Performance Analysis of Impurity Photovoltaic Effect in Solar Cells

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***Abstract*—An investigation has been performed to study the Impurity Photovoltaic (IPV) effect in a double junction solar cell. Impurity has been introduced separately and simultaneously in the two sub-cells which have been found to increase the cell performance. Moreover, it is obtained that impurity incorporated in the sub-cell with the lower current has the dominant effect on improvement. Improvement in short circuit current, fill-factor and efficiency of the double junction cell have also been quantified to demonstrate the enhancement compared to the case of single junction cell. Thus, this study predicts an efficient approach of improving performance of multijunction cells.**

***Index Terms*—Efficiency, impurity photovoltaic, multijunction, short circuit current, single junction.**

I. Introduction

Solar cell serves as a promising source of renewable energy. But compared to the conventional ones, solar power is still not cost effective for implementing in power grid. To make it feasible as an alternative energy source, the performance of solar cell needs to be improved. For higher efficiency, the device structure design, novel materials, epitaxial layer quality improvement and device process of improving optical absorption properties are presented in literature [1]-[6]. In this regard, multijunction solar cells based on III–V compound semiconductors have received much attention in recent years because they can provide wide range absorption in the solar spectrum from visible to infrared and generate high conversion efficiency [1]-[3]. This can not be achieved with a single junction cell which has limited wavelength response specified by bandgap.

On the other hand, IPV effect suggests the incorporation of deep impurities into the cell, which creates a sub-gap energy level leading to photogeneration of captured carriers from the deep defect level into an allowed band. Then sunlight of a longer wavelength than that equivalent to the sub-gap will be utilized to improve the cell efficiency. Thus IPV also enhances the performance of a solar cell in a similar manner, i.e. by extending the accessible range of frequency of photons via the introduction of impurity [4]-[6]. IPV effect increases the short circuit current density (J_{sc}) but at the same time, it slightly decreases the open circuit voltage (V_{oc}). However, multijunction cells provide a key benefit with a high open circuit voltage as their subcell voltages are additive. But their short circuit current is limited by the junction or cell producing the lowest current [3]. In fact, for a given illumination concentration, the short-circuit current density decreases as the number of PV junctions in the system is increased [3]. So, current matching between component cells in a multijunction setup is a crucial concern.

IPV effect can be an effective solution to this problem. If impurity is introduced in the cell with the lowest current in a multijunction setup, it can increase the short circuit current of that particular cell. Although open circuit voltage is decreased slightly due to impurity, this reduction is compensated compared to improvement of short circuit current and hence, the overall performance of the cell is improved.

To date, several single junction cells have been reported [4]-[6] in literature to have improved performance through IPV effect. But, to the best of our knowledge, there has been no attempt yet to incorporate IPV effect in multijunction solar cells. In this work, we investigate the IPV effect in a two junction cell and found it to be improving cell performance. Moreover, short circuit current density, fill-factor and efficiency have been quantified to demonstrate the enhancement compared to the case of single junction cell. The software used for simulation is wxAMPS [7].

II. Modelling Process

The model applied to IPV effect is modified Shockley-Read-Hall (SRH) model [8]-[9]. For a solar cell with idealized light trapping, the net recombination rate U via impurity is given by [5]-[6]

$$U = \frac{np - \left(n_1 + \tau_{n0} g_{nt}\right)(p_1 + \tau_{p0} g_{pt})}{\tau_{n0}\left(p + p_1 + \tau_{p0} g_{pt}\right) + \tau_{p0}(n + n_1 + \tau_{n0} g_{nt})} \quad (1)$$

$$\tau_{n0} = \frac{1}{\sigma_n^{th} v_T N_t}, \quad \tau_{p0} = \frac{1}{\sigma_p^{th} v_T N_t} \quad (2)$$

$$n_1 = N_C e^{\frac{-(E_C - E_t)}{kT}}, \quad p_1 = N_V e^{\frac{(E_V - E_t)}{kT}} \quad (3)$$

$$g_{nt} = N_t \int_{\lambda_g}^{\lambda_{n,max}} \sigma_n^{opt}\left(x, \lambda\right) \phi_{ph}\left(x\ \lambda\right) d\lambda \quad (4)$$

