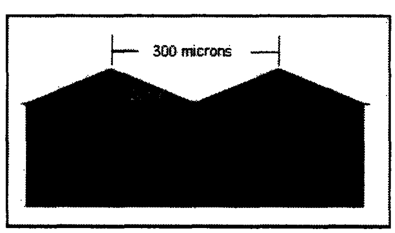

Figure 3.2: Cross Section of one groove on a patterned Bus Bar

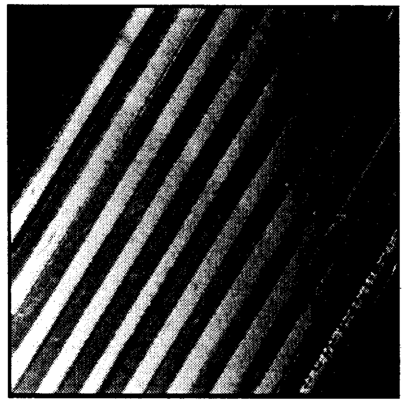

Figure 3.3: Magnified picture of a patterned Bus Bar taken by a Digital Pixera Microscope Camera mounted on a Nikon SMZ-U Microscope

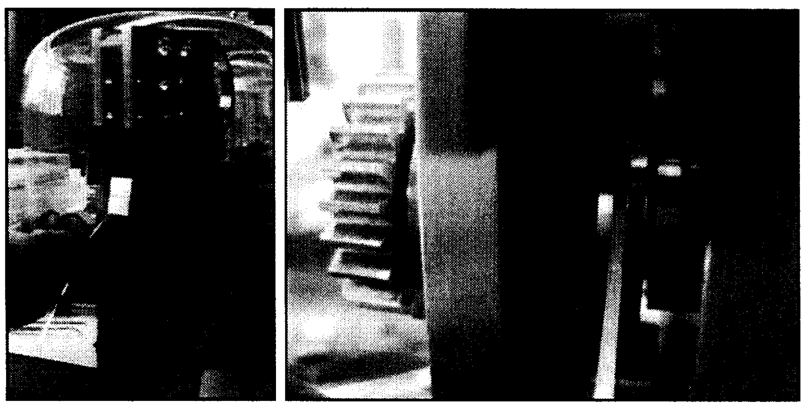

Figure 3.4: The above figures show the rolling mandrel mechanism. The silver plated ribbon is being fed into the rollers and will emerge patterned

3.4 Measure Reflectivity

3.4.1 Diffuse Reflectance Accessory

The equipment used to determine the amount of light reflected is an Integrating Sphere, also known as a Diffuse Reflectance Accessory. The Diffuse Reflectance Accessory (DRA) was used on the Cary 500i UV-Vis-NIR spectrophotometer. The main component of the DRA is a white sphere with ports for the sample, the light to enter, and a detector. Light at a specific wavelength enters through the port and is reflected off of the sample. It bounces around in the sphere until it reaches the detector. The detector measures how much light reaches it for any particular wavelength. The DRA has two settings 'D' and 'S.' Position 'D' measured diffuse reflectance only by positioning the sample perpendicular to the incident light. This allows for any specular component to be reflected out of the light entrance hole. Position 'S' measures total reflectance by positioning the sample at an angle 3°20min. The specular component of the light will not escape, and the total reflectance will include diffuse and specular reflectance [2].

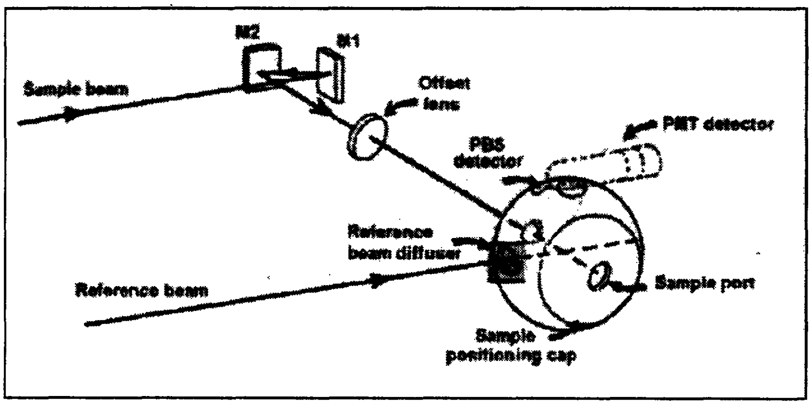

Figure 3.5: The optical design of the Diffuse Reflectance Accessory [2]

