Comparison of Ge, InGaAs p-n junction solar cell

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Abstract. In this paper, the effect of material parameters on the efficiency of Ge and InGaAs p-n junction solar cells which are most commonly used as the sub-cell of multi-junction solar cells are investigated and the results due to these two cells are compared. The efficiency of Ge ($E_G=0.67$ eV) solar cell which is easy to manufacture and inexpensive in cost, is compared with the efficiency of InGaAs ($E_G=0.74$ eV) solar cell which is coming with drawback of high production difficulties and cost. The theoretical efficiency limit of Ge and InGaAs solar cells with optimum thickness were determined by using detailed balance model under one sun AM1.5 illumination. Since the band gap values of two cells are close to each other, approximate detailed balance efficiency limits of 16% for InGaAs and 14% for Ge are obtained. When drift-diffusion model is used and the thicknesses and doping concentrations are optimized, the maximum efficiency values are calculated as 13% for InGaAs and 9% for Ge solar cell. For each solar cell external quantum efficiency curves due to wavelength are also sketched and compared.

1. Introduction

The photovoltaic solar cell is becoming widespread and very important as a clean energy source for the earth. However, the 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 must be improved. Researchers are 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 concentration [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, multijunction, intermediate and thermo photovoltaic solar cell structures are proposed [3]. In this study Ge 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 bandgap is known [5]. In this model the one sun efficiency limit of a single junction cell is found as 33.7% for $E_G=1.4$ 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.
2. Methods

In this study, p-n junction solar cell is investigated using detailed balance and drift-diffusion approaches whose details are given in the following subsections.

2.1 Detailed balance model

The detailed balance model, proposed by Shockley and Queisser in 1961 [5], was used to calculate the potential maximum efficiency that can be provided by solar cells. In this approach, carrier mobilities are assumed to be infinite and each of the absorbed photon is assumed to produce one electron hole pair. Only radiative recombination is taken into account. Current voltage variation of a solar cell is given as below [6]:

\[ J(V) = J_{SC} + J_{dark}(V) \]  

Here \( J_{SC} \) is short circuit current density obtained when the cell is illuminated under short circuit condition. \( J_{dark}(V) \) is the radiative recombination current density changing with cell voltage under dark condition. \( J_{SC} \) is calculated as follows:

\[ J_{SC} = Xq\int (1 - R(\varepsilon))(1 - e^{-\alpha(\varepsilon)w})N_{ph}(\varepsilon)d\varepsilon \]  

Where \( X \) represents sun concentration, \( q \) is electron charge, \( R \) gives amount of reflection due to refraction index differences, \( \varepsilon \) is energy, \( \alpha \) is absorption coefficient, \( w \) is the thickness of the cell and \( N_{ph} \) is the number of photons incoming to cell surface per unit area per unit time. The dark current term in Eq. 1 is given as:

\[ J_{dark} = q\int \frac{2\pi}{h} \left( 1 - e^{-\alpha(\varepsilon)w} \right) (e^{\frac{\varepsilon - \Delta\mu}{kT_C}} - 1)d\varepsilon \]  

Here \( h \) is Planck’s constant, \( c \) is the speed of light, \( k_B \) is Boltzmann constant, \( T_C \) is cell temperature and \( \Delta\mu = qV \) is amount of quasi fermi level split where \( V \) is output voltage of the cell. Using equations 1-3 current-voltage variation is obtained. Short circuit current, \( J_{SC} \), open circuit voltage, \( V_{oc} \), efficiency, \( \eta \) and fill factor, \( FF \) values are calculated from this variation.

\[ \eta = \frac{P_m}{P_i} \]  

\[ FF = \frac{P_m}{J_{SC}V_{oc}} \]  

Where \( P_m \) is maximum output power and \( P_i \) is the incident power density.

2.2 Drift-Diffusion model in semiconductors

Continuity equations and drift-diffusion current equations are used to model p-n junction [6]. In this model the electric field outside the depletion region is assumed to be zero. Therefore diffusion current is dominant in n and p sides and drift current is dominant in the depletion region. Inserting the
diffusion current equation into continuity equations [6] the following equations are obtained for p and n sides of the cell.

\[
D_e \frac{d^2 \Delta n}{dx^2} - \frac{rg}{n_{eq}} \frac{\Delta n}{\tau_e} = -g_{eh} \tag{6}
\]

\[
D_h \frac{d^2 \Delta p}{dx^2} - \frac{rg}{p_{eq}} \frac{\Delta p}{\tau_v} = -g_{eh} \tag{7}
\]

Where, \(D_e, D_h\) are the diffusion coefficients of electrons and holes respectively. \(\tau_e, \tau_v\) are Shockley-Read Hall (SRH) recombination carrier lifetimes, \(n_{eq}, p_{eq}\) represent carrier concentrations under thermal equilibrium and \(rg\) is radiative recombination coefficient given as below.

\[
rg = \frac{2\pi}{h^3 c^3} \int_0^\infty \alpha_e(\varepsilon) \varepsilon^2 \exp(-\varepsilon/k_B T_C) d\varepsilon \tag{8}
\]

g_{eh} in equations 6 and 7 is photo generation rate given as below:

\[
g_{eh}(x) = \int (1 - R(\varepsilon)) \alpha(\varepsilon) N_{ph}(\varepsilon) \exp(-\alpha(\varepsilon)x) d\varepsilon \tag{9}
\]

