ME 539/MSE 599: Renewable Energy 1

Project Report

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Team 2

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Luminescent Solar Concentrators System for Greenhouse Roof

<u>Abstract</u>

This project aims to enhance the efficiency of greenhouses by using a luminescent solar concentrator (LSC) system selectively tuned to capture green light. LSC solar cells consist of a luminescent material and solar cells that capture the re-emitted light. Wavelength-selective LSCs (WSLSCs) use a combination of luminescent materials to capture and concentrate light at specific wavelengths. The luminescent material, such as Aluminium Gallium Arsenide (AlGaAs), absorbs light and re-emits it at a longer wavelength, enabling the down conversion of green light into a more usable form. The design of a WSLSC that down converts green light and traps the re-emitted photons allows for more efficient energy conversion. The LSC system can capture up to 2.5% of the solar spectrum, increasing the efficiency of light capture and energy conversion, particularly in environments with lower levels of incoming light.

1. Introduction

Greenhouses are used for a variety of purposes, from small-scale home gardening to large-scale commercial agriculture. They can be used to grow a wide range of plants, including vegetables, fruits, flowers, and ornamental plants. Greenhouses work by allowing sunlight to pass through the transparent walls and roof, which traps the heat and increases the air and surface temperature inside. This creates a warmer and more humid environment than the outside temperature and humidity. The temperature and humidity levels can be further controlled through the use of ventilation systems, fans, and heating or cooling devices which consume electricity. In this project we decided to use Luminescent Solar Concentrator to selectively tune it for greenhouse.

Plants primarily absorb light in the visible spectrum, which includes wavelengths between 400 and 700 nanometers (nm). This range of wavelengths is sometimes called the photosynthetically active radiation region, the range of wavelengths which plants use for photosynthesis. Plants do not absorb light in the green part of the spectrum, which has wavelengths between approximately 500 and 600 nanometers (nm). Instead, they reflect most of the green light, which is why leaves appear green to our eyes. This unused light can be absorbed by solar cells and to power other systems. To selectively capture green light we used luminescent solar concentrators.
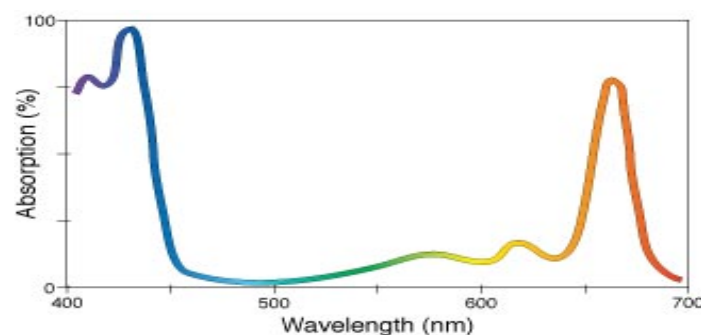

Fig1: Absorption spectrum of chlorophyll [1]

A Luminescent Solar Concentrator (LSC) solar cell is a type of solar cell that uses a luminescent material to concentrate sunlight onto a small solar cell. The LSC solar cell is made up of two parts: the luminescent material and the solar cell. The luminescent material can be a dye or quantum dot that absorbs light and then re-emits it at a longer wavelength. This re-emitted light is then trapped inside the LSC by total internal reflection, where the re-emitted light bounces around until it reaches the edge of the LSC. At the edge of the LSC, the trapped light is directed into a small solar cell, which converts the light into electricity. The solar cell is typically made of a semiconductor material, such as silicon or gallium arsenide. One of the advantages of LSC solar cells is that they can be made to be very thin and flexible, which makes them easier to install and integrate into various devices. They are also able to capture light from a wide range of angles, which means they can still generate electricity using diffused light sources. However, LSC solar cells have lower efficiency than traditional solar cells as they are mostly translucent.

2. **Device Design**

A wavelength selective luminescent solar concentrator (WSLSC) is a type of luminescent solar concentrator (LSC) that uses a combination of luminescent materials to selectively capture and concentrate light at specific wavelengths. In a WSLSC, the luminescent material is usually a combination of dyes or quantum dots that have different absorption and emission spectra. By carefully selecting the types and concentrations of these materials, it is possible to create a WSLSC that selectively captures light at certain wavelengths while allowing other wavelengths to pass through. The advantage of a WSLSC is that it can be designed to match the absorption spectrum

of a specific type of solar cell, such as a silicon or gallium arsenide solar cell. This allows for more efficient energy conversion because the captured light is matched to the specific properties of the solar cell [2].

2.1 **Device Structure**

To use WSLSC as a greenhouse plane, we had to design a luminescent solar concentrator which down converted the green light. The down conversion process occurs when a high-energy photon of light is absorbed by a luminescent material, which may be a dye or a quantum dot. This absorbed photon excites an electron within the luminescent material to a higher energy state. However, due to the nature of the luminescent material, this excited electron cannot remain in this higher energy state for very long and quickly relaxes back down to its original energy state. As the electron relaxes, it releases the excess energy in the form of a lower-energy photon, which is then emitted by the luminescent material. This re-emitted photon typically has a longer wavelength and lower energy than the original absorbed photon, which is why the process is referred to as down conversion. The re-emitted photons are trapped within the LSC due to total internal reflection and are directed towards the edge of the LSC, where they can be collected by a smaller solar cell for conversion into electricity. By using down conversion, LSC solar cells can increase the efficiency of light capture and energy conversion, particularly in environments with lower levels of incoming light. To convert used green light into usable light Lumegen Red 305 can be used. It is a red-colored dye that can absorb light in the blue-green region of the electromagnetic spectrum and re-emit it as longer-wavelength light in the red-orange region.Lumogen Red 305 is particularly useful in LSCs because it has a high molar absorption coefficient

and a high fluorescence quantum yield, which means it can efficiently absorb and emit light, respectively. This makes it an effective material for down conversion [3].
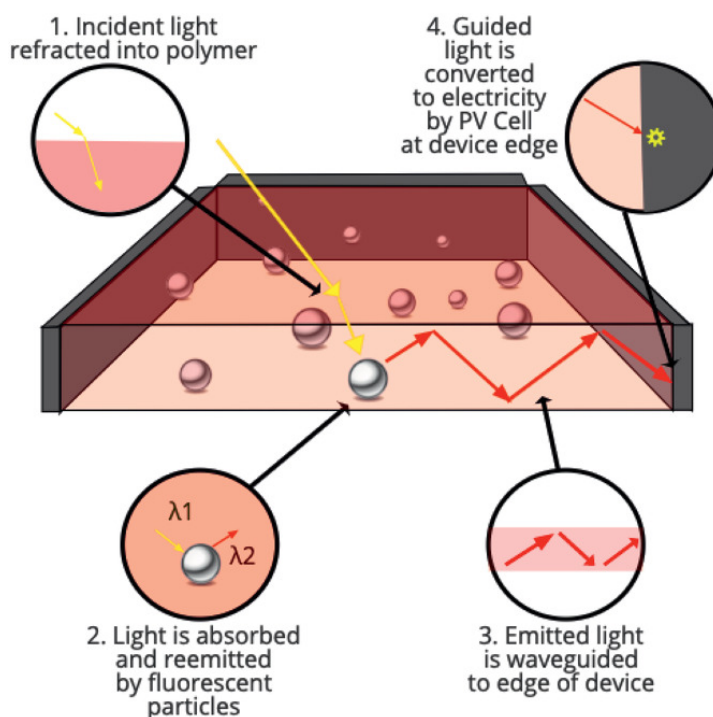

