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Modelling and bandgap opimization of multijunction solar cells for high efficiency photovoltaic performance

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Abstract:

Global energy use is rising yearly, resulting in a higher demand. Power plants must generate more electricity, thereby placing significant stress on the electrical grid. Solar engineering is a promising solution to this challenge. However, traditional silicon-based solar cells face inherent limitations. These cells rely on a single material, which restricts their power conversion efficiency by only capturing a very specific range of the sunlight spectrum.This study explores a novel concept in solar cell design that utilizes a multijunction approach, employing various semiconductor materials to create multiple p-n junctions within the cells. By strategically arranging these materials according to their energy bandgaps, the aim is to maximize the capture of the sunlight spectrum for enhanced power conversion and energy output, ultimately improving efficiency. The research was conducted using MATLAB software to focus on mathematical modeling. By analyzing designs from single junctions up to quintuple junctions and utilizing materials such as Germanium Sulfide, Gallium Arsenide, and Germanium, the study revealed that increasing the number of material layers significantly enhanced the performance of the solar cells. Notably, the quintuple junction solar cell demonstrated the highest efficiency, achieving 26.87% more efficiency compared to single junction cells, which recorded an efficiency of 42.63%.

Keywords: Solar; Multijunction; Energy bandgap; Semiconductor materials

1. Introduction

The future of the global economy is closely linked to advancements in industrial technologies. As researched by T. Ahmad, and D. Zhang (2020), "electricity is a key parameter of social and economic development." It encompasses various energy resource technologies that demand higher power usage, leading to challenges in balancing energy production and consumption by power plants. One significant concern is the increasing carbon emissions resulting from the heightened use of various raw materials, which adversely affect the environment [1, 2].

In response, renewable energy sources have gained prominence, with solar energy playing a critical role in promoting a clean energy society and reducing carbon emissions and other pollutants. However, reliance on fossil fuels to meet energy demands contributes to higher costs and significant carbon emissions.

A significant challenge in harnessing solar energy lies in the limitations of conventional solar cells, particularly those constructed from silicon. According to the Shockley-Queisser limit, the maximum efficiency achievable by silicon solar cells is approximately 33.7% [3]. This restriction in energy conversion efficiency stems from the reliance on a single p-n junction for electron excitation within these cells. Silicon is capable of capturing only a specific range of the solar spectrum, defined by its energy bandgap-the difference in energy between the top of the valence band and the bottom of the conduction band. Electrons can transition across this gap by absorbing energy from photons (light) or phonons (heat) that meet or exceed this energy threshold [4].

The efficiency of single-junction solar cells is constrained by inherent loss mechanisms [5]. Thermalization losses occur when the excess energy from high-energy photons is dissipated as heat instead of being converted into electrical energy. Meanwhile, spectral losses occur when photons with energies below the bandgap do not contribute to electricity generation. As the bandgap increases beyond the optimal value, the short-circuit current decreases significantly due to the absorption of fewer photons. Conversely, a smaller bandgap increases thermal losses from excess energy. As a result, single-junction solar cells cannot surpass this efficiency limit under standard conditions, highlighting the necessity of exploring alternative designs, such as multi-junction cells, which can achieve higher efficiencies by effectively utilizing a broader spectrum of sunlight [6].

A multijunction solar cell represents an advanced photovoltaic technology designed to optimize solar energy conversion efficiency by employing a configuration of multiple layers of semiconductor materials, each characterized by a specific bandgap [7, 8]. These bandgaps are meticulously engineered to capture distinct wavelengths of sunlight, thereby enabling the solar cell to effectively harness a wider spectrum of solar irradiance. Typically constructed from thin layers of various semiconductors, including gallium arsenide, indium gallium phosphide, and germanium, each layer is responsible for absorbing sunlight at different energy levels, thus maximizing the utilization of available photons. This layered architecture is strategically developed to address the intrinsic limitations of traditional single-junction solar cells by reducing energy losses associated with the disparity between the solar spectrum and the semiconductor bandgap. The multijunction solar cell embodies the principles of tandem or cascade solar cells, wherein each layer sequentially absorbs light and generates electron-hole pairs [9]. This technology is particularly well-suited for space applications and concentrated solar power systems, where high efficiency and compact design are of paramount importance. Ongoing advancements in materials science and fabrication methodologies continue to enhance the efficiency and commercial viability of multijunction solar cells, positioning them as a promising pathway for achieving superior energy conversion efficiencies in solar power generation [10].

In the construction of multijunction solar cells, the meticulous tuning of bandgaps plays a pivotal role in determining the energy levels of the photons that the cell can efficiently concentrate and convert into electricity. This process is not merely a technical adjustment; rather, it is a fundamental aspect essential for maximizing the energy conversion efficiency of the cell. Each semiconductor layer within the multijunction architecture is meticulously designed and engineered to exhibit a specific bandgap. This critical energy threshold delineates the precise wavelengths of light that each layer can absorb effectively.

