The University of British Columbia
Department of Electrical and Computer Engineering

EECE 492

Photovoltaic Systems and Silicon Solar Cells

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ABSTRACT

In this report an introduction will be given about what a solar cell is and a brief history of how solar cells came to be. Then we will go over the physics and analyze the structure of the solar cell and examine the semiconductor devices used in silicon solar cells. Next the report will go on to talk about silicon solar cells and how it works. The efficiencies of the solar cell will be examined and ways to improve the efficiencies will be brought up in this report. Furthermore, the report will discuss the usage of solar cells being used in photovoltaic systems as photovoltaic modules and arrays. Lastly, the report will discuss the application of photovoltaic systems.

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1.0 INTRODUCTION

A solar cell is a device that uses the suns radiation to produce electrical energy. Thin layers of materials called semiconductors are used to convert the sun light into electrical energy [1]. The most common material used for semiconductor devices is silicon. Therefore, in this report we will discuss the usage of silicon solar cells. The first silicon solar cell was created in 1954 at Bell Laboratories and only had an efficiency of six percent [2]. As more research was put into solar cells in the 1980s, their efficiencies started to increase. In 1985, research laboratories started to achieve efficiencies of 20% [3]. The photovoltaic industry started to grow and by 1997 there was a growth rate of 38% [3]. Currently, solar cells are being used around the world. They can be installed on the roof of someone`s household or photovoltaic plants can be built to produce electrical energy ranging in the megawatts for their surrounding cities [1,3]. What makes solar cells popular is that it is a clean and renewable source of energy. Since fossil fuel is a finite source of energy, we will eventually need to turn towards the use of renewable energy sources. As well, photovoltaics will not be harmful to the environment when compared to fossil fuels [3]. In this report we will review the physics of the solar cell, the basics of silicon solar cells, and its' applications in photovoltaic systems.

2.0 PHYSICS OF SILICON SOLAR CELLS

The silicon solar cell is one of the most popular types of solar cells being used today. Silicon solar cells have a market share of 86% of the market [2]. Below is a cross section of a p-n junction solar cell.

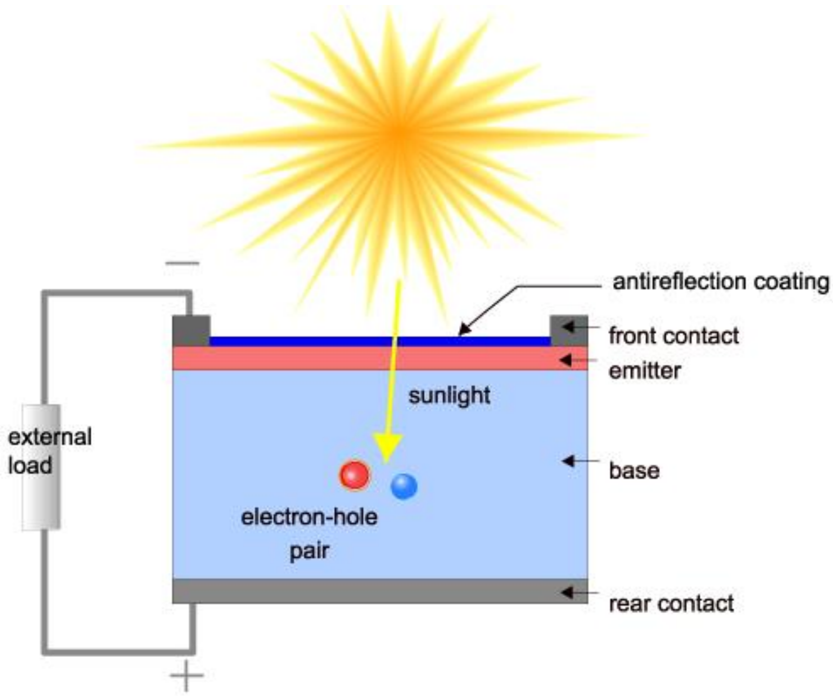

Figure 2.0
Cross Section of a Solar Cell
[3]

Looking at the above cross section we see that a solar cell is a large-area n-p diode which is designed to absorb sunlight and convert it into electrical energy using the photovoltaic effect [4]. The solar cell contains a P junction and an N junction. When the sunlight hits the solar cell an electron-hole pair is created. The electron and hole is then separated and travels through the front and rear contact and travels to the external load to produce electrical energy. In the next section we will go over the basics of a semiconductor to understand why it is important for a solar cell and how electrical energy is produced.

2.1 Semiconductors

A semiconductor contains materials that are from group IV of the periodic table or they can be from a combination of group III and group V or they can be from a combination of group II and group VI. Therefore, the properties of semiconductors can vary between each other. The figure below is the periodic table and the possible highlighted semiconductors [3].

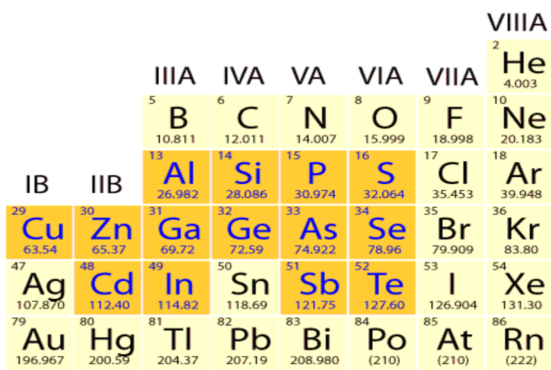

Figure 2.1.1
Periodic Table with the different types of semiconductors
[3]

The main material that will be discussed in this report is silicon because silicon solar cells is one of the most common solar cells being designed today [2]. The main parameters of the silicon semiconductor will be the band gap energy, the number of free carriers for conduction, and the recombination and generation of free electrons/holes because of the illumination of sunlight.

2.1.1 Silicon Semiconductor Structure

A semiconductor is made up of single atoms that bond together. They form an arrangement of atoms that are surrounded by eight electrons. As well, this arrangement is regular and periodic [3]. We will see this on the next figure that each atom contains a nucleus which is made up of a protons and neutrons and it is surrounded by the eight electrons.

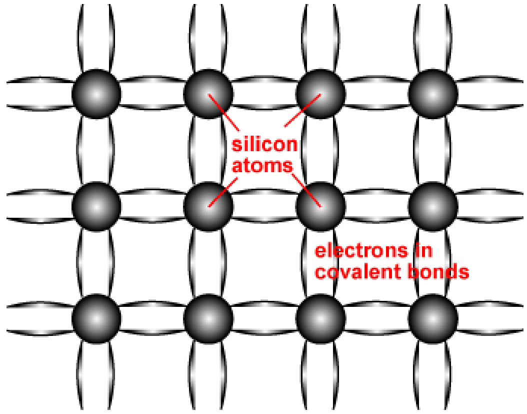

Figure 2.1.1.1
Silicon Crystal Lattice
[3]

As we can see from figure 2.1.1.1, each silicon atom has eight lines connected to it. Each line represents the electrons that touch it. Furthermore, the electrons that surround each silicon atom in the semiconductor are being shared with other atoms and this is called a covalent bond [3]. We observe that each atom is sharing eight electrons between the four surrounding atoms. This is the structure of a silicon semiconductor.

2.1.2 Band Gap Energy

One of the important parameters of semiconductors for the solar cell is the band gap energy. The band gap energy is the minimum energy required to excite an electron from the valence band to the conduction band [3]. In the valence band it is in a bound state and stuck, but when it is excited into the conduction band it is free to participate in conduction [3]. However, an additional conduction occurs in the valence band. When the electron is excited into the conduction band, it leaves an empty space in the valence band. Since there is an empty space in the valence band, a neighbouring electron can start to move into it and then it looks like a hole is moving around in the valence band. Therefore, the electron in the conduction band, and the hole in the valence bond participate in conduction and these electrons and holes are called carriers [3].

