DISORDER ENGINEERING FOR LIGHT-TRAPPING IN THIN-FILM SOLAR CELLS

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ABSTRACT: In this work we focus on randomly rough textures for light-trapping in thin-film silicon solar cells. We use a simple but accurate model of Gaussian roughness, and with rigorous calculations we demonstrate that optimized rough textures allow to approach the Lambertian Limit of absorption. These results are explained by a detailed analysis of the roughness optical properties, which can be easily correlated with the absorption enhancement in the solar cell absorber. Finally, we compare structures based on *crystalline* and *microcrystalline* silicon, to investigate the role of light-trapping as a function of *size* and *nature* (direct or indirect) of the energy band gap.
Keywords: light-trapping, thin films, roughness

1 INTRODUCTION

Proper light management is a key to achieve high efficiency thin-film solar cells, and a wide variety of light-trapping strategies has already been suggested [1,2,3]. In this regard, randomly rough textures [4] are particularly promising as intrinsically broadband scatterers, which can be optimized for a wide wavelength range, and simultaneously meet different requirements for light-trapping in different parts of the solar spectrum. Yet, the description of a realistic rough topography is complicated, which makes the optimization of such textures difficult.

In this work, we use a simple but accurate model of Gaussian roughness [5] to study in details light-trapping mechanism in thin-film solar cells with rough interfaces. With rigorous calculations we demonstrate that optimized rough textures allow approaching the Lambertian Limit of absorption [6]. These results are explained in terms of optical properties of the roughness. We also compare crystalline and microcrystalline silicon solar cells to investigate the role of light-trapping as a function of the properties of the energy band gap.

2 MODEL OF ROUGHNESS AND NUMERICAL APPROACH

We model rough textures as a one-dimensional Gaussian roughness, described by the root mean square (RMS) deviation of height σ and the lateral correlation length l_c. The algorithm used to generate randomly rough surface with a given statistical parameters has been derived in Ref. [7].

Optical properties of the considered rough interfaces and solar cells are modeled with Rigorous Coupled-Wave Analysis (RCWA) [8], with roughness described by the staircase approximation. The period of the computational cells is equal to 10 μm, much larger than the lateral correlation length of the roughness, which allows to neglect the effects of periodicity.

To validate this approach, we calculated Angular Intensity Distribution (AID) and haze of the monochromatic light transmitted through the rough interface with σ and l_c corresponding to the Neuchâtel or Asahi-U substrate. Then, we compared our results with the calculations performed for the two-dimensional measured topographies [9], obtaining very good agreement [5], and confirming that this simple model of roughness is capable of describing the optical properties of commonly used two-dimensional rough textures.

Reducing the dimensionality of the optical problem was possible, because the optical properties of the rough interfaces are isotropic. Therefore, instead of performing the calculations for 2D textures, we averaged the results obtained for an ensemble of 1D rough surface realizations. This step allowed to obtain accurate results at the significantly reduced computational cost.

3 TAILORING THE ROUGHNESS FOR LIGHT-TRAPPING

Solar cell structure investigated in this work, sketched in Fig. 1, consist of 1 μm thick crystalline absorber [10], 70 nm thick anti-reflection coating (ARC), and a silver back reflector [10]. The ARC is transparent, with refractive index equal to $n_{ARC} = 1.65$.

For the light-trapping optimization, we consider short-circuit current density J_{SC} as an appropriate figure of merit, since it reflects spectral features of the sunlight. J_{SC} is calculated following Ref. [11], considering AM1.5G spectrum [12] between 1.1-4.2 eV, and assuming unity carrier collection efficiency. For the structure sketched in Fig. 1, we calculated J_{SC} as a function of σ, from 0 to 300 nm, and l_c, from 60 and 220 nm. For different parameters of the rough interface, we kept the volume of silicon constant and equal to the volume corresponding to 1 μm thick absorber with a flat ARC/Si interface.

