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A simple analytical model of thin films crystalline silicon solar cell with quasi-monocrystalline porous silicon at the backside

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ABSTRACT

An analytical model that simulates the performance of an elementary thin silicon solar cell with a thin film quasi-monocrystalline porous silicon (QMPS) at the backside reflector is developed. A complete set of equations for the photocurrent generated under the effect of the reflected light is solved analytically in each region. The collection of the light absorbed by the QMPS layer has been discussed and the analytical solution of the light-generated current in this layer is derived. The maximum of the photocurrent density calculated in the present study is in accordance with the numerical values established by Bergmann et al. Furthermore, the influence that the layer's number of double porosities and high porosity have on the photovoltaic parameters is studied. It is demonstrated that the photovoltaic parameters increase with the number of double porosities that the layer might have in a given structure. When the QMPS layer is formed by three double-porosity layers 20%/80% and for a 5-μm-thick film c-Si, the backside reflector gives a total improvement of about 6 mA/cm^2 for the photocurrent density and 3.2% for the cell efficiency.

1. Introduction

The use of thin crystalline silicon solar cells, manufactured through various versions of large transfer processes, is one of the most promising approaches to achieve both performance improvement and cost reduction. This is partially due to the inexpensiveness of the material and the easiness of the manufacturing process [1–4]. Being a perfect light diffuser, the porous silicon (PS) or quasi-monocrystalline PS (QMPS) layer could be used as a backside reflector that enhances the effective thickness of the film c-Si through the light being reflected [2–4].

The reflectance of a multi-layered structure increases when the number of the layers in such a structure is increased. The gain in reflectance is intricately related to the absorption losses of QMPS which are increased by the total thickness of the multi-layered structure. It has been recently reported that for thin epitaxial silicon films (i.e. below 5 μm), the advantage of having a large number of repetitions reduces. This is because in the multi-layered PS there is more light absorption than in single-layered ones [5]. It is worth noting that most of the current experimental studies have employed a QMPS layer formed by four or six layers. Few experimental studies, however, have been reported to successfully introduce PS in silicon solar cells as an antireflective and passivating coating [6,7].

More recently, QMPS layers have been reported to have a significantly high absorption coefficient compared to crystalline silicon within the whole range of the solar spectrum of photovoltaic solar cell applications [8,9]. A semi-empirical model has been developed to account for the high absorption coefficient of QMPS layer which predicts the absorption coefficient of the QMPS layer in terms of different thickness, porosity and void size [8]. The transport parameters such as those of the minority carrier mobility and lifetime in QMPS layer have also been reported [10].

Several simulation models for thin film solar cells with QMPS layer or PS on the rear side have been developed to account for the improvement of photocurrent density and cell efficiency [2,3,11]. Most of these models, however, seem to focus solely on light reflected but paid little attention to the contribution of the QMPS to photovoltaic current generation coming from the light absorbed. An analytical study is deemed necessary for determining the potential uses of this material, particularly the number of layers it contains, as a backside layer in thin silicon solar cells. It is the purpose of this paper to present a simple analytical solution for the contribution that this material (QMPS) has in the improvement of photocurrent generation and the enhancement of the cell photovoltaic parameters, when acting as a backside reflector.

In the present study, we consider an elementary n$^+$pp$^+$ solar cell consisting of thin film crystalline silicon (regions n$^+$ and p)

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Nomenclature

q	electron charge
V_T	thermal voltage
L_n (L_p)	diffusion length of minority carriers in the base (emitter) region
L_n^*	effective diffusion length of minority carriers in the QMPS layer
D_n (D_p)	diffusion constant of minority carriers in the base (emitter) region
D_n^*	effective diffusion constant of minority carriers in the QMPS layer
τ_n	minority carrier lifetime in the base region
τ_n^*	effective minority carrier lifetime in the QMPS layer
N_a (N_d)	dopant concentrations in the base (emitter) region
N_a^+	dopant concentrations in the back region
$\alpha(\lambda)(\alpha^*)$	absorption coefficient in the c-Si (QMPS) at a wavelength λ
$\phi(\lambda)$	Incident photon flux
$R(\lambda)$	reflection coefficient at the front surface
W_{n+} (W_p)	emitter (base) thickness
W_c (W_{p+})	film c-Si (QMPS) thickness
$S_p(S_n^+)$	recombination velocity at the front (back) contact
$J_{ph,0}$	total photocurrent density of the conventional BSF silicon solar cell
$J_{ph,1}^R(J_{ph,2}^R)$	reflected photocurrent density by the back (front) contact
J_{ph}^{QMPS}	QMPS photocurrent density
ΔJ_{ph}	total increase in photocurrent density
$\Delta\eta$	total increase in cell efficiency
J_{0E} (J_{0B})	reverse saturation current density in the emitter (base) region
P_{in}	power density output (AM 1.5)
P_m	maximum power output of solar cell
V_m (J_m)	voltage (current density) at maximum power output

