Impurity photovoltaic effect in silicon solar cells doped with tellurium

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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 numerical study on the IPV solar cells doped with tellurium. The potential of the IPV solar cell is investigated. The influence of the light trapping on the IPV solar cell performance is discussed. It is found that cell efficiency can increase by about 3.0% 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.

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1. Introduction

Under the menace of energy crisis and environment pollution, solar cells are considered as one of the most promising technology for our future needs of clean and renewable energy. Silicon solar cells account for over 80% of the worldwide production of semiconductor solar cells [1]. Many approaches have been suggested to further increase the conversion efficiency of silicon solar cells for cost reduction [2-7]. The conversion efficiency of a silicon solar cell is mainly limited by the waste of the photons with energies less than the band gap [2]. While implementing the impurity photovoltaic (IPV) effect can utilize those lost photons [8-10]. Hence, the IPV effect may be a promising means to improve the cell efficiency. The mechanism of the IPV effect is to absorb sub-bandgap photons by introducing an impurity energy level in the semiconductor bandgap. This can enhance cell infrared response and improve cell performance. High efficiencies should be predicted for IPV solar cells. However, a challenge is to find a suitable impurity in silicon to create a good IPV effect. In this paper, we propose the tellurium (Te) impurity as a candidate used for IPV silicon solar cells. The potential of the IPV effect in silicon solar cells doped with Te is investigated by using the device simulator SCAPS [11]. The influence of the Te concentration and the light trapping coefficient on the cell performance is discussed. The quantum efficiency of the IPV cell is calculated to find the cause of efficiency change.

2. Methodologies

The operation principle of an IPV solar cell is shown in Fig. 1. Electron-hole pairs are additionally created by two-step absorption of infrared photons (shown on the left). That is, an electron is excited from the valence band to impurity level by sub-band photon $h\nu_1$. Then, the electron is excited from there to the conduction band by sub-band photon $h\nu_2$. If there is no IPV effect, electron-hole pairs are generated through absorption of photons with energy greater than the band-gap (shown on the right). A modified Shockley-Read-Hall model is applied for the presence of the IPV effect. The net recombination rate U via impurity is given by [8]

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

where n_1 and p_1 are the electron and hole concentrations when the Fermi level coincides with the impurity level, and

$$\tau_{n0} = \frac{1}{c_n N_t}, \quad \tau_{p0} = \frac{1}{c_p N_t} \quad (2)$$

$$g_{nt} = N_t \int_{\lambda_g}^{\lambda_{n,\max}} \sigma_n^{opt}(x,\lambda)\, \phi_{ph}(x,\lambda)\, d\lambda \quad (3)$$

$$g_{pt} = N_t \int_{\lambda_g}^{\lambda_{p,\max}} \sigma_p^{opt}(x,\lambda)\, \phi_{ph}(x,\lambda)\, d\lambda \quad (4)$$

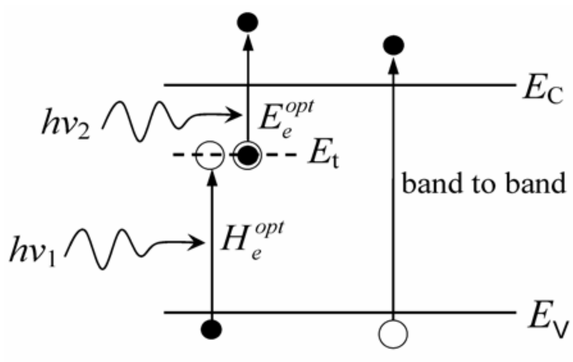

Fig. 1. The operation principle of the IPV solar cell.

where τ_{n0} and τ_{p0} are the lifetimes for electrons and holes, c_n and c_p the electron and hole capture coefficients, N_t the impurity concentrations, E_t the impurity energy level, g_{nt} and g_{pt} the optical emission rates from the impurity for electrons and holes, and σ_n^{opt} and σ_p^{opt} the electron and hole optical emission cross-sections of the impurity, respectively. In Eqs. (3) and (4), $\phi_{ph}(x,\lambda)$ is the photon flux at depth x from the incident surface for the wavelength λ and is given by

$$\phi_{ph}(x,\lambda) = \phi_{ext}\frac{1+R_b e^{-4\alpha_{tot}(\lambda)(L-x)}}{1-R_f R_b e^{-4\alpha_{tot}(\lambda)L}} e^{-2\alpha_{tot}(\lambda)x} \quad (5)$$

with

$$\alpha_{tot} = \alpha_{e-h} + \alpha_n + \alpha_p + \alpha_{fc} \quad (6)$$

where ϕ_{ext} is the external incident photon flux, R_f and R_b the internal reflection coefficients at the front and back surface of the cell, L the total length of the cell, α_{e-h} the band-to-band absorption coefficient, α_n and α_p the impurity absorption coefficients for electron and hole photoemission from the IPV impurity, and α_{fc} the absorption coefficient for free-carrier absorption, respectively.

