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A Methodology to account for the Finger Non-Uniformity in Photovoltaic Solar Cell

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Abstract

In this work we investigate the impact of a non-uniform finger in the front-side metallization on the performance of c-Si solar cells. For this purpose, we propose a methodology based on a mixed-mode simulation approach, which allows evaluating the solar cell properties by performing both numerical device simulations and circuit simulations. The finger roughness profile is modeled by means of Gaussian function. The impact of roughness on the solar cell efficiency is studied as a function of mean finger height, mean finger width and finger resistivity. The proposed methodology has been applied to typical roughness profiles realized with two different metallization techniques, the conventional single screen-printing (SP) and the double screen-printing (DP).

Keywords: solar cell; double screen-printing; finger roughness, finger non-uniformity, circuit simulation

1. Introduction

The design of the front-side metallization of solar cells must achieve a trade-off between contrasting requirements: improving the current carrying capability of the contacts by increasing the overall cross section of the metalized lines and increasing the light collection by reducing the shaded area on the cell's front surface [1-6]. DP is a well-established industrial process which allows to increase the finger aspect

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ratio and to reduce the silver paste consumption, and hence, the cost per watt. Furthermore, this method allows an improved control of the width and the height of the finger [3-5]. For a typical industrial solar cell, the main contribution to the series resistance comes from the finger line resistance, which accounts for roughly 40% [6]. The morphology of printed fingers is strongly affected by the screen characteristics (mesh count, open area) and the process parameters; finger roughness is detrimental for line conductivity because the local reduction of the finger height and cross-section area causes an increase of the equivalent series resistance. Proper modeling tools to quantitatively evaluate the impact of the finger roughness on the series resistance are mandatory to guide the metallization design and optimization. This work aims to develop a methodology for evaluating the impact of the finger roughness on the solar cell performance and to apply the proposed methodology to typical finger profiles realized with conventional SP and DP technology.

2. Methodology and Experimental

The proposed methodology is based on a mixed-mode simulation approach, which allows evaluating the solar cell properties by performing both numerical device simulations and circuit simulations.

Numerical device simulation is performed by means of Sentaurus TCAD simulator and allows evaluating a 2-dimensional domain of the cell which does not account for the conduction through the finger, referred as Simulation Block (SB) in Fig. 1. We considered c-Si solar cell 180μm thick with a uniform boron-doped base of 10^{16} cm^{-3} (1.5 Ωcm) and a 65 Ω/□ (phosphorous-doped) homogeneous emitter (peak concentration of 1.26 10^{20} cm^{-3} and junction depth of 0.4 μm) [5].

In order to account for the losses due to the finger resistance, circuit simulations are performed with SPICE simulator as schematized in Fig. 1. Each elementary block of the discretized finger can be modeled with a resistance R_i.

$$R_i = \rho_f \frac{\Delta L}{A_i} \tag{1}$$

$$A_i = H_i \cdot W_f \cdot F \tag{2}$$

$$\sigma_A = \sigma_H \cdot W_f \cdot F \tag{3}$$

ΔL is the length of the elementary block, W_f is the finger width, H_i and A_i are the finger height and cross-section area of the i-th elementary block, ρ_f is the finger resistivity and F is a correction factor that takes into account for the non-rectangular shape of the finger cross-section. By considering a constant metal width along the finger, the standard deviation of the cross-section area σ_A can be accounted by considering the standard deviation the finger height σ_H only, see eq. (2) and (3).

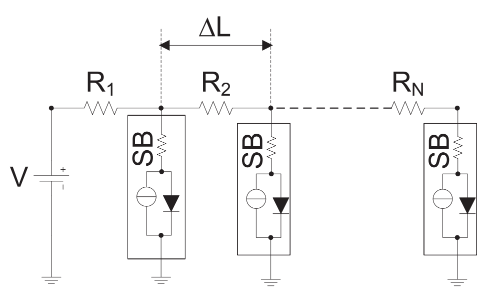

Fig. 1. (a) Equivalent circuit of a solar cell. The Simulation Block (SB) is obtained from Sentaurus simulations. The finger resistance R_i is calculated based on eq. (1)

In order to fully understand the impact of finger roughness and how the finger parameters affect the solar cell performance, we will consider a rough finger profile analytically generated. We define an average height H_m and an autocorrelation function for the height fluctuations [7]. The gaussian and the exponential type of autocorrelation function will be considered. The power spectrum for the Gaussian autocorrelation function is given by

$$S_E(k) = \sqrt{\pi}\sigma_H^2 \xi \exp\left(-\frac{k^2\xi^2}{4}\right) \tag{4}$$

and for the exponential type is given by

$$S_E(k) = \frac{2\sigma_H^2 \xi}{1 + k^2\xi^2} \tag{5}$$

where ξ is the correlation length, which defines an average period of the oscillations of the finger height, and $k = I\,(2\pi / N\,\Delta L)$, where N is the number of elementary blocks and $0 < I < N/2$.

