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Improving silicon solar cell efficiency by using the impurity photovoltaic effect

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Abstract

The necessity to find new forms of renewable energy is very important and urgent nowadays. The renewable sources of energy derived from the sun are one of the promising options. The photovoltaic cells as one of renewable energy sources have been largely studied in order to obtain cheap, efficient and secure PV cells. The conversion efficiency is the most important property in the PV domain. The most important aim of PV manufacturers is to reduce the price of the solar cells and increase their efficiencies above the Shockley Queisser limit. Third generation concepts have been studied recently in an attempt to improve solar cell efficiency above this limit. The impurity photovoltaic (IPV) effect is one of these concepts used to augment cell infrared response and therefore enhance cell conversion efficiency. The idea of the IPV effect is based on the insertion of deep defects in the solar cell. These defects provide a multistep absorption mechanism for sub-band gap photons to create new electron-hole pairs. In this paper we study numerically the potential of the IPV effect in crystalline silicon solar cell doped with a new IPV impurity. We investigate the effect of certain impurity and structure parameters on silicon solar cell characteristics such as short circuit current density J_{sc} , open circuit voltage V_{oc} , conversion efficiency and quantum efficiency QE using SCAPS simulator. We find that the incorporation of the IPV impurities into silicon solar cells can enhance spectral response, short circuit current density and conversion efficiency only under some conditions

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1. Introduction

The dominant loss mechanisms in conventional PV cells are the incapability to absorb sub band gap photons and thermalization of solar photons with energies exceeding the band gap energy. Third generation solar cells concepts have been proposed to tackle these two loss mechanisms. These concepts aim at using the complete spectrum by including novel mechanisms to create new electron hole pairs. The impurity photovoltaic effect (IPV) as one of these concepts is based on the inclusion of optically active impurities into the device. These defects create energy levels in the forbidden band which can create new free carriers by the absorption of low band gap photons. This effect can enhance IR response and improve solar cell performances. The IPV effect is largely studied numerically and theoretically in solar cells based on silicon [1-4], silicon carbide [5] and GaAs [6]. To significantly increase IR response by using the impurity photovoltaic effect, the challenge is to find the suitable impurity, structure and material. Ie to realize some strict necessities imposed either on the IPV impurity atoms or structure. Recently many works studied the ways to reach this goal. Kassai et al [7] showed that the IPV impurities must be located relatively far from the middle the band gap of the host material. Mid gap impurities have long been known to be responsible for non-radiative recombination and therefore work as recombination centers instead of useful impurities. Schmeits and Mani [2] confirmed that an improvement of crystalline silicon solar cell parameters is possible by choosing a structure with a BSF layer. Some theoretical and numerical calculations expected that high conversion efficiencies may be possible for wide band gap host material [5, 6].

Silicon doped with chalcogens can give a significant IR absorption [8]. This property renders Silicon very remarkable as possible candidate for below band-gap optoelectronic applications. Chalcogens atoms produce deep levels in the forbidden gap of silicon [9]. some researches suggest that, the presence of high concentration of substitutional chalcogens creates impurity bands within the silicon band gap. These bands can produce the observed broad sub-band-gap absorption [10-11]. Both selenium and sulphur incorporated into silicon lattice can enhance IR absorption making them of interest for applications in silicon solar cells [8,12]. Ref [12] demonstrated that the synthesis of selenium supersaturated silicon single crystal layers by pulsed laser induced mixing of evaporated thin selenium films on silicon wafers. Their optical characterization results, demonstrate that this material exhibits significant absorption in the IR range, with optical absorption coefficient ranging up to about 10^4 cm^{-1} . Ref. [8] Confirmed that the incorporation of sulphur impurities into silicon most possible creating bands of impurity levels in the forbidden band that can augment the creation of new carriers in microstructured silicon at infrared wavelengths near and below the band gap. Experimentally, Ref. [13] proved that the infrared photoresponse of silicon solar cells can be ameliorated by doping with optically active elements like Sulphur and some other elements. In this paper, we will incorporate selenium as new IPV impurities into silicon solar cell and study numerically the influences of IPV impurity concentration, the position of the energy level in the forbidden band and light trapping on solar cell parameters.

