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Simulation and Design of a High-Efficiency Four-Junction Solar Cell Using SILVACO ATLAS Software

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ABSTRACT

This research examines the development and performance analysis of multi-junction solar cells using numerical simulation techniques in SILVACO ATLAS. The study began with a single-junction (Ge) solar cell. It then progressed to a double-junction (InGaP/GaAs) solar cell. This structure broadened the spectral absorption and achieved good results, such as a short-circuit current density (13.24 mA/cm²), a conversion efficiency of (19.91 %), and a significant improvement in the fill factor (FF) of (86.5 %) compared to the single-junction cell. In the third stage, we introduced a third InGaAs sub-cell. The triple-junction cell increased the short-circuit current density to (20.79 mA/cm²), the total open-circuit voltage (Voc) to (2.012 V), and the conversion efficiency to (35.76 %). This was followed by a quad-junction cell made of InGaP/GaAs/InGaAs/Ge, enabling wide solar spectrum coverage. This arrangement achieved the best result with a short-circuit current density of (29.46 mA/cm²), a V_{oc} of about (2.32 V), a FF of (73 %) and a conversion efficiency of (49.53 %).

Keywords: Multi-junction solar cells, Numerical simulation techniques, Photovoltaic efficiency, SILVACO ATLAS software.

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محاكاة وتصميم خلية شمسية رباعية المفارق عالية الكفاءة باستخدام برنامج SILVACO ATLAS

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الملخص

يدرس هذا البحث تطوير وتحليل أداء الخلايا الشمسية متعددة الوصلات باستخدام تقنيات المحاكاة العددية عبر برنامج SILVACO ATLAS. بدأت الدراسة بمحاكاة خلية شمسية أحادية الوصلة (Ge)، بعد ذلك، تقدمت الدراسة إلى خلية شمسية ثنائية الوصلات (InGaP/GaAs)، وقد وسع هذا الهيكل الامتصاص الطيفي وحقق نتائج جيدة حيث بلغت كثافة تيار الدائرة القصيرة ($13.24\ mA/cm^2$)، وكفاءة التحويل (19.91 %) إلى جانب تحسن ملحوظ في عامل التعبئة (FF) بلغ (86.5 %) مقابل الخلية أحادية الوصلة. في المرحلة الثالثة، تم إدخال خلية فرعية ثالثة من InGaAs ، عززت الخلية ثلاثية الوصلات كثافة تيار الدائرة القصيرة إلى ($20.79\ mA/cm^2$)، و V_{oc} إلى (2.012 V)، وكفاءة تحويل (35.76 %). ثم خلية رباعية الوصلات من InGaP/GaAs/InGaAs/Ge، مما أتاح تمكين تغطية واسعة للطيف الشمسي . حقق هذا الترتيب افضل نتيجة حيث بلغت قيمة كثافة تيار الدائرة القصيرة ($29.46\ mA/cm^2$)، و V_{oc} يبلغ حوالي (2.32 V)، وقيمة FF (73 %) وكفاءة التحويل (49.53 %).

INTRODUCTION

Global energy demand is expected to increase by (50 %) by 2050, calling for the search for renewable and efficient energy sources [1]. Solar energy plays a key role in renewable energy due to its clean and inexhaustible nature, but the efficiency of conventional single-junction solar cells is limited by losses caused by the absorption of photons with energies mismatched with the energy bandgap of the semiconductor material used [2, 3]. To capture the largest percentage of wavelengths of a given solar spectrum, multi-junction solar cells with materials with different bandgaps are used to increase the overall cell efficiency. This efficiency gain occurs by stacking cell junctions with lower bandgaps below cell junctions with higher bandgaps [4]. This allows a larger portion of the incoming solar spectrum to be utilized, which in turn contributes to the overall cell output [5]. These photons were previously unable to interact with higher bandgap materials but can with lower bandgap materials. The total short-circuit current (I_{sc}) is limited to the cell with the lowest I_{sc}, while the total V_{oc} is additive for each added cell junction [6]. The overall thickness of a multi-junction cell, the choice of materials, and the doping concentrations determine how much of the spectrum is captured and used for electron-hole pair generation [7]. Multi-junction solar cells typically have higher efficiencies than their single-junction counterparts, but higher efficiencies come with increased manufacturing costs. For this reason, multi-junction solar cells are commonly used in aerospace applications [8]. with some triple- and quad-junction cells recording efficiencies of over (47 %) under concentrated illumination. Multi-junction solar cells consist of multiple semiconductor layers with engineered bandgap energies, each designed to selectively absorb a specific spectral region of solar radiation, thus maximizing photon utilization across the solar spectrum [9, 10]. This enables improved photovoltaic conversion efficiency compared to conventional cells [11]. This paper aims to achieve the best conversion efficiency by designing and simulating a quad-junction solar cell made of InGaP/GaAs/InGaAs/Ge materials. In this work, Silvaco TCAD software was used, which enables us to calculate the in-voltage (I-V) characteristics and its photovoltaic parameters, the most important of which are open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), power conversion efficiency (PCE), and in-voltage (P-V) characteristics. The default illumination spectrum is set to the international standard AM1.5, and the room temperature is (300 K).

