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Enhancing Efficiency of Two-bond Solar Cells Based on GaAs/InGaP

Yagub Sefidgar [1], Hassan Rasooli Saghai [*,1], Hamed Ghatei Khiabani Azar[2]

[1] Department of Electrical Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran.
[2] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

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Abstract: Multi-junction solar cells play a crucial role in the Concentrated Photovoltaic (CPV) Systems. Recent developments in CPV concerning high power production and cost effective-ness along with better efficiency are due to the advancements in multi-junction cells. This paper presents a simulation model of the generalized Multi-junction solar cell and introduces a two-bond solar cell based on InGaP/GaAs with an AlGaAs/GaAs tunnel layer.For enhancing the efficiency of the proposed solar cell, the model adopts absorption enhancement techniques as well as reducing loss of recombination by manipulating number of junctions and varying the material properties of the multi-junctions and the tunneling layer. The proposed Multi-junction solar cell model employing tunnel junctions can improve efficiency up to by 35.6%. The primary results of the simulation for the proposed structure indicate that it is possible to reduce the loss of recombination by developing appropriate lattice match among the layers; it is also likely to have suitable absorption level of the phonons. Simulation results presented in this paper are in agreement with experimental results.

Keyword: Two-Bond Solar Cell, Tunnel Layer, Lattice Matching, Recombination

1. INTRODUCTION

* Corresponding author. Email: **h_rasooli@iaut.ac.ir**

Energy is the major driving force for development of modern countries. The solar energy received by earth in interval of 60 mins is more than the energy consumed annually all over the world. [1] However, the incident solar energy is quite feeble requiring multiple energy converters to meet the world's energy consumption. Therefore high efficiency solar energy conversion is significant. Solar cells, also called photovoltaics, are devices converting the radiated energy from the sun into electricity through the photovoltaic effect. Solar cells are also promising eco-friendly energy source to decrease fossil fuels, and issues addressed by the global warming.

The range of energy gap or energy band for the semi-conductors used in the solar cells is 0.8-2.4 eV. The advancement in photovoltaic systems has resulted in the new generation of solar cell using large spectrum of solar radiation for better efficiency. Multi-junction solar cell (MJSC) is a collection of various photovoltaic junctions juxtaposed over one another via homo-junctions, intrinsic materials or tunnel junctions. Joining these solar cells together will lead to efficiently capture and convert a large range of photon wavelengths into electrical power. Currently, MJSCs can generate approximately twice as much power as the conventional solar cells [2–7].

Solar cells made of III-V semiconductor compounds have been depicting the significant energy conversion efficiencies compared to the other materials represented by silicon. [8] Besides the high efficiency, III-V semiconductor compound materials are favored due to the bandgap tunability by elemental compositions, higher photon absorption by the direct bandgap energies, higher resistivity against high-energy rays in space, and smaller efficiency degradation by heat than Si solar cells. [9,10]

This encompasses an innovative concept of CPV in which light is concentrated over the panel via reflectors. As the concentration level increases, Multi-junction does not only face tracking and thermal management issues but the resultant increase in current densities also influences the stability of the tunnel junction [11–15].

2. Device structure and simulation

Tunnel junctions are employed to improve functionality of LEDs, lasers as well as Multi-junction Solar Cells. The highest intensity of solar radiation occurs at the wavelength of 0.5 µm. Therefore, it is observed that the semi-conductors with an energy gap of 2.5 eV are suitable for absorption with maximum solar radiation. It is evident that at high wavelengths with an energy range of less than energy band gap, absorption decreases dramatically, and the material is almost transparent to this part of the light [16,17].

2.1. Recombination Processes

Defect or impurity within or at the surface of semiconductor is the major cause of carrier recombination. In GaAs solar cells, there are four main recombination processes, including surface recombination, radiative recombination, SRH recombination and Auger recombination as seen in Figure 1.

