Broad-band light-trapping in thin film crystalline silicon solar cells with engineered disordered photonic structures

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Abstract: We theoretically investigate light trapping in thin film crystalline silicon solar cells. By using one-dimensional photonic patterns and adding Gaussian disorder, the short-circuit current is increased up to values that nearly approach the Lambertian limit.

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OCIS codes: (040.5350) Photovoltaic, (050.5298) Photonic crystals.

1.   Introduction

In recent years light trapping with photonic crystal patterns has emerged as a hot research topic in order to develop high efficiency and low cost thin film solar cells. Up to now, many efforts have been made for the optimization of ordered structures, with typical periods comparable with the wavelength of solar light. Two physical effects play a major role in these nano-patterned devices: reduction of reflection losses, and coupling of light to the quasi-guided modes supported by these structures [1]. The latter effects are very important, especially for indirect band gap semiconductors like c-Si, which suffer from poor absorption in the infrared region. To quantify the absorption enhancement provided by patterns, a comparison with the Lambertian limit to light trapping is usually performed [2, 3]. It turns out that after an optimization of a simple periodic pattern, the overall absorption is still far from the Lambertian limit. In terms of the short-circuit current density J_{sc}, the best results are intermediate between the planar reference configuration and the Lambertian limit [1]. The reason is that for periodic structures only few diffraction orders can be excited and used for light trapping, hence a broader band light trapping scheme is needed. Here we suggest that the introduction of a controlled amount of Gaussian disorder in the photonic pattern might be the way to excite more diffraction orders and couple more light inside the solar cells.

2.   Structures under investigation and numerical methods

The structures under investigation are schematically shown in Fig. 1. To demonstrate the physical effects that are responsible for the absorption enhancement keeping a reasonable computational time, we limit our analysis to 1D structures and, correspondingly, generalise the light-trapping limit of Ref. [3] (which is valid for the case of arbitrary absorption) to the 1D case.
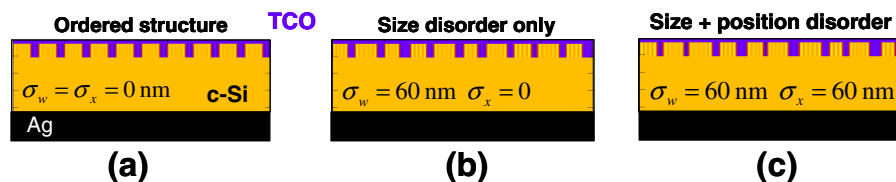

Fig. 1. Structures of the crystalline silicon solar cells under investigation: ordered structures **(a)**, structures with size disorder only **(b)**, and structures with both size and position disorder **(c)**.

The ordered structure is sketched in Fig. 1(a): a c-Si slab with thickness of 1 μm is etched on its front surface with an etching depth h=200 nm, silicon fraction f_{Si}=0.7, and with a period Λ=500 nm. These values are those that maximize the short-circuit current density [1], which is assumed as the figure of merit for this work. To improve this design, a
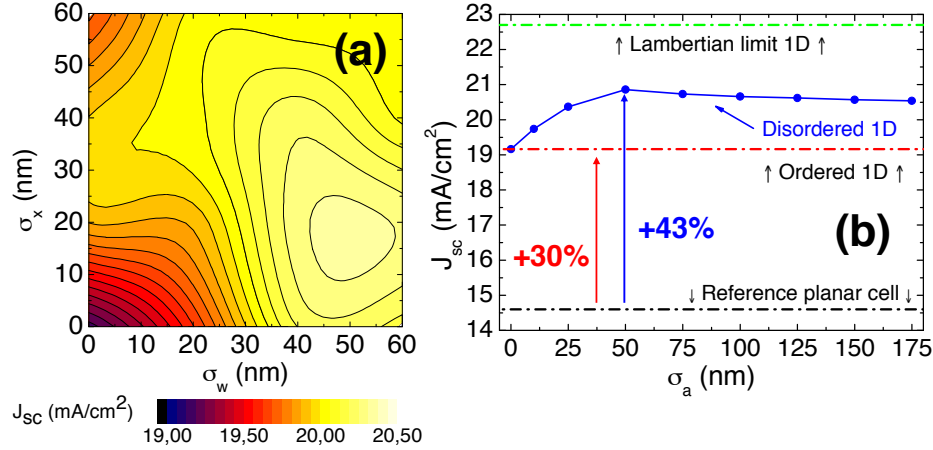
Fig. 2. Countour plot of the short circuit current density varying the disorders (σ_w, σ_x) **(a)**, and short circuit current density varying the disorder σ_a for the case of correlated Gaussian disorder **(b)**.

controlled amount of Gaussian disorder is introduced in the unit cell, as shown in Figs. 1(b) and 1(c). In the framework of a Fourier analysis we consider a super cell of length a=5 μm containing 10 silicon ridges of width w_i and centre at the position x_i. The width of the silicon elements is $w_i=w_0+\Delta w_i$, where the index i runs from 1 to 10, w_0 is the width of the ridge in the optimized periodic 1D lattice, and the quantity Δw_i follows a Gaussian distribution with zero average and standard deviation σ_w:

$$P(\Delta w_i) = \frac{1}{\sqrt{2\pi}\sigma_w}e^{-\Delta w^2/2\sigma_w^2}. \tag{1}$$