MATERIALS AND METHODS

Design of multi-junction solar cell

We built a single-junction Ge solar cell. Then, a double-junction InGaP/ GaAs solar cell. Then, a three-junction InGaP/GaAs/InGaAs solar cell. Finally, a four-junction cell consisting of the following components: InGaP/GaAs/InGaAs/Ge solar cell. Figure (1) below show the materials used to make the structures of cell.

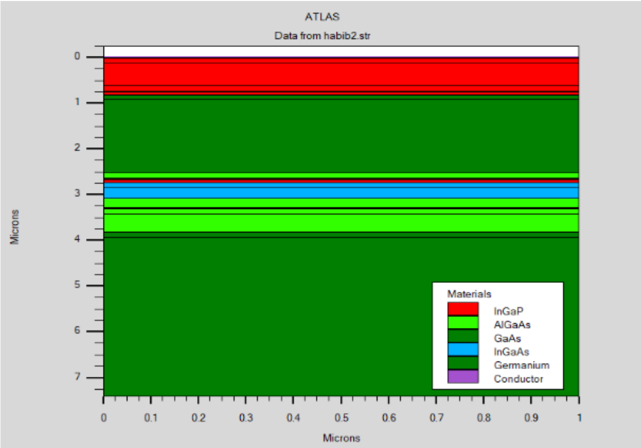

Fig. 1: Structure of Four- Junction InGaP/GaAs/InGaAs/Ge Solar Cell.

Data on the various materials used in the simulation and their individual properties are specified. The specific values used in the input panel are shown in Table (1). Each parameter is discussed separately. The physical properties of each material used in the solar cell construction were studied, with the energy bandgap, electron and hole mobility, absorption coefficient, etc., analyzed.

Table 1: Detailed overview of the physical parameters used in the simulation process [12-16].

Parameters	Ge	AlGaAs	GaAs	InGaP
Thickness (µ)	100	3.2	2	1.54
band gap (ev)	~0.66	~1	~1.43	~1.9
electron affinity (eV)	4.135	3.746	4.071	4.103
dielectric permittivity	16.01	12.05	12.91	11.82
CB effective density of states(1/cm^3)	1.04×10^{19}	6.8×10^{17}	4.71×10^{17}	6.9×10^{17}
VB effective density of states1/cm^3)	6×10^{18}	1.02×10^{19}	8×10^{18}	2×10^{19}
electron thermal velocity) cm/s)	3.1×10^{7}	4.4×10^{7}	1.8×10^{7}	1.5×10^{7}
hole thermal velocity (cm/s)	1.9×10^{7}	1.8×10^{7}	1×10^{4}	1×10^{5}
electron mobility (cm²/Vs)	3900	4100	8500	2500
hole mobility (cm²/Vs)	1900	300	400	300
shallow uniform acceptor density NA (1/cm^3)	5×10^{18}	1×10^{18}	1×10^{18}	1×10^{17}
shallow uniform donor density ND (1/cm^3)	5×10^{17}	5×10^{18}	5×10^{18}	5×10^{17}
absorption constant A (1/cm)	2.5×10^{5}	2.2×10^{5}	1×10^{5}	1×10^{5}

