A Ray Tracing Investigation of Light Trapping due to Grooves in Solar Cells

by

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ABSTRACT

The biggest problem the world faces today is finding a renewable energy source as fossil fuel reserves being depleted, and the ongoing burning of fossil fuels is destroying environments all over the world. Solar energy is the most abundant energy source but is too expensive compete with non-renewable sources. A way to increase the efficiency of solar cells is to texture the cell surface so that it traps light better, allowing more light to be absorbed and converted to electrical energy.

Professor Sachs and Dr. James Bredt have developed a texturing scheme that consists of trenches etched on the top surface of the silicon cell. The profile of the trenches will either be a simple semicircle or a parabola with a set aspect ratio. Our objective was to determine the optimal cross-sectional shape by using Zemax, a ray-tracing program that models light striking the cell. Solid Models of the solar cell with different texturing schemes were created, and then imported to Zemax where optical properties were modeled. Using a detector to measure how many times a ray struck the bottom surface of the cell, we were able to determine that a parabola with a unit aspect ratio was the optimal trench cross-section. The average number of detector hits for the unit aspect parabola was 3.68 ± 0.11 as oppose to 1 detector hit with no texture.

Another objective was to determine how light behaves when it strikes the cell at an oblique angle parallel to the trenches. Using Zemax again, we varied the angle of incidence and measured the number of times a ray struck the bottom detector. Up to an angle of incidence of 30°, the number of detector hits remains constant at 3.68 ± 0.05. After that however, the number of hits increases as the angle of incidence increases. Although this was not predicted, there are many explanations for it including the fact that the model cell is much shorter in width than the actual cell.

Overall, the parabolic trench with unit aspect ratio should be used to better trap light in solar cells, and therefore, increase their overall efficiency.

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1. Introduction

1.1 Energy Crisis

A huge concern in the world today is the depletion of fossil fuel reserves. With populations across the world spiking, and living standards growing day by day, the world's energy demand is increasing to unbelievable heights. Fossil fuels supply almost 90% of the world's energy, and according to the Hubbert's Peak Theory, we are currently in the peak of oil supply. This means that the supply of oil will only decrease from here on out, having a huge impact on the global economy. This falloff will have catastrophic affects on the US economy. Renewable energy resources are being researched right now, but the main problem is that their costs are not comparable to petroleum. The depletion of current fossil fuels is not the only force driving the need for a renewable energy source. Fossil fuel dependency also forces the US to depend on foreign "regimes that [the United States] would otherwise shun."[1] Much of the current crude oil that the United States imports is from countries in the Middle East, who have a long history of violence and warfare.

Burning fossil fuels also has catastrophic affects on the global environment. Recently, fossil fuels have been identified as the primary cause of global warming. In the US alone, over "90% of greenhouse gas emissions come from the combustion of fossil fuels."[2] "Future CO_2 levels are expected to rise due to ongoing burning of fossil fuels," causing global temperatures to rise to a point where they could have a drastic impact on the planet.[3] Additionally, fossil fuels generate sufuric and nitric acids when burned, that fall to the ground as acid rain. This has impacts not only on the environment, but also on buildings and other man-made structures. Finally, the manner in which fossil fuels are harvested has impacts on the environment. Offshore drilling for oil and coal mining in mountainous regions both have detrimental effects on the surounding environment.

It is clear that there is an enormous need for a renewable energy source to replace current fossil fuel consumption. However, which renewable source is best? Should the world harness energy from the sun, wind, water, or perhaps use nuclear resources? Wind and solar energy are both viable resources, but solar has much more potential. Nuclear power seems like a good alternative source of energy with a huge availability; however, it would be impossible to separate nuclear power from nuclear proliferation. Solar energy is the answer. The sun emits huge amounts of energy each day that if harnessed, could easily supply energy to the world. To put it in perspective, the amount of energy that the earth recieves from the sun in 500 hours is equal to 500 years worth of fossil fuel energy.[1] The main question becomes; how do we harness all of that solar energy?

1.3 Making Solar Cells Cost Effective

Solar cells convert light energy into electrical energy without producing any unwanted side effects. There is no shortage of sunlight nor is there a shortage of silicon, as it is the second most abundant element on the planet. So why aren't solar cells being widely used to produce electricity today? The main problem with solar cells is that they cost too much to compete with fossil fuels. To the end user, the cost of solar energy is about $7.00/Watt, which is not very competitive with coal-generated electricity.[4]

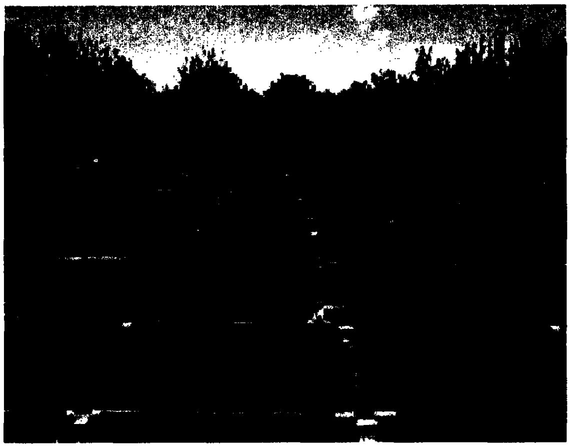

Figure 1: Photograph of an array of solar cells.

The most important component of a PV cell is the silicon that actually absorbs the light energy and converts it to electricity. The best or most efficient silicon is a mono-crystalline silicon wafer that operates at 20% conversion efficiency. However, it is very expensive to produce single crystal silicon. Multi-crystalline silicon is cheaper to produce, but only has a 16% conversion efficiency. Since multi-crystalline silicon makes up over 55% of the current market for silicon cells, the goal is to increase the efficiency of multi-crystalline silicon without adding additional manufacturing cost.[4]

1.4 Silicon Texturing

One of the ways to improve the efficiency of a cell is to texture the surface of the silicon. Texturing has a two-fold effect of reducing reflection losses and improving the light-trapping capabilities of the silicon cell. There are many different ways to texture silicon, but the overall purpose is to reduce reflections and to increase light-trapping. Figure 2 gives a general idea of how texturing reduces the overall reflectivity of the cell. The triangles are the textured surface and they reduce the reflectivity by "presenting a large fraction of inclined surfaces to the incident light."[4] When the light strikes an inclined surface and reflects, it has an additional opportunity to pass into the cell and be converted to electrical energy.

