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Light trapping in thin-film solar cells using dielectric and metallic nanostructures
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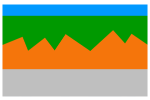
Summary

Photovoltaics (PV) is a sustainable and clean source of energy and the sun provides more than enough energy to make PV a major electricity source. To make PV fully competitive with conventional energy sources, a reduction of the cost per watt is required. This can be achieved by increasing the conversion efficiency of the modules or by decreasing manufacturing cost. Thin-film solar cells, which have substantially thinner absorber layers than conventional wafer-based solar cells, offer the potential for lower manufacturing costs. They can also serve as top cells in high-efficiency tandem solar cells. A major problem with thin-film solar cells is the incomplete absorption of the solar spectrum, which leads to a drastic reduction of the efficiency. To enhance the absorption of light in thin-film solar cells light trapping is required, in which nanostructures are integrated in the cell to enhance the path length of the light in the absorber layer. In this thesis we present new insights in light trapping in thin-film hydrogenated amorphous Si (a-Si:H) and Cu(In,Ga)Se_2 (CIGSe) solar cells. We experimentally study arrays of metallic and dielectric resonant scatterers at the front and at the back side of thin-film solar cells, and demonstrate efficient light trapping without deterioration of the electrical properties of the devices. We emphasize the relevance of minimizing optical losses in the light trapping patterns. We compare periodic and random scattering patterns and demonstrate the importance of the spatial frequency distribution in the scattering patterns. We present an optimization of the spatial frequency distribution of light trapping patterns that is applicable to all thin-film solar cell types. In Chapter 2 we present wafer-scale fabrication of nanoscale light trapping patterns using substrate conformal imprint lithography (SCIL). Using SCIL in combination with evaporation and lift off, we fabricate arrays of dielectric and metallic light trapping patterns both at the front and back side of thin-film solar cells. We fabricate patterned metal back contacts for thin-film solar cells by sputter coating printed sol-gel layers with metals.

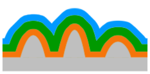
In Chapter 3 we study light trapping in ultra-thin a-Si:H solar cells, with absorber layer thicknesses of 90–150 nm, grown on top of periodically and randomly patterned metal back contacts. The cells show a broadband photocurrent

enhancement because of light trapping by the patterned back contact and an antireflection effect by the corrugated surface, which originates from conformal growth of the thin-film stack on a patterned back contact. We show that these light trapping patterns outperform the Asahi-U type pattern, which is the commercial light trapping standard for thin-film a-Si:H solar cells. We relate the photocurrent spectra to the spatial correlations in the light trapping patterns.

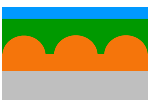
In Chapter 4 we demonstrate effective waveguide-mode coupling using plasmonic surface scatterers printed onto completed thin-film a-Si:H solar cells, with an absorber layer thickness of 350 nm, using substrate conformal imprint lithography (SCIL). Using numerical simulations, we show that an optimized array geometry can result in an enhanced red- and blue response of the device. The blue response of the device can be further enhanced using Al instead of Ag nanoparticles. We demonstrate that a broadband absorption enhancement can be obtained with dielectric scattering patterns consisting of arrays of TiO_2 particles, which efficiently scatter the light and have low optical losses.



In Chapter 5 we experimentally study the influence of patterning the Al-doped ZnO (AZO) buffer layer that is in between the metal back contact and the absorber layer in the same cell type as in Chapter 4. By comparing light trapping with randomly patterned metal back contacts covered with patterned or flat AZO layers, we show that patterning the AZO layer is indispensable for efficient light trapping in this cell geometry. Using numerical simulations, we demonstrate that light trapping can be further enhanced using purely dielectric scattering patterns, in which the AZO layer is patterned and the metal is completely flat. These dielectric scattering patterns efficiently scatter the light and do not suffer from Ohmic losses as is the case for plasmon resonances in Ag.



In Chapter 6 we present thin-film a-Si:H solar cells, with absorber layer thicknesses of 100 and 200 nm, deposited on top of random arrays of nanorods. These nanorods are grown by chemical bath deposition, which is an inexpensive, scalable and tunable growth process. Full device stacks, consisting of Ag, AZO, a-Si:H and ITO are deposited on top of the nanorods which results in radial junction solar cells. These cells show efficient light trapping and an enhanced blue response. Numerical simulations are in good agreement with experimental EQE data and show that absorption in the Ag layer of these rod cells is strongly enhanced with respect to flat cells. Further enhanced light trapping can be obtained by flattening the metal and only patterning the dielectric layers.



Dielectric back scattering patterns for light trapping are further studied in Chapter 7. This chapter focuses on periodic scattering patterns. We experimentally demonstrate broadband efficient light trapping in 350 nm a-Si:H cells periodically patterned AZO layers and show that these cells outperform reference cells on Asahi-U type texture. Due to conformal growth, also the bottom part of the a-Si:H layer is patterned. Since the AZO particle diameter is close to the array pitch, the AZO particles enclose a-Si:H scatterers. Using numerical simulations, we show that dielectric resonances occur both in the AZO particles in the a-Si:H scatterers and that the size of the a-Si:H scatterers is crucial for light trapping.

In Chapter 8 we use dielectric scattering patterns to achieve light trapping in ultra-thin CIGSe cells, with absorber layer thicknesses of 460 nm. We experimentally demonstrate a photocurrent enhancement in CIGSe cells with arrays of dielectric scatterers printed on the front side. Using numerical simulations, we show that the absorption enhancement is due to an antireflection effect rather than to light trapping. We experimentally demonstrate light trapping in CIGSe cells with arrays of SiO_2 particles at the CIGSe/Mo interface, which results in an efficiency gain from 11.0% to 12.4%. Using numerical simulations we show that these dielectric scattering patterns reduce the optical losses in the strongly absorbing Mo back contact. To further reduce absorption in the back contact, we replace the Mo layer by ITO and find that, even though there is transmission through the back contact, integrated absorption in a patterned cell on ITO can be as high as in a patterned cell on a Mo back reflector. This geometry could be interesting for tandem devices.

In Chapters 3-8 we showed that efficient scattering can be obtained with scattering patterns, both on the front and back side of the solar cell. In Chapter 9, we present insight in the spatial frequency distributions of the scattering patterns. We demonstrate the relation between peaks in absorption spectra and the power spectral density of spatial frequencies (PSD), which is the spatial Fourier transform of the scattering pattern. Using a Monte Carlo algorithm, we optimize arrays of dielectric scatterers to have elevated PSD in the spatial frequency range that overlaps with the waveguide modes of a specific device geometry. We also demonstrate an approach that gives more freedom in designing the PSD spectrum, which relies on the optimization of random textures.

Overall, this thesis provides fundamental insights in light trapping in thin-film solar cells and focuses on designs with large scattering efficiency, low optical losses, and a PSD spectrum that can be tailored to a specific device stack. It presents light trapping patterns that lead to significant absorption enhancement in thin-film solar cells without deterioration of the electrical properties. The concepts discussed in this thesis are applicable to all types of thin-film solar cells.