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A Heterodyne Graphene FET Detector at 400 GHz

Andrey A. Generalov[1], Michael A. Andersson[1], Xinxin Yang[1], Andrei Vorobiev[1], and Jan Stake[1]
[1]Terahertz and Millimeter Wave Laboratory, Department of Microtechnology and Nanoscience – MC2,
Chalmers University of Technology, SE-412 96, Gothenburg, Sweden

***Abstract*—We present a THz heterodyne detector based on a single layer graphene field effect transistor (GFET) integrated with a bowtie antenna at 400 GHz. The heterodyne detection is achieved by coupling RF and LO signals quasi-optically to the same GFET. The down converted IF signal is extracted via a coplanar stripline connected to the GFET source and drain terminals. The measured IF bandwidth is 5 GHz.**

I. INTRODUCTION

IMPLEMENTATION of graphene in field effect transistors (GFET) have the potential to create fast, sensitive and inexpensive room temperature THz detectors [1-3]. Additionally, graphene is compatible with silicon technology which makes it possible to integrate with existing devices and circuits. Currently the chemical vapor deposition (CVD) graphene allows for covering large areas and fabricate arrays of devices. The direct detectors based on GFET transistor were first demonstrated at 300 GHz [1], and further developed for 400 GHz [2], and 600 GHz [3]. The lowest noise equivalent power (NEP) of 130 pW/Hz$^{1/2}$ achieved in these detectors shows that it came close to compete with other types of room temperature THz detectors [4-6].

GFET direct detectors rectify the THz signal by a self-mixing in FET channel resulting in a dc response above the cutoff frequency of the transistor [1-3]. On the other hand, GFET detectors can be also used as fundamental or subharmonic mixers. If two signals at different frequencies are combined in the GFET detector, then a resulting response can be read out at intermediate frequency (IF).

The GFET subharmonic mixers were tested at 30 GHz [7], and at 200 GHz [8] as integrated circuits. The fundamental FET mixers were demonstrated in quasi-optical setups based on CMOS FETs [9], and on bi-layer GFETs [10] with the reported IF bandwidth of 1 GHz. Such heterodyne receiver opens an opportunity for more sensitive THz imaging and, in addition, allows for acquiring a phase information.

In this paper, we report a fundamental mixer at 400 GHz based on a heterodyne single layer GFET detector in quasi-optical setup. The implementation of the designated IF line to the GFET mixer allows to achieve the IF bandwidth up to 5 GHz.

II. DESIGN AND FABRICATION

The design of the GFET mixer is shown in Fig. 1. The signal is fed to the drain – source and the gate – source terminals simultaneously which is achieved by splitting the bowtie antenna as shown in Fig. 1 a). This corresponds to an equivalent circuit shown in Fig. 1 c). The schematic GFET detector structure in the center of the antenna is shown in Fig. 1 b) and the gate width and length are 2 μm and 2.5 μm, respectively.

The radius of the antenna is 160 μm to provide almost constant impedance of 65 Ohms above 350 GHz which allows for coupling both RF and LO signals in the frequency range of 350 – 500 GHz. The IF transmission line is a coplanar stripline (CPS), which is connected to the drain and source terminals of the GFET detector. The antenna is placed in the center of the hyper-hemispherical lens made of silicon. The radius of the lens is 2.5 mm and the extension is 0.75 mm. The lens together with a bowtie antenna and CPS IF line provides the directivity of 28 dB according to simulation results using CST Microwave Studio software. The CPS to CPW transition is used to connect the IF line to a SMA connector.

The high-resistivity Si substrate with a 300 nm SiO_2 layer was used for the fabrication of GFET heterodyne detectors. The substrate was covered with a single-layer CVD graphene using a dry transfer technique, which was supplied commercially by Graphenea [11]. A 300 nm thick gold is used for the source, gate, and drain electrodes, and a 20 nm thick Al_2O_3 is used as a gate dielectric. The detailed description of the fabrication process is presented in [2].

III. MEASUREMENTS

The schematic image of the experimental setup is shown in Fig. 2. Two VDI WR2.2-VNAX extenders were used as RF and LO sources. The sources are combined through a WR-2.2 directional coupler and the signal is transmitted through the WR-2.2 horn antenna into the Si lens with a detector. The VDI WR2.2-VNAX extenders are fed by signal generators SG1 and SG2 and controlled by a computer. LO is set to 383 GHz and the RF signal changes from 383 to 398 GHz which corresponds to IF up to 15 GHz. The IF signal is amplified with a 35 dB 0.1 – 15 GHz amplifier and characterized with a spectrum analyzer. A photograph of the experimental setup is shown in Fig. 3.

The RF and LO powers at the output of the directional coupler are calibrated at 383 GHz with an Erickson PM4 calorimetric power meter. For other frequency points the RF power is normalized to a direct detection response at those frequencies. This achieved by switching the signal generator SG1 to an amplitude modulation mode with the rate of 333 Hz and measuring the direct detection response with a lock-in amplifier.