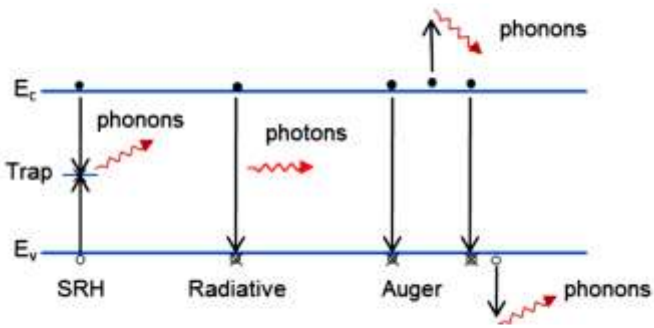

Fig. 1. Recombination processes in semiconductor

Minimizing surface recombination is crucial for high performance solar cells, in particular for thin solar cells. The higher surface recombination velocity Sr corresponds to the larger surface recombination, and vice versa [18].

2.2. Selection of the Materials

Among the solar cells that have been the focus of many studies in recent decades, the multi-band solar cell composed of different compounds has found a special position due to its high efficiency. These cells consisting of several layers of semi-conductors with different band gaps along with matched lattice constants are able to absorb a wide range of solar light spectrum. Therefore, solar energy can easily and widely convert to electric energy using the above-mentioned multi-bond cell. The use of solar cell based on quantum well is one of the most important issues that has attracted the attention of many researchers. The first quantum solar cell was made by Barnham et al. in Imperial College of London. They showed that quantum solar cells have higher efficiency than single-contact solar cells [19,25,26].

The single-junction solar cell P-N absorbs a photon with higher energy, so pair election produces a hole and this pair election separated from P-N junction because of inner field and creates current in outer circuit. If small band gap is selected, absorption increases, but the voltage of the circuit decreases again. For increasing the band gap voltage, a big band is selected that lowers the absorption again, so band gap is optimally selected. Adding quantum well structures to the intrinsic region of p-i-n diode is one of the solutions in this regard [27]. For higher efficiency, the direct band gap semiconductors such as GaAs and AlGaAS should be selected [20,28].

2.3. Two-Junction Solar Cell

In two-junction solar cells, several materials with different band gaps are grown on each other. Each semi-conductor layer located as a separate layer in the cell whole structure has the capacity to absorb a certain range of the wavelengths of radiative light of the solar spectrum and convert it into electricity. As a result, the layers under the semiconductor layers can be put on each other in a way that in the first layer the semiconductor having greater energy band than the other semiconductors in the whole structure is used so that it can absorb part of the spectrum with greater energy or short wavelength [21-23, 29, 30].

The bigger wavelengths which have less energy pass through the first layer of the structure and reach the lower layers which consist of semi-conductors with less band gap energy getting absorbed in the lower layers [31]. Besides having different semiconductor layers, the two-junction solar cell consists of some basic layers which are located in different parts of the cell structure [32]. Some of these layers include emitter and base layers, anti-reflecting coating, metal contacts, tunnel junction, the posterior surface field layer, window, and concentrators. The output of the energy of two-junction solar cell comes from the addition of the symmetric outputs to each individual layer. In this equation, E_{gi} refers to the band energy gap in the area of i^{th} cell [28, 33].

$$\eta_{(E_g)} = b \sum_{i=1}^{n} \eta_{(E_{gi})} \tag{1}$$

2.4. Multi-Junction Solar Cell Structure

The MJSC consists of a GaInP solar cell as the top layer, GaAs in the middle, and Ge layer as a bottom layer of the solar cell. InGaP as top cell and GaAs as bottom cell will form this double junction. These two together with a special junction known as tunnel junction are also provided with window layers. Window layer blocks surface recombination while facilitating the lattice change by introducing a gradient between the materials. Bi-directional current is also feasible by the tunnel junction.

2.5. Tunnel Junction

A tunneling in two-junction solar cell refers to the phenomenon of rapid movement of the carrier in the whole barrier potential. Tunneling is one of the most noteworthy aspects of charge transportation in two-junction solar cell.