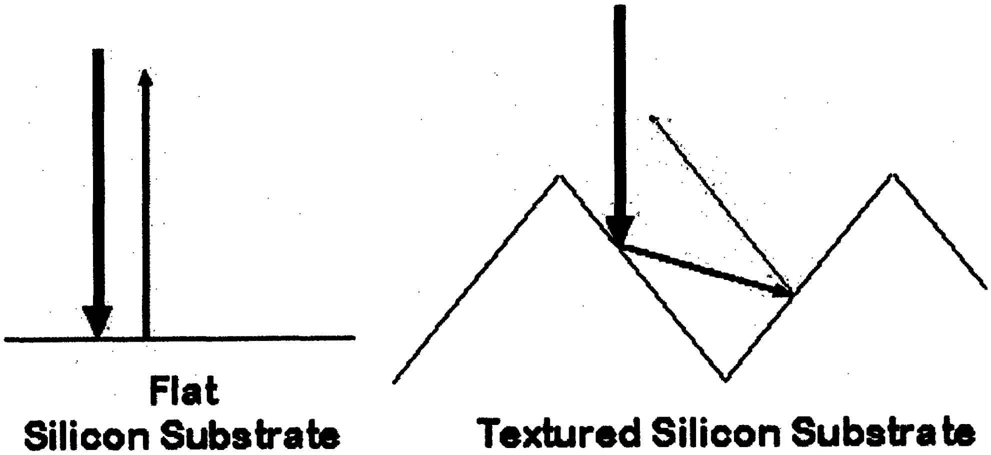

Figure 2: When light strikes a silicon substrate, some rays are reflected and never enter the silicon. A textured surface reduces this reflectivity by giving rays multiple opportunities to pass into the silicon.[5]

Texturisation of the silicon surface is also used to lengthen the path that the light takes inside the cell. If the optical path is longer, the light ray has a better chance of getting absorbed in the silicon. Figure 3 gives a general idea of how texturing increases the light path. Not only do the inclined surfaces cause the ray to refract into the cell at a flatter angle, but it also makes it more difficult for the ray to exit the cell. To exit, the ray must hit the surface at an angle less than the critical angle. Texturing makes it difficult for a light ray to strike the surface at such an angle.

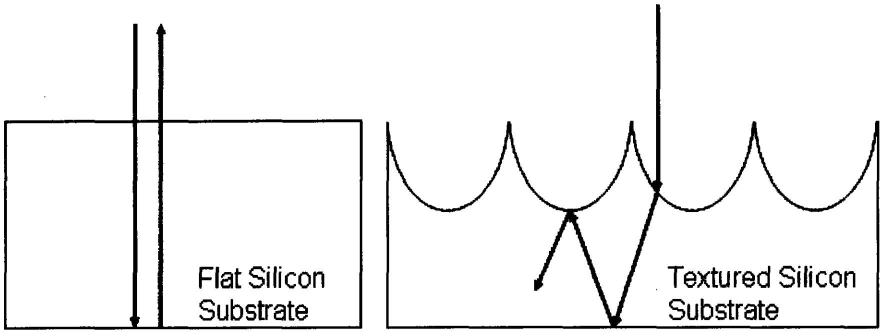

Figure 3: When light rays enter a silicon substrate, they travel until they are absorbed by the silicon. If rays take a longer path within the silicon, they have a better chance of getting absorbed. A textured silicon substrate helps trap rays better, by providing inclined surface which make it harder for a ray to strike at an angle less than the critical angle.

Currently, the random pyramids surface texture is the most widely used texture in single-crystal silicon. The random pyramids texture is created by applying alkaline etchants to the cell surface. These etchants eat away at the silicon in an uneven fashion, and cause "random pyramids" to form on the surface. These random pyramids increase the light path to some extent, but improvements can be made.

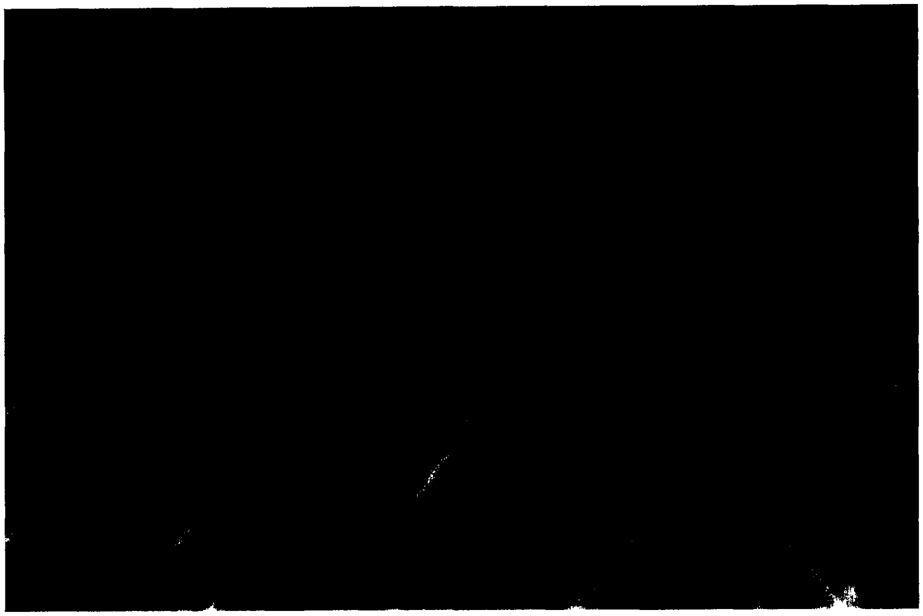

Figure 4: Electron Microscope image of the random pyramids textured surface. Etchants eat away at the silicon in an unorthodox fashion causing "random pyramids" to form on the surface. The pyramids are due to the crystalline structure of the silicon, and the texturing technique is the most widely used one today.[5]

Professor Sachs and Dr. Bredt have recently designed a new texturing pattern that should increase the efficiency of the cell by over 25% relative. The proposed surface texture is a pattern of grooves that run across the length of the cell. These grooves have some sort of semi-circular or parabolic cross-section, and should increase the conversion efficiency of the cell.

