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Study the Effect of Varying the Thickness of Intermediate Band on the Intermediate Band Solar Cells Efficiency

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Abstract

In this paper we have implemented a model for the intermediate band GaAs solar cell. The model predicts an increase in the efficiency beyond the theoretical limit for a single-junction solar cell. The numerical results obtained from this modelling shows that the intermediate band solar cell has higher efficiency than the reference cell when only radiative recombination is included in the intermediate band material. Furthermore, we have investigated the role of concentrators on the solar cells efficiency, and have studied the effect of varying the intermediate band physical thickness on the intermediate band solar cells efficiency. The solar cell efficiency can be optimized by optimizing band gap for each intermediate band physical thickness.

Keywords: Intermediate band solar cell; Concentration factor; Absorption coefficient; Flat band region

1.Introduction

The third generation solar cells employ a novel concept as compared to the standard single junction solar cell (SC). The intermediate band (IB) solar cells utilize more of the incoming photons through using an intermediate band placed in the band gap between the conduction and valence band. The band gap of the semiconductor (E_G) is divided into two sub-bands gaps E_L and E_H.

To create an electron-hole pair by absorption of photons with energies less than E_G, two transitions are necessary. In one of the transitions an electron is transferred from valence band (VB) to the intermediate band. In the second transition the electron is transferred from intermediate band to conduction band (CB). In addition, direct transfer of an electron from VB to CB is also possible.

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IB band has to be partially filled with electrons in order to provide both empty states to accommodate electrons being transferred from the VB to IB band and filled states to release electrons being pumped into the CB. A fundamental condition in the theory of IB solar cells is that carrier concentration in each of the bands is described by its own quasi-Fermi level; F_P for holes in the VB, F_i for electrons in the IB and F_n for electrons in the CB.This condition is fulfilled when the carrier relaxation time within each band is much shorter than the carrier recombination time between bands [1].
The output voltage (V) of the cell is given by [2]:

$$qv=F_n-F_P \tag{1}$$

We see that the voltage does not depend on F_i . IB SCs absorb more photons than the standard solar cells, This leads to an increased photocurrent and thus provides a higher efficiency.

The solar cell absorbs sunlight only from a small angular range, and this can be increased by using concentrator based on lenses or mirrors. Light is thus collected over a large area and focused to a solar cell of smaller area. By using a ratio X between the collector and cell area the incident flux density is increased by a concentration factor equal to X.

In this paper, First we will describe a model which we implemented for IB SC based on GaAs. Matlab is used for simulation of the solar cell. In this study, only contribution from IB material is taken into account. In the next step we will discuss the effect of varying thickness of IB on the efficiency. Finally, we will also peresent the results for X=1000 (maximum concentration).

2. A simple Model for the intermediate band solar cells

In this section we present the model of IB SC based on the research used in [3]. The Model includes only the contribution from the IB layer and assumes that the width of the flat band region is equal to the thickness of IB layer for all voltage ranges.

Fig.1 shows the model for forward biased IB SCs.

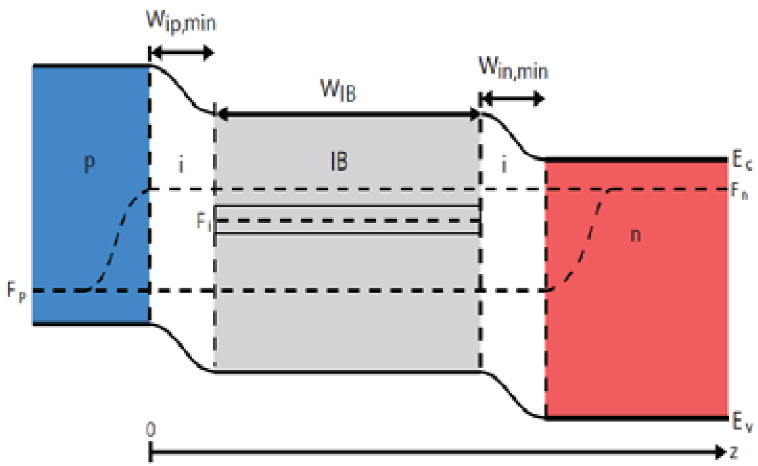

Fig.1. The structure for forward biased IB SCs used in the modelling, also shown the quasi-Fermi levels in this structure