To achieve optimal performance, the tuning of these bandgaps involves intricate adjustments to both the thickness and the material composition of each layer. Such tailored modifications ensure that the multijunction solar cell can absorb photons at a wide range of energy levels across the solar spectrum. By accommodating different energy photons with varying bandgap requirements, this approach allows for a comprehensive capture of sunlight, enhancing the overall energy conversion capability [11]. Moreover, the precision in tuning the band gaps is vital for fostering a harmonious integration among the various semiconductor materials. Each layer must seamlessly contribute to the collective energy conversion process, absorbing light at its designated wavelengths. This strategic alignment between the semiconductor characteristics and the diverse energy levels present in solar radiation is central to the multijunction solar cell's ability to convert sunlight into electrical energy with remarkable efficiency [12].

Equally important is the process of junction formation, which stands as a cornerstone in the development of solar cells, particularly multijunction ones. As semiconductor layers are systematically stacked to form the cell, interfaces emerge that serve as critical sites for junction formation. These junctions represent boundaries where the electrical properties of the semiconductor materials shift, resulting in distinct concentrations of charge carriers.

The formation of semiconductor junctions relies on a controlled doping process, wherein specific impurities are deliberately introduced into the material. This careful manipulation increases the density of either negative or positive charge carriers, creating an electric field across the junction. When sunlight strikes the cell, it generates electron-hole pairs. The electric field operates to separate these charge carriers, directing electrons toward the n-type region and holes toward the p-type region. This separation generates a flow of electrical current that is crucial for the cell's operation. The precision of junction formation is essential in minimizing recombination losses, where charge carriers recombine before contributing to current flow. By ensuring efficient charge carrier extraction, well-executed junction formation significantly impacts the overall performance and efficiency of the multijunction solar cell, reinforcing its role as a highly effective means of harnessing solar energy [13].

When exploring the multijunction concept, the combination of materials is inherently restricted by their lattice constants. When semiconductor materials with differing lattice constants are joined, the atoms at the interface are compelled into positions that deviate from their natural equilibrium spacing, resulting in mechanical strain within the crystal lattice. This strain can manifest as either compressive, when the material with the larger lattice constant is squeezed, or tensile, when the smaller lattice constant material is stretched. For minor lattice mismatches, typically below 1%, the strain is elastic, thereby maintaining the integrity of the crystal structure. However, for larger mismatches, the accumulated strain energy can become considerable, prompting the system to relax by forming defects such as dislocations. These defects can alter the lattice structure and affect the electronic properties at the interface, potentially modifying band alignment or introducing localized states that trap charge carriers. Such alterations can lead to reduced carrier mobility and diminish the efficiency of devices like solar cells. In this study, however, the aim is to enhance the efficiency of solar cells by employing mathematical modelling to demonstrate outcomes. Therefore, careful material selection was undertaken to minimize significant lattice mismatches that could adversely affect the performance of the design.

2. Development of the proposed multijunction solar cells

This study is centered on the innovative development of multijunction solar cells strategically designed to enhance solar efficiency significantly. The research employs the sophisticated MATLAB Simulink software, which facilitates a comprehensive approach to solar cell design. The creation of the multijunction configuration involves careful consideration of various computational blocks, each representing specific formulas essential for solar cell design. The process commences with the selection of suitable materials, followed by the determination of the desired number of junctions, which can range from a single junction to an advanced quintuple junction setup. A critical initial step in this process is calculating the energy bandgap at a nominal temperature of 300 Kelvin (approximately 25 °C). This energy bandgap is subsequently converted into wavelength values, enabling a detailed analysis of the visible light spectrum and the sunlight that the solar cells can effectively capture. This conversion is pivotal for optimizing the solar cell's responsiveness to solar energy. The design process progresses by calculating the reverse leakage current. This measurement is vital as it indicates the amount of current consumed by the devices, which can impact overall cell efficiency. Following this, calculations of the short-circuit current and open-circuit voltage are performed to ascertain the peak current and voltage that the solar cells can generate, providing insights into their operational capabilities.

The power output is simulated after conducting the necessary calculations to evaluate the performance of the solar cells. Under Standard Test Conditions (STC), this power output is then multiplied by the number of strings utilized in the design, specifically 10 strings, allowing for a comprehensive assessment of the overall energy yield. Fig. 1 to 7 present a visual representation of the project, featuring a block diagram that outlines the overall design and a detailed illustration of the calculation blocks within MATLAB Simulink. These figures serve as integral components of the study, providing clarity and facilitating further analysis of the multijunction solar cell design process.