Equations 6 and 7 are solved first under short circuit condition with appropriate boundary conditions and electron and hole concentration variations are obtained. These variations are used to calculate diffusion current contribution of p and n sides \((J_n = D_n d\Delta n/dx, J_p = -D_p d\Delta p/dx)\). Under dark condition dark current variation with the output voltage is also calculated. The photo and dark current contribution of the depletion region is given as below.

\[
J_{photo, dep} = -q \int_{w_n}^{w_p} (g_{eh}) dx \tag{10}
\]

\[
J_{dark, dep} = -q \int_{w_n}^{w_p} (-u_{rad} - u_{nr}) dx \tag{11}
\]

Here \(u_{rad}\) and \(u_{nr}\) are radiative and nonradiative recombination rates depending on output voltage. Summing the short circuit condition contributions of n side, p side and depletion region, total photo current of the cell is obtained. Similarly, total dark current is found by summing the dark current contributions of these three regions for varying values of output voltage. Finally, cell current-voltage variation hence \(J-V\) curve is obtained by subtracting the dark current from photo current and including the series \(R_s\) and shunt resistance \(R_{sh}\) effects [7]. \(J_{sc}, V_{oc}, FF\) and \(\eta\) values are obtained similar to DBM.

\(EQE\) curve is found from short circuit calculations [8].

\[
EQE = \frac{\text{electrons/sec}}{\text{photons/sec}} = \frac{J_{photo}(\lambda)}{qN_{ph}(\lambda)} \tag{12}
\]

Where \(\lambda\) is the wavelength and \(J_{photo}\) is the current density variation due to wavelength found by short circuit calculations.
3. Results and discussion

In this study, Ge and InGaAs 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 Ge and InGaAs are taken from [9].

3.1. Detailed Balance Approach Results

The detailed balance efficiencies of Ge and InGaAs p-n junction solar cells are obtained using real absorption coefficient values and including the effect of reflection due to refractive index differences. As seen from Fig. 1, limiting efficiency values of Ge and InGaAs cells are close to each other but Ge cell should be thicker with respect to InGaAs cell to achieve maximum efficiency.

![Figure 1. Detailed balance efficiency versus cell thickness for Ge and InGaAs cells](image)

The output parameters of both cells; $J_{SC}$, $V_{OC}$, $FF$, $w_{OPT}$ and $\eta$ are summarized in Table 1 when their efficiencies are maximum.

| Semiconductor | $J_{SC}$ (mA) | $V_{OC}$ (V) | $FF$ (%) | $W_{OPT}$ ($\mu$m) | $\eta$ (%) |
|---------------|---------------|---------------|----------|---------------------|-----------|
| Germanium     | 37.71         | 0.4980        | 80.36    | 3                   | 14.83     |
| InGaAs        | 40.88         | 0.4970        | 80.37    | 0.6                 | 16.014    |

3.2. Drift Diffusion Approach Results

Using drift diffusion equations given above, the efficiency variation of Ge and InGaAs solar cells with p type emitter thickness ($w_p$) and doping concentration ($N_A$) and n-type base thickness ($w_n$) and doping concentration ($N_D$) are investigated. For each cell, one of these parameters is changed while the others are kept constant at each simulation. Finally the optimum cell structures achieving maximum efficiency are obtained as seen in Table 2. InGaAs solar cell’s efficiency is slightly higher than Ge solar cell’s efficiency. Doping concentrations are nearly same but InGaAs solar is thinner with respect to Ge one.
Table 2. Optimum Ge and InGaAs solar cell structures and their output parameters

| Material     | $J_{SC}$ (mA) | $V_{OC}$ (V) | FF (%) | $W_N$ (µm) | $W_P$ (µm) | $N_A$ (cm$^{-3}$) | $N_D$ (cm$^{-3}$) | $\eta$ (%) |
|--------------|---------------|--------------|--------|------------|------------|-------------------|-------------------|------------|
| Germanium    | 35.75         | 0.3430       | 74.24  | 2.5        | 0.15       | $5 \times 10^{24}$ | $9 \times 10^{22}$ | 9.11       |
| InGaAs       | 39.94         | 0.3940       | 76.61  | 0.7        | 0.14       | $2 \times 10^{24}$ | $9 \times 10^{22}$ | 12.06      |

The J-V curve of the optimum cell structures given in Table 2 is shown in Figure 2.

Finally, external quantum efficiency curves for Ge and InGaAs solar cells are given in the Fig.3. Since the bandgap values are close to each other the EQE curves are also similar to each other.

![Figure 2. J-V curve of Ge and InGaAs solar cells](image)

![Figure 3. EQE curves of Ge and InGaAs solar cells](image)
4. CONCLUSIONS
Despite the close $E_G$ values, the maximum efficiency for Ge ($E_g=0.67$) is 9.11%, and maximum efficiency for InGaAs ($E_g=0.74$) is 12.26%. Ge and InGaAs do not give so high efficiencies when they are produced as p-n junction solar cells. But in multijunction solar cell structure they are used as bottom cell to absorb the low energy portion of the solar spectrum. In this study it is shown that these two materials show similar performance.

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