Following along with the optical design above, the sample beam hits Mirror M1 and is then reflected to M2. The beam travels through the lens and is focused into the entrance port and onto the sample port. The reflected beam is diffused throughout the sphere before being measured by the detector. The reference beam enters the sphere directly through the reference port and is dispersed [2]. The removable end cap has two positions shown in the cross section figures below.

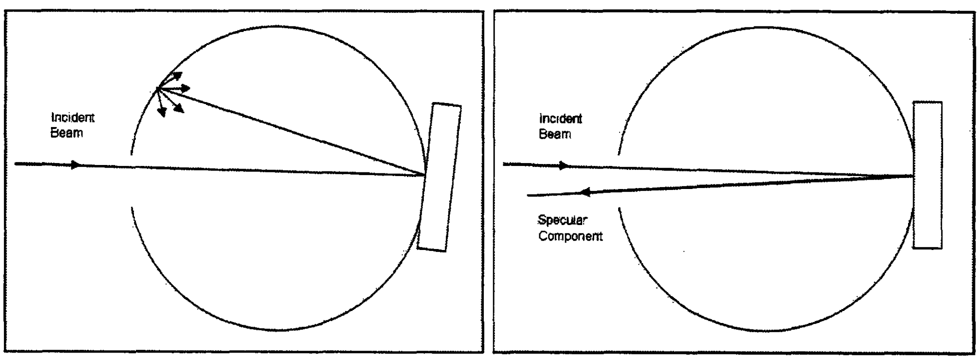

Figure 3.6: A cross section of the Integrating Sphere. The incident light enters at the left side and contacts the sample. The left figure indicates the position of the sample in the Specular setting, and the right figure depicts the Diffuse positioning.

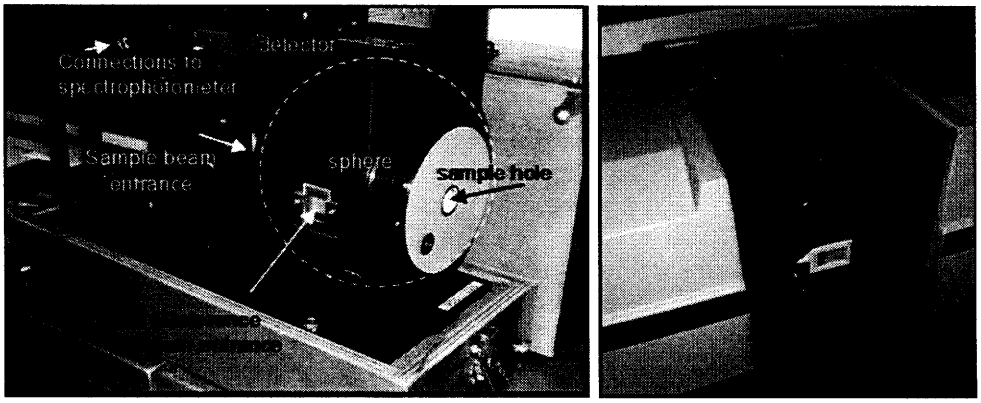

Figure 3.7: The Diffuse Reflectance Accessory. The left figure shows a picture of the accessory with parts labeled. The right picture shows the accessory installed inside the Cary Spectrophotometer.

