Ge/GaAs/InGaP Triple-Junction Solar Cells for Space Exploration

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ABSTRACT

In recent years, the use of photovoltaic cells has seen a massive surge. Spacecrafts such as the Europa Clipper, the International Space Station (ISS), and a number of satellites rely heavily on Solar Energy for their functionality and power consumption. For these spacecrafts, it is necessary to be under a precise total mass requirement. The weight and volume of Solar Cells has been of paramount concerns. It is critical for Solar Cells to have a good quantum efficiency such that it absorbs the maximum amount of solar irradiance. For this purpose, the use of multi-junction solar cells is ideal as they give a decent spread of the solar irradiance. Triple Junction cells have been proven to be easier to grow than higher multi junction cells and are more efficient than single junction cells [1]. InGaP/GaAs/Ge multi junction model is proposed to reduce the size of the solar cells without much loss in overall power generation and efficiency. This model was simulated and there were a number of cases that were tested. The thickness of the base layers, the doping concentration of the Tunnel Junctions of the cell, and the width of the overall cell were varied to see their effect on the efficiency. Changing these parameters does not affect the overall efficiency a lot; however, the single simulated device will be replicated and connected together multiple times when used. This was done by simulating the structure on Crosslight TCAD software. The simulations were done to test out the efficiency for the Europa Clipper in space close to Jupiter under AM0. To take this into account, the spectrum at Jupiter was used by the help of some Physics which has been discussed. Intensity decreases dramatically when near Jupiter compared to the intensity on Earth. Furthermore, due to very low temperatures close to 0K in space, the bandgap of the layers used increase. All these factors coupled together have a major impact on the device performance. The results obtained from the simulation have been shown in the results section of the paper.

1. INTRODUCTION AND MOTIVATION

There have been remarkable developments in the technology of Photovoltaic Cells designed for use in space. There has been a surge in the development, manufacturing, and use of multi-junction Solar cells all throughout. Initially, there were obstacles such as composition, overall size, and lattice matching of different junctions which have now almost been overcome by the use of transparent and conductive Buffer layer or Tunnel Junctions. This has led to the study of 5- and 6- junction solar cells. There has been a major shift towards the usage of triple junction solar cells due to their overall versatility. Solar Cells are the lifeline of spacecrafts. The ISS has 8 solar panels which are used to generate around 75-90 kW of power [1]. The weight, volume, and size of the Solar arrays used in the spacecrafts have always been of paramount concerns. Therefore, it is necessary to reduce the number of solar panels used with an insignificant tradeoff in the overall power generation by the panels used. For this purpose, the use of an InGaP/GaAs/Ge triple junction solar cell with two tunnel junctions is proposed.

There a large number of panels used which lead to an increase in the overall mass required. Especially for the Europa Clipper, which will be orbiting Jupiter's moon, has a strict precise overall weight requirement of 6001kg. To overcome this issue, it is vital to reduce the number of Solar arrays, not very significantly, and increasing the EQE of the panels used. The overall power consumption requirement remains the same, therefore a triple junction solar cell which can absorb almost all the solar irradiance available in space will benefit greatly. Reducing the weight would not only allow a more comfortable launch but also significantly reduce the cost of manufacturing, assembly, lifting a payload into space, and smaller number of solar arrays would lead to higher maneuverability. This would lead to development in the overall model of the orbiters, satellites, space stations, and UAVs which will heavily promote and push the boundaries of space exploration [1].

More a majority of spacecrafts, 3J solar cells are used due to the ease of growth. A number of MJ, thin film, and Si structures have been proposed. There are 5- junction cells such as AlGaInP/ AlGaInAs/GaInAs/GaInNAs/Ge solar cells which result in a decent efficiency but are difficult to fabricate due to lattice mismatching and therefore need more tunnel junctions and buffer layers. Having a higher number of buffers and tunnels lead to higher number of trap levels and growth defects which lead to higher unwanted recombination. The non-radiative recombination causes the lattice to heat up which is unwanted especially in a cell which has Ge due to its properties. The use of InGaP/GaAs/Ge 3J cells makes fabrication simpler compared to the 5- and 6- junctions and leads to higher efficiency compared to Si cells.

To improve the efficiency of the cell, it is critical to look at all the aspects while modelling the device. There has been a lot of research work for this purpose and hence there are a plethora of triple junction solar cell designs. One of the most prominent models which has been cited in a number of research papers is the one shown in Fig. 1.1 [2].