Our objective is to determine which cross-sectional shape will trap light the best. A problem with trying to determine which cross-sectional shape to choose and how each will perform is that it is very difficult to model how light rays will act in the cell. Light will refract into the silicon and bounce off surfaces, making it extremely difficult to determine exactly what type of light path one could expect. Therefore, we will use Zemax, a powerful ray-tracing program to model the path taken by light striking the surface vertically. Then, using fundamental laws of optics, we will develop a simplified model of the cell and try to predict the length of the light path for light striking the cell at an oblique angle. We will verify this model using Zemax. The ray tracing software should very precisely predict the path length of the light, allowing us to decide which groove shape will provide the longest optical path in the silicon cell.

2. Theoretical Analysis

Determining how a light ray will behave in a PV cell is a complex three-dimensional problem. Rays will enter the cell at various angles, and travel through the cell as a three-dimensional vector. This complexity can be simplified by separating the problem into two, two-dimensional problems. Once separated, these two problems can be solved and used to predict what will occur in certain situations. However, it is important to note that this is a simplifying assumption, and may not be accurate for all situations. It is believed that the separating assumption should be accurate for a variety of situations, and we will verify the assumption using Zemax. However, it is important to note that the actual light path can only be estimated. Zemax only outputs the number of internal reflections of a ray inside the PV cell. From this, the actual light path is estimated by:

$$L = 2R, \tag{1}$$

where L is the estimated light path and R is the number of internal reflections recorded by Zemax.

2.1 Separation of x and y directions:

In our model, we can separate how the light will act in each direction in order to determine the total path length of the light in the silicon. In other words, the optical path in the x-z plane will be independent of the optical path in the y-z plane, and the two solutions will be combined to determine the total path length.

A solid model of the cell is shown in Figure 4. Though it is a 3-dimensional object, we can separate the problem into two separate, two-dimensional problems. One problem will focus primarily on how the light travels in the x-z plane. The x-z plane is the left-most diagram in Figure 5 that shows the texturing of the silicon surface. In this problem, the texturing on the silicon surface will be the primary factor determining how a ray will behave in the cell.

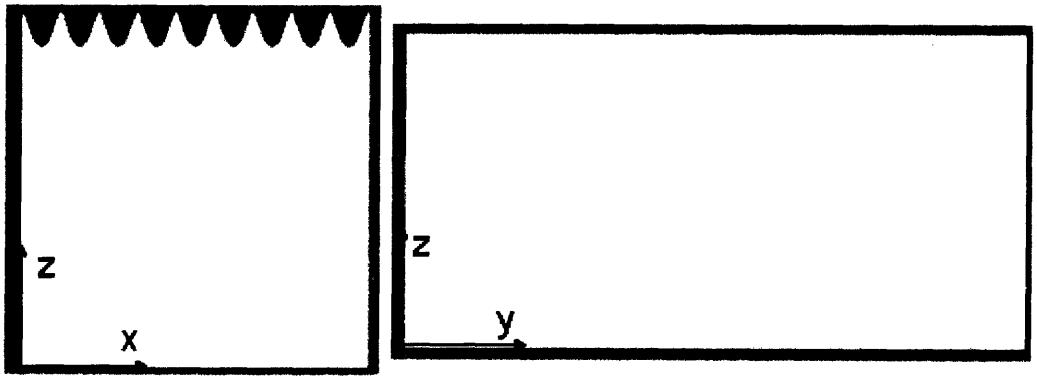

Figure 5: Two cross-sections of the textured silicon to show the directions we are concerned with. The x-z plane contains the texturing while the z-y plane contains the depth of the silicon. We will analyze the light in each regime separately, and combine the results to determine the total path length of the light.

The other problem will focus primarily on how the light behaves in the y-z plane. This plane is the right-most picture in Figure 5. In the y-z plane, we will determine how the angle of incidence of the incoming light affects the optical path taken in the silicon. The texturing should not have any impact on this light, and the only determining factor should be the angle of incidence.

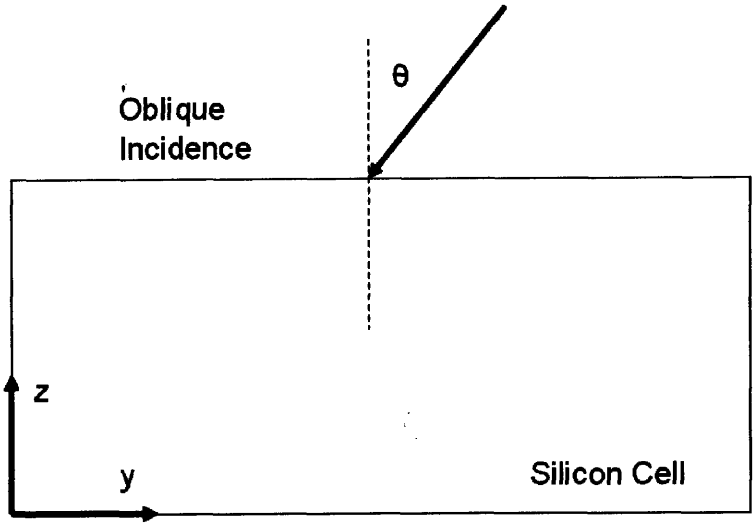

Figure 6: In the z-y plane we are concerned with how light will behave if it strikes the cell at an oblique angle.

2.2 Light path due to texturing

With these two separate problems, we first will determine how the light behaves when it enters through the texture (this behavior is observed by looking at the x-z face of the cell). We will determine this path length by assuming that the incident light strikes the textured trenches vertically. However, even assuming vertical incidence does not simplify the problem enough to allow us to make an accurate prediction of the path length of a ray. Therefore, we will be assisted by a ray-tracing program, to determine (on average) how far vertical rays travel in the cell. The actual distance that a ray travels will be estimated from the total number of internal reflections recorded by the ray-tracing program.

Different texturing patterns will be examined. From a semicircular cross-section to parabolas with different aspect ratios, we will analyze each one and decide which one will trap light the best in the PV cell. As mentioned before, it is very difficult to model how light will behave after it strikes these different textures. However, we do have some predictions on how well each will work.