3.4.2 Serdy Angular Reflectance Apparatus

The Serdy Angular Reflectance Apparatus is a machine designed and built by Emanuel Sachs and James Serdy. The machine measures the intensity of reflection of the sample as a function of the angle of reflection. The Laser, a model m780-51 with 650 nm wavelength, is adjusted by height and angle to shine at the sample. The sample is held in place by two magnets, and can be positioned by micrometers to an exact location. The sensor moves around the sample 180° and measures the intensity of reflection. The sensing platform has two photo sensors one of 3mm wide and the other of 1 mm wide. The aperture is masked on the smaller one for greater resolution in measurement. The sensing platform also carries a potentiometer, and sends the location of the sensor to channel 1 of the oscilloscope. For this experiment we used a Tektronix TPS 2014 digital oscilloscope to measure the reflective intensity. The sensor itself sends two outputs to the oscilloscope, one with the reflective intensity, and another magnified at 10 times that intensity. The controls allow for the sensing platform to sweep to the left, right, or stop, as well as to power the apparatus. The laser has its own on-off switch. All important surfaces are matte black to prevent reflection, and the traces are taken in total darkness.

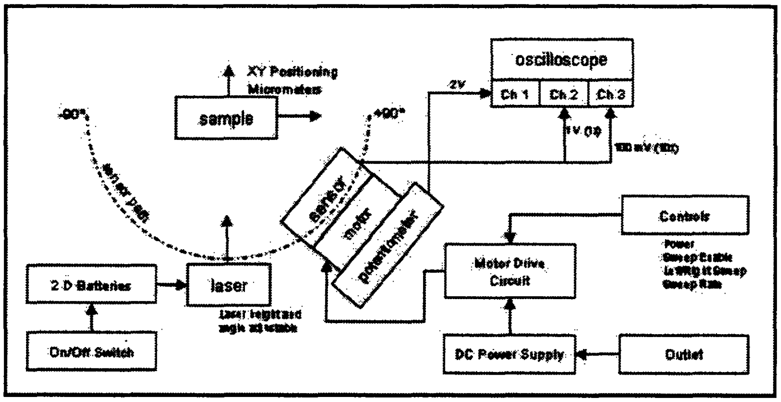

Figure 3.8: A block diagram of the Serdy Angular Reflectance Apparatus

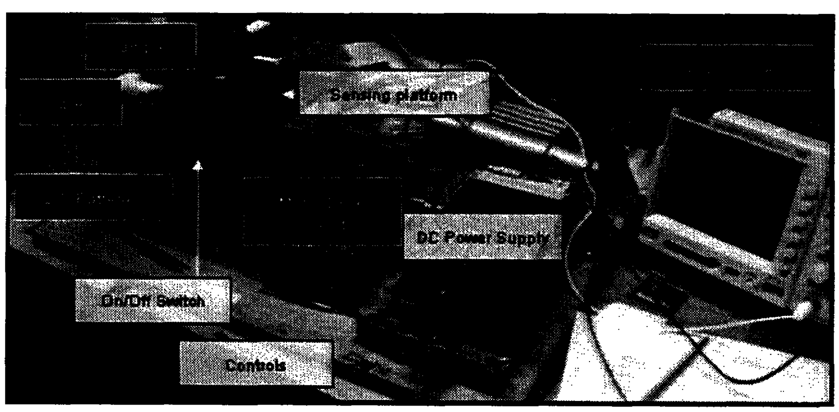

Figure 3.9: The Experimental setup of the Serdy Angular Reflectance Apparatus

Chapter 4

Results

4.1 Integrating Sphere Results

In order to test my samples on the Integrating Sphere, We needed to create an array of ribbon that would be large enough to cover the entire sample hole. With rolled ribbon, We created arrays of the Ulbrich silver and the Ulbrich silver/tin alloy. A picture of the Ulbrich silver ribbon array can be seen in Figure 4.1 below.

