A Review of Silicon Based Solar Cells and Gallium Arsenide Based Solar Cells Applications in Bangladesh and the United States

Ahsan J. Dipro, Racheida S. Lewis, Ph.D.

Abstract

This paper will present a comparative analysis of factors that affect the efficiencies and power outputs between Silicon Solar cells (both Monocrystalline and Polycrystalline) and Gallium Arsenide based solar cells (both Single-junctioned and Multi-junctioned). There are three research questions present in this paper along with their hypothesis and a subset of questions relevant to the main research question that aims to draw comparisons between these solar cells in varying conditions such as: temperature, light intensity, height from ground, etc. Each research question's hypothesis aims to answer which one of these solar cells would be better suited for what country between Bangladesh and the U.S. There is a summary of the paper at the end where the validity of each hypothesis is revisited, among which Research Question 1 hypothesis proved correct, Research Question 2 hypothesis proved partially correct and Research Question 3 hypothesis proved incorrect.

Research was done using works cited from different reputable sources and independent researchers. Works cited are listed at the end of the research paper and after each information is presented as they are taken from one or many sources. There is a common terms and explanations area in Appendix A for people who may be unfamiliar with some concepts regarding solar cells that were discussed in this paper, making the paper fairly beginner friendly.

Future work on my end would include researching not just one factor each time, but how multiple factors at the same time affect the performance of the solar cell and what the order of efficiency is, as I currently do not have access to necessary equipment to carry out my own independent research.

Introduction:

This paper will discuss the efficiency of solar cells, mainly how various factors including temperature, light intensity and some related external conditions affect the current and voltage produced in solar cells. Gallium Arsenide based solar cells and Silicon solar cells are the most common types of solar cells found and used in the world in the modern era. They are used in applications varying from deep space exploration to generating power and electricity in sunlight rich areas. These Silicon and Gallium Arsenide based solar cells come in two forms: Monocrystalline and Polycrystalline Silicon Solar cells and Single-junction and Multi-junction Gallium Arsenide (GaAs) solar cells. This paper will discuss topics such as the p-n junction as well as bandgap and doping related to the solar cells. Two important aspects of solar cells- open circuit voltage and short circuit current - will also be discussed in this paper. This paper will also discuss how much open circuit voltage and short circuit current affect the ratio of the total power produced by solar cells to the power provided to the solar cell from the light falling onto it, also known as Efficiency (η). This research paper will answer the following research questions:

1. What is the Effect of Temperature on Solar Cell Efficiency?
2. What is the effect of Increased Light intensity on temperature increase on efficiency of solar cells?
3. How does current and voltage vary in different lighting conditions?

A personal hypothesis of mine is present right after each main research question and has been used to show how my A levels (pre-university and without deep research) brain is thinking about how the answer to my questions may play out. At the end of every research question is a conclusion which is aimed at proving or disproving my hypothesis and stating the truth using actual conclusive research done by scientists in the lab.

Background Information:

The history of solar cells is a long yet intriguing conversation to have as it explains how we first came to research the potential of solar cells as a viable power source and their evolution throughout the years, from Selenium based solar cells to modern traditional Silicon based solar cells and the more sought after, GaAs based solar cells.

The history of solar cells began in 1839, when Alexandre Edmond Becquerel [1] discovered the photovoltaic effect. While in his lab conducting experiments related to platinum electrodes, he had discovered that when light was illuminated at the direction of the electrodes immersed in an acidic solution, current and voltage were being generated, laying the groundwork for the photovoltaic effect and thus modern solar cells. By 1873, Selenium (Se) was discovered to have a photovoltaic effect due to the efforts of researcher Willoughby Smith [2] and this marked the first successful practical test of electricity being generated from solid Selenium by other researchers in 1876. Later on by 1883, the first practical Selenium solar cell had been made and was able to achieve an efficiency of 1% which, although low at the time, was enough to pique the curiosity of up and coming researchers, many of whom recognized its future potential. Further progress came when scientists had learned more about light and electricity, including the photoelectric effect and discovery of photons, which was published in a paper by Albert Einstein [3] in 1905 explaining the effect, also earning him a Nobel prize in Physics in 1921. His paper provided the theoretical foundation of modern photovoltaic technology. Selenium was used as the main element of solar cells until Silicon was discovered to also have a photovoltaic effect later during history which eventually led to the commercialization of modern solar cells most commonly available.

Silicon and Gallium Arsenide based solar cells:

Silicon (Si) and Gallium Arsenide (GaAs) solar cells are the most common and most advanced type of solar cell technology present to humans in the modern era. From using more advanced GaAs based solar cells used in space missions and on satellites to the more commonly available and used Silicon solar cells; both are very impressive technologies and viable sources of generating power with having 30% and 23% mean efficiencies respectively which although lower than sources such as fossil fuel on average, they are renewable sources of energy and do not cause pollution which makes them overall very good for the environment and worth the lower efficiency compromise.

Reaching this point of solar cell advancement was not easy, however. It was only after the discovery of photovoltaic effect in the p-n junction of silicon that the first proper and practical silicon solar cell was created in 1954 after advancements in doping and semiconductor technology, achieving an efficiency of 6%, which was a huge milestone at the time. Initially however, Silicon solar cells were too expensive and too inefficient for the commercial market; their first practical use was in the Vanguard I [4] satellite during 1958, which used silicon solar cells as its main source of power generation and this satellite laid the groundwork for use of silicon solar cells in space related missions. After this, improvements in crystal growth, wafer manufacturing, and semiconductor processing significantly reduced production costs while improving silicon solar cells photovoltaic effect and as a result, their efficiency. During the same time, scientists discovered the potential of a Gallium Arsenide based semiconductor as a potential solar cell due to its direct Bandgap of 1.42 eV which enabled it to absorb much more light compared to silicon, which has an indirect bandgap, and thus achieve higher efficiencies [5]. By the 1990s, scientists had further improved GaAs based solar cells with the development of multi-junction solar cells which involved stacking up different semiconductor layers on top of each other with different bandgaps to absorb different amounts of the solar spectrum. This dramatically reduced energy losses and increased efficiency [6]. Today, modern day Silicon solar cells include two types: Monocrystalline and Polycrystalline which have a typical efficiency range of 20-24% and 15-20% respectively and dominate the consumer market by over 90% [7]. For GaAs based solar cells, a typical single junction can reach 30% efficiency whereas the ideal multi-junction can reach an efficiency of about 48% [8]. Both of these solar cells are actively used in space missions that are taking place to this day.

Research Question 1: What is the Effect of Temperature on Solar Cell Efficiency?

Hypothesis: I predict that GaAs based solar cells are more efficient in higher temperatures such as in the US compared to Silicon Solar cells which are more suited for lower temperatures such as in Bangladesh.

Silicon Solar cells (Monocrystalline and Polycrystalline):

What is the optimum temperature?

For both types of Silicon solar cells, there is no definitive optimum temperature. Rather, the optimum temperature is as cold as possible purely from its standpoint as a semiconductor of ideally 25°C which is defined as the STC (Standard Test Conditions) although a lower temperature can also be used. A colder temperature is preferred as Silicon solar cell efficiency degrades with increase in temperature. Monocrystalline solar cells are more resistant and degrade much less per unit increase in temperature due to their lower temperature coefficient as compared to Polycrystalline solar cells, giving them better heat resistance. Overall, the optimum temperature for both Monocrystalline and Polycrystalline solar cells can be considered 25°C according to the STC studies conducted in labs.

