Comparison of Large Area and Lumped Element Field-Effect Transistors for Broadband Detection of Terahertz

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***Abstract*— We compare Terahertz detection by large-area to antenna coupled lumped element field-effect transistors (FETs). The large radiation resistance of R_A=72 Ω of the antenna coupled device improves the responsivity by a factor of 150 as compared to the antenna-less large area device. The LA-FET is an order of magnitude more sensitive than expected from theory.**

I. INTRODUCTION

A CURRENT in the channel of a field-effect transistor (FET) modulates both the charge charrier velocity and the charge carrier density under the gate contact. THz signals fed into a FET are therefore self-rectified [1], yielding a read-out bias of

$$I_r \sim U_{THz}^2, \quad (1)$$

where U_{THz}^2 is the THz bias coupled to the device. Antenna coupled FETs have received much attention in the past delivering a competitive sensitivity for table-top experiments at room temperature [2]. The large radiation resistance R_A of the antenna strongly improves the THz bias coupled to the device by $U_{THz}^2 \sim 2PR_A$. However, antennas are very difficult to implement in the higher Terahertz range where the device size is in the range of the antenna dimensions. This boundary is roughly reached at 1-2 THz for devices with dimensions in the range of 10 µm².

Antenna-less, large area field-effect transistor (LA-FET) detectors are designed to meet the requirements of high-power ultra-short pulsed applications in particular for frequencies above 1 THz, being sensitive to both NIR and THz pulses. They allow for measuring the amplitude as well as the temporal delay between the pulses [3]. LA-FETs are therefore excellently suited for calibration and as reference detectors for pump-probe experiments using THz and NIR pulses, facilitating the temporal alignment between NIR and THz pulses [3]. They feature a high damage threshold (>65 kW), as well as a large linearity range [3]. Additionally they feature a response time faster than the used 30 GHz oscilloscope in the measurement with a rise time of 12 ps [3]. Further applications include autocorrelation measurements for pulse shape characterization [4].

In this study we compare the responsivity and biasing of detectors from both concepts, the antenna coupled lumped element FETs and the LA-FETs at room temperature. While designed for high-power facilities like free electron lasers with kW peak power levels, the LA-FET is still sensitive enough to measure µW-powers from continuous-wave table-top systems.

II. EXPERIMENTAL SETUP AND RESULTS

For the continuous wave (CW) characterization we use a 1550 nm operated photomixing setup [5] as sweep oscillator THz source, while the respective antenna coupled or LA-FET detector is used for detection. A Golay cell (Tydex) is used as power reference. Fig. 1 shows a schematic of the setup. The signal is modulated through the bias-modulation of the pin-diode photomixer. The rectified signal of the FET is measured using a lock-in amplifier at the frequency of the bias modulation of the THz emitter.

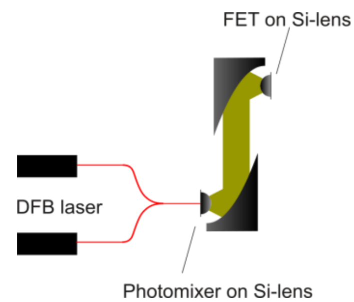

Fig. 1 Schematic drawing of the setup used for characterization of the THz induced signal in the antenna coupled FET and LA-FET.

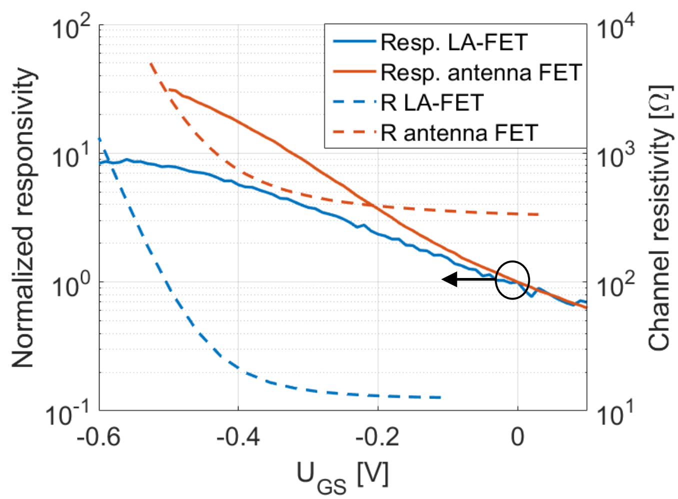

Fig. 2 Rectified signal of the LA-FET (solid, blue) and antenna coupled FET (solid, red) as function of the gate bias at 200 GHz. The detected voltage is normalized to the THz induced signal without gate bias. DC resistance of the LA-FET (dashed, blue) and antenna coupled FET (dashed, red) vs gate bias.

Both the LA-FET and the antenna coupled lumped element FET are mounted on a silicon lens for efficient coupling of the THz radiation through the backside. The diffraction-limited spot diameter at 200 GHz for the used experimental setup is ~2 mm in the substrate. The active area of the LA-FET is 0.33x0.33 mm^2 consisting of 0.33 mm wide transistors with a gate length of 1.5 µm connected all in parallel. The threshold bias is U_{GS}=-0.51 V ±0.05 V.