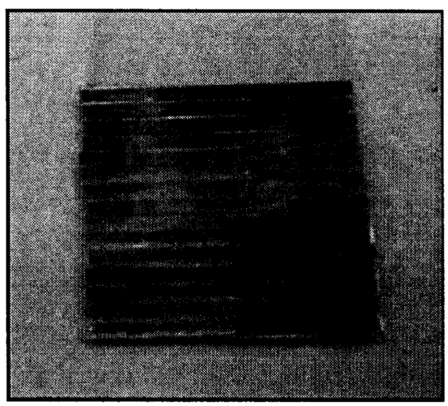

Figure 4.1: 1 inch by 1 inch Silver Plated Copper Ribbon Array

When testing these samples on the Integrating Sphere, We noticed some very strange data. When the sample's grooves were positioned vertically, the specular data was very far below the published values. If we rotated the sample 90° so the grooves were oriented in the horizontal direction and ran the test again, the data became much closer to the published values.

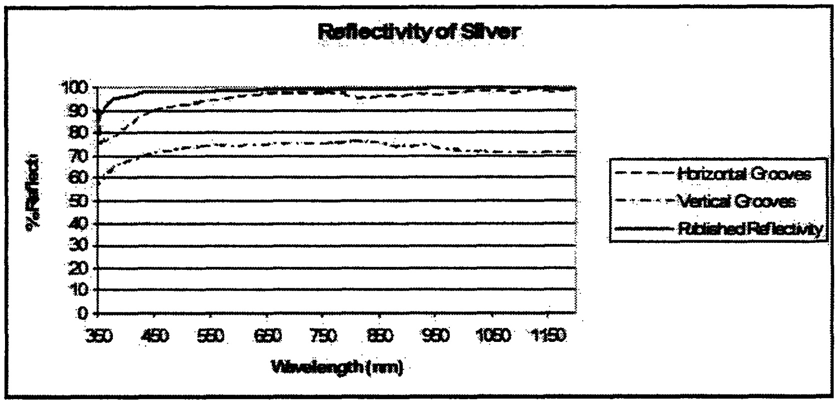

Figure 4.2: Silver Reflectivity with Grooves in the Horizontal and Vertical positions, and Published Results

By looking closely at the workings of the Integrating sphere, we can note that when measuring the specular component, the sample is held at a slight angle with respect to the entering light. In a flat sample, this would direct the specular component of the light onto the wall of the sphere. In our grooved sample, the majority of the light is reflected at an angle, and a significant amount of the reflected light escaped through the entrance hole. By orienting the grooves horizontally, the light is reflected above and below the entrance hole, allowing for a more accurate assessment of the reflectivity of the sample.

The predicted silver values are very similar to the horizontally grooved silver with only a slight decrement. We can account for this in several ways. When the silver plated copper ribbon is produced in industry, it undergoes an annealing step. This step is designed to seal the ribbon from tarnish, but in the heat treating process, the finish of the silver may be compromised. Also, when creating the array, it is possible that there was some overlap or very small gapping. Any light that would come into contact with imperfect areas would produce imperfect reflection.

The published data on the reflectivity of tin was much more scarce than that of silver, and the measured results of the Ulbrich silver/tin alloy ribbon were much higher than the published pure tin values.

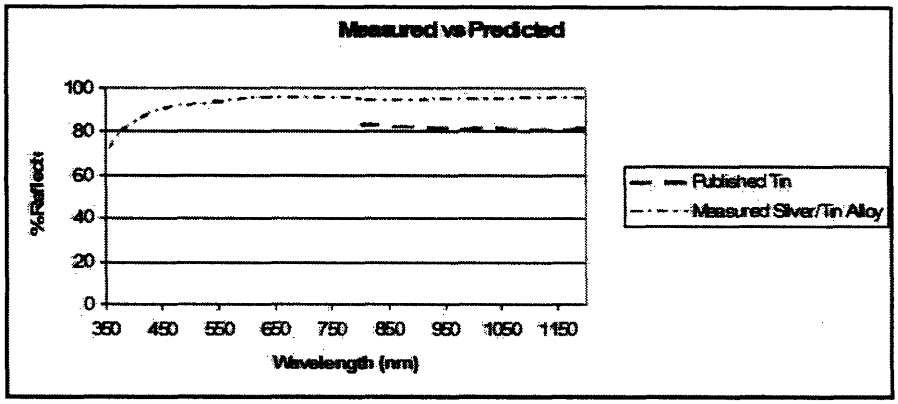

Figure 4.3: Tin/Silver Alloy Reflectivity Results vs Published Tin Reflectivity

While the measured tin/silver alloy's reflectivity appeared to have the same spectral dependence as the published values, it was higher by 15%. One interpretation is that the 3.5% silver in the alloy increased the reflectivity of the material. If we follow this assumption, we can discount the alloy by 15% to simulate and estimate tin's reflectivity.