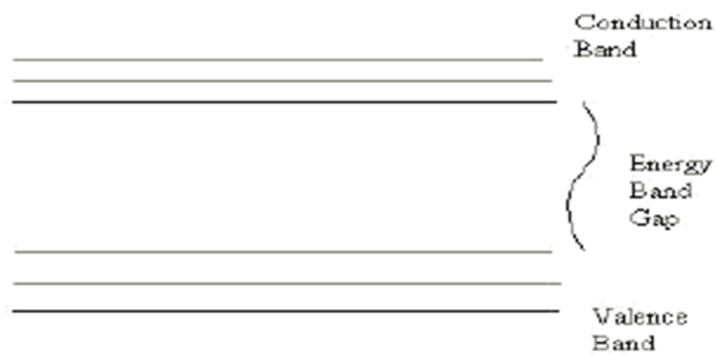

Figure 2.1.2.1
Conduction and Valence Band with the Energy Band Gap

Figure 2.1.2.1 shows an image of what the conduction and valence band looks like. The vertical axis represents different energy levels. So when the electron is excited to the conduction band, it is being brought up to a higher energy level.

2.1.3 Carrier Concentration

From the previous section we learned what free carriers are. Free carriers are the electrons and holes that are participating in conduction. The concentration of these carriers is called the instrinsic carrier concentration [3]. The intrinisic carrier concentration tells us the number of electrons in the conduction band and the number of holes in the valence band. The number of carriers will depend on two parameters; the band gap of the material and the temperature of the material. Therefore, if the band gap of the material is high, the number of carriers will be low and this will affect the conductivity of the material. Later we will learn why the band gap and carrier concentration is important in determining the solar cells efficiencies.

2.1.4 Doping of Semiconductor Materials

From the previous section we learned that silicon requires 4 electrons to bond with another element. Using atoms that contain one more valence electron than silicon to dope the silicon material will create an "n" type semiconductor material [3]. Silicon is typically doped with phosphorous to become an n type semiconductor. Phosphorus uses four of the electrons from silicon to produce covalent bonds. Then there is an extra electron from the phosphorus and because of this extra electron this makes the semiconductor n-type [5]. We can look at it this way, where the orbit of the silicon atom is the valence band, and the electrons that are free and not attached to the silicon atom is in the conduction band. The silicon material can also be p-type by using an element that only has 3 electrons to dope. For example, a dopant used to substitute silicon is boron. Boron only has 3 electrons in the valence band to interact with the other silicon atoms. This means that only three covalent bonds are possible and as a result a hole is present [5].

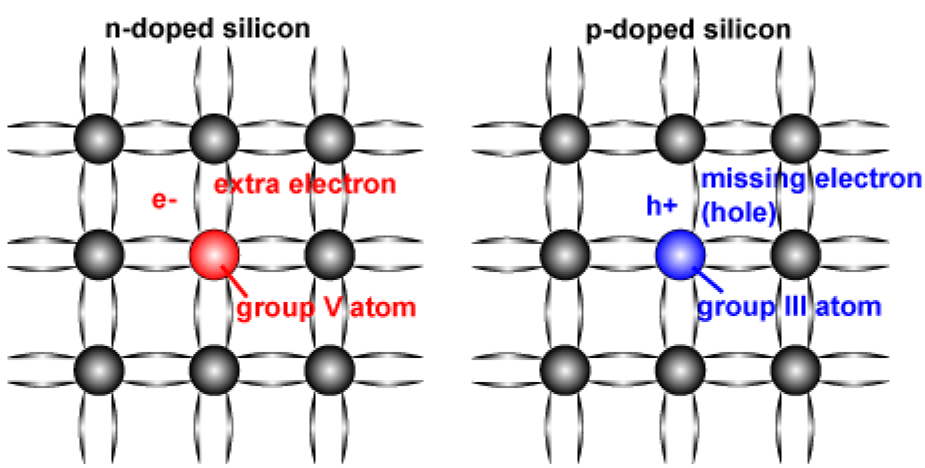

Figure 2.1.4.1
N-type and P-type Doped Silicon Semiconductor
[3]

Looking at figure 2.1.4.1 the n-doped silicon has an extra electron that is not part of the valence band. This electron came from the phosphorus element since it had five electrons and the silicon atom only required four electrons. Looking at the p-doped silicon, one of the covalent bonds is not completed. A hole is present because boron has three electrons instead of four like silicon or five like phosphorus. This makes the semiconductor material p-type.

2.1.5 Semiconductors and Their Absorption of Light

Now we will learn why band gap energy plays an important role in the efficiency of silicon solar cells. When light illuminates onto semiconductors they can either be absorbed, reflected, or nothing will happen. We will later learn that light that is reflected off of semiconductors will decrease the efficiency of the solar cell. However, for now we will not consider reflection, and assume that all the light hits the semiconductor. Sunlight contains photons and we know that these photons have energy because they have different wavelength [3]. This energy can be described by:

$$Ephoton = \frac{hc}{\lambda}$$

Equation 2.1.5.1
Energy of a Photon from incident Light
[3]

After the photons hit the semiconductor it can either be absorbed by the semiconductor or it just passes through the material. To determine if the photons are being absorbed the energy of the photons must be greater than or equal to the band gap energy of the semiconductor. If the energy of the photon is greater than the band gap energy that means the photon will have enough energy to excite the electrons out of the valence band and into the conduction band. Thus, carriers are generated (These can also be called electron-hole pairs).

There are three cases that can occur. The first case is when the energy of the photon is less than the band gap energy. In this case the electron in the valence band will not be excited into the conduction band and the photon is not absorbed. The second case is when the energy of the photon is equal to the band gap energy. In this case the electron is excited into the conduction band from the valence band. An electron-hole pair is created and the photon is efficiently absorbed. Finally, in the last case the energy of the photon is greater than the energy of the band gap and this means the electron is excited into the conduction band, but it is excited to a much higher energy state. However, the electron will release the excess energy as thermal energy to fall back down to the edge of the conduction band. The thermal energy is considered to be a waste of energy and will be one of the reasons why the efficiency of solar cells is small [3]. The absorption of photons will be important for solar cells because this will determine the generation of current of a solar cell.

2.1.6 Recombination

After when the electron is excited into the conduction band it is in a meta-stable state. It will eventually stabilize and go to a lower energy state in the valence band. When the electron goes back into the valence band, it will eliminate the hole and this process is called recombination. In silicon solar cells, there are two main types of recombination that occur. The first type of recombination is auger recombination. This recombination involves three carriers. When an electron and hole recombine, energy is given to another carrier (another electron in the conduction band) which eventually establishes itself back to the conduction band edge [3]. The second type of recombination that occurs is due to defects in the semiconductor material. This recombination is also called the Shockley-Read-Hall recombination. This type of recombination only occurs in materials that have defects in it and no silicon solar cell is perfect. What happens is the electron (it can be the hole) is trapped by a certain energy level in a region that was produced because of the defects in the silicon crystal then a hole (or electron) goes into that region before the electron is moved to the conduction band and they recombine. We will later find out that recombination is not good for solar cells because no current or power can be generated [3]. There are other details about recombination, for example the time it takes before it recombines, but this report will not go over the specifics.

2.2 P-N Junction

From figure 2.0 we learned that the structure of silicon solar cells is a p-n junction diode. This means that the silicon solar cell is a combination of an n-type semiconductor and p-type semiconductor material. This will be important in solar cells because in p-n junctions potential energy barriers are formed and this will facilitate the separation of the electron-hole pairs generated from photons into a current [3].

