Optical properties of crystalline silicon nanowires

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Abstract

Silicon has a high refractive index. In form of silicon nanowires (SiNWs), that have diameters of the order of the wavelengths of visible light, strong resonant enhancement can be expected and makes this type of nano-materials good candidates for all sorts of photonic devices. In form of randomly grown SiNW ensembles they show a high absorptivity for the whole visible spectrum. We discuss the optical properties of both individual SiNWs and randomly grown SiNW ensembles. Mie calculations are in good agreement with our experimental observations.

Experimental

To examine the transmittance spectra of SiNWs ensembles, they have to reside on transparent substrates such as glass. On glass substrates commercially available gold colloids of various well controlled diameters (British Biocell Int.) have been suspended and immobilized using 3-Aminopropyltriethoxysilane (APTES). The gold colloids catalyze the one dimensional growth of SiNWs in a chemical vapor deposition process (CVD) following the vapor liquid solid (VLS) principle. We used silane as precursor and Argon as carrier gas. To investigate the optical properties of individual SiNWs some SiNWs have been removed from the growth substrates and led flatly on new, clean substrates.

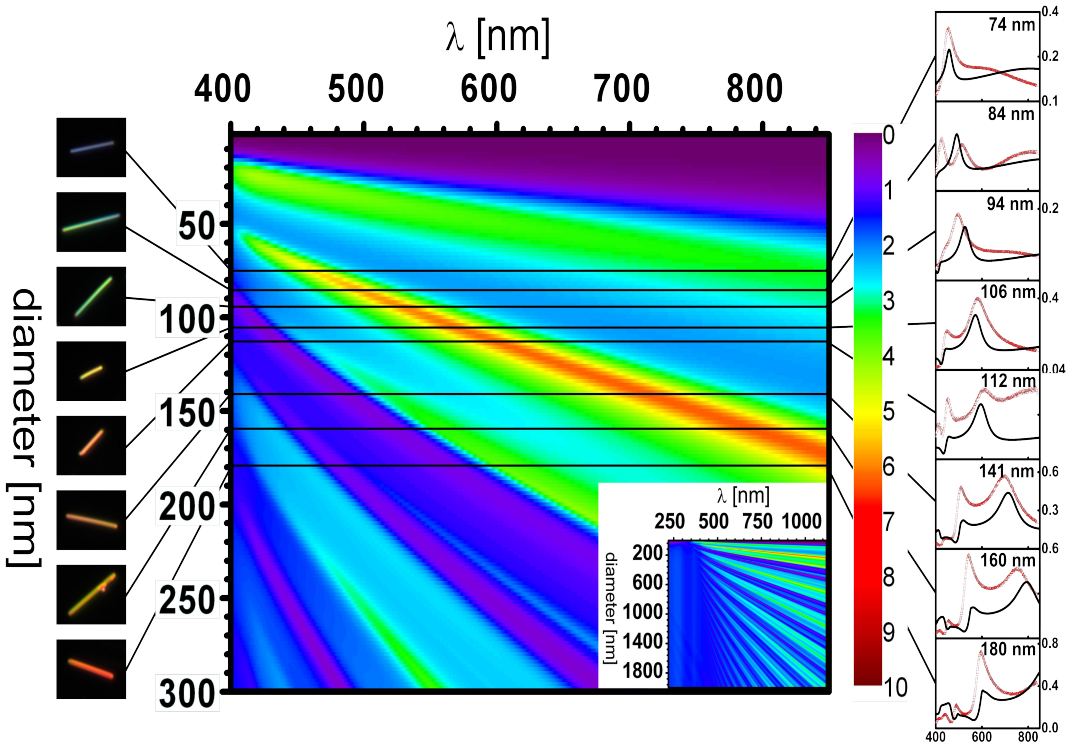

Figure 1: Calculated scattering efficiencies Q_{sca} for an angle of incidence ξ=90°, diameters d=[2nm, 300nm], λ=[400nm,850nm] and non polarized light. Solid black lines indicate the position of the measured spectra. On the right side normalized measured scattering spectra are shown (red lines), the black lines in the graphs are the corresponding calculated scattering efficiencies Q_{sca}. The scattering efficiencies have been scaled with a constant factor for each SiNW to match the measured spectra. On the left side optical dark field micrographs of the corresponding SiNWs are shown. The diameters of the SiNW have been measured using an atomic force microscopy (AFM).
Insets: Q_{sca} for d=[2nm, 2000nm] and λ=[220nm,1120nm]

Results

Optical properties of individual SiNWs

Our experimental findings of the scattered light of individual SiNWs are in qualitative agreement with the calculated scattering efficiencies Q_{sca} using Mie theory, cf. fig. 1.