Theory Approach

Multi-junction solar cells are advanced technologies designed to increase the photovoltaic conversion efficiency energy conversion compared to traditional single-junction solar cells [9]. These cells are based on the arrangement of several layers of semiconductors, so that each layer has an energy gap (E_g) are different, allowing them to absorb specific wavelengths from the solar spectrum, thereby reducing remission losses and increasing conversion efficiency [17]. The theoretical efficiency of multijunction cells is calculated according to the sum of the competencies of each layer, where the upper limit of the theoretical efficiency is determined using the Shockley-Queisser Limit equation [18]:

$$\eta = \sum_{i=1}^{n}(E_g)n_i \qquad \dots (1)$$

Where η is the overall efficiency of the multi-junction solar cell, n_i is the efficiency of each layer based on its bandgap E_g. The total current in multi-junction solar cells, the current is determined by the layer with the least current generation, according to the current-limiting equation [19]:

$$J_{total} = \min(J_1, J_2, J_3, \dots\dots, J_n) \qquad \dots (2)$$

Meanwhile, the total open-circuit voltage is obtained by summing the voltages of each junction:

$$V_{oc} = \sum_{i=1}^{n} V_{oc,i} \qquad \dots (3)$$

Where J_{total} is the total current output of the solar cell, J_i is the current generated by each junction, V_{oc} is the total open-circuit voltage, $V_{oc,i}$ is the open-circuit voltage of each junction. Since each layer in a multi-junction cell may operate at different currents, tunnel junctions are used between layers to facilitate the transfer of electrons with minimal energy loss. The tunnel current is described by the quantum tunneling equation:

$$J_T = J_0 (\frac{-2d\sqrt{2mE_g}}{\hbar} \qquad \dots (4)$$

J_T is the tunnel junction current, J_0 is the initial current of the junction, d is the thickness of the tunnel layer, where m is the effective electron mass and $\hbar$ is the reduced Planck constant [20].

3- RESULTS AND DISCUSSION

By comparing the current-voltage curves of all cells, it can be seen that increasing the number of junctions leads to an increase in V_{oc}, As noted in Figure (2) which enhances the solar cell's efficiency in energy conversion. However, the resulting electric current remains almost constant between all types because the final current of the cell depends on the layer with the lower current[17]. In multi-junctions solar cells, photon absorption is divided between different layers in order for each layer absorbs a specific part of the solar spectrum based on its energy gap. This reduces heat wastage and improves the utilization of the solar spectrum, making multi-junction cells more efficient than single-junction cells [21]. Despite the improvement in voltage, the design of multi-junction cells is very complex and requires accurate matching between currents, as any difference in currents between layers can limit the overall performance of the cell. Therefore, these cells require precise distortion control, optimize electrical transmission between layers, and reduce recombination losses to ensure the highest possible efficiency [9, 22]. Figure (2) shows the current-voltage curve of a multi-junction solar cell. We notice that the current-voltage curve increases greatly with the increase in the number of junctions as a result of the absorption of all wavelengths of photons incident on the cell.

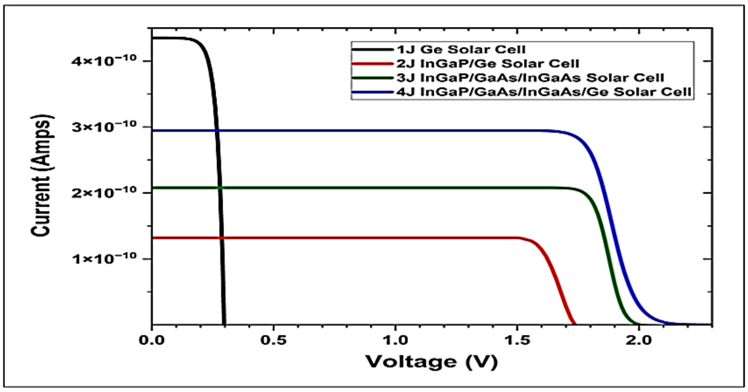

Fig. 2: The voltage response applied across four types of solar cells, from the single-junction cell (1J) to the four-junction cell (4J).

Table (2) shows the main performance metrics of the multi-junction solar cell: open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), and power conversion efficiency (PCE) with the change in junction type from 1J to 4J . We find that the open circuit voltage increases with the increase in the number of junctions, and the short circuit current also increases. Table (2) also shows that PCE increases from (9.08 %) to (49.53 %). The fill factor (FF) value decreased due to the increase in recombination and internal resistance of the cell.

Table 2: Summarizes the key output parameters for 1J, 2J, 3J, and 4J solar cells.