In a p-n junction when an n-type and p-type material is joined this causes excess electrons from the n-type material to diffuse to the p-type material. The same idea occurs in the p-type material where the holes diffuse to the n-type material. Diffusion occurs because it is trying to reach an equilibrium state. However, when the electrons move to the p-type material it leaves behind positive ion cores in the n-type material. The same occurs for the holes that leave the p-type material. It leaves negative ion cores in the p-type material. This then causes an electrical field to occur and a depletion region (the barrier) is formed. As well, a built-in voltage is formed in this region [3].

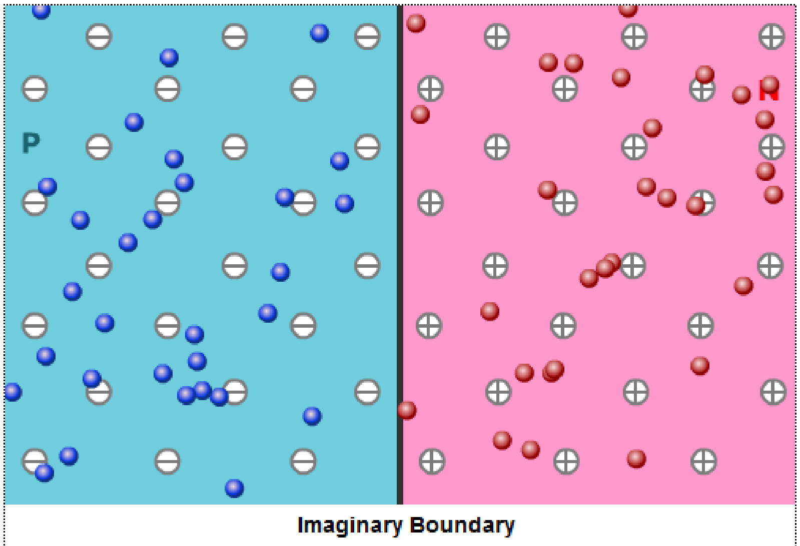

Figure 2.2.1
P (blue) and N (red) type semiconductor separated.
[3]

Figure 2.2.1 represents two different types of materials, one being n-type and the other being p-type. However, once we combine them this occurs:

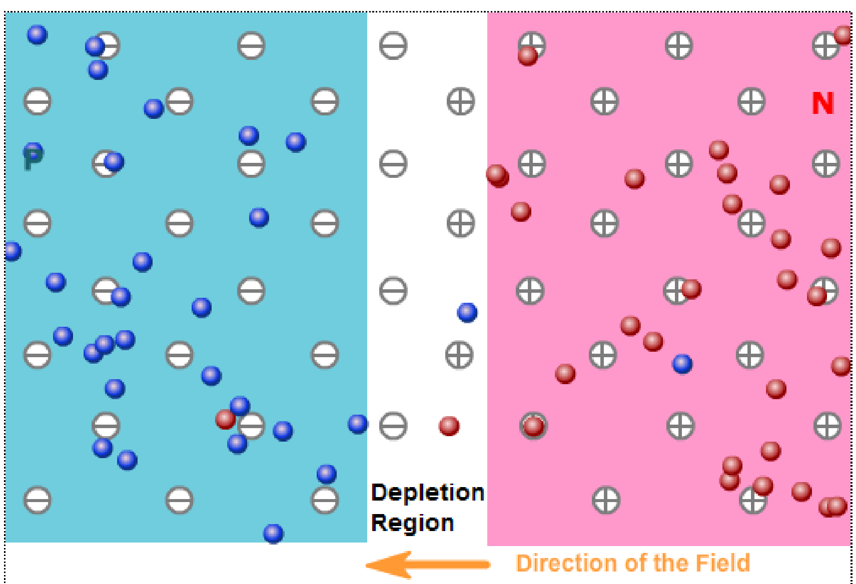

Figure 2.2.2
N-type (red) and P-type (blue) Material Combined to form a P-N Junction
[3]

Looking at figure 2.2.2 we can see that when both of the materials are combined we observe that carriers are crossing into the opposite region. The ions left behind due to electrons and holes drifting will cause an electric field going from the n-type to the p-type region. Furthermore, the depletion region is formed. Next we will look at the case where the p-n junction is being biased by a voltage.

2.2.1 P-N Junction Under Bias

Semiconductors have three modes of operation, but we will only look at one case, the steady state case. In this case there is an external input like an applied voltage, but in the case of solar cells it will be the light from the sun [3]. The first steady state case that will be observed is when the p-n junction is under a forward bias.

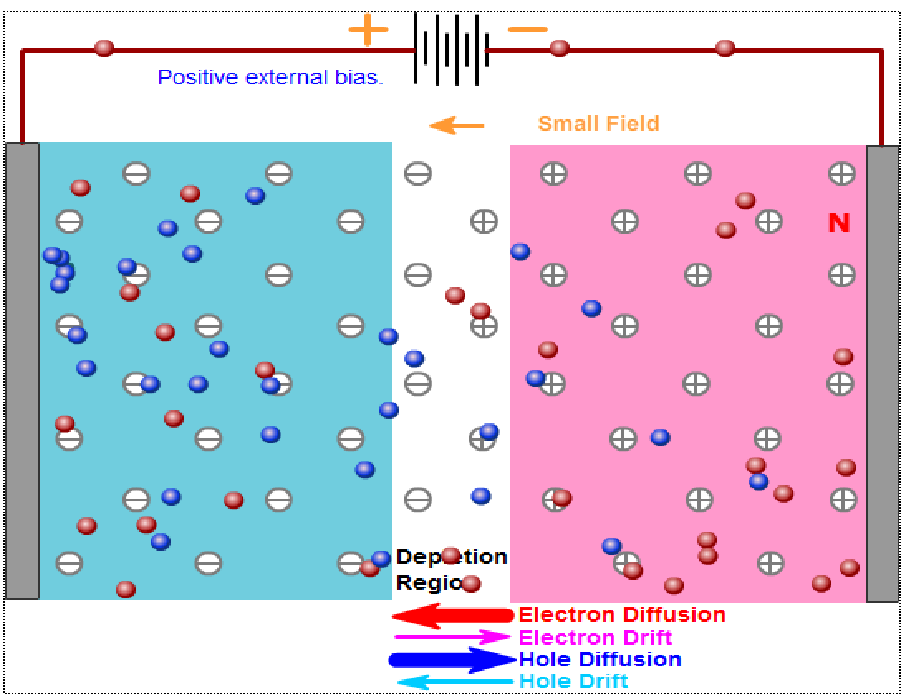

Figure 2.2.1.1
P-N Junction under Forward Bias
[3]

Looking at Figure 2.2.1.1 a forward bias p-n Junction is when the applied potential on the n-side is in contact with the negative part of the bias, while the p-side is in contact with the positive part of the bias. As well, the electric field between the depletion region is lowered. The reason why is because when the p-n junction is forward biased it creates an electric field that goes in the opposite direction of the field in the depletion region. Therefore, if the electric field is lowered in the depletion region it is easier for electrons and holes to diffuse across the depletion region because the potential barrier is reduced [7]. This leads to electrons from the n-side going to the p-side of the junction generating a current. Looking at figure 2.2.1.1 we observe that electrons are travelling from the p-side to the n-side and then through the wire.

In the second case there is a reverse bias. The positive potential is applied to the n-side contact. In this case the barrier of the depletion region is increased. Since the barrier is increased the electrons on the n-side do not have enough energy to diffuse over the barrier to the p-side then the current is mostly from the p-side having electrons drifting to the n-side [7].

Now that we know that the silicon solar cell is made up of p and n type semiconductor materials, we can now examine and discuss the silicon solar cell.

3.0 SILICON SOLAR CELLS

After learning about what a semiconductor is and what makes the silicon solar cell we can now look at the silicon solar cell and examine how the silicon solar cell works. We will also go over the equivalent circuit model and how to determine the efficiency of the silicon solar cell.