What is the operating temperature range?

Standard Monocrystalline and Polyicrystalline solar cells have an operating temperature range specified by manufacturers of about -40°C to +85°C according to international standards [9]. This represents the limit of structural integrity and physical tolerance the solar cell can handle before it succumbs to physical or mechanical damage. However, in the real world scenario, they usually have an operating temperature range from about 35°C to 65°C. As they absorb light and hence thermal energy from the sun directly, their internal temperatures are about 20°C-30°C hotter than that of the surrounding air [10]. A temperature greater than the operating range may significantly drop the efficiency and make the power output not worth the price of installation and energy payback time. As Bangladesh has a more humid climate as well as an average temperature range of about 15°C-35°C throughout the year, both Monocrystalline and Polycrystalline solar cells would perform at their greatest efficiency here due to their low internal temperature and hence less degradation in this climate as compared to that in the United States of America where the average temperature is much higher than Bangladesh and would degrade the solar cells efficiencies more.

Is it dependent on materials, bandgap, or PN junction function?

Bandgap: The Bandgap plays a crucial role in determining a solar cell's efficiency and power output. For standard silicon solar cells, the bandgap is about 1.12 eV. Having a high bandgap (e.g., >1.3 eV) provides the solar cell with low temperature dependance, ultimately making it more resistant to reduction in efficiency at higher temperatures. But as Silicon has a low bandgap, when temperature increases, the reduction in efficiency per unit increase in temperature is a lot more compared to solar cells with a higher bandgap such as the 1.42 eV bandgap of GaAs solar cells. As a result, both types of silicon solar cells are heavily limited in their potential at higher temperatures due to the fixed bandgap of Silicon [5].

Materials/doping: Materials are the determining factors behind the bandgap of solar cells. Silicon solar cells have a fixed bandgap of 1.12 eV so it can be implied that Bandgap, which is the most important aspect of a solar cell's performance, is directly dependent and proportional to the material. Doping is used to create the solar cells positive and negative sites (the p-n junction) for the flow of electricity by the generation of electron-hole pairs as light is incident on solar cells. However, it is less crucial than bandgap and material when it comes to resisting temperature changes within the solar cells [5].

GaAs Solar cell:

What is the optimum temperature?

For both single and multi-junction GaAs solar cells, there is no definitive optimum temperature. Rather, they perform their best at 25°C (STC) or at lower temperatures just like Silicon solar cells [10], [8]. A colder temperature is preferred due to it being a semiconductor and also because its performance and overall efficiency begins to degrade per unit increase in temperature. However, their degradation per unit increase in temperature is much less as compared to traditional Silicon solar cells and thus they can perform better than silicon solar cells in temperatures higher than 25°C and maintain a greater efficiency [11]. Among the types, Single-junction GaAs solar cells are preferred as even though multi-junction may have higher potential, they are much less consistent with their output and highly sensitive to weather change and as a result may degrade very easily compared to which single-junction GaAs solar cells are much more durable and more consistent with their power output, thus providing a greater efficiency with less degradation [12].

What is the operating temperature range?

Gallium Arsenide (GaAs) based solar cells have a standard operating range specified by manufacturers to be from -65°C to +125°C according to international standards. This limit represents maximum structural integrity and physical tolerance the solar cell can handle before it is permanently degraded and damaged [13]. In a real world scenario, however, the solar cells have a typical operating temperature ranging from about 35°C to 65°C across various weather conditions. As they absorb light and thermal energy directly from the sun, typically their internal temperatures are 20°C-30°C hotter than that of the surrounding air [10]. As they have a low temperature coefficient, the fall in efficiency per unit increase in temperature is much lower than that when compared to other solar cells (i.e. Silicon solar cells) and are much more resistant to efficiency drops and degradation and allow them to maintain a consistent power output [10], [11]. As a result, they are far better suited for The United States of America where the average temperature ranges from -5°C to 45°C which makes Gallium Arsenide based solar cells much better for use in the United States due to the efficiency it provides for the price paid for it and its installation compared to Bangladesh where the average GDP per capita being much lower than the US would make GaAs solar cells much more expensive and not worth the price of it and its installation [14].

Is it dependent on materials, bandgap, or PN junction function?

Bandgap: The bandgap plays a crucial role in determining a solar cell's efficiency and power generation. Usual Gallium Arsenide (GaAs) based solar cells have a fixed bandgap of 1.42 eV, which is a very high bandgap and is the reason for its very low temperature coefficient which allows it to not degrade in efficiency and maintain a consistent power output over a very wide temperature range. Furthermore, GaAs is a direct bandgap material which allows it to absorb photons far more efficiently and in a greater amount as compared to Silicon solar cells and it overall wastes less input power provided to it [5].

Materials/doping: Materials are the determining factors behind the bandgap of solar cells. Gallium Arsenide based solar cells have a fixed bandgap of 1.42 eV so it can be implied that Bandgap, which is the most important aspect of a solar cell's performance, is directly dependent and proportional to the material. Doping is used to create the solar cells positive and negative sites (the p-n junction) for the flow of electricity by the generation of electron-hole pairs as light is incident on solar cells. However, it is less crucial than bandgap and material when it comes to resisting temperature changes within the solar cells [5].

Conclusion:

Gallium Arsenide based solar cells are far better suited for a wide temperature range to be useful for their price of installation and the modules. As a result, they are far better suited to be used in the United States of America as temperatures there can vary from -5°C to +40°C where temperatures are more inconsistent and require a solar cell that is well adapted to these varying temperatures all year round. On the other hand, Silicon Solar cells are better to be used in a small temperature range with much more consistent temperature variation all year round. Bangladesh is perfect for this as the price of Silicon solar cells modules and installations and the amount of power they produce are much more affordable than GaAs solar cells based on Bangladesh's GDP per capita and the efficiency makes them worth it as the temperature range is from 15°C to 35°C which is less extreme than that of the United States [14], [20].

Research Question 2: What is the effect of Increased Light intensity on temperature increase on efficiency of solar cells?

Hypothesis: As Light intensity increases, temperature of the solar cell begins to rise. Therefore as temperature increases, overall efficiency of the solar cell begins to fall with increasing light intensity. As a result, I believe Silicon solar cells to be better for Bangladesh than the US and GaAs solar cells to be better for the US compared to Bangladesh.

What is the optimum light intensity?

Just like temperature, solar cells do not have a fixed optimum light intensity. Instead the Optimum light intensity is within a range when once exceeded, the performance and overall efficiency of the solar cell begins to drop rapidly. As such, the optimum light intensity of solar cells is about 0.05-1 Sun, where 1 Sun = 1000W/m^2 amount of irradiance and this 1000W/m^2 limit is based on the Standard Test Conditions (STC) above which if the irradiance is greater, massive amounts of internal heat and hence a large amount of internal resistance starts to build up within the solar cell which negatively affects the its power output and efficiency and hence, causes it to degrade more quickly in performance [5], [15]. As shown in the formula below:

$$\boxed{\textit{Power Loss} = (\textit{Current})^2 \times \textit{Resistance}}$$

where, as current increases, internal resistance increases and power loss also increases. However, on earth sunlight almost never reaches an irradiance greater than 1000W/m^2 (1 Sun) and hence we don't have to worry that much regarding light intensity becoming an issue [16]. Below, I will discuss the specifics of light intensity effects for Silicon and GaAr solar cells.