Fig. 2 shows typical 3D profiles of metal fingers measured with a laser profilometer in the case of SP and DP which were used to calculate the cross-section area and the finger height, as a function of the longitudinal position. In Table 1, we reported the average value of the finger width (W_f), height (H_m) and area (A_m), as well as the standard deviation of the height and area fluctuations. We found out that the same correction factor F satisfies both eq. (2) and eq. (3), meaning that the major source of fluctuations are related to the finger height. Moreover the correlation length ξ is evaluated for both SP and DP profiles.

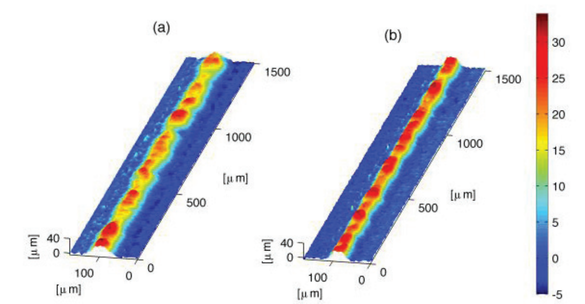

Fig. 2. Measured finger profiles for single printing (a) and double printing (b) technology

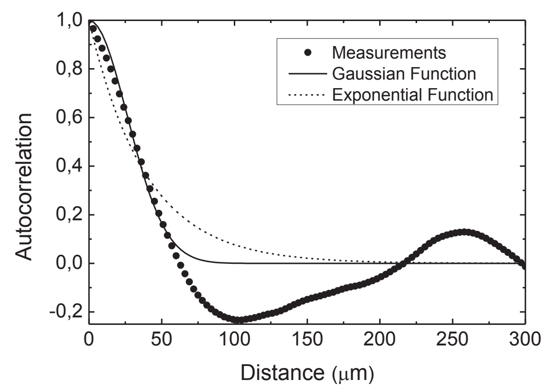

Fig. 3. Fitting of the autocorrelation function related to measured profile of the SP finger (parameters are reported in Table I) with two types of function: gaussian and exponential

Table 1. Experimental parameters of SP and DP metallization

	W_f (μm)	H_m (μm)	A_m (μm^2)	σ_H (μm)	σ_A (μm^2)	F	ξ (μm)
SP	95	20.7	1002.9	5.1	247.0	0.51	36.2
DP	75	23.9	932.1	3.9	140.4	0.52	24.6

The autocorrelation of the finger height, calculated on an experimental profile, is reported in Fig. 3. We can observe that the gaussian function better matches the experimental data. For this reason, in the reminder of the paper we will consider the gaussian autocorrelation function for the profile generation. In order to fully understand the impact of finger roughness and how the finger parameters affect the solar cell performance, we will consider a finger profile randomly generated. The finger parameters to be investigated are: standard deviation of the height, average height, metal resistivity and width.

By comparing the IV curve of the Simulation Block and the IV curve resulting from the circuit simulation the equivalent series resistance, due to the finger, can be easily calculated as

$$R_F = \frac{\Delta V}{I_0} \qquad (6)$$

where ΔV is the difference of voltage between the two IV curves evaluated at the same I_0 current density.

3. Results and Discussion

In Fig. 4 we report the equivalent finger resistance dependence on the finger roughness, on the mean finger height, on the finger resistivity and on the printing process (SP or DP). The finger resistance has been calculated according to (6). In Fig. 5a and Fig. 5b the efficiency of the solar cell is evaluated as a function of the finger roughness for both SP (W_f = 95µm) and DP (W_f = 75µm), in case of metal resistivity of 3 10^{-3} mΩ·cm and 6 10^{-3} mΩ·cm, respectively. Similar trends are observed for the series resistance and the efficiency. As expected, an increase of finger roughness results in a degradation of efficiency. For example, in case of SP with ρ_f = 6 10^{-6} Ω·cm and H_m = 20µm, the efficiency degradation at σ_H = 5µm is $\Delta\eta$ = 0.03%$_{abs}$. The degradation typically increases when the finger resistivity is higher (since the fluctuations in the resistance of each elementary block are proportional to the metal resistivity). Another important observation from Fig. 5 is that the impact of roughness on the efficiency is higher when te