The tunneling process is non-local; nevertheless, we have to assume the spatial profile of the energy bands. The spatial division of the electrons generated in the conduction band resulted from the holes generated in the valence band is necessary to consider and it is shown in figure 2[34].

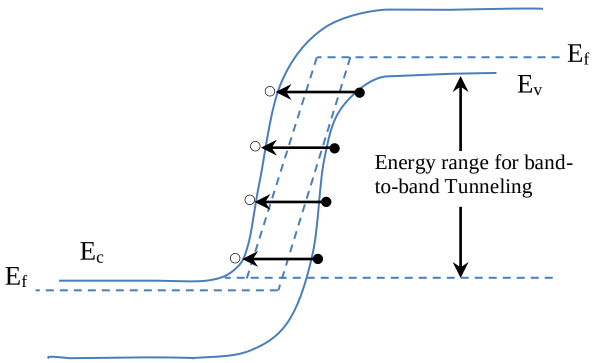

Fig. 2. Schematic band diagram of a tunnel junction.[34]

Tunnel layer causes low resistance and creates effective capabilities. In a regular junction, conductivity occurs when the junction is in direct bias. Theoretically, both areas of tunnel junction have been described using exponential functions. Because of this feature of particular *IV* changes, tunnel junction has a major effect on the behavior of two-junction solar cell. The general features of the I-V of the tunnel junction can be expressed using the following equations:

$$J_{total} = \frac{V(t)}{V_p} J_T + J_X + J_{TH} \tag{2}$$

$$J_T = J_p e^{1 - \frac{V(t)}{V_p}} \tag{3}$$

$$J_x = J_v e^{A_2 (v(t) - (v_v)} \tag{4}$$

$$J_{TH} = J_s e^{\frac{qV(t)}{kt}} - 1 \quad (5)$$

In these equations, J_{total} is the total tunnel diode current density, J_T is the statement of the closed form of the tunneling current density which is a description of the particular behavior for tunnel diode, J_X is extra tunneling current density, J_{TH} refers to the feature of a regular diode, $J_p$refers to the peak current density, V_p is the peak voltage, J_V is the valley current density, V_v is the valley voltage, A_2 refers to the cross sectional area, Js refers to the saturated current density, k is Boltzmann's constant value, T is temperature at Kelvin's degree, and q is the electric charge of an electron. Because of having less energy gap, the quantum wells also absorb the photons with less energy from the respective materials, and, as a result, increase the short circuit current. In quantum wells the recombination of the trapped carriers is increased, and leading to lower open circuit voltage. The deeper quantum wells have the greater numbers of energy levels and electrodes which leads to greater output current [36].Similarly, the thicker quantum wells have the lower number of energy levels and moreover, the distance between the levels increases, and the number of electrons on them decreases leading to less output current. The important point about tunneling is the fact that the distribution of the carriers depends on the temperature and the thickness of the barrier. In other words, this distribution increases with higher temperatures and thinner barriers.

2.6. Lattice matching for GaAs semiconductor materials along with calculation of the efficiency for multi-junction solar cell

The alloy obtained from combining two materials with given proportions produces a compound material with specific features. It means that $Ga_x\ In_{1-x}\ P$ of the features of this alloy changes when the proportion of the combined materials are set at a specific range. This is documented by a linear equation shown below, but it can often be estimated. For example, the constant of α network for GaAs can be estimated as *α=5.6,* $\alpha_{Gap} = 5.45A$, $\alpha_{Inp} = 5.87A$. For matching the network of $Ga_x\ In_{1-x}P$ with *GaAs,* the following equation should be maintained:

$$\alpha_{GaAs} = \alpha_{Gap}x + \alpha_{Inp}.(1 - X) \Leftrightarrow X = \frac{\alpha_{GaAs} - \alpha_{Inp}}{\alpha_{Gap} - \alpha_{Inp}} \quad (6)$$

