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A NUMERICAL INVESTIGATION ON P-I-N SOLAR CELLS EFFICIENCY

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Abstract
The paper presents a set of numerical simulations performed in the frame of a two scales model development for a single-solar cell under AM0 standard solar spectrum. The charge transport and Poisson's equations in one dimension are solved in terms of electron density, hole density and electrostatic potential using a finite-element approach. The current density model considers both the diffusion in neutral regions and the drift within depletion layer. The calculations are done for equilibrium and under forward bias voltage. The aim of the numerical computations is to obtain the J-V curves and the conversion efficiency. The presented results of numerical simulations quantify the influence of the most important material parameters on the cell performances.
Keywords: solar cells, p-i-n structure, J-V characteristic, conversion efficiency.

1. Introduction

The p-i-n solar cells (hydrogenated amorphous silicon (a-Si:H), for example) have been extensively investigated for use as low-cost solar cells. Practical use of p-i-n solar cells as an electric power source requires improvements in collection efficiency and stability. Together with the theoretical studies focused on the developing and improvement of the models describing the transport phenomena inside the converter, the computer modeling has become a necessary element in solar cell design and analysis. Numerical treatment offers a deeper comprehension of the structure, achieving a complete control on the various parameters and defining their role in the device operation [1-4]. The considered structure consists of a middle intrinsic (i-type or undoped) layer between a p-type layer and a n-type layer (p-i-n structure). This geometry sets up an electric field between the p- and n-type regions that stretches across the middle intrinsic resistive region. Light generates free electrons and holes in the intrinsic region, which are then separated by the electric field. In particular, our analysis is based on the numerical solution of Poisson's equation with the space-charge density ρ described by both the charge due to impurities and free charge of electrons and holes. Our study focuses on how the problem variables (potential and charge concentrations) could change under a forward biasing. A numerical model has been developed to find the current density by solving the transport and continuity equations. The role of the device geometry and dopant concentrations on the conversion efficiency of the solar cell is studied.

2. Mathematical model

In our computations a one-dimensional p-i-n solar cell illuminated from p-side is considered. The distribution of electric potential is described by the Poisson's equation:

$$\frac{d^2\phi}{dx^2} = -\frac{1}{\varepsilon} q\left(N_d(x) - N_a(x) + p(x) - n(x)\right) \tag{1}$$

where ϕ is the electric potential, ε is dielectric constant, *p(x)* and *n(x)* are the concentration of free charge of holes and electrons respectively, $N_d(x)$ and $N_a(x)$ are the concentration of ionized donors and acceptors and *x* is the spatial coordinate [3].

The current density was obtained by the solution of the electron and hole continuity equations:

$$-\frac{1}{q}\frac{dJ_n(x)}{dx} = G(x) - R(x) \tag{2}$$

$$\frac{1}{q}\frac{dJ_p(x)}{dx} = G(x) - R(x) \tag{3}$$

where

$$J_n = -q\mu_n n(x)\frac{d\phi}{dx} + qD_n\frac{dn(x)}{dx} \tag{4}$$

and

$$J_p = -q\mu_p p(x)\frac{d\phi}{dx} - qD_p\frac{dp(x)}{dx} \tag{5}$$

are the electron and hole current densities. *G(x)* is the generation rate, *R(x)* is the recombination rate, μ_n and μ_p are the mobility of free electrons and holes, D_n and D_p are the diffusion coefficients of electrons and holes, respectively.

The generation rate *G(x)* of charge carriers in the semiconductor layer at the depth *x* is:

$$G(x) = \int_{\lambda_{\min}}^{\lambda_{\max}} [1 - R(\lambda)]\alpha(\lambda)N_{ph}(\lambda)e^{-\alpha(\lambda)x}d\lambda \tag{6}$$

where α(λ) is the absorption coefficient, $N_{ph}(\lambda)$ is the incident photon flux, $R(\lambda)$ is the reflection coefficient at front surface. $\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and maximum wavelengths of the considered solar spectrum. The recombination rate *R(x)* is related to the excess electron ($\Delta n(x)$) and hole ($\Delta p(x)$) concentrations and the lifetime of electrons (τ_n) and holes (τ_p) as follows [3]:

$$R(x)_n = \frac{\Delta n(x)}{\tau_n}\ ,\ R(x)_p = \frac{\Delta p(x)}{\tau_p}\ . \tag{7}$$

3. Results and Discussions

The system (1)-(3), together with appropriate boundary conditions [3,4] was solved using a free access code, FreeFEM++ [5], based on the finite element method. We considered an abrupt p-i-n structure, with the doping profile of the impurity assumed uniform throughout each semiconductor up to the junction. For the validation of the program, computations were performed for different values of the dopant concentrations (N_a, N_d) and relative lengths of p, i and n regions, the total length of the device (L) being fixed. The material parameters used for numerical computations were specific to Si at 300 K [3], and are kept the same for all the simulations. The solar cell is considered illuminated with an AM0 spectrum, divided in 66 energy segments, producing 1358.3 W/m^2.

A set of numerical results obtained for $N_a = N_d = 1.5\ 10^{15}$ cm^{-3} and $l_p=l_i=l_n=0.33L$, for a fixed length of the device, $L=3.33$μm, are presented in figures 1a-c. The effect of the illumination on the J-V characteristic is presented in figure 1d.

In order to characterize the cell performance the short circuit current density (J_{sc}), the open circuit voltage (V_{OC}), the efficiency (η) and the fill factor (F_f) were determined in each case. The results are synthetically presented in Table 1.

