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Enhanced Solar Energy Conversion Through Optimized Multijunction Photovoltaic Cells

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Abstract

As technology advances, the demand for energy sources continues to grow. In response to this demand, renewable energy has emerged as a key solution, leveraging environmentally friendly methods such as photovoltaic technology. However, existing solar cells exhibit low efficiency and power conversion rates. This study aims to identify the optimal materials and number of junctions necessary to enhance solar cell efficiency through the multijunction concept, which has been modelled using Matlab Simulink. The research employed various equations to design solar cells, including calculations for energy bandgap, reverse leakage, short circuit current, open circuit voltage, and power output. The findings revealed that a quadruple junction utilizing specific semiconductor materials achieved an impressive efficiency of 58.84%, a notable improvement compared to the 11.03% efficiency of single-junction solar cells.

1. Introduction

A multijunction solar cell represents a cutting-edge advancement in photovoltaic technology, meticulously engineered to boost solar energy conversion efficiency significantly. This innovative device achieves remarkable performance by stacking multiple layers of specialized semiconductor materials, each meticulously crafted with a specific bandgap. These tailored bandgaps allow the solar cell to selectively capture distinct wavelengths of sunlight, facilitating a more efficient utilization of the diverse spectrum of solar irradiance. Typically, a multijunction solar cell is constructed from ultra-thin layers of various semiconductors, such as gallium arsenide, indium arsenide, and lead telluride. Each layer possesses the unique ability to absorb sunlight at different energy levels, effectively maximizing the reception of incoming photons. This sophisticated layered architecture is designed specifically to address and overcome the limitations found in conventional single-junction solar cells, particularly by reducing energy losses that occur due to the mismatch between the solar spectrum and the semiconductor bandgap [1][2].

The design of multijunction solar cells is rooted in the principles of tandem or cascade solar cells, where each layer functions sequentially to absorb light and generate electron-hole pairs. This capability not only enhances the overall energy conversion potential but also makes multijunction cells particularly ideal for demanding applications, such as space exploration and concentrated solar power systems, where high efficiency and compact design are paramount [3].

Building solar cells uses several key layers that work together to capture sunlight. The top layer, called the anti-reflection coating (ARC), reduces light loss and increases sunlight absorption. Often referred to as the window layer, it lets light enter the solar cell. This layer is usually made from a thin, transparent conductive oxide (TCO), such as zinc oxide (ZnO) or cadmium sulfide (CdS), which ensures good transparency and conductivity.The window layer mainly allows light in and collects charge carriers. The ARC focuses on minimizing reflection to capture more light. The emitter layer is essential for the performance of p-type solar cells. It is doped with boron to create “holes,” which act as charge carriers. When sunlight hits the solar cell, it generates electron-hole pairs in the base layer. The electric field between the emitter and base layers drives holes toward the emitter, contributing to electric current. In n-type solar cells, the thinner emitter layer is doped with phosphorus or arsenic to collect electrons efficiently. The base layer, typically n-type, consists of silicon doped with phosphorus to add more free electrons. This layer converts sunlight into electricity by energizing electrons when photons strike it. The charge separation occurs at the junction with the emitter layer. The thickness of the base layer affects efficiency; a thicker base can absorb more sunlight but may also increase charge loss.Finally, the back surface field (BSF) is at the back of the solar cell. This heavily doped layer creates an internal electric field to prevent unwanted charge carriers from recombining at the rear surface. The BSF helps keep more minority carriers in the bulk of the cell, leading to higher current density and overall efficiency.arrangement in the basic construction of a solar cell[3][4].

Furthermore, continuous advancements in materials science and fabrication techniques are crucial in elevating the efficiency and commercial viability of multijunction solar cells. These ongoing innovations promise to unlocking even higher energy conversion efficiencies in solar power generation, positioning multijunction cells as a pivotal solution for the future of sustainable energy [4].

In the construction of multijunction solar cells, the precise tuning of bandgaps is essential for determining the energy levels of photons that will be absorbed by the cell. This tuning process is a fundamental aspect crucial for optimizing energy conversion efficiency. Each semiconductor layer within the multijunction structure is meticulously engineered to have a specific bandgap, which sets the energy threshold for the wavelengths of light it can effectively capture. Adjustments in the thickness and composition of these layers allow for efficient absorption of photons at various energy levels across the solar spectrum. This tailored approach enables the multijunction solar cell to harness a broader range of sunlight by accommodating different energy photons with specific bandgap requirements. The tuning process is vital for harmonizing semiconductor materials, allowing each layer to play a role in the overall energy conversion by absorbing light at designated wavelengths. Such precision in tuning bandgaps is central to the capacity of multijunction solar cells to convert sunlight into electrical energy with enhanced efficiency, ensuring a strategic alignment between the semiconductor materials and the diverse energy levels present in solar radiation [5].

