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Thick and Thin Film Solar Cells: New Formulation

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Solar cells rely on photogeneration of charge carriers in *p-n* junctions and their transport and subsequent recombination in the quasineutral regions. Several basic issues concerning the physics of the operation of solar cells remain obscure. This paper discusses some of those unsolved basic problems. In conventional solar cells, recombination of photogenerated charge carriers plays a major limiting role in the cell efficiency. High quality thin-film solar cells may overcome this limit if the minority diffusion lengths become large as compared to the cell dimensions, but, strikingly, the conventional model fails to describe the cell electric behavior under these conditions. A new formulation of the basic equations describing charge carrier transport in the cell along with a set of boundary conditions is presented. An analytical closed-form solution is obtained under the linear approximation. It is shown that the calculation of the open-circuit voltage of the solar cell diode does not lead to unphysical results in the new given framework.

Keywords: Solar cell, Recombination, Transport phenomena, Thin films.

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Introduction

Charge carrier transport underlies in the electrical behavior of any semiconductor device and, in particular, of solar cells. Despite efforts made over the years to model satisfactorily the transport of charge-carrier in semiconductors, some important questions remain unanswered. These questions need to be addressed to correctly model present and future devices.

One of these open questions is how to model carrier recombination. The mathematical expression routinely used to model the recombination rate, [1], is basically incorrect. It has been recently demonstrated that it contradicts Maxwell's equations, and hence a new corrected model must be developed [2, 3]. This problem was partly addressed in previous works (see [4]). Recombination is a key feature when describing carrier transport in solar cells because it strongly affects the electrical response of the semiconductor at all levels of external excitation. A remark that must be made about the need for a correct modeling of recombination is that in devices operating under a strong excitation (the operation of solar cells lies in this regime), the importance of a correct formulation of the recombination terms is even more important.

The set of Poisson and transport equations cannot be solved analytically in general, so some simplifications must be introduced to obtain a closed-form solution. One approximation commonly used to solve this system of equations is the assumption of quasineutrality (QN) [3, 5]. The use of the QN approximation is acceptable if the sample and the diffusion lengths are both larger than the Debye length. Although QN has been routinely used in semiconductor device modeling for many years, the role of space charge in the formation of the current-voltage (I−V) characteristic in a semiconductor is still controversial.

A very important question is the choice of the boundary conditions used when solving the carrier-transport equations. It should be noted that the expressions commonly used are valid only for semiconductor devices operating in open-circuit conditions (see [6]). Since in normal operation a currents flow at the terminals, the widespread use of boundary conditions for open-circuit conditions is incorrect. For closed-circuit conditions, a different set of boundary conditions needs to be derived. This problem has only been addressed in the last few years [7–9].

All the above-mentioned issues need to be addressed when modeling any semiconductor devices. Thin-film solar cells technology is one of the strongest technologies in the steadily growing photovoltaic market [10]. In this paper we will address a very basic problem encountered when modeling cells with large values of the minority diffusion lengths.

It is important that all the above problems arise even at low light levels. Therefore, below we will limit ourselves to the linear approximation, when it is possible to obtain an analytical solution.

I. *p-n* diode

The commonly accepted electrical model for the current density-voltage characteristic $(J-V)$ of an ideal $p-n$ junction is [11]:

$$J = J_0 exp\left(\frac{V}{V_T} - 1\right), \tag{1}$$

where J is the diode current density, V is the bias voltage, V_T is the thermal voltage, and J_0 the reverse-saturation current density that for a long abrupt diode is:

$$J_0 = V_T\left(\frac{\sigma_p^n}{L_D^n} + \frac{\sigma_n^p}{L_D^p}\right), \tag{2}$$

