Study of Impurity Photovoltaic Effect with Different Doping Materials using SCAPS Simulator

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Abstract- To improve conversion efficiency for crystalline silicon solar cells, impurity photovoltaic (IPV) effect has been proposed as an approach for application of new concept solar cell. In this paper, we have carried out a comparative study of IPV solar cells doped with thallium, indium and vanadium. The potential of the IPV solar cell is investigated with different doping materials. It is found that an increase of 2.72%, 2.95% and 3.81% for conversion efficiency can be obtained by indium, thallium and vanadium impurities respectively by the IPV effect. The influence of the light trapping on the IPV solar cell performance is discussed. It is found that cell efficiency can increase by about 2.88% due to the IPV effect. In addition, light trapping has very important impact on the IPV solar cell property. A good light trapping should be required to obtain better device performance for IPV solar cells.

Index Terms- Conversion efficiency, impurity photovoltaic effect, light trapping, SCAPS Simulator, silicon solar cell.

I. INTRODUCTION

The impurity photovoltaic effect (IPV) has attracted much attention as an approach to improve solar cell performance by introducing sub-band gap absorption mechanisms [1–3]. It can be exploited by intentionally adding impurities, acting as defect levels lying deeply within the forbidden gap. Photons having energies below the band gap Eg of the host material can excite electrons and holes from the defect to the conduction and valence band, respectively, thereby increasing the short-circuit current Jsc of the solar cell: this is called IPV effect. It is however also recognized that the deep defect states also act as recombination centres and hence reduce the open-circuit voltage Voc [1].

The IPV concept was proposed by Wolf in 1960 [4] His idea was to use energy levels Et within the forbidden energy gap of the device to permit subband gap absorption by doping the material with suitable impurities. His results are very optimistic. In the begging of these studies (IPV studies) there was a considerable reservation over the benefit of the IPV effect. The IPV has been experimentally observed on silicon and other materials in several times. The impurity photovoltaic effect can, in principle, increase the conversion efficiency of a conventional single junction solar cell by the introduction of optically active impurities or defects into the device. However, the existence of energy levels within the semiconductor band gap is considered as a source of non radiative recombination (Shockley–Read–Hall (SRH) recombination) at the same time. This recombination can negate any benefits. To overcome these problems and to tip the scale in favour of IPV, many studies have been presented recently. In 1994, Keevers and Green [5] presented a new treatment of the IPV effect, in which they use deep level impurities for changing the balance in favour of IPV cells. Their calculations, showed a small efficiency increase in silicon solar cell doped with indium. Schmeits and Mani [6] confirmed numerically an improvement in solar cell performances was theoretically possible if the correct device structure was selected. They proposed a new structure (p+-n-n+) , where the n layer close to the contact is essentially free of deep defects safeguarding a reasonable value of the built-in voltage and the open circuit voltage.

In this work, we present a comparative study of the IPV effect in different impurity element doped crystalline silicon solar cells with SCAPS [7]. SCAPS is a one-dimensional solar cell device simulator, developed at ELIS, University of Gent, which is freely available to the PV research community. Here we have studied some impurity elements like indium, thallium and vanadium which have trap level Et-Ev , 0.157eV, 0.26eV and 0.36eV respectively.

II. THEORY OF IMPURITY PHOTOVOLTAIC EFFECT

In the Shockley–Read–Hall (SRH) recombination model, electron and hole transition through the impurity is governed by capture, thermal and optical emission of carriers. As illustrated in Fig. 1, the IB allows the absorption of sub-band gap photons: the absorption of photon hν1 pumps an electron from the valence band (VB) to the IB, while the absorption of photon hν2 causes an electronic transition from the IB to the conduction band (CB). The net recombination rate U via the impurity is given by [8,9]

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

$$\tau_{n0} = \frac{1}{c_n N_t} \quad \text{and} \quad \tau_{p0} = \frac{1}{c_p N_t} \tag{2}$$

$$n_1 = N_c e^{-(E_c-E_t)/kT}, \quad p_1 = N_v e^{-(E_t-E_v)/kT} \tag{3}$$

$$g_{nt} = N_t \int_{\lambda_n min}^{\lambda_n max} \sigma_n^{opt}(x,\lambda)\phi_{ph}(x,\lambda)d\lambda, \tag{4}$$

$$g_{pt} = N_t \int_{\lambda_p min}^{\lambda_p max} \sigma_p^{opt}(x,\lambda)\phi_{ph}(x,\lambda)d\lambda \tag{5}$$

where n_1 and p_1 are the electron and hole concentrations, σ_n^{opt} and σ_p^{opt} are the electron and hole photoemission cross-sections of the impurity. N_t is the density of the defect. Terms in g_{nt} and g_{pt} describe the IPV effect. In a Lambertian cell, the photon flux $\Phi_{ph}(x,\lambda)$ at a depth x for photon wavelength λ is given by the following equation:

$$\phi_{ph}(x,\lambda) = \phi_{ext}(\lambda)\frac{1+R_b e^{-2\alpha_{ext}(\lambda)(L-x)}}{1-R_f R_b e^{-2\alpha_{ext}(\lambda)L}} e^{-\alpha_{ext}(\lambda)x}, \tag{6}$$

where R_f and R_b are the internal reflection coefficients at the front and back surface of the cell, L is the total length of solar cell, and $\Phi_{ext}(\lambda)$ is the external incident photon flux. Eq.(6) and the parameters R_f and R_b describe the light trap of the solar cell.