The structure of the IPV Si solar cell is n^+-p-p^+. For the n^+ emitter layer, the thickness and doping concentration are d=1 μm and $N_D=10^{18}$ cm^{-3}, respectively; for the p base layer, d=100 μm, $N_A=10^{17}$ cm^{-3}; for the p^+ layer d=5 μm, $N_A=10^{18}$ cm^{-3}. The donor-type IPV impurity Te is assumed to be only contained in p base layer. The energy level of Te in Si is at 0.14 eV below the conduction band edge [12]. The electron and hole capture coefficients are set as 3.5×10^{-7} and 2.4×10^{-14} cm^{3}s^{-1} [12,13], respectively. Basic parameters used for the IPV Si solar cell at 300 K are listed in Table 1 [8,10,14]. The electron and hole photoemission cross-sections of the Te impurities are calculated in accordance with the model of Lucovsky [15]. σ_n^{opt} and σ_p^{opt} are assumed to be zero for the photons with energy above bandgap. The absorption of free carriers is ignored. The simulated illumination is AM 1.5G, 100 mW/cm^2. R_f and R_b are set to be 0.999 and 0.9999, respectively.

Table 1. Basic parameters for the silicon solar cell used in this study (at 300K).

Parameter and unit	Value
Energy gap (eV)	1.12
Dielectric constant	11.9
electron affinity (eV)	4.05
Effective conduction band density (cm^{-3})	2.80×10^{19}
Effective valence band density (cm^{-3})	2.65×10^{19}
Electron mobility (cm^{2}V^{-1}s^{-1})	1350
Hole mobility (cm^{2}V^{-1}s^{-1})	450
Surface recombination velocity (cm/s)	10^4
Tellurium energy level E_C-E_t (eV)	0.14
Refractive index	3.42
Effective mass of electron (m_e^*/m_0)	0.26
Effective mass of hole (m_h^*/m_0)	0.69

3. Results and discussion

3.1 Effect of tellurium concentration

Fig. 2 shows the short-circuit current density as a function of the Te impurity concentration. It can be seen that the short-circuit current density increases from 40.27 to 45.65 mA/cm^2 with increasing the tellurium concentration N_t when $N_t \le N_A$. This is due to the fact that the tellurium level is fully emptied so that sub-bandgap photons can be absorbed by the electron photoemission process from the valence band to the tellurium level. When the tellurium impurity concentration N_t is larger than the doping concentration N_A, the short-circuit current density decreases. The overcompensation of the tellurium impurity for the base doping makes electron photoemission from the tellurium level to the conduction band maximized. This reduces the photon flux ϕ_{ph} available for the electron photoemission process from the valence band to the tellurium level and results in the decrease of the short-circuit current density.

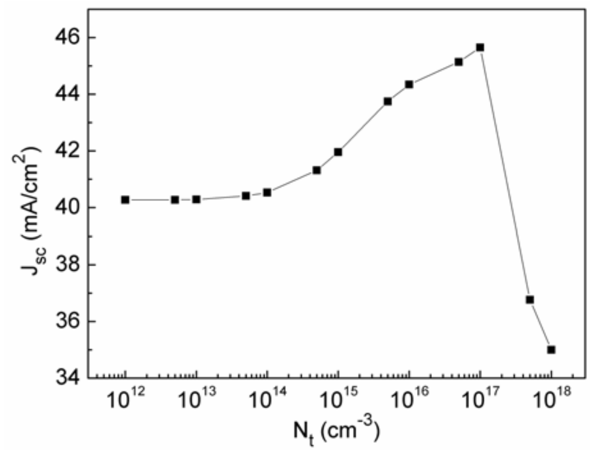

Fig. 2. Short-circuit current density as a function of the Te impurity concentration.