with a thin film QMPS back region (p$^+$ type). The increase in the photocurrent generated under the effect of the reflected light by the rear surface in the base region $J_{ph,B}^R$ and the emitter region $J_{ph,E}^R$ are solved analytically, including the QMPS photocurrent density J_{ph}^{QMPS} contributed to by the light absorbed when the reflected light is not fully total. In addition, in our survey we have taken into account the photocurrent generated effect on the second reflection that occurs at the level of the front surface. The QMPS layer is modeled by an effective recombination velocity at the back surface in the base reverse saturation current density. First, we compared our theoretical results pertaining to the maximum photocurrent generated under the effect of the optimum reflected light to the numerical results established by Bergmann et al. in order to enhance the reliability of our theory. The effect of the reflectance of the multi-layered structure (QMPS layer) on the increase of the photocurrent density ΔJ_{ph}, as well as the cell efficiency $\Delta\eta$ is also studied.

2. Theoretical model

We consider an n$^+$pp$^+$ solar cell structure with a QMPS at the back (p$^+$ type), as illustrated in Fig. 1. The total photocurrent density $J_{ph}(\lambda)$ at a wavelength of an elementary cell under illumination can be written as follows:

$$J_{ph}(\lambda) = J_{ph,0}(\lambda) + J_{ph,1}^R(\lambda) + J_{ph,2}^R + J_{ph}^{QMPS}(\lambda) \tag{1}$$

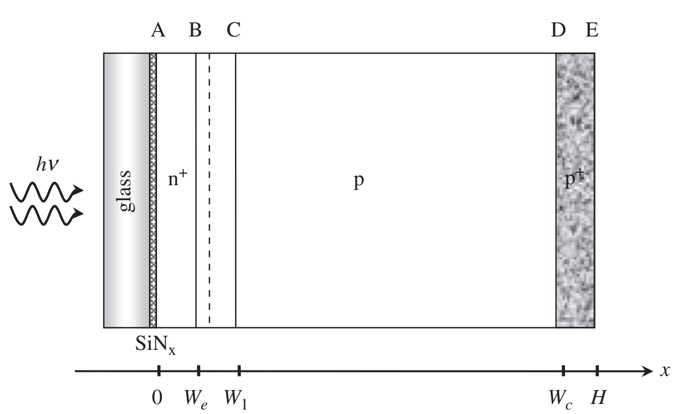

Fig. 1. One-dimensional schematic model of an elementary solar cell with a QMPS layer on the rear side.

where $J_{ph,0}(\lambda)$ is the total photocurrent density collected from different regions in a conventional BSF silicon solar cell [12]. As for the other components they stand for the following: $J_{ph,1}^R(\lambda)$ is the photocurrent density contributed to by the photo-generated carriers within the base and the emitter regions due to reflected light by the rear surface, $J_{ph,2}^R(\lambda)$ is the photocurrent density contributed to by the presence of a second optically rough front surface, and $J_{ph}^{QMPS}(\lambda)$ is the photocurrent density contributed by the absorbed light in the QMPS layer. The solution of the current continuity equation for $J_{ph,2}^R(\lambda)$ is similar to the n$^+$ and p regions except for the generation rate of minority carriers that decreases the level $R_d \exp(-2\alpha W_c)$ where R_d is the reflectance at the back region.

2.1. Photocurrent density contributed by the reflected light

The increase in photocurrent density that results from the light reflected by the rear surface is expressed by

$$J_{ph,1}^R(\lambda) = J_{ph,B}^R(\lambda) + J_{ph,E}^R(\lambda) \tag{2}$$

where $J_{ph,B}^R(\lambda)$ and $J_{ph,E}^R(\lambda)$ are the photocurrent densities collected from the base and the emitter regions, respectively.

Under illumination, the diffusion equation in the base region affects the reflected light, and may be written as follows:

$$D_n \frac{d^2(\Delta n)}{dx^2} - \frac{\Delta n}{\tau_n} = -g_{ref}(x,\lambda) \tag{3}$$

where Δn represents the concentration of the excess minority carriers (electrons) and D_n and τ_n are the minority electron diffusion constant and lifetime in the p-region, respectively. The generation rate of minority carriers (electron) for the reflected light is given by

$$g_{ref}(x,\lambda) = (1-R)R_d \phi\alpha \exp(-\alpha(2W_c - x)) \tag{4}$$

The boundary conditions for the base photocurrent case are as follows:

$$\Delta n(x = W_1) = 0 \quad (\text{at } x = C) \tag{5}$$

$$\left.\frac{d\Delta n}{dx}\right|_{x=W_c} = -\frac{S_{e,pp^+}}{D_n}\Delta n(x = W_c) \quad (\text{at } x = D) \tag{6}$$