σ_n^p (σ_p^n) is the electron (hole) conductivity of minority carriers in the p-side (n-side) of a junction diode; L_D^n and L_D^p are, respectively, the hole and electron minority carrier diffusion lengths of minority carriers in n- and p-sides defined as:

$$L_D^n = \sqrt{D_p}\tau_p, \qquad L_D^p = \sqrt{D_n\tau_n} \tag{3}$$

$D_n(D_p)$ is the electron (hole) diffusivity and τ_n (τ_p) is the electron (hole) minority carrier lifetime. A quick examination of J_0 (and this directly translates into the global current density, j) reveals that in the limiting case $\tau_{n,p} \to \infty$(i.e. in absence of bulk recombination) $J_0 \to 0$ and, vice versa, when $\tau_{n,p} \to 0$ (i.e. under strong bulk recombination) $J_0 \to \infty$. Since in both limiting cases the conventional model leads to unphysical results, the model needs to be properly modified and corrected. Note that the former problems persist even for small values of the applied voltage $(V/V_T \ll 1)$ for which Ohm's law holds:

$$J = J_0(\frac{V}{V_T}) \tag{4}$$

The fact is that when obtaining equation (1), two contradictory conditions are used. On the one hand, it is believed that all external voltage drops inside the quasi-neutral regions. On the other hand, equilibrium $p-n$ regions are considered semi-infinite, so their resistance is very high, and the entire voltage drop falls on them.

Let us pay attention to another important point. In equation (1) there are no geometric dimensions of the $p-n$ structure, so it is impossible to analyze the cases of thin-film and thick-film structures.

A very important question is the choice of the boundary conditions used when solving the carrier transport equations. It should be noted that the expressions commonly used are valid only for semiconductor devices operating in open-circuit conditions (see, for instance Ref. 6). Since in normal operation a currents flow at the terminals, the widespread use of boundary conditions for open-circuit conditions is incorrect. For closed-circuit conditions, a different set of boundary conditions needs to be derived. This problem has only been addressed (Ref. [5] and [7-8]) in the last few years.

Using conventional transport equations for electrons and holes [1, 6] and boundary conditions [5,7-8] we derived the expression of the dark current density versus the applied voltage of an abrupt $p-n$ structure with uniform doping profile at each side of the junction for small values of the applied voltage:

$$J = \frac{V}{\frac{l_n}{\sigma_n^n} + \frac{l_p}{\sigma_p^p} + \frac{L_D^n L_D^p}{L_D^p \sigma_p^n cth\frac{l_n}{L_D^n} + L_D^n \sigma_n^p cth\frac{l_p}{L_D^p}}} \tag{5}$$

where $l_n(l_p)$ is the n-side (p-side) length of the sample, L_D^n and L_D^p are the minority diffusion lengths in the n- and p-region respectively and $\sigma_n^n(\sigma_p^p)$ is the n-side (p-side) cell conductivity due to majority carriers. It can be readily show using Eq. (2) and Eq. (4) that the reverse-saturation current density contained in Eq. (5) greatly differs from the commonly used one (Eq. (2)) and, in strong contrast with the later it does not leads to unphysical results in the two limiting cases above discussed: $\tau_{n,p} \to \infty$ and $\tau_{n,p} \to 0$.

Ideally, the general mechanism of conduction in *p-n* junctions is minority carrier injection (or extraction). But in a real diode (see below) some other mechanisms exist, and this is why for a correct description of the problem it is necessary to consider both minority and majority carriers.

Under weak volume recombination both carrier diffusion lengths $L_D^{n,p}$ are larger than the length of the structure (thin film structure). In absence of surface recombination, the transport in the diode may be studied by using a simple circuit: two $n-n$ and $p-p$ junctions arranged in parallel that are mutually uncoupled (see Fig. 1).

To prevent the carrier lifetimes from being infinite a new mechanism of conductivity appears without minority carrier injection [12]:

$$J_0 = V_T\left(\frac{\sigma_p^n}{l_n} + \frac{\sigma_n^p}{l_p}\right). \tag{6}$$

