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Performance Comparison of Si and InGaN p-n Junction Solar Cell

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Abstract— Solar cell is a device which converts solar energy (light-photon) into electricity and is so termed as Photovoltaic device. In this paper, the effect of material parameters on the efficiency of Si(low band gap material) and InGaN(wide band gap material) p-n junction solar is investigated and the results due to these two cells are compared. InxGa1−xN has a direct bandgap span from the infrared (0.69 eV) for InN to the ultraviolet (3.4 eV) of GaN. The efficiency of Si (EG=1.1 eV) , is compared with the efficiency of InGaN (EG=2.66 eV) solar cell. With the help of drift- diffusion model , optimized thicknesses and doping concentrations, the maximum efficiency values are calculated for InGaN and for Si solar cell. The bandgap parameter versus fill factor/open circuit voltage (Voc)/Short circuit current (Jsc) and power conversion efficiency (PCE) are calculated and is considered for evaluation on MATLAB. The solar cell performance is determined by its parameters, viz.,short circuit current density (Jsc), open circuit voltage (Voc), fill factor (FF) and efficiency (Z). In addition to theoretical results, the experimentally determined performance parameters of silicon solar cells in comparison with InGaN are determined.

Index Terms— Band Gap**,** Fill Factor, Matlab, Maximum Power, Open Circuit Voltage, Photovoltaic Effect, Shockley Queisser Efficiency Limit , Short Circuit Current.

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1 INTRODUCTION

The photovoltaic solar cell has become a popular green/clean source energy source. However, the power conversion efficiency of conventional and commercially available solar cells is still very low. To be competitive with the conventional energy source the efficiency of photovoltaic cell still remains a big challenge. Photovoltaic energy conversion relies on the number of photons striking the earth (photon is a flux of light particles) .On a clear day, about 4.4 x 10^17 photons strike a square centimeter of the Earth's surface every second. Only some of these photons - those with energy in excess of the band gap - can be converted into electricity by the solar cell.

Researchers are making lot of effort in studying on both new technologies to improve the efficiency of single junction solar cells and new solar structures which are able to absorb a larger part of solar spectrum. Si is the most popular material for single junction solar cell production since it has a developed technology due to other electronic applications. The highest efficiency reported for Si single junction solar is 27.6% under 100 sun concentrations [1]. GaAs single junction solar cell whose highest reported efficiency is 29.1% under 117 sun is a direct band gap material that is popular for especially space applications [2].

In order to use solar spectrum more efficiently, multi-junction, intermediate and thermo photovoltaic solar cell structures were proposed [3].

In this study Si and InGaAs single junction solar cells which are used as the bottom cell of triple junction solar cells are investigated [4]. Most common approaches to model a p-n junction solar cell are detailed balance model (DBM) and drift-diffusion model (DDM). DBM proposed by Shockley and Queisser in 1961 is used to calculate the efficiency limit of the cell if the band-gap is known [5]. In this model the one sun efficiency limit of a single junction cell is found as 33.7% for EG=1.4 eV under some certain assumption. To have more realistic results DDM is preferred which includes the material parameter effects as doping concentrations, carrier mobility etc. In this study, both DBM and DDM calculations are carried out under AM1.5 illumination for Ge and InGaAs p-n junction solar cells whose bandgap values are close to each other.

1.1 Literature Survey

The table 1 shown below enlists the research work done by other researcher's in this topic.