Silicon Solar cell (Both Monocrystalline and Polycrystalline):

For silicon solar cells, the optimum light intensity for monocrystalline and polycrystalline solar cells differ due to their different crystal structure and arrangement despite their bandgap being the same as previously discussed in Section 1. More information about this will be discussed in Section 3. As such, the optimum light intensity of Monocrystalline and Polycrystalline Silicon solar cells is about 0.05-1 Sun worth of irradiance [5], [15].

Gallium Arsenide (GaAs):

For the two types of Gallium Arsenide based solar cells - Single and Multi-junctioned - both have a different optimum light intensity range. For Single-junctioned GaAs solar cells, the optimum light intensity is around 1 Sun (or 1000W/m^2) worth of irradiance and for Multi-junctioned GaAs solar cells, the range is about 200-1000 Suns (200,000 W/m^2 to 1,000,000 W/m^2) worth of irradiance . These are the ranges at which both type of GaAs solar cells show their best performance and achieve their highest efficiency and going beyond this range can cause massive amounts of internal heat to build up and hence large internal resistance forming within the solar cell while also causing massive increase in current and as a result causes lower power output and efficiency [11], [15], [17].

What is the operating light intensity range required?

Silicon Solar cells (Both Monocrystalline and Polycrystalline):

Silicon Solar cells do not have a standard light intensity operating range stated by manufacturers. Instead, it is considered to be around 200 W/m^2 to 10000 W/m^2 (0.2 Sun to 10 Sun) as per tests conducted by different university laboratories and independent scientists and researchers on low light intensity and high light intensity conditions. This is the range for which these silicon solar cells can efficiently absorb and convert photons into electricity without suffering from massive efficiency loss and thermal degradation [5], [18].

In a real world scenario however, the normal operating light intensity range is about 0.4 to 1 Sun amount of irradiance through various weather conditions as Earth's irradiance almost never exceeds 1 Sun worth [16]. For an irradiance outside the operating light intensity range, the power output and overall efficiency of the solar cell begins to drop. For example, on a dark rainy day with low to no sunlight present, irradiance below 0.2 Sun would make the solar cell produce negligible amounts of power. At the same time if the irradiance is above 1 Sun, the excess would build up and cause build of high internal resistance within the solar cell which is especially true for Polycrystalline solar cells due to its grain boundary effect which would cause large drops in efficiency in Silicon solar cells [19].

In Bangladesh, the instantaneous light intensity present at any given time on sunny days averages from approximately 0.1 to 1 Sun and the total accumulated amount of irradiance is about an average of 4-6 Suns daily depending on different times of the year and weather. This makes Silicon solar cells much more suited to be used in Bangladesh where the amount of irradiance never exceeds 1 Sun where if the solar cells were used in the US, irradiance may sometimes reach above 1 Sun causing major efficiency and performance drops in the solar cell and degradation of the solar cell overall [20], [21].

Gallium Arsenide (GaAs) Solar cells (Both Single-junctioned and Multi-junctioned):

Gallium Arsenide based solar cells do not have a specific light intensity operating range specified by manufacturers as light intensity range for solar cells is difficult to measure. In fact, GaAr light intensity varies greatly depending on the structure of the solar cell. For both multi-junctioned and single-junctioned, there are two types of designs used to create the solar cells: Flat-plane and Non-Flat plane. Their difference lies in the way light falls on them. For Flat-Plane GaAs solar cells, light intensity falling onto it is kept unconcentrated and falls evenly throughout and as for Non-flat planes, light is concentrated at a single point of the solar cells and the intensity is multiplied significantly [5], [11], [22], [23].

Flat Plane

Flat-plane Gallium Arsenide solar cells can absorb both direct sunlight and diffused/scattered sunlight that may come from clouds. Due to this, however, they have an operational light intensity range that is much lower than that of non-flat plane GaAs solar cells, for both single and multi-junctioned. As such, the operational light intensity is considered to be about 0.2-10 Sun (200-10,000 W/m^2 worth of irradiance under AM1.5G or AM0 spectrum) for both single and multi-junctioned flat-plane solar cells averaged from multiple verified sources, including tests conducted by independent researchers and scientists. These are the most commonly found Gallium Arsenide based solar cells [5], [8], [11], [22].

Non-flat Plane

Non-flat plane solar cells are also referred to as Concentrator (CPV) solar cells. These special type of solar cells take advantage of Fresnel Lenses or parabolic mirrors in order to concentrate light onto a single point in the solar cell and magnify their intensity (In Sun) by 10x to 100x for single-junctioned non-flat plane solar cells and about 10x to over 1000x for multi-junction, thus allowing the non-flat plane single-junctioned GaAs solar cell to have a normal operating range of 10-100 Suns (10,000-100,000 W/m^2 worth of irradiance) and advanced multi-junctioned ones to have the potential from 10-1000+ Sun (10,000-1,000,000 W/m^2 worth of irradiance) averaged from multiple verified sources and independent researchers and scientists who have conducted these experiments in the lab. This allows a small non-flat plane GaAs solar cell to produce as much efficiency as one produced by a much larger flat-plane one, the only downside being that it has to keep absorbing concentrated light in order to maintain its output as it cannot absorb diffuse/scattered light like flat-plane solar cells can [11], [17], [23], [24].

What is the difference in absorption of light between different materials?

Silicon Solar cells (Both Monocrystalline and Polycrystalline):

As Silicon solar cells are of two types which have different crystal structures, their sunlight absorption amount varies between Monocrystalline and Polycrystalline solar cells. Specifically, Monocrystalline silicon solar cells have a much higher absorption of sunlight as they have fewer defects and are not limited by grain boundaries that are present in Polycrystalline solar cells, instead Monocrystalline solar cells have a continuous and uniform crystal structure which helps them absorb more sunlight and photons, approximately 90-95% of which are incident on them with anti-reflective coating present on such solar cells and also results in fewer electron-hole pair recombination to occur across the solar cell which in turn generates more current and hence higher amounts of power and efficiency than Polycrystalline solar cells [5], [15], [25].

As Polycrystalline solar cells have more defects, are not continuous and uniform with their crystal lattice and are limited by the grain boundaries, they are only able to absorb approximately 80-90% of the photons that are incident on them considering the presence of an anti-reflective coating on them. The grain boundaries may scatter incident light and stimulate faster electron-hole pair recombination resulting in less overall current and hence power being generated inside the solar cells [5], [15], [19].

Gallium Arsenide (GaAs) Solar cells (Both Single-junction and Multi-junction):

As there are two types of Gallium Arsenide based solar cells, Single-junctioned and Multi-junctioned, the light absorption of each of these solar cells varies from each other [11], [17]. This is because of the difference in their structures and because of which, multi-junctioned GaAs solar cells are able to absorb a much higher amount of light than single-junctioned ones. Multi-junctioned Gallium Arsenide solar cells are made by stacking up three p-n junctions of decreasing bandgap on top of each other with the anti-reflective coating present on the top most cell with highest bandgap. This allows the multi-junctioned GaAs solar cell to absorb light of a much higher wavelength and range and overall allows more photons to be absorbed as the top most cell with highest bandgap absorbs photons with higher intensity whereas the middle and low bandgap cells absorb photons of lower energy and energy less than the top most bandgap, as a result having much less wasted energy than Single-junctioned cells which only have a structure consisting of a single layer of Gallium Arsenide of a fixed bandgap, doped with a p-n junction and covered by an anti-reflective coating on top [11], [17], [26].