2. Theory

Keevers et al [1] presented theoretically a new treatment of the IPV effect in silicon solar cells based on modified Shockely Read Hall model for recombination through impurities. The recombination rate expression, is given by

$$U = \frac{np - n_1^* p_1^*}{\tau_{n0}(p + p_1^*) + \tau_{p0}(n + n_1^*)} \quad (1)$$

where n and p are the electron and hole concentrations respectively,

$$n_1^* = n_1 + \tau_{n0} g_{nt} \quad \text{and} \quad p_1^* = p_1 + \tau_{p0} g_{pt} \quad (2)$$

$$n_1 = N_c e^{\frac{-(E_c - E_t)}{KT}} \quad \text{and} \quad p_1 = N_v e^{\frac{-(E_t - E_v)}{KT}} \quad (3)$$

The n_1 and p_1 are the electron and hole concentrations after impurity doping. N_c and N_v are the effective densities of states in the conduction and valence bands. E_t is the impurity energy level, E_c and E_v are the conduction and valence band edge. τ_n and τ_p are the Shockely Read Hall (SRH) lifetimes for electron and hole concentrations after illumination and are given by

$$\tau_{no} = \frac{1}{\sigma_n v_{th} N_t} \quad (4)$$

and

$$\tau_{po} = \frac{1}{\sigma_p v_{th} N_t} \quad (5)$$

where σ_n and σ_p are the electron and hole capture cross sections, v_{th} is the carrier thermal velocity and N_t is the impurity concentration. g_{nt} , g_{pt} are the electron and hole optical generation rates respectively and they are given by

$$g_{nt} = N_t \int_{\lambda_{n \min}}^{\lambda_{n \max}} \sigma_n^{opt}(x, \lambda) \phi_{ph}(x, \lambda) d\lambda \quad (6)$$

and

$$g_{pt} = N_t \int_{\lambda_{p \min}}^{\lambda_{p \max}} \sigma_p^{opt}(x, \lambda) \phi_{ph}(x, \lambda) d\lambda \quad (7)$$

where σ_n^{opt} and σ_p^{opt} are the electron and hole photoemission cross sections of the impurity and $\phi_{ph}(x, \lambda)$ is the photon flux density at a depth x inside the lambartien cell and at wavelength λ . Moreover, $\phi_{ph}(x, \lambda)$ can be expressed as

$$\phi_{ph}(x, \lambda) = \phi_{ext}(\lambda) \frac{1 + R_b e^{-2\alpha_{tot}(\lambda)(L-x)}}{1 - R_b R_f e^{-2\alpha_{tot}(\lambda)L}} e^{-\alpha_{tot}(\lambda)x} \quad (8)$$

where $\phi_{ext}(\lambda)$ is the external incident photon flux. L is the total length of the cell. R_b and R_f are the internal front and rear reflectances respectively and $\alpha_{tot}(\lambda)$ is the total absorption coefficient. And is given by

$$\alpha_{tot}(\lambda) = \alpha_n(\lambda) + \alpha_p(\lambda) + \alpha_{fc}(\lambda) + \alpha_{e-h}(\lambda) \quad (9)$$

Where α_n and α_p are the absorption coefficients for electron and hole photoemission from the impurity level. α_{fc} is the absorption coefficient for free carrier absorption, α_{e-h} is the band to band absorption coefficient.

3. Numerical results and discussion

The solar cell structure used in this paper is an n^+-p-p^+ junction, consists of a thin n emitter ($0.3\mu m$), a P base region with thickness of $50\mu m$ and a P^+ layer with thickness of $1\mu m$ serving as a back surface field (BSF layer). The doping of n^+ , P and P^+ layers is fixed at $10^{18} cm^{-3}$, $10^{17} cm^{-3}$ and $10^{18} cm^{-3}$ respectively. The chalcogen impurities (Se in this case) were introduced into the base region. The values of front and back surface recombination velocities were taken $S_n = S_p = 10^4 cm/s$. The Selenium impurity concentration is varied to study its influence on our solar cell parameters such as V_{oc} , I_{sc} , η and QE. To study the role of light trapping on our parameters we will vary the values of the back and front reflectances. In this work, we use SCAPS simulator [14] developed at Elis University of Gent to calculate our parameters under standard illumination (AM1.5G, $100mW/cm^2$, 300K) and the Lucovsky model [15] is used to calculate the optical capture cross sections. Selenium in silicon is generally considered to form a donor level at 0.225 eV below the conduction band edge [16]. The main parameters used in this simulation are summarized in table 1[17-19]