Cell Type	V_{oc} (V)	Jsc (mA/cm^2)	FF (%)	PCE (%)
1J Ge	0.29	42.6	71.9	9.08
2J InGaP/Ge	1.73	13.24	86.5	19.9
3J InGaP/GaAs/InGaAs	2	20.79	85.42	35.7
4J InGaP/GaAs/InGaAs/Ge	2.3	29.46	73	49.53

The high performance of the 4J solar cell, as indicated by Figure (3), is a result of the careful optimization of material composition, doping concentrations, and layer thicknesses. The multi-junction approach allows for efficient absorption of a broad range of the solar spectrum, while high-quality materials and well-designed tunneling junctions ensure effective charge carrier collection and minimal recombination losses. This leads to a high J_{sc}, V_{oc}, and ultimately, a very high efficiency of (49.5 %).

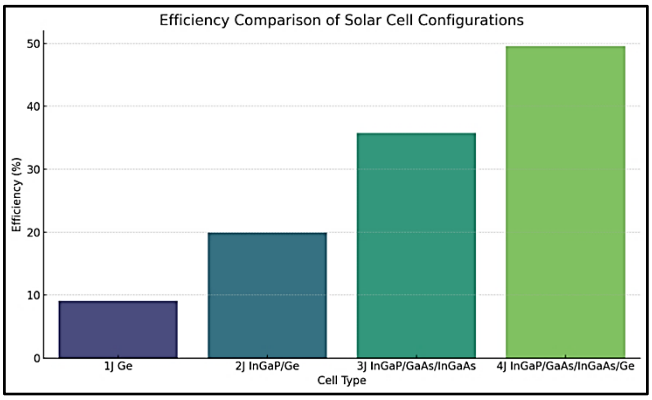

Fig. 3: Efficiency comparison of solar cell configurations.

What distinguishes a four-junction cell is the high total voltage output (V_{oc}), as each junction adds additional voltage to the final voltage, while the total current is determined based on the lowest current produced by a sequential junction. Despite this limitation, the final output of power (PM) is high due to high voltage as show in Figure (4), resulting in a very high conversion efficiency of up to (50 %). To maintain the flow of charges between the different layers, a mechanism known as "tunnel junction" was used, which are thin layers with high grafting (p++/n++) that allow charges to move through the energy barrier using the quantum phenomenon, without causing a loss of potential or an increase in the internal resistance of the cell.

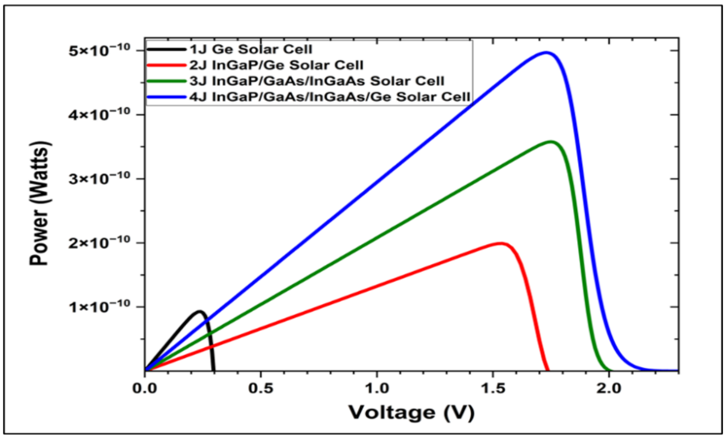

Fig. 4: The relationship between power and voltage for different types of multi-junction solar cells, from 1J to four-junction cell.

CONCLUSION

Simulation results using Silvaco Atlas software showed that the 4J four-junction solar cell, composed of InGaP/GaAs/InGaAs/Ge, performs well compared to other single-junction, double-junction, and triple-junction designs. This performance is attributed to this type of cell's ability to absorb a wide range of the solar spectrum. Each layer is designed to absorb a specific range of photons based on its bandgap. The four-junction solar cell achieved good outputs with V_{oc} (2.3 V), Jsc (29.46 mA/cm²), FF (73 %), PCE (49.53 %), and peak power (4.95×10^{-10} Watt). With this design, the four-junction cell proves to be a promising option for use in satellites, space systems, and concentrated solar power plants, combining intelligent electronic design with comprehensive spectral utilization.

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Author contribution: Authors contributed equally in the study.

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