A novel scattering-type SNOM-tip featuring a micro-integrated bias-free optically driven terahertz pulse emitter

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***Abstract*—In this work we present a new approach to enhance the measurement speed and signal-to-noise ratio of scattering-type scanning near-field optical microscopy (s-SNOM) systems aiming for time-domain operation at terahertz frequencies. It is based on a standard atomic-force-microscope (AFM) tip that is supplemented with an integrated THz source. This device is offering an efficient solution to reduce coupling losses between THz pulse emitter and the scattering tip – one of the main performance limiting factors in current state-of-the-art systems.**

I. Introduction

SCANNING near-field optical microscopy (SNOM) using atomic force microscope (AFM) tips as scattering elements has become a powerful tool for optical imaging with nanoscale resolution [1]. A scattering-type SNOM (s-SNOM) is typically based on a conventional atomic force microscope (AFM). Information about the local optical properties of the sample is obtained through light directed to and scattered from the probing tip. Here, the optical resolution is mainly given by the radius of the applied tip apex governing the light/material interaction – independent of the wavelength of the incident light. Spatial resolutions as good as 10 nm can be achieved in this way [2]. While this approach works very well at the infrared, it is much less efficient at the Terahertz range. The reasons for this reduced efficiency are the huge coupling losses between the THz emitter/detector components and the scattering AFM-tip as well as the general lack of powerful THz sources. In this work, we introduce a new approach offering a strong reduction of THz emitter coupling losses by using a micro-mechanical integration of emitter and scattering tip into a single device.

II. Results

In this work, a standard AFM tip commercially available from Rocky Mountain Nanotechnology [3] is used as the basis for the manufacture of the new probe with integrated THz emitter. The AFM tip consists of a ceramic body with a metallic electrode pad on top, which is connected to a cantilever structure leading to a sharp tip at its end. An InGaAs chip with a size of 200 µm x 200 µm x 1.2 µm is attached to the front facet of the ceramic body of the AFM tip in a position directly adjacent to the metallic cantilever of the probe, but not disturbing an optional oscillatory movement of the tip in later measurements. The mechanical resonance frequencies have been measured before and after the tip modification and showed only negligible changes. Fig. 1 shows the configured THz AFM tip brought into close distance to a sample FZ silicon wafer with 10-nm-thick Cr structures on its top surface. For THz pulse generation, the InGaAs chip is optically excited by near-IR pulses from a femtosecond laser running at 100 MHz pulse repetition rate, 780 nm wavelength and 90 fs pulse duration.

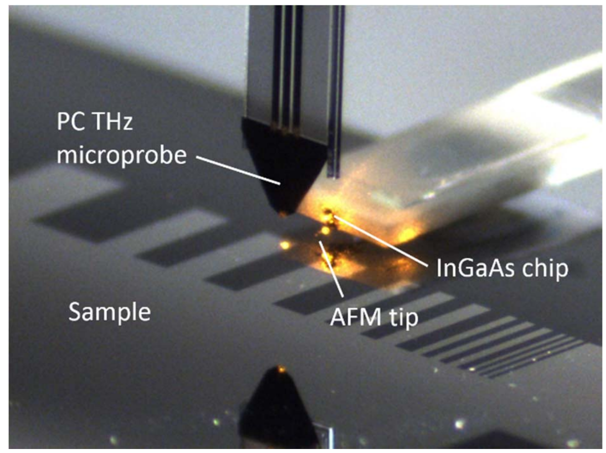

Fig. 1. Microscope camera image of the AFM-tip with integrated bias-free emitter chip and a photo-conductive microprobe used for the detection of the emitted THz signal. The AFM-tip is raster-scanned over a FZ-silicon sample wafer featuring Cr-based thin-film structures.

The optical excitation pulse generates a photocurrent surge at the InGaAs surface [4], which results in a THz surface wave propagating along the cantilever to the tip apex. Hereby, the main issue of coupling free-space THz radiation to the tip is effectively avoided. In our first tests we captured the THz field radiated from the tip with a photoconductive microprobe detector [5] placed in < 1mm distance to the tip using a classic optical pump/probe scheme [6]. The polarization direction recorded with the probe is oriented vertical to the sample surface. Two exemplary transients measured with the tip being in contact with Si and Cr, respectively, are shown in Fig. 2. The measured transients are characterized by an initial pulse (t = -3

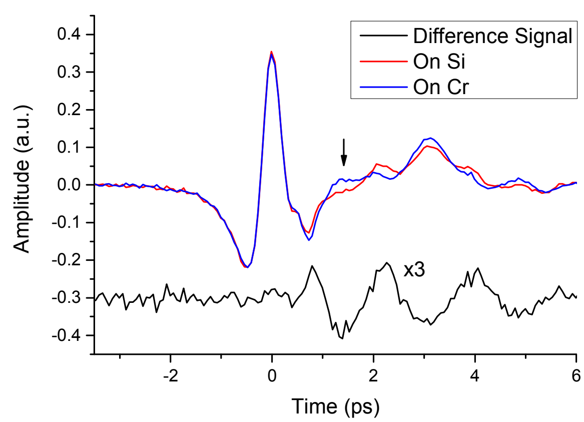

Fig. 2. THz time-domain transients recorded by the photoconductive near-field probe in sub-mm distance to the AFM-tip emitter as shown in Fig. 1. The black curve is showing the amplitude difference between the tip "on Si" and "on Cr" transients.

