GE05

Study on the Efficiency of the $GaInP_2$/GaAs/Ge Multijunction Solar Cell

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***Abstract*— In this paper, theoretical efficiency has been calculated for multiple junction solar cells for air mass 1.5 global spectra by using the spectral p-n junction model. This efficiency depends on the incident spectrum, bandgap, temperature of cells. Here $GaInP_2$ has been used as the top cell, GaAs as the middle cell, Ge as the bottom cell .To produce optical transparency and maximum current conductivity between top and bottom cells, these three materials are lattice matched. Using the mathematical formulation by Matthias et al and studying the properties of $GaInP_2$, GaAs and Ge the theoretical efficiency for the triple junction solar cells have been estimated 41.8%. Developments of the cell at different stages and future prospects for the realization of super-high-efficiency and low-cost multijunction solar cells are also discussed.**

INTRODUCTION

Single-junction solar cells are limited in efficiency. The maximum theoretical limit depends on the incident spectrum. If a high band gap is chosen to obtain a high voltage cell, the current is low because most of the solar spectrum is sub-band-gap light, and, therefore, is not absorbed. If the band gap is decreased so that most of the spectrum is absorbed, then the voltage of the cell is decreased. Tandem solar cells can provide higher efficiency. Here we report the theoretical efficiency of a series connected multijunction solar cell with optimized cell thicknesses. Reduction of top-cell thickness results in significant increase in the efficiencies for a range of band-gap combinations. The primary increase in efficiency results from an increase in current as the top-cell thickness is optimized. For ideal cell (i.e, cells with low surface recombination velocities) the thinner top cells also lead to increased open circuit voltages, resulting in even greater improvements in the efficiencies. Selection of top cell materials is important for high efficiency tandem cells. $GaInP_2$ as a top cell material (lattice-matched to GaAs), $GaInP_2$ has some advantages such as lower interface recombination rate, less oxygen problem and good window layer material compared to AlGaAs. Top cell characteristics depend on the minority carrier lifetime in the top cell layers. The lower surface recombination rate is obtained by introducing AlInP window layer and the highest minority carrier lifetime is obtained by introducing a buffer layer and optimizing the growth temperature.

METHODOLOGY

The calculations assumed zero losses from reflection, grid coverage and series resistance. The short-circuit current density J_{sc} was calculated directly from the irradiance data [1]. The photon flux F is calculated from the irradiance I and wavelength.

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

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

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, was calculated for each cell as the sum of the currents for the n-type and p-type layers [2].

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

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

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

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

Where N_c and N_v are the densities of state in the conduction and valance band, E_g is energy 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 & the excess energy (> E_g) is wasted as heat.

Then total current density

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

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

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

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

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

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

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

Thus the equation for maximum voltage is

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

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

And the equation for maximum current density is

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

Efficiency of solar cell is

$$\eta = \frac{V_{oc} \times I_{sc} \times F.F.}{P_{in}} \times 100\% \quad (14)$$

RESULT

The theoretical solar cell efficiency has been calculated. Wet consider the total input power density is 1000 W/m ^{2} for the AM1.5 global spectrum at 298K temperature It has been calculated the short-circuit current is 16mA/cm^2. The calculation assumed zero losses from reflection, grid coverage, and series resistance. It has been calculated that the maximum theoretical efficiency of GaInP$_2$/GaAs/Ge multijunction solar cell is 41.8%.

Table I. Material parameters for Solar cells

Parameter	Top Cell GaInP$_2$	Middle Cell GaAs	Bottom Cell Ge
M_c	1	1	1
M_v	3	1	1
μ_e	4000 (cm^2/Vs)	8500 (cm^2/Vs)	3900(cm^2/Vs)
μ_h	200 (cm^2/Vs)	400 (cm^2/Vs)	1900(cm^2/Vs)
m_e^*/m_e	0.155	0.067	1.64
m_h^*/m_e	0.460	0.473	0.28
τ_{SRH}	10^{-5} (s)	10^{-5} (s)	10^{-5} (s)
B	7.5×10^{-10}(s^{-1}cm^3)	7.5×10^{-10}(s^{-1}cm^3)	7.5×10^{-10}(s^{-1}cm^3)
N_A	10^{17}/ cm^3	10^{17} /cm^3	10^{17} /cm^3
N_D	2×10^{18}/ cm^3	2×10^{18}/ cm^3	2×10^{18}/ cm^3
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^{-9} m

Table II. The result is given below

Junction	Bandgap (E_g)	Leakage current (J_0)	Open-circuit voltage(V_{oc})
Top cell (GaInP$_2$)	1.90 eV	(1.02×10^{-24}) mA/cm^2	1.49V
Middle cell (GaAs)	1.42 eV	(1.69×10^{-17}) mA/cm^2	1.06V
Bottom cell (Ge)	0.67 eV	(5.49×10^{-3}) mA/cm^2	0.21V