Fig2: Light absorption process of luminescent solar concentrator [3]

The amount of solar spectrum this LSC is targeting is 27 % of the solar spectrum which is known as absorption spectrum effectively. The percentage of light between 400 nm and 600 nm in the solar spectrum depends on various factors such as atmospheric conditions, location, and time of day. However, a commonly used approximation is based on research which shows that it is around 27 % [4]. The efficiency of photoluminescent dye in an LSC depends on several factors such as its chemical structure, and the concentration of the dye. For Lumegen Red 305 this efficiency is high around 85%. However another factor that affects the overall efficiency is downconversion efficiency which represents percentage of absorbed light down
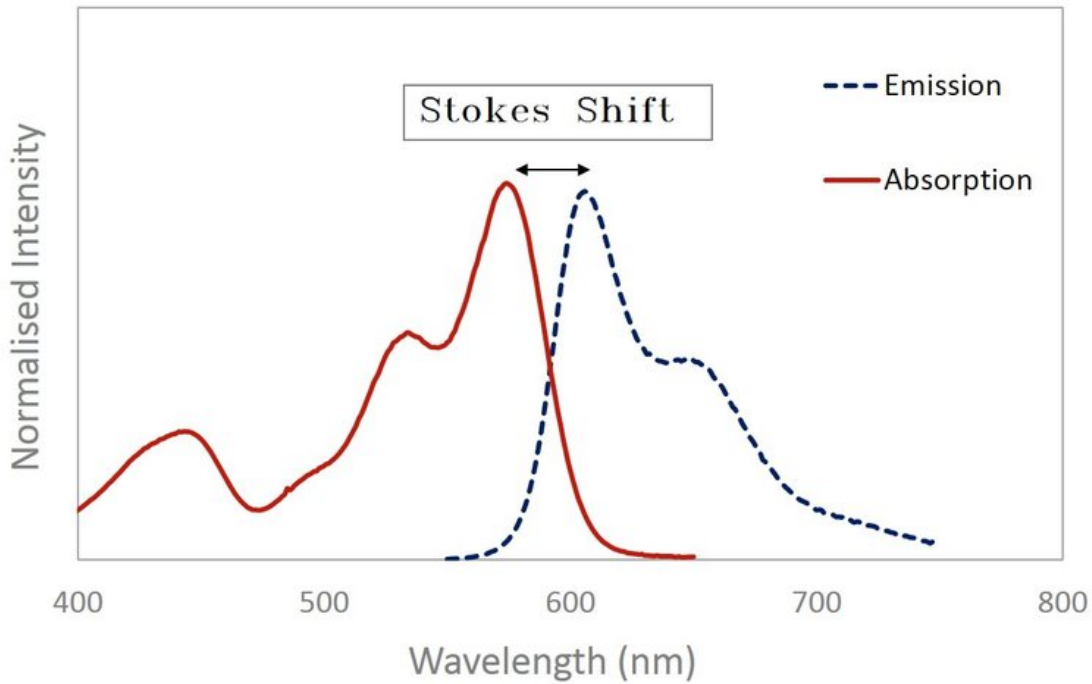
converted.

Fig3: Downstroke conversion of Lumegen Red 305 [5]

Waveguide efficiency depends on the internal refraction and transparency of the waveguide. For this project waveguide efficiency was estimated around 75% for 15 cm. The photons which are successfully waveguide after being down-converted by the photoluminescent dye are then absorbed by the solar panel on the edge. The efficiency of light converted into electrical energy from solar cells would be based on the monochromatic photovoltaic efficiency (MPE). This efficiency was estimated by using simulation from solarcore. This would result in overall efficiency given by following equation:

$$\eta(LSC) = \eta(PL) \times \eta(WG) \times \eta(DC) \times \eta(MPE) \times \eta(abs)$$

Based on research the dimension of 30 cm x 30 cm 0.5 cm was used as this gave the best efficiency from the waveguide [4]

2.1.1 Solar cell materials and design

Window: m = AlGaAs, w = 30nm, $N_a=5 \times 10^{24}$, Al=0.4

Emitter: m = n_AlGaAs, w = 150nm, $N_d=8 \times 10^{22}$, Al=0.2

Base: m = p_AlGaAs, w = 1000nm, $N_a=1 \times 10^{24}$, Al=0.2

BSF: m = AlGaAs, w= 200nm, $N_d=2 \times 10^{24}$, Al=0.3

Substrate: m = GaAs

Fig4: Solar cell design

To build the solar cell, our initial design is by using a window layer on top followed by an emitter and then base which is followed by back surface field and then we have the substrate. The terms "emitter" and "base," which are well-established in the literature and useful for describing the function of the layers in a p-n junction. Our main material for the solar cell is AlGaAs. The energy band gap E_g of $Al_xGa_{1-x}As$ alloys depends on the aluminum content x. In the range of $x < x_c = 0.45$ the gap is direct. At $x > x_c$ the gap is indirect which we can understand from the diagram below. At room temperature (300 K) the dependency of the direct gap on aluminum content x can be calculated by the equation[6]:

$$E_{g,dir}(x) = 1.422 \text{ eV} + x\ 1.2475 \text{ eV}$$

In this equation the symbols have the following meaning: $E_{g,dir}$ - direct energy band gap of $Al_xGa_{1-x}As$ for $x < 0.45$, x- aluminum fraction of the $Al_xGa_{1-x}As$ alloy
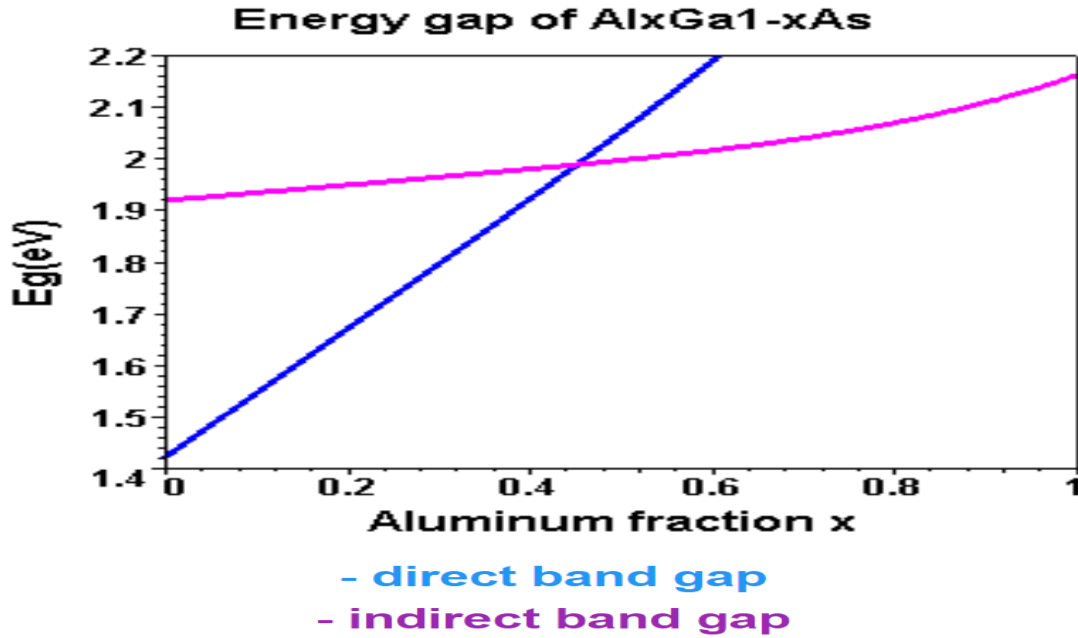
Fig5: Energy gap of AlGaAs [7]

Our window layer is of material AlGaAs with width = 30nm and number of acceptors N_a=5x10²⁴ and we set the Aluminium concentration to be 0.4. Our emitter layer is of n-type material of AlGaAs with width = 150 nm and number of donors N_d=8x10²² and we set the Aluminium concentration to be 0.2. Our base layer is of p-type material of AlGaAs with width = 1000 nm and number of acceptors N_a=1x10²⁴ and we set the Aluminium concentration to be 0.2. The emitter is usually thin to keep the depletion region near where the light is strongly absorbed and the base is usually made thick enough to absorb most of the light. Our back surface field (BSF) layer is of material AlGaAs with width = 200 nm and number of acceptors N_a=2x10²⁴ and we set the Aluminium concentration to be 0.3. Reduced surface recombination velocity (SRV) is one way that Back Surface Field (BSF) has been used to improve solar cell performance.

Adding a highly doped layer to the wafer's rear surface is one way to make BSF. Depending on the type of the dopant in wafer, the BSF layer could be either p^+ or n^+. We can also do a study to compare the performance of BSF layers both in p-type and n-type wafers in order to understand the effect of BSF on both wafer types. Our substrate layer is of material GaAs.
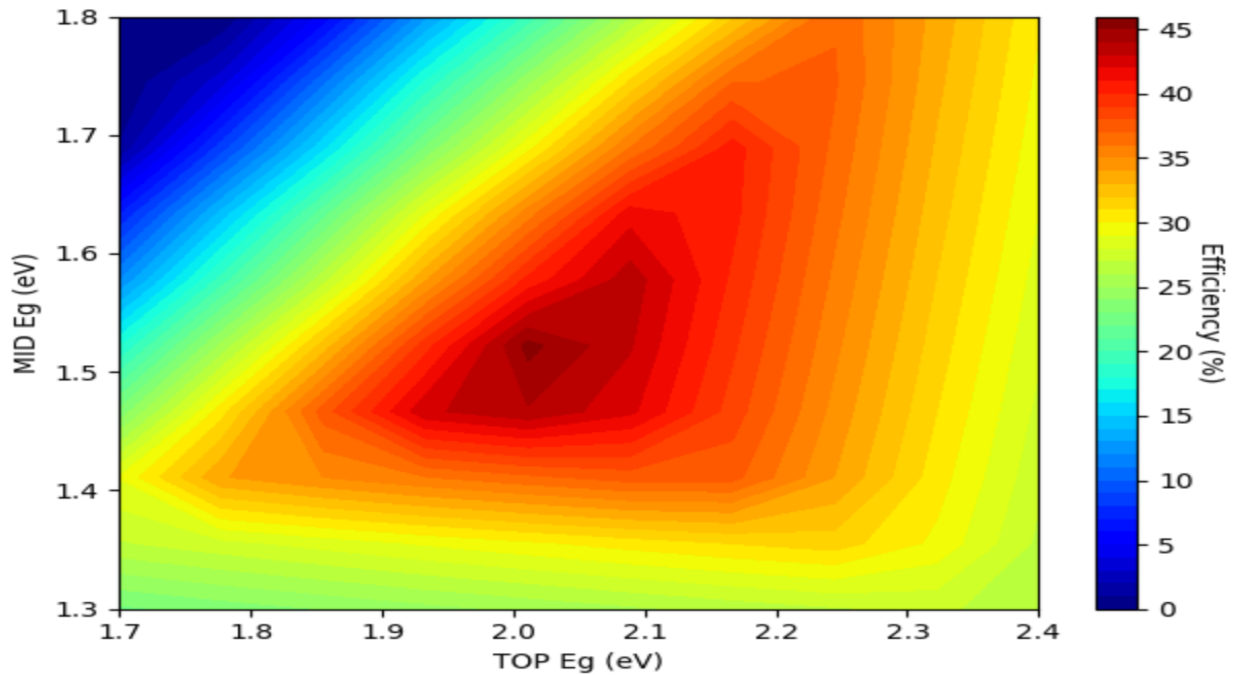

Fig6: Heatmap of efficiency for top versus middle/bottom layer energy gap

The concentration of aluminum for the top layer which is the window layer and the middle layer and bottom layer which is emitter and base respectively was chosen such that we get the maximum efficiency which can be seen from the above diagram. We calculated the efficiency as the ratio of the power at the maximum power point from the IV curve to the power density of the light. So based on this analysis and from the energy gap curve of AlGaAs we chose concentration of aluminum to be around 0.4 which corresponds to around 2.0 eV band gap energy for top layer and for the other two layers we chose concentration to be 0.2 as it corresponds to bandgap energy between 1.5 eV
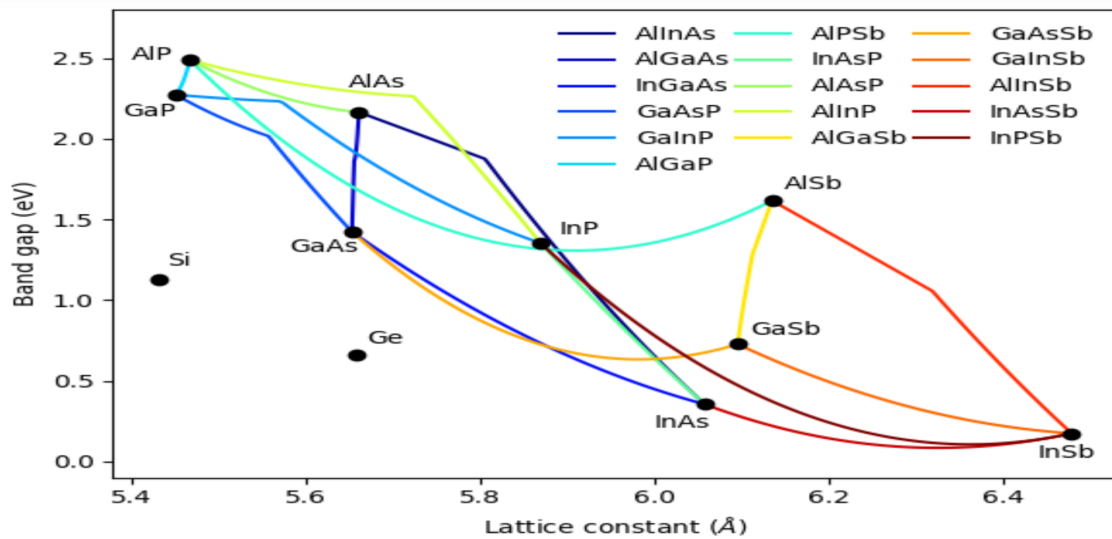
and 1.6 eV.