The structure consists of an Upper p-layer, followed by an intrinsic layer with width $W_{ip,min}$. $W_{ip,min}$ is the minimum width of the depletion region between p and the intrinsic layers set by V_P equal to a voltage $V_{max,p}$ equal to the open-circuit voltage over the p-i junction. It is designed that most of the IB layer to be contained in a flat band region, Thus an intrinsic layer is employed. After the intrinsic layer of width $W_{ip,min}$ follows an IB material of width W_{IB} , a second intrinsic layer of width $W_{in,min}$ is employed. $W_{in,min}$ is the minimum width of the depletion region between n-layer and i-layer by setting V_n equal to a voltage $V_{max,n}$ equal to the open-circuit voltage over i-n junction. Finally the n-layer is placed below the intrinsic material.

2.1 IB SC with only radiative recombination in the flat band region

The electron and hole concentration in the conduction band and valence band are influenced by the presence of an intermediate band. *n* can be expressed as [4]:

$$n=n_{0,IB}e^{\mu_{CI}/k_BT} \quad (2)$$

And *p* can be expressed as:

$$p=p_{0,IB}e^{\mu_{IV}/k_BT} \quad (3)$$

Where $n_{0,IB}$, $p_{0,IB}$ is the equilibrium electron and hole concentration in the CB and VB respectively.

The introduction of an IB makes it necessary to consider the generation rates for VB to CB transitions G_{CV}(z), IB to CB transitions G_{CI}(z) and VB to IB transitions G_{IV}(z). The generation rates depend on the absorption coefficient (α) for the specific transition through the relations:

$$G_{CV}(z)=\int_{E_G}^{\infty}[1-R(E)]\alpha_{CV}(E)F(E)e^{-\alpha_{CV}(E)z}\,dE. \quad (4)$$

$$G_{CI}(z)=\int_{E_L}^{E_H}[1-R(E)]\alpha_{CI}(E)F(E)e^{-\alpha_{CI}(E)z}\,dE. \quad (5)$$

$$G_{IV}(z)=\int_{E_H}^{E_G}[1-R(E)]\alpha_{IV}(E)F(E)e^{-\alpha_{IV}(E)z}\,dE. \quad (6)$$

F(E) is the photons flux.The absorption coefficients for the different transitions are taken to be non-overlapping which gives the integration limits in equations (4-6).We omit the generation of charge carrier due to photon recycling in this model. Photon recycling is the process where photons generated by radiative recombination are reabsorbed in the material to generate charge carriers.

By having an intermediate band three radiative recombination processes are possible:

- Recombination between the CB and VB
- Recombination between the CB and IB
- Recombination between the IB and VB

The current-voltage characteristic of the solar cell is found by simultaneous solution of:

$$J=-\left(J_{np}(w_{ip})+J_{p,IB}(w_{ip})\right) \quad (7)$$

And

$$J=-\left(J_{pn}(w_{ip}+w_F)+J_{n,IB}(w_{ip}+w_F)\right) \quad (8)$$

For the current density together with the relation between the quasi-Fermi levels spliting given below:

$$\mu_{IV}(w_{ip})+\mu_{CI}(w_{ip}+w_F)=qV. \quad (9)$$

Where the J_{np} is the electron current density from the p-layer and the J_{pn} is the hole current density from the n-layer.

3. Results and discussion

In this section we give results from the modeling of IB solar cell. In this model the p- and n-layers are required to separate the electrons and holes to avoid recombination. Generation and recombination in these layers are set equal to zero. The width of flat band region is held constant with voltage and equal to the thickness of IB layer W_F=W_{IB}.