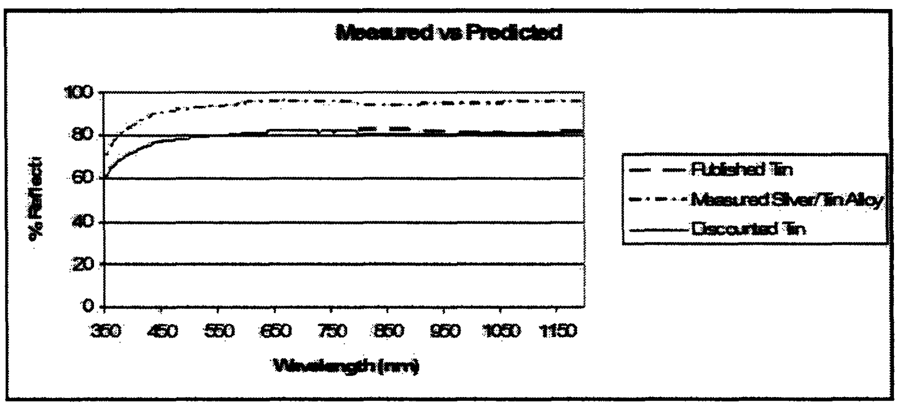

Figure 4.4: Tin/Silver Alloy discounted to Expected Tin Reflectivity

Another interpretation could be that the patterning and array construction created too many variables for concrete data. In future tests, we would hope to re-measure the reflectivity with an un-patterned bulk sample. Even without this uncertainty, the silver remains slightly higher than the alloy with the exception of at a few wavelengths. This fact remained consistent throughout all the tests, when compared with the discounted tin, the silver reflects 18.4% more light.

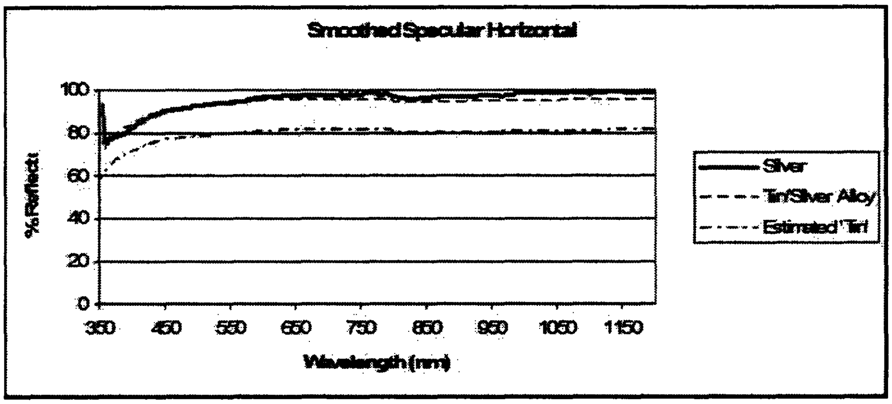

Figure 4.5: Silver, Silver/Tin Alloy, and Discounted Tin comparison. This data was taken with the grooves oriented in the horizontal position on the Specular Setting. Data has been smoothed to eliminate noise.

4.1.1 Tarnishing

Both silver and the tin array samples were tested over a month long period. They were stored in sealed plastic bags with 3M Anti-Tarnish Strips. These strips serve to extract oxygen from the limited air supply so that the material cannot oxidize. Even with these precautions, the silver showed 0.5-2.5% deterioration in reflectivity over this time. The tin showed more resilience to tarnishing by only deteriorating at maximum 2.1%.