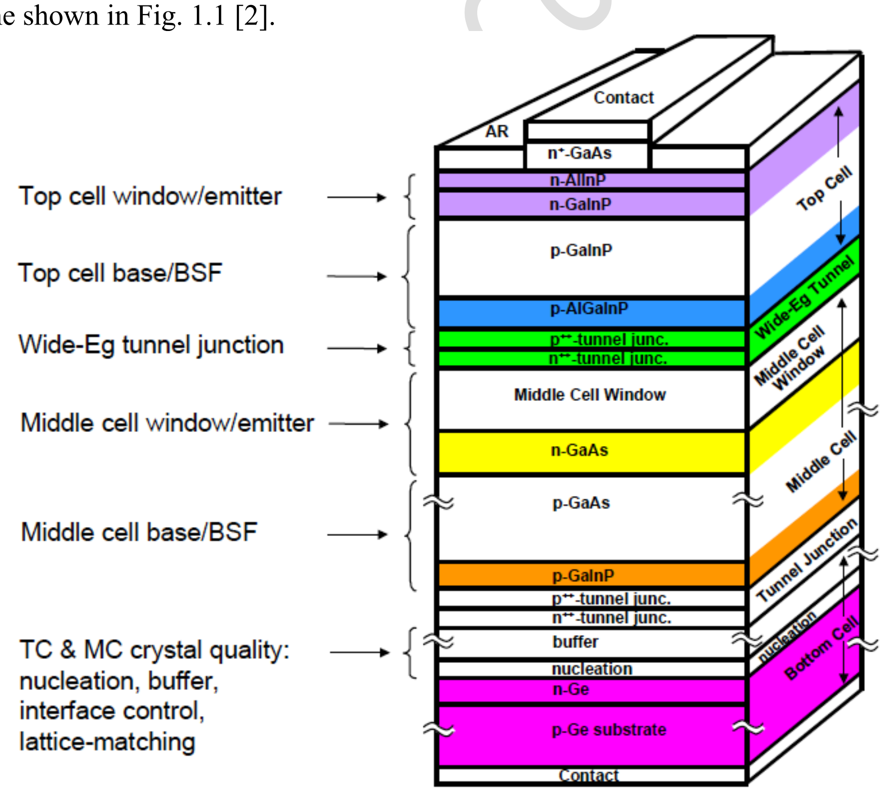

Fig 1.1: Cross-section of epitaxial layers of Ge/GaAs/InGaP design [2]

Crosslight (TCAD) has been used to optimize this model in Jupiter and the irradiance spectrum of Jupiter was used for the various simulations.

2. TECHNICAL BACKGROUND

Every material has a conduction band and valence band. At 0K for an isolated material, all the electrons of the material are attached to the lattice and are in the valence band. For electrons in a material to be able to conduct, it is necessary for them to be in the conduction band. The region between the conduction band and valence band is known as the Band Gap. There can be no free carriers in the band gap. For insulators, the conduction band edge is at a significantly higher energy level compared to the valence band edge (E_C-E_V=E_G>5eV). In metals, the conduction band edge is at a lower energy level compared to the valence band edge, this means that the valence band and conduction band share electrons and hence metals are very conducting. Semiconductors are those materials which have an energy bandgap between 0eV and 5eV. There are a number of ways to utilize the unique properties of semiconductors. When an electron gets energy greater than the bandgap energy (E_G), the electron can jump on to the conduction band which leads to the lack of electron or 'hole' in the valence band which has a positive charge equal in magnitude to that on an electron.

Solar Cells are optoelectronic devices that generate power when light is incident on them. A solar cell is a semiconductor device which can be represented as a PN junction diode which operates by the Photovoltaic Effect. According to the Photovoltaic Effect, an incident photon with energy greater than the bandgap of the material can be absorbed to generate an Electron Hole pair (EHP). The electron ends up in the conduction band and the hole in the valence band. An electric field can be used for carrier separation as electrons and holes move in the opposite direction in the presence of an electric field.

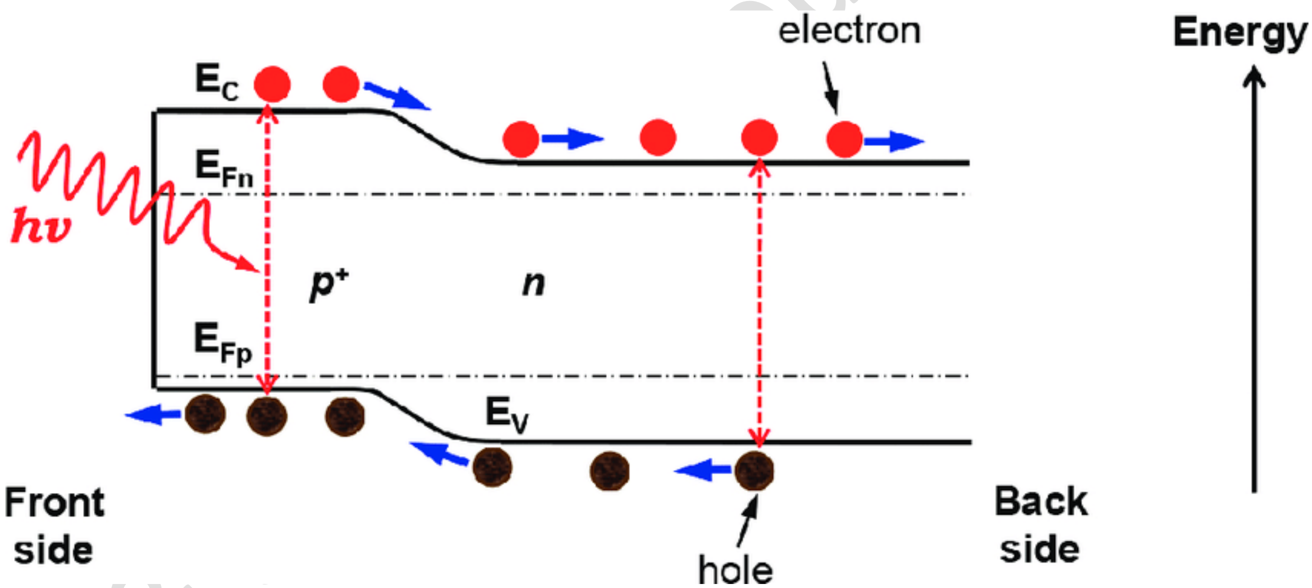

Fig 2.1: Photon Absorption Mechanism [3]