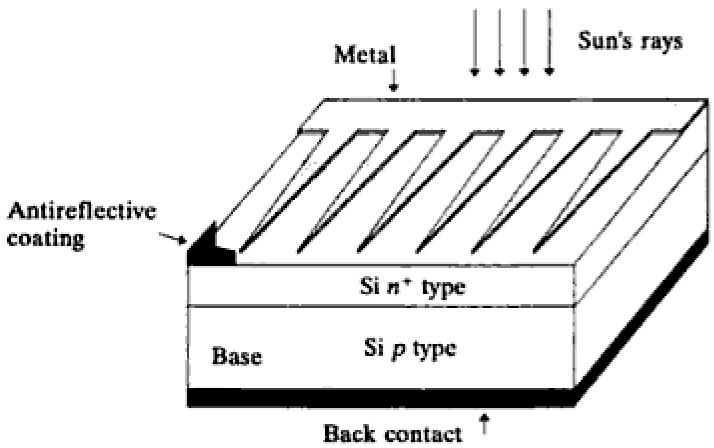

Figure 3.0.1
Structure of Silicon Solar Cell
[6]

Looking at figure 3.0.1 we now know what this structure represents. It is a p-m junction silicon solar cell. The silicon has been doped to make it p-type, and it has also been doped to make it an n-type material. The n-side can also be called the emitter, and the p-side is also known as the base in this figure. With both the silicon materials combined it has become a p-n junction silicon solar cell. We also learned from the previous section that a electric field is produced and this electric field will be responsible in separating the electron-hole pairs formed when the solar cell is illuminated by sunlight [6]. The electrons and hole will travel through the metal and back contacts when they are separated. Lastly, an antireflective coating is added on top of the solar cell where the light will hit to decrease the amount of incident light being reflected.

3.1 Silicon Solar Cell Operation

When sunlight hits the silicon solar cell, the solar cell can either absorb the photon, or the photon can pass through. We learned from the previous section that the band gap energy of the materials plays a crucial role in the absorption of photons. We know that the energy of the photon has to be equal to or greater than the band gap energy of the solar cell. Silicon has a band gap energy of approximately 1.12 eV(electron Volt) [4].

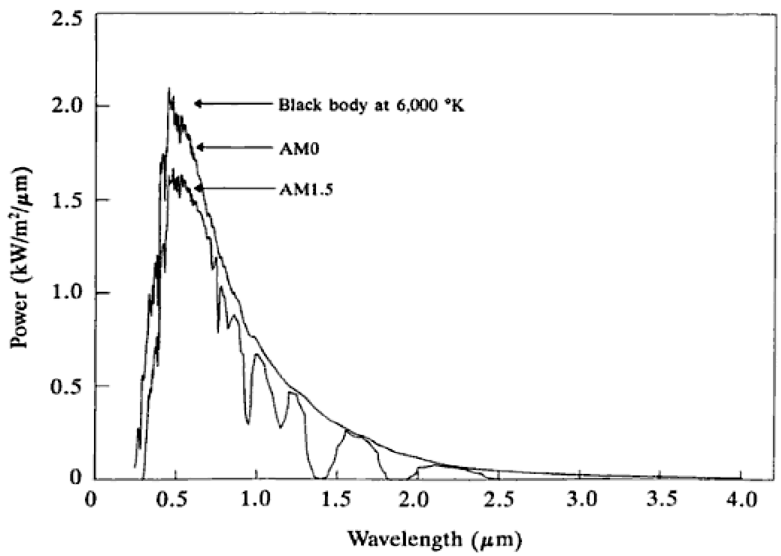

Figure 3.1.1
Solar Spectral irradiance
[6]

Looking at the graph above, figure 3.1.1, we can see what the wavelength of each photon is. The goal of solar cells is to be able to convert as much of this as possible. However, using single material solar cells will not be possible. The reason is because the band gap of silicon is 1.12 eV. Therefore, silicon solar cells can only absorb photons that have an energy of 1.12 eV or higher. Even when it absorbs energy that is higher than 1.12 eV it will have energy lost to heat due to excess energy [6].

Now looking at the photons that do get absorbed by the solar cell we can connect the solar cell to a load. The electric field will be produced across this load and this will generate current by separating the electron-hole pairs generated. Therefore, the solar cell is functioning as a generator of electrical energy.

3.2 Generation of Current in Silicon Solar Cell

To generate current in the solar cell there are two processes that occur. The first process has been discussed and that is the absorption of the photons that hit the device to generate electron-hole pairs [3]. The second process is the collection of these electron-hole pairs by the p-n junction. The p-n junction will not let these electron-hole pairs recombine. The carriers are separated by the electric field that is produced by the p-n junction. If the hole for example reaches the junction from the n-side, it will be swept across the junction by the electric field into the p-side. We can connect the emitter and the base to show a short-circuited current.

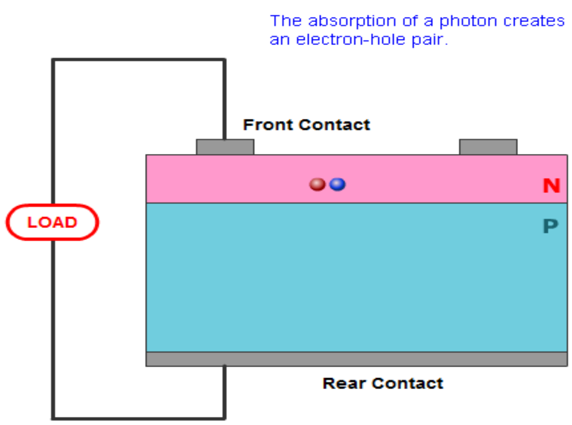

Figure 3.2.1
Generation of an Electron-Hole Pair
[3]

In figure 3.2.1 the light is illuminated onto the solar cell and an electron-hole pair is generated. The electron hole-pair is then separated and the electron travels through the wire as we will see on figure 3.2.2.

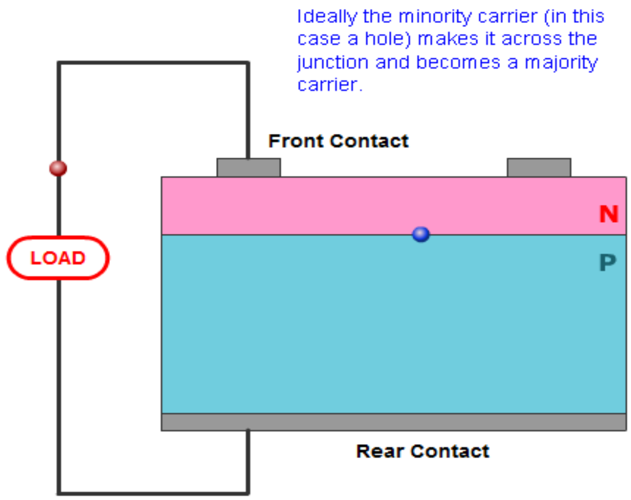

Figure 3.2.2
Generation of a Short Circuited Current
[3]

As we can see from figure 3.2.2 the hole, the minority carrier, is then pushed into the p-side where it becomes a majority carrier. The electron then travels through the short-circuited wire generating current. However, since the electron-hole pair is meta-stable there is a certain time that they will recombine, and if they recombine then no current or power will be generated [3].

Furthermore, there is a collection probability if the electron-hole pair will be collected by the p-n junction to contribute to the light-generated current [3]. This probability depends on the region the electron-hole pair is generated. If the electron-hole pair is generated in the depletion region it will be separated apart by the electric field right away, so the probability in the depletion region is 1, but as it moves further away from the junction the probability decreases and this means there is a higher chance of recombination [3].

3.3 The Photovoltage

We learned about light-generated carriers (electron-hole pairs), but this by itself does not generate power. For power to be generated a voltage is needed as well. We learned before that the carriers are separated by the field of the p-n junction. The electrons move to the n-side and the holes move to the p-side and in short circuit conditions the electrons can leave the solar cell and generate a short circuit current.

