Development of near-field microscopy for THz imaging

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Abstract

The first demonstration of THz imaging by Hu and Nuss [1] has stimulated many suggestions for applications ranging from biomedical imaging to semiconductor device inspection. However, many applications demand a microscopic resolution. For instance, THz imaging of biological cells would require submicron spatial resolutions because many cells have dimensions of the order of 10 μm. Even finer resolutions would be required in semiconductor technology where today many devices are smaller then 1 μm. Such resolutions are not easy to reach with THz technologies, because of the long wavelength of THz radiation (1 THz corresponds to a wavelength of 300 μm). Many works took up the challenge to reduce spatial resolutions down to the 1 μm barrier and recently our group demonstrated a resolution of 150 nm [2].

Introduction & overview

Most of the pioneering works on THz imaging made use of far-field techniques [1,3]. The spatial resolutions of these approaches are limited by Rayleigh's criterion to dimensions of about the wavelength. However, far-field techniques have a high throughput and thus allow for images with a high dynamic range. Furthermore, far-field techniques have the potential for parallel recording of many image points, provided that arrays of THz detectors are used. Resolutions that go beyond the diffraction limit can be achieved in the near-field regime. The standard approach is to use a metallic aperture in proximity to the sample and to image individual points sequentially. In THz imaging, resolutions down to 7 μm were demonstrated by using subwavelength metallic apertures [4, 5] or dynamic apertures that were induced by optical gating techniques [6, 7]. However, the application of both approaches is limited because of the reduced transmission through subwavelength apertures. The intensity of the image signal decreases with the sixth power of the aperture's diameter.

Apertureless scanning near-field microscopes (SNOMs) have been demonstrated successfully in the near-infrared and in the microwave range [8, 9]. They allow for spatial resolutions that go far beyond the diffraction limit, while providing at the same time a reasonable image contrast. In this approach, the near-field is sampled by a sharp metallic tip. Scanning the surface with the probe images the permittivity of the sample because the image contrast depends on the dielectric properties of the tip-surface system. First works on apertureless imaging at THz frequencies demonstrated resolutions of about 10 μm [10]. Recently, our group reported a spatial resolution of about 150 nm [2], which gives THz techniques access to the nanoworld.

Apertureless THz near-field microscopy

The THz pulses used in our THz-SNOM are generated by femtosecond laser excitation of InAs and have a bandwidth of about 3.0 THz. After transmission through the microscope head the pulses are time-resolved by electro-optic sampling. Figure 1 schematically shows the microscope head. The THz beam is focused to a diffraction limited spot with a diameter of about 4 λ. At the focal spot the THz field is sampled by a tungsten probe, which is held in proximity to the sample's surface. The probe has an overall length $l >> D$ and a tip-radius of either 1 μm or 100 nm. Imaging is achieved by moving the sample with respect to the probing tip. What distinguished our THz-microscope from most other SNOMs, which are operated in the visible or infrared is that we detect the radiation that is specularly propagating through the microscope head. This allows us to measure the amplitude and phase relationships between incident THz pulses and the image signal.

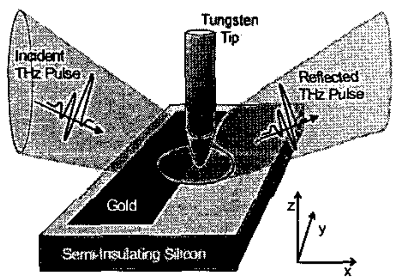

Fig. 1: Schematic of the head of the THz-SNOM. The field strength of the specularly reflected THz signal depends on the near-field between tungsten tip and surface.

Figure 2 shows a THz image of a metallic grating, which consists of 10 μm wide gold lines. The grating lines are clearly resolved, which indicates that the near-field under the tip is imaged. Linear scans across the edge of a grating line allow for a direct determination of the spatial resolution. An example is shown in Fig. 3. In this experiment a tungsten probe with 100 nm tip radius was used. The upper curve in Fig. 3 shows the control current that is run through the tip in order to locate the edge of the grating line. The THz signal clearly reproduces the step and indicates a spatial resolution of 150 nm. More detailed experiments showed that the minimum spatial resolution is mainly given by the radius of the tip used. However, the spatial resolution crucially depends on the distance between tip and surface. Submicron resolutions can be achieved only when the tip-surface distance is smaller than 50 nm.

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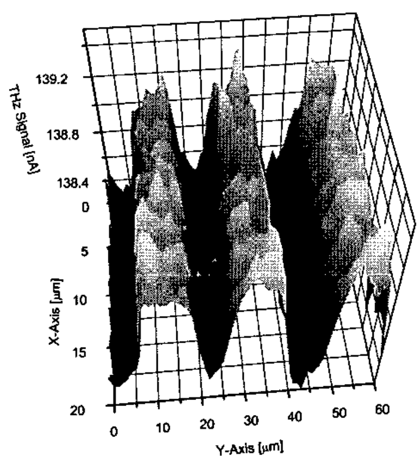

Fig. 2: Terahertz image of a gold grating on silicon. The grating lines have a width of 10 µm. During imaging the tip was held at constant height. The total acquisition time was less than 10 minutes.

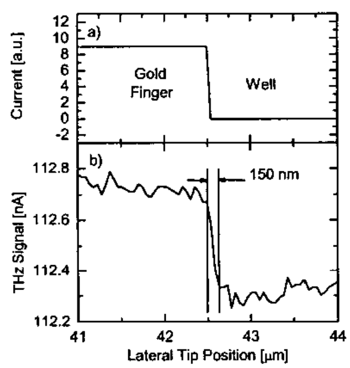

Fig. 3: Linear scan across the edge of a grating line. The data were obtained by keeping the tungsten probe at a constant height of less than 20 nm above the top of the structure. a) Abrupt change of the control current indicating the edge of the grating line. b) Terahertz signal.

Imaging mechanism of apertureless THz techniques

The current understanding of apertureless near-field imaging is that the tip-surface system forms a Mie scatterer and that imaging results from the dependence of the scattering cross sections on the permittivity of the sample's surface [11]. However, several of our experimental observations are incompatible with this framework: i) The image contrast of our THz-SNOM is about 0.5% and exceeds those values expected from Mie theory by orders of magnitude. ii) We observe an enhancement of the specularly transmitted THz signal when the permittivity under the probing tip increases (see Fig. 2), while Mie theory predicts the opposite. iii) According to Mie theory the imaging signal should reveal a spectral dependence proportional to λ^{-n} with $n=1$ or $n=4$ for absorption or scattering respectively. In contrast, our THz data clearly show a resonance at a frequency at about 0.5 THz. These findings indicate that apertureless THz imaging may result from a novel imaging process.

We developed a novel model for apertureless imaging that considers the macroscopic parameters of the tip-surface system such as inductance, capacitance, and input resistance. The model calculations agree qualitatively and quantitatively with the experimental data and reproduce in particular the huge image contrast, the signal enhancement and the spectral dependence of the THz signal. Thus, we conclude that THz imaging is dominated by a nearly resonant AC coupling [12].

Conclusions

Terahertz near-field imaging techniques are attractive for numerous applications in research areas such as the bio-sciences or the nano-sciences. Spatial resolutions down to several micrometers can be achieved when imaging is performed through subwavelength apertures. Alternatives are apertureless techniques. They allow for submicron spatial resolutions while providing at the same time a reasonable image contrast of about 0.5 %. The imaging process results from a resonant AC coupling between scanning tip and surface. The process may be of relevance in other spectral ranges such as the mid-infrared or the microwave region if the resonance of the tip-surface system is tuned to the frequency range of interest.

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