Junction formation is a vital process in constructing solar cells, particularly in multijunction designs. In these cells, semiconductor layers are added, creating interfaces that serve as sites for junction formation. These junctions represent boundaries where the electrical properties of the semiconductor materials change, leading to distinct charge carrier concentrations. Semiconductor junctions are established through controlled doping, where specific impurities are introduced into the material to enhance the concentration of either negative or positive charge carriers. This deliberate modification generates an electric field across the junction, facilitating the separation of photo-generated electron-hole pairs when exposed to sunlight. This separation produces an internal electric potential that drives electrons towards the n-type region and holes towards the p-type region, thereby generating a flow of electrical current. Accurate junction formation is essential to minimize recombination losses, ensure efficient charge carrier extraction, and enhance multijunction solar cells' overall performance and efficiency [6].

When delving into the multijunction solar cell concept, it becomes apparent that the selection of semiconductor materials is critically constrained by their lattice constants. These constants, which define the periodic arrangement of atoms within a crystal, play a vital role in maintaining structural integrity when different materials are joined [7][8]. When semiconductors having differing lattice constants are bonded, the atoms at the interface are forced into configurations that deviate from their natural equilibrium spacing. This misalignment introduces mechanical strain within the crystal lattice, which can manifest in two primary forms: compressive strain, where the material with the larger lattice constant is compressed, and tensile strain, where the smaller lattice constant material is stretched. For minor differences in lattice constants, generally below 1%, the resultant strain is typically elastic, allowing the crystal structure to maintain its integrity without permanent deformation. However, as the lattice mismatch increases beyond this threshold, the accumulated strain energy can reach significant levels, compelling the system to adjust through the formation of defects such as dislocations. These dislocations disrupt the regular atomic arrangement and can lead to alterations in the electronic properties at the interface [9-12]. Notably, such defects can modify band alignment—affecting how energy levels align between the materials and introducing localized states that can trap charge carriers. This trapping effect can lead to diminished carrier mobility, ultimately reducing the efficiency of essential devices like solar cells. In the context of this study, the primary objective is to enhance the efficiency of solar cells through sophisticated mathematical modelling that predicts performance outcomes. To achieve this goal, meticulous material selection was executed to mitigate substantial lattice mismatches that have the potential to negatively impact the performance of the solar cell design. By carefully choosing materials with compatible lattice constants, this research aims to create an optimal environment that supports efficient charge transport and maximizes energy conversion efficiencies in multijunction solar cells[13-15].

1.1 Development of Project

This study is dedicated to the development of advanced multijunction solar cells, aimed at significantly enhancing the efficiency of solar energy conversion. The design process utilizes Matlab Simulink software, which serves as a powerful platform for modelling and simulating the complex behaviours of these solar cells. To create an effective multijunction configuration, several critical calculation blocks must be established, each representing specific formulas pertinent to solar cell design. A key aspect of this research involves the meticulous selection of materials, as well as the determination of the desired number of junctions, ranging from single to quintuple configurations. The process begins with a thorough calculation of the energy bandgap at a nominal temperature of 300 Kelvin (equivalent to 25℃). This crucial step enables the translation of the energy bandgap into corresponding wavelength values, which is essential for understanding how effectively solar cells can capture various segments of the visible light and sunlight spectrum. Following the energy bandgap analysis, the next phase involves determining the reverse leakage current, an important parameter that quantifies the current consumed by the device. This is followed by the calculation of short-circuit current and open-circuit voltage, which helps in identifying the maximum current and voltage outputs achievable by the solar cells. The overall efficiency of the solar cells is then simulated based on the calculated power output under Standard Test Conditions (STC). This power output is further analyzed in conjunction with the design's string array configuration, which consists of 10 strings, to evaluate the performance metrics comprehensively. Illustrations, such as Figure 1 until Figure 6, visually represent the project's block diagram and the calculation framework within Matlab Simulink, aiding the understanding of the design's structural and functional aspects.[16][17].