When $\tau_{n,p} \to 0$, (strong recombination, thick film, see Fig. 2),

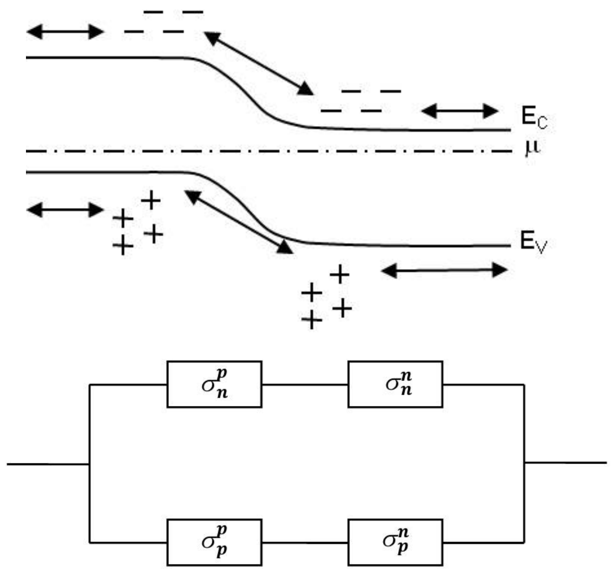

Fig. 1. Schematic of the carrier flow in the $p-n$ junction when volume recombination is weak in the diode ($\tau_{n,p\to\infty}$). E$_C$ and E$_V$ are the conduction and the valence band-edges respectively. Electron and hole flows are mutually uncoupled and independently contribute to the current at the device terminals.

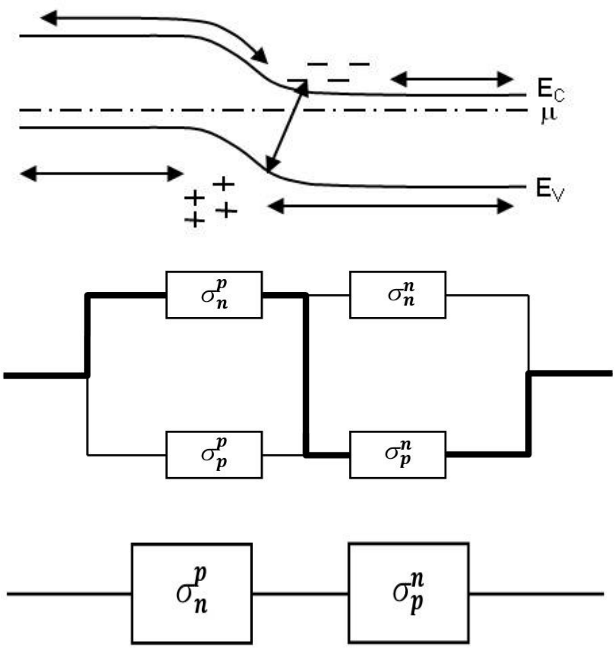

Fig. 2. Schematic of the carrier flow in the $p-n$ junction when volume recombination is strong in the diode ($\tau_{n,p}\to 0$). For strong recombination, both electron and hole flows are strongly coupled at the diode junction.

$$J = V\left(\frac{l_n}{\sigma_n^n}+\frac{l_p}{\sigma_p^p}\right)^{-1}. \quad (7)$$

If $L_D^n \ll \frac{\sigma_n^p}{\sigma_n^n} l_n$ and $L_D^p \ll \frac{\sigma_p^n}{\sigma_p^p} l_p$, thick film,

$J_0 = V(\frac{l_n}{\sigma_n^n}+\frac{l_p}{\sigma_p^p})^{-1}$ (see Fig. 3).

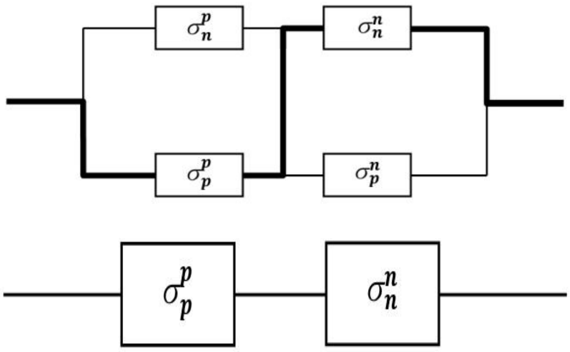

Fig. 3. Schematic of the carrier flow in the $p-n$ junction when volume recombination is very strong.

II. New model for thin-film solar cells

Equation (1) may be rewritten for a solar cell under illumination as [13]:

$$-J = J_0 exp\left({}^{V}/_{V_T}-1\right)+J_I, \quad (8)$$

where J_I is the photocurrent and J is additionally related to the generated voltage V through the external resistive load (R) in the circuit and the solar cell area (S) as shown on Fig. 4:

$$J = \frac{V}{RS} \quad (9)$$

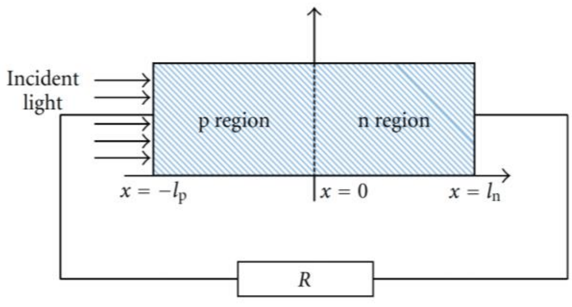

Fig. 4. Solar cell diode with an external resistor load.