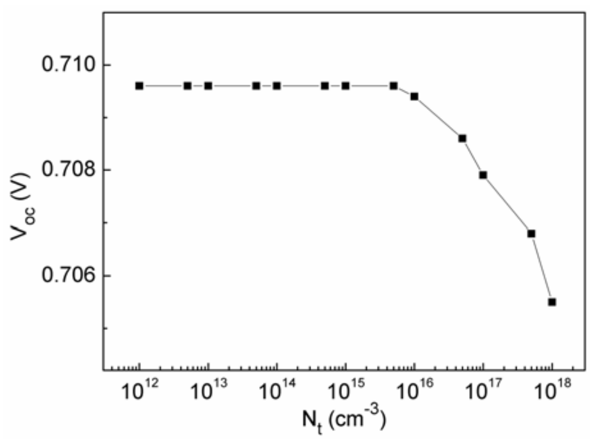

Fig. 3. Influence of Te impurity concentration on the open-circuit voltage.

Fig. 3 illustrates the influence of Te impurity concentration on the open-circuit voltage. It can be found that the open-circuit voltage decreases slightly. This attributes to the special cell structure n^+-p-p^+, which can keep a high value for the built-in voltage, safeguarding the open-circuit voltage [9].

In Fig. 4, we plot the cell efficiency as a function of the Te impurity concentration. We found that the conversion efficiency increases from 25.03% to 27.82% with increasing the tellurium concentration N_t when $N_t<N_A$. The increase is resulted from the improvement of the short-circuit current density and the decrease of the open-circuit voltage. The net gain of 2.79% for cell efficiency indicates that the IPV solar cell doped with Te is a promising approach to improve cell performance.

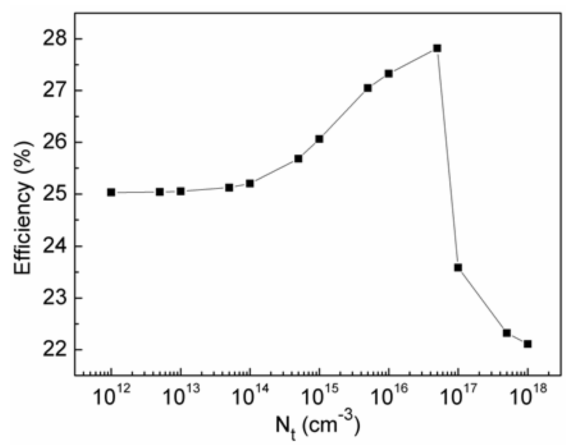

Fig. 4. Cell efficiency as a function of the Te impurity concentration.

3.2 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 27.82% can be obtained when R_f =0.999 and R_b=0.9999. If R_f =R_b=0.93, a maximum efficiency of the solar cell is only 24.28%. 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" [16].

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

R_f	R_b	J_{sc} (mA/cm^2)	V_{oc} (V)	η (%)
0.999	0.9999	45.65	0.7079	27.82
0.999	0.999	45.14	0.7079	27.32
0.999	0.97	42.76	0.7078	26.09
0.999	0.93	41.03	0.7076	25.10
0.97	0.999	42.90	0.7076	26.18
0.93	0.999	41.31	0.7073	25.27
0.93	0.97	40.48	0.7072	24.78
0.93	0.93	39.65	0.7070	24.28

To examine the contribution of the IPV effect, we plot the spectral response of the cell with different light trapping coefficient. 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.

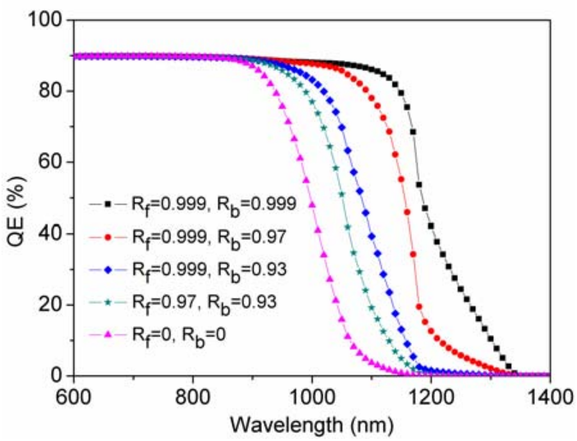

Fig. 5. Spectral response of the cell with different light trapping coefficients.

4. Conclusions

A numerical study has been carried out to investigate the potential of the IPV effect in tellurium-doped silicon solar cells. It is shown that an increase of 2.79% for conversion efficiency can be obtained by the IPV effect. The improvement of the IPV solar cell performance attributes to the extension of the infrared response. A good light trapping is necessary to obtain a higher conversion efficiency for IPV solar cells. Our results indicate that the IPV effect in silicon solar cells doped with tellurium is a promising way for improvement of cell efficiency.

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