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Analysis of Theoretical Efficiencies of GaInP$_2$/GaAs/Ge Multijunction Solar Cell

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ABSTRACT

In this paper, modifying the spectral p-n junction model the theoretical efficiencies have been calculated for a GaInP$_2$/GaAs/Ge multijunction solar cell for both the airmass AM1.5 global and AM1.5 direct normal under 1 sun condition. Based on these efficiencies, performance of this solar cell is analyzed. The increased bandgap and sun concentration would for the increased efficiency as well. These theoretical efficiencies of GaInP$_2$/GaAs/Ge multijunction solar cell have been achieved upto 38.16%% for AM1.5G, and 41.38% for AM1.5D under 1 sun condition respectively due to thinning the top cell thickness.

Keywords: Theoretical efficiency, Multijunction solar cell, ASTM G173-03 reference spectra.

1. Introduction

Single junction solar cell can utilize only a part of the spectrum of light. The efficiency of the single junction solar cell is lower in the range. Multijunction solar cell could overcome the limitation of the single junction solar cell and could provide the higher efficiency. The idea of converting different parts of the incident spectrum by different layers of a multijunction solar cell has been taken into account since 1951**[1, 2]**. In 1982, the theoretical and experimental studies of multijunction solar cells have been reviewed by Loferski **[3]**. In 1987, spectral p-n junction model by M. E. Nell et al has been given, which is widely used in tandem cell **[4]**. Modifying short-circuit equation and reverse saturation current equation of spectral p-n junction model and considering thickness, S. R. Kurtz et al give another model for two junction series connected tandem solar cell in 1990 **[5]**.

The efficiency of a solar cell depends on the incident spectrum, the temperature of the cell, and the irradiance or concentration of the light **[6]**. Increasing the concentration of the sunlight to the maximum value (~46000 suns) contributes in theoretical efficiencies 10–20% (absolute) which is higher than the corresponding one-sun efficiencies **[7]**. Change in the spectrum gives a smaller effect (typically 1–4% absolute) **[8]**. Two parameters responsible for the multijunction solar cell efficiency are short circuit current density and open circuit voltage **[9]**. Short-circuit current density depends on the solar irradiance and the wavelength of the spectrum. Where open-circuit voltage depends on short-circuit current, reverse saturation current and temperature. Reverse saturation current is also very important parameter and it depends on surface recombination velocity, thickness and temperature. Surface recombination velocity is connected to diffusion constant and minority carrier life time both for electron and hole and is decreased with the increase of minority carrier life time. Minority carrier life time could be increased by introducing buffer layer and optimizing the growth temperature. However lower the surface recombination velocity; lower the reverse saturation current which in turn increases the open-circuit voltage that consequently increase the solar cell efficiency. It has been shown that bandgap is also a strong function of the theoretical efficiency of the three junction series connected multijunction solar cell. Selection of the semiconductor materials is very important for high efficiency multifunction cells. In our work, it has been reported and analyzed the theoretical efficiencies of a three junction series connected multijunction solar cell with optimized top cell thicknesses. Here GaInP$_2$ with band gap 1.9eV is used as top cell whereas GaAs with bandgap 1.42eV and Ge with 0.67eV are used respectively as middle and bottom cell. All these three materials are lattice matched.

The theoretical efficiencies have been calculated in different conditions and consequently the performance of the cell is analyzed. A modified version of the standard equations has been used for calculating of the electrical characteristics of the multijunction solar cell **[4, 5, 10-12, 22]**. Modification of spectral p-n junction model by Nell and Barnett facilitates the respective calculation in this work **[4]**.

2. Theoretical Model

The short-circuit current density J_{sc} was calculated directly from the ASTM G173-03 reference spectra derived from SMARTS v. 2.9.2 (AM1.5) **[13]**. As the layers of this multijunction solar cell are connected in series, excess photocurrent in an upper junction can be radiatively transferred to the lower layers as topmost junction could absorb more photon than the lower junction **[14, 15]**. The photon flux F is calculated from the irradiance I and wavelength λ.

$$J_{sc} = e \times F \tag{1}$$

$$F = \frac{\lambda I}{hc} \tag{2}$$

where, e is electronic charge, F is photon flux, h is Plank constant, λ is wavelength of incident , and c is velocity of light

The reverse saturation current density, J_0, has been calculated for each cell as the sum of the currents for the n-type and p-type layers [2].

