Appl. Phys. A (2017)123:350
DOI 10.1007/s00339-017-0967-5

Applied Physics A
Materials Science & Processing

Impact of high electric field on the detailed balance limit of efficiency of solar cells

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Received: 12 January 2017 / Accepted: 7 April 2017

Abstract This paper presents a theoretical model showing the effect of impact ionization on the efficiency of a solar cell. An electric field is applied to a silicon solar cell, inducing ionization of charge carriers. Based on the detailed balance limit calculation, the results show an increase in efficiency with the increase of the electric field in the scale on which carrier's multiplication is observed.

Abbreviations

h	Planck's constant (6.626×10^{-34} Js)
c	Photons propagation speed (3×10^{8} m/s)
q	Charge of electron (1.6×10^{-19} C)
λ	Mean free path (Å)
k	Boltzmann's constant (1.38×10^{-23} J/K)
T_c	Cell's temperature (°K)
T_s	Sun's temperature (6000 °K)
E_g	Gap energy (eV)
f_ω	Geometrical factor
Q_s	Number of quanta for blackbody radiation of temperature T_s
t_s	Probability that an incident photon of energy greater that E_g will enter the body at temperature T_s and produce a hole–electron pair
E_o	Applied electric field to pn junction (V/cm)
Q_c	Number of quanta for blackbody radiation of temperature T_c
t_c	Probability that an incident photon of energy greater that E_g will enter the body at temperature T_c and produce a hole–electron pair

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1 Introduction

High electric field applied to a pn junction induces the ionization of charge carriers and thus their multiplication. This process has often been used to evaluate the breakdown voltage or the ionization rate of electrons and holes [1–3]. Impact ionization of charge carriers is of great interest in the improvement of solar cell efficiency. This process induces the multiplication of charge carriers, because an electron in the conduction band (or a hole in the valence band) gains sufficient energy from an external source to excite an electron in the valence band or in the intermediate band. Several works focused on impact ionization have been carried out [4–18] and theoretically shown to exceed the detailed balance limit of a conventional solar cell calculated by Shockley and Queisser [19]. Würfel reached a maximum efficiency of 85% for a vanishing band gap of the solar cell by considering the impact ionization phenomenon to generate hot electrons [13]. Furthermore, considering the impact ionization effects on the efficiency of intermediate band solar cells, Gorji [18] obtained a thermodynamic efficiency of 81.2% which was higher than the maximum efficiency of 63.2% for an intermediate band without impact ionization mechanism.

The multiplication of charge carriers based on the applied electric field to a pn junction could be an interesting solution to reach a high efficiency of the solar cell. The aim of this work is to propose a model of estimating the efficiency of a solar cell submitted to impact ionization by taking into account the effect of impact ionization on the detailed balance limit of efficiency of pn junction solar cells published by Shockley and Queisser [19]. One assumes that the impact ionization affects fraction of the recombination–generation current which is radiative in the absence of radiative disturbance.

2 Theoretical model

Each free carrier from radiative recombination–generation which acquires sufficient energy from applied electric field is able to generate additional free carriers via multiple collisions. The probability that an electron gains the threshold energy for ionization is given by Eq. (1) [20, 21]. The generation rate of additional free carriers is proportional to this probability through Eq. (2), where $\frac{qE_o}{E_i}$ is the maximum value of this rate and λqE_o is the energy gained by the electrons:

$$P = \exp\left(-\frac{E_i}{qE_o\lambda}\right), \tag{1}$$

$$\alpha = \frac{qE_o}{E_i}\exp\left(-\frac{E_i}{qE_o\lambda}\right). \tag{2}$$

In the above equations, E_o is the applied electric field, E_i is the ionization threshold energy, and λ is the mean free path which is the average distance between collisions. Several papers evaluated experimentally the value of the mean free path for different semiconductors [22–26].

It has been shown in [21] that in the case of two bands (one conduction band and one valence band) and for $m_e = m_h$ (where m_e is the effective mass of electron and m_h is the effective mass of hole), the ionization threshold energy is given by

$$E_i = \frac{3E_g}{2}. \tag{3}$$

One assumes that free electrons generated through impact ionization are contained in the recombination–generation current which is radiative. Thus, the fraction of the recombination–generation current which is radiative is defined by

$$f_c = f_c' + f_c'', \tag{4}$$

where f_c' is the fraction of radiative current in the absence of impact ionization and f_c'' is the fraction of radiative current generated through impact ionization and it is defined as

$$f_c'' = \alpha_e l, \tag{5}$$

In the above equation, α_e is the generation rate of electrons per centimeter and l is the thickness of the cell. Several papers have evaluated the parameter α_e based on Eq. (2). Reference [3] found the generation rate of electrons in silicon pn junction equal to $\alpha_e = 7.03 \times 10^5 \exp\left(\frac{-1.231\times10^6}{E_o}\right)$ /cm, for $1.75 \times 10^5 \le E_o \le 6.4 \times 10^5$ V/cm.

