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Charge carrier profiling with MIR and THz s-SNOM

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Abstract—In the past years, it has been shown that s-SNOM (scattering-type scanning near-field optical microscopy) is a powerful technique to probe different light-matter interactions. Among them, charge carriers present different optical responses in the mid-infrared (MIR) and terahertz (THz) regions. Here we show that THz s-SNOM is highly sensitive to small changes in charge carrier concentration in a semiconductor, with spatial resolution at the nanometer scale.

I. INTRODUCTION

Scattering-type Near-field Optical Microscopy (s-SNOM) is a powerful technique able to probe the local optical properties of different materials at the nanometer scale, overcoming the classical optical diffraction limit [1]. This is achieved by focusing electromagnetic radiation onto the tip of an atomic force microscope (AFM), operating in tapping-mode at an oscillation frequency Ω , which induces a near-field interaction between the tip apex and the sample surface due to a nano-antenna effect. The spatial resolution scales with the tip apex geometry rather than with the wavelength of light or illuminated spot size. By detecting the scattered light at higher harmonics of the tip frequency $n\Omega$ and using interferometric detection to suppress the far-field background, both the near-field (NF) amplitude (S_n) and phase (ϕ_n) can be recovered [1,2]. Hence, s-SNOM can probe the local dielectric function of a material. This is of particular interest in semiconductor science and technology, where near-field microscopy enables the characterization of nanostructured conducting materials. The terahertz (THz) range is therefore a relevant spectral region to probe charge carriers in semiconductors, as the plasma frequency lies in this frequency range or above and strongly modifies the dielectric response. However, achieving nanoscale lateral resolution with high signal-to-noise ratio (SNR) with THz s-SNOM remains challenging [3,4], mainly due to the mismatch between typical AFM tip lengths (15-20 μm) and THz radiation wavelength (30 μm - 3 mm). This issue can be circumvented by enhancing the scattering efficiency, which can be achieved by using AFM probes with longer tip shaft designed to operate in the THz range [5-10]. Here we demonstrate charge carrier profiling in a boron-doped Si sample with high SNR, sensitivity and nanoscale resolution for carrier concentration down to $\sim 10^{17} \text{ cm}^{-3}$.

II. RESULTS

The s-SNOM setup used in the experiments consisted of a neaSNOM microscope (Neaspec GmbH) with a Michelson interferometer configuration, operating both in the mid-infrared (MIR) and THz ranges. As laser sources, we used a tunable external cavity quantum cascade laser (QCL) in the

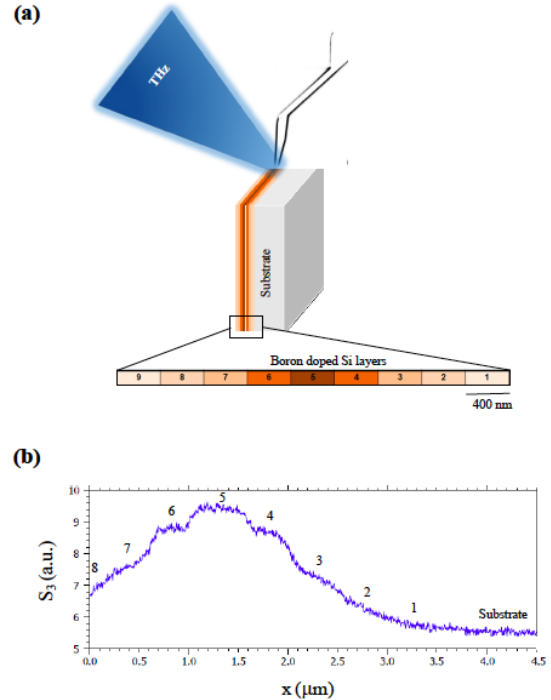


Fig. 1. (a) Schematic of the s-SNOM measurement setup and studied Maya sample, showing the Si doped layers. (b) THz s-SNOM line scan profile for the optical amplitude S_3 (averaged over 32 lines), obtained for a laser wavelength of $\lambda = 118 \mu\text{m}$ (2.52 THz).

MIR ($\lambda = 8.3 - 11.1 \mu\text{m}$, Mircat, Daylight Solutions Ltd.), and a CO₂ laser-pumped methanol THz gas laser (FIRL-100, Edinburgh Instruments Ltd.) in the THz ($\lambda = 118 \mu\text{m}$, $f = 2.52$ THz). The p-polarized laser source is focused on the apex of the AFM probe and sample surface by a parabolic mirror, which is also used to collect the light scattered by the AFM probe with the near-field information. This optical signal is combined with the reference beam and finally sent to a HgCdTe detector (Kolmar Tech. Inc.) for the MIR or to a pulse-tube-cooled InSb hot electron bolometer (QMC Instruments Ltd.) for the THz range. All optical signals are demodulated at $n\Omega$ (S_n and ϕ_n). Pt-coated Si AFM probes with different tip shaft lengths were employed to simultaneously acquire the sample topography and optimize the optical signal: $L \sim 20 \mu\text{m}$ in the MIR (Arrow NcPt, Nanoworld), and $L = 70 \mu\text{m}$ in the THz (LProbe, Vmicro SAS) [5-10]. To access and map charge carriers at the nanometer scale, a sample consisting of nine 400 nm-thick boron-doped Si layers was investigated. The layers were grown by chemical vapor

deposition (CVD) with a pyramid-like profile (hereafter referred as Maya) on a slightly p-type boron-doped ($\sim 7\text{-}10\ \Omega\cdot\text{cm}$) Si(001) substrate, and finally polished in the transverse section to obtain a flat sample [11], as shown schematically in Fig. 1a. The obtained THz s-SNOM line scan profile is shown in Fig. 1b for the amplitude signal S_3 (third harmonic), averaged over 32 lines (using homodyne detection, without phase modulation [1]). As can be seen, a different optical contrast is obtained across the line scan, showing that the pyramid-like doping profile of the Maya sample is well resolved with nanoscale resolution. From layer 9 to layer 5 (from left to the top of the pyramid in Fig. 1a), the dopant concentration changes from approximately 5×10^{17} to $4\times 10^{19}\ \text{cm}^{-3}$. The doping is symmetric with respect to the top of the pyramid (layer 5), and the right side corresponds to the Si substrate [11], as shown in Fig. 1a. In Fig. 1b, the scan was performed between approximately half of layer 8 ($1.7\times 10^{18}\ \text{cm}^{-3}$) and the substrate, to prevent scanning over the sample edge. The obtained profile demonstrates that the optical contrast is related to the doping concentration and thus to the THz conductivity of each layer, even for small doping differences. Previous THz s-SNOM studies of low doping in semiconductors, already demonstrating the potential application of THz s-SNOM as a tool for characterizing conductivity at the nanoscale, probed carrier concentrations with a variation of at least one order of magnitude [3]. Here we show that, thanks to longer tips, the sensitivity in the THz range can even be improved to lower doping variation, while keeping a nanoscale lateral resolution and high SNR.

III. SUMMARY

In conclusion, we have shown that improved optical contrast can be obtained by optimizing probe geometry, enabling the characterization of low doping in semiconductors. THz nanoscopy is therefore a powerful, highly sensitive and non-destructive technique to probe conductivity of semiconductors with nanoscale resolution, as well as to study a variety of physical phenomena in fundamental science and technology.

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