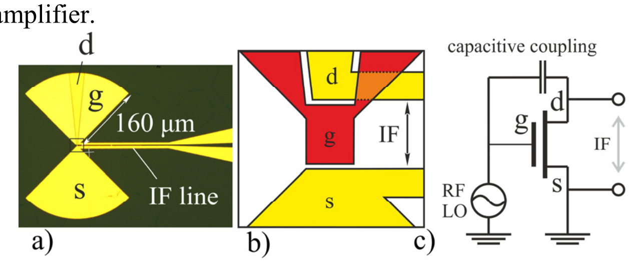

Fig. 1. a) A microscope image of the fabricated GFET detector with a CPS IF line b) A schematic illustration of the GFET detector in the center of the bowtie antenna c) A circuit diagram of GFET detector

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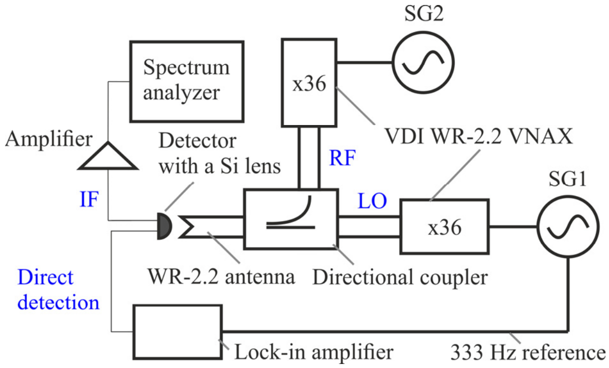

Fig. 2. A schematic image of the experimental setup.

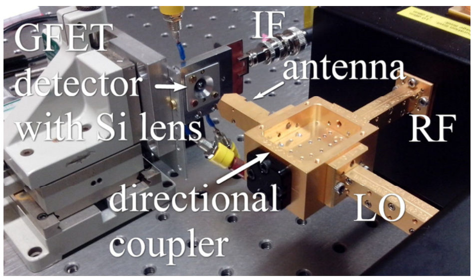

Fig. 3. A photograph of the experimental setup.

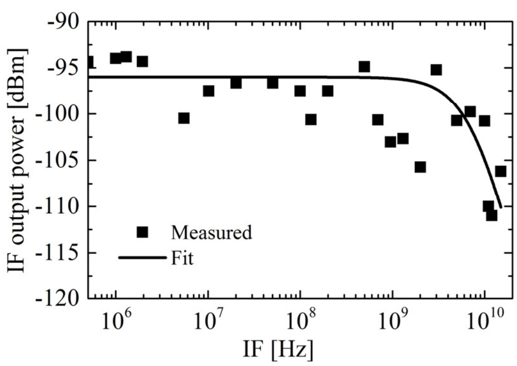

Fig. 4. IF bandwidth of the GFET heterodyne detector at LO 383 GHz.

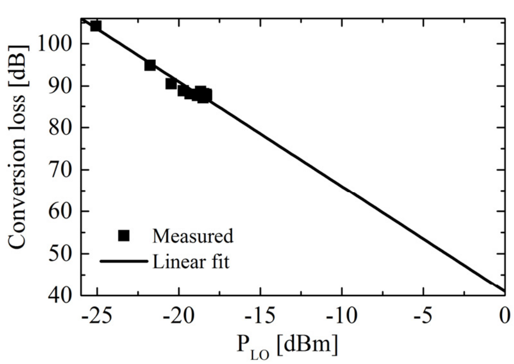

Fig. 5. Conversion loss versus LO power of the detector at IF 5.5 GHz.

IV. RESULTS

The heterodyne measurements at LO 383 GHz are presented in Fig. 4 for the IF ranging from 500 kHz to 15 GHz. The measured IF gain data is fitted with a function in dB scale:

$$G = G_0 - 20\log(1 + \omega^2\tau^2), \qquad (1)$$

where G_0 is an IF gain at low frequency, ω is the angular frequency and τ is the response time. The 3-dB bandwidth of the detector is 5 GHz, which corresponds to a response time τ of 21 ps. The IF bandwidth can be limited by a bonding wires connection between the CPS line on Si chip and the CPS line on the IF measurement block. The conversion loss versus LO power is shown in Fig. 5 at LO 383 GHz, RF 388.5 GHz, and IF 5.5 GHz. In this range, the dependency vs. LO power is close to linear and is fitted with the linear function in Fig. 5. Due to low available LO power, the conversion loss is 87 dB at maximum available LO power of -18.5 dBm. Assuming the linear dependency in the wider range of LO power, it is possible to estimate the conversion loss of 40 dB at LO power of 0 dBm.

V. CONCLUSIONS

The GFETs have a potential for creating high frequency sensitive detectors based on a resistive self-mixing and operating at room temperature. The presented results prove the fast operation with low response times of these GFET THz detectors. The design of a fundamental heterodyne GFET detector is presented for 400 GHz and the measurement results show IF bandwidth of 5 GHz corresponding to a response time of 21 ps. This allows for a future in depth research of the mixing mechanisms in the GFET mixers and determining the limits of their performance.

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