TABLE 1

LITERATURE SURVEY

	Title	Author	Year	Features
1.	Comparison of Ge, InGaAs p-n junction solar cell	M. Korun, T.S. Navruz	2016	The effective paramters of Ge and InGaAs have been compared.
2.	Efficient silicon solar cell with	James Bullock,	2016	There is a marked

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	dopant-free asymmetric heteroconatcts.	Mark Hettick, Jonas Geissbuhler, Alison J. Ong, Thomas Allen, Carolin M. Sutter-Fella		increase in the solar cell efficiency which provides increased cost to performance ratio.
3.	Progress in Indium Gallium Nitiride Materials for Solar photovoltaic energy conversion	Dirk V.P. McLaughlin, Joshua M.Pearce.	2013	There is a great potential of $\text{In}_x\text{Ga}_{1-x}\text{N}$ in photovoltaic industry in future.
4.	High internal and external quantum efficiency InGaN/GaN solar cells	Elison Matioli, Carl Neufeld, Michael Iza, Samantha C. Cruz, Ali A. Al-Heji, Xu Chen, Robert M. Farrell, Stacia Keller, Steven DenBaars, Umesh Mishra, Shuji Nakamura, James Speck, Claude Weisbuch	2011	The most of the absorbed photons of light are converted into holes and electrons due to high measured IQE.
5.	Growth and characterization of InGaN for photovoltaic devices	C. Boney, I. Hernandez, R. Pillai	2010	The photoresponse of InxGa1-xN devices with x up to 0.54 is attained with respect to turn-on energies below 2.0 eV.
6.	InGaN/GaN multiple quantum well solar cells with long operating wavelengths	L.W. Wu, Q.K. Xue R.Dahal, B.Pantha, J.Li, J.Y. Lin, H.X. Jiang	2009	Fill Factor is nearly 60%
7.	Fabrication & characterization of InGaN p-i-n homojunction solar cell	Xiao-mei Cai, Sheng-wei Zeng, Bao-ping Zhang	2009	At the band edge, there is a high efficiency of absorption of InGaN which makes it useful in absorbtion of light with minimum layer thickness
8.	High quantum efficiency InGaN/GaN solar cells with 2.95eV bandgap	Carl J. Neufeld, Nickholas G. Toledo, Samantha C.Cruz, Michael Iza, Steven P. DenBaars, Umesh K.	2008	Alloys of InGaN have high energy radiation resistance suitable for PV applications and have peak internal quantum efficiency Ni of 94%.
9.	Modelling of InGaN/Si tandem solar cells	Lihua Hsu, W. Walukiewicz	2008	These are the most efficient solar cells which are so formulated to have high thickness from a factor of 40 by using internal reflections

2 SOLAR PHOTOVOLTAIC CELL

2.1 Working of Solar Cell-PN Diode

As the photons from light energy of sun smashes off loose electron of Si the electric field created drives the electron in orderly manner resulting electric current to flow.The solar cell works in several steps:

- Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon.
- Electrons are excited from their current molecular/atomic orbital. Once excited an electron can either dissipate the energy as heat and return to its orbital or travel through the cell until it reaches an electrode. Current flows through the material to cancel the potential and this electricity is captured. The chemical bonds of the material are vital for this process to work, and usually silicon is used in two layers, one layer being bonded with boron, the other phosphorus. These layers have different chemical electric charges and subsequently both drive and direct the current of electrons.
- An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.
- An inverter can convert the power to alternating current (AC).

2.2 Effect of Band-gap on p-n junction Solar Cell

In physics, the electrons of insulators, metals and semiconductors lies within the a few energy bands and are held by the atomic forces and electrons cannot lie in any other region. The term band gap can be defined as the difference between the bottom level conduction band and the top level valence band. The materials at an absolute zero, having the smaller band gap are referred as the insulator but the materials which allow the transportation of electrons due to excitation from valence band to conduction band are referred as semiconductors. When an external force is applied such as photons of sunlight, the electrons get excited and lifted from one band to another.In physics, the electrons of insulators, metals and Below given table 2 represents the band gaps in electron volts (eV) of different materials at temperature 300 degrees kelvin (81°F).