We can use the ideal diode equation (Equation 1) and the equivalent circuit (Fig 2.2) to derive an equation for the current at a voltage bias for a solar cell. The result is Equation 2.

Equation1: $I(V) = I_{op} - I_0\left[e^{\frac{qV}{kT}} - 1\right]$, I_0 = saturation current, I_{op} = optically generated current

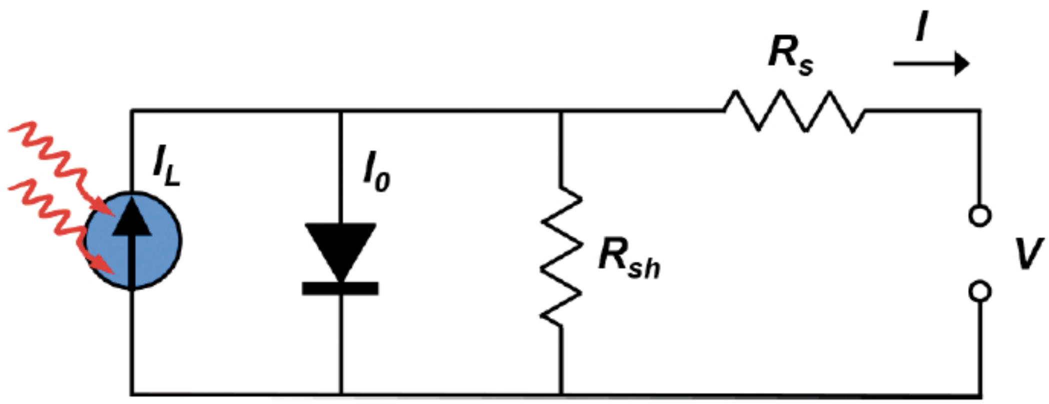

Fig 2.2: Equivalent Circuit of Solar Cell; R_{sh}= Shunt Resistance, R_s= Series Resistance [3]

For Solar Cells, we want the series resistance to be as low as possible and the shunt resistance to be as high as possible. These conditions drive us closer to ideality. Series resistances usually arise from contacts and affects the voltage, whereas, shunt resistance arises due to side wall leakage and affects current.

Equation 2: $I(V) = I_{op} - I_0\left[e^{\frac{q(V+IR_S)}{kT}} - 1\right] - \frac{V+IR_S}{R_{sh}}$

The resulting IV curve is used to find the output power in illumination and to find the fill factor (FF) and efficiency which are important parameters while analyzing solar cells.

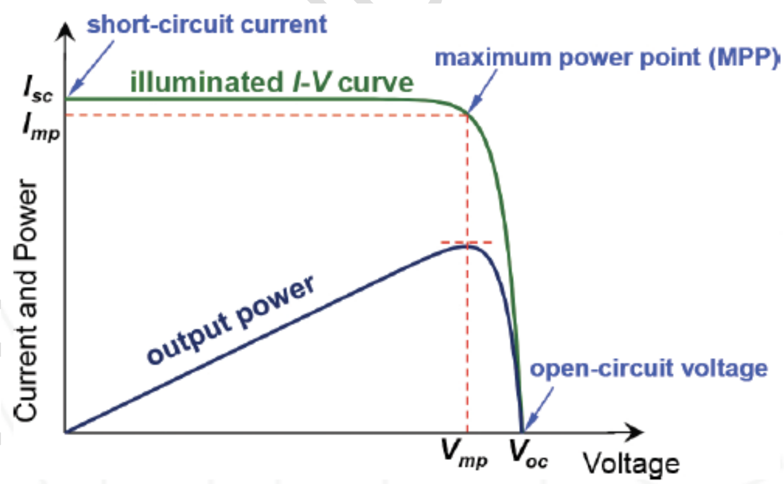

Fig 2.3: IV Curve, output power, maximum power point. [3]

$$Fill\ Factor\ (FF) = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$$

$Efficiency\ (\eta) = \frac{V_{oc}I_{sc}FF}{P_{in}}$, where P_{in} is the input power

Another critical factor for solar cells is the use of Direct bandgap semiconductors over Indirect bandgap semiconductors. Direct Bandgap materials are best suited for optoelectronic devices since they have the lowest energy for the conduction and valence band at the same value of momentum which is not the case for Indirect bandgap material. Some momentum is supposed to be accounted for when we look at either absorption or emission using indirect bandgap materials. The compensation for the momentum reduces the efficiency of the device.