Fig7: Lattice constant versus band gap for AlGaAs

This above diagram shows the properties of AlGaAs from the AlAs and GaAs material where the lattice constant is similar for both these materials but at the cost of different band gap energy. AlGaAs have higher carrier mobility, improved carrier confinement of carriers in the quantum well channel, and larger conduction band discontinuity.
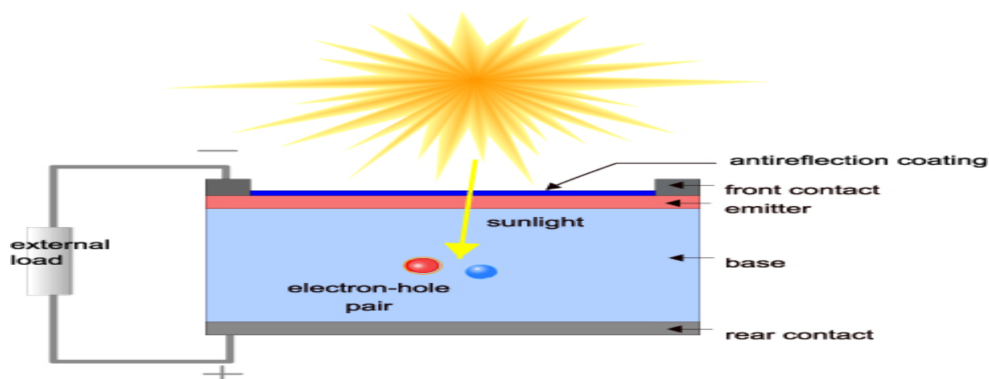
2.2 Working and Simulation

Fig8: Cross Section of the cell with circuit/load [8]

The "light-generated current"—the current produced by a solar cell—is produced by two essential processes. In the first step, incoming photons are absorbed to form electron-hole pairs. In the event that the incident photon's energy exceeds the band gap, electron-hole pairs will be produced in the solar cell. In contrast, because they are meta-stable, electrons in p-type materials and holes in n-type materials can only persist for about as long as the minority carrier lifetime before recombining. The electron-hole pair that produces light is lost if the carrier recombines, and no current or power can be produced. By utilizing a p-n junction to spatially separate the electron and the hole, a second process—the collection (separation) of these carriers—prevents this recombination. Ideally, the minority carrier in our case the holes makes it across the junction and becomes a majority carrier. In other words, the electric field present at the p-n junction acts to separate the carriers and the electric field at the p-n junction sweeps the light-generated minority carrier across the junction, where it becomes a majority carrier, if the minority carrier ever makes it there. The light-generated carriers flow across the external circuit/load if the solar cell's emitter and base are connected (i.e., if the solar cell is shorted) and the electron meets with the hole and completes the circuit. In the diagram above, the optimal flow at short circuit is depicted. Minority carriers cannot cross a semiconductor-metal boundary and to prevent recombination they must be collected (separated) by the junction if they are to contribute to current flow. The accumulation of light-generated carriers does not generate power on its own. A voltage and a current must be produced in order to generate power. The "photovoltaic effect" is a process by which a solar cell generates voltage. The assortment of light-created transporters by the p-n intersection makes a development of electrons on the n-type side and openings to the p-type side of the intersection. The carriers leave the device as

light-generated current, so there is no charge build-up during a short circuit. In any case, on the off chance that the light-created transporters are kept from leaving the sun oriented cell, the assortment of light-created transporters causes an expansion in the quantity of electrons on the n-type side of the p-n intersection and a comparable expansion in openings in the p-type material. The net electric field is decreased as a result of the opposite electric field being generated at the junction as a result of this charge separation. The diffusion current rises when the electric field is reduced because it acts as a barrier to the forward bias diffusion current's flow. A voltage crosses the p-n junction, establishing a new equilibrium. The difference between illumination current (I_L) and the forward bias current is the solar cell current. The junction's forward bias increases to the point where the net current is zero and the light-generated current is exactly balanced by the forward bias diffusion current in open circuit conditions. The "open-circuit voltage" is the voltage required to balance these two currents.

2.3 <u>Simulation result and discussion</u>

We calculated the quantum efficiency based on two methods which are Beer-Lambert (BL) law which states that loss of light intensity when it propagates in a medium is directly proportional to intensity and path length and poisson_drift_diffusion method which is a numerical method.
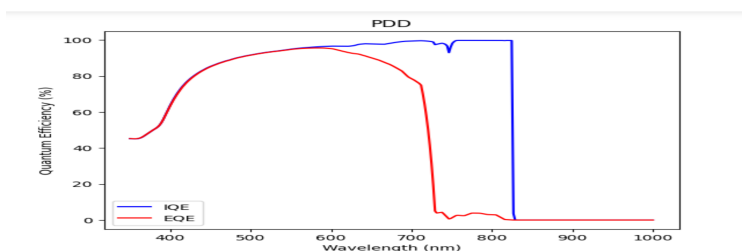

