



## Low-frequency Noise Characterization of Graphene FET THz Detectors

Downloaded from: <https://research.chalmers.se>, 2025-06-18 04:16 UTC

Citation for the original published paper (version of record):

Yang, X., Vorobiev, A., Jeppson, K. et al (2018). Low-frequency Noise Characterization of Graphene FET THz Detectors. International Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz, 2018-September. <http://dx.doi.org/10.1109/IRMMW-THz.2018.8510404>

N.B. When citing this work, cite the original published paper.

© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, or reuse of any copyrighted component of this work in other works.

# Low-frequency Noise Characterization of Graphene FET THz Detectors

Xinxin Yang<sup>1</sup>, Andrei Vorobiev<sup>1</sup>, Kjell Jeppson<sup>1</sup>, Jan Stake<sup>1</sup>, Luca Banszerus<sup>2</sup>, Christoph Stampfer<sup>2</sup>, Martin Otto<sup>3</sup> and Daniel Neumaier<sup>3</sup>

<sup>1</sup>Chalmers University of Technology, SE-41296 Gothenburg, Sweden

<sup>2</sup>RWTH Aachen University, DE-52074 Aachen, Germany

<sup>3</sup>AMO GmbH, DE-52074 Aachen, Germany

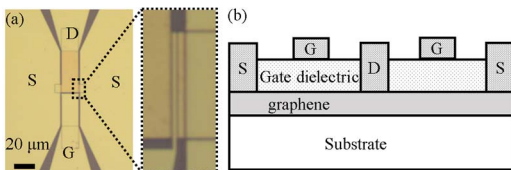
**Abstract**—Graphene field-effect transistors are promising for direct detection of THz signals at room temperature. The sensitivity of such detectors can be in part limited by the low-frequency noise. Here, we report on the characterization of the low-frequency noise of graphene field-effect transistor THz detectors in the frequency range from 1 Hz to 1 MHz. The room-temperature Hooke parameter is extracted to be around  $2 \times 10^{-3}$ . The voltage responsivity at room-temperature and the corresponding minimum noise equivalent power at 0.3 THz are estimated to be 11 V/W and 0.2 nW/Hz<sup>0.5</sup>, respectively, at a modulation frequency of 333 Hz, which shows comparable results with other detector technologies.

## I. INTRODUCTION

GRAPHENE, with its high carrier mobility and saturation velocity, is a promising material for high-frequency devices. In recent years, room-temperature THz detectors based on graphene field-effect transistors (GFETs) have been demonstrated [1, 2]. An important figure of merit of direct power detectors is the noise equivalent power (NEP), which corresponds to the lowest detectable power [3]. Most of previous studies have estimated the NEP of GFET THz detectors based on responsivity measurements and thermal noise calculations. Assuming a short integration time, the low-frequency noise can be avoided. However, impurities and other defects introduced during the fabrication process are expected to contribute to the low-frequency noise [4, 5], and thereby degrade the detector performance. It is important to understand the noise spectrum for detector applications. In this work, we have characterized the low-frequency noise in GFET THz detectors. This allows us to find a low frequency limit of the modulation frequency, above which the low-frequency noise is negligible.

## II. RESULTS

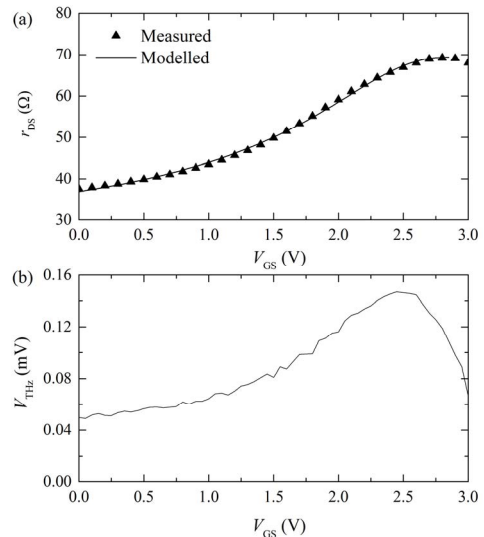
GFET THz detectors were fabricated using monolayer CVD graphene made by RWTH and AMO as in [2]. Fig. 1 shows an optical micrograph and a schematic cross-sectional view of a GFET THz detector with a mesa length ( $L$ ) of 0.7  $\mu\text{m}$ , a gate length of 0.5  $\mu\text{m}$  and an effective channel width ( $W$ ) of