Thus, the modified open circuit voltage of [19] is defined by

$$V_{op} = \frac{kT_c}{q}\ln\left(\frac{(f_c' + f_c'')f_\omega t_s Q_s}{2t_c Q_c}\right). \tag{6}$$

By setting $f = \frac{f_\omega t_s}{2t_c}$, Eq. (6) turns to

$$V_{op} = \frac{kT_c}{q}\ln\left(\frac{(f_c' + \alpha_e l)fQ_s}{Q_c}\right), \tag{7}$$

where

$$Q_s = \left[2\pi(kT_s)^3/(h^3c^2)\right]\int_{x_g}^{\infty}\frac{x^2\mathrm{d}x}{e^x - 1}, \tag{8}$$

$$Q_c = \left[2\pi(kT_c)^3/(h^3c^2)\right]\int_{x_g}^{\infty}\frac{x^2\mathrm{d}x}{e^x - 1}, \tag{9}$$

$$x_g = \frac{E_g}{kT_s}. \tag{10}$$

Shockley and Queisser [19] defined the maximum efficiency of the solar cell as a product of four components: (1) the ultimate efficiency $\mu(x_g)$; (2) the ratio of the open circuit voltage to the energy gap of the cell $\upsilon(x_g, x_c, f)$; (3) the impedance matching factor $m(\upsilon x_g/x_c)$; and (4) the probability that a photon will produce an electron–hole pair t_s. Thus, the mathematical expression of efficiency is written as

$$\eta(x_g, x_c, f, t_s) = t_s\mu(x_g)\upsilon(x_g, x_c, f)m(\upsilon x_g/x_c), \tag{11}$$

where

$$\mu(x_g) = \frac{x_g\int_{x_g}^{\infty}\frac{x^2\mathrm{d}x}{e^x-1}}{\int_0^{\infty}\frac{x^3\mathrm{d}x}{e^x-1}}, \tag{12}$$

$$\upsilon(x_g, x_c, f) = \frac{V_{op}}{V_g}, \tag{13}$$

$$m(\upsilon x_g/x_c) = \frac{(\upsilon x_g/x_c)^2}{\left(1+(\upsilon x_g/x_c)-\exp\left(-\frac{\upsilon x_g}{x_c}\right)\right)\left(\frac{\upsilon x_g}{x_c}+\ln\left(1+\frac{\upsilon x_g}{x_c}\right)\right)}, \quad (14)$$

$$x_c = \frac{T_c}{T_s}, \quad (15)$$

$$V_g = \frac{E_g}{q}. \quad (16)$$

3 Results and discussion

The results obtained are based on the modified detailed balance limit of solar cell efficiency [19]. Recent studies [27–30] have shown the limitations of charge carrier's multiplication in the improvement of the efficiency of the solar cells. These studies mainly are based on the multiplication of charge carriers due to excess photon energy. According to [29], the energy of the photons having a limit value in the solar spectrum, therefore, the ionization threshold energy alone is sufficient to neutralize the importance of the multiplication of charge carriers in the increase of the efficiency of the solar cells. However, the use of an external energy source such as the application of an electric field could provide an excess of energy well above the ionization threshold energy and able to produce additional free carriers. In this study, carrier's multiplication induced by the external source of energy influences the output energy of the solar cell through the product α_e-l which is the fraction of generated electrons via impact ionization. This product depends on the applied electric field. Therefore, the efficiency of the solar cell is a function of electric field.

For simulations, the value of α_e is the one calculated at [3] and given in Sect. 2. Figures 1, 2 plotted the efficiency of silicon solar cell in a function of electric field, respectively, for $0 \le E_o \le 1.75 \times 10^5$ and $1.75 \times 10^5 \le E_o \le 6.0 \times 10^6$ V/cm. These figures show that the efficiency of the cell is constant with the increase in electric field out of the range in which carrier's multiplication is observed. There is an increase in efficiency with the increase of the electric field in the range, where the generation rate is defined.

In the proposed model, the efficiency is 29.74% when $E_o = 0$ V/cm. This value approximates the value of 30% which is the detailed balance limit of Shockley and Queisser for silicon [19]. The increase in efficiency is observed from $E_o = 8 \times 10^4$ V/cm.