In this equation, almost X≅ 0.52 is returned. The GaP ($Ga_{0.52}\ In_{0.98}P$) has an energy band of Eg = 2.35 ev, and InP has an energy band of Eg = 1.42 ev. Therefore, in this case the energy is obtained in the following manner:

$$Eg^{GaInp} = X.\ Eg^{Gap} + (1 - x)Eg^{Inp} \quad (7)$$

in which a total number equals with *Eg = 1.42 ev* is returned [36]. The total efficiency is obtained using the following equation:

$$\eta = \frac{V_m I_m}{P_{in}} = \frac{j_{sc} \times V_{oc} \times FF}{P_{in}} \quad (8)$$

in which I_m *and* V_m are the current and voltage at maximum power respectively, and j_{sc} is the short circuit current, P_{in} is the input power, and FF is the efficiency factor, which is obtained by equation 9 or 10. V_{oc} is the open circuit voltage with zero current density, which is obtained by equation 11 based on Figure 4.

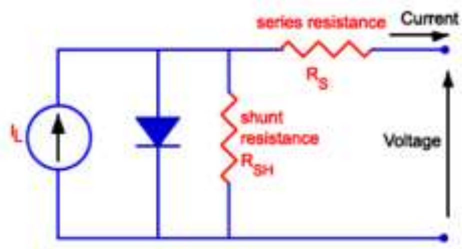

Fig. 4. The equivalent parasitic series and shunt resistances in a solar cell circuit

$$FF = \frac{P_{max}}{j_{sc}\,V_{oc}} = \frac{V_m I_m}{j_{sc}\,V_{oc}} \tag{9}$$

$$FF = \frac{V_{oc} - ln(V_{oc} + 0.72)}{V_{oc} + 1} \tag{10}$$

$$V_{oc} = \frac{q}{nkT} V_{oc} \tag{11}$$

3. Result and discussion

In Table I combination of GaInP, GaAs and Ge solar cells in multi-junction cell via window layer and tunnel layer, has resulted in higher open-circuit voltages than their individual respective cells.

Table I: Short circuit current, open circuit voltage, and energy bandgap of individual and integrated cells

	ISC (mA/cm2)	VOC (volts)	Eg (eV)
GaInP Cell	11.01	1.30	1.90
GaAs Cell	25.25	1.425	0.94
Ge Cell	45.60	0.244	0.65
Triple Junction Cell	17.729	2.652	3.92
Dual Junction Cell	19	2.481	2.81

The simulation results indicate that for lower level of concentration, the Multi-junction Solar cell with GaAs tunnel junction would be better choice. By giving rise to the level of solar insolation, this tunnel junction represents negative resistive path to the carries, instead of facilitating the cell with their negligible resistance path. This could be potentially manipulated by increasing the peak tunneling current of the GaAs junction , however, when cell current crosses the peak tunneling current - there would be dramatic change in its performance. This modification in cell functionality is either has to be compensated by the power system or cell should only be extended to the area in which insolation level falls in to its operating range. The structure of the two-junction solar cell is shown in Figure 5.

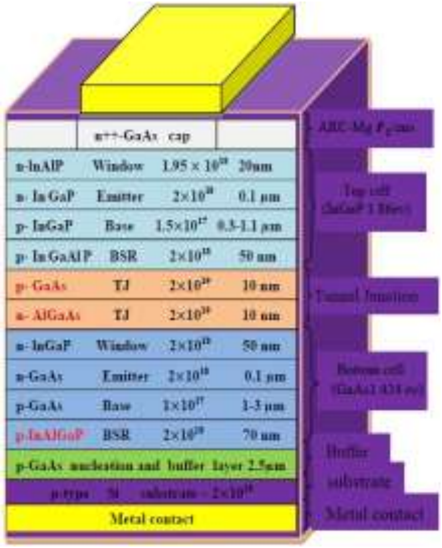

Fig. 5. The Structure of the proposed two-junction solar cell with a tunnel layer of (GaAs – Al GaAs) and Bsr (p-InA1GaP)

Dual junction includes *GaInP* in the top cell and *GaAs* in the bottom cell. Moreover, these layers are connected to each other via a special junction, called tunnel junction. The window layer never lets these levels be a pair and has no lattice changes by decreasing the heat (slope) between two materials so the window junction solves the problem of lattice mismatching. Band gap of selected material for semiconductor in the first level has a bigger voltage in comparison with whole structure, so it can absorb part of photon with more energy. Tunnel junction allows the flow of the current in both sides [14].