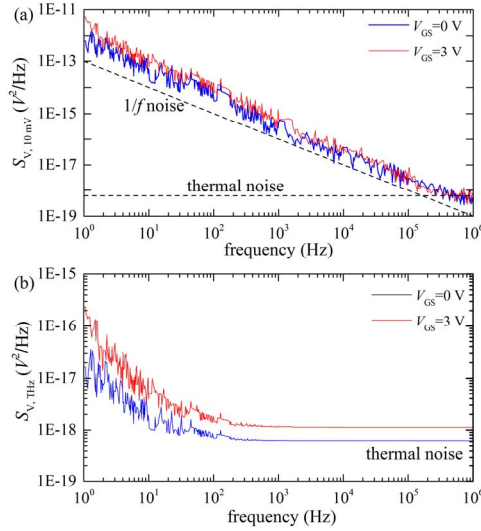
**Fig. 1.** Optical micrograph (a) and schematic cross-sectional view (b) of a GFET THz detector with a gate length of 0.5  $\mu\text{m}$ , and an effective channel width of 20  $\mu\text{m}$  (two 10- $\mu\text{m}$  wide gates in parallel).

20  $\mu\text{m}$  (two 10- $\mu\text{m}$  wide gates in parallel). The rectified THz voltage ( $V_{\text{THz}}$ ) was measured on-wafer using Cascade T-Wave ground-signal-ground probes and an SR830 lock-in amplifier. The 0.3-THz input signal was modulated at 333 Hz. The THz source was composed of a WR-3.4 extender driven by an Agilent 8275D signal generator. The input THz power was around 80  $\mu\text{W}$  considering of the insertion loss of the probes and the return loss of the detectors. The voltage noise spectral density ( $S_{V,10\text{mV}}$ ) of the low-frequency noise was measured at room temperature using a Keysight E4727A Advanced Low-Frequency Noise Analyzer. During the experiment, the sample was placed inside a grounded metal box to minimize environmental noise. The drain-source voltage ( $V_{\text{DS}}$ ) was set to 10 mV since limitations in the setup sensitivity make it hard to measure the noise level with the same drain bias as low as  $V_{\text{THz}}$ . The gate leakage current was less than 0.6 nA posing only negligible effects on the noise level.

Fig. 2 (a) shows the measured drain-source resistance ( $r_{\text{DS}}$ ) of a typical GFET THz detector plotted versus the gate voltage ( $V_{\text{GS}}$ ). By fitting the measured resistance to the model described in [6], the electron mobility, the residual carrier concentration, and the contact resistance were extracted to be 2000  $\text{cm}^2/\text{Vs}$ ,  $1.7 \times 10^{12} \text{ cm}^{-2}$ , and 22  $\Omega$ , respectively. The charge carrier concentration ( $n$ ) was estimated to be in the range from  $1.7 \times 10^{12}$  to  $5.5 \times 10^{12} \text{ cm}^{-2}$ . Fig. 2 (b) shows the rectified THz voltage as a function of  $V_{\text{GS}}$ . The rectified THz voltage is in the range from 0.04 to 0.16 mV.



**Fig. 2.** (a) The measured drain-source resistance of the detector as a function of  $V_{\text{GS}}$  (symbols), together with the fitting result (solid line). (b) The measured rectified THz voltage of the detector as a function of  $V_{\text{GS}}$  without drain-source bias at 0.3 THz.



**Fig. 3.** (a) Measured noise spectral density of the detector vs.  $V_{GS}$  at  $V_{DS}=10$  mV. (b) Calculated noise spectral density of the detector vs.  $V_{GS}$  at  $V_{DS}=V_{THz}$ .

Fig. 3 (a) shows the noise spectral density of the detector measured at two different gate voltages together with the thermal noise calculated as in [1]. It can be seen that the noise spectral density reveals a  $1/f$  dependence. The observed  $1/f$  noise is caused by low-frequency fluctuations of the channel resistance due to fluctuations in carrier concentration and/or mobility [4, 5]. The  $1/f$  noise ( $S_{V,1/f}$ ) at a 10 mV drain-source voltage can be estimated by subtracting the calculated thermal noise. Assuming negligible current-induced heating effects, the Hooge model [7] can be used to estimate the  $1/f$  noise of the detector with a drain-source bias at  $V_{THz}$  from,

$$S_{V,THz,1/f} = S_{V,1/f} \left( \frac{V_{THz}}{V_{DS}} \right)^2,$$

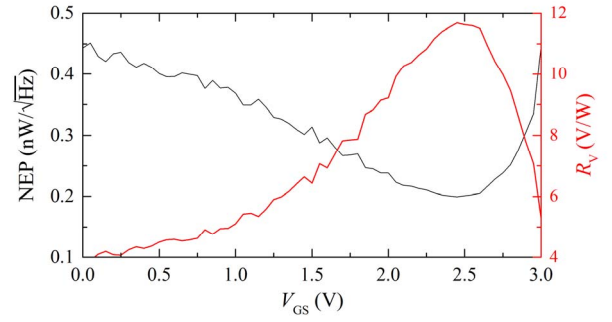
where  $V_{DS}=10$  mV. The noise spectral density ( $S_{V,THz}$ ) at  $V_{THz}$  can now be obtained by again adding the previously subtracted thermal noise as shown in Fig 3 (b). As shown by the graph, the total noise is defined mainly by the thermal noise at frequencies higher than 100 Hz. This means that we can eliminate the effects of the  $1/f$  noise by using modulation frequencies higher than 100 Hz.