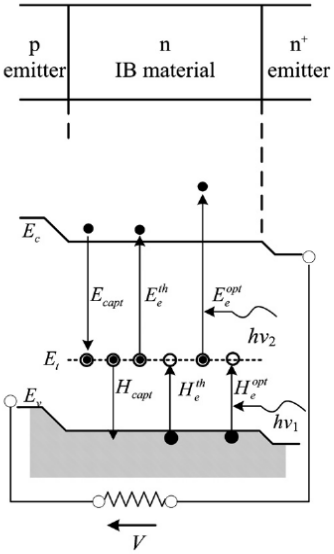

Fig. 1. *Illustration of the fundamental operation of the IPV solar cell.*

III. RESULTS AND DISCUSSION

A. Numerical model and parameters

Our structure is a crystalline silicon p+–n–n+ solar cell, where the indium impurity concentration is zero in the n+ layer. The corresponding thicknesses and shallow doping densities of the layers are respectively (2 µm, $N_A = 10^{18}$ cm^{-3}), (100 µm, $N_D = 10^{17}$ cm^{-3}) and (20 µm, $N_D = 10^{18}$ cm^{-3}). The parameters characterizing Si and the indium, thallium and vanadium impurities at 300K are summarized in Table 1.

Table 1: Basic parameters for the silicon solar cell used in this study

Properties	**Values**
Energy gap Eg	1.12 eV
Electron mobility μ_n	1350 cm^2/V s
Hole mobility μ_p	480 cm^2/V s
Dielectric constant ε_s	11.7

Energy level E_t-E_v : indium	0.157 eV
thallium	0.26 eV
vanadium	0.36 eV

The effect of location of deep level of impurities, its concentration and the light trapping on the solar cell performance were investigated. In ref. [10] Johan Verschraegen et al observed that efficiency is maximal when the impurity is at 0.20 to 0.25 eV for the silicon solar cell and at 0.30 to 0.35 for GaAs solar cell above the valence band (i.e. when the impurity located far from the middle of the band gap). To examine this we have plotted a calculated graph (using SCAPS simulator) of the conversion efficiency η as function of the energy level of the impurity $E_t - E_v$. for a Si solar cell (shown in fig 2).

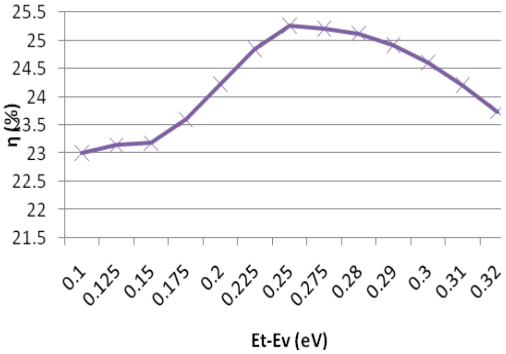

Fig. 2: *Calculation of the conversion efficiency η as function of the energy level of the impurity* $E_t - E_v$*. for a Si solar cell*

From the above figure we have seen that maximum efficiency can be observed for trap level near 0.25eV, this verifies Johan Verschraegen results.

B. Impurity concentration factor

On the basis of our structure of crystalline silicon p^+–n–n^+ solar cell, we have plotted simulation graphs between conversion efficiency and impurity concentration for different impurities as shown in fig 3.

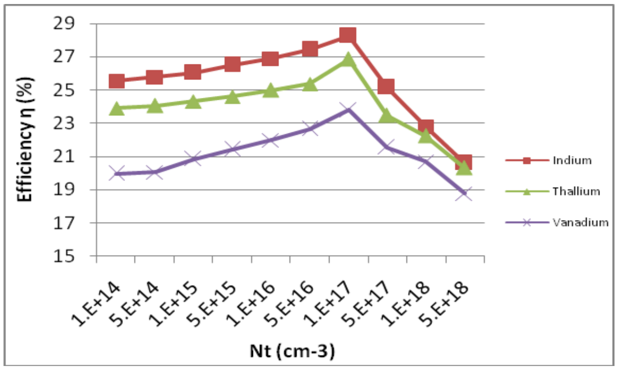

Fig 3: *Comparative study of conversion efficiency for indium, thallium and vanadium impurity as a function of Nt.*

In Fig 3, it can be seen that the highest efficiency was acquired at $N_t = N_D = 10^{17}$ cm^{-1}. The efficiency increases with increasing N_t only when $N_t < N_D$ after that it decreases rapidly. We found from fig.3 that the conversion efficiency increases from 25.55% to 28.27% with increasing the indium concentration N_t when $N_t < N_D$. The increase is resulted from improvement of short circuit current density and small decrease in open circuit voltage. The net gain in efficiency is 2.72% indicates an improvement of performance of solar cell doped with indium by IPV effect. Similarly, we found net gain in efficiency 2.95% and 3.81% for solar cell doped with thallium and vanadium respectively. Although we found maximum efficiency for indium impurity yet we have highest improvement in the efficiency for vanadium impurity.