2.1 Mathematical modelling

Solar cell design involves crucial mathematical formulas and modelling. When using MATLAB software, the arrangement of the block model with a specific formula is important in order to get accurate results. Thus, these block models have several steps starting from energy bandgap value calculation, reverse leakage current, short circuit current, open circuit voltage, power and output efficiency. When dealing with multijunction solar cells, the energy bandgap is the core process of designing this type of solar cell. Thus, tailoring the bandgap must consider real-world situations. In this research, the calculation involves the formula in (1) [14] and Fig. 2. Nominal bandgap energy for specific semiconductor material is negatively correlated with the temperature at 25 °C. α and β hold the constant value of $4.73^{10^{-4}}$ and 636. T is set to 300 K, which is equivalent to 25 degrees Celsius, and $E_g(0)$ is the actual energy bandgap value at a specific semiconductor.

$$E_g = E_g(0) - \frac{\alpha T^2}{T+\beta} \tag{1}$$

where;
E_g = Energy bandgap
α = Alpha constant ($4.73^{10^{-4}}$)
β = Beta constant(636)
T = Temperature (300 K)

When designing solar cells, the wavelength value is widely used in order to determine the solar spectrum captured by the solar cell. On top of that, the energy bandgap value gained at nominal temperature must be converted to wavelength value using a formula at (2) [14] similar to Fig. 3. h represents Planck's constant, which holds the value

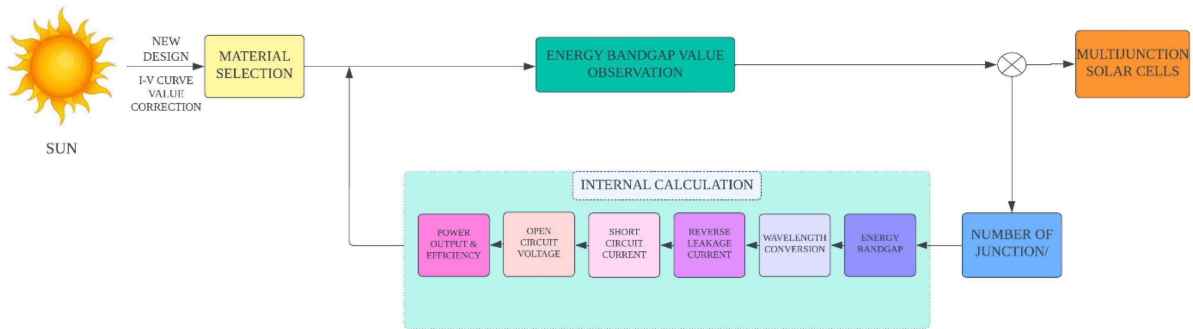

Figure 1. Block diagram of the proposed multijunction solar cells.

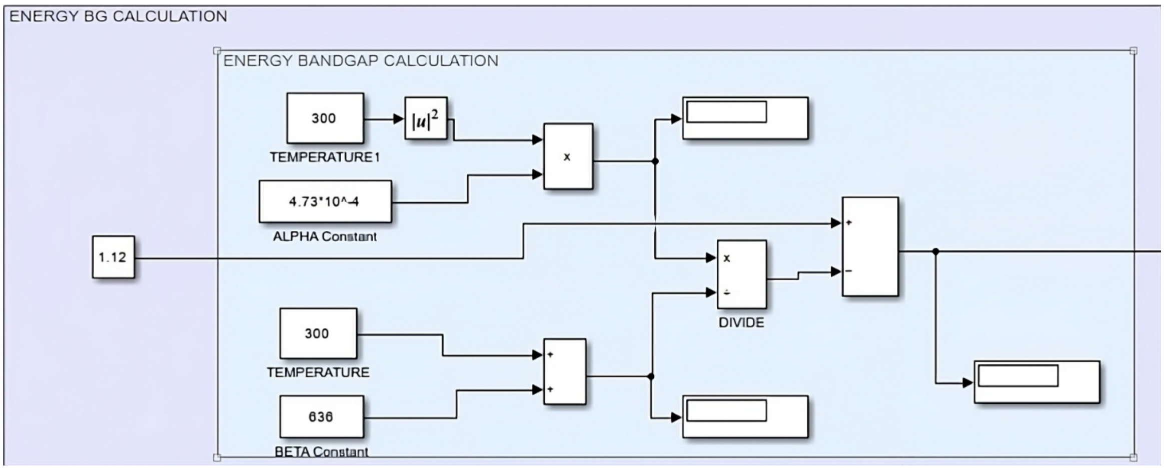

Figure 2. Energy bandgap calculation block.

of $6.626^{10^{-34}}$ and c is the speed of light value at 3^{10^8}. q is the charge of an electron ($1.6^{10^{-19}}$) Multiplied by the energy bandgap in the Joule unit [14].

$$\lambda = \frac{hc}{E_g \cdot q} \tag{2}$$

where;
λ = lambda (wavelength)
h = Plank's constant ($6.626^{10^{-34}}$)
c = speed of light (3^{10^8})
q = charge of electron ($1.6^{10^{-19}}$)