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$$g_{pt} = N_t \int_{\lambda_g}^{\lambda_{p,max}} \sigma_p^{opt}(x,\lambda)\phi_{ph}(x\ \lambda)\,d\lambda \quad (5)$$

In the expressions, n and p are the electron and hole concentrations, τ_{n0} and τ_{p0} the lifetimes for electrons and holes, g_{nt} and g_{pt} the optical emission rates from the impurity for electrons and holes, n_1 and p_1 the electron and hole concentrations when the Fermi level coincides with the impurity level, N_t the impurity concentrations, v_T the thermal velocity, E_t the impurity energy level, σ_n^{th} and σ_p^{th} the electron and hole thermal capture cross sections, E_C and E_V the conduction and valence band edges, N_C and N_V the effective densities of states in conduction and valence bands, σ_n^{opt} and σ_p^{opt} the electron and hole optical emission cross sections of the impurity, $\phi_{ph}(x,\lambda)$ is the photon flux at depth *x* from the incident surface for the wavelength.

Since we have kept p type IPV layers, we will be using n type impurity. For GaP, Ge (doped in Ga) can act as an n type impurity which will form an impurity energy level 0.204 eV below the conduction band [10]. n_1 and p_1 in this case would be 8.188×10^{18} cm^{-3} and 6.78×10^{15} cm^{-3} respectively. For the particular composition of InGaAs used in this setup, most of the shallow n type impurity (such as Te, Ge, S) will form an energy level approximately 0.1 eV below the conduction band [12]. n_1 and p_1 in this case would be respectively 2.167×10^{17} cm^{-3} and 8.596×10^{15} cm^{-3} . For electron and hole optical emission cross sections of the impurity in both of the materials, a reasonable value of 8.188×10^{18} cm^{-3} has been taken. Both of the optical emission cross sections are assumed to be zero above bandgap energies [4].

For the single junction Silicon cell, Mg is used as donor type impurity with an impurity energy level 0.26eV below the conduction band as it gives best performance for Mg impurity in Silicon [5] and cell dimension in Fig 1 (b) is also used according to [5].

III. Results for Multijunction and Single Junction Cell

Fig. 1 shows the simulated structure of the double junction and single junction cell along with the respective layer type, thickness and doping concentration. In the III-V compound InGaAs, fraction of In is 0.2 and of Ga is 0.8. Top and bottom surface reflectivity have been kept respectively 0 and 1. Basic parameters used for the cell are taken from [5], [10]-[11]. All simulations were performed at 300K and under illumination of AM 1.5G, 100mW/cm^2. For double junction cell, at first, the simulation was done without impurity. Then impurity was added in IPV layers of GaP and InGaAs, separately and simultaneously.

n type GaP emitter layer, 0.005 μm, 1×10^{17} cm^{-3}
p type GaP IPV layer, 0.25 μm, 1×10^{16} cm^{-3}
p^+ type GaP base layer, 0.01 μm, 1×10^{17} cm^{-3}
p type GaP tunnelling layer, 0.001 μm, 1×10^{18} cm^{-3}
n type GaP tunnelling layer, 0.001 μm, 1×10^{18} cm^{-3}
n type InGaAs emitter layer, 1.0 μm, 1×10^{19} cm^{-3}
p type InGaAs IPV layer, 40 μm, 5×10^{18} cm^{-3}
p^+ type InGaAs base layer, 4.0 μm, 1×10^{19} cm^{-3}

(a)

Si n emitter layer- 1 μm, 1×10^{18} cm^{-3}
Si p IPV layer- 100 μm, 1×10^{17} cm^{-3}
Si p+ base layer- 5 μm, 1×10^{18} cm^{-3}

(b)