TABLE 2

BAND GAP OF DIFFERENT MATERIALS

Material	Symbol	Band Gap (eV)
Silicon	Si	1.11
Cadmium telluride	CdTe	1.49
Cadmium selenide	CdSe	1.73
Copper oxide	CuO	1.20
Gallium arsenide	GaAs	1.43
Indium phosphide	InP	1.35
Selenium	Se	1.74

2.3 Ideal Solar Band Gaps

The main reason behind the inefficiency of solar cell is that the photovoltaic cells are not responsive to the overall spectrum of sunlight. The photons of energy having the band gap less than the silicon will not be absorbed the cell and simply pass through the cell. Due to this the 18% of the light is being wasted which is striking the cell. The photons with energy above the bandgap also get wasted in the form of heat or light and contributes to the overall 49% of the wastage of the light. Hence 67% of the sunlight is being wasted and only 33% sunlight is utilized to generate electric current.

3 METHODS

P-N junction solar cells can be implemented using two approaches: detailed balance and drift-diffusion. These approaches are discussed below:

3.1 Detailed Balance Model

The detailed balance model was given in 1961 by Shockley and Quiesser [5]. This model is used to determine the maximum solar cell efficiency. In this model, the mobilities of all the carriers are supposed to be infinite and it is also assumed that each absorbed photon of light generate an electron-hole pair. The radiative recombinations are only being considered.

Current voltage variation of a solar cell is given as below [6]:

$$J(V)=JSC + J\ dark(V)$$

Here, JSC is short circuit current density which is obtained when the solar cell is illuminated under the condition of short circuit. Jdark (V) is the radiative recombination current density changing with cell voltage under dark condition. Short circuit current, JSC and open circuit voltage, Voc and efficiency, η and fill factor, FF values are calculated from this variation.

$$\eta = Pm/Pi$$

$$FF = Pm/JSCVOC$$

Where Pm is maximum output power and Pi is the incident power density.

3.2 Drift-Diffusion Model

For the computation of the p-n junction, the Continuity equations and the drift-diffusion current are used [6]. The drift-diffusion model, the drift current is prominent in the depletion region and the diffusion current is prominent in p and n sides and the electric field outside the depletion region is supposed as zero. On using the diffusion current equation into continuity equations [6]. The following given equations are attained on n and p sides of the cell.

The ten equations are:

Charge density equation (1)

$$\rho = q(p - n + N_d^+ - N_a^-) \quad (1)$$

Electric field and potential equations (2) and (3)

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon} \quad (2)$$

$$\frac{d\phi}{dx} = -\mathcal{E} \quad (3)$$

Carrier density equation (4) and (5)

$$n = n_i e^{(F_n - E_i)/kT} \quad (4)$$

$$p = n_i e^{(E_i - F_p)/kT} \quad (5)$$

Drift and Diffusion current equations (6) and (7)

$$J_n = qn\mu_n\mathcal{E} + qD_n\frac{dn}{dx} \quad (6)$$

$$J_p = qp\mu_p\mathcal{E} - qD_p\frac{dp}{dx} \quad (7)$$

Continuity equation (8) and (9) in steady state with SHR recombination

$$0 = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{np - n_i^2}{n + p + 2n_i\cosh(\frac{E_t - E_i}{kT})}\frac{1}{\tau} \quad (8)$$

$$0 = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{np - n_i^2}{n + p + 2n_i\cosh(\frac{E_t - E_i}{kT})}\frac{1}{\tau} \quad (9)$$

4 I-V CHARACTERISTICS OF SOLAR CELL

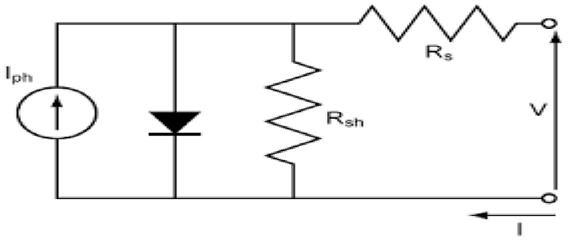

Fig. 1 Equivalent circuit of solar cell

The incident light and the operating point of the solar cell are the two main parameters on which the I-V characteristics of the solar cell depends. When a p-n junction solar cell [7] is illuminated, and when the external circuit is set to be short circuit then the current in the cell is because of the EHPs of the light as represented in Fig. 1. This current is known as the photocurrent (Iph) or the short circuit current (Isc). By definition of current, this is opposite to the photo current and is related to the intensity of the incident radiation, Iop, by

