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### **► To cite this version:**

B. Walter, E. Mairiaux, D. Vignaud, Sophie Eliet, Jean-Francois Lampin, et al.. Terahertz near-field imaging using batch-fabricated cantilevers with 70  $\mu\text{m}$  long tips. 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Sep 2019, Paris, France. pp.1-2, <10.1109/IRMMW-THz.2019.8874242>. <hal-02398422>

**HAL Id: hal-02398422**

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Submitted on 14 Aug 2021

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# Terahertz near-field imaging using batch-fabricated cantilevers with 70 $\mu\text{m}$ long tips

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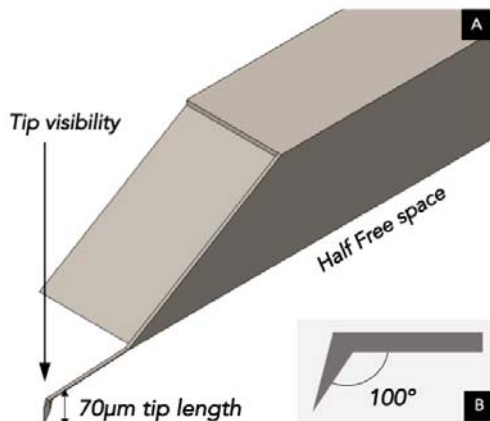
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**Abstract**—Batch-fabricated atomic force microscopy cantilevers with tip longer than 70  $\mu\text{m}$  are reported. They are designed to increase terahertz focusing in scattering optical near-field imaging. Terahertz imaging of graphene samples with sub-100 nm features is presented.

## I. INTRODUCTION

Atomic force microscopy (AFM) is a commonly used technique to image surfaces at the nanoscale. Since its invention and the emergence of batch-fabricated cantilevers with integrated nanotips [1], a few decades of instrumental research led to the emergence of different families: general purpose machines upgradable with electrical measurements, AFMs dedicated to biology, AFM for vacuum operation. By coupling AFM with optical approaches like Raman spectroscopy or scanning near-field optical microscopy (SNOM), one can achieve spectroscopy with nanometric spatial resolution [2-6].

Terahertz (THz) radiation can resonantly interact with fundamental excitations of molecules and solids, which offers powerful spectroscopic tools [3]. However, reaching a submicronic lateral resolution by using the scattering SNOM (s-SNOM) technique in the THz range with large signal-to-noise ratio remains difficult. This is partly because currently available AFM tip technology is not able to manufacture tips longer than 15-20  $\mu\text{m}$  length. As a consequence, such tips lead to low antenna effect due to the large mismatch between tip length and THz wavelength (typically 100  $\mu\text{m}$ ). Previous works demonstrated the interest of THz-resonant antenna tips [4], using focused ion beam assembly sequences.



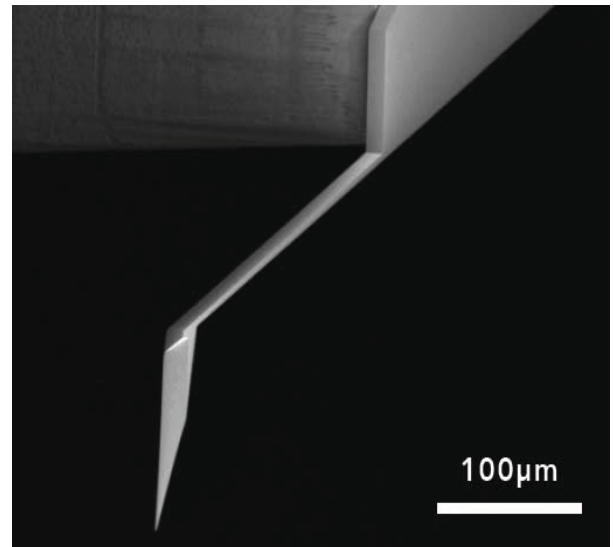
**Fig. 1.A:** Schematic view of the Lprobe cantilever and its holder. The cantilever and the tip are placed at one corner of the holder. The free solid angle around the tip is extended compared to commercial probe thanks to the half free space given by the specific shape of the cantilever holder. **B:** The angle between the tip and the cantilever let an optical path to see the tip end from the top.

## II. RESULTS

In standard commercial AFM probes, the cantilever is placed at the center of the supporting chip. Due to our probe process, the tip and the cantilever are located in the lateral part of the supporting chip and thus is called the Lprobe (fig. 1A).