The parabolas that we test will remain constant in width and vary in depth. The parabola's aspect ratio is defined as its height divided by its width. We tested parabolas ranging from a ¼ aspect ratio to a 2 aspect ratio, and each is shown in Figure 6. The deeper parabolas should trap light better than shallower ones because they provide surfaces with greater angles that make it harder for rays to escape. However, there should be an aspect ratio, where making the parabola deeper does not add much more benefit to the light trapping capabilities of the cell. If the optical path is plotted versus the parabola aspect ratio, we expect a curve that increases initially and eventually flattens out as the aspect ratio increases. The optimal aspect ratio will be defined as the deepest parabola, where making it any deeper will not increase the light trapping capabilities of the cell.

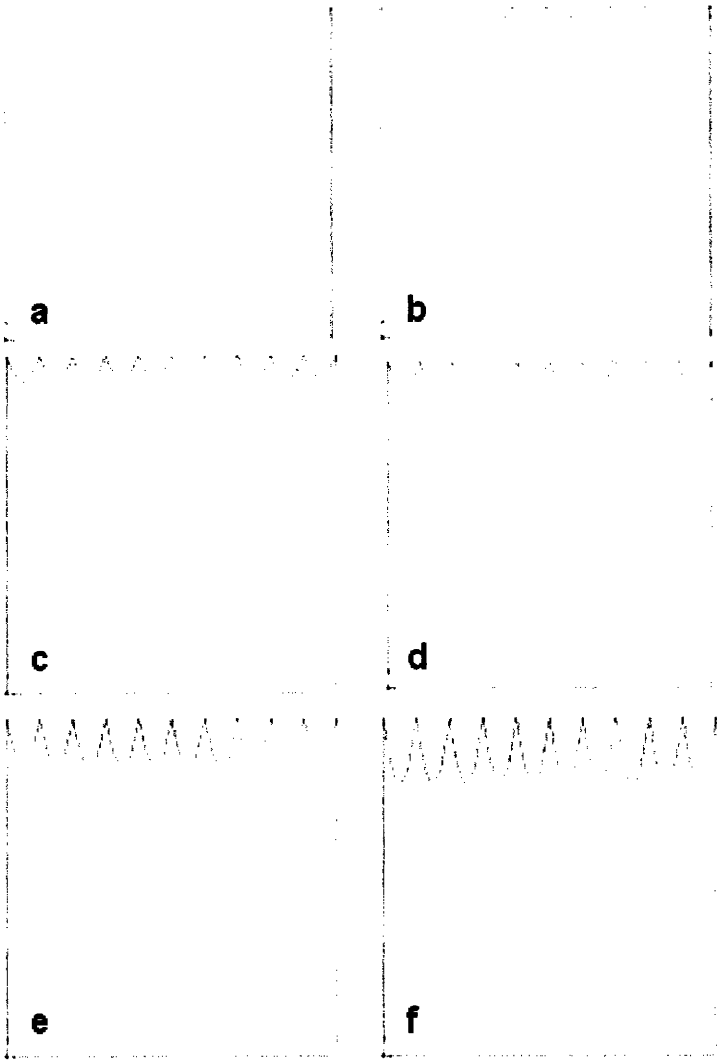

Figure 7: Cross-section of each parabola that was tested. a) ¼ aspect ratio parabola. b) ½ aspect ratio parabola. c) ¾ aspect ratio parabola. d) 1 aspect ratio parabola. e) 1.5 aspect ratio parabola. f) 2 aspect ratio parabola.

2.3 Oblique Incidence:

One of our main objectives is to determine the path length of rays that strike the cell at an oblique angle. Here, we are only worried about oblique incidence in the y-z plane, and the texturing has no effect on the incoming light ray. If we take a cross section at the point where the ray strikes the surface, we would see a ray entering a two-dimensional rectangle (Figure 8).

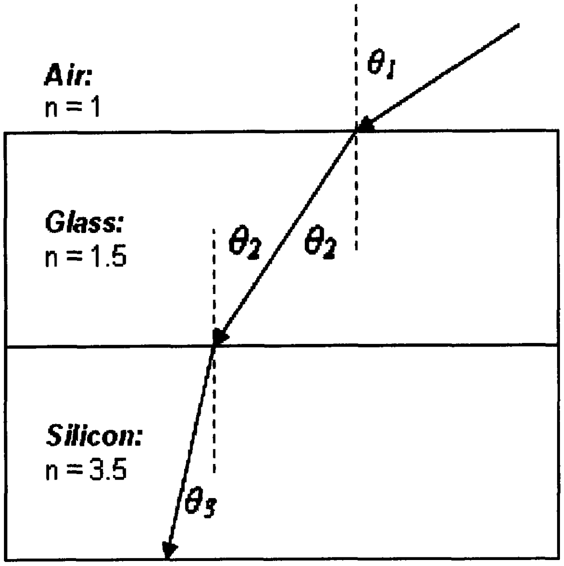

Figure 8: Schematic diagram of a light ray entering the solar cell at an angle in line with the texturing. The ray first gets refracted into the glass and then into the silicon according to Snell's Law.

The ray will first strike the glass surface at an angle and refract into the glass at an angle according to Snell's Law. This angle of refraction will be given by

$$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right), \tag{2}$$

where θ_2 is measured from the surface normal, n_1 is the index of refraction of air, n_2 is the index of refraction for the glass, and θ_1 is the angle of the light striking the surface of the glass. The maximum angle that θ_2 can achieve is when the incoming light is perfectly horizontal. Solving equation (2) with $n_1 = 1$, $n_2 = 1.5$, and $\theta_1 = 90^\circ$, we determine that the maximum angle of refraction is $\theta_2 = 41.8^\circ$. This angle is significant and is referred to as the critical angle for total internal reflection (TIR). If a ray travels in the glass with an angle greater that 41.8°, it will be internally reflected, and not be able to leave. This is not possible in a rectangular cell where the ray refracts in, because as noted before, the angle of refraction cannot exceed the critical angle.

The ray will continue at its refracted angle until it strikes the surface of the silicon, where it will refract again. Equation (2) will still hold, but now the indexes are that of glass and silicon respectively. If we rewrite equation one with new subscripts denoting glass and silicon, we get the angle of refraction in silicon to be

$$\theta_3 = \sin^{-1}\left(\frac{n_2}{n_3}\sin\theta_2\right). \tag{3}$$

Again, let us examine what the maximum angle of refraction will be in the silicon. The maximum angle of incidence is now only 41.8°, and the index of refraction for silicon is approximately 3.5. Solving equation (3) with $n_2 = 1.5$, $n_3 = 3.5$, and $\theta_2 = 41.8^\circ$, we find that the maximum angle of refraction in the silicon is $\theta_3 = 16.6^\circ$.