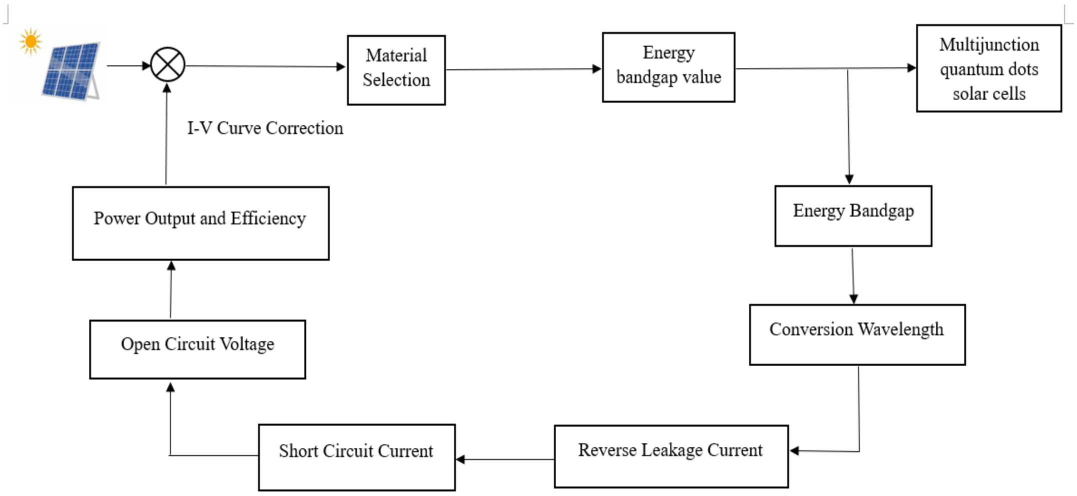

Fig. 1 *Block diagram of project*

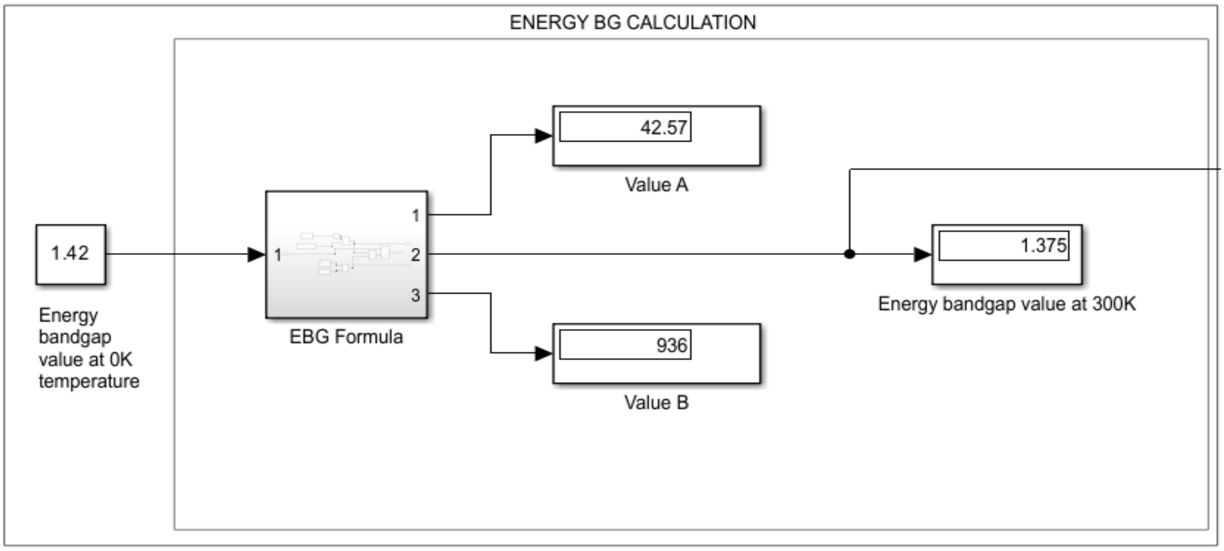

Fig. 2 *Energy bandgap calculation block*

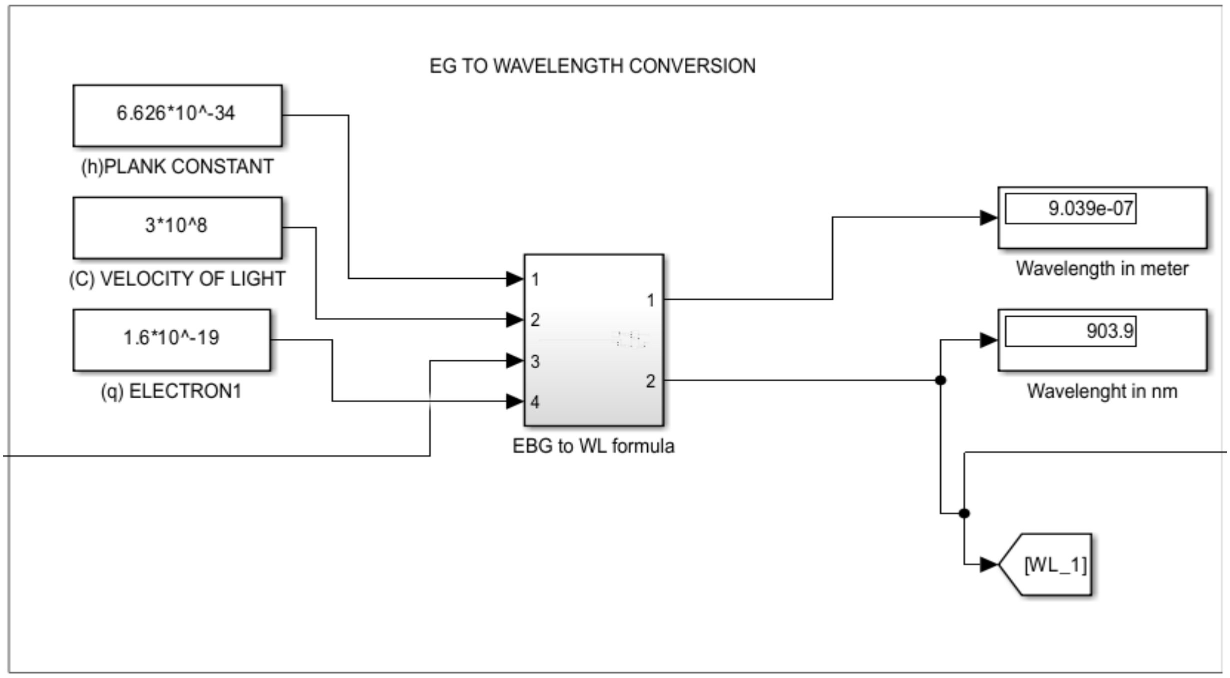

Fig. 3 *Energy bandgap to wavelength conversion calculation block*

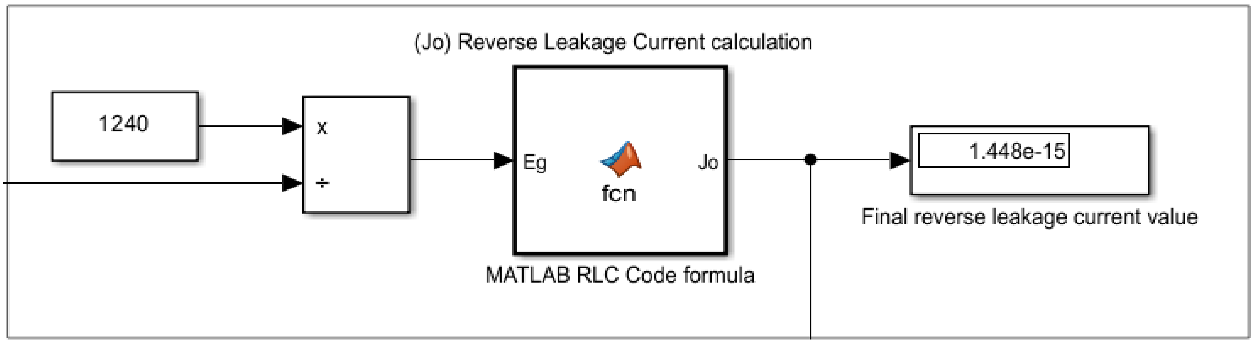

Fig. 4 *Reverse leakage current calculation block*

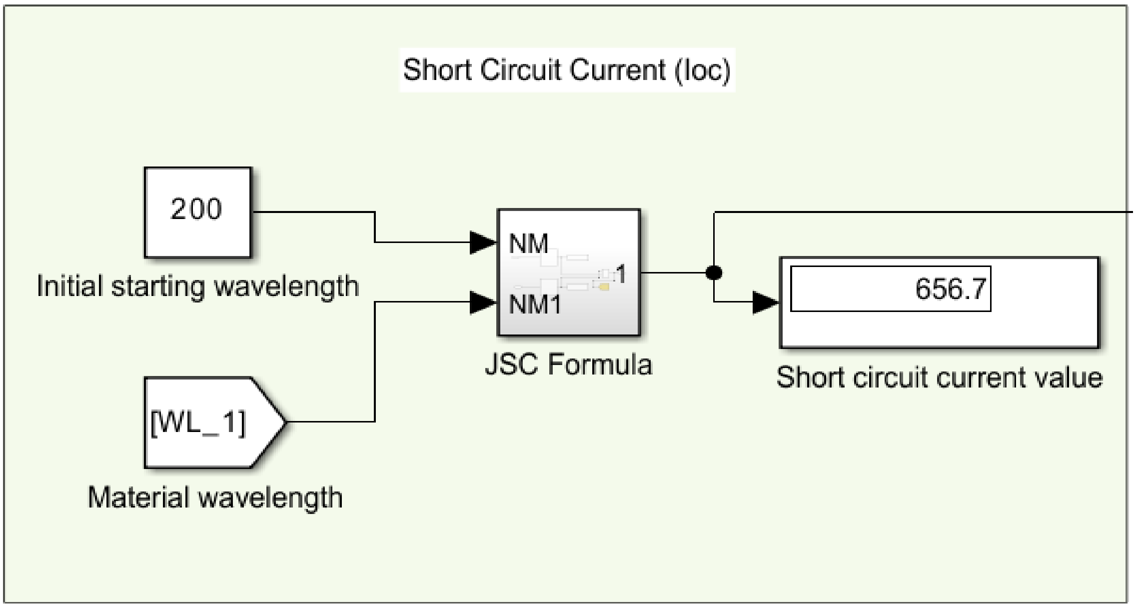

Fig. 5 *Short circuit current calculation block*

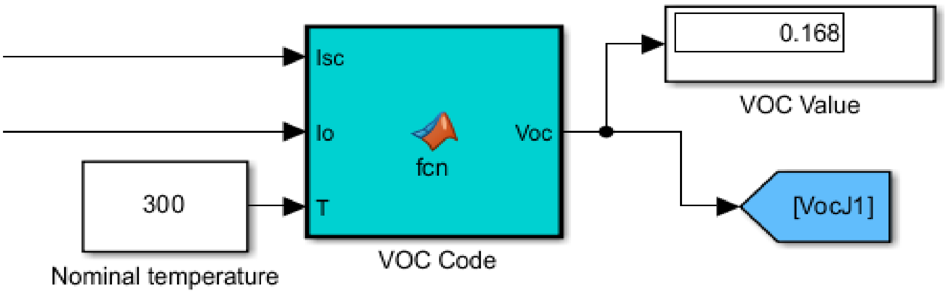

Fig. 6 *Open circuit voltage calculation block*

2. Result and Discussion

The calculation of each process for designing multijunction solar cells is further explained.

2.1.1 Material Selection

Figure 7 to 9 shows the semiconductor material used for each junction design from single to quintuple junction, as well as the layering structure of the solar cell's design which require a few layering material for producing a valid design of solar cells. Each material is arranged by the highest energy bandgap value at the top, followed by a lower energy bandgap value. The material arrangement is crucial where a higher energy bandgap value will capture a wider spectrum of sunlight for more energy conversion[18]. The selection of materials for multijunction solar cells hinges critically on their compatibility regarding lattice mismatch, which is essential for optimizing performance. When integrating various layers in multijunction configurations, significant attention must be paid to prevent the selection of incompatible material pairs. Neglecting to consider lattice mismatch can lead to undesirable epitaxial growth between the junctions, creating defects on the surface. These defects hinder the smooth movement of electrons the primary carriers of electric current during the conversion process, ultimately reducing the overall efficiency of the solar cells.

In the realm of photovoltaic materials, Gallium Arsenide is widely used, yet Indium Arsenide and Lead telluride also present themselves as viable alternatives, particularly due to their favourable lattice constants, typically ranging from approximately 5.6 to 5.7 Angstroms. This close alignment in lattice structure facilitates better integration and minimizes the risk of mismatches, thereby enhancing the performance and longevity of the multijunction solar cells. The lattice value recorded is approximately 4%, which can still leverage the efficiency of the solar cells, as portrayed in Figure 8.