The material parameters used are given in Table1.

Table.1. material parameters taken from [4,5] for α

Band gap	E_L=0.57 ev, E_H =1.10 ev , E_G =1.67 ev
Thickness	W_{IB} =1.3µm
Mobility	$\mu_{n,f}$ =$\mu_{p,f}$=2000 $cm^2/$Vs
Absorption coefficient	α_{CI} = 4×10^4 cm^{-1} for $E_L < E < E_H$,else 0 α_{IV} =4×10^4 cm^{-1} for $E_H < E < E_G$,else 0 α_{CV} = 4×10^4 cm^{-1} for $E_G < E$,else 0
Sun temperature	$T_s = 6000k$
Cell temperature	$T_c = 300k$
Effective densities of states	$N_C = N_V = 5 \times 10^{18}\ cm^{-3}$
Concentration factor	X=1000

The thickness of the IB layer is $W_{IB} = 1.3\mu m$ is and the values of the band gap which provides the maximum efficiency for the maximum concentration [5]. This thickness has been optimized for the concentration X=1000. The mobility and effective density of states that shown in Table.1 are the values used for mobility and effective density of states in the VB and CB in the intermediate band layers.

The current-voltage characteristic obtained from our simulation by using these parameters is shown in Fig.2. The important parameters describing the solar cell behavior are given in Table 2.

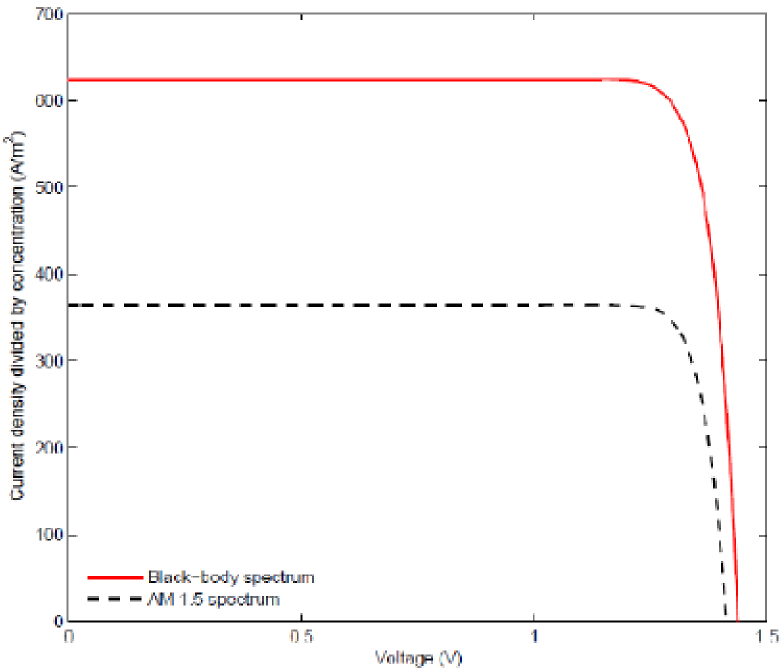

Fig.2. current-voltage characteristic for a concentration X=1000 obtained using black-body spectrum (red line) and AM 1.5 spectrum (dashed, black line)

As seen from Fig.2 the short-circuit current obtained from the modelling is much smaller when the black-body spectrum is incident on the solar cell. This is reasonable since the black-body spectrum has a larger intensity. The open-circuit voltage for the both cases is of the same order. The efficiency is 48.64% using the black-body spectrum with an incoming flux of 1596 W/m^2 and 45.34% using the normalized AM 1.5 spectrum with an incoming flux of 1000 W/m^2.

Table.2. parameters describing the behavior of an IB solar cell for a concentration X=1000 obtained using the black-body spectrum and the AM 1.5 spectrum.