The lumped element FET is 30 µm wide and has a gate length of 1 µm. It is connected to a broadband logarithmic spiral antenna with a radiation resistance of R_A=72 Ω and outer dimensions of 1.2 x 0.75 mm^2. It features a slightly higher threshold bias of U_{GS} =-0.55 V ±0.05 V, attributed to

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the shorter gate. The effective receiving area of the attached spiral antenna is A=λ^2G/4π, yielding an effective receiving area of 0.51x0.51 mm² at 200 GHz and 0.34x 0.34 mm² at 300 GHz, i.e. about 2.6 times larger than the cross section of the LA-FET at 200 GHz and about the same cross section at 300 GHz. Both FETs are processed on the same semiconductor material to ensure direct comparability of the design. The FETs are epitaxially grown (Al-)GaAs high electron mobility transistors (HEMT) featuring a 2DEG 30 nm underneath the surface with an electron mobility of ~6000 cm²/Vs at room temperature.

In a first step, the optimum biasing conditions are determined, considering both responsivity and noise floor. Fig. 2 shows the detected bias due to the rectified THz signal vs. gate bias for both samples under investigation, normalized to the received bias at U_{GS}=0V. The LA-FET shows a maximum of detected bias slightly above threshold at a bias of U_{GS}=-0.56 V±0.05 V. At this point, the SD resistance of the device remains still considerably small at a value of 0.5 kΩ due to the large number of parallel array elements. The calculated Johnson noise due to this resistor is only $\sqrt{4k_BTR}$ =2.8 nV/$\sqrt{Hz}$ which is considerably lower than the input noise of the used lock-in amplifier of 5 nV/$\sqrt{Hz}$ The LA-FET noise floor is therefore mainly determined by post-detection electronics. For the antenna coupled FET, the characteristics are only recorded to U_{GS}=-0.5 V since the device features already a resistance of 5 kΩ at this bias, causing excessive Johnson noise of 8.9 nV/$\sqrt{Hz}$ which reduces the dynamic range of the detector for biases even closer to threshold.

Fig. 2 also shows that the antenna coupled lumped element FET features a larger responsivity enhancement compared with the LA-FET when the devices are operated closer to threshold. This is attributed to the larger and steeper increase of channel resistance, $R_{Ch}(U_G)$, of the antenna-coupled receiver which is also shown in Fig. 2. From basic transistor theory [6,7] follows that the rectification effect produces a photocurrent, I_{ph}, that is subsequently transformed into a bias drop over the source-drain (differential) resistance, U_{ph}= $I_{ph}(U_G)R_{Ch}(U_G)$, if coupled to a high impedance load as the lock-in amplifier. While $I_{ph}(U_G)$ depends mainly on the HEMT material (i.e. channel depth and mobility), which is identical for both designs, and the coupling efficiency determined by the radiation resistance, the serial connection of wide FETs within the LA-FET causes a much lower and also less steep resistance as compared to the antenna-coupled FET, resulting in a weaker increase of the read out bias when approaching the threshold bias. Parasitic contributions are included with the efficiency η. Summarizing the above findings, the bias responsivity of FETs can be summarized as

$$\Re_V \sim \eta R_A R_{Ch}(U_G) \qquad (2)$$

Fig. 3 depicts the THz responsivity for the antenna coupled lumped element FET (solid, blue) and the LA-FET (solid, red), normalized to the maximum value of the antenna-coupled FET, The antenna coupled FET shows factor of ~150 higher responsivity at 300 GHz than the LA-FET at a gate bias of U_{GS}=-0.5V for the antenna coupled device as compared to the LA-FET at the optimum bias of U_{GS}=-0.6V. At 300 GHz, the effective receiving area of antenna-coupled and large area device should be very similar, allowing for a direct comparison of the responsivities for extracting the radiation resistance of the LA-FET. Evaluating and comparing Eq. (2) for both designs yields an experimentally obtained radiation resistance of the LA-FET of 0.1 Ω at 300 GHz for the same efficiency η. Interestingly, this is about an order of magnitude larger than obtained from a theoretical model presented in ref. [5], Eq. 90, where we assumed an effective dipole length of 7.5 µm, corresponding to the source-drain distance of the LA-FET. The difference could be assigned to much smaller parasitic serial resistance of the LA-FET as compared to the antenna coupled FET suggesting a higher efficiency η of the LA-FET.

In summary, we have compared an antenna coupled lumped element FET rectifier to a large area FET rectifier and found that the LA-FET is an order of magnitude more sensitive than expected from theory. We further expect that the LA-FET becomes more efficient than antenna-coupled devices at higher THz frequencies, where antennas are more difficult to design due to a comparatively large lumped element device size that does not fit well into the antenna any more.

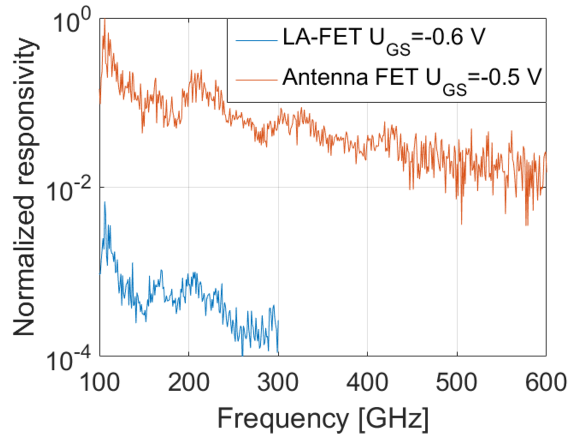

Fig. 3 Responsivity of the large-area (blue) and antenna coupled lumped element field-effect transistor (red).

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