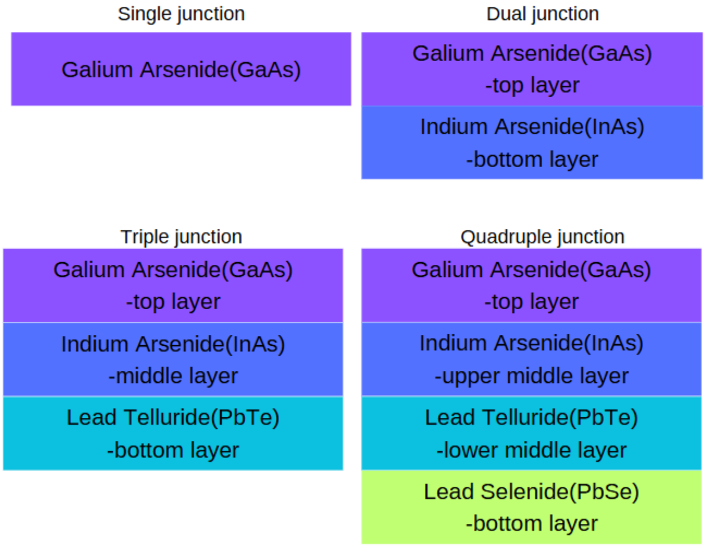

Fig. 7 *Material of junction design*

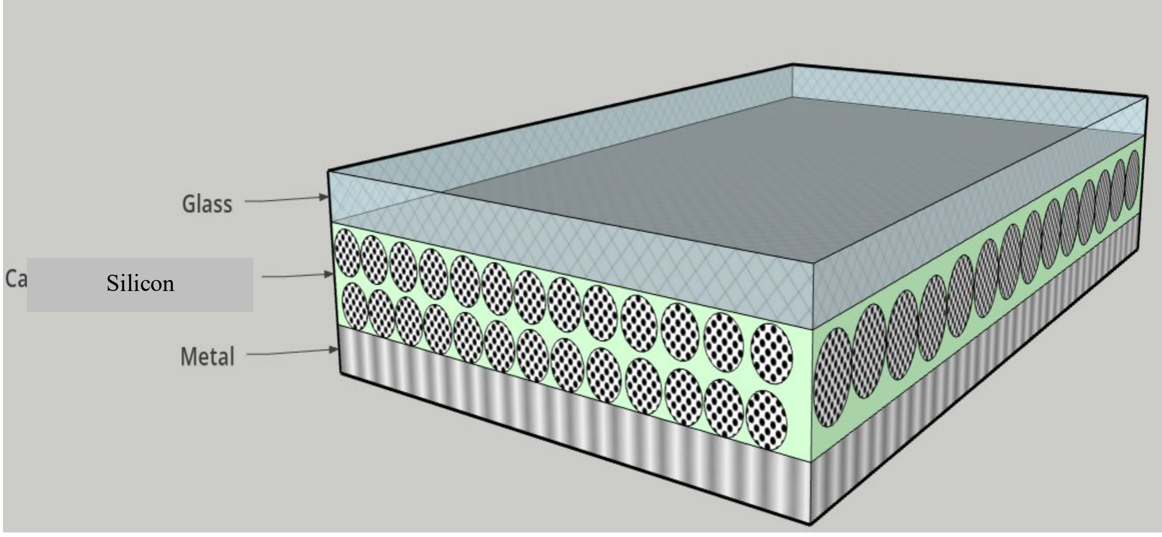

Fig. 8 *Layering structure of single junction solar cells*

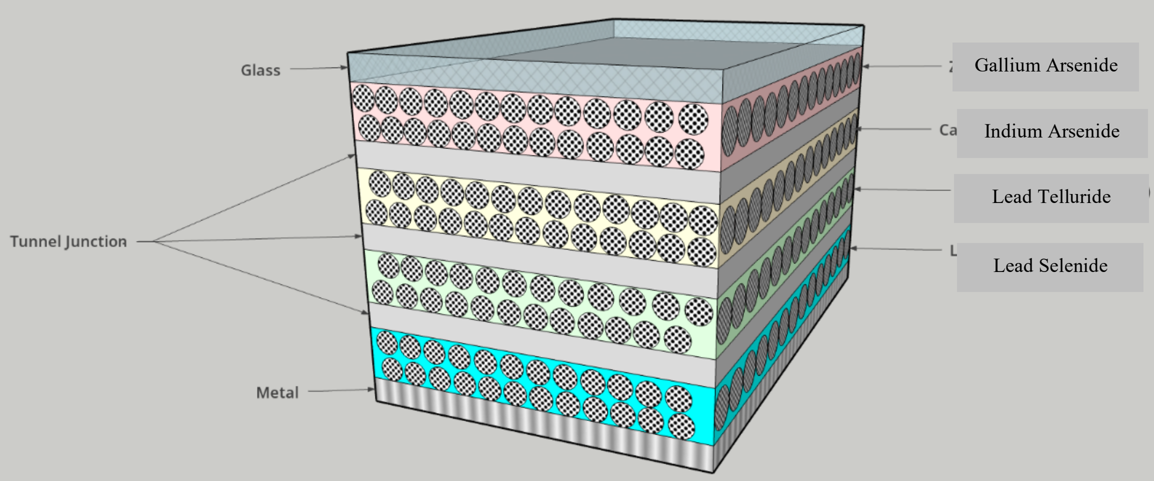

Fig. 9 *Layering structure of quadruple junction solar cells*

2.1.2 Energy Bandgap Calculation

In table 1, it was observed that the energy bandgap value experienced a slight decrease when sunlight interacted with the solar cells at a temperature of 25℃. This reduction in the bandgap is a well-documented phenomenon resulting from the interactions between electrons and phonons that occur as temperature rises. As thermal energy increases, these interactions can lead to the loss of some energy, ultimately affecting the material's electronic properties. However, in this study, the increment of temperature about 300K, which is equivalent to 25℃, only decreases about 3% to 4.5%, with the energy losses kept at a very minimum value. In theory, a higher energy bandgap value in solar cells is associated with increased efficiency, allowing them to convert solar energy into electrical energy more effectively. However, in practical applications, the optimal energy bandgap for most solar cells typically falls within the range of 1.1 to 1.4 eV. This presents an intriguing paradox: as the temperature rises, the energy bandgap value tends to diminish, yet this thermal effect can inadvertently keep the solar cell's design aligned with the desirable range for optimal performance. Therefore, it is essential to strike a balance, as maintaining a higher energy bandgap not only enhances the overall efficiency of the solar cells but also ensures that they operate effectively under varying environmental conditions. This interplay between temperature and bandgap is crucial for developing advanced solar technologies that maximize energy capture and conversion[19][20].