The results of the optimization, shown in Fig. 2, revealed that J_{SC} mainly depends on σ, with a modest, in this parameter range, bell-like dependence on l_c.

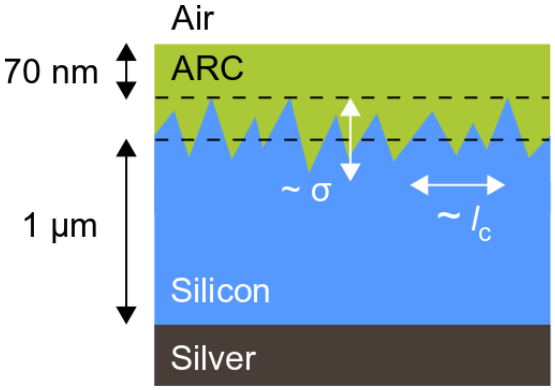

Figure 1: Investigated solar cell structure with 1 μm thick silicon absorber. The rough interface between transparent anti-reflection coating (ARC) and silicon is described by RMS deviation of height σ and lateral correlation length l_c.

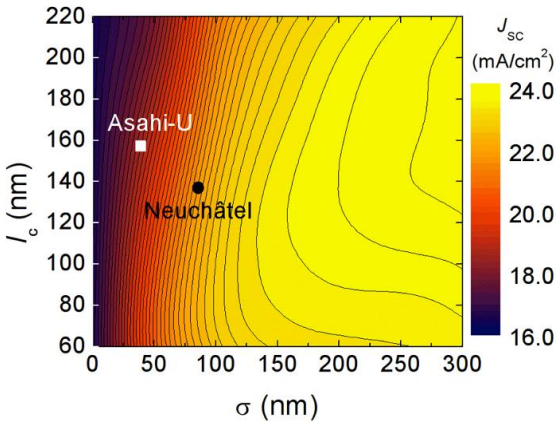

Figure 2: Short-circuit current density as a function of lateral correlation length l_c and RMS deviation of height σ, calculated for 1 μm thick c-Si solar cell sketched in Fig. 1.

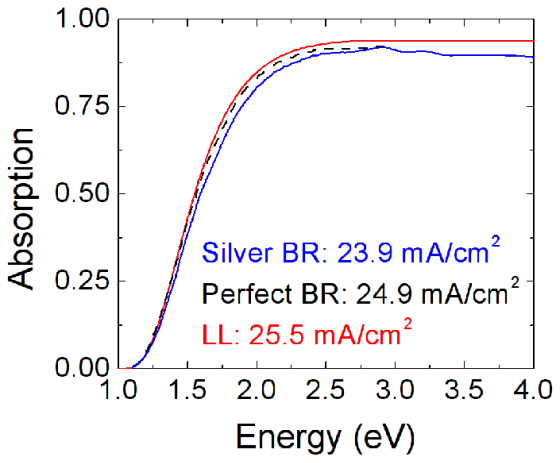

Figure 3: Absorption in 1μm thick c-Si solar cell with the optimized rough interface (σ = 300 nm, l_c = 160 nm), compared with the corresponding one-dimensional Lambertian Limit. To quantify the losses in the silver back reflector, structure with a perfect mirror was also considered.

In Fig. 3, absorption in 1μm thick c-Si solar cell with the optimized rough interface (σ = 300 nm, l_c =160 nm) is compared with the corresponding one-dimensional Lambertian Limit [13]. To provide more accurate comparison, reflection losses at the Air/ARC interface were included in the Lambertian Limit. Moreover, derivation of the Lambertian Limit assumes perfect back reflector, thus we performed additional calculations, replacing silver with a perfect metal. This allows to quantify losses at the rear surface. It can be seen that in the low energy range, absorption calculated for the structure with a perfect back reflector follows the theoretical limit. Small discrepancy can be seen only in the high energy region, where the effective wavelength in silicon becomes smaller than the correlation length of the roughness. The solar photon flux in this region, however, is small anyway.