Now, we wish to develop an expression for the angle of refraction in the silicon as a function of the angle of incidence of light striking the glass. This relation is given by combining equations (2) and (3). The angle of refraction in the silicon is given by

$$\theta_3 = \sin^{-1}\left(\frac{n_1}{n_3}\sin\theta_1\right). \tag{4}$$

It is interesting to the note that the index of refraction of glass does not enter equation (4). However, the index of glass is still important because it determines the critical angle for total internal reflection in the silicon. Additionally, it is important to note that this only works for a flat cell. Given the modeling assumption, we can use this equation for the x-z case but we must rely on ray tracing for the y-z case.

2.4 Reflection and path-lengthening

The bottom surface of the solar cell is assumed to be a mirror, so when the ray refracts into the silicon, we assume that it then reflects off the bottom surface. Because the angle of reflection cannot exceed the critical angle, the ray's path will not be lengthened through additional internal reflections. Rather, the only effect that the oblique incidence will have on the optical path is that it will cause the light to travel at an angle in the y-direction (Figure 9). Thus, the ray will travel further than if the light strictly entered vertically.

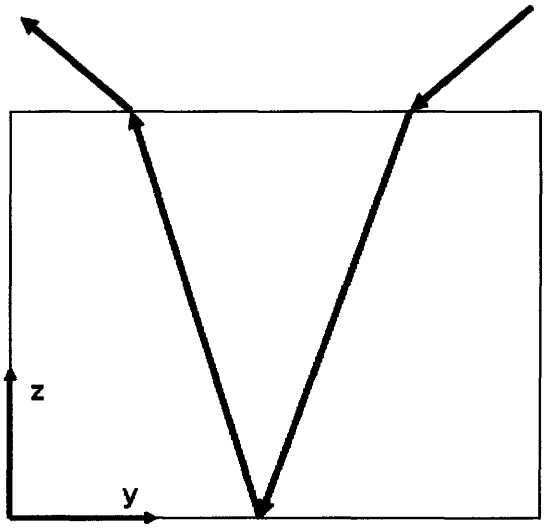

Figure 9: Diagram showing the modeling assumption that oblique incidence will not add any internal reflections to the optical path. The light will refract into the silicon, reflect off the back surface, and then refract back into the glass. Because the light refracts in, it cannot achieve an angle greater than the critical angle of internal reflection.

Looking at Figure 10 below, we see that each ray segment is lengthened by some factor due to its oblique path. If we assume that the silicon is of unit thickness, L = 1, we determine the new length of each ray segment to be $\frac{1}{\cos\theta_3}$, where θ_3 is the angle of refraction in the silicon.

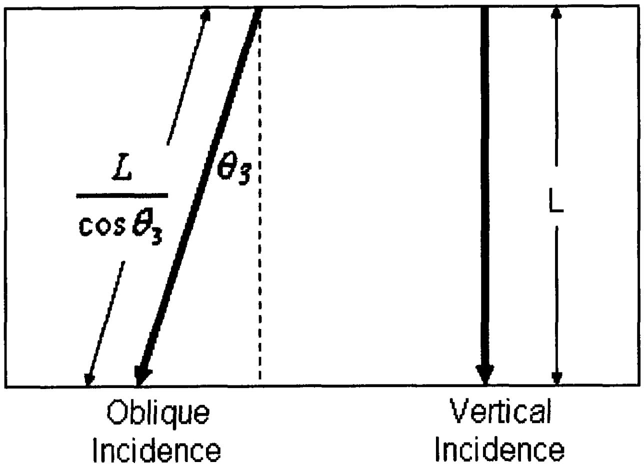

Figure 10: Diagram depicting the longer path taken by the ray when it enters the cell at an angle. The oblique incidence causes each ray segment to be lengthened by a factor of 1/cosθ.

If we go back to the vertical incidence, the texturing in the x-direction causes the light to bounce around in the cell with some number of internal reflections. This total number of internal reflections will in no way be affected by oblique incidence. However, the total distance traveled in the cell with increase, as now each reflection will be lengthened by some factor. Reverting back to equation (1), the average distance that a ray travels with vertical incidence is *2R* (where *R* is the number of internal reflections). Now, with the light entering the silicon at some angle, the light path will be that constant times the lengthening factor:

$$L = \frac{2R}{\cos\theta_3}. \qquad (5)$$

Using equations (4) and (5), we can predict how far light will travel in the cell when light strikes at an oblique angle. First, the average distance that a ray travels with vertical incidence is found (and is the *2R* from equation (1)). Then, knowing the angle of incidence and using equations (4) and (5), we can predict the optical path of an oblique ray.

3. Experimental Procedure

Our objective is to determine what cross-sectional shape will trap light the best in the PV cell. Due to the complexities of the groove shapes, Zemax, a ray-tracing program was used to model light striking and refracting into the surface of the silicon.

3.1 Overview of Zemax

Zemax was the main tool used to analyze the light trapping capabilities of various surface textures. Zemax is a ray-tracing program that models and assists in the design of optical systems. It allows three-dimensional shapes to be created within the program itself, and it also accepts objects imported from other programs (solid models). The solids are arranged in a three-dimensional space using the 3D Layout Viewer; which allows the user to easily move objects to their desired location. These solids are then assigned an index of refraction; allowing Zemax to determine how light will travel within them. Other than solids with a specific index of refraction, surfaces can also be created with different properties. Surfaces can be assigned mirror properties, so that light reflects off just as if it strikes a perfect mirror.

Once the appropriate system is set-up, a light source must be added to the system. The light source can be a planar or point source, and will emit the desired number of light rays. To detect these rays, a detector can also be added to the system. Detectors can record various things, but in our experiment, they were used to determine the total number of times a light ray struck the detector. This detection number is the number of internal reflections and is used to estimate the path length by means of equation (1).

3.2 Creating Solid Model of PV Cell:

A solid model of the proposed PV cell was first created in Solid Works®. Two separate parts were created: the glass covering and the textured silicon. The silicon was first created from a .2 x .2 mm box. Ten semicircles with a .02 mm diameter were placed on the top surface, with their open surface facing outward, away from the cell (Figure 11). The shape was extruded .4 mm, twice the width of the box.