Since the efficiency of the cell is an increasing function of the electric field existing at the terminals of the cell, then the question that should be asked is certainly how to generate a high electric field in the cell to considerably increase the number of charge carriers and hence the efficiency. In the present study, an efficiency of more than 42% (an increase of more than 12% compared to an ordinary silicon solar cell) could be achieved for an applied electric field of 6×10^5 V/cm. This efficiency is obtained at an open circuit voltage of 1.1954 V. Perhaps, it would be difficult for an ordinary solar cell to generate such an electric field; however, the use of an external source to achieve high values of the electric field could be an interesting solution. It is true that this option raises another concern, since a solar cell is an energy generator and not a consumer; however, a state of equilibrium or compensation

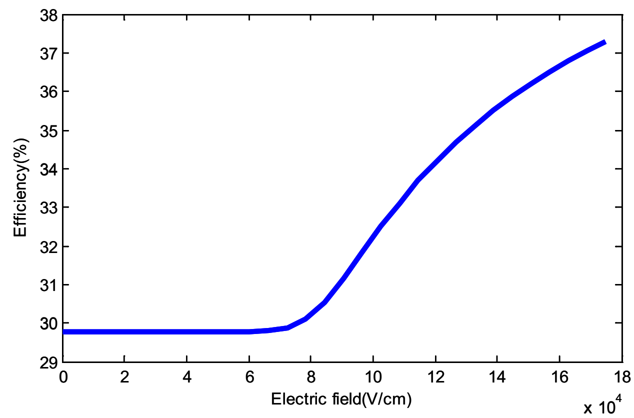

Fig. 1 Efficiency for a silicon solar cell ($E_g = 1.12$ eV and $l = 350$ µm) submitted to impact ionization induced by an applied electric at temperature $T_c = 300$ °K exposed to a blackbody sun at temperature $T_s = 6000$ °K. $f_\omega = 2.18 \times 10^{-5}$, $f_c' = 1$, $t_s = 1$, $t_c = 1$. Electric field is in the range $0 \le E_o \le 1.75 \times 10^5$ V/cm. $\alpha_e = 7.03 \times 10^5 \exp\left(\frac{-1.231 \times 10^6}{E_o}\right)$/cm

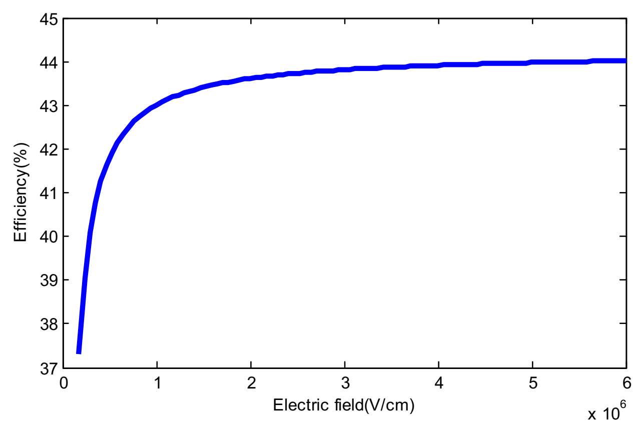

Fig. 2 Efficiency for a silicon solar cell ($E_g = 1.12$ eV and $l = 350$ µm) submitted to impact ionization induced by an applied electric at temperature $T_c = 300$ °K exposed to a blackbody sun at temperature $T_s = 6000$ °K. $f_\omega = 2.18 \times 10^{-5}$, $f_c' = 1$, $t_s = 1$, $t_c = 1$. Electric field is in the range $1.75 \times 10^5 \le E_o \le 6.0 \times 10^6$ V/cm. $\alpha_e = 7.03 \times 10^5 \exp\left(\frac{-1.231 \times 10^6}{E_o}\right)$/cm

can be obtained depending on the obtained efficiency. Suppose, for example, that an electric field of 10^8 V/cm applied to a solar cell would yield 85% efficiency and that the generator of this electric field is the equivalent of 30% of the generated percentage. Then, taking into account the efficiency of an ordinary solar cell (30%), an addition percentage of 25% could be achieved. In this case, the use of a low cost electric field generator could be a very interesting solution. Other parameters could be taken into account in the evaluation of the efficiency of a solar cell submitted to impact ionization such as the choice of the type of technology, since the generation rate of the charge carriers is also a function of the used material.

4 Conclusion

In this paper, the effect of applied electric field on the efficiency of a photovoltaic solar cell has been studied. A method for estimating the efficiency of solar cell submitted to impact ionization has been proposed. Theoretically it has been shown that a high applied electric field to a pn junction could be a very promising solution to reach a high efficiency of the solar cells. The prospect of this work is to reflect on his practical feasibility particularly on how to generate a high electric field into the solar cell.

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