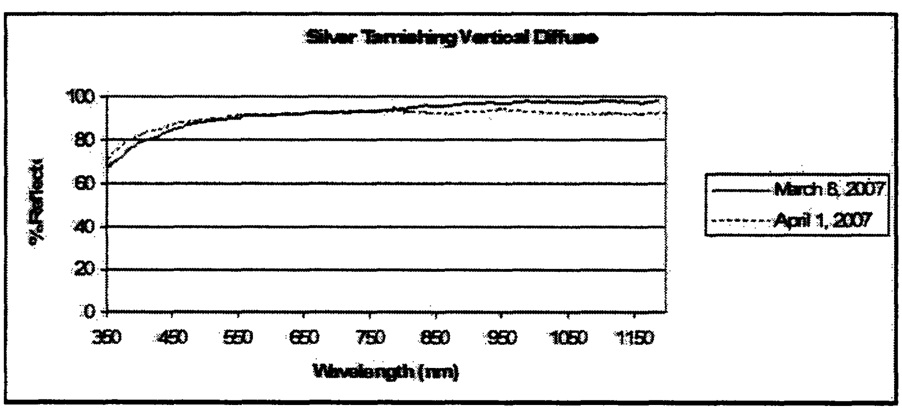

Figure 4.6: Silver Sample Tests taken one month apart. Grooves held in the vertical position, Integrating Sphere on Diffuse setting.

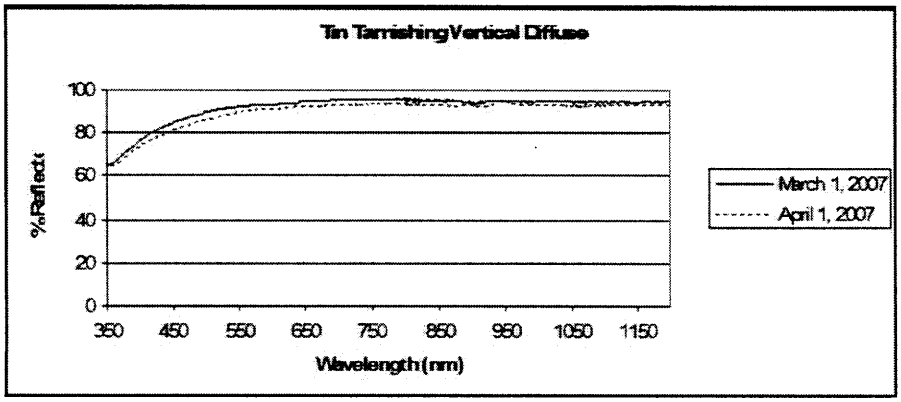

Figure 4.7: Tin Sample Tests taken one month apart. Grooves held in the vertical position, Integrating Sphere on Diffuse setting.

4.2 Serdy Angular Reflectance Apparatus Results

From the Serdy Angular Reflectance Apparatus, we were able to measure the intensity of reflection as a function of angle. Using the data collected by the 3mm wide photo sensor, we were able to determine the amount of light reflected at each angle. Knowing that light will only be redirected to the sample if it is deflected from the sample at an angle greater than 42°, we were able to integrate and determine how much of the total reflected light fell within this parameter.