The third model was calculated to determine the thermal stability and heat dissipation. Reverse leakage current must be kept at the lowest value, as the rise of this value leads to overheating and reduces the device's performance. Equation (3) [14] and Fig. 4 portray the parameters involved in the calculation area. A is the area of solar cells in A/m^2 at 1^{10^8}. Under exponential mode, k is the Boltzmann's constant holding value of $1.38066^{10^{-23}}$ and T at 300 K.

$$J_o = A \cdot e^{\frac{qE_g}{kT}} \tag{3}$$

where;
J_o = Reverse leakage current
A = area of solar cells (A/m^2 at 1^{10^8})
K = Boltzman's constant ($1.38066^{10^{-23}}$)

Paradoxically, while maintaining reverse leakage current at a small value, short circuit current must be elevated in order to multiply the overall power generation. Short circuit current is a crucial parameter that is closely related to asses light absorption efficiency. On each subcell layer, a higher short circuit current value subsequently increases the solar spectrum captured, hence maximizing the energy produced. The formulas used are as in (4) and (5), as illustrated in Fig. 5 [14].

$$\text{Spectral response} = \text{EQE}\frac{q\lambda^{10^{-9}}}{hc} \tag{4}$$

$$\text{Jsc} = \text{SR} \cdot \text{Eb} \tag{5}$$

where;
EQE = External Quantum Efficiency
Jsc = Short circuit current
SR = Spectral response
Eb = Energy earth density (1360 W/m^2)

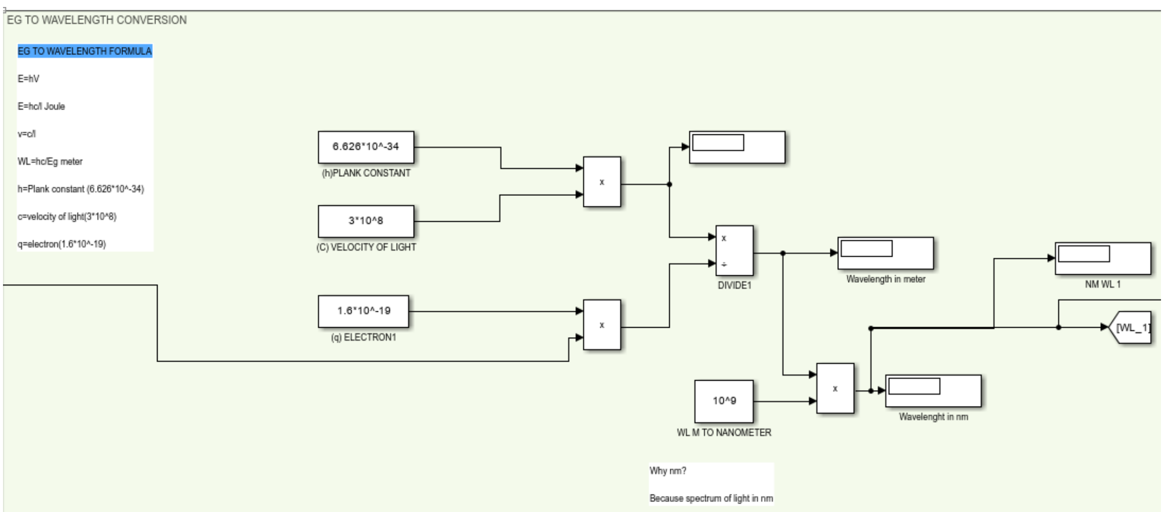

Figure 3. Energy bandgap to wavelength conversion calculation block.

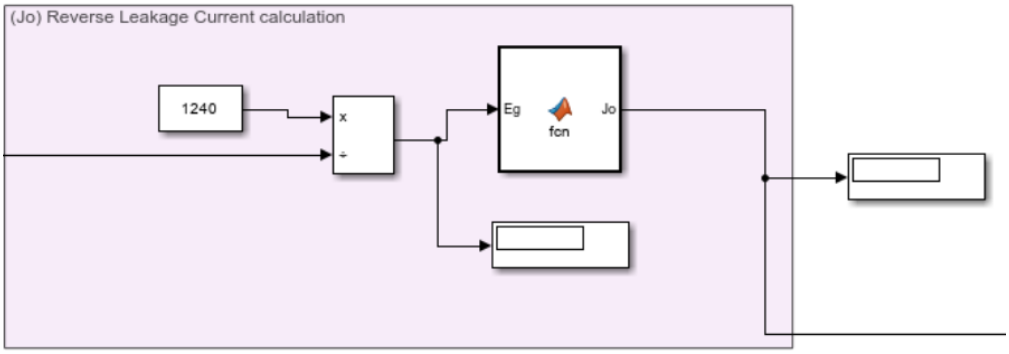

Figure 4. Reverse leakage current calculation block.