PERFORMANCE ANALYSIS

The efficiency of the series-connected multijunction cell under irradiance spectra air mass (AM) 1.5 global has been calculated as 41.8%. The efficiency of a solar cell depends on the incident spectrum, the temperature of the cell, and the irradiance or concentration of the light [3]. In a multijunction solar cell, by splitting the spectrum in parts and directing each to a solar cell with a suitable bandgap, the efficiency of the energy conversion can be increased. The same task is done by semi-transparent reflectors to materials with different bandgaps [4]. The effect of using different materials properties for calculation of J_o and absorption co-efficient (α) of the top cell is considered. For the detailed design of solar cells in the tandem structure the absorption coefficient has also to be taken into account to determine the dimensions and doping of the solar cells. For lower surface velocities, the V_{oc} increases as the p layer is thinned. However, it should be noted that the V_{oc} is expected to decrease as the cell is thinned when the surface-recombination velocity is high. The same is equally applicable to n-type material if all subscripts are replaced appropriately. For a serial two-terminal tandem system the short-circuit currents of cells has to be matched for higher efficiency. The optimal top-cell thickness would achieve for the current-matched condition at the maximum-power point, rather than under short-circuit conditions as we have calculated. The series resistance of a solar cell depends on the junction depth, impurity concentration of p-type and n-type regions and the arrangement of the front-surface ohmic contacts [5]. However this series resistance decreases the short circuit current but here open circuit voltage (V_{oc}) is also increased so the efficiency is a trade-off. The reverse saturation current density (J_o) depends on the bandgap and the temperature. If the temperature is increased reverse saturation current density is also increase. The concentrator configuration focuses multiple times the intensity of the sun on the solar cells and concentrator thin-film multi-junction solar cell is fabricated on inexpensive substrates such as Si and polycrystalline material for realizing (with efficiency more than 30%) and low cost cells if one can reduce the dislocation density to less than 5 ~ 10^5 cm^{-2} and increase the grain size to more than 0.1 cm [6]. To estimate realistic tandem solar-cell performance the efficiency calculations are carried out with added optical losses, which reduce the short circuit current and electrical losses, which reduce the generated, middle and bottom cells.

Table III. Summary of research activities of III−V compound multijunction solar cells in the world

Solar cells	Condition	Efficiency	Organization	Year
GaInP/GaInAs/Ge (ATJ)	AM AM0,1sun, 0.1353 W/cm2, 28°c	27.5%	EMCORE	2001[7]
GaInP/GaInAs/Ge (CTJ)	AM1.5D,1 sun	35%	EMCORE	2002[8]
GaInP/GaInAs/Ge	AM1.5D, LM,lowAOD,66suns,0.26cm2	35.2%	Boeing-Spectrolab	2003[9]
GaInP/GaInAs/Ge	AM1.5D, MM,low AOD,175 suns, 25°c	36.9%	Boeing- Spectrolab	2004[10]
GaInP/GaInAs/Ge	AM1.5D, 236 suns(=23.6W/cm2), AM 1.5D,low AOD spectrum 0.2691cm2 aperture area, 25°c ±1°c	39%	Boeing-Spectrolab	2005[11]
GaInP/GaInAs/Ge	AM1.5D, MM, 179 suns,low AOD	39.3%	Boeing-Spectrolab	2006[12]
GaInP/GaInAs/Ge	AM1.5D, MM, 240x conc (=24 W/cm2),25°c ,low AOD	40.7%	Spectrolab	2007[13]
GaInP/GaInAs/GaInAs	inverted growth (↓), MM,325.7xconc (~326 suns),0.1 cm2, 3-different lattice constant	40.8%	NREL	2008[14]
GaInP/GaInAs/Ge	AM 1.5D, MM, 299x conc (Spectrolab),454x conc (Fraunhofer) ASTM G-173-3	41.1%	Spectrolab, Fraunhofer	2009[15]
GaInP/GaInAs/Ge	AM1.5D,LM,364.2suns=36.42W/cm2(~364x conc), 0.3174cm2 designated area, 25°c, ASTM G-173-03 spectrum	41.6%	Boeing-Spectrolab	2009 [15,16

[Note: MM: Metamorphic, LM: Lattice Match]

CONCLUSION

We have calculated the theoretical efficiencies of multijunction solar cells with top cell thicknesses optimized to achieve current matching. Thinning the top-cell thickness in some cases resulted in large increases in the calculated efficiencies. In cases of low surface recombination velocities the V_{oc} is also increased when the top-cell was thinned. The basic physics for multijunction solar cell was discussed. Present status of these cells was discussed along with its present status.

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