$Isc = -Iph = -kIop$

But when a voltage is applied on the external load which is given by V = IR. This voltage reduces the built-in potential as well as the barrier for the current carriers at the junction. Similarly in forward biased p-n junction, the current is increased on the external biased. This current opposes the photocurrent of the device and called the drift current. The diffusion current is caused due to the minority charge carrier. Hence, the net current is given as

$I = -Iph + Id$

$Id = Is0\, [\exp(eV/kBT) - 1]$

$I = -Iph + Is0\, [\exp(eV/kBT) - 1]$

Where, Id is the forward bias current and Is0, reverse saturation current, and external voltage, V.

When there is no light, the dark characteristics is same to that of I-V characteristics of p-n junction. The photocurrent (Iph) and the open circuit voltage can be calculated by the equations

$Iph = Is0\, [\exp(eVoc/kBT) - 1]$

$Voc \approx kBT/e \ln[Iph/Is0]$

When the value of flux of photon is high, the value of photocurrent is also high and hence, the Voc will also increase. The reverse saturation current for the p-n junction is given by

$Is0 = ni2\, [De/LeNa + Dh/Lh\,Nd]$

By selecting the material of high band gap, the reverse saturation current can be reduced due to which ni is also reduced. But due to this, the wavelength of the material which is absorbed is also decreased and this effect the reduction of Iph. The total power solar cell circuit power is given as

$P = IV = Is0V\, [\exp(eV/kBT) - 1] - Iph\, V$

In order to have maximum power, its derivative with respect to voltage must be zero. This gives a recursive relation in current and voltage.

$dP/dV = 0$

$Im \approx Iph\, (1 - kBT/eVm)$

$Vm \approx VOC - kBT/e \ln(1 + eVm/kBT)$

$Pm = ImVm \approx Iph\, [Voc - kBT/e \ln(1 + eVm/kBT) - kBT/e]$

The area related to Vm and Im gives the maximum power. Hence, it can be concluded that the maximum power is directly proportional to the Voc and can be enhanced by reducing the Is0 which means that high Eg and low ni are important the tradeoff is that less sunlight is absorbed as shown in Fig. 2.

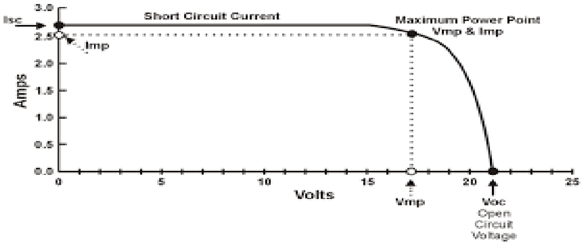

Fig. 2 Curve between Voc and Isc

4.1 Fill Factor

The Fill Factor (FF) of a solar cell can be estimated by comparing the maximum power to the theoretical power (PT) that can be the output together of short circuit current and open circuit voltage represented by a curve shown in Fig. 3.

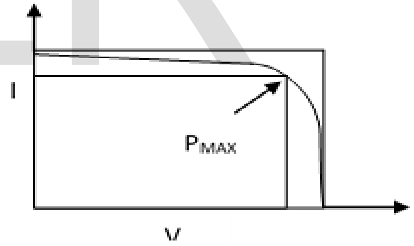

Fig. 3 Curve between V and I to obtain Fill Factor

4.2 Efficiency

The efficiency [8] of the solar cell can be defined as the fraction of maximum power to the input power and is given as:

Efficiency=Vmp*Imp/I*A1

Where Vmp = voltage at peak power,

Imp = current at peak power,

I = solar intensity per square meter,

A1 = area on which solar radiation fall

5 PRACTICAL IMPLEMENTATION OF SINGLE DIODE

When any current source is placed in parallel with diode, then this symbolizes the ideal solar cell. But on contrary, no photovoltaic cell is ideal and hence series and shunt resistances are placed in the model as shown in Fig. 4.