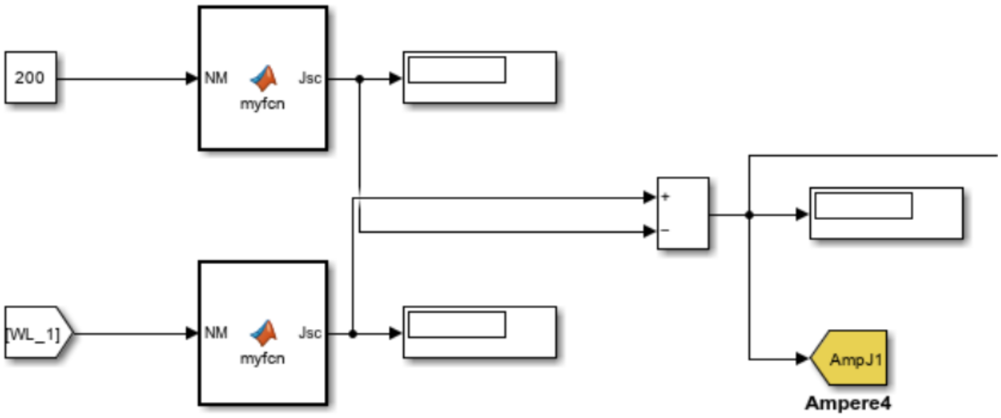

Figure 5. Short circuit current calculation block.

Spectral response is calculated for tuning the device's sensitivity to different wavelengths. In terms of multijunction design, adjusting the spectral response will capture a broader wavelength for power conversion. EQE refers to external quantum efficiency, placed at a constant value of 0.85. Short circuit current is obtained by multiplying the spectral response by the energy of the Earth's density at 1362 Watts [15]. The next process is to calculate the open-circuit voltage. This parameter determines the highest voltage generated when the current is not flowing in the solar cell. The higher value of open circuit voltage indicates a higher capability for solar cells to convert energy. The formula used for this mathematical model is in (6), as illustrated in Fig. 6 [14].

$$V_{oc} = \frac{kT}{q} \log\left(\left(\frac{J_{sc} + J_o}{J_o}\right) + 1\right) \tag{6}$$

The last model shown in Fig. 7 concludes the efficiency of the design, where power output is calculated by multiplying the open circuit voltage and short circuit current under Standard Test Conditions (STC), which is also multiplied by the 10-string array used. Power input is determined by the nominal irradiance of 1000 Watts [14].

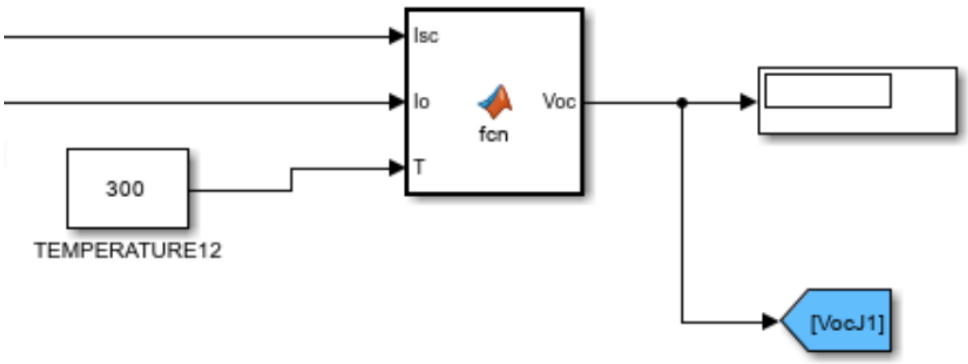

Figure 6. Open circuit voltage calculation block.

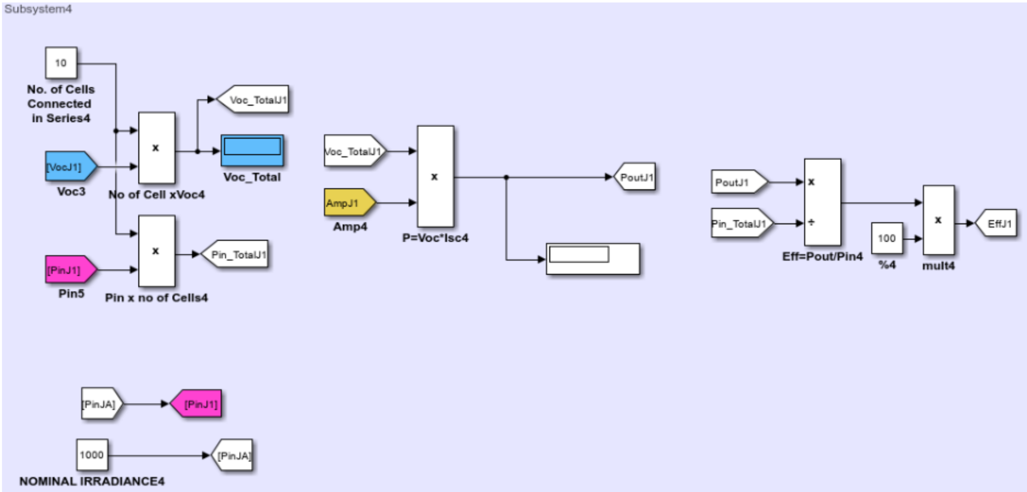

Figure 7. Power output and efficiency calculation block.