Table 1 *Energy bandgap value*

Single	0K	1.42	-		
	300K	1.375			
Dual	0K	1.42	0.36	-	
	300K	1.375	0.3145		
Triple	0K	1.42	0.36	0.32	-
	300K	1.375	0.3145	0.2745	
Quadruple	0K	1.42	0.36	0.32	0.27
	300K	1.375	0.3145	0.2745	0.2245

2.1.3 Wavelength Conversion and Reverse Leakage Current Calculation

In Table 2, it is clearly illustrated that there exists an inverse correlation between the wavelength value and the energy bandgap of the material. This relationship is pivotal as the electromagnetic spectrum is fundamentally derived from the solar energy that impacts the cell's surface in a waveform manner. The visible light spectrum, which ranges from approximately 400 nanometers (nm) to 800 nm, encompasses the ideal wavelength values that allow the solar cell to absorb photons efficiently. This efficient photon absorption is essential for maximizing energy output and optimizing the cell's performance in harnessing solar energy[21]. The wavelength able to be captured was up to 5533 nanometers, which provides more raw photons for electrical conversion.

As depicted in Table 3, lower wavelength values are directly associated with a significant reduction in reverse leakage current. This phenomenon is crucial since the reverse leakage current signifies parasitic currents that can drain energy from solar cells, ultimately leading to a decrease in their overall efficiency. By meticulously regulating and maintaining these wavelength parameters within a narrow and optimized range, we can substantially improve both the performance and lifespan of solar energy systems. This attention to detail not only fosters enhanced energy output but also ensures the long-term reliability and effectiveness of solar technologies[22].

Table 2 *Wavelength value for each junction*

Single	(GaAs)=903.9nm	-		
Dual	(GaAs)=903.9nm	(InAs)=3950nm	-	
Triple	(GaAs)=903.9nm	(InAs)=3950nm	(PbTe) =4526nm	-
Quadruple	(GaAs) = 903.9nm	(InAs) = 3950nm	(PbTe) =4526nm	(PbSe) = 5533nm

Table 3 *Reverse leakage current value (Ampere)*

Single	(GaAs)=$1.45 10^{-15}$	-		
Dual	(GaAs)=$1.45 10^{-15}$	(InAs) = 812.3	-	
Triple	(GaAs)=$1.45 10^{-15}$	(InAs) = 812.3	(PbTe) = 3797	-
Quadruple	(GaAs)=$1.45 10^{-15}$	(InAs) = 812.3	(PbTe) = 3797	(PbSe) = $2.61 10^{4}$

2.1.4 Short Circuit Current and Open Circuit Voltage Calculation

In Tables 4 and 5, the data illustrates the values for short circuit current and open circuit voltage in solar cells. The short circuit current represents the maximum current produced by the solar cells when no external load is connected, resulting in a voltage of zero across the terminals. This scenario reflects the cells' ability to generate electricity under ideal conditions. In contrast, the open circuit voltage indicates the highest voltage achievable by the solar cells when no current is permitted to flow. This scenario occurs under maximum illumination without any load. The short circuit current value obtained in Table 4 indicates the early impression of high-performance solar cell design as the value becomes higher along with the addition of layers. In addition, the increment in open circuit voltage value proves the design relevant for producing high-efficiency energy output.

As indicated in the tables, the configuration of multiple layers in these solar cells significantly enhances both the short-circuit current and the open-circuit voltage. This multi-layer structure allows for improved light absorption and energy conversion efficiency, thereby theoretically producing a higher power output. The data underscores the benefits of advanced solar cell designs in optimizing energy generation.

Table 4 *Short circuit current value (Ampere)*

Single	(GaAs) = 656.7	-		
Dual	(GaAs) = 656.7	(InAs) = 2842	-	
Triple	(GaAs) = 656.7	(InAs) = 2842	(PbTe) =537	-
Quadruple	(GaAs) = 656.7	(InAs) = 2842	(PbTe) =537	(PbSe) = 940.3

Table 5 *Open circuit voltage value (voltage)*

Single	(GaAs) = 0.168		-		Total =0.168V
Dual	(GaAs) = 0.168	(InAs) = 0.2059	-		Total =0.3739V
Triple	(GaAs) = 1.052	(InAs) = 0.03893	(PbTe) =0.003424	-	Total =1.095V
Quadruple	(GaAs) = 1.052	(InAs) = 0.03893	(PbTe) =0.003424	(PbSe) = 0.0009162	Total =1.096V

2.1.5 Efficiency of Multijunction Solar Cell Design

In figure 10, the stark contrast in efficiency between different types of solar cells is clearly illustrated. The quadruple junction solar cell stands out with an impressive efficiency of 58.84%, significantly surpassing the single junction variant, which only achieves a modest 11.03%. This dramatic increase in efficiency can be attributed to the incorporation of multiple semiconductor materials, each forming distinct junctions that are stacked strategically. This design allows for a greater power output as the number of junctions increases.