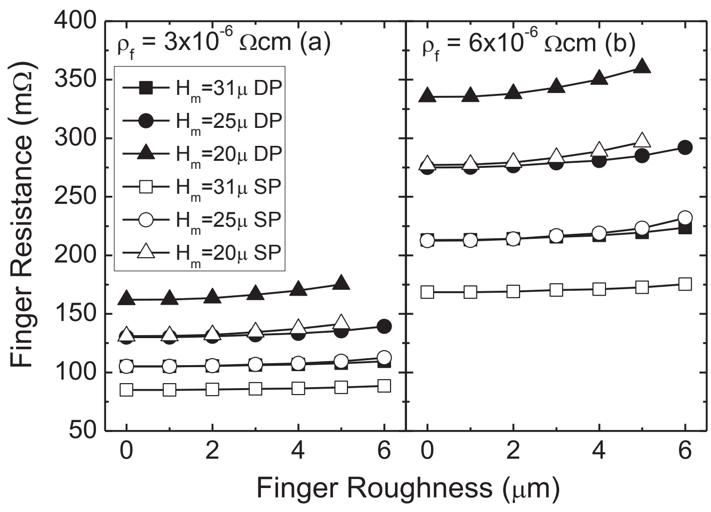

Fig. 4. Finger resistance as a function of the roughness for different H_m. The parameters of the finger are: length 5.05cm, ξ = 25µm.

average height H_m reduces. In fact, for a given height roughness, the reduction of H_m increases the probability to find elementary blocks with a very small height (very large resistance), which acts as a bottleneck. Moreover, for a given average height and finger roughness, the efficiency gain of DP over SP increases when reducing the metal resistivity. For example, by considering H_m = 25µm and σ_H = 6µm, the efficiency gain reduces from $0.15\%_{abs}$ for $\rho_f = 3\ 10^{-6}$ Ω·cm to $0.12\%_{abs}$ for $\rho_f = 6\ 10^{-6}$ Ω·cm. Finally, if we consider all the experimental parameters reported in Table 1, the efficiency gain of DP compared to SP is $\Delta\eta = 0.19\%_{abs}$ for $\rho_f = 3\ 10^{-6}$ Ω·cm and $\Delta\eta = 0.17\%_{abs}$ for $\rho_f = 6\ 10^{-6}$ Ω·cm.

4. Conclusions

In this work, we propose a methodology aimed to investigate the impact of finger non-uniformity on the performance of photovoltaic solar cells. The methodology is based on a mixed-mode simulation approach, which allows to evaluate the solar cell properties by performing both numerical device simulations and circuit simulations.

Typical roughness profiles have been experimentally measured in case of conventional single screen-printing (SP) fingers and the double screen-printing (DP) fingers. The auto-correlation of the fingers is well represented by a Gaussian correlation function. By using the proposed methodology and by synthesizing the finger roughness with random profiles generated with a Gaussian autocorrelation function we found that: i) the equivalent finger resistance depends on the bias point; ii) an increase of finger roughness causes a degradation of efficiency; iii) the impact of finger roughness reduces when the metal resistivity is decreased; iv) taller finger are less affected by the height fluctuations; v) the advantage of DP over SP are higher in case of smaller metal resistivity. Finally, by calibrating the finger properties with the experimental data of DP and SP, simulation reveals an efficiency gain of DP with respect the SP of $0.19\%_{abs}$.

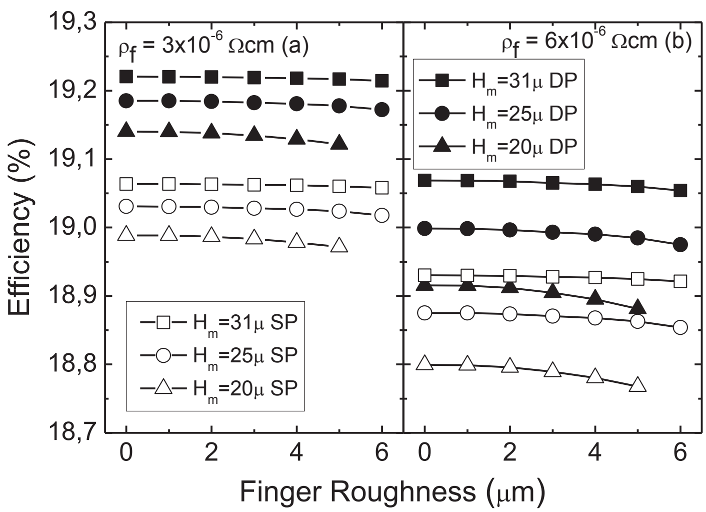

Fig. 5. Efficiency as a function of finger roughness for different H_m. For DP: W_f =75µm, finger length 5.05cm, F = 0.52 ξ = 25µm. For SP: W_f = 95µm, finger length 5.05cm, F = 0.51 ξ = 25µm

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