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***Abstract*— Coupling an electromagnetic wave at GHz to THz frequencies into the channel of a graphene field-effect transistor (GFET) provokes collective charge carrier oscillations of the two-dimensional electron gas (2DEG) known as plasma waves. Here, we report the very first experimental and direct mapping of the electric field distribution in a gated GFET at nanometer length scales using scattering-type scanning near-field microscopy (s-SNOM) at 2 THz. Based on the experimental results we deduce the plasma wave velocity for different gate bias voltages, which is in good agreement with the theoretical prediction.**

I. Introduction

Plasma waves on the gated two-dimensional electron gases (2DEGs) in field-effect transistors (FETs) [1] attracts attention since FETs have become uniquely interesting for detecting electromagnetic waves at THz frequencies. At those frequencies, the 2DEG no longer behaves quasi-statically; the dynamic response to the external THz stimulus launches a plasma wave of collective electron oscillations within the 2DEG that propagates much slower as compared to the speed of light in vacuum. To date, no direct proof for this Dyakonov-Shur hypothesis is known, with all reports and findings so far delivering only indirect evidences. On the other hand, clear experimental evidences for the existence of plasma waves in THz FETs exist in various forms, most persuasively through demonstrating the plasmon-resonant behavior in high-mobility devices at cryogenic temperatures [2]. What is missing to date, however, is this direct visualization of plasma waves within the channel of such a THz FETs. This exactly is the goal of our study presented here: we directly map the plasma waves within the GFET using s-SNOM at THz frequencies.

II. Setup and Results

Figure 1 depicts our experimental setup. The GFET consist of a 2.7-μm-long graphene (Gr) channel bridging between source (S) and drain (D) contacts. Source, drain and gate (G) are shaped in the form of a bow-tie antenna to feed in the 2-THz field (from the FELBE free electron laser) into the gated graphene channel. The s-SNOM tip accesses the GFET from the top and scatters the near field into a hot-electron bolometer for far-field detection. Figure 2a) displays a typical near-field scan. As shown, the electrodes show a slightly different near-field cross section due to shadowing of the cantilever as it sits quasi above the source electrode. Additionally, the GFET channel shows an enhanced near-field signal close to the source electrode. When carefully analyzing individual scan lines recorded along the Gr channel for different gate voltages, with one second integration which is 20 times larger than for

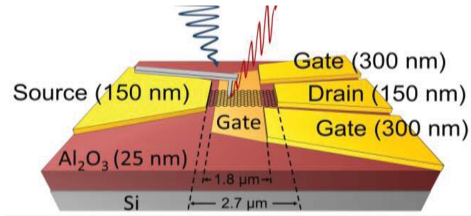

Fig. 1. *Bottom-gate graphene field-effect transistor (gfet) similar to [2]. Source, drain and gate electrode form a bow-tie antenna for coupling-in the thz field. The s-snom tip maps the local field of the plasma wave in the graphene channel.*

2D image, we find clear signatures for such a plasma wave, decaying as a function of distance. As a result using standard electron scattering times and Fermi velocity v_f for graphene [4], we are able to quantify the plasma wave velocity v_{pl} as a function of gate voltage as displayed in figure 2b), with v_{pl} = 3.5 – 7.5 v_f being in good agreement with literature values. Moreover, we find a clear minimum for the velocity v_{pl} that well matches to the charge neutrality point, as was deduced from IV-curves recorded from the GFET device.

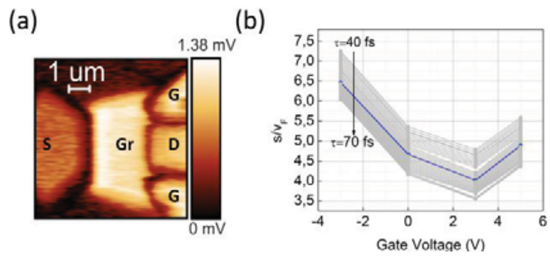

Fig. 2. *(a) Near-field scan of the device at 2 THz; (b) Deduced plasma wave velocity for different gate voltages.*

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