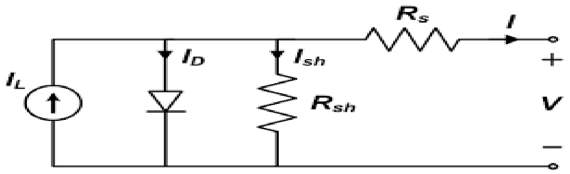

Fig. 4 Equivalent circuit of solar cell (single diode model)

RS is the intrinsic series resistance and RP is the equivalent shunt resistance which has a very high value. Applying Kirchoff's law to the node where Iph, diode, RP and Rs meet, and the equation is given as:

$Iph=Id+ Irp+ I$

We get the following equation for the photovoltaic current:

$I=Iph - Ibrp - Id$

$I= Iph - Irs [\exp ((V+I Rs) / VT) - 1]-[(V + I Rs) / RP]$

The photovoltaic cell is made up of collaboration of various units of larger modules called photovoltaic modules which are connected to each other in the series-parallel configuration. The PV mathematical can be given by the equation:

$I=Iph- Irs [\exp(q*v/K*T*A)-1]$

The cell reverse saturation current Irs varies with temperature according to the following equation:

$Irs=Irr[T/ Tr]^3\exp((q* Eg/ K*A)[1/ Tr-1/T])$

The temperature dependence of the energy gap of the semiconductor is given by

$Eg= Eg (0)-(ALPHA *T2)/(T+BETA)$

6 SIMULATION

Matlab code for Photovoltaic cell

```
clear all;
clc;
T=302;
Tr=298;
S=[100 80 70 50 40];
%S=70;
ki=0.00023;
Iscr=3.75;
Irr=0.000021;
k=1.38065*10^(-23);
q=1.6022*10^(-19);
VT=25;
A=2.15;
Eg=1.21;
V0=[0:1:300];
for i=1:5
Iph=(Iscr+ki*(T-Tr))*((S(i))/100);
Irs=Irr*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));
I0=Iph-Irs*(exp(V0)/(VT*A)-1);
P0 = V0.*I0;
figure(1)
plot(V0,I0);
axis([0 20 0 50]);
grid on
xlabel('Voltage open circuit (voc)in volt');
ylabel(' Short circuit Current(Isc)in amp');
title(' Isc VS voc curve');
hold on;
figure(2)
plot(V0,P0);
axis([0 20 0 80]);
xlabel('Voltage in volt');
ylabel('Current in amp');
title('Power vs voltage curve');
hold on;
grid on
figure(3)
plot(V0,I0,V0,P0);
axis([0 20 0 50]);
xlabel('Voltage & voc  in volt');
ylabel('Power in watt & Isc in ampere');
title(‘Pmax curve');
hold on;
grid on
figure(4)
plot(I0,P0);
axis([0 20 0 100]);
xlabel('Current in amp');
ylabel('Power in watt');
title('Power vs Current');
hold on;
grid on
end
```

7 RESULTS

In this study, Si and InGaN p-n junction solar cells are investigated using the detailed balance and drift diffusion approaches under AM1.5 spectrum and the results are compared. The optical and electrical parameters of Si and InGaN are taken from [9]. The detailed balance efficiencies of Si and InGaN p-n junction solar cells are obtained using real absorption coefficient values and including the effect of reflection due to refractive index differences. The results plotted on MATLAB considering various parameters are shown in Fig. 5-9.