The I-V characteristics simulated with Silvaco Tcad/Atlas modeling software [35] are shown in Figure 6 with a spectrum of Am 1.5 in Figure 7. The simulation results are shown in Table 2 [14]. The structure of the proposed solar cell includes *GaAs/Al GaAs* tunnel junction and the window of *GaAs* buffer.

The simulation results show the real performance of tunneling probability at different concentration levels for increasing the applied voltage. Therefore, it can be concluded that I –V characteristics of the two-junction solar cells is sensitive to radiation due to the existence of the tunneling layer. Besides, the right selection of the materials in the upper and lower cells and tunnel junction can increase efficiency.

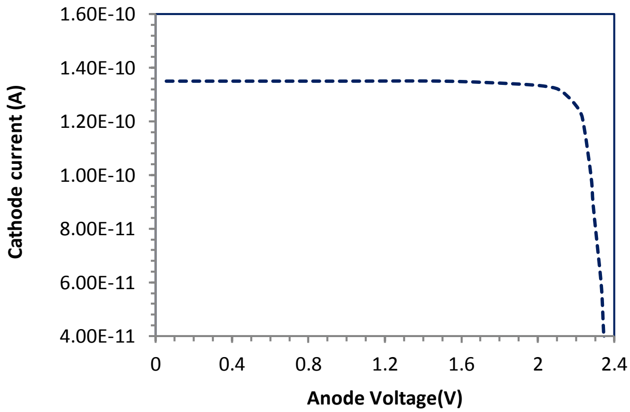

Fig. 6. Voltage current curve of the solar cell structure with Al GaAs – Al GaAs tunnel layer

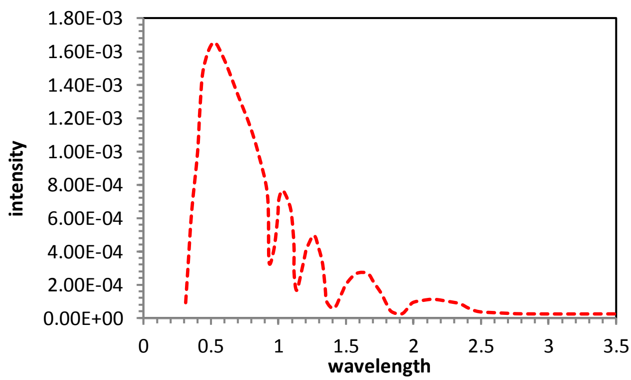

Fig. 7. The curve of Am 1.5 spectrum with Al GaAs – Al GaAs tunnel layer

The changes made in this structure are described compared to the main structure of the tunnel layer and BSR in the second layer. Due to the special capabilities of the materials used and matching between the lattice and the concentration of the materials, efficiency increases. The materials used for the tunnel layer and the BSR of the second layer include (*n-AlGaAs/p- GaAs*) and (*p-InAlGaP*), respectively. The generalized I-V characteristics simulated with tunnel junctions are shown in Figure 8, and the same characteristics with a spectrum of Am.1.5 are shown in Figure 9. Moreover, the results of simulation for the proposed two-junction structure in Silvaco are shown in Table II. The results of the changes in the proposed simulation of the solar cell increased efficiency from 27.8% to more than 35.6%, indicating very good improvement [15,16].