The key parameter to realise a good IPV effect is the position of energy levels of the defect in the gap of the semiconductor. In ref. [20] the researchers observed numerically that the efficiency is maximal when the impurity is located between 0.20 to 0.25 eV for the silicon solar cell and at 0.30 to 0.35 eV for GaAs solar cell above the valence band. To examine the influence of the impurity energy level location

in the gap on the IR response, Figure 1 shows the quantum efficiency as a function of wavelength for different donor energy levels ($E_c - E_i$). In this calculation, both front and back reflectances (R_f and R_b) are taken close to unity and the impurity concentration is $8 \times 10^{16} \text{ cm}^{-3}$.

Table 1. Main parameters used for our simulation.

Property	Value
Si band gap energy (eV)	1.12
Dielectric constant	11.9
Electron mobility (cm^2/Vs)	1350
Hole mobility (cm^2/Vs)	480
Selenium energy level below the conduction band edge (eV)	0.225
Defect type	Donor
Electron thermal capture cross-section (cm^2)	10^{-13}
Hole thermal capture cross-section (cm^2)	10^{-23}
Electron effective mass	1.08
Hole effective mass	0.55
Refractive index	3.42

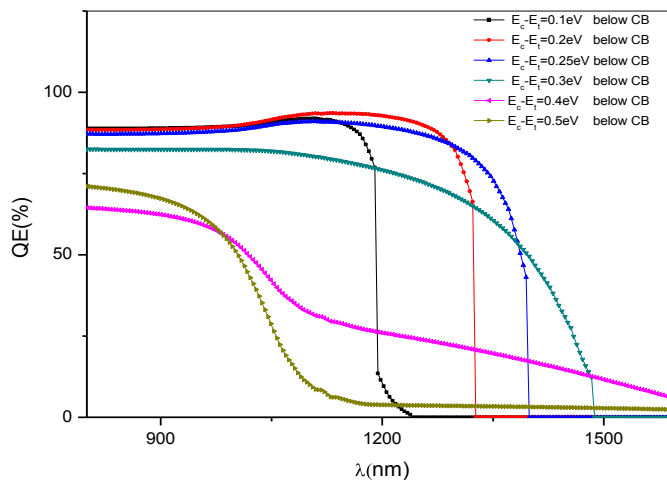


Figure 1 Quantum efficiency QE as a function of wavelength λ for different impurity energy levels $E_c - E_i$

From this figure, we show that the *IPV* effect can improve the IR absorption of silicon solar cells only when the energy level is located far from the middle of the band gap and the *IPV* effect extends the spectral response in the infrared range only for relatively deep defects between 0.1 to 0.3 eV above the conduction band and the best range is between 0.2 to about 0.3 eV from the conduction band edge. For the energy levels located near the middle of the band gap, we observe a severe degradation in QE parameter.

To study of the influence of impurity concentration N_t on our PV parameters, we vary the N_t values from 5×10^{15} to $1 \times 10^{18} \text{ cm}^{-3}$. Selenium impurities are incorporated into the base region of our solar cell. Figure 2 (a and b) shows that the short circuit current density and the conversion efficiency increase with increasing impurity concentration only when N_t is inferior than the base shallow doping N_a . The reason of this enhancement is that the lower concentration values can keep the selenium impurity level fully emptied which enhance the absorption in the IR region by the electron photoemission process from the valence band to the Se level and then increase cell efficiency and short circuit current. Inversely at larger impurity concentration, the efficiency and short circuit current density diminish with increasing impurity concentration in this case the photoemission process from the Se level to the conduction band is governed. This can lead to a decrease in these two parameters.

