

Nanoscale infrared near-field mapping of free-carrier concentration in single semiconductor nanowires

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Semiconductor nanowires have gained tremendous interest in recent years due to their promising electronic and opto-electronic properties [1, 2]. For the implementation of semiconductor nanowires into devices it is crucial to precisely control the doping concentration of the nanowires. For tuning the fabrication process, new analytical tools are needed to quantitatively determine the doping concentration.

Dopants in single nanowires can already be measured using atom probe microscopy (APM) or transmission electron microscopy (TEM). But due to surface and shielding effects [3] not all dopants are ionized yielding a lower number of free-carriers. For the performance in electrical and opto-electronic devices the number of free carriers therefore is of utmost importance. Scanning-probe methods like scanning capacitance microscopy (SCM) and scanning spreading resistance microscopy (SSRM) can map the free-carriers. However, quantitative imaging is hardly achieved with SCM, and SSRM is a destructive method. Here we demonstrate that scattering-type scanning near-field optical microscopy (s-SNOM) can map free-carriers in single modulation-doped InP nanowires with nanoscale resolution, quantitatively and non-destructively.

s-SNOM offers an excellent optical resolution in the 10nm range independent of the wavelength [4] and allows for mapping the chemical composition [5], structural properties such as strain [6], and free-carriers in semiconductor devices [7]. It 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. 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.

Using s-SNOM we study the free-carrier properties in single modulation-doped InP nanowires, which were grown using the vapor-liquid-solid (VLS) method. For s-SNOM imaging, the nanowires were mechanically transferred onto a silicon substrate. Fig. 1 shows simultaneously recorded topography and IR images of a single nanowire. While the topography shows a homogeneous wire surface, the IR images reveal the differently doped wire segments. We also observe a material contrast between the InP wire and the gold particle. The latter is used to catalyze the wire growth. Within this

contribution we will discuss the contrast mechanisms as well as the sensitivity of s-SNOM to free-carrier properties.

In conclusion, we demonstrate free-carrier profiling of individual doped InP nanowires. With s-SNOM we provide a contactless, non-destructive method, which allows quantitative local measurements of the free-carrier concentration in nanowires with nanoscale resolution. Improved modelling and spectral extension of s-SNOM to the THz frequency range could make the method a powerful tool for free-carrier profiling not only of nanowires, but also of other doped nanostructures and nanodevices.

References:

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Figures:

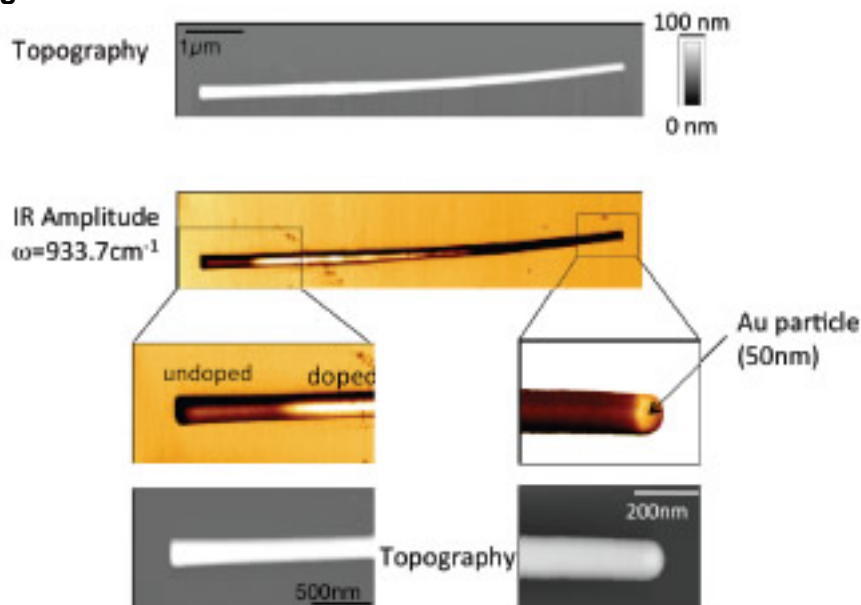


Fig 1: Topography and infrared amplitude s_2 of a representative InP nanowire recorded simultaneously at an IR laser frequency of 933.7cm^{-1} ($10.71\mu\text{m}$ wavelength). The infrared images clearly reveal the differently doped nanowire sections and the material contrast between InP and the gold particle used to catalyze the nanowire growth.