Fig9: Wavelength versus quantum efficiency using poisson drift diffusion

We used two methods in order to find out the internal (IQE) and external quantum efficiency (EQE).
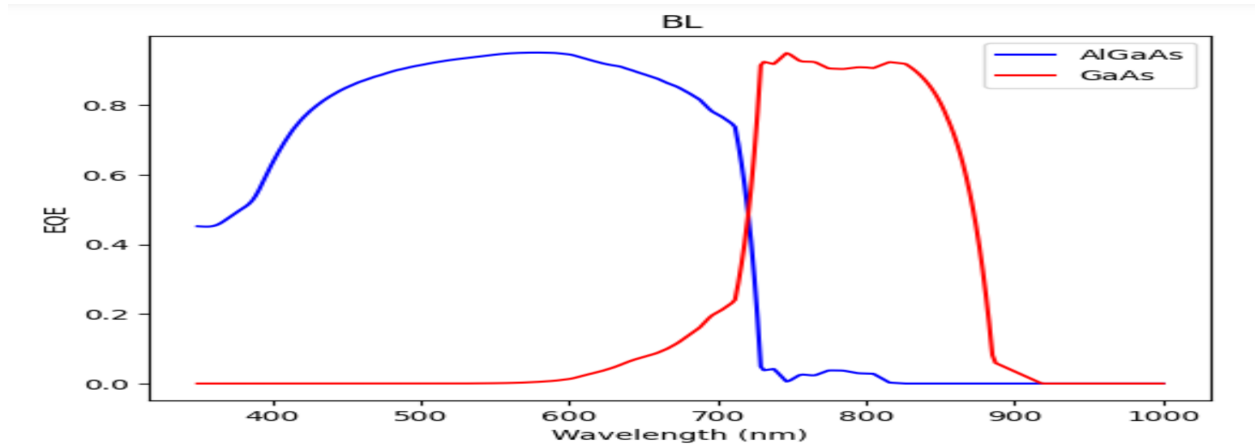

Fig10: Wavelength versus external quantum efficiency using Beer-Lambert law

We observed that the IQE is higher compared to EQE and we are getting around 80% EQE within our required wavelength. Also by BL method we tried to show that AlGaAs has better EQE than GaAs for our required wavelength of above 500 nm and below 800 nm which is another reason we chose AlGaAs.
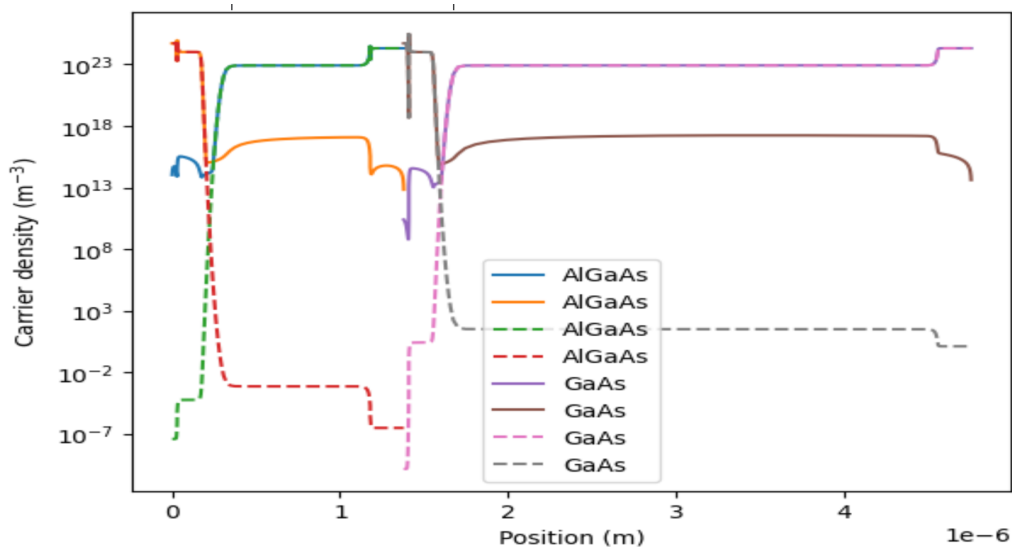

Fig11: Position versus carrier density for GaAs and AlGaAs

The above diagram shows the carrier density value as the position varies along the cell and it is evident that the carrier density of AlGaAs is higher which again constitutes for higher performance. The dashed line corresponds to equilibrium state values and solid lines correspond to short circuit values.
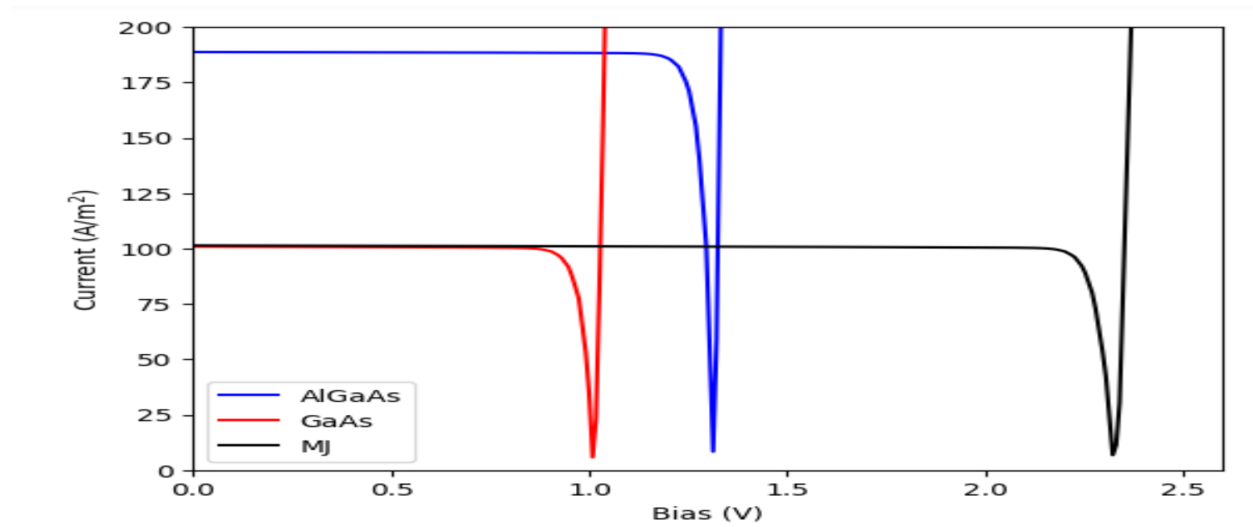