As a result, single-junctioned solar cells can only absorb approximately 60-65% of the light incident on them while the rest of the energy is lost due to some photons having lesser amounts of energy than the bandgap, not causing an electron to jump [15], [17] whilst Multi-junction Gallium Arsenide solar cells can absorb approximately 90-95% of the light falling onto them as a result of the three stacked layers being able to absorb more photons of varying light intensity. Less amount of power as such is generated by the single-junctioned Gallium Arsenide cells as there are fewer formations of electron-hole pairs and more recombination, thus reducing overall efficiency of the solar cell as compared to that of Gallium Arsenide based cells which can form multiple electron-hole pairs and generate more power [11], [17].

Conclusion

As Earth's light intensity almost never goes above 1 Sun, for practical uses, Single-junctioned flat-plane Gallium Arsenide based solar cells and Silicon solar cells are the best options to use for generating power. Although multi-junctioned cells can also be used, they have a much higher efficiency drop as temperature increases with increased light intensity along with the fact that they are generally more expensive. From the section, it also can be concluded that the operating light intensity range for Flat-plane Gallium Arsenide solar cells and the operating light intensity for Silicon solar cells are similar. Due to this, Silicon solar cells would be much better to be used in Bangladesh due to the light intensity never exceeding 1 Sun and thus it would suffer less efficiency drops and also due to the fact that Silicon solar cell are cheap to install and gain back the costs from power production from which overall suits the GDP per capita of Bangladesh. As such it can also be concluded that: Gallium Arsenide based solar cells are much better to be used in the US where there is a higher probability of irradiance exceeding 1 Sun which would cause less efficiency drops in GaAs solar cells than Silicon, also including the fact that the US's GDP per capita makes it worth the return in the long term [14], [20].

Research Question 3: How does short circuit current and open circuit voltage vary in different lighting conditions?

Hypothesis: I predict that Silicon Solar cells are better for Bangladesh due to it having relatively less rainfall and more bright weathers and that Gallium Arsenide based solar cells are better for the US as there is more rainfall and cloudy weather there.

What is the short circuit current and open circuit voltage produced during different weather conditions?

Short Circuit Current

For both types of Silicon solar cells and both types of Gallium Arsenide based solar cells, as light intensity increases, the short circuit current produced by the solar cell increases. This is because, as more light strikes the surface of the solar cells, more electron-hole pairs are generated within the solar cell causing more electrons to move around the external circuit and as such, produce higher current. Similarly, as light intensity decreases, short circuit current also begins to decrease with the solar cell linearly. As a result it can be concluded that Short Circuit current is directly proportional to Light intensity falling on the solar cell as shown below [5], [15], [27]:

Short Circuit Current ∝ Light Intensity

Open Circuit Voltage

For both types of Silicon solar cells and Gallium Arsenide based solar cells, the open circuit voltage increases or decreases logarithmically as light intensity increases or decreases respectively. This is because, as more light strikes the surface, the photogenerated current increases, causing charge carriers (electrons and their respective hole pairs) to build up at the p-n junction. This accumulation lowers the internal electrostatic barrier, which exponentially increases the forward-bias recombination current required to balance the photogenerated current. Similarly, as light intensity decreases, less charge carriers accumulate, allowing the internal electrostatic barrier to be higher and cause open circuit voltage to decrease. As a result, it may be concluded that Open Circuit Voltage is directly proportional to the logarithm base *e* of Light intensity as shown below [5], [15], [28]:

Open Circuit Voltage (V_{oc}) ∝ In(Light Intensity)

Silicon Solar cells (Both Polycrystalline and Monocrystalline):

Between Monocrystalline and Polycrystalline Silicon solar cells, Monocrystalline has higher production of short circuit current at all weather conditions as compared to Polycrystalline solar cells due to its grain boundary effect [19]. As explained in RQ2, Polycrystalline cells' grain boundary effect in its crystal structure hinders the free movement of electrons during electron-hole pair generation and recombination as these act as recombination sites that trap the photogenerated charge carriers within the solar cell, causing less production of short circuit current and open circuit voltage due to its higher recombinations and overall it generates a lower power output and has lesser amount of efficiency as compared to Monocrystalline Silicon solar cells which lack this grain boundary effect in their crystal structure. As a result, it can be concluded that Monocrystalline Silicon solar cells have higher Short Circuit Current and larger Open circuit Voltage than Polycrystalline solar cells at all weather conditions [5], [15].

Gallium Arsenide Based Solar cells (Both Multi-junction and Single-junction):

For Short circuit current, between Single-junctioned and Multi-junctioned Gallium Arsenide based solar cells, Single-junctioned cells produce a higher amount of short circuit current than Multi-junctioned across all weather conditions [11], [17]. Single-junctioned cells absorb photons of a fixed bandgap into one single layer that produces the photogenerated current whereas Multi-junctioned Gallium Arsenide cells have three layers parallelly stacked on top of each other in series which have different bandgaps. Due to this light spectral mismatch, the overall current produced is limited by cells with the lower bandgap and as a result, they produce a much lower amount of Short circuit current as compared to Single-junctioned solar cells [11], [17], [26].

However, the Open Circuit Voltage is a different story. The Open circuit voltage production of Multi-junctioned cells is much higher (about 3x) than that of Single-junctioned solar cells under the same weather conditions [11], [17]. In Multi-junctioned cells, the different sub-cell layers with descending bandgaps are stacked parallelly in series, the Voltage across the different layers add up to give a higher total open circuit voltage produced in the solar cell. Across decreasing light intensity however, the voltage loss of Multi-junctioned cells is higher than that of Single-junctioned as the voltage losses also similarly accumulate across the three layers. Overall, Multi-junctioned solar cells are better in terms of power output and efficiency in this case as the voltage multiplication is higher than the current multiplication of single-junction Gallium Arsenide based solar cells [11], [17], [26].

What is the amount of Short Circuit Current and Open Circuit Voltage produced depending on the height the solar cell is placed at?

For both types of Silicon solar cells and Gallium Arsenide based solar cells, the short circuit current and open circuit voltage increase as height is increased [5], [16]. This is because: as height is increased, the amount of irradiance falling on the solar cells increases as there is less scattered and blocked light by the atmosphere. Similarly to Section (i) of this question, Short Circuit Current linearly increases with height as light intensity is directly proportional to height and decreases when height is decreased [5], [16], [18]. Hence, it may be concluded that Short Circuit Current is directly proportional to height as shown below:

Short Circuit Current ∝ Height of Solar cell from ground

Similar to Short circuit current and Section (i), the Open Circuit Voltage of both types of Silicon and Gallium Arsenide based solar cells also increases logarithmically with height as there is higher amount of light falling onto the surface of the solar cells, producing more electron-hole pairs and photogenerated current which when accumulated, lower the internal electrostatic barrier [5], [16], [28]. Therefore it can be concluded that Open Circuit Voltage is directly proportional to the log base ***e*** of height as shown below:

Open Circuit Voltage (V_{oc}) ∝ ln(Height of solar cell from ground)

Silicon Solar cells (Both Polycrystalline and Monocrystalline):

Between Monocrystalline and Polycrystalline Silicon solar cells, Monocrystalline has higher production of short circuit current at the same heights as compared to Polycrystalline solar cells mainly due to its grain boundary effect. As explained in RQ2, Polycrystalline cells' grain boundary effect in its crystal structure hinders the free movement of electrons during electron-hole pair generation and recombination as these act as recombination sites that trap the photogenerated charge carriers within the solar cell, causing less production of short circuit current and open circuit voltage due to its higher recombinations and overall it generates a lower power output and has lesser amount of efficiency as compared to Monocrystalline Silicon solar cells which lack this grain boundary effect in their crystal structure. As a result, it can be concluded that Monocrystalline Silicon solar cells have higher Short Circuit Current and larger Open circuit Voltage than Polycrystalline solar cells at the same heights [5], [19], [29].

