Optimizing Gaussian Disorder at Rough Interfaces for Light Trapping in Thin-Film Solar Cells

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Abstract: We present a theoretical study of rough interfaces to obtain light trapping in thin-film silicon solar cells. Disorder parameters were optimized by rigorous calculations with short-circuit current density as a figure of merit.

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1. Investigated Structure and Model of Gaussian Disorder

Reducing solar cell active layer thickness improves quality of the films and decreases material consumption [1]. Yet, the device performance deteriorates due to poor absorption, especially in thin crystalline silicon layers which are the focus of this work. For this reason increasing optical thickness of the device by light-trapping [2] is a fundamental issue in thin-film solar cell design. A particularly interesting approach to obtain light-trapping is the use of properly optimized rough interfaces [3, 4].

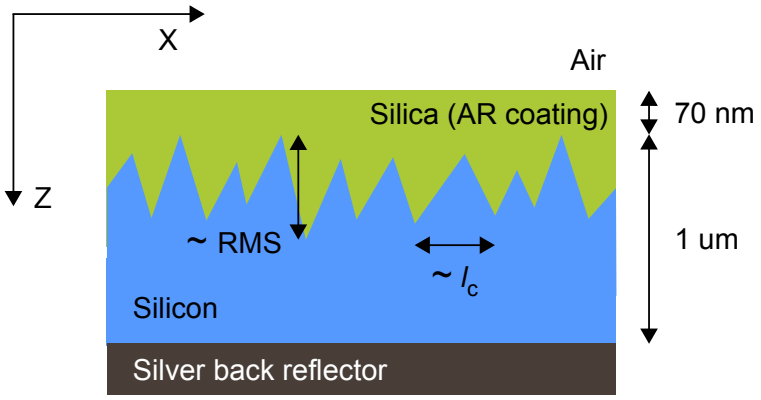

Fig. 1. Investigated structure with rough interface incorporated in 1 μm thick crystalline silicon slab.

The investigated structure is shown in Fig. 1. It consists of a 70 nm thick homogeneous SiO_2 layer on a 1 μm thick crystalline silicon slab, and a silver back reflector. The top layer is used as an anti-reflection (AR) coating, while the rough interface between the silicon and silica layers is responsible for light trapping. Optical functions for c-Si were taken from Ref. [5].

Here we consider a one-dimensional rough interface, which is described by the root mean square (RMS) of height σ_{RMS} and the correlation length l_c [6]. The correlation length is proportional to the lateral size of the roughness features, and it is defined as the distance at which the normalized Gaussian correlation function $W(|x|) = \exp\left(-x^2/l_c^2\right)$ decreases by $1/e$ [7]. The algorithm used here to generate random surface profiles with given statistical parameters σ_{RMS} and l_c was derived in Ref. [8]. Analogous models were used previously for treating diffraction losses in photonic crystal waveguides [9].

2. Numerical Methods

Absorbance spectrum $A(E)$ in the active layer was obtained by solving Maxwell's equations using Rigorous Coupled-Wave Analysis [10, 11]. In our approach we require structures composed of layers that are periodic in the plane of the