However, if we do not let the electrons and holes leave the circuit this causes the carriers to build up at the junctions and increase the number of electrons in the n-side and the number of holes in the p-side. This generates an electric field that opposes the electric field in the depletion region. Because the electric field in the depletion region is decreased, the potential barrier is decreased and this allows diffusion current to increase and for recombination to occur. Therefore, the forward bias current is increased and under open-circuit conditions the forward bias current is equal to the photo generated current [3]. This forward bias current is also called the "dark current" [6]. Thus, the net current is equal to zero when the solar cell is open-circuit and producing a open-circuit voltage. However, we will later learn that we cannot use the open-circuit voltage to generate power just like we cannot use the short-circuit current to generate power.

3.4 The Dark Current

In the previous section we learned about the dark current and how it is generated under open-circuit conditions. Since carriers are building up on both sides of the junctions there will be some electrons in the p-side and some holes in the n-side. Furthermore, since the barrier is lowered due to the decrease in the electric field there will be diffusion occurring. This means that recombination will occur in the p-side, n-side and the depletion region [6].

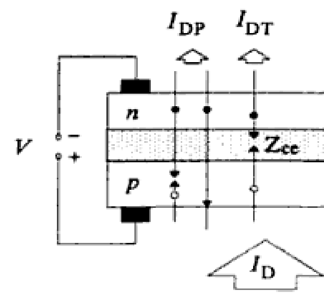

Figure 3.4.1
Components of the Dark Current (Black dots are electrons) (White dots is holes)
[6]

Figure 3.4.1 shows us how the dark current is generated by recombination because of the bias voltage. Looking at I_{DP} we see that it is generated by the electron recombining with the hole as it enters into the p-region. This is also how the current I_{DN} is generated, but instead the hole enters into the n-region and recombines with an electron. Lastly, I_{DT} is generated by the electron and hole recombining in the depletion region [6].

As well, the dark currents can vary exponentially when considering the bias voltage. Therefore the dark currents can be represented as,

$$I_D(V) = I_0 \left[\exp \frac{eV}{mkT} - 1 \right]$$

Equation 3.4.2
Exponential Representation of the Dark Current
[6]

Where Io represents the "dark" saturation current,
V is the bias voltage
ID is the dark current

eV is an electron volt
k is the boltzmann's constant
T is the absolute temperature.

Io is an important parameter because this determines the recombination current and if there is more recombination occurring that means Io will be larger [3].

Now that we have determined the generated current from the solar cell and the dark current we can determine an equivalent circuit model.

3.5 Equivalent Circuit Model of Silicon Solar Cells

We learned about the generated current from the solar cell and the dark that is generated by the bias voltage. Now we see what the equivalent circuit model looks like.

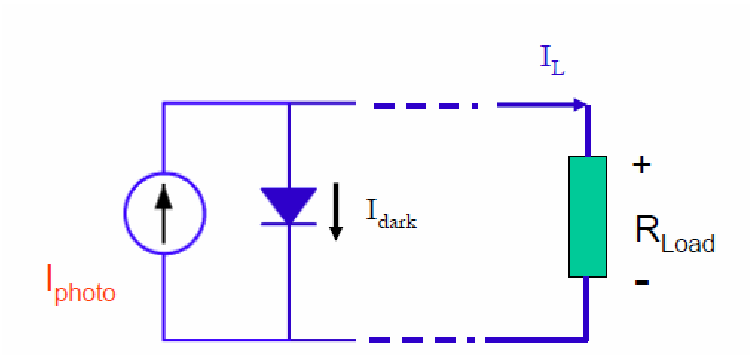

Figure 3.5.1
Equivalent Circuit Model of Silicon Solar Cells
[8]

Looking at figure 3.5.1 we see that a current across the load resistance will generate a voltage; however, the generated voltage will give us a dark current. From looking at the model we see the equation becomes:

$$I_L = Iphoto - I_{Dark}$$

Equation 3.5.2
Total Current
[8]

Therefore, the dark current can take away from the photo generated current. However looking at the circuit we see that if we make the load resistance really small the dark current will be equal to zero and that the output current will be equal to the photo generated current (This is the short-circuit current case where the voltage drop will be very small). However, if we make the load resistance really large we end up getting the open-circuit voltage case and the dark current is equal to the photo generated current. This will make our total current equal to zero and this makes sense because no current can travel through an open-circuit. If we plug in equation 3.4.2 into equation 3.5.2 for the dark current we will produce a graph that looks like this,

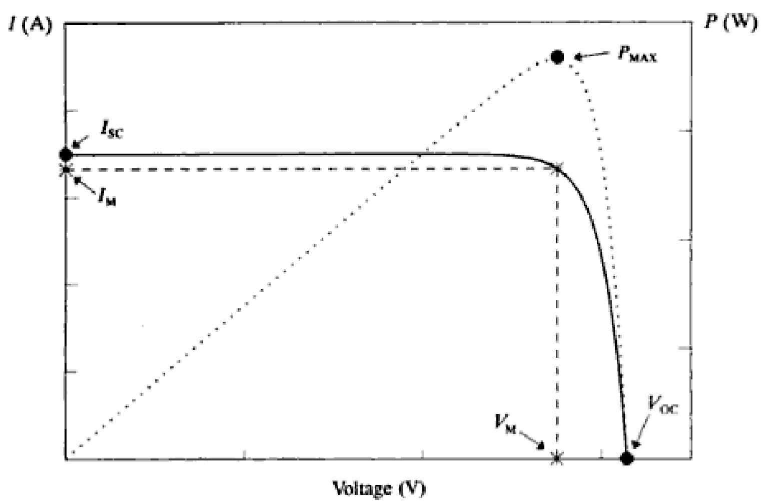

Figure 3.5.3
Current-Voltage (I-V) Characteristic Curve of Silicon Solar Cells
[6]

Looking at this graph we can see why the short-circuit current and open-circuit voltage is not reasonable to generate power. If we choose either one, we will get a value of zero for the other parameter. Therefore, to get the maximum power, the maximum voltage and maximum current needs to be found. These two points will give the largest area under the I-V curve. This point that gives you the maximum power is also called the maximum power point [8].

3.5.1 Efficiency of Silicon Solar Cells

Using the IV curve from the previous section we can determine the fill factor which represents the maximum power attainable from a solar cell. The fill factor is a ratio between the maximum power attainable by the solar cell divided by the product of short-circuit current and open-circuit voltage.

$$FF = \frac{I_M V_M}{I_{SC} V_{OC}}$$

Equation 3.5.1.1
Fill Factor
[6]

Therefore we can determine the maximum power generated by the solar cell,

$$P_M = FF\ I_{SC} V_{OC}$$

Equation 3.5.1.2
Maximum Power
[6]

Then we can determine the efficiency of the solar cell,

$$\eta \equiv \frac{I_M V_M}{P_L} \equiv \frac{FF\ I_{SC} V_{OC}}{P_L}$$

Equation 3.5.1.3
Efficiency of a Solar Cell
[6]

PL is the total power that is coming from the sun light that is absorbed by the solar cell.

In this section of the report we have determined how to calculate the theoretical efficiency of silicon solar cells. We have learned how silicon solar cells work, but the efficiency of the silicon solar cell is only 24.7 % [4]. From previous sections we learned that the efficiency is low because of the band gap of the silicon, the short-circuit current and open-circuit voltage is not attainable, and the recombination of electron-hole pairs. However, another factor that affects the efficiency of the solar cell is light being reflected off it.