Let us assume a one-dimensional problem for a single-diode solar cell such as the one given in Fig. 4. According to the values of the diffusion lengths in Si, in c-Si thin-film solar cells, or in a-Si ones of nanometer thickness [14], the following inequality will hold:

$$l_{n,p} \ll L_D^{n,p}. \quad (10)$$

From Eq. (10) it follows that $L_D^{n,p}$ and$\tau_{n,p}\to\infty$; therefore, recombination is negligible and according to (2) $J_0\to 0$ and, moreover, from Eq. (8), the basic model leads to the unphysical result (see Fig. 5b): $J\sim -J_I$, i.e., the p-n junction behaves as a current-source that translates photoexcitation into current at any value of the diode-voltage independently of the $p-n$ junction properties.

It follows from the above that the framework of basic equations conventionally used to model solar cells fails in

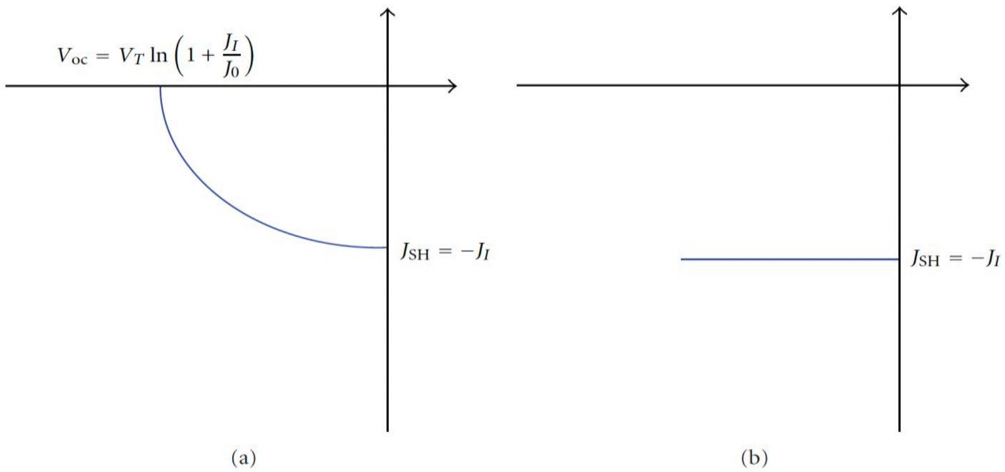

Fig. 5. $J - V$ characteristic of an ideal solar cell with the short- and open-circuit expressions for the axis-intercept points V_{OC} and J_{SN}, respectively, (a). $I - V$ characteristic in the limiting case of a thin-film cell $l_{n,p} \ll L_D^{n,p}$ (b).

high-quality thin-film solar cells [15]. Regardless of its apparent simplicity, since this framework constitutes the foundations of any electrical modeling of a solar cell diode, the discussed problem will persist in any other model that one can build; therefore, it is crucial to identify the origin of the problem and modify the basic model to build a new framework free from unphysical errors. In this paper a new model is presented and used to analytically show that in a simple case the new framework does not fail to correctly describe the limiting case of a thin-film solar cell.

Let us assume once again that inequality of Eq. (10) holds and, accordingly, the solar cell recombination is negligible. The macroscopic description of the transport of nonequilibrium charge is done with the continuity equations for the electron and hole current densities [3]. Since volume recombination is negligible and, accordingly, there is only band-to-band photogeneration, conditions the QN approximation reduces to equality of nonequilibrium concentrations of electrons and holes. To solve these equations we need to determine and impose enough boundary conditions at the semiconductor interfaces [8].

As result, we obtain (see Fig. 6):

$$J_I + V\left(\frac{l_p}{\sigma_n^p} + \frac{l_n}{\sigma_p^n}\right)\frac{\sigma_n^p \sigma_p^n}{l_n l_p} = -J. \quad (11)$$

We must compare the obtained equation with a linearization of Eq. (8):

$$J_I + V\frac{J_0}{V_T} = -J. \quad (12)$$

This Eq. (12) is a main result of this work.

