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Published in:
CLEO: Applications and Technology 2018

Link to article, DOI:
[10.1364/CLEO_AT.2018.JM1A.3](https://doi.org/10.1364/CLEO_AT.2018.JM1A.3)

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Pizzuto, A., Klarskov, P., & Mittleman, D. M. (2018). Bias dependence of laser terahertz emission nanoscopy. In *CLEO: Applications and Technology 2018* (Vol. 2018). IEEE. Optics Infobase Conference Papers
https://doi.org/10.1364/CLEO_AT.2018.JM1A.3

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Bias Dependence of Laser Terahertz Emission Nanoscopy

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Abstract: We demonstrate depletion of terahertz emission from semiconductors by applying a DC bias between a substrate and an AFM probe operating in tapping mode. The depletion is strongly dependent on the probe tapping amplitude. © 2018 The Author(s)

OCIS codes: (180.4243) Near-Field Microscopy; (320.7130) Ultrafast Processes in Condensed Matter, Including Semiconductors

1. Introduction

Laser terahertz emission microscopy (LTEM) uses femtosecond optical pulses to induce terahertz emission from a material to probe its charge carrier dynamics. Using a scattering-type scanning near-field optical microscope (s-SNOM) with a small conductive atomic force microscopy (AFM) probe [1] allows for confinement of the incoming laser beam as well as the generated THz field to a subwavelength scale, increasing imaging resolution by up to three orders of magnitude compared to the diffraction limit for conventional LTEM [2]. In this study, we apply a DC bias between the near-field microscope tip and selected semiconductor wafers to observe its effects on the emitted THz radiation as well as its dependence on the tip tapping amplitude.

2. Experiment

Fig.1: (a) Schematic of biased tip-enhanced LTEM. (b) Depleting THz waveforms in InAs A for 0 V bias, 10 V bias, and 25 V bias at 520 nm tapping amplitude

For nanometer-resolved LTEM, we couple a near-infrared (NIR) beam (820 nm, 100fs, 80 MHz repetition rate, 40mW) to a commercial near-field microscope (Neaspec) in tapping-mode. The tip of the AFM probe is an 80/20 PtIr alloy (Rocky Mountain Nanotechnology) which is approximately 80 μm long and tapers to 20 nm wide at its apex. It taps at approximately 21 kHz, with a user-controlled amplitude on the order of hundreds of nm. Near-infrared pulses photoexcite charge carriers in a semiconductor wafer, which emits broadband THz radiation due to the sub-surface dipole induced by the photo-Dember effect [3]. The AFM tip serves both to confine the NIR pulses under the tip and out-couples the THz near-field signal, which we then detect using electro-optic sampling (EOS) and a lock-in amplifier locked to the tip tapping frequency [1]. Forward-scattered NIR light is blocked before the THz detection by a teflon filter which transmits the THz pulses.

Using an external DC supply, we apply a bias voltage between the tip and the sample, which is a bare semiconductor wafer. We then measure the emitted THz field. We compare results from two InAs wafers of different carrier concentrations and one InSb wafer. While THz sources have also been used in combination with Scanning

Tunneling Microscopes (STM) to modulate tunneling currents and hence adding both time-resolution and improved spatial resolution to the STM technique [4], it is important to note that our study is distinct from this; we have explicitly verified that there is no tunneling current between the tip and sample.

3. Results

Waveforms for three values of applied DC bias in sample InAs A (p-doped, carrier concentration $\sim 10^{16} \text{ cm}^{-3}$) are shown in Figure 1b. We observe significant signal depletion for increasing bias. As shown in Figure 2a, all three samples (InAs A, InAs B (p-doped, carrier concentration $\sim 10^{18} \text{ cm}^{-3}$) and InSb (nominally undoped, carrier concentration $\sim 10^{14} \text{ cm}^{-3}$)) give similar results: the applied DC bias results in a decrease in the measured THz field, approximately independent of the sign of the bias.

Fig. 2: (a) Peak THz field vs. DC bias, for 3 different samples (b) Peak THz signal emitted from InAs with increasing positive bias for three tip tapping amplitudes.

Figure 2b shows the decrease in the peak THz field from sample InAs A with increasing positive bias, for three tapping amplitudes. As the tapping amplitude increases, we observe a larger peak field as well as a decreased sensitivity to the applied DC bias.

One possible cause of this DC bias dependence is the creation of a depletion region near the semiconductor surface; charge carriers may build up in the vicinity of the tip, screening the photo-excited THz dipole. It is also possible that the bias changes the local refractive index of the substrate, decreasing the sample's NIR absorption and therefore its THz emission. The higher tapping amplitude allows us to probe deeper into the substrate [5, 6] and overcome some of these carrier or refractive index effects. In future studies, we will perform further THz nanoscopy experiments to probe the wafers' local carrier dynamics around the tip.

4. References

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