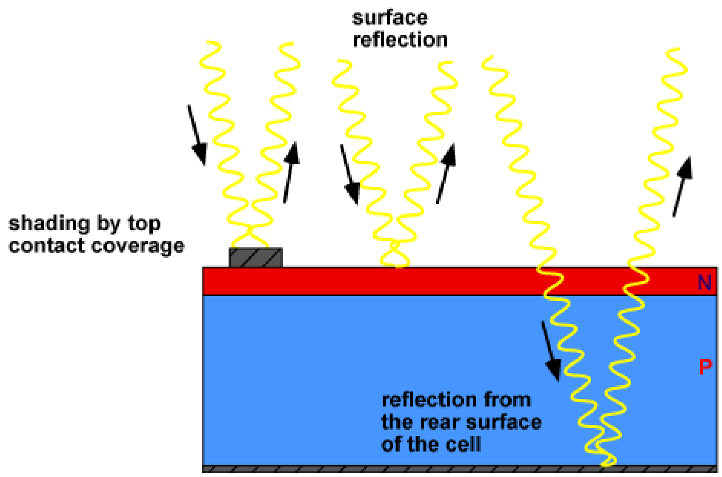

Figure 3.5.1.4
Optical Losses on Silicon Solar Cells
[3]

In figure 3.5.1.4 we see that light is being reflected at the top of the solar cell and this is causing the efficiency of the solar cell to decrease. There are ways to reduce the optical losses and that is by adding anti-reflection coatings on top of the surface of the cell and surface texting can be done on top of the cell.

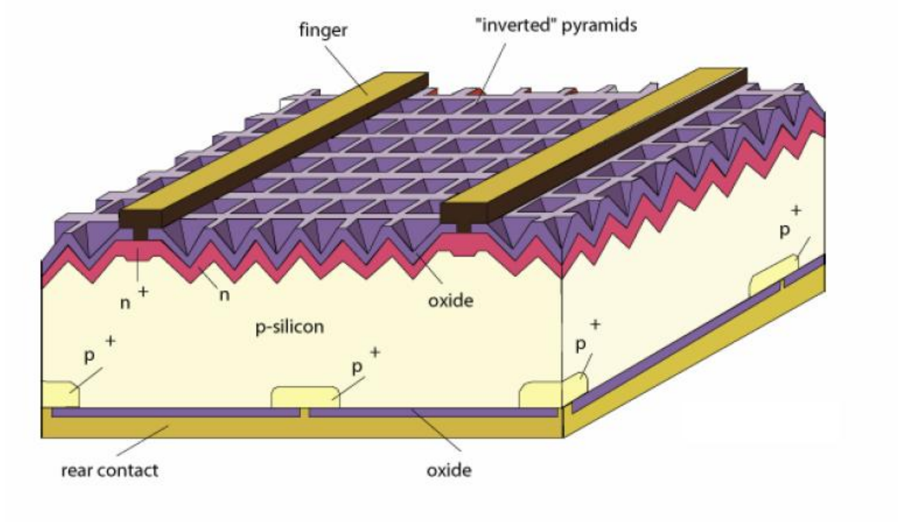

Figure 3.5.1.5
Solar Cell Structure
[4]

In figure 3.5.1.5 we can see that surface texturing has been done to the top of the solar cell. The surface has an egg like carton shape and when light hits it, if it gets reflected it has the chance to hit another side to get absorbed by the solar cell [4].

Overall, the silicon solar sell is a device that is able to convert sun light into electrical energy. The efficiency of silicon solar cells can still be improved on if we limit the amount of recombination that occurs in the cell when the carriers are generated. Furthermore, efficiency can be increased by using anti-reflective coatings to prevent light being reflected from the solar cell.

4.0 MODULES AND ARRAYS OF SILICON SOLAR CELLS

We learned about silicon solar cells in the previous section, however in applications the amount of solar cells used is a lot more than just one. Typically a module structure consists of 36 solar cells connected in series [3]. We will call these photovoltaic modules (PV modules). There are many different types of PV modules and these modules can last over 20 years [3].

4.1 Module Circuit Design

A PV module consists of 36 silicon solar cells all connected in series to increase the power and voltage compared to a single solar cell. The voltage of the PV module is chosen to work with a 12V battery [3].

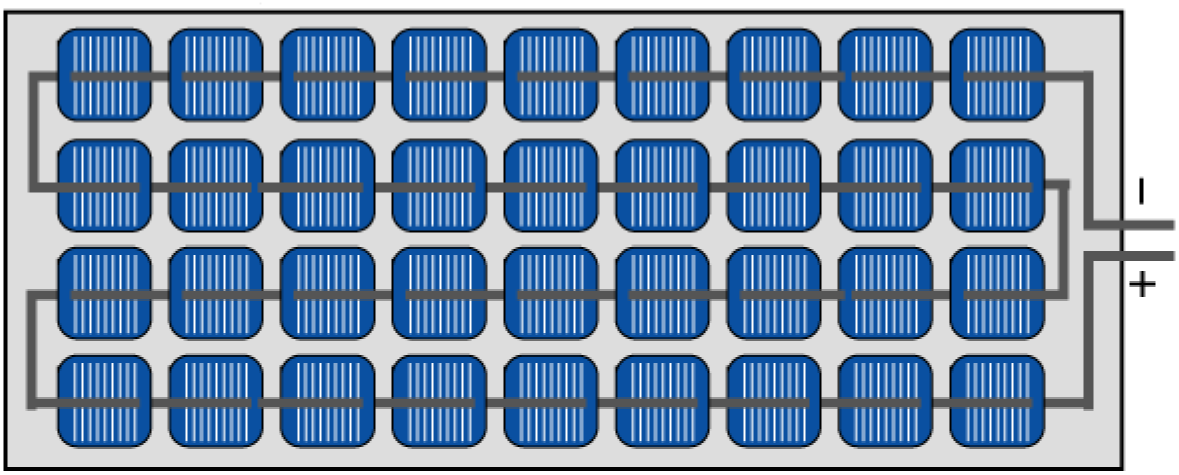

Figure 4.1.1
PV Module (36 Solar Cells in Series)
[3]

We can determine the maximum power point of this PV module the same way as we did before for the individual solar cell. Since all the solar cells in this PV module have the same electrical characteristic and they experience the same insulation and temperature this means that all the cells will operate at the same voltage and current [3]. The I-V curve of this PV module is the same for a single solar cell except it is scaled by the amount of solar cells there are connected in series or parallel. This PV module can then be represented by this equation,

$$I_T = M \cdot I_L - M \cdot I_0 \left[\exp\left(\frac{q \frac{V_T}{N}}{nkT} \right) \right]$$

Equation 4.1.2
Output Current of the PV Module
[3]

IT represents the output current
M represents the number of cells in parallel
N represents the number of cells in series
VT is the total voltage from the circuit
Io is the saturation current from a single cell
n is the ideality factor of a single cell

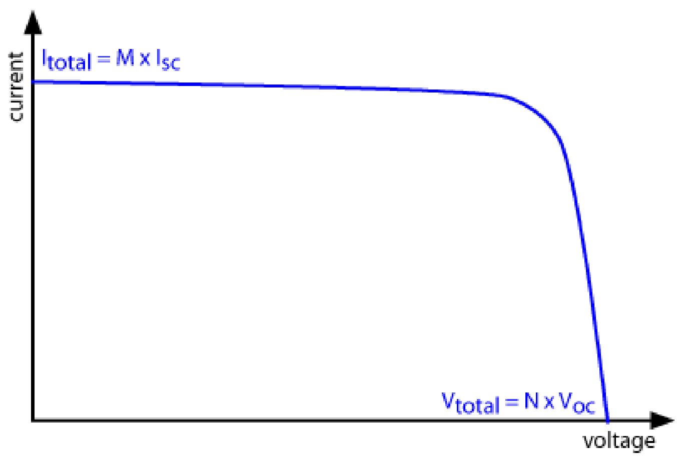

Figure 4.1.3
I-V Curve of a PV module
[3]

Looking at the above figure we see that the current does not scale up when we add more solar cells in series, and the only thing that changes is the open circuit voltage. However, the current can be scaled up if the cells are connected in parallel.