Fig12: IV curve for AlGaAs and GaAs and total

The above diagram shows the IV curve for our solar cell model which implies we have higher power output for AlGaAs than GaAs.
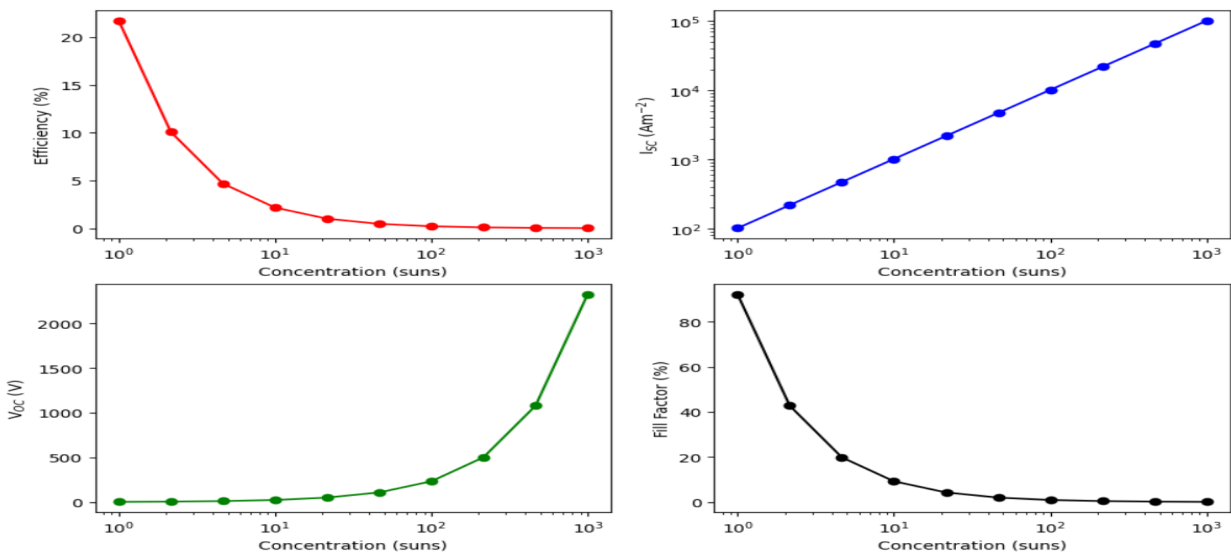

Fig13: Plot of efficiency, Isc, Voc, fill factor versus concentration (suns)

The above diagram shows analysis of how the efficiency, short circuit current, open circuit voltage and fill factor vary with concentration. This above analysis showed expected result for short circuit current as the solar cell's short circuit current varies linearly to light intensity; consequently, the value of the device operating under 10 suns would be ten times that of a comparable device operating under one sun. However, this impact won't give an expansion in proficiency, in light of the fact that the incident power increases linearly as well with the concentration. However, with concentration, V_{oc} should logarithmically increase with light intensity but we are getting unexpected results due to the losses at the junction which was not well-defined. Similar are the cases with efficiency and fill factor which expectedly should increase to certain concentrations. To account for these issues we tried to add some well defined tunnel junctions, anti reflective coating (ARC), back reflection and quantum wells to the solar cell.
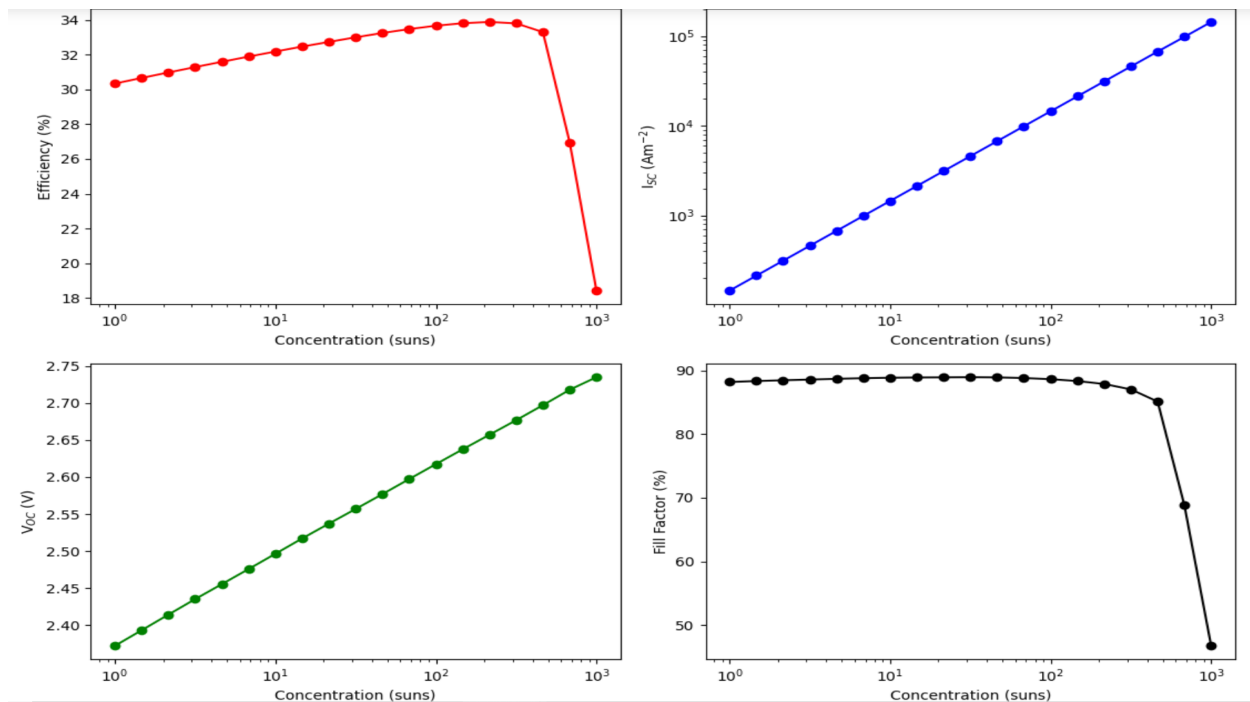

Fig14: Plot for efficiency, Isc, Voc and fill factor versus concentration (suns) after defining junction and wells

The above diagram shows after incorporating the changes to the cell which therefore gives us expected results. The efficiency benefits of concentration might be reduced by the increased losses from the series resistance as short circuit current increases and as well by the increased temperature of the solar cell operation. As losses from short circuit current are dependent on the square value of the current, power loss from series resistance increases with the concentration square. In log-log and semilog plots, respectively, Isc and Voc exhibit the expected linear trend, while the fill factor increases for low concentrations before continuously decreasing from 20 suns and, more specifically, 200 suns. A limited carrier transport across the QW region, which experiences charge accumulation and electric field damping under concentration, may be the cause of the initial smooth drop in the fill factor. However, the failure of the tunnel junction, which was intended to have a low peak current, is the cause of the abrupt drop at higher concentrations. At one sun, efficiency is just above 30 percent. As concentration increases, it reaches its peak around 200-300 suns later. The efficiency decreases further as the concentration is increased rapidly.

3. System Design and Integration

Below sections gives us a detailed analysis of our solar cell application and tools used for simulation

3.1 Analysis

Using parameters and value for efficiency and based on the area of the module we could determine that the overall efficiency of the panel is around 2.5%. This drop comes in part with the fact the solar panel is only absorbing a small proportion of the solar

spectrum and its job is not to collect the majority of the infrared light. This down conversion efficiency and waveguide efficiency can increase using PCHMA inside of PMMA [9]. However this would increase overall cost. Target was to produce a concentrator system which is cheap and easy to produce. Using PMMA and lumegen red 305 accomplish both tasks of making the luminescent solar concentrator. Assuming 1000 W/m², and factoring only 2.5% energy being absorbed. Based on this assumption 25 w would be generated for meter square.