By making alloys and growing semiconductors on top of each other, all bandgaps can be achieved. For Multi Junction Solar Cells, since they are grown layer on top of layer, lattice matching is essential for any output and efficiency [5]. During epitaxial growth of semiconductors, there cannot be abrupt changes in the lattice constants, a change of about 2% can be compensated by lattice strain. Lattice mismatch in a device leads to a number of defect and dangling bond formation which drastically reduces efficiency.

Defects in a structure can lead to high recombination rate, both radiative and non-radiative recombination. When an electron from the conduction band combines with a hole in the valence band to emit a photon, it is known as radiative recombination. LEDs are based on radiative recombination. There are two types of non-radiative recombination: Auger Recombination and Shockley-Read-Hall (SRH) Recombination. Auger Recombination is a three-particle process which leads to heating up of the lattice as the energy released by the EHP recombination is absorbed by another electron in the conduction band. SRH or Trap Assisted recombination are very common in devices with high defect density. Basically, there is a trap level in the Band Gap region due to defects and carriers can be trapped in this region. Any form of electron hole recombination is undesirable in Solar Cells as it reduces the efficiency [4].

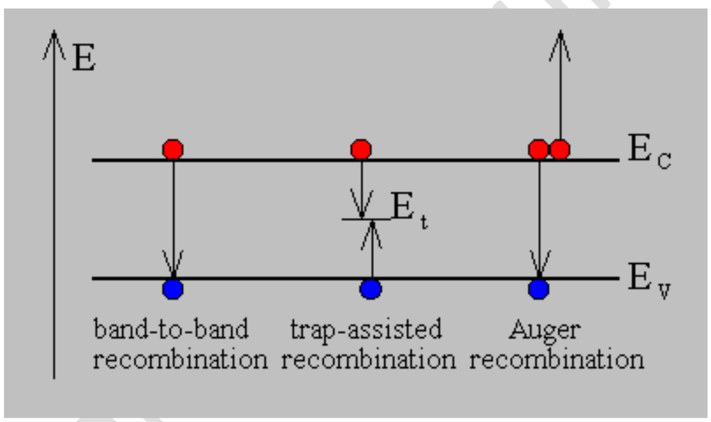

Fig 2.4: EHP Recombination mechanism [4]

3. DEVICE STRUCTURE, DESIGN, AND RELATED PHYSICS

There are a number of designs proposed various institutions for Solar Cells use in space. The simulated structure is proposed for use in Europa Clipper which orbits Europa- the moon of Jupiter. Therefore, the device has been simulated with the solar irradiance spectrum of Jupiter. The design used for simulation in Crosslight was a Triple Junction Ge/GaAs/InGaP solar cell to cover the overall spectrum.

For a spacecraft like the Europa Clipper, it is critical to get as much irradiance as possible; therefore, we want to cover the whole spectrum by using a structure that can absorb all the wavelengths for power generation and high efficiency. Hence, a triple junction solar cell has been proposed over a single or double junction double junction cell. Even though higher energy photons are absorbed by the semiconductor, after crossing the bandgap of the semiconductor, the remaining energy of the photons is used up as thermalization- *phonon creation* - which heats up the lattice as illustrated in Fig (3.1). Only the energy equal to the Bandgap Energy (E_g) is used up for carrier generation. The extra energy ($E = h\nu - E_g$) is the kinetic energy gained by the generated electron and hole. The generated EHPs lose this gained kinetic energy which leads to the creation of phonons and is dissipated as heat. This absorbed energy does NOT create any carriers and therefore reduces the overall efficiency of the device [6].

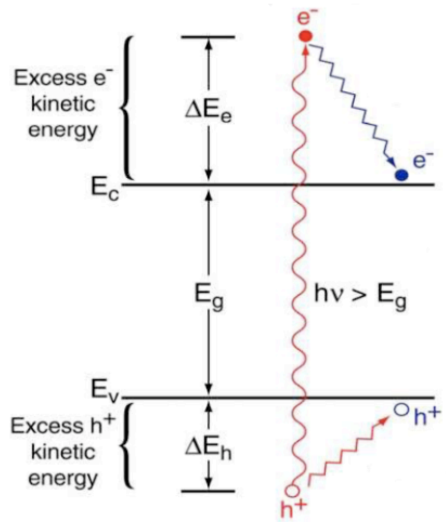

Fig 3.1: Thermalization of generated EHP for photon energy greater than the bandgap. As shown, the extra energy is gained by the EHP as Kinetic energy which is dissipated and heats up the lattice. This reduces the efficiency [6].

To reduce this effect of thermalization and get higher efficiency, we choose to use triple junction solar cells instead of single or double junction devices. This raises the question of increasing the number of junctions to 5 or 6 or even higher. A critical factor in that case is lattice matching the various junctions; thus, there are major problems with the epitaxial growth of these devices. To solve the issue of lattice matching, buffer layers need to be added to the solar cells which increases unwanted absorption and leads to the creation of defects which increase non-radiative recombination. All of these factors lead to the reduction of efficiency which are not as prominent in 3J cells as the growth process is comparatively easier.