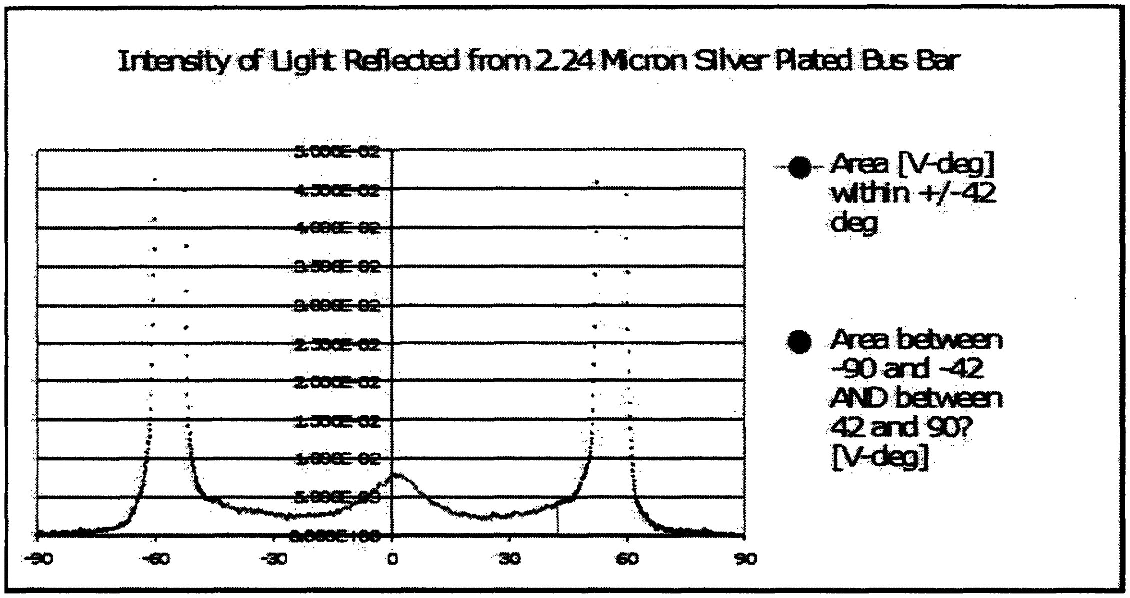

Figure 4.8: Intensity of Light Reflected from the 3.2 Micron Silver Plated Bus Bar with respect to Angle

In the figure above, light that fell within the center gray zone (i.e. at an angle less than ± 42°) would not be recaptured due total internal reflection. The integral of the light outside of that angle represents the percentage of reflection that will undergo TIR.

For these tests, we used a single patterned ribbon as our sample. In addition to using the Ulbrich silver plate and tin ribbons, we also silver plated copper bus bars in order to simulate different thickness of silver. We arrived at these thickness by using Equation 3.7 which calculated thickness plated per unit time, and multiplying that thickness by a plating efficiency of 70%. The silver plate was thick enough for both tests that no copper showed through. Table 4.1 below provides the amount of light recaptured from each type of material.

Table 4.1: Percentage of Light that will undergo Total Internal Reflection for the Given Material

Material	% of Reflected Light
Ulbrich Tin/Silver Alloy Ribbon, rolled	90.2%
Ulbrich Silver Ribbon, rolled	91.5%
2.24 micron Silver Plated Copper	94.5%
0.35 micron Silver Plated Copper	88.0%

4.3 Cost

In order for silver plating to be used in production, it must be a financially viable option. We can determine this by calculating the added benefit from silver plating and the material cost of plating

We know that bus bars shade 2-4% of light from the Solar Cell. If we assume we have a solar panel with 3% shading, we can estimate that silver plating will help us to recapture that light. We need to discount the percentage for imperfect grooves or too-shallow angles, so we can estimate that we will get back 75% of the shaded area. This will enable us to get back 2.25% of the light.

The variable cost for a solar cell is $2 per Watt. If we are getting back 2.25% of our light, it will give us an added benefit of $0.044 per Watt. In order to break even, this is the maximum amount we can afford to spend on silver on a per Watt basis. As of May 2007, the cost of standard exchange bar form silver is $430 per kilogram. Knowing the cost of silver and its density, we can calculate a volume per watt of $9.97 * 10^{-9}\ \frac{m^3}{W}$.

In order to calculate the thickness we can afford to plate, we need to know the area plated per Watt. A typical solar cell is 150 mm by 150 mm with two 2.5 mm^2 wide bus bars. A 15% efficient solar cell can generate 150 Watts per square meter. If we calculate the area of cell and multiply by this number, we can deduce that a typical solar cell generates 3.375 Watts. The area of the bus bar divided by the number of Watts generated gives us area plated per Watt of 0.00022 $\frac{m^2}{W}$.