Gallium Arsenide Based Solar cells (Both Multi-junction and Single-junction):

For Short circuit current, between Single-junctioned and Multi-junctioned Gallium Arsenide based solar cells, Single-junctioned cells produce a higher amount of short circuit current than Multi-junctioned when placed at the same height. This is because it absorbs photons of a fixed bandgap into one single layer that produces the photogenerated current whereas Multi-junctioned Gallium Arsenide cells have three layers parallelly stacked on top of each other in series which have different bandgaps. Due to this light spectral mismatch, the overall current produced is limited by cells with the lower bandgap and as a result, they produce a much lower amount of Short circuit current as compared to Single-junctioned solar cells [11], [17], [26].

However, the Open Circuit Voltage is a different story. The Open circuit voltage production of Multi-junctioned cells is much higher (about 3x) than that of Single-junctioned solar cells at the same height [11], [17]. This is because, as the different sub-cell layers with descending bandgaps are stacked parallelly in series, the Voltage across the different layers add up to give a higher total open circuit voltage produced in the solar cell. Across decreasing light intensity however, the voltage loss of Multi-junctioned cells is higher than that of Single-junctioned as the voltage losses also similarly accumulate across the three layers [11], [17]. Overall, Multi-junctioned solar cells are better in terms of power output and efficiency in this case as the voltage multiplication is higher than the current multiplication of single-junction Gallium Arsenide based solar cells [11], [16], [17], [26].

Conclusion

For all of the solar cells above, it can be concluded that during different weather conditions, Monocrystalline Silicon solar cells perform much better than Polycrystalline solar cells due to Polycrystalline cell's highly limiting Grain Boundary Effect which causes electrons to get stuck and hinder their free movement and cause faster electron-hole pair recombination. As a result, Monocrystalline Silicon solar cells produce a higher amount of Short Circuit Current and Open Circuit Voltage than Polycrystalline Silicon solar cells [5], [18]. In contrast, Single-junctioned GaAs solar cells produce higher amounts of Short circuit current but lower amount of Open Circuit Voltage as compared to the Multi-junction counterpart [11], [17]. This is because: as Multi-junction is made up of 3 layers with different bandgaps stacked on top of each other while Single-junction is made up of one layer with fixed bandgap, the current produced by the lowest bandgap layer in multi-junction GaAs cells limits its short circuit current generation but three layers stacked on top of each other allows voltage to accumulate across layers, allowing it to produce higher voltage than Single-junctioned whereas Single-junctioned GaAs cells having just one layer with fixed bandgap allows it to have a higher current and photogenerated current is constant [11], [26].

Due to Bangladesh having a lower amount of rainfall and thus less cloudy weather in recent years as compared to the US, Silicon solar cells are much better for Bangladesh as it operates best under less cloudy conditions and Bangladesh's GDP per capita allows the installation and power production from these cells at all climates suitable to use [14], [18], [20]. Meanwhile, as cloudy weather is more common in the US, Gallium Arsenide based solar cells are better as its overall power and voltage production in cloudy weathers is much higher than of Silicon solar cells, which is great as weather conditions in the US are rather unpredictable and fluctuating all year round. Hence, in terms of efficiency, Silicon solar cells are better suited for Bangladesh whilst the more durable Gallium Arsenide based solar cells are much better suited for the US [11], [14], [18], [20].

Summary of Paper

This research paper focused on understanding the knowledge around solar cells and sought to address three research questions. Each research question tested a personal hypothesis given the task of gaining new knowledge in the subject area.

For Research Question 1 “What is the Effect of Temperature on Solar Cell Efficiency?” My hypothesis was that GaAs based solar cells are more efficient in higher temperatures such as in the US compared to Silicon Solar cells which are more suited for lower temperatures such as in Bangladesh. Through this research, my hypothesis was correct as the variance of temperature in the US has a higher range compared to the temperature present in Bangladesh, Gallium Arsenide based solar cells indeed do appear to be better performing in the US where the temperature can reach extremes which are far more suited to be handled by Gallium Arsenide solar cells. Silicon Solar cells are as a result much better for a country such as Bangladesh where the variance in temperature throughout the year is low and consistent, thus reaching less extremes. As such, due to their price of installation and maintenance being much lower than Gallium Arsenide based solar cells, they also fall into the affordability category as Bangladesh’s GDP per capita is much lower than that of the US which makes solar cells a less commonly found energy source within the country.

Moving on to Research Question 2, “What is the effect of Increased Light intensity on temperature increase on efficiency of solar cells?” My hypothesis was, as light intensity increases, the temperature of the solar cell begins to rise; therefore as temperature increases, the overall efficiency of the solar cell begins to fall with increasing light intensity. As a result, I believed Silicon solar cells to be better for Bangladesh than the US and GaAs solar cells to be better for the US compared to Bangladesh. This statement turned out to be partly true as our irradiance never practically goes above 1 Sun, Single-junctioned Gallium Arsenide based solar cells and Silicon solar cells are best to be used for increasing light intensity. Although, using multi-junctioned Gallium Arsenide based solar cells is also an option, due to it suffering from higher efficiency drops in higher temperatures and having a constant requirement of concentrated light falling on top of it to generate optimal power, it falls behind Silicon solar cells (both types) and single-junctioned Gallium Arsenide solar cells under overall average of light intensities throughout the year. It is to be noted that sometimes during the year, solar irradiance may reach over 1 Sun in countries with a higher average temperature throughout the year, such as the US. This makes Single-junctioned Gallium Arsenide based solar cells far more suited to be used in the US as their degradation per unit increase in temperature is less while also having a higher operating temperature. It can also be, therefore, concluded that Silicon Solar cells are far better suited for Bangladesh where reaching light intensities above 1 Sun is very rare and their lower

GDP per capita makes Solar cells energy payback from installation cost and maintenance worth it.

Finally, in Research Question 3 “How does short circuit current and open circuit voltage vary in different lighting conditions?” My hypothesis was, I predict that Silicon solar cells are better for Bangladesh due to it having relatively less rainfall and more bright weather and that Gallium Arsenide based solar cells are better for the US as there is more rainfall and cloudy weather there. My hypothesis was proven incorrect as stated given the fact that the weather in both countries vary significantly and thus, weather dependent lighting conditions have minimal impact on solar cells’ performance. However, my prediction that Silicon solar cells are more efficient in Bangladesh is correct. Rainfall and cloudy seasons for Bangladesh and the US vary and sometimes one can have more amounts of rainfall than the other. However, as rainfall in Bangladesh is mostly present during the rainy season whereas the US has it all year round, it is logical to assume that on average the US has higher amounts of rainfall throughout the year as compared to Bangladesh where rainfall only primarily occurs during the monsoon season. As such, Silicon solar cells are better suited to Bangladesh as the weather stays mostly consistent throughout the year with bright sunny days of irradiance of 1 Sun or more thus allowing higher amounts of power production throughout the year. As the US has a varying weather condition throughout the year, Gallium Arsenide based solar cells are much more useful there as they are more resistant to changing weather conditions and can remain consistent with their power output and efficiencies throughout the year with these varying weather conditions.