C. Effect of light trapping

In SCAPS program, the degree of light trapping is adjusted by the internal reflection coefficients R_f at the front and R_b at the back of the cell. We varied the internal reflection coefficients to study the effect of light trapping on the IPV solar cell performance. As shown in Table 2, it is observed that a maximum efficiency of 26.85% can be obtained when R_f =0.9999 and R_b=0.9999. If $R_f = R_b = 0$ (i.e. no light trapping), a maximum efficiency of the solar cell is only 23.97%. This indicates that light trapping is very important for improving IPV solar cell performance. A good light trapping can make silicon solar cells effectively absorb those weak infrared lights since silicon is an indirect bandgap semiconductor. An effective way for obtaining a good light trapping is to use a Bragg reflector structure consisting e.g. of thin alternating layers of AlAs and (Al_xGa_{1-x})As. This structure was reported to “reflect nearly 100% of long-wavelength photons” [11].

Table 2: Effect of light trapping coefficient on the IPV solar cell performance.

R_f	R_b	V_{oc} (V)	J_{sc} (mA/cm^2)	η (%)
0.9999	0.9999	0.8084	42.47	26.85
0.999	0.9999	0.8084	42.457	26.83
0.999	0.999	0.8084	42.443	26.82
0.999	0.97	0.8077	42.038	26.60
0.99	0.95	0.8072	41.737	26.42
0.97	0.999	0.8079	42.111	26.65
0.93	0.999	0.8073	41.766	26.44
0.93	0.97	0.8069	41.511	26.28
0.95	0.90	0.8061	41.089	26.00
0.90	0.90	0.8057	40.883	25.87
0	0	0.8007	38.049	23.97

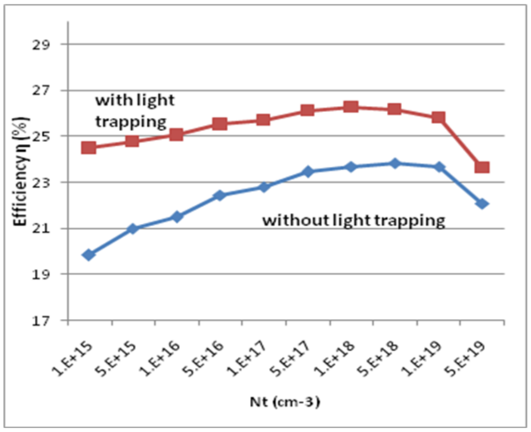

Fig 4: *Effect of light trapping on efficiency*

As shown in Fig. 5, the IPV effect causes the extension of the infrared response, especially 1000-1300 nm wavebands. The infrared extension comes from the sub-bandgap absorption in the solar cell. When the light trapping is better, the infrared extension is wider. From these facts, we can further confirm that the IPV effect with good light trapping should improve cell performance.

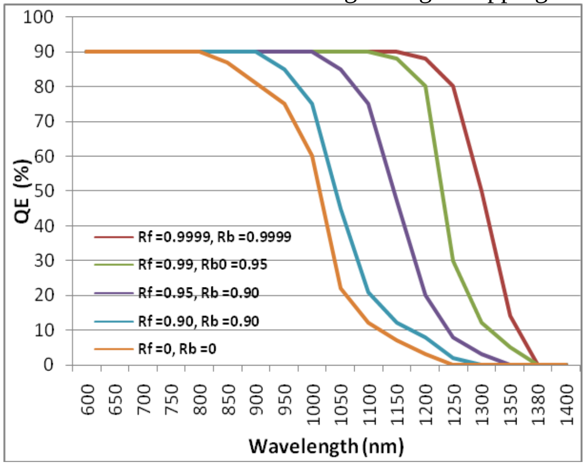

Fig 5 : *Effect of light trapping on sub-bandgap spectral response with* $N_t = 10^{17}$ cm^{-3} .

IV. CONCLUSION

A comparative study has been carried out to investigate the potential of the IPV effect in impurity-doped silicon solar cells. It is shown in fig 3, that an increase of 2.72%, 2.95% and 3.81% for conversion efficiency can be obtained by indium, thallium and vanadium impurities respectively by the IPV effect. A good light trapping is necessary to obtain a higher conversion efficiency (as shown in fig 4) for IPV solar cells. It is found that cell efficiency can increase by about 2.88% due to the IPV effect. The improvement of the IPV solar cell performance attributes to the extension of the infrared response shown in fig. 5. Our results indicate that the IPV effect in silicon solar cells doped with vanadium is a promising way for improvement of cell efficiency.

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