Fig. 1. Structure of simulated cell: (a) double Junction, (b) single Junction

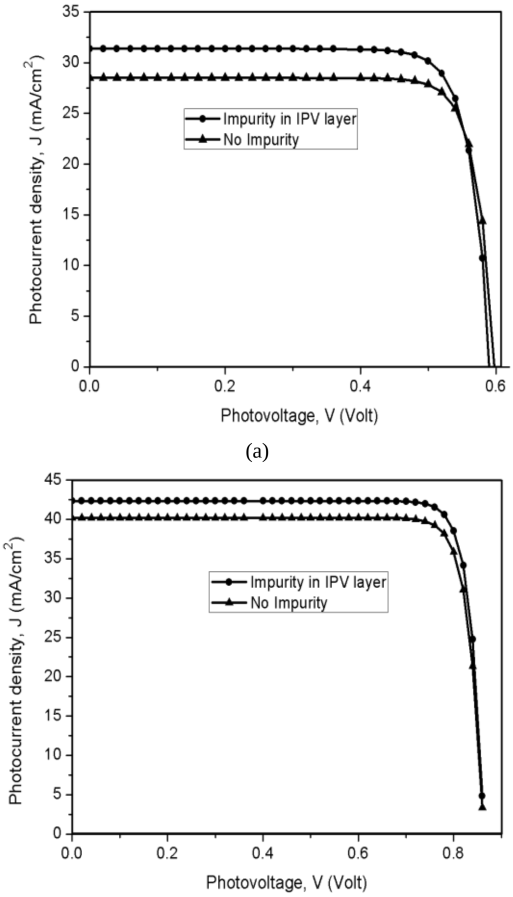
TABLE I: Performance of Solar Cells with Voc, Jsc, Fill-Factor and Efficiency

Solar Cell	Impurity	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η (%)
Single Junction	No impurity	0.597	28.51	82.75	14.096
	Impurity in Si	0.589	31.39	81.48	15.083
Double Junction	No impurity	0.862	40.20	86.07	29.83
	Impurity in GaP	0.86	40.07	86.63	29.91
	Impurity in InGaAs	0.863	42.48	86.04	31.54
	Impurity in both layers	0.862	42.35	86.70	31.66

Fig. 2 shows the I-V characteristics of the single junction cell without and with impurity and double junction cell without impurity and with impurity in both IPV layers. Table I shows the values of different performance parameters for both cells. For a single junction cell, when impurity is introduced, J_{sc} increases by 2.88 mA/cm^2 and efficiency η is improved by 0.986% compared to no impurity single junction cell.

However, for double junction cell, the effect of impurity is greatly dependent on the sub-cell where impurity is introduced. For impurity introduced only in GaP cell, short circuit current density J_{sc} is 40.07 mA/cm^2 and efficiency is

29.91% which results in a minor improvement of η by 0.08% compared to the conventional no impurity double junction cell. But for impurity only in InGaAs with the same concentration, J_{sc} and η show an improvement of 2.28 mA/cm^2 and 1.71%. The best case of increase of η over no impurity double junction cell is found to be 1.83% when impurity is introduced in both the IPV layers with the same concentration, along with a J_{sc} increase of 2.15 mA/cm^2.



(a)

(b)

Fig. 2. Effect of IPV in Solar Cell: (a) single Junction, (b) double Junction

Moreover, fill-factor has also increased significantly when impurity is incorporated in both IPV layers of double junction cell although it reduced slightly in single junction cell by impurity inclusion. The results, therefore, demonstrate that double junction solar cell exhibits quantitative improvement in Jsc, η and fill-factor with impurity inclusion in IPV layers which is comparable to or in most of cases, higher than single junction counterparts.

It has been stated before that the short circuit current in a multijunction cell is determined by the sub-cell producing the lowest current [3]. It is apparent from the results that in this case, InGaAs is that sub-cell. That is why impurity introduced in GaP does not result in any significant improvement.

IV. Conclusion

This work presents a numerical study carried out to investigate the effect of impurity in double junction solar cells which has been found to improve cell performance in terms of short circuit current and efficiency. Impurity introduced in the sub-cell with the lower current has been found to have dominant impact on cell performance. With impurity in both sub-cells, an increment of 1.83% in efficiency is obtained from that of without impurity. Change in cell performance with impurity incorporation has been greater than single junction cells in most of cases. Thus, IPV effect reveals an effective approach to improve multijunction solar cell performance.

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