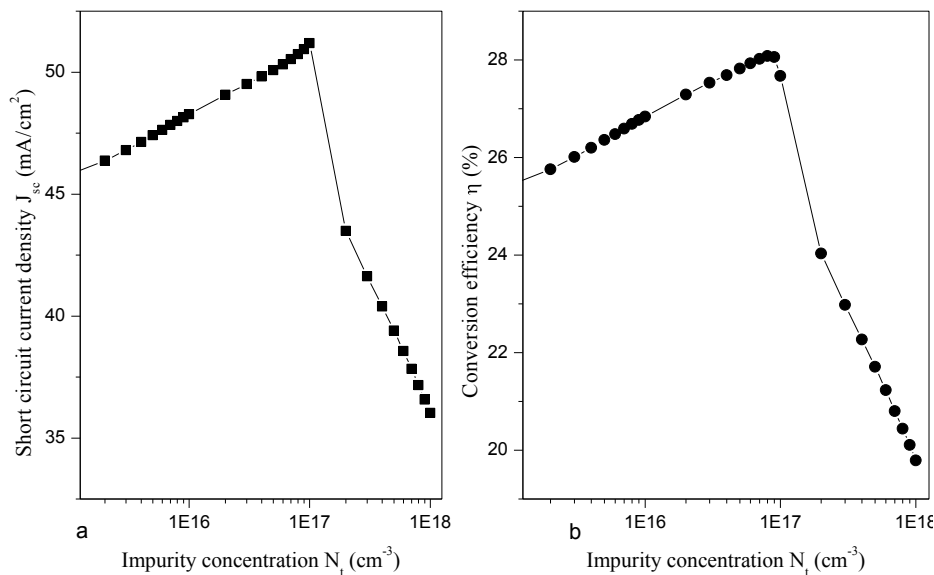


Figure 2. (a) Short circuit density J_{sc} and (b) conversion efficiency η of n^+-p-p^+ silicon solar cell as a function of selenium impurity concentration N_t

In Figure 3, we plot the open circuit voltage of the PV cell as a function of selenium concentration. From this figure, we notice that the open-circuit voltage remains constant when N_t is below the base shallow doping concentration and decreases with increasing impurity concentration. The choice of $n^+ pp^+$ structure with a BSF layer is behind its unchanged value when $N_t < N_a$. This structure

can keep reasonable values of the open-circuit voltage. The observed degradation when $N_t > N_a$ is because of the increase in the recombination through deep defects.

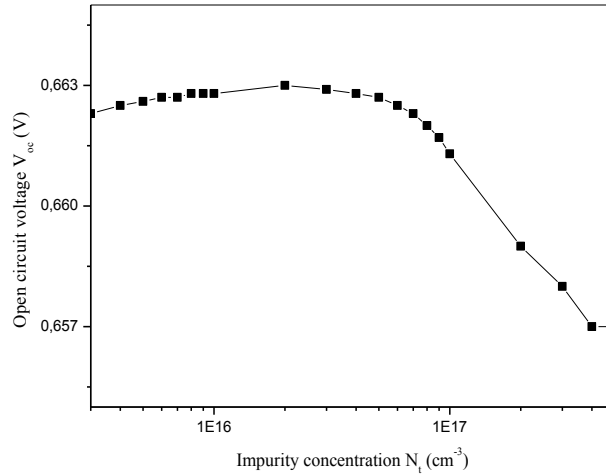


Figure 3: Open circuit voltage as a function of selenium impurity concentration for an ideal light trapping.

Silicon as indirect band gap material absorbs infrared light quite weakly and its thick layer does not absorb the long wavelength light in one pass through the wafer. This effect becomes more considerable for thinner layers. Light trapping can let light bounces up and down many times in the silicon layer, this can increase the optical path length. So, with light trapping, the penetration of infrared light will improve the role of the IPV effect which is based on the absorption of sub gap photons to create new e-h pairs. The internal reflection coefficients at the front and back surface of the cell (R_f and R_b) are used to express the effect of light trapping. In this part, three different light trapping values are considered ($R_f = R_b = 1$), ($R_f = 0.93$, $R_b = 0.97$) and ($R_f = R_b = 0.8$). The Selenium impurity concentration is taken equal to $9 \times 10^{16} \text{ cm}^{-3}$. From Fig. 4, it is found that an improvement in short circuit density is obtained for the perfect light trapping values ($R_f = R_b = 1$). For more real light trapping, we observe a degradation in J_{sc} . We conclude from these calculations that the excellent light trapping has an important role on observing a significant IPV effect.

