

for $\sigma = 80$ nm, compared to $\sigma = 200$ nm, which is necessary to achieve that high J_{SC} in the corresponding structure with a rough interface. Thus, use of a hybrid interface might allow to achieve Lambertian light trapping even with relatively small values of σ that correspond to common (Asahi-U and Neuchâtel) substrates, as shown previously in Fig. 2.

These findings show that a hybrid interface is a promising approach to achieve broad-band absorption enhancement with shallow roughness. As a final remark, we stress that the scattering properties of a hybrid interface are no longer isotropic. Thus, the connection between 1D model and the optical properties of 2D system in the case of a hybrid interface is not as straightforward as it is for isotropic rough interfaces.

7. Conclusions

In this contribution, we have used a simple but accurate model of Gaussian roughness to study light-trapping in thin-film solar cells with rough interfaces. We have considered solar cells made of different materials (c-Si and μ c-Si), showing that without light trapping, absorption in the structure is mainly determined by the *nature* (direct/indirect) of the energy band gap, while for efficient light trapping, the band gap *size* is the most important.

We have demonstrated that short-circuit current density in c-Si and μ c-Si solar cells with optimized roughness is very close to the J_{SC} corresponding to the Lambertian Limit. Since the optical properties of randomly rough interfaces are isotropic, we expect that 2D structures with optimized roughness will approach the 2D Lambertian Limit. This, for an absorbing layer of 1 μ m, would give J_{SC} close to 31.9 mA/cm² for c-Si solar cell and 29.7 mA/cm² for μ c-Si solar cell. Moreover, the optimal parameters of the roughness are expected to be the same for 1D model and for real 2D substrates. We stress that the values of J_{SC} given here include reflection losses at the Air/ARC interface. Assuming perfect anti-reflection action, we calculate J_{SC} in a structure with the 2D Lambertian Scatterer to be 33.9 mA/cm² (c-Si) and 31.6 mA/cm² (μ c-Si).

The concept of a hybrid interface, which is a combination of a randomly rough interface and a diffraction grating, allowed to achieve significant absorption enhancement with a shallow roughness. The purpose in reducing the vertical size of the roughness was to assure good electrical properties of a rough interface. This study confirms that a combination of ordered and disordered photonic structures may be beneficial for light trapping in thin-film solar cells, in line with recent findings documented in the literature for other kinds of systems [7, 10, 34, 41].

Finally, the model of roughness considered here is able to predict the scattering properties of realistic rough surface topographies, such as Neuchâtel and Asahi-U substrates. In view of recent progress in fabrication of thin monocrystalline silicon films and of the possibility of using nanoimprint lithography, structures presented in this work are compatible with present-day technologies and can be realised in practice on large areas and at low cost.

Acknowledgments

The authors are grateful to Franz-Joseph Haug, Olindo Isabella, and Thomas Lanz for helpful discussions. This work was supported by the EU through Marie Curie Action FP7-PEOPLE-2010-ITN Project No. 264687 "PROPHET" and Fondazione Cariplo project 2010-0523 "Nanophotonics for thin-film photovoltaics". We also acknowledge CINECA/CASPUR project "Disorder" under the ISCRA initiative, for the availability of high performance computing resources and support.