Symmetry Effects in Broadband, Room-Temperature Field Effect Transistor THz Detectors

Stefan Regensburger,[1] Martin Mittendorff,[2;3] Stephan Winnerl,[2] Hong Lu,[4] Arthur C. Gossard,[4] and Sascha Preu[1]

[1]Dept. of Electrical Engineering and Information Technology, Technische Universität Darmstadt, Germany

[2]Helmholtz-Zentrum Dresden-Rossendorf, Germany

[3]Institute for Research in Electronics and Applied Physics, University of Maryland, USA

[4]Materials Department, University of California, Santa Barbara, USA

Abstract — **Rectifying large area field-effect transistors (LA-FETs) are excellently suited for aligning high power pump-probe experiments. They offer the possibility of single-shot measurements, as well as the simultaneous measurement of optical near infrared pulses and their respective temporal delay. This paper studies the phase of the rectified signal of LA-FET detectors for low (~100 GHz) and high (~3.9 THz) THz frequencies. At low frequencies, the sign of the rectified current can be inverted by a source-gate bias while at high frequencies the sign remains constant.**

I. INTRODUCTION

Pump-probe experiments imply high peak powers. The advent of high peak power THz sources such as free electron lasers (FELs) enables this class of experiments at THz frequencies. In order to align the delay between pump and probe pulses, we have developed large area field effect transistors (LA-FETs) that are capable to detect both THz and near infrared pulses with a temporal resolution in the range of 30 ps [1].

A priori FETs are symmetrical devices regarding the ohmic source (S) and drain (D) contacts, and the Schottky gate contact [2]. In a simplified picture, THz radiation is rectified along the channel of the transistor under the gate via simultaneous modulation of the charge carrier density and velocity through the THz current. Whether the THz signal is rectified at the drain side or the source side of the gate crucially depends on how the THz signal is fed to the device. The two possibilities feature an opposite sign of the rectified current. This competition reduces the detector performance. Detectors have to be designed such that only one of the two mechanisms dominates the performance. To a certain degree, this can be achieved by the geometric layout of the device or by the biasing conditions. We therefore investigate devices with a different geometric layout and biasing both at the free electron laser FELBE in Dresden and in a continuous-wave (CW) setup.

II. SETUP

The investigated LA-FET detectors feature an area of 0.3 mm x 0.3 mm as illustrated in the inset of Fig. 1, attached to a silicon lens. The source contact is defined as the contact closer to the gate electrode. The LA-FET design does not feature an additional antenna. Instead, the THz electric field with a polarization along the source-drain direction directly couples to the transistor channels. Deliberate launching the THz signal from one side only into the transistor channel is much more difficult than in antenna-coupled devices where the antenna can be attached to source and gate, e.g., and drain being grounded which breaks the symmetry of the device.

Pulsed measurements were performed at the free electron laser FELBE, Helmholtz-Zentrum Dresden-Rossendorf at frequencies between 1.3 THz and 3.9 THz. A 30 GHz oscilloscope reads out the rectified THz signal. The single frequency FEL pulse is focused on the device using a parabolic mirror. The calculated spot size at 1.3 THz matches the device dimensions. At higher frequencies, the THz spot is (much) smaller than the device, excluding that the THz power is coupled to the pads for electrical connection or the wiring as was found as the major coupling mechanism in ref. [3]. This is confirmed by polarization-sensitive measurements: The polarization along the SD direction yielded about 4 times higher signal than the orthogonal polarization. Further, the sign of the signal did not depend on alignment, excluding major coupling through the pads which should yield opposite signs when the source pad or the drain pad is hit, respectively. For CW, a modulated backward wave oscillator around 100 GHz is used as source. The signal is focused on the detectors by a high NA=0.3 dielectric lens. The rectified signal is read out by a lock-in amplifier. The polarization extinction of a factor of 8.5 was even larger than for the pulsed measurements, indicating that the signal originates from the device and not from pads.

III. RESULTS

We investigated two different detector designs with a stronger and weaker asymmetry of the gate position in the channel. Device A has a SG distance of 1.75 µm and a GD distance of 5.25 µm with a gate width of 4 µm. Device B has a SG distance of 2 µm and a GD distance of 3 µm with a gate width of 2 µm. As a result, the asymmetry by gate position in the design B is much smaller than for device A. The gate width of device A and B correspond to about 7 and 3 times the effective rectification length at 100 GHz respectively. The FETs are therefore operated in the long gate regime.

In Fig. 1 the signal of the LA-FET detector A as well as the lock-in phase of the measurement is shown. Applying a negative gate bias, the CW data at 93 GHz show a zero crossing of the signal at -0.2 V gate voltage ($U_{thr}\approx$-0.5 V) represented by a phase flip of 180°. This sign flip indicates that the THzwave is coupled oppositely to the gated area of the FET. For THz frequencies, external grounding and circuitry does not result in proper AC/THz potential definition at the rectifying element.

While the DC potential of the gate is well defined, ground loops etc. can cause an AC floating gate. The THz signal can couple from either side into the gated region, depending on the impedance distribution within the device. At 93 GHz, the gate is only weakly coupled by the fringing capacitance between S and G electrodes.