Optical properties of disordered SiNWs ensembles

The absorption of disordered SiNW ensembles has been measured using an integration sphere. The measured and fitted absorption spectra are shown in fig. 2a. The fit parameters R_0 and σ describe the radii distribution of the SiNWs in the ensembles. N_0 is the mean number of interaction events before a photon leaves the SiNW ensemble. The parameter c shows to some extent how dense the SiNWs are in the ensemble. A low value for c indicates a very dense Si NW ensemble. The corresponding parameters used to fit the graphs in fig. 2a are shown in fig. 2b.
There is a general trend to a higher degree of absorption of the SiNW ensembles when bigger gold colloids are used. Interestingly the absorption of the SiNW ensemble catalyzed with larger gold colloids occurs in SiNWs with only a slightly larger radius, according to our model. The raise in the absorption of the mats catalyzed by larger gold colloids may be attributed to the enhanced scattering efficiencies of SiNWs with bigger diameter and thus leading to a larger mean number of interaction events N_0 of the photons with the SiNWs before they can leave the mat.

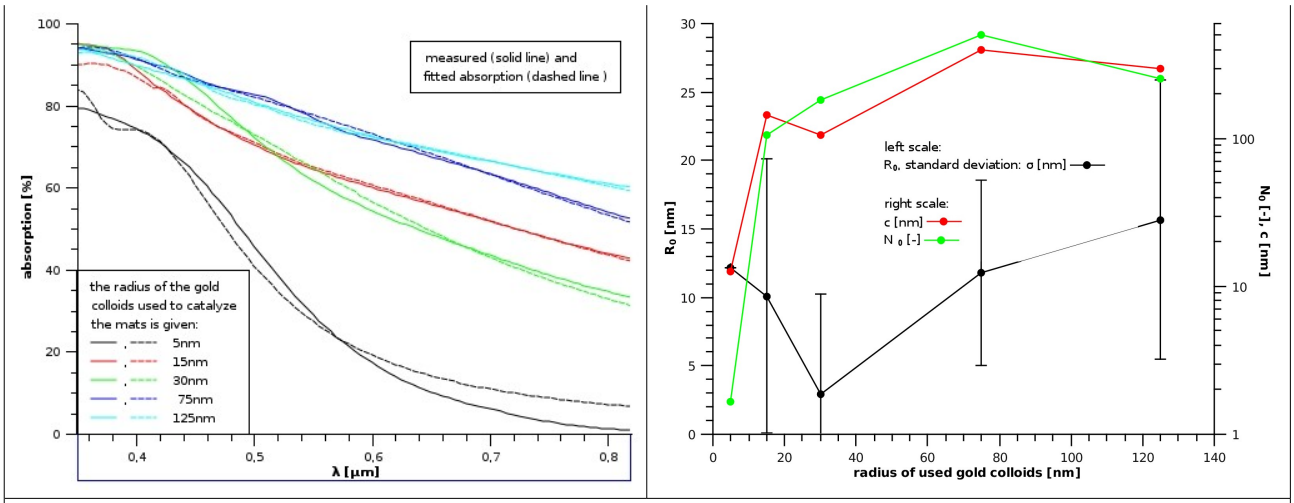

Figure 2: optical properties of SiNW ensembles; a) measured and fitted absorption spectra;
b) fit parameters (as described in the text)

Conclusion

The scattering efficiencies of SiNWs have been calculated using Mie-theory depending on the angle of incidence ξ of the illuminating light, the wavelength and the diameters of the SiNWs. Calculated dependencies of scattering and absorption efficiencies very well coincide with experimental findings of scattering of white light in an optical microscope. This results, depending on the diameter of the SiNW, in a colored appearance of the SiNWs ranging from violet to red.
The absorption of disordered SiNW ensembles has been measured and is in good agreement with our fits. Bigger gold colloids as catalysts lead generally to an increased absorption of the SiNW ensembles.