What’s Next?

This is the theoretical research paper for now that was made and compiled using multiple reputable sources. However, this paper does not fully address all of the factors a solar cell is affected by. This research paper focused on how only one or two factors affect a solar cell’s power output at a time but did not address how these factors jointly affect the performance of the solar cell and most reputable sources also did not address all of the factors at play during the same time. Therefore, this research paper serves more like a draft of factors I would like to research further into the future as a stepping stone for what’s to come next and also to verify the results that came from the reputable sources for myself in the future when I am able to afford the research. Once I have access to sufficient equipment I would like to research further and carry out my own practical testing on these topics and lingering questions as currently I do not have the equipment nor money required to buy them. If given the chance, I would like to investigate research on solar cell performance such as how when all the factors in the research paper are at play at once or what the maximum amount of load a solar cell needs for it to completely stop functioning is. In the end, there is still a lot regarding solar cells I do not yet know due to my status as a high school student and my current study level hindering me from researching deeper into the hidden science behind solar cells and what the more prominent factors are that are driving them.

As solar cell technology continues to advance every year, It won't be long before we discover a new semiconductor that is capable of achieving much higher efficiencies than the standard Gallium Arsenide solar cells or Silicon solar cells that are commonly used nowadays. Only time will show us the future possibilities.

References

[1] Wikipedia. (2026, July 21). *Edmond Becquerel*. Wikipedia. Retrieved July 29, 2026, from https://en.wikipedia.org/wiki/Edmond_Becquerel

[2] Smith, W. (n.d.). *Willoughby Smith*. Wikipedia. https://en.wikipedia.org/wiki/Willoughby_Smith

[3] Wheeler, J. A., Smith, S., Nadolny, R., Scoffield, L., & Einstein, A. (n.d.). *Albert Einstein*. Wikipedia. https://en.wikipedia.org/wiki/Albert_Einstein

[4] *Vanguard 1*. (n.d.). Wikipedia. https://en.wikipedia.org/wiki/Vanguard_1

[5] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. Hoboken, NJ, USA: Wiley-Interscience, 2006, pp. 663–690

[6] K. A. Bertness, S. R. Kurtz, D. J. Friedman, A. E. Kibbler, C. Kramer, and J. M. Olson, "29.5%-efficient GaInP/GaAs tandem solar cells," *IEEE Electron Device Letters*, vol. 15, no. 4, pp. 125–127, Apr. 1994.

[7] A. Richter, M. Hermle, and S. W. Glunz, "High-efficiency crystalline silicon solar cells: Status and perspectives," *Energy & Environmental Science*, vol. 6, no. 6, pp. 1740–1765, 2013.

[8] M. A. Green, E. D. Dunlop, M. Yoshita, N. Kopidakis, K. Bothe, and G. Siefer, "Solar cell efficiency tables (Version 62)," *Progress in Photovoltaics: Research and Applications*, vol. 31, no. 7, pp. 651–663, Jul. 2023.

[9] *Terrestrial Photovoltaic (PV) Modules - Design Qualification and Type Approval - Part 1: Test Requirements*, IEC Standard 61215-1:2021, International Electrotechnical Commission, Geneva, Switzerland, 2021.

[10] E. Skoplaki and J. A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations," *Solar Energy*, vol. 83, no. 5, pp. 614–624, May 2009.

[11] S. P. Philipps, F. Dimroth, and A. W. Bett, "High-efficiency GaAs-based solar cells," in *Advances in Solar Energy*, San Francisco, CA, USA: International Solar Energy Society, 2012, pp. 115–158.

[12] D. C. Law *et al.*, "Future technology pathways for ultra-high efficiency multijunction solar cells," *IEEE Journal of Photovoltaics*, vol. 1, no. 1, pp. 101–109, Jul. 2011.

[13] *Qualification General Specification for Solar Cells, Space*, ECSS-E-ST-20-08C, European Cooperation for Space Standardization (ECSS), Noordwijk, Netherlands, 2012.

[14] *World Development Indicators*, The World Bank, Washington, DC, USA, 2023. [Online]. Available: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD

[15] A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, 2nd ed. Chichester, West Sussex, UK: John Wiley & Sons, 2011, pp. 63–112.

[16] C. A. Gueymard, "The sun's total and spectral irradiance for solar energy applications and solar radiation models," *Solar Energy*, vol. 76, no. 4, pp. 423–453, Apr. 2004.

[17] R. R. King *et al.*, "Band-gap-engineered architectures for high-efficiency multijunction concentrator solar cells," *Journal of Physics D: Applied Physics*, vol. 41, no. 3, p. 033001, Feb. 2008.

[18] A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, 2nd ed. Chichester, West Sussex, UK: John Wiley & Sons, 2011, pp. 63–112.

[19] J. H. Werner, "Origin of grain boundary barriers in polycrystalline silicon," *Solid State Phenomena*, vol. 37–38, pp. 213–218, 1994.

[20] M. J. Khan, A. K. Bhattacharjee, and M. R. I. Sarker, "Assessment of solar energy potential and solar radiation modeling in Bangladesh," *Renewable Energy*, vol. 156, pp. 1198–1209, Aug. 2020.

[21] *Global Solar Atlas*, World Bank Group, Washington, DC, USA, 2023. [Online]. Available: https://globalsolaratlas.info

[22] *Standard Solar Spectral Irradiance Tables Standard Air Mass 1.5*, ASTM Standard G173-03, ASTM International, West Conshohocken, PA, USA, 2020.

[23] A. Luque and V. M. Andreev, *Concentrator Photovoltaics*, Berlin, Germany: Springer-Verlag, 2007, pp. 11–45.

[24] E. F. Fernandez, A. J. Garcia-Loureiro, and G. P. Smestad, "A review of optical and thermal management in concentrator photovoltaics (CPV)," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 621–637, Sep. 2014.

[25] H. K. Raut, V. A. Ganesh, A. S. Nair, and S. Ramakrishna, "Anti-reflective coatings: A critical, in-depth review," *Energy & Environmental Science*, vol. 4, no. 10, pp. 3779–3804, Oct. 2011.

[26] M. A. Green, *Third Generation Photovoltaics: Advanced Solar Energy Conversion*, Berlin, Germany: Springer-Verlag, 2003, pp. 57–81.

[27] C. Honsberg and S. Bowden, "Short-Circuit Current," *PVCDROM*, 2019. [Online]. Available: https://www.pveducation.org/pvcdrom/solar-cell-operation/short-circuit-current

[28] M. A. Green, *Solar Cells: Operating Principles, Technology, and System Applications*, Englewood Cliffs, NJ, USA: Prentice-Hall, 1982, pp. 85–102.

[29] A. A. F. Husain, W. Z. W. Hasan, S. Shafie, M. N. Hamidon, and S. S. Pandey, "A review of silicon photovoltaic module technologies, thermal models and efficiency temperature coefficients," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2258–2268, Feb. 2018.