For the device, it was critical to use semiconductors that would cover all the wavelengths emitted by the Sun. The device simulated had a Germanium (Ge) substrate and base layer, GaAs and $In_{0.5}Ga_{0.5}P$ base. The energy bandgap of Ge, GaAs, and $In_{0.5}Ga_{0.5}P$ are 0.74 eV, 1.43 eV, and 1.76 eV [7]. This design covers a wide range of wavelengths as depicted in Fig 3.2.

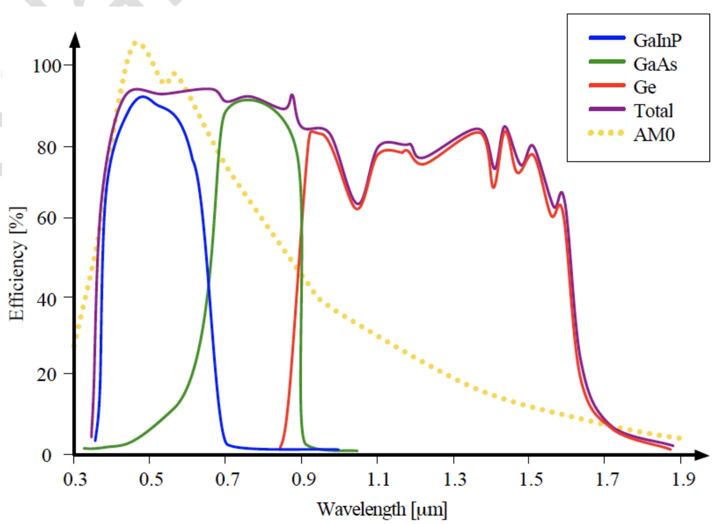

Fig 3.2: Wavelength spectrum covered by the base layers of the proposed structure [8]

The discussion for the modelling has another, very crucial, factor left which needs to be taken into account and that is the fact that we are testing the cell for use for Europa- one of Jupiter's many moons. The solar irradiance near Jupiter is orders of magnitudes lower compared to that of Earth. This affects the design significantly as now we have lower intensity which means that the number of incident photons; consequently, lesser number of EHPs and power are generated. It was assumed that the solar radiation intensity (*H*) is inversely proportional to the distance between the sun and the location at which the intensity is measured. The solar constant (in W/m^2) for Earth and Jupiter are 1353 and 50 respectively; therefore, it was calculated that *H* decreases by a factor of approximately 27 [9]. Therefore, optimization of thickness and doping concentration of layers was required. The *H* incident was calculated using the following formula:

$$H = H_{sun} \frac{R_{sun}^2}{D^2}$$

where R_{sun} is the radius of the sun, *D* is the distance from the center of the sun, and H_{sun} is the power density at the Sun's surface [10].