Quantum efficiency QE is the most important parameter in solar cells domain. The increase in it is a good sign for improved carriers collection. The QE parameter can show us how photons of different wavelengths can contribute to the short circuit current. In this last part, Three different selenium concentrations are considered : $N_t = 0$ i.e without IPV effect, $N_t = 9 \times 10^{15} \text{ cm}^{-3}$ and $N_t = 9 \times 10^{16} \text{ cm}^{-3}$. The internal reflections are set to $R_f = R_b = 1$. From figure 5, we observe an extension of IR light between 800 to 1360 nm. This signify that a fraction of the short-circuit current of our cells is generated by sub band gap mechanism as a result of selenium doping.

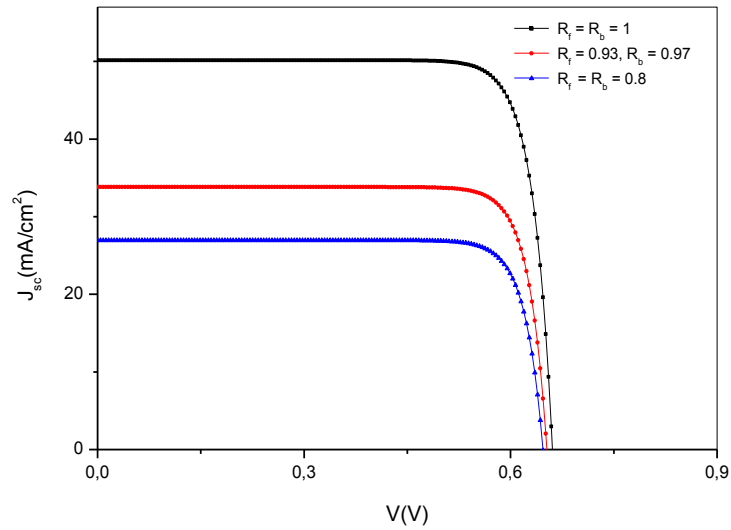


Figure 4 Current–voltage characteristics for the n+-p-p+ silicon solar cell with Se impurity concentration $N_t=9 \times 10^{16} \text{ cm}^{-3}$ and for different values of R_i and R_b .

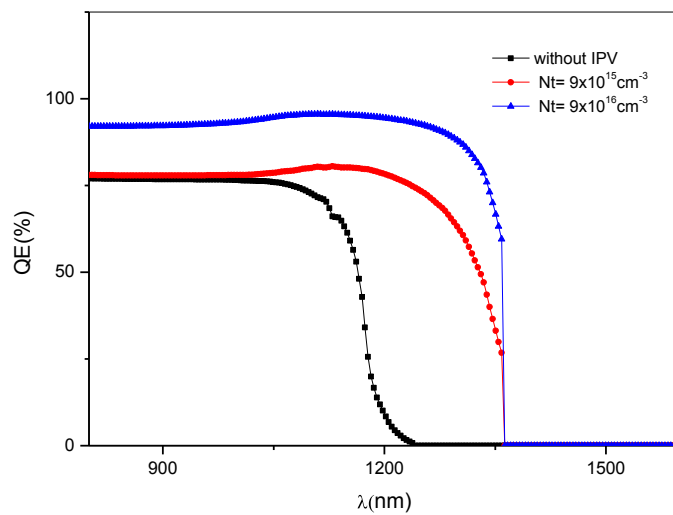


Figure 5 Quantum efficiency (QE) of Selenium doped Silicon solar cell with and without IPV

4. Conclusion

Using SCAPS simulator, Solar cell parameters versus Selenium concentrations are presented. The performance of the IPV solar cell under different internal reflectance values is examined. Our results

show that a significant progress can be noticed in the short-circuit current and efficiency when impurity concentration approaches the base doping concentration and the choice of a structure with a BSF layer can safeguard a reasonable value of the built-in voltage and the open-circuit voltage. The IPV effect needs higher values of the internal reflection coefficients to augment its role. The IPV effect using selenium impurities extends the spectral response in the infrared range especially from 800 to about 1360 nm.

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