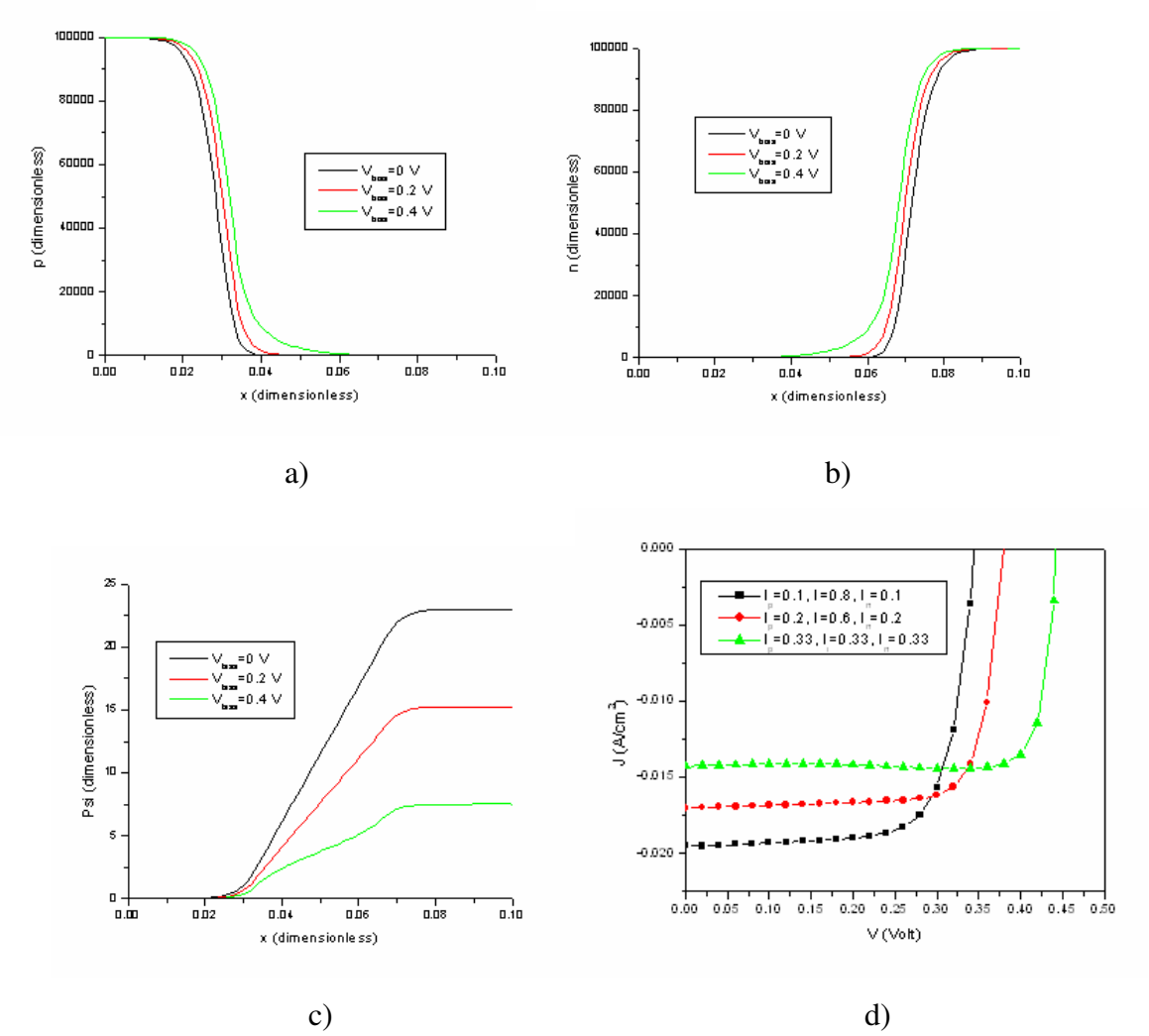
Table 1: Numerical results.

Case	$N_a=N_d$ (cm^{-3})	l_p/L	l_i/L	l_n/L	J_{sc} (mA/cm^2)	V_{OC} (V)	F_f (%)	η (%)
1.	$1.5\ 10^{15}$	0.1	0.8	0.1	19.5	0.345	72.4	3.65
2.	$1.5\ 10^{15}$	0.2	0.6	0.2	17	0.380	77.5	3.71
3.	$1.5\ 10^{15}$	0.33	0.33	0.33	14.25	0.444	85.7	4.05

The computed efficiencies are small, but this is a consequence of choosing failsafe parameter values used only for validation of the program. A subsequent performance optimization will follow in order to integrate the code in our NANOPV solar cell simulation program. This improved version will also consider optimized geometry and quantum well structure inside the i-region.

4. Conclusions

A numerical model is developed to find the current density by solving numerically the transport and continuity equations. The analysis focuses on the role of the device's geometry on the efficiency of the cell, in order to enhance its performances.



a) b)

c) d)

Fig. 1: Calculated profiles for (a) the holes density, (b) electrons density, and (c) electrostatic potential, respectively, in the case $l_p = l_i = l_n = 0.33L$ and $N_a = N_d = 1.5\ 10^{15}$ cm^{-3}; (d) Calculated J-V characteristics for cells with different lengths for the p, i and n regions, but with fixed dopant concentrations ($N_a = N_d = 1.5\ 10^{15}$ cm^{-3}).

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