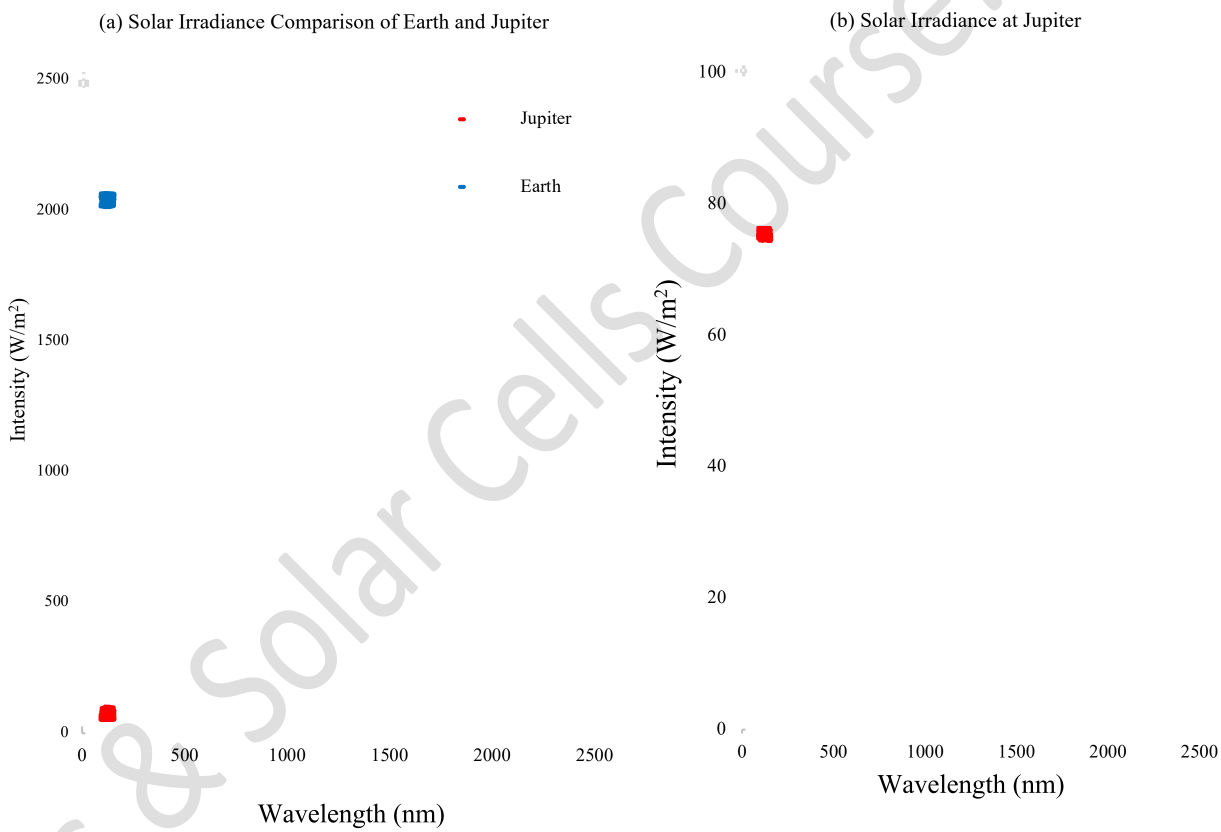

Fig 3.3: Plot of AM0 Solar Irradiance for (a) Earth and Jupiter compared (b) Jupiter

There were a number of layers added to the design. For designs similar to the one proposed, a Tunnel Junction is used to reduce the electrical resistance between two sub-cells. The tunnel junctions are thin heavily doped layers to increase the tunneling between layers connected the two sub-cells. Surface recombination velocity was reduced by the addition of Window layers, carrier scattering near the tunnel junction was reduced by the use of a back-surface field (BSF). The base layers are moderately p doped layers where EHPs are generated. All the aforementioned layers are used to generate EHPs and then separate them [8]. Fig 3.4 provides the schematic of the model used for simulation in Crosslight.

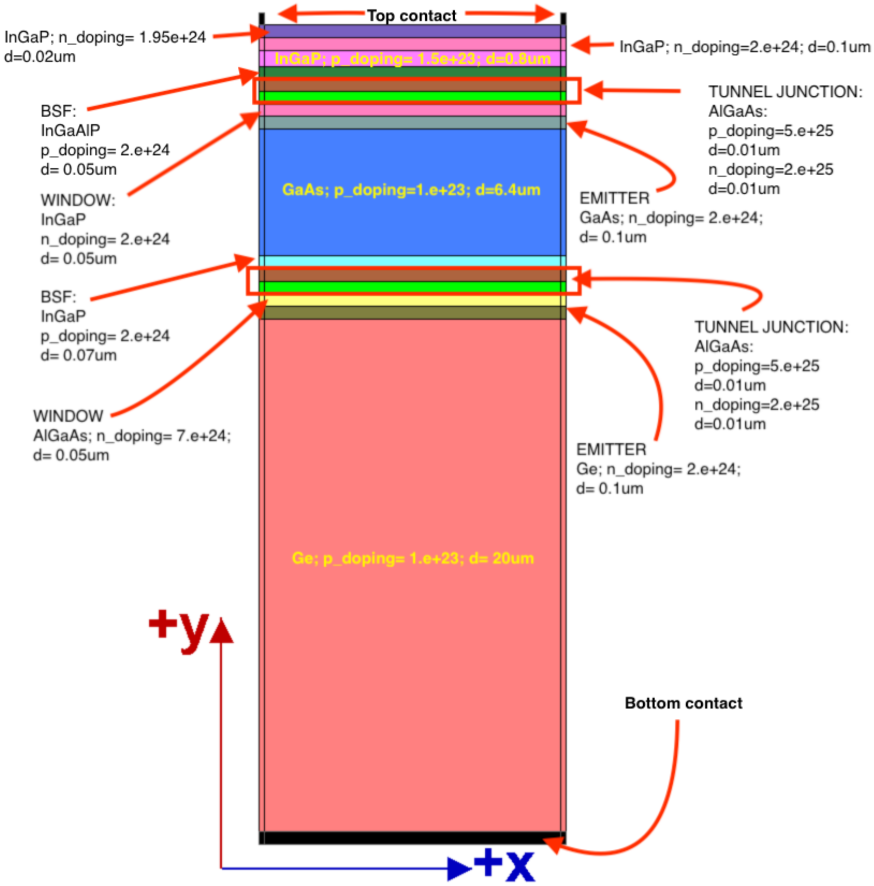

Fig3.4: Ge/GaAs/InGaP Triple Junction Cell design schematic of prototype
(all doping concentration are in m^{-3})

4. SIMULATION RESULTS AND ANALYSIS

The APSYS (Advanced Physical Models of Semiconductor Devices) application of the TCAD software Crosslight was used to model, simulate, and analyze the proposed solar cell. APSYS is based on 2D/3D finite element analysis (FEA) which is -a practical application of the Finite Element Method (FEM)- used in engineering and related analysis. Like other FEA based software, APSYS uses mesh generation techniques and makes bigger complicated problems into many smaller problems which allows easier representation of the final solution. APSYS was used to simulate multiple different structures with based on the prototype of Fig 3.4. A number of parameters were varied to get different efficiencies, V_{oc}, I_{sc}, and Fill factor (FF).