3. Results and discussions

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

3.1 Material selection

Fig. 8 illustrates the various semiconductor materials employed in the design of junctions, ranging from single to quintuple configurations. Each material is meticulously organized according to its energy bandgap value, starting with the highest at the top and descending to lower values. This strategic arrangement is vital, as materials with higher energy band gaps can capture a broader spectrum of sunlight, thereby facilitating greater energy conversion efficiency. The selection and stacking of these materials follow specific guidelines to ensure optimal performance. All selected materials belong to the III-V group, known for their crystalline structures, contributing to their effectiveness in solar applications. A key principle in this stacking process is lattice matching. For successful fabrication and epitaxial growth, it is essential that the materials exhibit minimal lattice mismatch; significant discrepancies can jeopardise the integrity of the layers. If the lattice mismatch is substantial, it can induce increased lattice disorder and reduce the adhesion energy between the layers, adversely affecting phonon transmission and thermal conductance at the interface. In cases of extreme lattice mismatch, these complications can lead to poor crystallinity, diminished mechanical stability, and weakened electronic properties. Such issues ultimately limit the performance and reliability of semiconductor devices, including solar cells, underscoring the importance of careful material selection and arrangement in multi-junction designs [17, 18].

3.2 Energy bandgap calculation

In Table 1, the energy bandgap value slightly decreased when sunlight at 25 °C struck the solar cells. The decrement of the value is a common phenomenon where electron-phonon interactions happen as the temperature increases, causing it to lose some energy. The energy bandgap is crucial when designing multijunction solar cells. The higher bandgap is placed at the top layer in order to capture a low wavelength, followed by a lower bandgap. The energy bandgap serves as a critical threshold for the excitation of electrons within photovoltaic cells. When photons interact with the cell material, the incident light must possess energy that is equal to or greater than the bandgap to facilitate the transition of electrons from the valence to the conduction bands. The implementation of multi-layer cells can significantly enhance the process of electrical conversion by the electrons. The optimal bandgap for efficient solar cells is generally situated within the range of 1.1 eV to 1.5 eV. Within this range, photons from the solar spectrum, particularly those within the visible light spectrum, are absorbed most effectively. A bandgap that is excessively high may result in a substantial number of incoming photons lacking sufficient energy to excite electrons, thereby

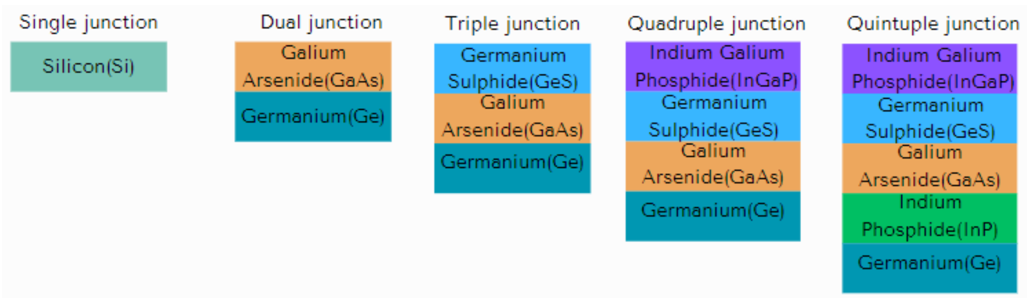

Figure 8. Material for multijunction design [16].

leading to inadequate absorption and diminished efficiency. Conversely, a bandgap that is too low can result in the dissipation of excess energy as heat rather than its conversion into electrical energy when photons exceed the required energy threshold. For instance, silicon solar cells, which are prevalent in the market, exhibit an indirect bandgap of 1.1 eV, which restricts their absorption efficiency. In contrast, materials such as gallium arsenide (GaAs) offer a direct bandgap of approximately 1.42 eV, allowing for effective light absorption and improved efficiency in photovoltaic applications. This study aims to optimize the energy bandgap in various materials to achieve the highest efficiency for a newly conceptualized solar cell design.