The positions of the centres of the silicon elements are $x_i = x_{i0} + \Delta x_i$, where x_{i0} is the position of the centre of the ith ridge in the ordered configuration, and the quantity Δx_i is Gaussian distributed with zero average and standard deviation σ_x:

$$P(\Delta x_i) = \frac{1}{\sqrt{2\pi}\sigma_x}e^{-\Delta x^2/2\sigma_x^2}. \tag{2}$$

The standard deviations σ_w and σ_x have been varied from 0 to 60 nm, where this upper limit is given by overlapping between the silicon elements inside the unit cell. The etching depth h and the silicon fraction f_{Si} are the same of the ordered configuration. We calculated the optical spectra of these photonic structures using Rigorous Coupled Wave Analysis [1, 4, 5].

3.   Results

In our analysis we calculated the short-circuit current density J_{sc} for 20 equivalent structures with the same σ_w and σ_x. In Fig. 2(a) we show the J_{sc} for the best configuration as a function of σ_w and σ_x. Two main features emerge from this plot: the J_{sc} increses from J_{sc}=19.1 mA/cm^2 (ordered structure) up to J_{sc}=20.4 mA/cm^2 (optimized disorder, σ_w=50 nm and σ_x=20 nm); and the maximization of J_{sc} requires correlation between σ_w and σ_x, in particular the maximum lies along the line $\sigma_w=2\sigma_x$. This result suggests that a different analysis based on the use of a single statistical parameter σ_a can be performed. In particular, the maximization of J_{sc} can be done by taking:

$$\sigma_w = f_{Si}\sigma_a \quad \sigma_x = \frac{f_{Si}\sigma_a}{2} \quad \Longleftrightarrow \quad \sigma_w\sigma_x = \frac{f_{Si}^2\sigma_a^2}{2}. \tag{3}$$

In this way, the analysis of the disorder is much faster, since only one parameter is involved. For each value of σ_a we calculated the J_{sc} for 50 equivalent structures. The best results are shown in Fig. 2(b), together with a comparison with the reference planar cell with the same thickness, and with the corresponding 1D Lambertian limit. As it is shown, upon adding the Gaussian disorder the J_{sc} increases from 14.6 mA/cm^2 for the planar configuration up to 20.9 mA/cm^2 for the best disordered configuration (σ_a=50 nm), with an increase up to +43%. This value is very close to

the 1D Lambertian limit (J_{sc}=22.7 mA/cm^2). For comparison, with an optimized 1D ordered structure the maximum enhancement is only +30%. A better insight of the effect of the disorder can be obtained by looking at the spectral contributions dJ_{sc}/dE to the short-circuit current density shown in Fig. 3.
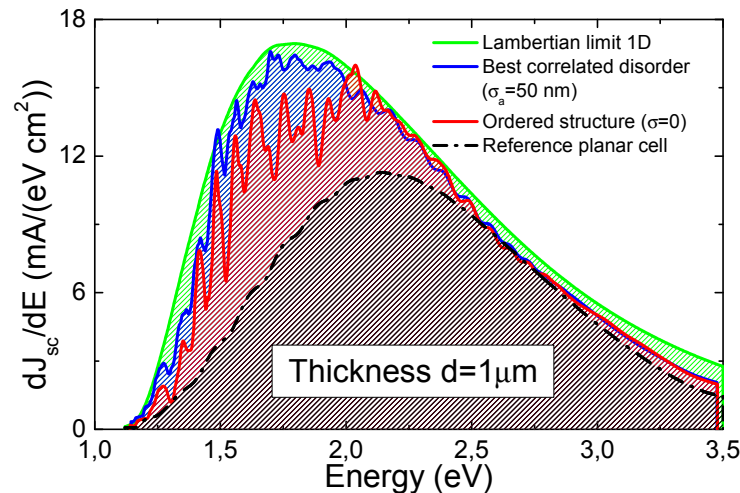

Fig. 3. Spectral contributions dJ_{sc}/dE to the short-circuit current for the reference planar configuration (black dash line), for the optimized 1D ordered structure (red line), for the optimized correlated disordered structure (blue line), and for the corresponding 1D Lambertian limit (green line).

As expected, the reference planar configuration, which has no pattern, suffers from poor absorption below 2 eV. In the optimized ordered structure the absorption is increased via diffraction, which couples the incident light to the quasi-guided modes. However, such absorption is still far from the Lambertian limit, and deep minima are evident below 2 eV. A better result is obtained with the engineered Gaussian disorder, which increases the fraction of light coupled into the device below 2 eV, giving an absorption very close to the 1D Lambertian limit. These results demonstrate that a proper combination of order and disorder is a promising route towards an optimal design for light-trapping.

4.   Conclusions

We theoretically investigated light trapping in thin film crystalline silicon for solar cells comparing ordered and disordered 1D designs. Disordered structures are found to perform better than the ordered ones, since the coupling of light to the quasi-guided modes is enhanced. The disorder has been analyzed and engineered, paying special attention to the benefits of the correlation between size and positional disorder, which maximizes the short-circuit current developed by the devices. Our best results are very close to the Lambertian limit in 1D.

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