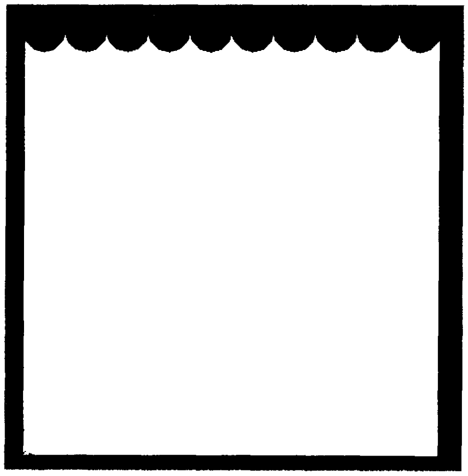

Figure 11: A screenshot of the silicon solid model with semicircular trenches.

The glass portion of the PV cell was then created beginning with an identical .2 x .2 mm box as before. The same ten semicircles with .02 mm diameter were placed on the top surface. However, now, the open surfaces were facing into the cell, creating a round extrusion, rather than an indentation (Figure 12). The shape was then extruded .4 mm.

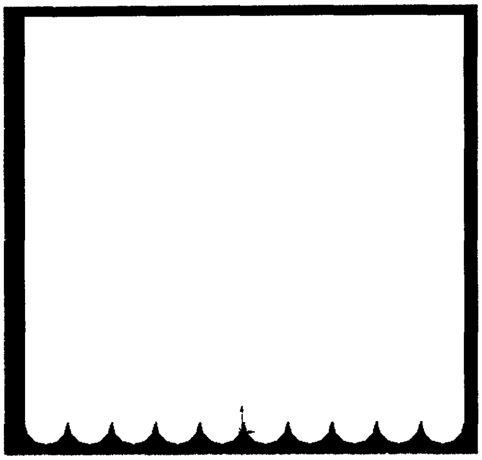

Figure 12: A screenshot of the glass solid model with semicircular trenches.

The identical process above was repeated using parabolas rather than semicircles. The width of the parabolas remained constant at .02 mm, and their depth was varied from .005 mm to .04 mm. This allowed us to test parabolas with aspect ratios of¼, ½, ¾, 1, 1.5, and 2.

Additionally, the above seven solid models were recreated, now with gaps located between the trenches. The gaps were given a width of approximately 11% of the width of each trench. The purpose of the gaps was to mimic a non-perfect etching of the trenches. In practice, the trenches will most likely not touch but rather a fine plateau will exist. A schematic of the cell with gaps located between the trenches is shown in Figure 13.

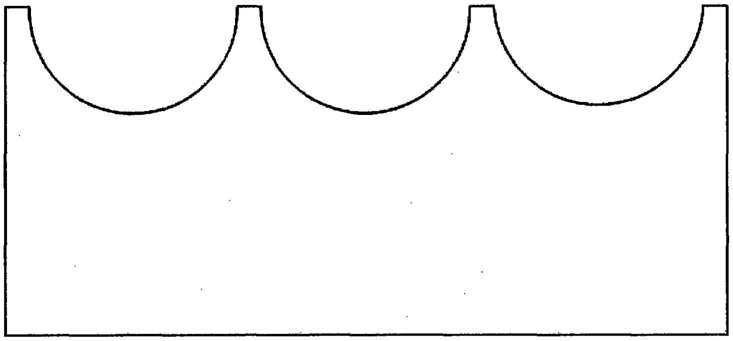

Figure 13: A close-up of the silicon texturing with gaps between each semicircular trench.

3.3 Importing Solid Model to Zemax

The solid models of the textured silicon and glass were then imported to Zemax as a .STEP file. Once imported, the material for each solid was determined. From the existing Zemax catalog, a Schott glass with an index of refraction of $n = 1.51$ was chosen as the material for the glass surface. There were no materials in the Zemax catalog with properties similar to silicon. Therefore, one was created and assigned an index of refraction of $n = 3.5$.

Once in Zemax, the two rectangular prisms were aligned to make a continuous prism with the texturing located at the interface. This was done by looking at a 3D wireframe model of the objects, and changing their position. Once aligned, mirrored surfaces were added to the four outside sides of the prism (shown in Figure 14). The reason for these mirrors was that the actual size of the PV cell is much bigger than the solid model we created. An attempt was made to create a cell that is actual size, but it simply was too large to be handled correctly in Zemax. However, it seemed more than reasonable to create a cell with a width and height of ten times the width of the textured trenches. Also, to allow for the analysis of oblique incidence, a depth of 20 times the width of a trench was employed. The mirrors on each surface were therefore used to mimic a full-length cell. It is assumed that they do not alter the light path in any significant manner, and the results should be relatively accurate.

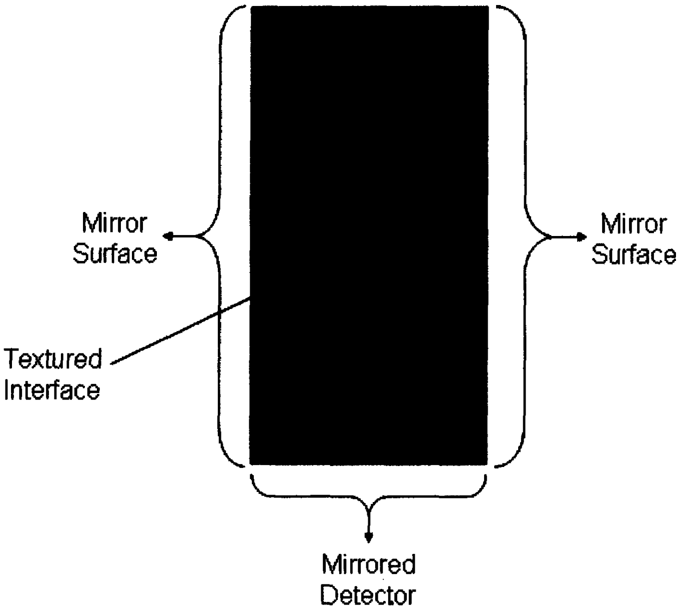

Figure 14: Cross-section of the modeled cell in Zemax. The sides (including the front and back surfaces) are mirrors to reflect rays back within the cell. A detector with a mirror finish is placed at the bottom of the cell to reflect rays back within the cell and detector the number of times rays strike the bottom surface.