$$J_0 = e\left(\frac{D_e}{\tau_e}\right)^{\frac{1}{2}}\frac{n_i^2}{N_A}\left(\frac{S_e(\frac{\tau_e}{D_e})^{\frac{1}{2}}\cosh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+\sinh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}{S_e(\frac{\tau_e}{D_e})^{\frac{1}{2}}\sinh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)+\cosh\left(\frac{x_p}{\sqrt{D_e\tau_e}}\right)}\right) + e\left(\frac{D_h}{\tau_h}\right)^{\frac{1}{2}}\frac{n_i^2}{N_D}\left(\frac{S_h(\frac{\tau_h}{D_h})^{\frac{1}{2}}\cosh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+\sinh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}{S_h(\frac{\tau_h}{D_h})^{\frac{1}{2}}\sinh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)+\cosh\left(\frac{x_n}{\sqrt{D_h\tau_h}}\right)}\right) \tag{3}$$

where, D_e is diffusion current constant for electron, D_h is diffusion current constant for hole, τ_e is minority carrier life time for electron, τ_h is minority carrier life time for hole, n_i is intrinsic carrier concentration, N_A is acceptor concentration, N_D is donor concentration, S_e is surface recombination velocity of electron, S_h is surface recombination velocity of hole, X_p is thickness of p-layer and X_n is thickness of n-layer. The diffusion constants D_e, and D_h were calculated from the Einstein's relation-ship:

$$D_e = \frac{kT\mu_e}{e} \tag{4a}$$

$$D_h = \frac{kT\mu_h}{e} \tag{4b}$$

Here, μ_e is mobility of electron, μ_h is mobility of hole, k is Boltzmann's constant. The minority carrier life time τ_e and τ_h were calculated from

$$\frac{1}{\tau_e} = \frac{1}{\tau_{SRH}} + BN_A \tag{5a}$$

$$\frac{1}{\tau_h} = \frac{1}{\tau_{SRH}} + BN_D \tag{5b}$$

Here, τ_{SRH} is Shockley-Read-Hall life time; B is direct band-band recombination co-efficient. The surface recombination velocities of electron S_e and hole S_h were calculated from

$$S_e = \frac{D_e}{L_e} = \frac{D_e}{\sqrt{\tau_e D_e}} = \sqrt{\frac{D_e}{\tau_e}} \tag{6a}$$

$$S_h = \frac{D_h}{L_h} = \frac{D_h}{\sqrt{\tau_h D_h}} = \sqrt{\frac{D_h}{\tau_h}} \tag{6b}$$

The intrinsic carrier concentration n_i^2 were calculated from

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$$

$$n_i^2 = 4M_c M_v\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{\frac{3}{2}} \exp\left(\frac{-E_g}{kT}\right) \tag{7}$$

where N_c and N_v are the densities of state in the conduction and valance band, E_g is band gap of the material,

T is temperature in Kelvin, M_c and M_v are number of equivalent minima in the conduction band and valance band, m_e^* and m_h^* are the effective mass of electrons and holes respectively. A cell with band gap E_g when exposed to the solar spectrum, a photon with energy greater than E_g, contributes an energy of E_g to the cell output and the excess energy (> E_g) is wasted as heat.

Then total current density

$$J = J_0\left(e^{\frac{qv}{KT}} - 1\right) - J_{ph} \tag{8}$$

Open circuit voltage V_{oc} can be calculated from this equation by putting $J = 0$,

$$V_{oc} = \left(\frac{kT}{e}\right) ln\left[\left(\frac{J_{sc}}{J_0}\right) + 1\right] \tag{9}$$

For a given J_{sc} the V_{oc} increases logarithmically with decreasing J_0 Output power density P can be calculated from

$P = VJ$

$$P = V\left[J_0\left(e^{\frac{qv}{KT}} - 1\right) - J_{sc}\right] \tag{10}$$

The condition for maximum power density can be obtained when $dP/dV = 0$

$$\frac{d}{dV}\left[V\left[J_0\left(e^{\frac{qv}{KT}} - 1\right) - J_{sc}\right]\right] = 0 \tag{11}$$

Thus the equation for maximum voltage is

$$V_m = V_{oc} - \frac{1}{\beta} ln(1 + \beta V_m) \tag{12}$$

where, $\beta = \frac{e}{kT}$

The equation for maximum current density is

$$J_m = J_0 \beta V_m e^{\beta V_m} \cong J_{sc}\left(1 - \frac{1}{\beta V_m}\right) \tag{13}$$

3. Calculation and Results

In this work, the theoretical efficiency of $GaInP_2$/GaAs/Ge multijunction cell has been calculated at 300K. We considered the total power densities 1000 W/m^2 and 900 W/m^2 for the AM1.5G and AM1.5D respectively **[16]**. The required parameters of different layers of the semiconductor materials for the stack of cells are considered in the analysis, finally which yield the results for the efficiency presented in the following table at 300K. Simulations have been performed using in-house code written for MATLAB (MathWorks Inc.).