Model 1 is considered to be the base cell was the first device, it had a 11µm thick Ge base, 3.5µm GaAs base, 0.45µm InGaP, and 5µm wide. The tunnel junctions were made of AlGaAs, each layer in both junctions was 0.01µm wide, and the p layers had a doping of 5×10^{25} m^{-3} and the n layers had a doping of 2×10^{25} m^{-3}. The energy band diagram of model 1 is shown in Fig 4.1(a) along with the Current Density(J) versus Voltage (V) curve. The open circuit voltage (V_{oc}) was found to be ~2.33V and the Short circuit current density (J_{sc}) was ~0.61 mA/cm^2, a fill factor of 88.5% and an efficiency of 25.394%. The cross-sectional flow of the relative energy density has been shown in Fig. 4.2 and we see what we expect. As light flows through the cell and goes from ~15μm to 0μm in the device, the energy absorbed by each layer increases. This is proved by the decrease of Relative Energy Density with the decrease in y. It is expected that the light absorption is uniform in the x direction.

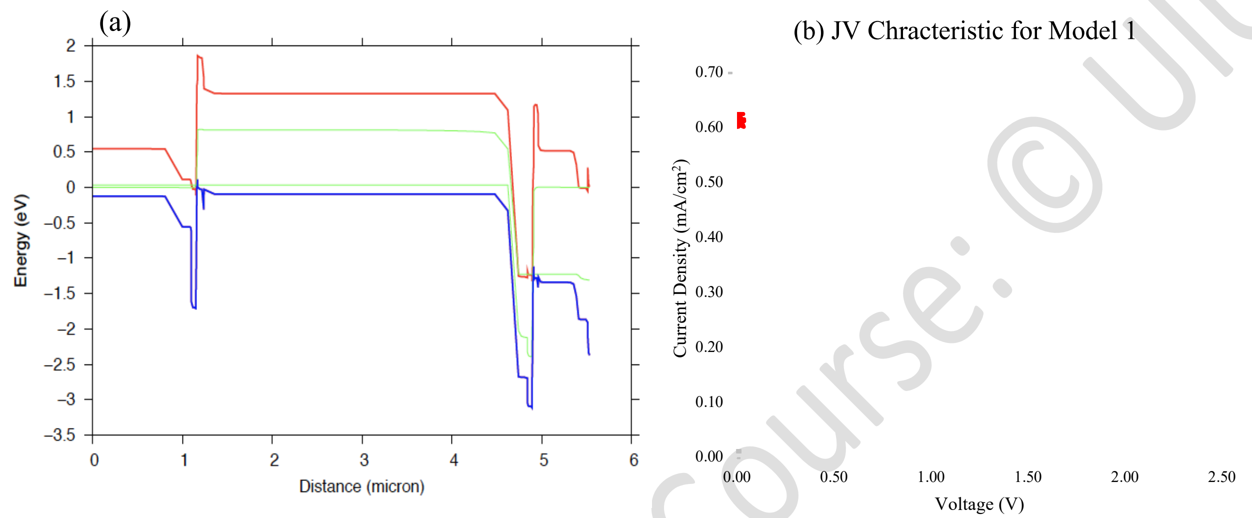

Fig 4.1: (a) Energy band diagram and (b)JV Characteristic of Model 1

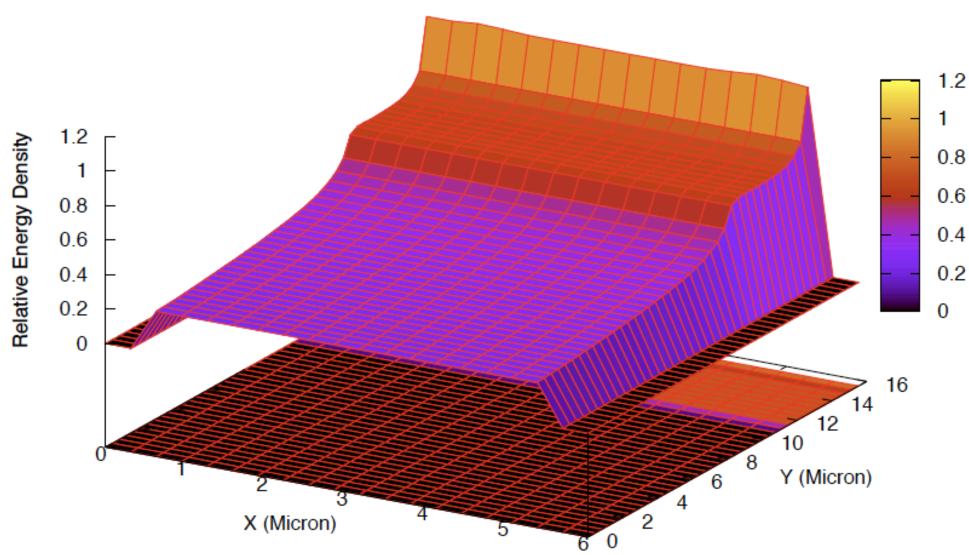

Fig 4.2: 3D plot (cross-sectional) of Relative energy density through the solar cell

Table 4.1 includes all the changes made to the thickness of the base layers, the width of the overall structure, and the doping concentration of the Tunnel Junction (TJ) along with the resulting efficiency.