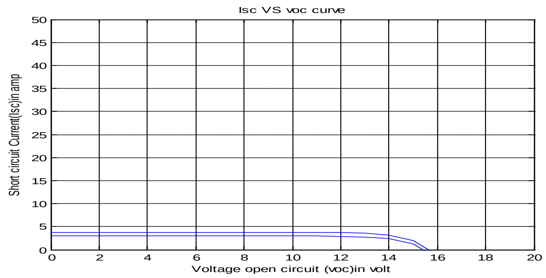

Fig. 5 Short circuit current and open circuit voltage curve

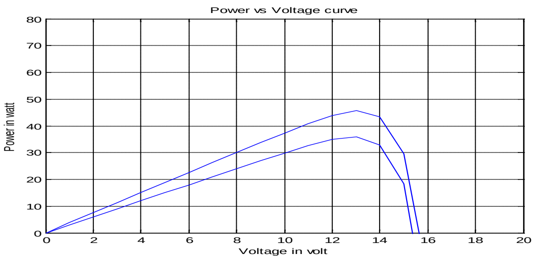

Fig. 6 Power Vs Voltage curve

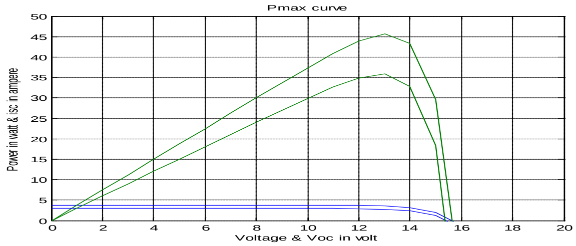

Fig.7 Maximum power curve

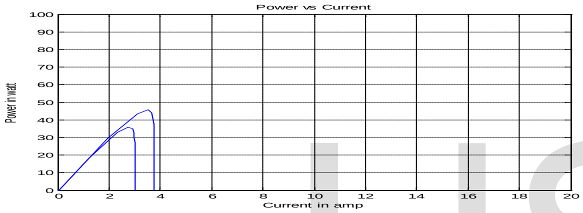

Fig. 8 Power Vs Current curve

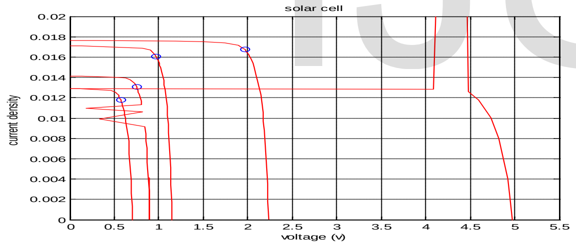

Fig. 9 Current Vs voltage

TABLE 3

COMPARISON RESULT CONSIDERING VARIOUS PARAMETERS FOR SI AND INGAN

Material	Pmax	Voc	Isc	Fill factor	Efficiency
IN20Ga80N	0.0329	2.2313	0.0176	0.8372	24.3181
IN57Ga43N	0.0155	1.1505	0.0171	0.7896	11.4895
IN68Ga32N	0.0098	0.8989	0.0141	0.7701	7.2253
IN78Ga22N	0.0068	0.7051	0.0129	0.7436	4.9924
Silicon s=100 (radiation)	52	15	3	260	52
s=80 (radiation)	39	15	4	6.25	48.7

The comparison table 3 above clearly shows if band gap is small then efficiency will be more as of silicon Eg is 1.1 ev efficiency obtained is 52 % under radiation of 100 w/m2 and as band gap increases the efficiency get reduce as seen in InGn EG=2.66 ev efficiency obtained is 24.3% .

8 CONCLUSION

At low band gap open circuit voltage is low and at higher band gap short circuit current is low. Theoretical calculation shows that the efficiency for a single band gap semiconductor is maximum 33% at a band gap 1.4 eV for AM1.5 solar spectrum. Hence it is mentioned that band gap for solar cells should be around 1.5 eV. While in case of multi-junction solar cell they act as bottom cells even to absorb the lower portion of energy of the entire solar spectrum. This study shows that the overall performance of the two solar cells is almost similar. The generalized form of solar cell has been developed and verified. The structure which is proposed in this paper consumes the solar radiation intensity and temperature of cell as input and provides I-V, P-V and P-I curve as output.

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