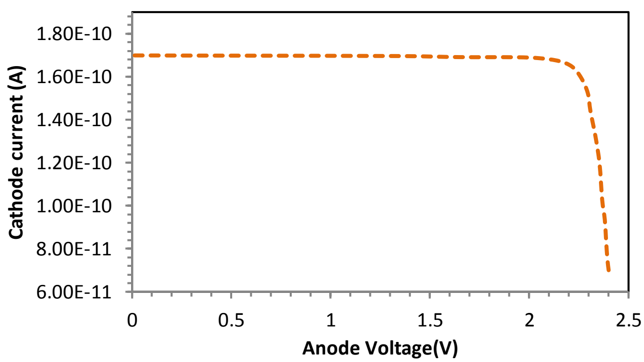

Fig. 8. Voltage current curve of the solar cell structure with tunnel layers of (GaAs – Al GaAs) and Bsr (p- InAlGaP)

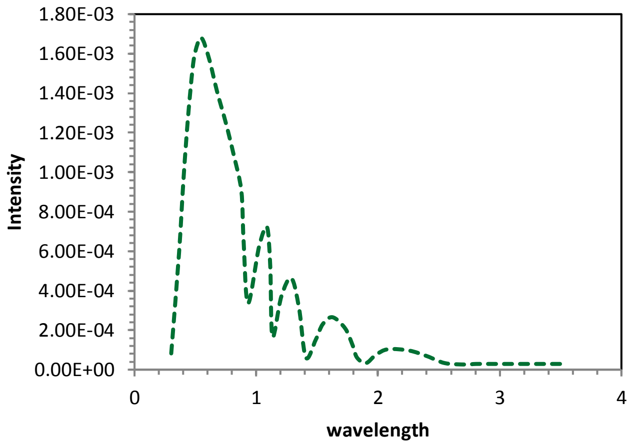

Fig. 9. The Am 1.5 spectrum curve with a tunnel layer of (GaAs – Al GaAs) and Bsr (p – InAlGaP)

Table II. The simulation results of the structure of the proposed and reference two-junction solar cell

The simulation results of the structure of the reference two-junction solar cell[14].	The simulation results of the structure of the proposed two-junction solar cell
ATLAS>EXTRACT> init infile="solarex03_1.log" EXTRACT> extract name="Jsc" Jsc=1.45451e-010 EXTRACT> extract name="JscmAcm2" JscmAcm2=14.5451 EXTRACT> extract name="Voc" Voc=2.38059	ATLAS> EXTRACT> init infile="solarex03_1.log" EXTRACT> extract name="Jsc" Jsc=1.71201e-010 EXTRACT> extract name="JscmAcm2" JscmAcm2=17.1201 EXTRACT> extract name="Voc" Voc=2.44474

EXTRACT>extract name="Pm"	EXTRACT> extract name="Pm"
Pm=2.90515e-010	Pm=3.72756e-010
EXTRACT> extract name="Vm"	EXTRACT> extract name="Vm"
Vm=2.20003	Vm=2.25
EXTRACT> extract name="Im"	EXTRACT> extract name="Im"
Im=1.26663e-010	Im=1.65669e-010
EXTRACT> extract name="FF"	EXTRACT> extract name="FF"
FF=87.2316	FF=89.0606
EXTRACT> extract name="Eff"	EXTRACT> extract name="Eff"
Eff=27.8913	Eff=35.6156
EXTRACT>	EXTRACT>

4. Conclusion

Tunneling is a substantial aspect of charge transport in multi-junction solar cells. Tunneling layer represents low resistance as well as efficient performance where a particle tunnels through a barrier. In a customary junction, conduction occurs while the junction is forward biased whereas a forward-biased tunnel junction will increase three functional regions where a rise in forward voltage corresponds to a decrease in forward current. All regions of tunnel junctions are depicted by exponential functions. Due to these peculiar IV characteristics, tunnel junction has a crucial affect in Multi-junction Solar Cell.

In this paper, we proposed a novel structure for a solar cell using Silvaco software to simulate our structure. Many techniques have been employed manipulating current and efficiency such as absorption enhancement as well as reducing loss of recombination. Not only could we increase the amount of current but also efficiency from 27.8% to 35.6% by changing material of second layer Bsr (p-InA1GaP) and increasing the absorption of hole photons and changing in material of tunnel junction (n-A1GaAs / p-GaAs) which is a considerable improvement .

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