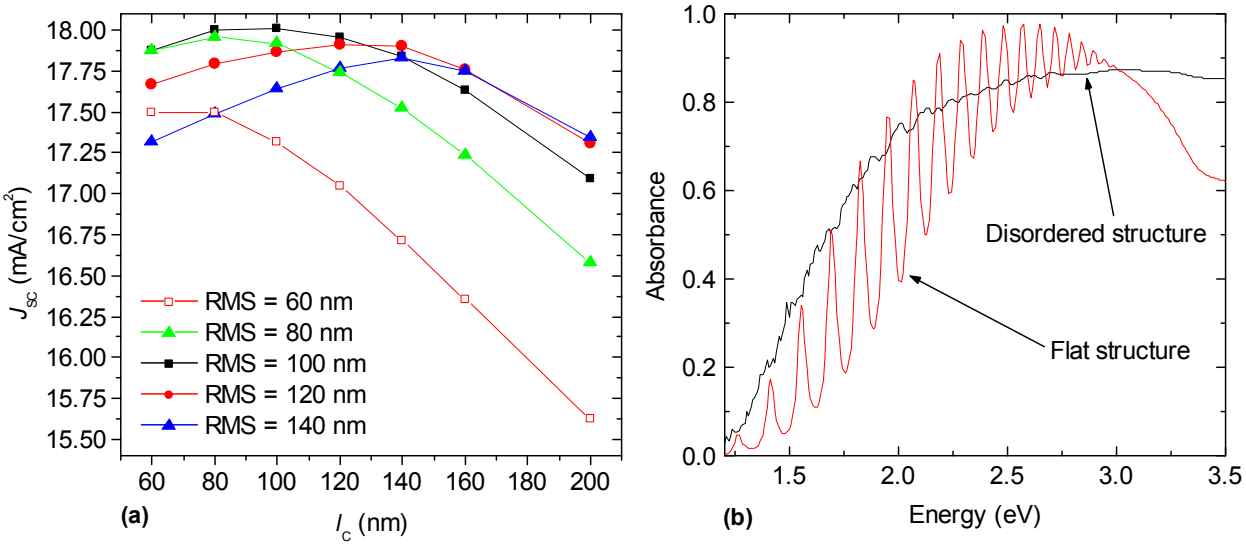

Fig. 2. (**a**) Short-circuit current density as a function of correlation length for several different values of surface profile RMS. In the case of flat structure ($\sigma_{\mathrm{RMS}} = 0\,\mathrm{nm}$) $J_{\mathrm{SC}} = 14.3\,\mathrm{mA/cm^2}$. (**b**) Absorbance spectra for structure with optimal disorder parameters ($l_c = \sigma_{\mathrm{RMS}} = 100\,\mathrm{nm}$) compared with absorbance spectra for flat structure ($\sigma_{\mathrm{RMS}} = 0\,\mathrm{nm}$).

cell and homogeneous in the other direction. Thus, the rough surface profile was discretized in the vertical direction, and we considered a computational cell sufficiently large to neglect effects of periodicity.

The short-circuit current density can be taken as a good figure of merit [12], and it can be calculated directly from the absorbance spectrum as [13]:

$$J_{\mathrm{SC}} = e \int A(E) \frac{\mathrm{d}N}{\mathrm{d}E} \mathrm{d}E, \tag{1}$$

where e is the electron charge, and $\mathrm{d}N/\mathrm{d}E$ is the number of photons with energy in the range of $(E, E + \mathrm{d}E)$ incident on unit area in unit time. Here we assumed 100% e-h collection efficiency (i.e., unitary internal quantum efficiency). Lower and upper limits for integration range were set to 1.2 eV and 3.5 eV respectively. As in our previous work [12, 14], incident solar spectrum was approximated with black body spectrum at temperature of 5800 K normalised to the standard irradiance of $100\,\mathrm{mW/cm^2}$.

3. Results and Discussion

Results of random surface optimization are presented in Fig. 2 (a) where the short-circuit current density is plotted as a function of correlation length for several different values of surface profile RMS. Since we aim at correlating absorption enhancement with a given set of disorder parameters (σ_{RMS} and l_c) rather than with a particular surface realization, each point in the figure corresponds to an average over an ensemble of ten different surface realizations with the same statistical parameters.

It can be seen that the highest short-circuit current density is achieved for $l_c = \sigma_{\mathrm{RMS}} = 100\,\mathrm{nm}$, but with some tolerance to different values of correlation length. For comparison, in the case of flat structure ($\sigma_{\mathrm{RMS}} = 0\,\mathrm{nm}$) we obtained $J_{\mathrm{SC}} = 14.3\,\mathrm{mA/cm^2}$.

Absorbance spectra for structure with optimal disorder parameters and structure with flat $\mathrm{Si/SiO_2}$ interface are compared in Fig. 2 (b). It is shown that disordered structure performs considerably better in low energy range, whereas flat structure gives higher absorbance in high energy range. It can be explained by the fact that AR coating layer on the top of the device is not optimized and anti-reflection action is not sufficient. Results can also be interpreted in terms of angular distribution function (ADF) and haze of transmitted radiation. Further research focused on disordered structures for light trapping in thin-film solar cells and improving anti-reflection action, with reference to both crystalline silicon and amorphous silicon solar cells, is in progress.

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