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Light Trapping in Solar Cells Using Resonant Nanostructures
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Summary

Photovoltaics is a sustainable and environmentally clean source of energy that has the potential to become a major source of energy for our society. In order for this to happen, photovoltaics needs to be economically competitive with other conventional energy sources. This can be achieved by reducing the production costs of solar panels and by improving their photovoltaic conversion efficiency. For Si solar cells, both challenges can be achieved by reducing the thickness of the solar cell. However, major optical losses occur when the thickness of Si solar cell is reduced, due to incomplete absorption of light.

In this thesis, we investigate new ways of enhancing light absorption in Si solar cells by using nanostructures that show resonant interaction with light. We study the fundamental aspects of resonant scattering of light by metallic and dielectric nanoparticles placed on top of thick and thin dielectric substrates. If optimally designed these nanostructures can lead to efficient light coupling and trapping in solar cells. This allows the realization of novel solar cell architectures with higher efficiency that can be made at lower costs.

Chapter 2 presents the nanofabrication techniques used to fabricate the nanoparticles. Substrate conformal imprint lithography (SCIL) is presented as a large area, non-expensive, high-fidelity technique to fabricate nanoparticle arrays on full wafers. Furthermore, a reactive ion etching (RIE) recipe based on fluorine compound gases is used to fabricate Si nano-pillar arrays on large-area Si wafers.

In Chapter 3, we study with numerical simulations the scattering of light by Ag plasmonic nanoparticles placed on a substrate. In particular, we identify the key role of Fano resonances and we define guidelines for designing a plasmonic antireflection coating (ARC) for Si solar cells.

Based on these results, in Chapter 4 we demonstrate that an optimized array of plasmonic Ag nanoparticles placed on top of a Si wafer provides an effective antireflection effect which outperforms a standard Si3N4 coating. This is a result of a full parameter space optimization carried out with numerical simulations. We use electron beam lithography (EBL) to fabricate Ag nanoparticle arrays on crystalline Si solar cells. Reflection spectroscopy is used to quantify the light coupling into the Si solar cells.

In Chapter 5 we discuss the possibility to use the near-field enhancement of plasmonic (Ag) nanoparticles embedded in a solar cell, to enhance the absorption of light in the active layer of the cell. We find that this approach cannot be used for crystalline or amorphous Si solar cells as Ohmic losses in the metal nanoparticles dominate over the absorption in the semiconductor. However, Ag nanoparticles can be used to enhance the absorption of light in ultrathin organic/polymer based solar cells.

Chapter 6 presents a new way of suppressing the reflection of light from a Si surface. The reflectivity of a full-size Si wafer is reduced from over 35% to 1.3% (averaged over the solar spectrum) by covering the wafer with an optimized array of Si Mie resonators. The wafer patterned with a Si nanoparticle array appears thus completely black. The low reflectivity is maintained for angles of incidence up to 60°. Several fundamental aspects of light scattering by Mie resonances in the Si nanoparticles and the coupling into the substrate are studied.

The same Si Mie coating is used in Chapter 7 to study light trapping in thin (20-100 μm) and ultrathin (1-20 μm) crystalline Si solar cells. We use numerical simulations

to calculate the absorption in the thin Si slab covered with the Si Mie coating. An electrical model including bulk and surface recombination is then used to estimate the solar cell efficiency. We demonstrate that for realistic values of surface recombination velocity and carrier bulk lifetime, 20-μm-thick Si solar cells with efficiency of 21.5% can be made.

In Chapter 8 we experimentally demonstrate light trapping beyond the Lambertian $4n^2$ limit using Si Mie nanoscatterers. Thin film polycrystalline Si layers are made on glass and patterned with an array of Si nanocylinders. Total reflection and transmission spectroscopy is used to measure the absorption spectrum of the thin Si slab with the Si Mie coating, and compare it to that of a flat Si slab. In the infrared spectral range, optical path length enhancements up to a factor of 65 are measured, well beyond the geometric Lambertian $4n^2$ limit for Si at this wavelength.

Chapter 9 presents a TiO_2/Al_2O_3 Mie coating that combines very good antireflection properties with excellent surface passivation. The antireflection effect stems from the preferential forward scattering of light by Mie resonances in the TiO_2 nanoparticles and yields a solar-spectrum averaged reflectivity as low as 1.6%. An ultrathin Al_2O_3 layer provides excellent passivation of the Si surface, with a surface recombination velocity of only 3.3 cm/s after fabrication of the TiO_2 nanoparticles.

Finally, Chapter 10 presents several new concepts and ideas for integrating plasmonic and Mie nanoparticles on realistic solar cell designs. We show that resonant nanostructures can be beneficial not only for several crystalline Si solar cell designs, but also for GaAs and polymer cells. Practical aspects such as the effect of polymer and glass encapsulation of solar modules are also analyzed.

Overall, this thesis provides new fundamental insights in light scattering and trapping by resonant metallic and dielectric nanoparticles integrated with solar cells. The results may be used to design Si solar cell with higher efficiency that can be made at lower costs.