4.1.1 PV Module Materials

PV modules built need to endure different types of environment. The solar cells can be easily damaged if it is not protected in some sort of way when put into harsh environments. Solar cells are thin and they can be mechanically damaged and the electrical contacts can be damaged by rain or water vapour [3]. Therefore, the solar cells need to be protected by an outer shell.

To protect the PV modules a transparent surface is put on top of the solar cell. An encapsulant and frame is put around the outer edge of the module. As well, there is a rear layer in the back of the solar cell.

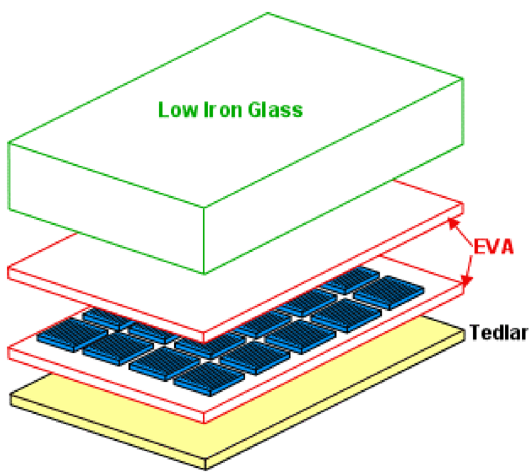

Figure 4.1.1.1
PV module
[3]

Looking at figure 4.1.1.1 we can see how the PV module is protected.

When choosing the front surface material, the glass needs to have a high transmission of light with wavelengths that the solar cells can absorb and it should have a low reflection ratio. We learned from previous sections we can use anti-reflective coating; however, in this case we cannot because it cannot withstand certain weather conditions [3]. Lastly, the front surface needs to be impervious to water, it has to be able to withstand UV exposure and it has to have low thermal resistivity [3].

Next an encapsulant is used to provide the solar cells adhesion between the top and rear surfaces of the PV module [3]. This encapsulant (in our case EVA, ethyl vinyl acetate) needs to be able to withstand UV exposure, be optically transparent, and be stable at certain temperatures [3]. Then the encapsulant is then heated up to bond the whole PV module together.

Next a rear surface is used to prevent water from getting into the modules. As well, the rear surface needs to have a low thermal resistance. Typically Tedlar is used as the rear surface [3]. Lastly, a frame is put around the PV model. This is how the PV module is protected and designed to withstand different environments and weather conditions.

4.2 Mismatch Losses

If the solar cells in a PV module do not have similar electrical properties this could lead to mismatch losses. As well if the solar cells in the module experience different conditions this could also lead to mismatch losses. The reason why this is a problem is because if there are mismatch losses the output of the PV module will be determined by the worst solar cell in the module [3]. For example if one of the cells is shaded and the others are not this could lead to the cell that is shaded dissipating power instead of powering the load [3]. If the cell is dissipating power it could lead to damages to the module [3]. Next we will go over the different types of mismatches that could occur.

4.2.1 Mismatch Losses of Cells Connected in Series

One of the popular types of PV modules is solar cells connected in series. We saw one in the previous section with 36 silicon solar cells connected in series.

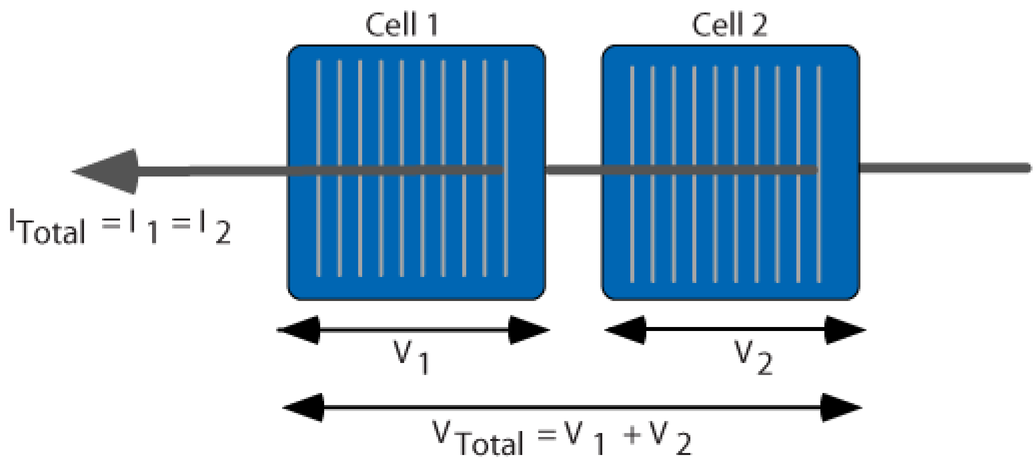

Figure 4.2.1.1
PV Module of Two Cells Connected in Series
[3]

As we can see from figure 4.2.1.1 when cells are connected in series the total current is the current coming from one of the solar cell; however, the total voltage output is all the voltages added up of each cell. In this case, if there is a mismatch between the currents in the PV module, the output current will be equal to the solar cell producing the lowest current. There are two types of mismatches that can occur in the PV module. The first mismatch is the open-circuit voltage mismatch. Looking at figure 4.2.1.1 if one of the voltages is decreased this means the total voltage is decreased, but the current does not change [3]. This this leads to a PV module generating less power. The second case is when there is short-circuit current mismatch. This leads to one of the currents being lower than the other solar cells. The total current will be of the lowest producing current solar cell and this will lead to lower power being generated.

4.2.2 Shading

The short-circuit current mismatch can occur when the PV module is being shaded (covered). If one of the solar cells is shaded the output current will be the current that is produced by this shaded solar cell [3].

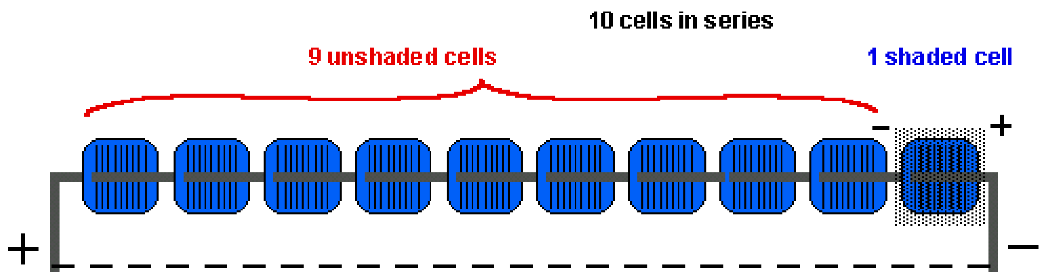

Figure 4.2.2.1
Shading of a PV module
[3]

Furthermore, hot-spot heating can occur when one of the cells is shaded. If the PV module produces the short-circuit current of the bad cell the extra current produced by the unshaded cells will forward bias themselves. This in turn makes the shaded cell become reverse bias and the extra current is then dissipated over the shaded cell. This leads to an increase in heat over the one shaded cell and eventually damages the shaded cell and makes it become defective [3].

An approach to this problem is using a bypass diode. A bypass diode is placed in parallel of the solar cell with opposite polarity. If there are no cells shaded, the diode will become reverse biased and act as an open-circuit. However, when one of the solar cells becomes shaded the bypass diode will start to conduct and this will then allow the total current to flow into the external circuit [3]. The extra current will not forward bias the unshaded cells and the reverse bias across the shaded cell is reduced by the diode.