Table 1: Parameters of the materials for three layers junctions at 300K temperature

Parameter	Top Cell $GaInP_2$	Middle Cell GaAs	Bottom Cell Ge
λ	0.654×10-6m	0.875×10-6m	1.775×10-6m
M_c	1	1	1
M_v	1	1	1
μ_e	4000 (cm^2/Vs) **[5]**	8500 (cm^2/Vs) **[5]**	3900(cm^2/Vs) **[10]**
μ_h	200 (cm^2/Vs) **[5]**	400 (cm^2/Vs) **[5]**	1900(cm^2/Vs) **[10]**
m_e^*/m_e	0.155 **[5]**	0.067 **[5]**	1.64 **[10]**
m_h^*/m_e	0.460 **[5]**	0.473 **[5]**	0.28 **[10]**
τ_{SRH}	10^{-5} (s)	10^{-5} (s)	10^{-5} (s)
B	$7.5\times10^{-10}(s^{-1}cm^3)$	$7.5\times10^{-10}(s^{-1}cm^3)$	$7.5\times10^{-10}(s^{-1}cm^3)$
N_A	$10^{17/}$ cm^3 **[5]**	10^{17} /cm^3 **[5]**	10^{17} /cm^3 **[10]**
N_D	2×10^{18} cm^3 **[5]**	$2\times10^{18/}$ cm^3 **[5]**	$2\times10^{18/}$ cm^3 **[10]**
X_n	100×10^{-9} m	100×10^{-9} m	100×10^{-9} m
X_p	208×10^{-9} m	300×10^{-9} m	400×10^{-6} m

Table 2: The obtained values for the multijunction solar cell analyzed

AM	V_{oc}(V)	J_{sc} (mA/cm^2)	V_m(V)	J_m(mA/cm^2)	η(%)
AM 1.5D	2.4601	16.04727	2.3402	15.87103	41.2
AM 1.5G	2.4650	16.43511	2.3451	16.25498	38.1

The analysis assumed zero losses from reflection; grid coverage and series resistance. However experimentally, these loss factors lower the cell efficiency. Moreover other loses factors such as absorption, recombination, interface reflection etc in different layers further lower the cell efficiency. It is evident that non-ideal factors lower the conversion efficiency typically to the range of 10 to 15% **[17]**. The highest obtained experimental efficiency for $GaInP_2$/GaAs/Ge multijunction solar cell is '32.0 ± 1.5 %' for AM1.5G under 1 sun condition **[18]** and '41.6± 2.5 %' under 364 suns condition as reported by Spectrolab **[18, 19]**.

4. Performance

The thickness of the top cell, bandgap and surface recombination velocity have a significant role in cell efficiency. The top cell thickness would be the adjusted parameter. Moreover thinning the top cell thickness could increase the cell efficiency. Theoretical cells efficiencies are a strong function of the materials' bandgap **[20]**. If the bandgap has been varied anomalously from 1.70eV to 1.90eV **[21]**, efficiency is increased linearly from 34.83% to 38.11% for AM1.5G and from 37.70% to 41.26% for AM1.5D respectively as shown in Fig: (a). From Fig: (b) band gap has been varied anomalously from 1.2eV to 1.42eV; efficiency is also increased from 34.5% to 38.11% for AM1.5G and from 37.35% to 41.26% for AM 1.5D respectively. From Fig: (c) top cell thickness has been varied from 150nm to 600nm; efficiency varied from 37.68% to 38.16% for AM 1.5G and 40.21% to 41.38% for AM 1.5D respectively.