3.3 Wavelength conversion and reverse leakage current calculation

In Table 2, the wavelength value is inversely proportional to the energy bandgap. The conversion is needed as the magnetic spectrum comes from the solar energy striking the cell area in wave form. Visible light ranges from 400 nm to 700 nm, which represents the optimal wavelength values for solar cells to effectively extract photons and maximize energy output. Wavelengths lower than this range are often not efficiently utilized by conventional solar cells due to their limited absorption capabilities associated with a fixed bandgap. Wavelengths can be classified into three main categories: Ultraviolet (UV), which encompasses wavelengths shorter than 400 nanometers; the Visible light region, spanning from 400 nm to 700 nm; and Infrared, which includes wavelengths of 700 nm and above. Multijunction solar cells are designed to harness a broader spectrum of wavelengths, typically ranging from 300 nm to 1200 nm, depending on the materials used.

Reverse leakage current significantly impacts solar cells, leading to various degradation mechanisms that affect their performance and lifespan. Particularly, when solar cells are subjected to reverse bias conditions-often due to partial shading or defects-leakage current tends to increase. Research shows that even minor reverse currents, around 10 mA, can cause noticeable increases in leakage current over time, which typically stabilizes after approximately 10 minutes of exposure.

This leakage often results in the formation of damaged areas on the cell surface that may appear as "burned spots" under microscopic examination. These defects create pathways for current flow that compromise the cell's integrity by reducing shunt resistance, thereby affecting the overall I-V characteristics of the module. When the reverse current rises to 100 mA, the leakage current becomes more severe, although it may not immediately lead to a complete breakdown. However, it can considerably alter the module's operating characteristics.

High reverse currents are linked to hot spots or localized heating, which can further degrade the cell and potentially cause total failure if not managed properly. Therefore, controlling reverse leakage current is crucial for ensuring that photovoltaic systems operate efficiently and reliably, especially under conditions that create reverse bias, such as shading. Additionally, as illustrated in Table 3, lower wavelength values produce lower reverse leakage current values. These values must be kept in a small range as the reverse leakage current acts as the current that will consume the solar cells and decrease efficiency [19].

3.4 Short circuit current and open circuit voltage calculation

Tables 4 and 5 portray the values of short-circuit current and open-circuit voltage. A short circuit current represents the current generated by the solar cells when no external load is connected, and the voltage across is zero. The short-circuit current (Isc) is a vital parameter in multijunction solar cells, as it signifies the maximum current generated

Table 1. Energy bandgap value.

Single		Dual		Triple		Quadruple		Quintuple	
0 k	300 k	0 k	300 k	0 k	300 k	0 k	300 k	0 k	300 k
1.12	1.075	1.43	1.385	1.6	1.555	1.9	1.855	1.9	1.855
		0.67	0.6245	1.43	1.385	1.6	1.555	1.6	1.555
				0.67	0.6245	1.43	1.385	1.43	1.385
						0.67	0.6245	1.3	1.255
								0.67	0.6245

Table 2. Wavelength value for each junction.

Single	Dual	Triple	Quadruple	Quintuple
(Si) = 1156 nm	(GaAs) = 897.3	(GeS) = 799.2 nm	(GaInP) = 669.9 nm	(GaInP) = 669.9 nm
	(Ge) = 1989 nm	(GaAs) = 897.3	(GeS) = 799.2 nm	(GeS) = 799.2 nm
		(Ge) = 1989 nm	(GaAs) = 897.3	(GaAs) = 897.3
			(Ge) = 1989 nm	(GaInAs) = 990.3
				(Ge) = 1989 nm

Table 3. Reverse leakage current value.

Single	Dual	Triple	Quadruple	Quintuple
(Si) = 0.005236 A	(GaAs) = 9.849e-16 A	(GeS) = 1.402e-18 A	(GaInP) = 1.329e-23 A	(GaInP) = 1.329e-23 A
	(Ge) = 0.0005236 A	(GaAs) = 9.849e-16 A	(GeS) = 1.402e-18 A	(GeS) = 1.402e-18 A
		(Ge) = 0.0005236 A	(GaAs) = 9.849e-16 A	(GaAs) = 9.849e-16 A
			(Ge) = 0.0005236 A	(GaInAs) = 1.48e-13 A
				(Ge) = 0.0005236 A

when the cell is illuminated and short-circuited, thereby directly influencing the overall efficiency of the device. In these solar cells, which comprise multiple subcells specifically optimized for various segments of the solar spectrum, Isc is predominantly dictated by the subcell that exhibits the lowest photocurrent. Therefore, achieving balance in the current generation across all layers is essential for optimal performance. Current mismatch among subcells can result in diminished efficiency and heightened thermal losses, as surplus energy generated by higher-performing subcells may be dissipated as heat rather than being converted into electrical energy. Consequently, optimizing Isc through advancements in materials and enhancements in device architectures is imperative to improve the performance of multijunction solar cells and to transcend traditional efficiency thresholds. As indicated in Table 4, the current values among different materials exhibit considerable disparities, which may contribute to reduced efficiency. Nonetheless, these differences may also assist in maintaining the solar cell's performance at an optimized level.