The arrangement of these junctions is crucial; by optimizing the energy bandgap of each layer, the solar cells can effectively capture a broader spectrum of sunlight. As a result, the excitation of electrons within the junctions is enhanced, which leads to a more significant generation of electrical power. This advanced technology illustrates the potential of multi-junction solar cells to harness solar energy more efficiently than their single-junction counterparts.

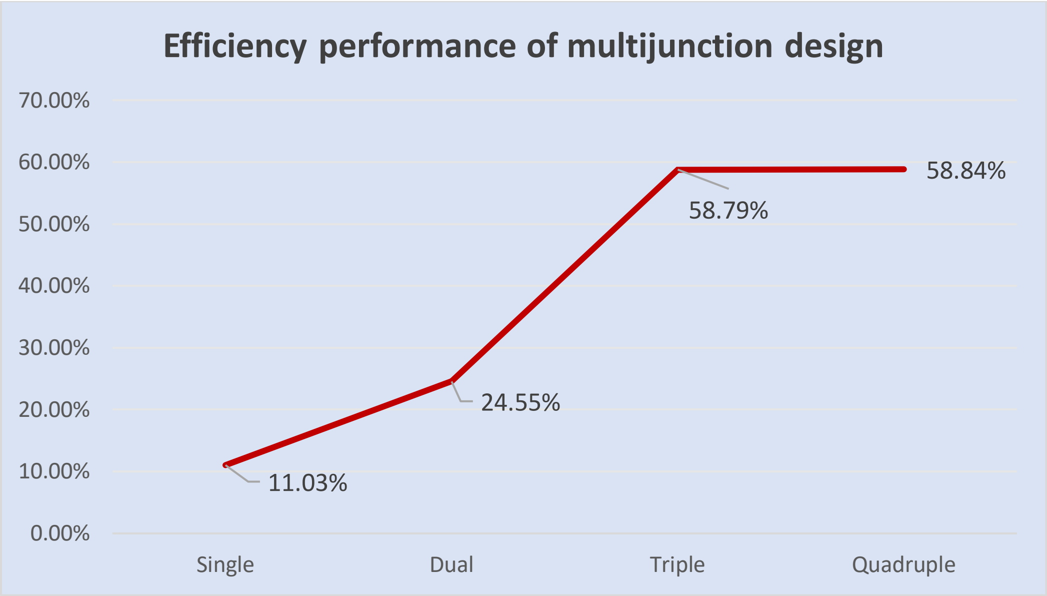

Fig. 10 *Efficiency of multijunction design*

3. Conclusion

This paper observed the effectiveness of multijunction solar cell design for efficiency increment. Four types of design are proposed in this project, which are single junction to quadruple junction. The outcomes demonstrated that among the four types of design, the quadruple junction records the highest value of efficiency, which is 58.84%. Single junction has the lowest value of efficiency, which is 11.03%, due to the single material used. The movement of electrons in a single junction design becomes stagnant as no other material is stacked together. Thus, by stacking and wafering multiple layers of semiconductor material, the power output can be increased and efficiency boosted. However, this design is by simulation on MATLAB Simulink only. The efficiency of real-world applications might differ as many other factors must be considered, such as the tuning and fabricating process, as the complexity at this stage is high complexity. Furthermore, this study presents an opportunity for expansion by investigating novel combinations of materials and increasing the number of junctions. In the context of the multijunction concept, it is paramount to optimize the manufacturing costs. The multijunction approach often encounters challenges associated with the production of additional junctions due to the expenses related to rare earth elements used as raw materials. Therefore, the development of cost-effective production methods while ensuring high efficiency should be prioritized in future research endeavours.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: ***Study conception and design**: Muhammad Aliff Hafeez Bin Azman, Sim Sy Yi.* ***Data collection:** Muhammad Aliff Hafeez Bin Azman, Lee Zhi Jie.* ***Analysis and interpretation of results:** Sim Sy Yi, Muhammad Aliff Hafeez Bin Azman, Guo Xian Min, Lee Zhi Jie.* ***Draft manuscript preparation:** Muhammad Aliff Hafeez Bin Azman, Mohd Abdul Talib Mat Yusoh, Alvin John Lim Meng Siang.* ***Structural and engineering perspective:** Guo Xian Min, Alvin John Lim Meng Siang.* ***Industry insights and validation:** Alwin Soh Wei Yeow*

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