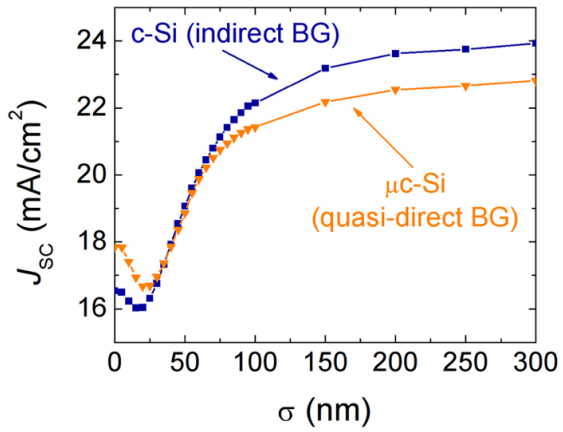

Figure 4: Short-circuit current density as a function of RMS deviation of height σ of the rough interface, calculated for 1 μm thick c-Si and μc-Si solar cells. Lateral correlation length is equal to l_c = 160 nm.

4 LIGHT-TRAPPING AND ENERGY BAND GAP

To explore the difference in the optical performance between materials with different energy band gaps, we calculated short-circuit current density as a function of σ for 1 μm thick c-Si and μc-Si [14] solar cells. Lateral correlation length was equal to l_c = 160 nm, which was found to be the optimal value for both materials. The results, shown in Fig. 4, indicate that for the flat structure, absorption in the c-Si solar cell (indirect band gap) is lower than absorption in the μc-Si solar cell (quasi-direct band gap). Yet, when the roughness is large enough, the c-Si structure outperforms the one made of μc-Si.

Relative J_{SC} enhancement, compared with the structure with a flat ARC/Si interface, for c-Si and μc-Si is 45.6% and 28.1%, respectively. At the same time, for flat cells, J_{SC} for μc-Si was nearly 8% higher than for c-Si. Therefore, as long as efficient light-trapping is provided, the material with a lower band gap gives a higher absorption, regardless of the nature (direct or indirect) of the energy band gap.

This behavior can be explained by the fact that the c-Si solar cell with the optimal rough texture can absorb more light, comparing to the μc-Si structure, in the energy region close to the c-Si band gap, where the AM1.5G spectrum is particularly rich.

5 SCATTERING PROPERTIES OF ROUGH INTERFACES

Light transmitted through the rough texture can be described by: 1) Angular Intensity Distribution (AID), which gives the intensity of scattered light as a function of the scattering angle, and 2) haze, which is the ratio of the intensity of scattered light to the total intensity of transmitted light [15].

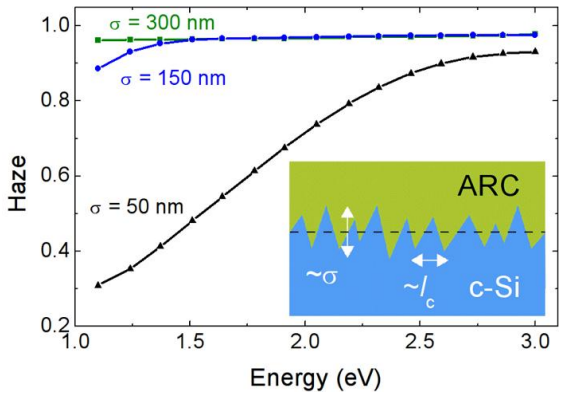

Figure 5: Haze of transmitted light as a function of energy for increasing RMS deviation of height σ and l_c = 160 nm, calculated for the rough interface sketched in the inset. Both ARC and c-Si layers are assumed to be semi-infinite.