Once the cell was complete with mirrors on all four sides, a detector was placed on the bottom surface of the cell (shown in Figure 13). In Zemax, we made the detector a perfect mirror even though the actual cell has an imperfect mirror on its bottom surface. The detector reflects rays, and in the process, records how many times a ray strikes and bounces off. If we multiply the total hits by two, this method gives a rough estimate of the total distance that a light ray travels in the cell. The ray goes through the cell, strikes the detector, and reflects back out of the cell. If the detector recorded one hit (for one incident ray), two would be a good estimate of the total light path in terms of cell thicknesses. Although it does not account for the fact that the ray might travel in the silicon at an angle, it provides a way to compare the differences between the various texturing profiles. For comparison purposes, we will only compare the number of detector hits for each texture profile (not two times the number of detector hits).

Finally, a rectangular ray source was added to the system. The source was a .2 x .2 mm rectangle and located in the center of the top surface of the glass (the surface which rays will penetrate). It was placed .1 mm away from the glass, and set to emit 300 rays, randomly spaced across its area. This large number of rays was chosen to give a good estimate of the average path length of a ray.

3.4 Measuring Path Length with Vertical Incidence

Beginning with the semicircular texture, 300 rays were sent into the cell, and the total number of detector hits was recorded. This number was divided by 300 to get the average number of detector hits per ray. This procedure was then repeated 12 times, to again, get a better estimate of the average number of detector hits. The mean of the 12 trials was found, and the uncertainty of the data was determined using the t-statistic method. The procedure was repeated for the six different parabolas, all of the data was compiled and compared, to determine which trench shape resulted in the highest number of detector hits.

3.5 Measuring Path Length with Oblique Incidence

The effect of oblique incidence was determined using the parabolic profile with unit aspect ratio. This is assuming that oblique incidence will have the same effect on the total light path regardless of the surface texture. First, the source was shifted to the rear of the cell, so that light would strike at the rear and continue to the front of the cell. The source was then tilted by 10 degrees so that rays strike the top surface of the glass at an angle of 10 degrees with respect to the normal. At this angle, 300 rays were sent into the cell, and again, the total number of detector hits was recorded.

The above procedure was repeated for incident angles up to 70 degrees, at an interval of 10 degrees. As the angle increased, the source was placed further behind the cell so that rays enter as close as possible to the rear of the cell. The data was then compiled and compared against the theoretical model.

4. Results and Discussion

4.1 Vertical Incidence

Following the procedure above, we were able to determine how well each texturing profile trapped light. The results are shown in Table 1, and include uncertainty representing a 95% confidence interval (determined with the t-statistic approach).

Profile Shape	**Detector Hits**
Semicircle	2.95 ± 0.15
Parabola (1/4)	3.32 ± 0.10
Parabola (1/2)	3.51 ± 0.11
Parabola (3/4)	3.54 ± 0.14
Parabola (1)	3.68 ± 0.11
Parabola (1.5)	3.72 ± 0.10
Parabola (2)	3.64 ± 0.11

Table 1: Table showing the number of detector hits for each profile shape with the uncertainty representing a 95% confidence interval. The number of detector hits increases as the parabola aspect ratio increases. However, it eventually flattens out and no benefit is achieved by making the parabolas deeper.

From the data, we determine that the parabola with a 1.5 aspect ratio traps light the best in the silicon. However, it appears that at the parabola with unit aspect ratio, the light trapping begins to plateau. Accounting for the uncertainty in the measurements, it can be noted that above the parabola with unit aspect ratio, there is very little added light trapping if the trenches are made deeper.

The results from Table 1 are also plotted in Figure 13. Prior to conducting any experiments, we predicted that the optical path would increase as parabola's aspect ratio increased. At some aspect ratio, the number of detector hits would flatten off, and increasing the ratio any further would not be warranted. Figure 15 gives the number of detector hits for each aspect ratio. It also contains a line that increases sharply, and flattens out as the aspect ratio increases. Although the precise ratio where the flattening would occur was not estimated, the data definitely follows the trend we expected. Additionally, it shows us that increasing the aspect ratio beyond unity, does not substantially increase the overall light trapping capabilities of the cell.

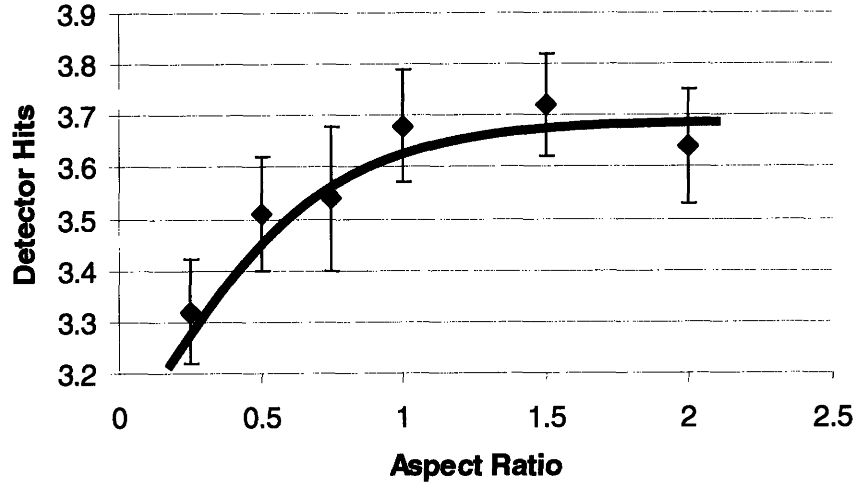

Figure 15: Graph of the number of detector hits versus the aspect ratio of the parabola. The data closely follows what was predicted: the number of detector hits increases sharply and flattens out as the aspect ratio increases. The optimum parabola has a unit aspect ratio.

We also determined the effect of gaps located between each trench as a result of imperfect etching. The gaps were approximately 11% of the width of the trench in all cases. The parabola with a ¼ aspect ratio was not tested, because we were unable to properly create the cell in SolidWorks. Multiple tries were given to create the cell with parabolas with ¼ aspect ratios, but an error arose every time. The results with this omission are shown in Table 2.

