Nanoscale Free-Carrier Profiling of Individual Semiconductor Nanowires by Infrared Near-Field Plasmon Resonance Spectroscopy

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Semiconductor nanowires have gained tremendous interest in the recent years as potential building blocks for future nano-opto/electronic devices. [1-4] A successful implementation of semiconductor nanowires into devices essentially relies on the control and the experimental verification of the local free-carrier concentration. However, quantitative free-carrier profiling of individual nanowires is still a challenging task. Here we report a quantitative method, which is based on local infrared (IR) plasmon resonance spectroscopy employing scattering-type scanning near-field optical microscopy (s-SNOM).

s-SNOM is typically based on atomic force microscopy (AFM) where the tip is illuminated with a focused laser beam and the tip-scattered light is detected simultaneously to topography (see Fig. 1a). Using metallic tips, the strong optical near-field interaction between tip and sample modifies the scattered light allowing for probing the local dielectric properties with nanoscale resolution. Unavoidable background contributions are suppressed by vertical tip oscillation at frequency Ω and subsequent higher-harmonic demodulation of the detector signal at $n \cdot \Omega$ with $n \geq 2$ [8]. Combining this higher harmonic demodulation with interferometric detection, background-free near-field optical amplitude s_n and phase φ_n contrast imaging is possible. s-SNOM offers an excellent optical resolution in the 10nm range independent of the wavelength [5] and allows for IR mapping the chemical composition [6], structural properties such as strain [7], and free-carriers in semiconductor devices [8].

We use s-SNOM operating at IR frequencies between 890 and 1100 cm^{-1} to measure the free-carrier concentration in single modulation-doped InP nanowires. Fig. 1b shows a typical amplitude image of two nanowires, revealing three segments. The highly doped central segment apprears much brighter than the two adjacent undoped segments. This contrast can be explained by a plasmon-resonant near-field interaction between the AFM tip and the free carriers in the doped nanowire segment. The near-field resonance occurs close to the plasma frequency of the free carriers and shifts to higher frequencies with an increasing free-carrier concentration *n*. We can thus determine the free-carrier concentration by fitting the experimental spectra with model calculations describing the tip-sample near-field interaction (Fig. 1c).

Imaging nanowires as thin as 20 nm, we find nanoscale variations of the free-carrier concentration, which can be attributed to local growth defects. [9] The spatial resolution we achieve in these experiments is about 20 nm (λ/500), i.e. nearly three orders of magnitude below the diffraction limit.

With s-SNOM we provide a contactless, non-destructive optical nanoscopy tool, which allows quantitative local measurements of the free-carrier concentration in semiconductor nanowires with nanoscale spatial resolution. Improved modeling and spectral extension of s-SNOM to the THz frequency range [10] could make the method a powerful tool for free-carrier profiling not only of nanowires, but also of other semiconductor nanodevices and photonic nanostructures.

References

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Figures

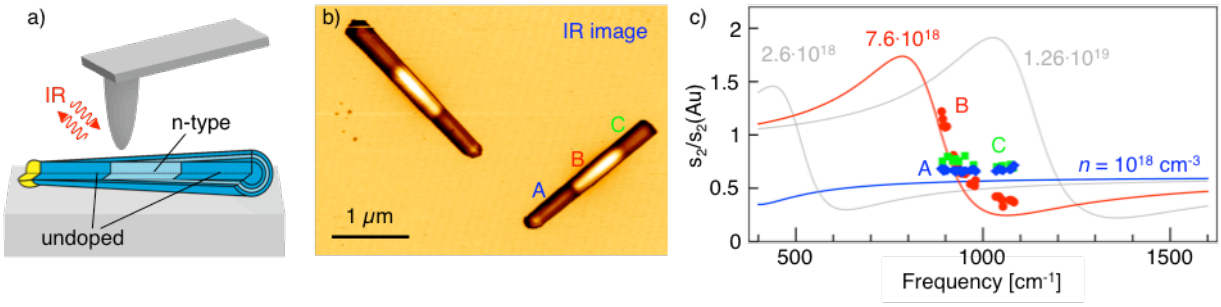

Figure 1: Infrared near-field mapping of modulation doped InP nanowires. (a) Schematic illustration of free-carrier profiling of modulation-doped semiconductor nanowires by infrared (IR) s-SNOM. (b) Amplitude s_2 image of two representative InP nanowires recorded at an IR laser frequency of 893 cm^{-1}. (c) Experimental (symbols) and calculated (solid lines) local IR near-field amplitude spectra along a single InP nanowire.