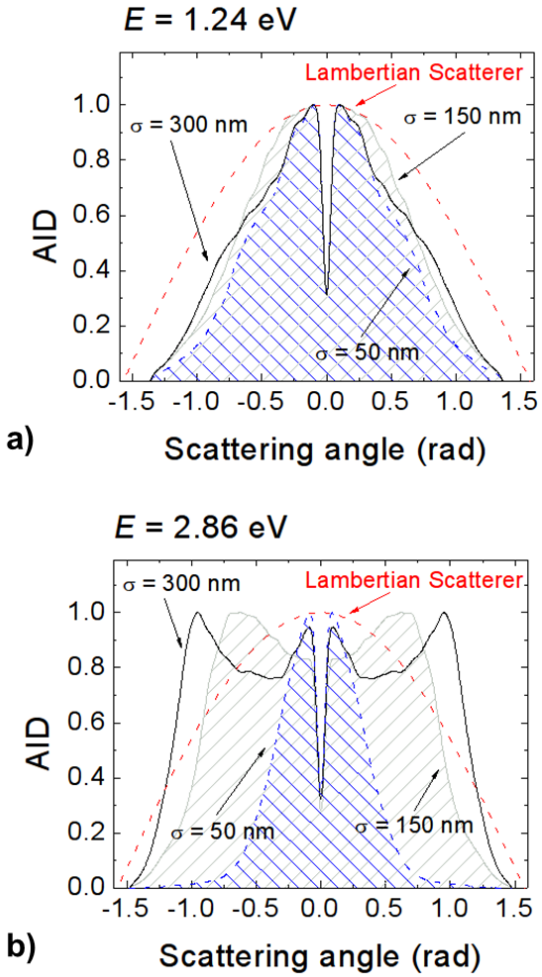

Figure 6: Angular Intensity Distribution (AID) of transmitted light at (a) E = 1.24 eV and (b) E = 2.86 eV, calculated at three values of σ and for l_c = 160 nm.

In Fig. 5, we show haze as a function of energy for increasing σ and the optimal l_c = 160 nm. For a modest σ = 50 nm, the haze increases steadily with the energy, from 0.3 up to 0.9. High haze is obtained for σ = 150 nm and σ = 300 nm. In this case, both curves are identical except small discrepancy in the low energy region. Indeed, J_{SC} saturates above σ = 150 nm, and therefore changes in haze observed for σ larger than this saturation value should be minor.

Angular Intensity Distribution at low and high energy (E = 1.24 eV and E = 2.86 eV) is shown in Fig. 6. For each energy, AID was calculated at three different values of σ and for l_c = 160 nm. When increasing σ, the intensity of light scattered at large angles is also increased, and the shape of the AID becomes less regular, particularly in the high energy region, where AID exhibits two symmetrical peaks at σ = 150 nm and σ = 300 nm. These peaks, observed also in the experimental studies of random textures [16], are attributed to the constructive interference in the rough interface. Moreover, this AID is different from the cosine distribution corresponding to the Lambertian Scatterer. This leads to the somehow unexpected conclusion that in the high energy region, absorption very close to the Lambertian Limit is achieved with the non-Lambertian scattering distribution.

These results give clear correlation between the scattering properties of the interface and J_{SC} enhancement, showing that optimal rough texture scatters the incident light at large angles, and more than 90% of the light is diffused.

6 CONCLUSIONS

In this work, we used a simple and accurate model of Gaussian roughness to demonstrate that optimized rough textures allow to approach the Lambertian Limit of absorption. These results were explained in terms of Angular Intensity Distribution and haze of the light transmitted through the rough interface, showing clear correlation between the optical properties of the interface and absorption enhancement in the solar cell absorber. Moreover, we demonstrated that absorption very close to the Lambertian Limit can be achieved with the non-Lambertian angular distribution of scattered light. Finally, we compared structures based on crystalline and microcrystalline silicon, showing that without light-trapping (small σ), absorption in the structure is mainly governed by the nature (direct/indirect) of the energy band gap, while for efficient light-trapping (large σ), the band gap size is the most important factor.

7 ACKNOWLEDGMENTS

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