Finally, in order to calculate our maximum affordable thickness, we can simply divide the volume per Watt and the area per Watt. Our maximum thickness that we would be able to plate and still generate benefit from our solar cell is 44.8 microns. In our testing, plating as little as 0.35 microns produced a very high light capture. Plating 2.24 microns resulted in 94.9% of reflected light undergoing TIR; the most reflected light of any tested material. From this reflection data, we can conclude that the benefit of silver plating far outweighs the material costs.

Plating silver does allow for greater reflectivity of light and increased power output of the solar panel. The deciding factor in the decision to use silver over tin would be the manufacturing costs. In order to manufacture silver plated bus bars, one would need to apply the coatings in a very particular order. First, we would need to apply the silver to one side and roll the bus bar. This silver must not contain any tin, or else the tin will alloy with the copper during the annealing process. Only pure, fully annealed copper can be used in bus bars. The next process would be to apply the solder layer to the underside of the bus bar so that the bar can be easily attached to bus bars. If this process can be done for less than the difference in benefit and material cost, then silver could be an economically viable option.

Chapter 5

Conclusions and Recommendations

5.1 Summary

The purpose of this project was to determine if silver could be a viable plating alternative to tin on solar panel bus bars. In pursuing this question, we tested the reflectivity of the rolled materials, measured their angular reflectance, and calculated the added benefit in terms of cost.

5.1.1 Reflectivity

The reflectivity of the materials was tested on a Diffuse Reflectance Accessory in an Cary Spectrophotometer. We used a 1 square inch array of rolled Ulbrich silver and rolled Ulbrich tin/silver alloy ribbon. We tested the reflectivity of each material with respect to published results, and found that the silver plate performed with little deviation from the expected results. The silver/tin alloy reflected only 2% less light as the pure silver, and behaved with the same specular dependence as pure tin, only 15% higher. One interpretation is that the 3.5% silver in the alloy significantly increased the reflectivity of the material. Another interpretation could be that the patterning and array construction created too many variables for concrete data. In any case, the silver proved to have a very high reflectivity and verified the published results.

Tarnishing

As the tests were performed over a month long period, we also tested the tarnishing properties of the silver and the silver/tin alloy. Over the course of the month, they were stored in sealed bags with anti-tarnishing paper. The result was that the silver tarnished 0.5-2.5% and the silver/tin alloy tarnished 0.1-2.1%.

5.1.2 Angular Reflectance

The next step in the process was to measure the angular reflectance of a single rolled bus bar of different materials. Using the Serdy Angular Reflectance Apparatus 3.4.2, the results of the angular reflectance are shown below in Table 5.1.

Table 5.1: Percentage of Light that will undergo Total Internal Reflection for the Given Material

Material	% of Reflected Light
Ulbrich Tin/Silver Alloy Ribbon, rolled	90.2%
Ulbrich Silver Ribbon, rolled	91.5%
2.24 micron Silver Plated Copper	94.5%
0.35 micron Silver Plated Copper	88.0%

The 2.24 micron plate of pure silver had the most light undergo total internal reflection. These results verify that silver plating can capture a large percentage of light.

5.1.3 Cost

The additional benefit generated by the silver plating far outweighs the material costs. Our maximum thickness that we would be able to plate and still generate benefit from our solar cell is 44.8 microns. In our testing, plating as little as 0.35 microns produced a very high light capture. Plating 2.24 microns resulted in 94.9% of reflected light undergoing TIR; the most reflected light of any tested material. The material costs support the use of silver as an alternative plating for bus bars, but the deciding factor will come down to the manufacturing costs. If the industry can plate silver at less than the difference of benefit and material costs, then silver plating could be a feasible option.

5.2 Future Recommendations

In order to completely determine if silver plating bus bars could be a viable option, we would recommend continued research. In each of the tests, it would be useful to compare the results to a current industry standard tin plating bus bar and a rolled tin plated bus bar. The specular reflectivity data could benefit from comparisons of bulk samples to the rolled arrays to understand how much light was lost because of the contour. In addition, it would be beneficial to determine the optimal thickness for a silver plate with respect to reflected light. Finally, as the technology continues to develop, increased information as to the manufacturing processes could lead to a more precise cost benefit analysis.

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