Spectrum	$\frac{J_{sc}}{X}(A/m^2)$	$V_{oc}(V)$	$\eta(\%)$
Black-body	624.3	1.438	48.64
AM 1.5	364.6	1.414	45.34

The difference in efficiency using the two spectras is, however, dependent on the band gap in the solar cell [6]. The band gaps E_G =1.67 ev and E_H =1.10 ev are more suitable the black-body spectrum as compared to the AM 1.5 spectrum. The efficiency is therefore higher when the black-body spectrum is employed.

3.1 The effect of variation of thickness of the IB layer, Z_{IB} ,on the efficiency

As mentioned Photon recycling is not included in the models used in this paper. This means that the thickness of the IB layer has to be optimized [7]. Four different values of the thickness of the IB layer are used: $W_{IB} = 0.65\mu m$, $W_{IB} = 1.3\mu m$, $W_{IB} = 2.6\mu m$, $W_{IB} = 5.2\mu m$. For each case, the value of the band gap E_H is varied to obtain the highest efficiency. Only radiative recombination in the IB layer is included and concentration factors X=1000 is used.

For X=1000, the efficiency varies as a function of band gap E_H for the four thickness of IB layer as shown in Fig.3. The current-voltage characteristic using the optimum band gaps for each of the four thickness is shown in Fig.4. Important parameters describing the behavior of the solar cell are listed in table3.

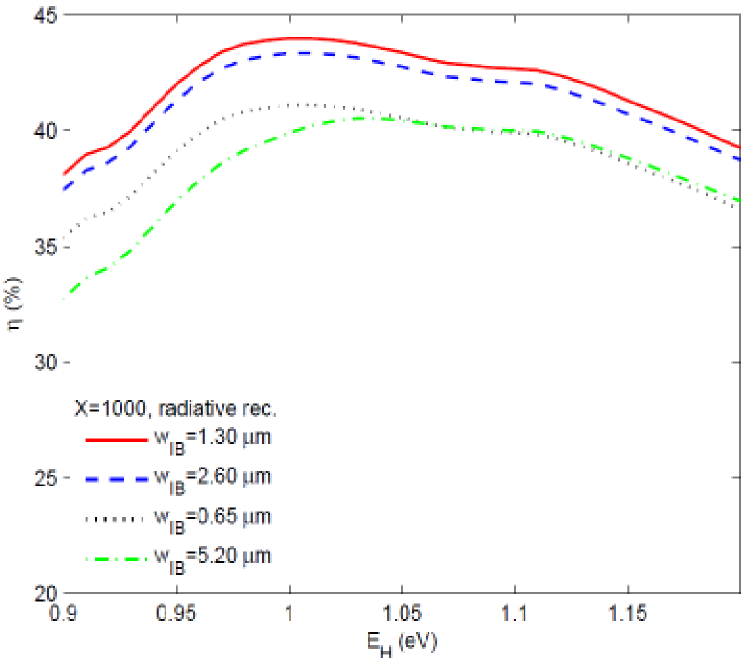

Fig.3. Efficiency as function of band gap E_H using four different thickness of IB layer