As for open circuit voltage, it represents the maximum voltage that can be produced when there is no current flowing in the solar cells. Open circuit voltage is another crucial parameter, especially when designing multijunction solar cells. Maintaining a high value of Voc ensures that higher efficiency can be achieved. Thus, as stated in the table, multiple layers are able to produce higher values of these parameters, which will produce higher power output theoretically.

3.5 Efficiency of multijunction solar cell design

In Fig. 9, the highest efficiency recorded is the quintuple junction, which holds a value of 42.63%, which has a 26.87% increment compared to a single junction, producing very low efficiency, which is 15.7%. The efficiency increases as more semiconductor material creates more junctions stacked together, producing higher power output. As there are multiple junction presences in the solar cells arranged with a proper energy bandgap, the excitation of electrons in the junction increases and power generation increases. The electrical conversion on a higher number of junctions utilizes the maximum sunlight spectrum as the

Table 4. Short circuit current value.

Single	Dual	Triple	Quadruple	Quintuple
(Si) = 892.2 A	(GaAs) = 650.6 A	(GeS) = 559.1 A	(GaInP) = 438.4 A	(GaInP) = 438.4 A
	(Ge) = 1019 A	(GaAs) = 91.56 A	(GeS) = 120.6 A	(GeS) = 120.6 A
		(Ge) = 1019 A	(GaAs) = 91.56 A	(GaAs) = 91.56 A
			(Ge) = 1019 A	(GaInAs) = 86.76 A
				(Ge) = 932.1A

Table 5. Open circuit voltage value.

Single	Dual	Triple	Quadruple	Quintuple
(Si) = 0.1759 V	(GaAs) = 0.1678 V	(GeS) = 1.228 V	(GaInP) = 1.521 V	(GaInP) = 1.521 V
	(Ge) = 0.1794 V	(GaAs)=1.011 V	(GeS)=1.188 V	(GeS) = 1.188 V
		(Ge) = 0.3153 V	(GaAs) = 1.011 V	(GaAs) = 1.011 V
			(Ge) = 0.3153 V	(GaInAs) = 0.8803 V
				(Ge) = 0.313 V
Total = 0.1759 V	Total = 0.3427 V	Total = 2.5543 V	Total = 4.0353 V	Total = 4.9133 V

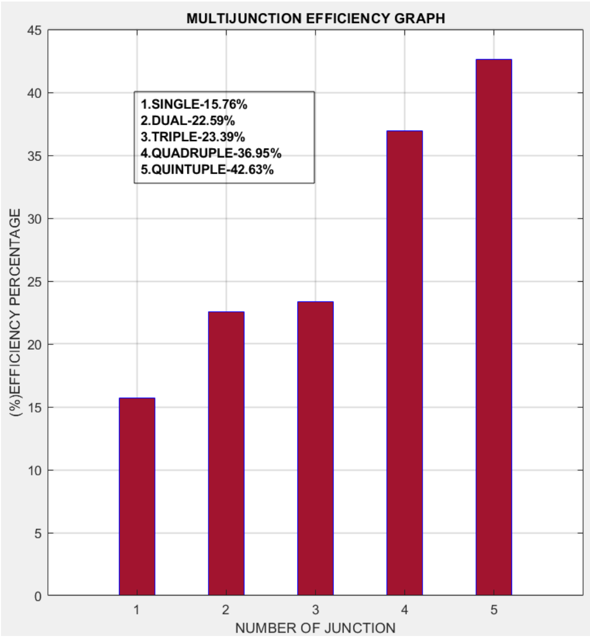

Figure 9. Efficiency for multijunction design.

fuel for this conversion. A wider spectrum, ranging from 300 nm to 1200 nm, ensures higher efficiency as the current density gradually increases with open circuit voltage. The suitability between material and tolerable current mismatch allows maximum power to be produced in a total of two to five junctions. However, as more layers desire to be stacked, the selection of compound semiconductors meets some challenges due to the fabrication complexity and higher risk in epitaxial growth recombination.

4. Conclusion

This study examined the efficacy of multijunction solar cell designs in enhancing efficiency. The project proposed five distinct designs, ranging from single junction to quintuple junction configurations. The findings revealed that, among the five designs, the quintuple junction achieved the highest efficiency value of 42.63%. Conversely, the single junction exhibited the lowest efficiency at 15.7%, attributable to the use of a single material. In single junction designs, electron movement tends to stagnate due to the absence of additional materials stacked together. Consequently, by stacking and wafering multiple layers of semiconductor materials, both power output and efficiency can be significantly improved. It is important to note that these results are based solely on simulations conducted within MATLAB Simulink. The efficiency observed in real-world applications may vary, as numerous other factors—including the tuning and fabrication processes-must be taken into account, introducing a significant degree of complexity at this stage.

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Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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