Identifying the second terms in the left-hand side of (11) and (12), we obtain a new expression for the current density J_0:

$$J_0 = \left(\frac{l_p}{\sigma_n^p} + \frac{l_n}{\sigma_p^n}\right)\frac{\sigma_n^p \sigma_p^n}{l_n l_p} V_T. \quad (13)$$

This new expression does not exhibit an unphysical behavior ($J_0 \to \infty$) in thin-film solar cells, $l_{n,p} \ll L_D^{n,p}$ (Fig. 5b). Figure 6 gives the two axis-intercept points (V_{oc} and J_{SH}) of the $I - V$ characteristic, it can be trivially verified that the x-intercept point (V_{oc}) will remain at a finite value independently of the minority carrier's diffusion lengths at each side of the junction and the diode dimensions. Since the analytical model presented in this paper was obtained by a linearization of the full model and some other approximations have been used to simplify the mathematical problem, the large signal $I - V$ is not properly obtained (Fig. 6), but the framework of transport equations and boundary conditions can be solved numerically to study any real solar cell diode.

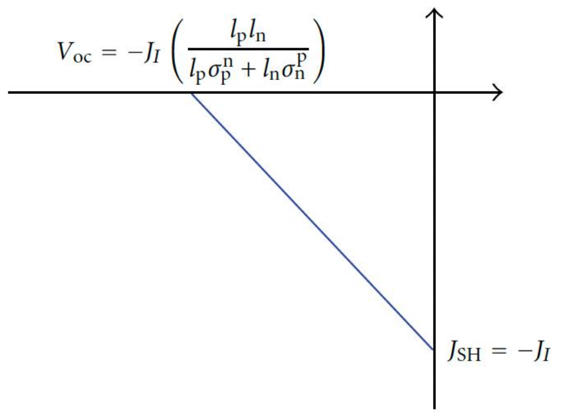

Fig. 6. $J - V$ characteristic of an ideal thin-film solar cell with the new expression for the x axis-intercept point V_{oc}.

Conclusions

Solar cells rely on photogeneration of charge carriers in $p - n$ junctions and their subsequent recombination in the quasineutral regions. Several basic issues concerning the physics of the operation of solar cells remain obscure. In this paper we briefly discussed some of those unsolved basic problems: need for not unphysical models of the carrier recombination and revision of the QN concept. In conventional solar cells recombination of photogenerated charge carriers plays a major limiting role in the cell

efficiency. High quality thin-film solar cells may overcome this limit if the minority diffusion lengths become large as compared to the cell dimensions, but, strikingly, the conventional model fails to describe the cell electric behavior under these conditions. A new formulation of the basic equations describing charge carrier transport in the cell along with a set of boundary conditions is presented. An analytical closed-form solution is obtained under a linear approximation. In the new framework given, the calculation of the open-circuit voltage of the solar cell diode does not lead to unphysical results.

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Товсті та тонкі плівки для фотоелектрики: нові парадигми

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Сонячні батареї базуються на фотогенерації носіїв заряду в p-n-переходах, їх транспорті та подальшій рекомбінації у квазінейтральних областях. Кілька основних питань, що стосуються фізики сонячних елементів, залишаються невиясненими. У цій статті обговорюються деякі з цих невирішених основних проблем. У звичайних сонячних елементах рекомбінація фотогенерованих носіїв заряду відіграє головну обмежувальну роль у ефективності елемента. Високоякісні тонкоплівкові сонячні батареї можуть подолати цю межу, якщо дифузія неосновних носіїв стає великою порівняно з розмірами комірки, і, що вражає, звичайна модель за цих умов не може описати електричну поведінку комірки. Наведено нове формулювання базових рівнянь, що описують транспорт носіїв заряду в комірці разом із набором граничних умов. У лінійному наближенні отримано аналітичний закритий розв'язок. Показано, що розрахунок напруги холостого ходу діода сонячної батареї не призводить до нефізичних результатів у новій заданій структурі.

Ключові слова: сонячний елемент, рекомбінація, явища переносу, тонкі плівки.