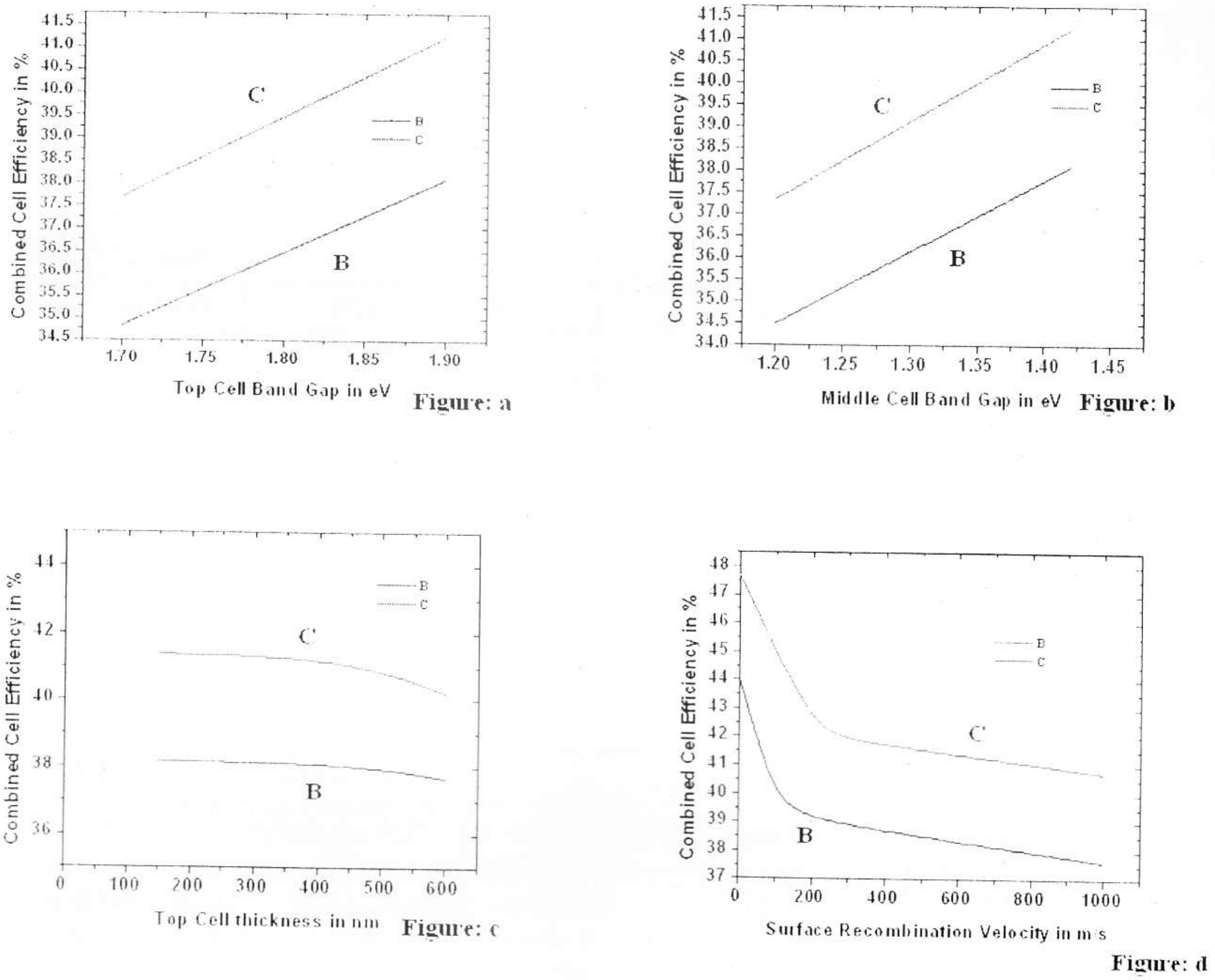

Figure: a **Figure: b** **Figure: c** **Figure: d**

Fig. 1: Fig: (a) Top cell band gap versus efficiency; (b) Middle cell band gap versus efficiency; (c) Top cell thickness versus combined cell efficiency are graphically shown; (d) Surface recombination velocity versus combined cell efficiency. [In the graphs (a, b, c, d) line 'B' is refers to AM1.5G and line 'C' is for AM 1.5D]

In this study we got six different surface recombination velocities in three different layers for electron and hole. In our treatment, we varied the top and middle cell surface recombination velocities, because bottom layers' velocities are very small with respect to the top and middle layer. From fig: (c) top cell thickness has been varied from 150nm to 600nm; efficiency decreased 38.13% to 37.47% for AM1.5G and 41.2% to 40.1% for AM1.5D respectively. From Fig: (d) surface recombination velocity has been varied from $0 ms^{-1}$ to $1000 ms^{-1}$ (as the velocities are approximately equal for electron and hole) efficiency is decreased 44.02% to 37.62% for AM 1.5G and 47.69% to 40.74% for AM 1.5D respectively. Moreover it is found that more the absorption coefficient more the photon energy will be absorbed. In the series connected multijunction cell, the series resistance decreases the short circuit current which in turn increases the open circuit voltage.

5. Conclusion

The theoretical efficiencies of $GaInP_2$ /GaAs/Ge solar cell have been worked out for AM1.5G and AM1.5D under one sun condition respectively. The effects of bandgap, top cell thickness and surface recombination velocity have been elucidated and it could be concluded that thinning the top cell thickness and increasing the bandgap, the efficiencies of the solar cell could increased. Other material combinations like $GaInP_2$ /GaAs/ GaAsBi could also be studied to improve the efficiency.

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