3.2 Software used

We used the solcore[10] package which is a multi-scale python library for modeling semiconductor materials and solar cells for simulation.

4. Manufacturing and Production

Below sections give us a detailed analysis of manufacturing and production.

4.1 Manufacturing Introduction:

Manufacturing an aluminum gallium arsenide (AlGaAs) solar cell involves several steps, including the following:

1. Substrate preparation: Start with a substrate, usually made of a material like gallium arsenide (GaAs), that will serve as the base for the solar cell. The substrate is cleaned and treated to remove any impurities or contaminants that could affect the performance of the solar cell.

2. Growth of the active layer: A layer of AlGaAs is grown on the substrate using a method like molecular beam epitaxy (MBE) or metalorganic vapor phase epitaxy

(MOVPE). The exact composition of the AlGaAs layer depends on the desired bandgap energy and efficiency of the solar cell.

3. Patterning and doping: The AlGaAs layer is patterned into specific shapes and sizes using lithography and etching techniques. It is then doped with impurities such as silicon (Si) or tellurium (Te) to create p-type and n-type regions, which will form the junction of the solar cell.

4. Contact deposition: Metal contacts are deposited on the front and back of the solar cell to allow for electrical connections. These contacts are usually made of materials like gold (Au) or aluminum (Al).

5. Anti-reflection coating: A layer of anti-reflection coating (ARC) is deposited on the front surface of the solar cell to reduce reflection and improve light absorption. This layer is typically made of a material like silicon nitride (SiNx).

6. Encapsulation: The solar cell is encapsulated with a protective layer of glass or polymer to protect it from the environment and provide mechanical support.

7. Testing: The completed solar cell is tested to ensure that it meets the required specifications for efficiency, power output, and durability.

For manufacturing our material we choose the Molecular Beam Epitaxy (MBE) method because it's particularly good for making high-quality (low-defect, highly uniform) semiconductor crystals from compounds, or from a number of different elements, instead of from a single element. It also allows extremely thin films to be fabricated in a very precise, carefully controlled way.

The disadvantage was because it's a slow and laborious method (crystal growth rate is typically a few microns per hour), which means it's more suited for scientific research laboratories than high-volume production, and the equipment involved is complex and

very expensive[11].

Molecular Beam Epitaxy (MBE):

To make a new crystal using MBE, we start off with a base material called a substrate, which is a semiconductor material such as silicon, germanium, or gallium arsenide. First, we heat the substrate, typically to some hundreds of degrees (500–850°C or about 930–1560°F in the case of gallium arsenide)[11].

Then the machine fires relatively precise beams of atoms or molecules (heated up so they're in gas form) at the substrate from "guns" called effusion cells. Each effusion cell is open at one end and consists of a tapering crucible (a kind of heat-resistant cup) filled with the material it's going to "fire," an electrically controlled heater, and a thermocouple for measuring and regulating its temperature. The number of cells depends on the complexity of the crystal being produced, there can be as many as 8–14 of them. For our case it consists of 3 effusion cells. Like the substrate, the cells are heated to high temperatures, a maximum of about 1500–1600°C or so (2700–2900°F)[11].
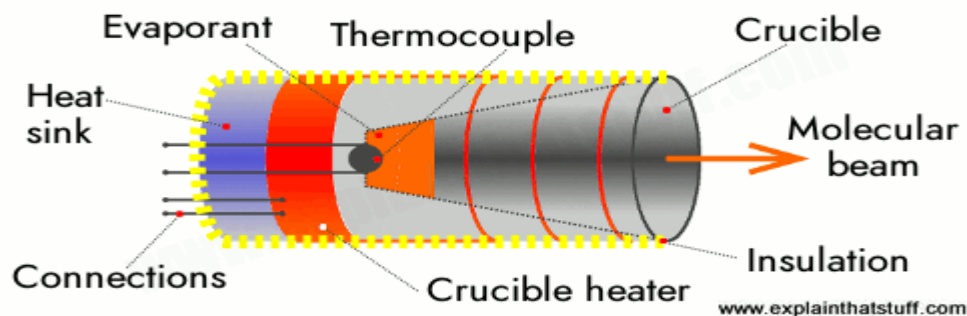

Fig15: Effusion cell structure[11]

We need one cell for each different beam, shooting a different kind of molecule at the substrate. The molecules land on the surface of the substrate, condense, and build up very slowly and systematically in ultra-thin layers, so the complex, single crystal grows one atomic layer at a time. Very slowly means *very* slowly, typically at a rate of a few microns, or fractions of microns, per hour. That's why MBE is an example of what's called thin-film deposition.
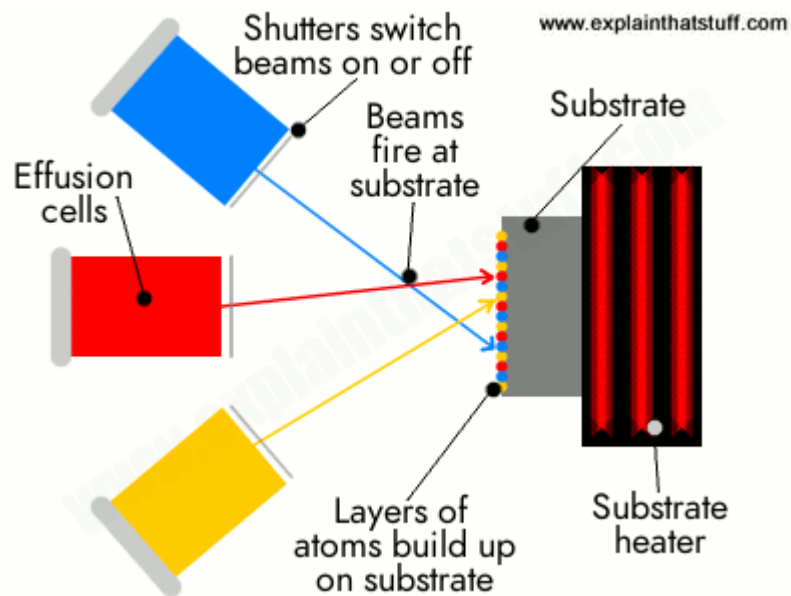

Fig16: MBE setup[11]

Fig17: MBE in action[11]

One reason that MBE is such a precise way of making a crystal is that it happens in highly controlled conditions: extreme cleanliness and what's called an ultra-high vacuum (UHV), so no dirt particles or unwanted gas molecules can interfere with or contaminate the crystal growth. "Extreme cleanliness" means even cleaner than the conditions used in normal semiconductor manufacture; an "ultra-high vacuum" means the pressure is so low that it's at the limit of what's easily measurable as little as one hundred trillionth of atmospheric pressure[11].