Appendix A: Explanations for Common Terms

Bandgap: The bandgap of a solar cell is the energy threshold determining factor: it determines how much light a solar cell can collect in one instance and turn it into electricity. In order to understand what a bandgap of a material is, we must understand the concepts of the valence band and conduction band. As we know from chemistry: Electrons have different energy levels and they can jump through energy levels when they absorb a certain amount of energy. The valence band as such is the lowest energy state where electrons normally are and the conduction band is the second band where if a certain amount of energy equal to/greater than the bandgap is absorbed by the material, the electron jumps from the valence band to the conduction band. This energy for the jump has to be more than or equal to a materials bandgap and the higher the bandgap, the better it is for the solar cells power absorption. For example: As Silicon solar cells have a bandgap of 1.12 eV, when photons emitting energy greater than or equal to 1.12 eV are absorbed by the solar cell, it generates electron-hole pairs as electron jumps from valence to conduction band which is the main factor for generating electricity. However, when energy more than 1.12 eV (or bandgap) is absorbed by the solar cell, the excess energy is lost as only 1.12 eV energy is being taken to cause each electron to jump or i.e. when a photon with energy 1.3 eV that falls is absorbed by a silicon solar cell, only 1.12 eV of energy is taken from it to cause an electron to jump and the rest of the 0.18 eV of energy is wasted. This is why solar cells with higher bandgap are preferred such as GaAs solar cells which have a bandgap of 1.42 eV resulting in much less energy being lost as photons are absorbed by it to cause an electron to jump.

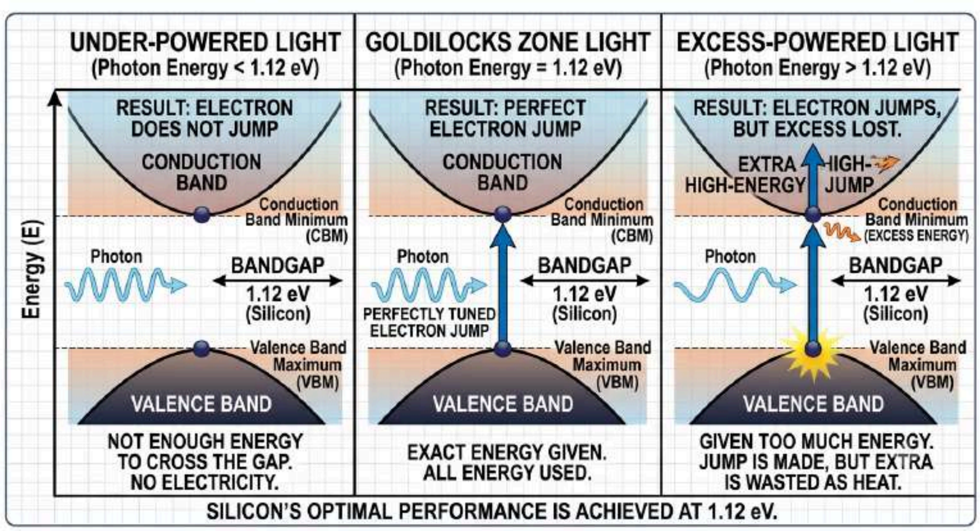

Figure 1: This image was generated using Google Gemini for better understanding of the concept explained above

Doping: Doping is an essential feature in the production of solar cells. They are used to create the negative and positive terminals of a solar cell to improve its electricity generation. Doping is essentially the addition of small impurities to pure semiconductor materials so that they can be used to generate electron hole pairs. For example: in pure silicon used to create semiconductors, as pure silicon has 4 electrons in its outer shell (In the covalent bonds formed with other Silicon atoms), an element such as Phosphorus is added to it as it has 5 valence electrons (1 more than that of Silicon). This extra electron is used for the jump caused from the valence band to the conduction band, thus creating the negative (n) doping and junction of the solar cell. Similarly, an impurity such as Boron is added to another side of the solar cell as it has 3 valence electrons (1 less than silicon) thus creating a hole in the positive (p) junction of the solar cell and this is positive doping. This creates an electric field between the negative and positive junction. This allows electron-hole pairs to form when the solar cell absorbs energy from photons. This n-p doping is done across multiple different points throughout the whole semiconductor material of each solar cell to maximize generation of electricity. **Figure 2 is provided to make the concept easier to grasp.**

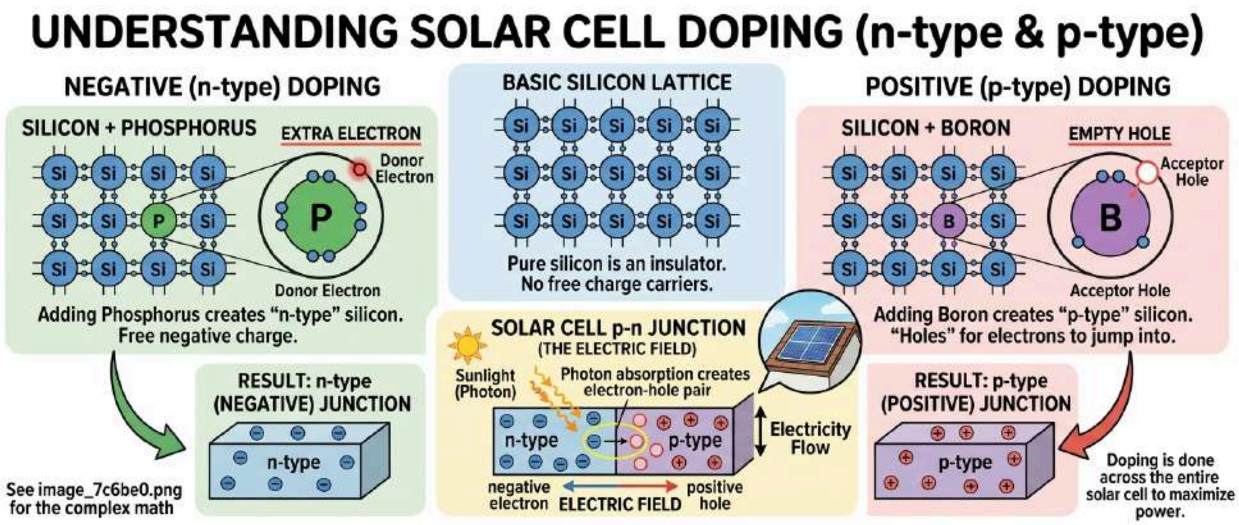

Figure 2: This image was generated using Google Gemini for the better understanding of the concepts explained above

Electron-hole pairs: They are the driving force behind electricity generation in Solar cells. After the **n-p junction** is generated by doping, when photons with sufficient energy are absorbed by the solar cell, it causes an electron from the negative (n) terminal to jump from valence band to the conduction band and this electron flows through the external circuit from the negative junction round the circuit to the positive (p) junction where it recombines with a hole and thus generates electricity in the process. The electron, however, is not used up during this process and doesn't immediately recombine with the hole. Instead, as more and more photons are absorbed, more electron-hole pairs are generated and the cycle of separation and recombination can occur repeatedly for a vast amount of time. **Figure 3 shows the process in more detail.**