– 0.5 ps) which stays unchanged while the sample is moved from Si to Cr below the AFM tip. After t = 0.5 ps, however, a clear and well reproducible difference between the signals measured on Si and Cr is visible. We interpret this behavior by considering a directly transmitted initial part which is not interacting strongly with the sample surface and a later superimposed part generated by the excitation of a cantilever surface-mode which is strongly interacting with the sample surface. The amplitude difference between the transients measured on Si and Cr is also shown in Fig. 2. The difference signal corresponds to the form of a damped oscillation starting at 0.5 ps.

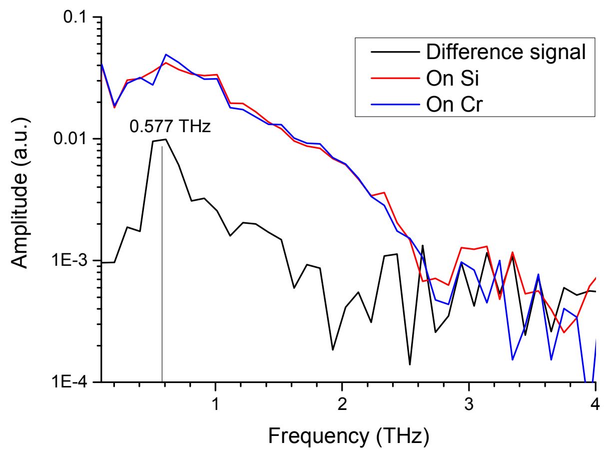

Fig. 3. Frequency-domain spectra of the transients shown in Fig. 2.

To further analyze the spectral behavior of the recorded signals we have plotted the corresponding Fourier-transformed time-domain signals of Fig. 2 in Fig. 3. The spectrum of the difference signal highlights a resonance around 0.6 THz, which is very close to a λ/2-resonance of the AFM cantilever, considering a cantilever length of approx. 250µm. The fact, that this resonance becomes selectively visible by changing the probing position from Si to Cr is a first indication, that a near-field interaction could be involved. The spectra of the directly recorded signals reveal a usable bandwidth of ca. 2.5 THz as well as an amplitude increase for the signal on Cr vs. Si around the resonance frequency. A next order 3λ/2-resonance at 1.8 THz is not clearly visible, though it would be still inside the usable spectral range.

A first proof, that the monitored THz signals are indeed caused by a near-field interaction which must be controlled by the contact area of the tip is given by the mapping data obtained by line scans over a Si-Cr edge shown in Fig. 4. The analysis of the individual line scans exhibits a sub-1-µm spatial resolution, which was in this initial study the resolution limit of the scanning system. Ongoing work is now directed to the integration of the THz emitting AFM-tip into a nanoscopic scanning system with tapping-mode demodulation in order to demonstrate directly a tip-radius limited spatial resolution in the order of 100 nm or below. It should be noted that – thanks to the high efficiency of the applied tip-excitation mechanism – the extraction of the near-field signal contribution succeeded even without using demodulation techniques. However, a controlled and material-friendly operation as given by the

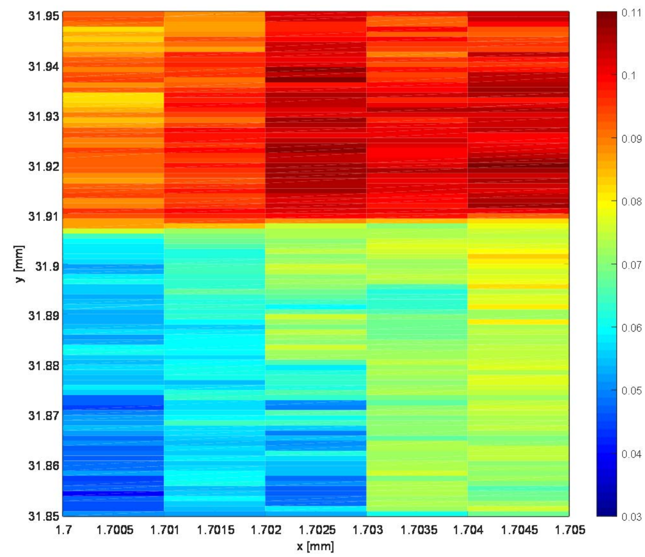

Fig. 4. THz amplitude mapping obtained from line scans over a Si-Cr edge in lateral steps of 1 µm. The shown THz amplitude corresponds to the time delay position marked by the arrow in Fig. 2 where a maximum contrast is achieved.

tapping-mode of typical AFM systems is still needed to make this approach practically usable in the future.

III. Summary

In this work, we introduce a new approach for THz s-SNOM measurements in the time-domain, which will help to speed up measurements by increasing the excitation efficiency of the scattering probe. An important advantage of this method is that it should be compatible with a large number of existing AFM systems, since no major system modifications are required for the integration of the new THz probes.

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