4.2 Cell Production

The cost of manufacturing aluminum gallium arsenide (AlGaAs) solar cells per square meter using molecular beam epitaxy (MBE) can vary widely depending on a number of factors. Some of the key factors that can influence the cost include:

1. The cost of raw materials, including aluminum, gallium, arsenic, and other consumables.
2. The cost of equipment, including MBE equipment and other fabrication tools.
3. The cost of labor, including salaries, benefits, and other personnel expenses.
4. The cost of energy, including electricity and other utilities.
5. The cost of overhead, including rent, insurance, taxes, and other expenses.

Taking these factors into account, it's difficult to give a precise estimate of the cost of manufacturing AlGaAs solar cells using MBE. However, based on industry data and estimates, the cost can range from a few hundred dollars to several thousand dollars per square meter.

For example, a study published in 2018 estimated the manufacturing cost of GaAs and AlGaAs solar cells to be around $400-500 per square meter [15], based on an analysis of

raw material and equipment costs, as well as production yield and efficiency. Another study published in 2019 estimated the manufacturing cost of AlGaAs solar cells to be around $800 per square meter, based on a similar analysis.

It's worth noting that these estimates are based on certain assumptions and may not reflect the actual cost of manufacturing AlGaAs solar cells in specific cases.

4.3 Cell/Module Cost and Estimated Pay-back Time

Below sections show detailed cost estimates and energy payback time.

4.3.1 Cell/Module Cost

So, to work on cell/module production we came up with few assumptions and added all possible expenses together to get the overall cost for manufacturing this system.

To provide a rough estimate, the cost of raw materials, equipment, labor, and other expenses is $1,000 per wafer, and each wafer produces approximately 50 AlGaAs solar cells. This would result in a cost of approximately $7,500 (375 cells) for 60 square cm, assuming that the entire surface area is covered with AlGaAs solar cells [14]. The evaluated price of Luminescent Solar Concentrator comes around $45 per square meter.

The cost of raw materials, equipment, labor, energy, and other expenses can vary widely depending on several factors, such as the location of the manufacturing facility, the size and complexity of the AlGaAs solar cells being produced, the production volume, and the availability and cost of resources such as electricity and labor.

Here is a breakdown of the estimated costs based on different categories:

- Raw Materials:
    a. Aluminum (Al) and gallium (Ga) sources: $150

b. Arsenic (As) source: $50

c. Substrate: $200

- Equipment:

    a. MBE chamber: $400

    b. Wafer handling and cleaning equipment: $100

- Labor:

    a. Technical staff: $50

    b. Maintenance staff: $50

- Energy:

    a. Electricity: $50

    b. Liquid nitrogen: $50

- Other Expenses:

    a. Gases (e.g. nitrogen, hydrogen): $50

    b. Chemicals and consumables: $100

    c. Facility and overhead costs: $100

- Concentrator material cost:

    a. PMMA ad

Total estimated cost per wafer: $1,000

Based on this data the overall evaluated cost is approximately $300/Watt.

4.3.2 Estimated Payback Time

The Estimated Payback Time (EPBT) is used to estimate the time it takes for a solar energy system to generate enough energy to compensate for the energy that was required to manufacture, install, and maintain the system. It is typically expressed in

years.

The EPBT depends on a variety of factors, including the efficiency of the solar cells, the energy required to manufacture and transport the materials, the energy required to install the system, and the expected lifespan of the system.

Our estimated EPBT for Aluminium Gallium Arsenide (AlGaAs) with Molecular beam epitaxy technique and total solar efficiency of 2.5% gives us 22.9 years. This is the amount of time it would take for our Luminescent Solar Concentrator module to pay back the energy it took during development.

5. <u>Conclusion</u>

Overall luminescent solar concentrators has limited potential in this area. However, the most expensive part of our design was the Photovoltaic cell. Using perovskite or an organic cheaper cell design with high band gap would reduce the cost and make it viable. Other stable solar cells such as CdTe PV cells could also be used however it would remain a challenge to grow them on a PMMA waveguide. Using other cells the efficient cost of the cell would reduce drastically and make it viable for greenhouse use. Through our simulation and using ideal AlGaAs for the solar cell the max efficiency calculated was found to be 2.5%. This low number is majority due to its design parameter to only absorb green light thus reducing the overall efficiency as it is a small part of the solar spectrum.

References:

[1] *NASA GISS: Research Features: The full palette of photosynthesis* (no date) *NASA*. NASA. Available at: https://www.giss.nasa.gov/research/features/201311_kiang/

[2] Loik, M.E. *et al.* (2017) "Wavelength-selective solar photovoltaic systems: Powering greenhouses for plant growth at the food-energy-water nexus," *Earth's Future*, 5(10), pp. 1044–1053. Available at: https://doi.org/10.1002/2016ef000531

[3] Papakonstantinou, I., Portnoi, M. and Debije, M.G. (2020) "The hidden potential of luminescent solar concentrators," *Advanced Energy Materials*, 11(3), p. 2002883. Available at: https://doi.org/10.1002/aenm.202002883

[4] Corrado, C. *et al.* (2016) "Power generation study of luminescent solar concentrator greenhouse," *Journal of Renewable and Sustainable Energy*, 8(4), p. 043502. Available at: https://doi.org/10.1063/1.4958735

[5] Lumogen red 305 fluorescent dye absorption (red) and emission spectra. Available at:

https://www.researchgate.net/figure/Lumogen-Red-305-fluorescent-dye-absorption-red-and-emission-spectra_fig3_326579362

[6] Sadao Adachi: "GaAs and Related Materials", World Scientific Publishing Co. 1994

[7] Energy gap for AlGaAs at https://www.batop.de/information/Eg_AlGaAs.html

[8] Crosection of cell with load at

https://www.pveducation.org/pvcdrom/solar-cell-operation/solar-cell-structure

[9] Ostos, F.J. *et al.* (2020) "High-performance luminescent solar concentrators based

on Poly(cyclohexylmethacrylate) (PCHMA) films," *Polymers*, 12(12), p. 2898. Available at: https://doi.org/10.3390/polym12122898

[10] D. Alonso-Álvarez, T. Wilson, P. Pearce, M. Führer, D. Farrell, N. Ekins-Daukes, Solcore: a multi-scale, Python-based library for modeling solar cells and semiconductor materials, *Journal of Computational Electronics* (2018)

[11] https://www.explainthatstuff.com/molecular-beam-epitaxy-introduction.html

[12]https://www.globalpetrolprices.com/USA/electricity_prices/#:~:text=USA%2C%20June%202022%3A%20The%20price,of%20power%2C%20distribution%20and%20taxes

[13] Molecular Beam Epitaxy of Ultra-High Quality AlGaAs/GaAs Heterostructures: Enabling Physics in Low-Dimensional Electronic Systems. Michael J. Manfra Department of Physics, School of Electrical and Computer Engineering, and School of Materials Engineering

[14] Cost Modeling of Thin-Film III-V Multijunction Solar Cells" by M. Steiner.

[15] "Manufacturing Cost Analysis of 10kW Inverter with High-Frequency SiC Gate Drivers for Solar Applications" by C. Li.