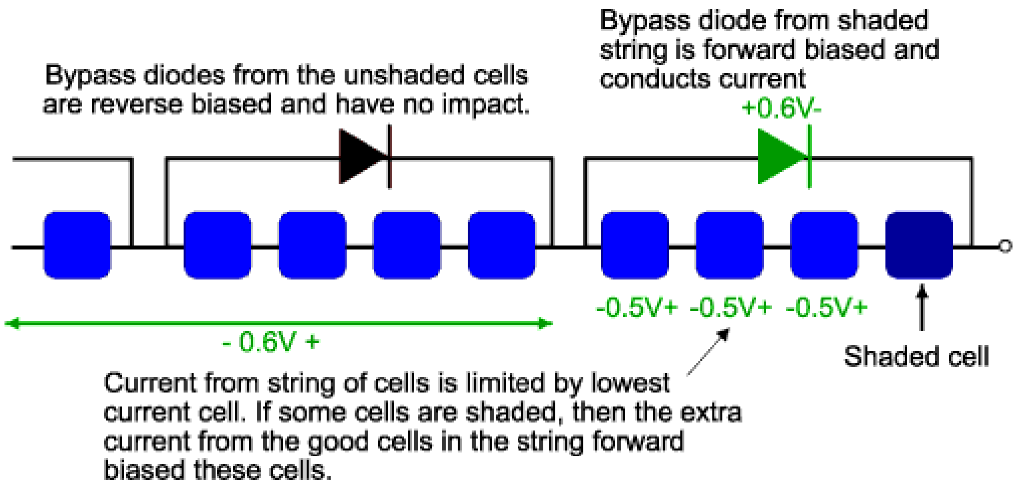

Figure 4.2.2.2
Bypass Diode being used on Several Solar Cells
[3]

Since it would be too expensive to use a single diode for each silicon solar cell, they are placed across groups of solar cells [3]. As the cell is shaded in figure 4.2.2.2 the diode conducts and current travels through the diode. Therefore, using bypass diodes, photovoltaic modules can deal with coverage issues.

4.2.3 Mismatch effects in Arrays

As we move onto using more PV modules, we will eventually create arrays of individual PV modules that will be connected in parallel and series. A problem that can come from arrays of PV modules is an open-circuit in one of the series string. This will lead to a decrease in the total output current and thus lead to a decrease in power generation.

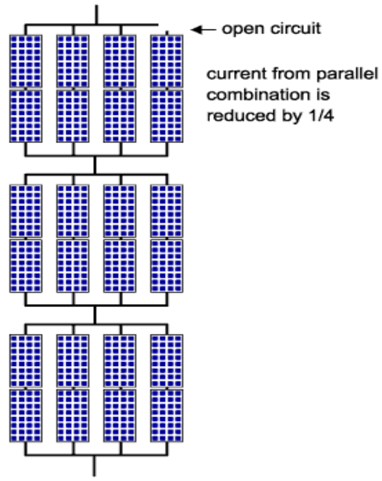

Figure 4.2.3.1
Array of PV Modules with an open-circuit
[3]

This open circuit can occur if the array of PV modules is shaded. Figure 4.2.3.1 shows the worst case that can happen and that is when no current is going through one of the series PV modules. This leads to a decrease in power generation.

We learned before that a bypass diode can help a PV module when there are mismatches, but sometimes the bypass diode can create problems in an array of PV modules.

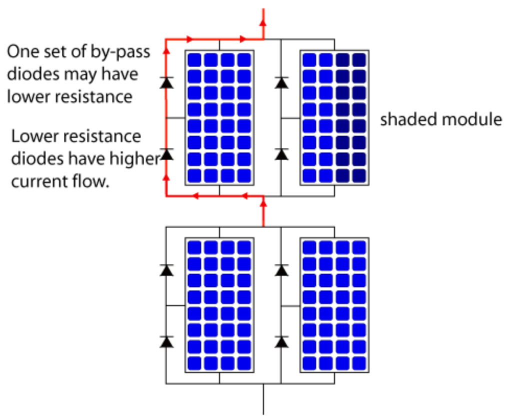

Figure 4.2.3.2
Bypass diodes in a PV array Module
[3]

In figure 4.2.3.2 we see that when there is a mismatch in the PV module, the bypass diode will conduct and current will travel through it. But, if there is too much current going into the bypass diode the diode will heat up. If the diode is heated up the effective resistance of it will decrease. This means more current will flow into the bypass diode and this will cause heat issues and this can lead to damaging the PV modules.

4.3 PV Module Temperature

Since the solar cells in the PV module are encapsulated, it is altering the heat that flows into and out of the PV module. Therefore, this increases the temperature of the PV module. The increase in temperature of the PV module will decrease the voltage and this will lead to the output power decreasing. Furthermore, increasing the temperature will damage the PV module because of thermal expansion [3].

5.0 APPLICATIONS OF PHOTOVOLTAIC MODULES

The amount of PV module applications is numerous. In this section we will go over some of the different types of applications PV modules have been used for.

5.1 Building- Integrated Photovoltaics (BIPV)

One of the main applications of PV modules is building-integrated photovoltaics (BIPV). These are buildings that contain photovoltaic modules built into them. The first installation of BIPV was in 1991 in Aachen, Germany [9]. The PV modules were added into the curtain wall facade with isolating glass. Today there are PV modules which are designed for the sole purpose of integrating them into buildings. They are able to fit into standard facade and roof structures [9].

Figure 5.0.1
BIPV in the facades
[9]

The application of BIPV has become so big that products have been developed specifically for this application [10]. For example a roof tile was made with PV modules and it could be laid out and nailed onto the roofs of homes just like normal roof tiles [10]. Buildings will be the most ideal structure to install PV systems because they will provide the demand for energy to things close by [10].

5.2 Satellites

One of the first applications of PV modules is satellites integrating PV modules. Satellites needed a reliable source of energy, but it also needed to be light in weight. The best choice for this application was PV modules even though they were expensive. The PV modules were an ideal choice for the satellites because it could use the sun's energy and did not have to be changed as often as batteries, so they were reliable [10].

5.3 Remote Industries

Some industries required PV applications and they were also cost effective to use. For example telecommunication industries used PV systems to power relay and repeater stations and power telephones in remote areas [10]. Furthermore, PV systems have been used for cathodic protection. Metals in remote areas needed protection from corrosion, and to stop this corrosion a small DC voltage is needed and these can be long pipe lines that need to be taken care of in the middle of nowhere. Thus, PVs are used to provide power along the lines at regular intervals to stop the pipes from corrosion [10].

5.4 Grid-Connected Systems

One of the ideas of using PV modules is to have a small-scale grid connection. This idea is where in a grid connected systems there will be small generators connected to the grid and these small generators will be produced by self-producers who are using PV systems to generate power. Thus, there will not only be one main centralised electricity distributor [10]. This is different from what we are use to because usually there is only one main centralised electricity distributor and these are the large-scale generating plants. However, the main distributor can collect power from the self-producers. In doing so, they can maximise savings in utility upstream operations and then using PV systems they can fully exploit the economic benefits of using them [10]. Since large portions of electricity is consumed in buildings, the best place to add the PV modules is the building itself.

6.0 CONCLUSION

In this report an overview of silicon solar cells was given. Solar cells are a renewable and clean source of energy. The physics behind silicon solar cells is complicated, but there are many applications it can be used for. The silicon solar cell is made up of two semiconductor material and the efficiency of the solar cell is affected by certain parameters like the band gap energy of the semiconductor and the recombination of carriers in the semiconductor material. The efficiency of the silicon solar cell can still be improved on through the design of the silicon solar cell. Furthermore, there are many applications that use these solar cells. Using silicon solar cells as photovoltaic modules is a challenging task still due to environmental conditions and the mismatches that can occur, however through careful engineering and designing of photovoltaics it can be made into a reliable source of energy. Not only will it be clean energy, but it will also be renewable source of energy. Furthermore, as utility companies become more favourable over small grid-connected systems, photovoltaics will start to become more popular because it will directly supply power to the people who use the electrical energy.

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