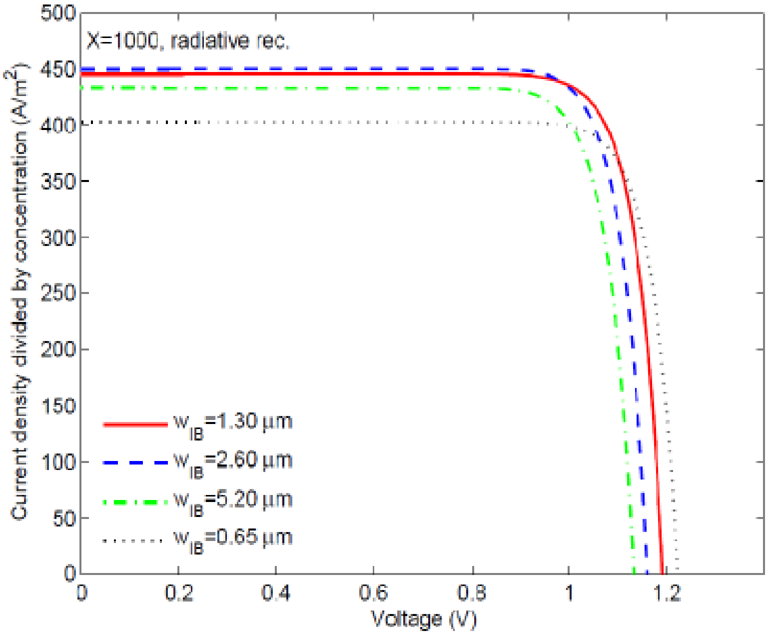

Fig.4. Current-voltage characteristic of an IB solar cell using four different thickness of the IB layer. The optimum band $E_H = 1.010\ eV$ for $W_{IB} = 0.65\mu m$, $E_H = 1.000\ eV$ for $W_{IB} = 1.3\mu m$, $E_H = 1.010\ eV$ for $W_{IB} = 2.6\mu m$ and $E_H = 1.030\ eV$ for $W_{IB} = 5.2\mu m$

Table.3. parameters describing the behavior of an IB solar cell for four different thickness of IB layer using the optimum value of E_H and X=1000.

$W_{IB}(\mu m)$	E_H	$\frac{J_{sc}}{X}(A/m^2)$	$V_{oc}(V)$	$\eta(\%)$
0.65	1.010	402.83	1.224	41.13
1.3	1.000	445.88	1.197	44.00
2.6	1.010	450.09	1.162	43.35
5.2	1.030	433.40	1.136	40.54

The highest efficiency 44% is obtained for W_{IB} =1.3μm and the band gap $E_H = 1.000$ eV. the IB layer is then wide enough to absorb lots of photons and at the same time is narrower than the electron and hole diffusion lengths, equal to $L_{n,IB}$ =11.1 μm and $L_{P,IB} = 4.1\mu m$ for $E_H = 1.000\ eV$. This gives high photocurrent. The dark-current increase with increasing thickness of the IB layer [8,9]. This is the reason for the decrease in open-circuit voltage with increase in thickness of IB layer. The increase of photocurrent is, however, higher than the increase of dark-current increasing W_{IB} from 0.65μm to 1.3μm. This gives a higher efficiency for W_{IB} equal to1.3μm than for W_{IB} equal to 0.65 μm. as expected, change in the band gap changes current density. For X=1000 the short-circuit current density is largest for $W_{IB} = 2.6\mu m$. The reason why the wider layer gives a higher current density for X=1000 is that for a higher concentration more photons are available for absorption and the layers can be wider. The decrease in open-circuit voltage leads, however, to a maximum efficiency for $W_{IB} = 1.3\mu m$ rather than for $W_{IB} = 2.6\mu m$.

4. conclusion

In this paper we have modelled intermediate band solar cells for concentration X=1000. The thickness of the intermediate band material and the values of the band gaps $E_L, E_H and\ E_G$ affect the current-voltage characteristic. We found optimum band gaps for different thicknesses of the intermediate band material. The results show that for a width of the intermediate band material equal to 1.3 μm and using GaAs as the barrier layers, GaAs gives the highest efficiency by using the value of E_H obtained from photoluminescense. The intermediate band layer used in the IB solar cell should be placed in the flat band region to obtain a high efficiency and should be then partially filled. Both the VB to IB and IB to CB transition are then present at the same time. The thickness of the IB layer should be thick to be contained in the flat band region to avoid the increase recombination in a wide layer. A greater band gap E_G gives less photocurrent, but a higher open-circuit voltage.

The type of recombination in the IB layer is important. In this paper only radiative recombination is considered. The positive effect of using of the light concentration is also shown. Using the optimum thickness and band gaps the efficiencies obtained for the solar cells for X=1000 are much higher than for X=1.One has to remember however, that series resistance increases for high concentration and high injection condition may arise. This is not included this model.

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