Ge (µm)	GaAs (µm)	InGaP (µm)	Width (µm)	TJ Doping Compared to model 1	Eff (%)
11	3.5	0.45	5	Model 1	25.394
20	3.5	0.45	5	Same	25.628
20	6.4	0.45	5	Same	25.632
20	6.4	0.82	5	Same	24.164
20	6.4	0.82	10	Same	23.983
20	6.4	0.82	15	Same	24.035
11	3.5	0.45	10	Same	25.220
11	3.5	0.45	8	Same	22.951
11	3.5	0.45	5	Double	25.461
15	4.8	0.62	10	Double	24.952
15	5	0.8	10	Double	25.239
15	5	0.8	15	Double	25.298
20	5	0.8	15	Double	25.405
20	6.4	0.82	10	Double	23.985

Table 4.1: Simulation results for Ge/GaAs/InGaP solar cell for AM0

Current matching is best showcased by the cell with 15µm Ge base, 4.8µm GaAs base, 0.62µm InGaP base, and width of 10µm as shown in Fig. 4.3.

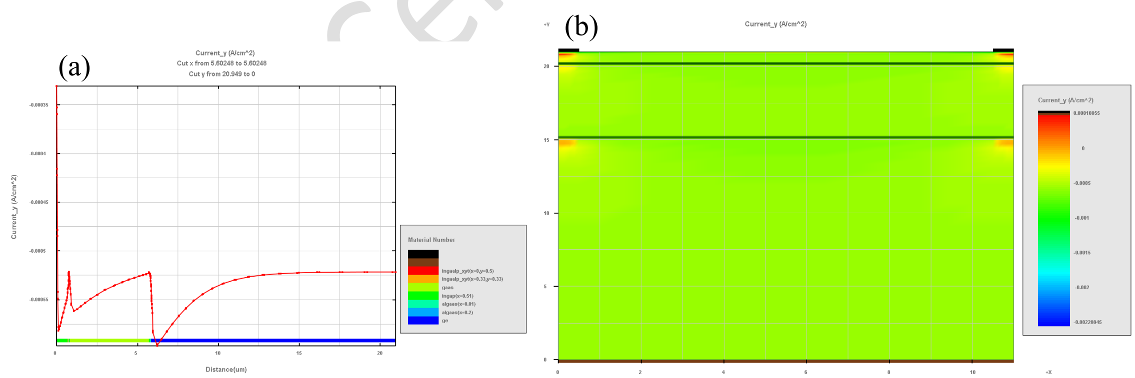

Fig 4.3: (a)Cross-sectional Current in through the cell along the vertical length of the cell and (b) the current density distribution

The results obtained from the simulations were varied and close scrutiny along with theoretical reasoning was applied to get to a logical conclusion. Overall, it can be claimed that an increase in the layer thickness increases efficiency until a maximum point after which increasing the thickness results in diminishing returns for efficiency. The thicknesses of the absorbing layers should have the same relative increase to maintain *current matching*. The width of structure should be increased with the increase in thickness. Finally, the doping concentration of the tunnel junction should one order of magnitude higher than that of the base and lesser than two orders of magnitude higher than the concentration of the base. These optimization points need to be found due to the simultaneous need of current matching, smaller number of defects, and high efficiency. The maximum efficiency achieved through simulations is 25.632%, a fill factor of about 88.21%, the Short circuit current density is 0.616 mA/cm^2, and open circuit voltage is 2.31V.

5. CONCLUSION AND SUMMARY

There are a number of tradeoffs to the simulated design, the most notable one being the small range of spectrum absorbed by the GaAs base layer. The use of an InGaAs layer with variable composition will help with the absorption of the Solar irradiance. Overall, the current density generated is low and hence for use in spacecrafts like the Europa Clipper, the cells need to be connected a very large number of these solar cells in series and parallel to get a decent power output. By further changing the parameters varied, a higher optimal point might be achieved. Apart from this design, however, the use of InGaN/GaN solar cells can provide some promising results. If we vary the In and Ga content in InGaN, we can get cover the whole solar irradiance.

For the use of Solar Cells in the Europa Clipper, high efficiency devices are required due to the comparatively smaller solar radiation intensity. Therefore, it is vital that the cells used cover the entire solar radiation that reaches it. Practically, there are a number of obstacles due to the defects created due to the growth processes, the efficiency decreases. TCAD software Crosslight simulations were performed to analyze the effects of changes in a number of parameters on the efficiency. There were small changes in the Fill factor, open circuit voltage, and short circuit current which all affect the efficiency. The average V_{oc} was between 2.30V and 2.35V whereas the J_{sc} was between 0.610 mA/cm^2 to 0.620 mA/cm^2. Current matching, which is essential for cells, was achieved by keeping the percentage increase/decrease in the thickness of the layers the same. In general, modifying the thickness of the layers of the solar cell, changing the doping concentration of different layers, and changing the size of the cell can be used to find an optimal point of high efficiency for Ge/GaAs/InGaP triple junction cells.

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