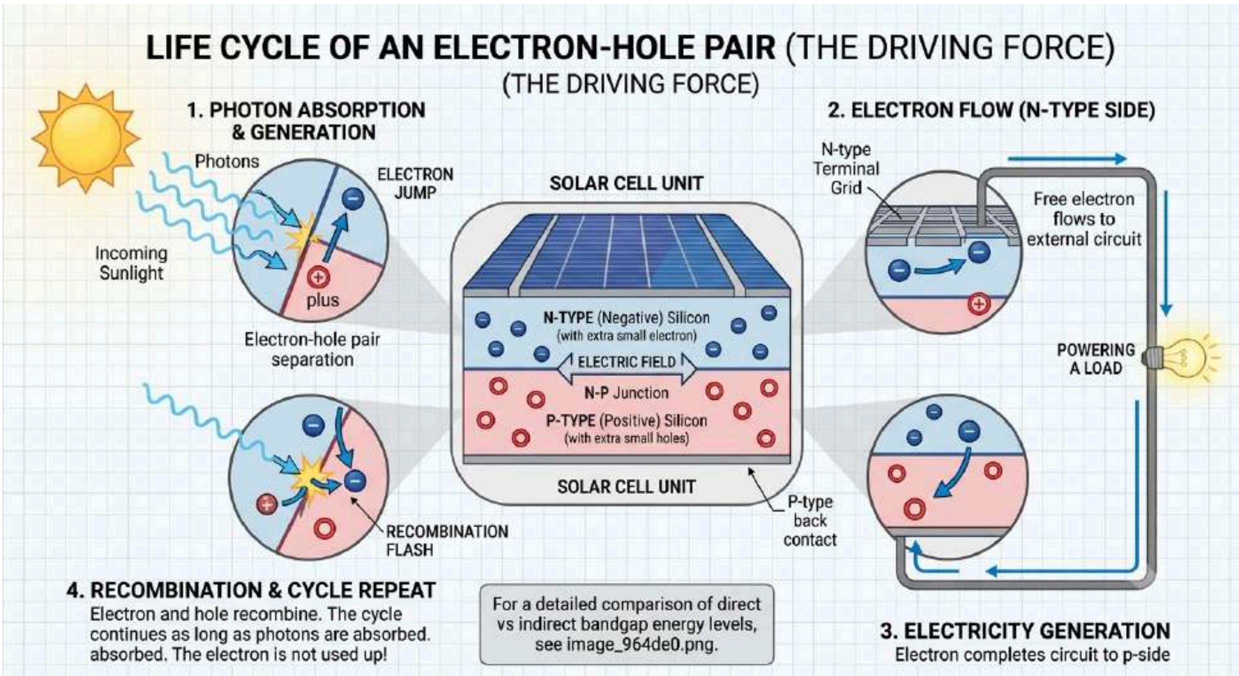

Figure 3: This image was created using Google Gemini for better understanding of the concepts explained in the above text

Sun (Unit): 1 Sun is defined as the light intensity used in Standard Test Conditions (STC). As a result, 1 Sun = $1000 W/m^2$ where it is referencing the irradiance of the sun.

Standard Conditions: It is the industry standard set of laboratory conditions used to evaluate the rate and performance of solar cells; mainly the power output and electrical efficiencies. These conditions include: Temperature of 25°C, An Irradiance of $1000 W/m^2$ and Air Mass 1.5 Global (AM1.5G)

Photogenerated Current: It is the instantaneous current that is produced directly by photons striking the surface of solar cells.

Grain boundary effect of Polycrystalline Silicon Solar cells: The grain boundary effect of Polycrystalline Silicon solar cells is the main reason behind why Polycrystalline solar cells are cheaper and less efficient than the monocrystalline variant. While Monocrystalline silicon solar cells are made up of a continuous crystal lattice structure, polycrystalline cells consist of many small silicon crystal grains, which when merged, create the grain boundaries. At these grain boundaries, the silicon atoms which usually have four bonds have one less bond creating regions of unpaired bonds or ‘dangling bonds’. As free charge carriers move through the material of the solar cell, they are captured by these unpaired (dangling) bonds and this results in the formation of a Depletion zone as same like charges accumulate and repel each other. An internal electric field is established which causes photo-generated electrons to be drawn towards the boundary surface and be trapped by an energy trough created at the boundary due to the bending of the valence band and conduction band. As a result, they undergo recombination with holes. This process converts the absorbed photon energy into wasted heat energy rather than useful electrical current, significantly reducing the cell's overall power output and efficiency, causing it to be worse overall compared to monocrystalline silicon solar cells.

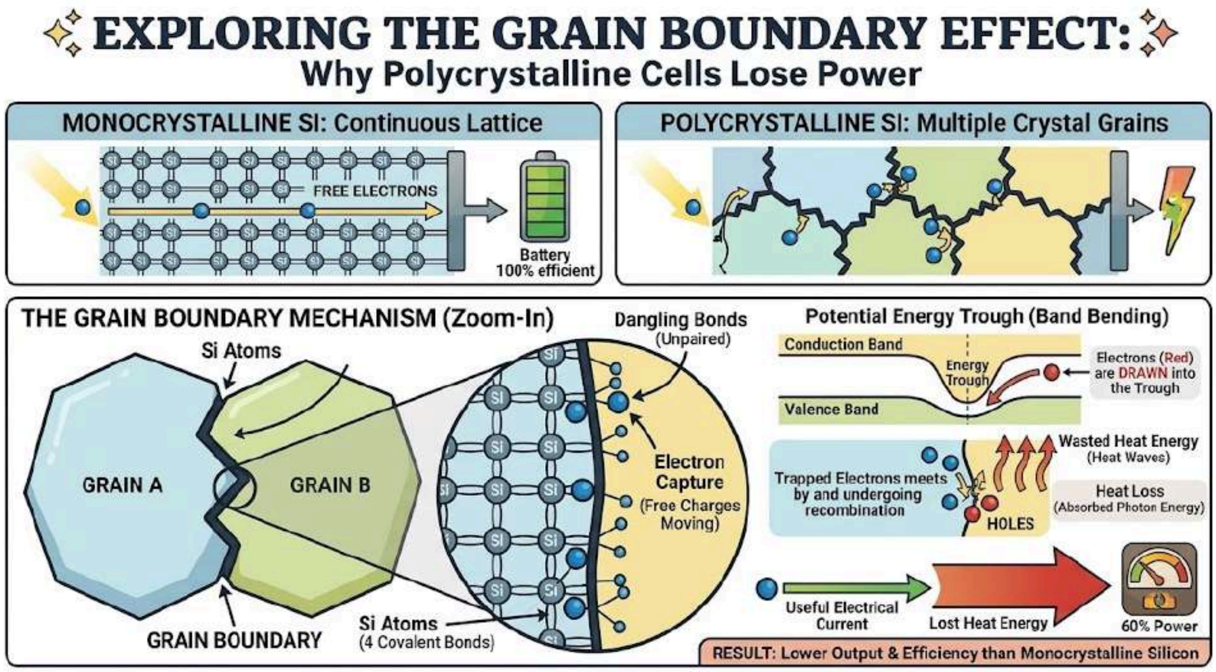

Figure 4: This image was created using Google Gemini for better understanding of the concepts explained in the above text

Short Circuit Current: The maximum electrical current that a solar cell can produce when its output terminals are connected together with having zero external resistance (Resistance = 0).

Open Circuit Voltage: The maximum amount of electrical voltage produced by a solar cell when there is no current flowing through it and when external resistance is infinite (Resistance = ∞).