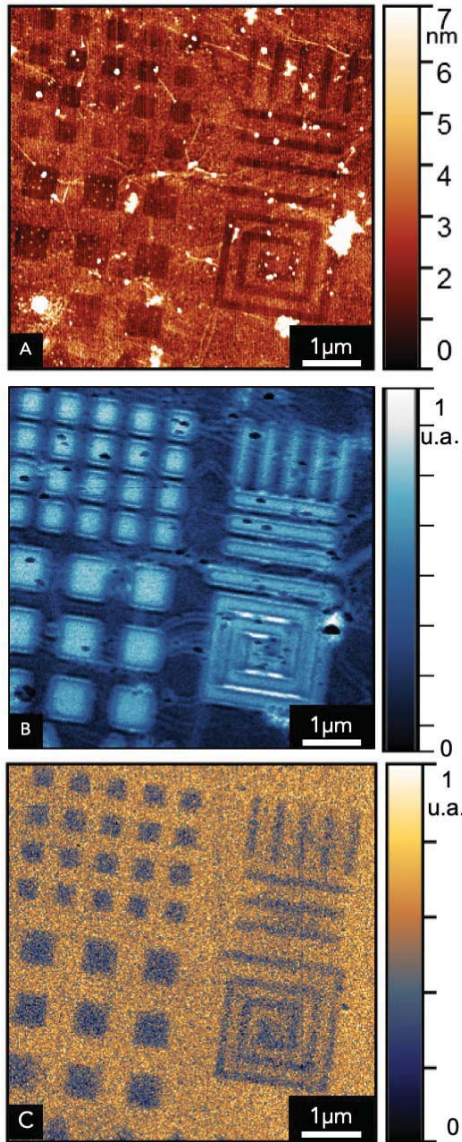
During s-SNOM experiments, it is critical to be able to localize the tip in order to focus the laser on it. The fabrication process gives access to a wide range of cantilever parameters regarding the resonant frequencies and stiffnesses as well as tip geometry. The angle between the tip and the cantilever can be tuned between  $\pm 45^\circ$  around the orthogonal position ( $90^\circ$ ). In this work, the angle between the tip and the cantilever is  $100^\circ$  (fig 1B). This configuration enables the tip visualization from above and eases the s-SNOM experiment.

On figure 2, we present the first batch of fabricated cantilever tips with up to 70  $\mu\text{m}$  long tips. Since the cantilevers and the tips are batch fabricated, geometrical parameters and mechanical parameters are reproducible with dispersion less than 5%.



**Fig. 2.** SEM picture of the Lprobe cantilever featuring a 70  $\mu\text{m}$  long silicon monolithically integrated tip. The cantilever is coated with 25 nm of platinum. The tip apex is less than 25 nm. Cantilever parameters: resonant frequency: 220 kHz – stiffness: 20 N/m.

The Lprobe was mounted onto a commercial s-SNOM (model Neasnom from *Neaspec GmbH*) and two experiments were performed. In a first experiment, the microscope was coupled to a mid-infrared (MIR) quantum cascade laser (QCL) and a liquid nitrogen cooled HgCdTe detector. Tip illumination



**Fig. 3.** The imaged sample is a graphene monolayer transferred on SiO<sub>2</sub> and patterned using e-beam lithography. Both spiral and straight lines are 100 nm wide. The graphene layer is etched inside the patterns. A: topography (AFM signal). B: s-SNOM mid-infrared image at  $\lambda = 10 \mu\text{m}$  (2<sup>nd</sup> harmonic demodulation). C: s-SNOM THz image at  $\lambda = 118 \mu\text{m}$  (2<sup>nd</sup> harmonic demodulation).

was performed using a 10  $\mu\text{m}$  wavelength (optical power 3 mW). In a second experiment, the microscope was coupled to a CO<sub>2</sub>-pumped CH<sub>3</sub>OH THz laser (*Edinburgh Instruments*) and a 4 K-cooled THz InSb hot electron bolometer (*QMC Instruments*). The wavelength used in this work was 118  $\mu\text{m}$ . The measured THz power at the input of the microscope was 25 mW.

In order to assess the new Lprobes capabilities for s-SNOM imaging, we used graphene samples since graphene optical properties in both infrared and THz range were already studied in near-field [5-7]. A graphene monolayer was grown on a copper foil and transferred on an oxidized silicon substrate [7,8]. We patterned the graphene monolayer [8] using e-beam

lithography and plasma etching to fabricate a demonstration sample with 100 nm linewidth features.

As presented in figure 3, simultaneous topography and s-SNOM images were recorded. In both cases the 2<sup>nd</sup> harmonic of the tip modulation frequency was used for demodulation of the signal coming from the detector. The first experiment was done using the MIR laser and the second using the THz laser but exactly the same area of the sample was scanned. The topography image (fig. 3A) shows the graphene layer etched in the squares, bars and spiral patterns. Some spots due to sample contamination during the various steps of the process are also visible (white areas). The MIR s-SNOM image (fig. 3B) shows a strong contrast between graphene and etched areas. Typical signatures of grain boundaries are visible on the graphene areas. They are due to plasmonic excitations at the boundaries that interfere with plasmonic excitations due to the probe tip [5]. These damped plasmonic oscillations are also visible at the etched boundaries of the patterns. Strong signal enhancement is visible in the arms of the spiral pattern due to constructive interferences from both sides. The THz s-SNOM image (fig. 3C) shows clearly a reduction of signal in the etched patterns. The signal to noise ratio is less than in the MIR case but a lateral resolution of less than 50 nm is also demonstrated.

### III. SUMMARY

Using our new Lprobe design we are able to record images of graphene in the MIR and the THz ranges with a lateral resolution of less than 50 nm. This is a first step toward future THz Lprobes designed to have specific resonances in the THz in order to increase the signal to noise ratio.

### ACKNOWLEDGMENT

We acknowledge the Equipex Excelsior ANR 11-EQPX-0015 for funding part of this work and the RENATECH network.

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