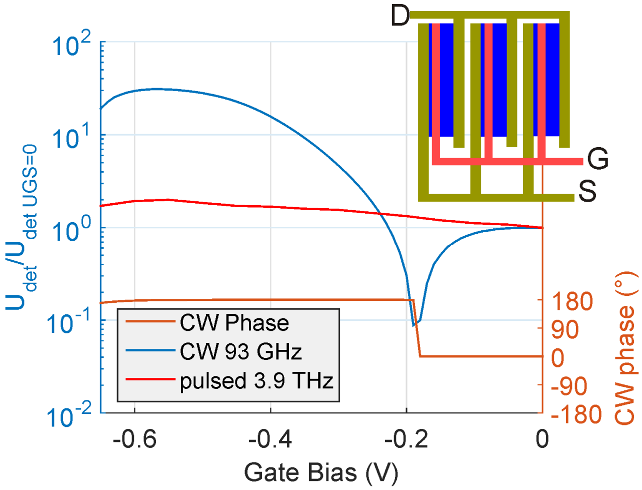

Fig. 1. Signal from the LA-FET detector A as a function of the applied gate bias for 93 GHz and 3.9 THz (left axis). For the CW data, the corresponding lock-in phase is shown as well (right axis). The inset shows a scheme of the asymmetrical LA-FET detector.

The access resistance of less than 1 Ω at zero gate bias is much smaller than the capacitive impedance and therefore dominates the device performance. When the device resistance is increased by pinching off the channel, carriers in the channel are repelled from the source side, causing a sign flip of the signal and a zero-crossing, as shown in Fig. 1 around -0.2 V. In contrast, the gate bias vs. responsivity characteristics of the pulsed data at 3.9 THz show a smooth behavior without a zero crossing or sign flip, showing stronger coupling of gate and source.

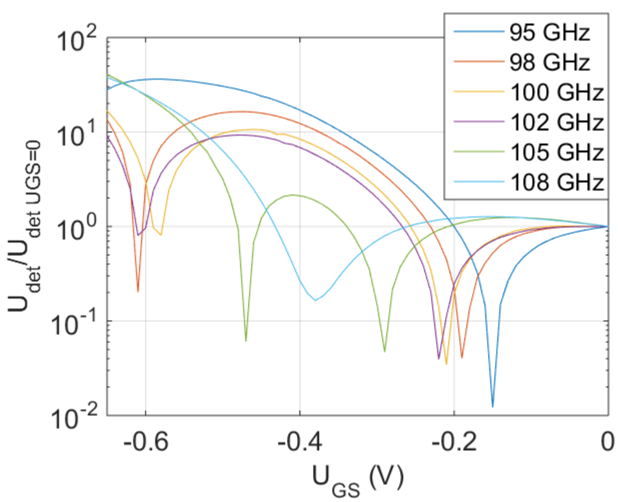

Fig. 2. Signal from the LA-FET detector A as a function of the applied gate bias for around 100 GHz in a CW measurement. At the local minima of the Signal, the sign flips. The gate bias of the sign flip changes with THz frequency.

In Fig. 2, the frequency dependent signal is shown over several frequencies around 100 GHz for device A. When increasing the frequency, the zero crossing shifts further to more negative gate biases. At 100 GHz, a second sign flip appears and shifts to less negative biases for higher frequencies. As this second sign flip is below threshold it can be attributed to a bolometric detection mode. For 108 GHz the two different sign flips unite to one global minimum.

The frequency resolved gate bias dependence of device B is shown in Fig. 3. It also shows two sign flips, but in contrast to device A, the voltage of the sign flip differs and does not simply increase with frequency but rather shows a chaotic behavior. This is due to the almost symmetric FET structure.

An additional detector design with an even stronger asymmetry compared with design A, shows a behavior with a single sign flip only at gate biases around -0.4 V to -0.5 V and a weaker frequency dependence. This device thus shows a smaller frequency dependence in the detection in correspondence with the larger asymmetry by design.

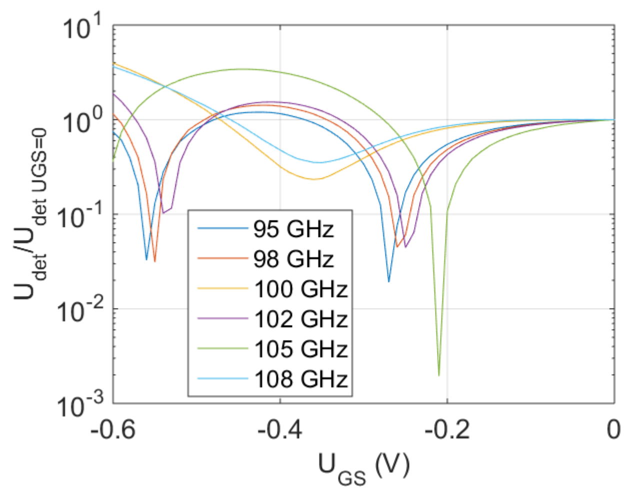

Fig. 3. Signal from the LA-FET detector B as a function of the applied gate bias for around 100 GHz in a CW measurement. At the local minima of the signal, the sign flips. The gate bias of the sign flip changes with THz frequency.

IV. Summary

We have shown that the sign of the rectified THz signal by FETs can be controlled by geometry and gate bias at low THz frequencies. In pulsed measurements, however, the gate bias characteristics show a smooth behavior without zero crossing and sign flip. This indicates that the SG capacitance results in a shunt at higher THz frequencies in the pulsed measurements, dominating the device behavior over the DC biasing conditions.

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