We can evaluate the Hooge parameter based on  $S_{V,1/f}$  and the device parameters [7]

$$\alpha_H = \frac{S_{V,1/f}}{V_{DS}^2} * Nf \approx 2 \times 10^{-3},$$

where  $N=nWL$  is the number of carriers.  $\alpha_H$  is 2~3 orders of magnitude larger than those of mature semiconductors [7].

Fig. 4 shows the room-temperature THz voltage responsivity ( $R_V$ ) and the NEP, which are important figures of merit for the direct power detector. The voltage responsivity was calculated as in [2], and the NEP was obtained as  $NEP = \sqrt{S_{V,THz}}/R_V$ . The maximum  $R_V$  is 11 V/W at  $V_{GS}=2.5$  V, and the corresponding minimum NEP is 0.2 nW/Hz<sup>0.5</sup>. The NEP is at the same level as other detector technologies, e.g. 0.65 nW/Hz<sup>0.5</sup> for silicon MOSFETs [8], 0.4 nW/Hz<sup>0.5</sup> for InP DHBTs [9] and 0.1 nW/Hz<sup>0.5</sup> for AlGaIn/GaN HEMTs [10].



**Fig. 4.** NEP and voltage responsivity of the detector as a function of  $V_{GS}$  with a signal frequency of 0.3 THz.

### III. SUMMARY

We have characterized the low-frequency noise of GFET THz detectors and found that modulation frequencies should be higher than 100 Hz to eliminate the effects of the  $1/f$  noise. In this work, the Hooge parameter is around  $2 \times 10^{-3}$ , which is 2~3 orders of magnitude larger than those of mature semiconductors. The room-temperature responsivity and the corresponding minimum NEP at 0.3 THz were estimated to be 11 V/W and 0.2 nW/Hz<sup>0.5</sup>, respectively. These values show the potential of GFET THz detector to compete with other detector technologies.

### ACKNOWLEDGMENT

This work was supported in part by the EU Graphene Flagship Core 1 Project and in part by the Swedish Research Council (VR) under Grant No. 2017-04504.

### REFERENCES

- [1] L. Vicarelli et al., "Graphene field-effect transistors as room-temperature terahertz detectors," *Nat. Mater.*, vol. 11, no. 10, pp. 865–871, 2012.
- [2] A. A. Generalov et al., "A 400-GHz graphene FET detector," *IEEE Trans. THz Sci. Technol.*, vol. 7, no. 5, pp. 614–616, 2017.
- [3] S. van Berkel et al., "THz imaging using uncooled wideband direct detection focal plane arrays," *IEEE Trans. THz Sci. Technol.*, vol. 7, no. 5, pp. 481–492, 2017.
- [4] A. A. Balandin, "Low-frequency  $1/f$  noise in graphene devices," *Nat. Nanotechnol.*, vol. 8, no. 8, pp. 549–555, 2013.
- [5] A. Kaverzin, et al., "Impurities as a source of  $1/f$  noise in graphene," *Phys. Rev. B*, vol. 85, no. 7, p. 075435, 2012.
- [6] S. Kim et al., "Realization of a high mobility dual-gated graphene field-effect transistor with  $Al_2O_3$  dielectric," *Appl. Phys. Lett.*, vol. 94, no. 6, p. 062107, 2009.
- [7] J. Sikula et al., *Advanced experimental methods for noise research in nanoscale electronic devices*. Springer Science+Business Media, 2006, vol. 151.
- [8] K. E. Seery et al., "Characterization of Si-MOSFET CMOS devices for detection at 170 to 250 GHz," *SPIE OPTO*, San Francisco, United States, vol. 105311R, Jan. 27-Feb. 1, 2018.
- [9] N. Dyakonova et al., "Reducing noise equivalent power in InP DHBT terahertz detector by biasing the collector," *2017 ICNF*, pp. 1–4, Vilnius, Lithuania, Jun. 20–23, 2017.
- [10] D. Čibiraitė et al., "Enhanced performance of AlGaIn/GaN HEMT-based THz detectors at room temperature and at low temperature," *2017 42nd IRMMW-THz*, pp. 1–2, Cancun, Mexico, Aug. 27–Sept. 1, 2017.