Profile Shape	Detector Hits
Semicircle	3.03 ± 0.07
Parabola (1/4)	N/A
Parabola (1/2)	3.12 ± 0.05
Parabola (3/4)	3.14 ± 0.05
Parabola (1)	3.41 ± 0.15
Parabola (1.5)	3.42 ± 0.14
Parabola (2)	3.44 ± 0.16

Table 2: Table showing the number of detector hits for each profile shape, now with gaps located between the trenches. The overall trend is almost identical to the texturing with no gaps. However, as could be expected, the number of detector hits decreases when gaps are present.

As expected, the number of detector hits decreased when there were gaps present between the trenches. This is a result of there being flat areas where there once were inclined surfaces, making it easier for rays to escape the cell. It is very odd that the number of detector hits actually increased for the semicircular profile. However, the uncertainty in our measurements could definitely account for this discrepancy. For the parabolas with varying aspect ratios, the trend is identical to the case where the trenches touch. The number of detector hits increases up to an aspect ratio of one, and flattens off as the parabola gets deeper. Therefore, the parabola with unit aspect ratio is still the cross-sectional shape that traps light the best. Additionally, it can be noted that when etching the grooves in the silicon, it is desired to make the trenches as close as possible. Here, with gaps of 11% of the width of the trench, the number of detector hits decreased by 9.5% on average. If the gaps could be minimized, the silicon will trap light better.

4.2 Oblique Incidence

The effect of light striking the surface of the glass at an oblique angle was determined by analyzing the parabola with unit aspect ratio. The results are shown in Table 3.

Angle of Incidence (Degrees)	Detector Hits
0	3.68
10	3.85
20	3.64
30	3.61
40	4.40
50	5.24
60	6.04
70	9.20

Table 3: Table showing the number of detector hits as the angle of incidence increases. The number of hits remains approximately constant up to an angle of incidence of 30°. After that, the number of detector hits grows, and at 70^0 its almost three times the number of hits at vertical incidence.

According to the theory, the total optical path of a ray should increase as the angle of incidence increases. The reason for this lengthening is that rays will now travel at an oblique angle rather than straight into the cell. Since our method records detector hits and not the actual distance that a ray travels, the number of detector hits should be constant with respect to the angle of incidence (according to our modeling assumption). Table 3 shows that the number of detector hits remains constant up to an angle of incidence of approximately 30°. After this, the number of detector hits begins to rise, and at 70°, there are almost three times as many detector hits as there are with vertical incidence.

To better view the data, a graph of detector hits versus the angle of incidence of incoming rays is shown in Figure 16. According to the theory, the graph should be a horizontal line with the number of detector hits constant regardless of the angle of incidence. However, the actual number of detector hits begins to increase slightly at 40°.

The number of hits continues to increase as the angle of incidence increases, and at 70°, the number of hits is 250% of what it was predicted to be.

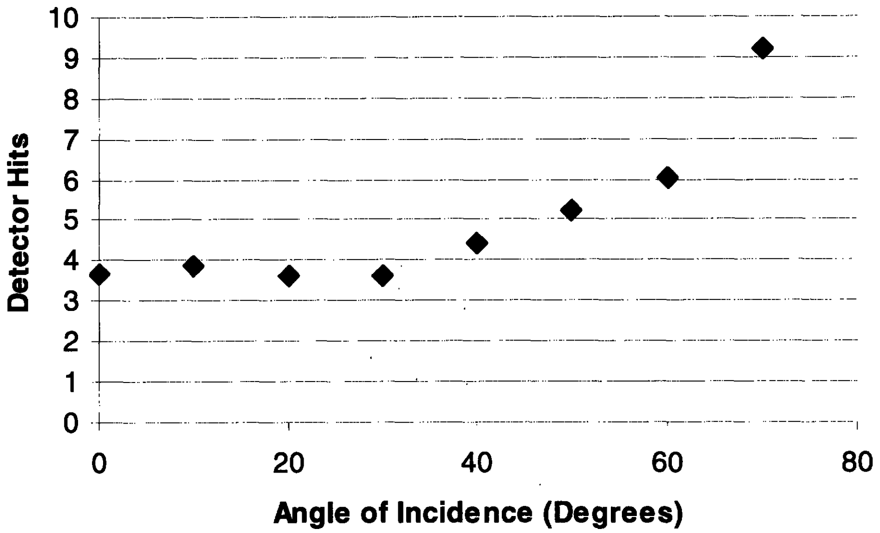

Figure 16: Graph of the number of detector hits versus angle of incidence of light striking the cell. The number of hits remains constant up to an angle of 30°, and increases steadily thereafter.

In modeling oblique incidence, we assumed that the problem could be separated into two different two-dimensional problems. However, according to the results, this assumption is not valid for incident angles greater than 40°. In reality, a light ray is a three-dimensional vector with components in all three dimensions. In order for the detector to record an additional hit, a ray must be internally reflected within the cell. Internal reflection only occurs when the angle of the ray exceeds the critical angle for total internal reflection. Because a ray is a three-dimensional vector, the extra angular component due to oblique incidence must be accounted for to determine if the ray internally reflects. According to the results, the added component due to oblique incidence is negligible for angles up to 40°. After that, the additional angular component significantly affects the number of internal reflections. Therefore, the modeling assumption that we developed is only applicable for incident angles up to 40°.

5. Conclusions and Recommendations

Our initial objective was to determine which texturing profile was most effective in trapping light in the solar cell. Using Zemax to simulate light striking the cell, we determined that a parabolic trench with unit aspect ratio is the optimal texturing shape. Deeper parabolas do not substantially improve the light trapping capabilities of the cell. In addition, the trials with plateaus located between the trenches also show that the unit aspect parabola is the best cross-sectional shape.

Another objective was to determine the effect of rays entering the cell at an oblique angle. We predicted that the number of detector hits should remain constant as the angle of incidence varies. However, the data shows that the angle of incidence actually increases as the angle of incidence increases. The initial purpose of examining oblique incidence was the fear that light might not be trapped as well when it enters at an oblique angle. Therefore, it is not necessarily bad news that the number of detector hits increased as the angle of incidence increases. However, it would be very beneficial to examine this theory further. The first step would be try to develop a three dimensional model of a ray traveling through the cell. Although this would be difficult and complex, it would greatly help in determining the true affects of oblique incidence. Beyond this, it is noted that light entering the cell at an oblique angle will not decrease the light path, but actually help it more than we actually believe.

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