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Improving 8×8 TeraFET array 2.85 THz-sensitivity by Liquid-Nitrogen cooling in a compact Cryostat

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Abstract— The application of antenna-coupled field-effect-transistors (TeraFETs) as fast and sensitive room-temperature power sensors for Quantum-Cascade-Laser based gas-sensing applications has recently been demonstrated. In this contribution, we report on the realization of a liquid-nitrogen cooled (77 K) TeraFET-system consisting of an 8×8 TeraFET detector array, recently reported for room-temperature operation. We also present the design, implementation and testing of ultra-low-noise readout electronics operating from DC to $f_{-3dB} \approx 3$ MHz with flat amplification. Due to the operation at 77 K, we found experimental, optical (non-area normalized) Noise-Equivalent-Power (NEP) of around $438 \text{ pW}/\sqrt{\text{Hz}}$ with potential to further decrease to below $192 \text{ pW}/\sqrt{\text{Hz}}$ using further optimized low-noise electronics. The current system provides a maximum experimental SNR of approx. 64 dB for 2.06 mW incident power.

I. INTRODUCTION

TeraFETs (Antenna-coupled field-effect transistors) can be applied as fast and sensitive room-temperature power-sensors for terahertz quantum-cascade-laser (QCL) applications in the 2–5 THz band [1,2]. Recently, we demonstrated applications as sensors for methanol gas spectroscopy experiments at 3.4 THz. A major advantage of TeraFETs over established detectors is their frequency selectivity to the THz-range and fast response time enabled by a plasmonic detection mechanism (e.g., $f_{-3dB} > 16$ MHz, could be achieved for a TeraFET+QCL system) [2,3]. Here, we demonstrate a sensitivity increase in the detection of 2.85-THz radiation, through cooling an 8×8 TeraFET detector array with liquid nitrogen (LN₂, 77 K; details on implementation of the detector described in [2]).

II. EXPERIMENTAL DETAILS

The system’s housing is based on a commercial dewar for LN₂ cooling and offers sufficient vacuum supply valves (Fig. 1). To enable optical access, we used a THz transmissive thin polypropylene foil (20 μm) clamped in an in-house built frame. Low-noise readout electronics, consisting of two JFET-buffer elements and two operational amplifier stages (×100 gain) are protected from external noise sources in a metal box (Fig. 1). was developed and characterized for flat DC–5-MHz operation.¹ For TeraFET characterization, the QCL was kept at a temperature of 10 K, while applying a constant bias current of 800 mA. For this configuration, the optical terahertz power was

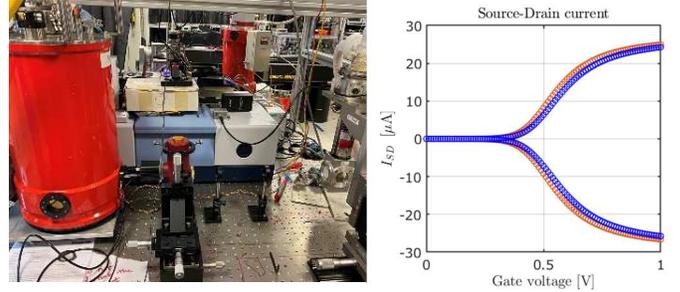


Fig. 1. Left: Photograph of the experimental setup. The 2.85 THz radiation is guided through from the Quantum-Cascade Laser (operated in a cryostat) via two TPX-lenses to the described compact liquid nitrogen (LN₂)-cooled detector system (compare size of system to a conventional bolometer (vendor: QMC instruments)). The alignment of the detector system was achieved via manually controllable XYZ stage. Right: Experimental IV characteristic of the detector at room temperature and at 77 K.

determined to be $P_{\text{THz}} = 180 \mu\text{W}/400 \mu\text{W}$ at the detector position using a calibrated THz power meter (vendor: TK Instruments). The beam was guided from QCL to the TeraFET through two TPX-lenses resulting in a gaussian beam profile at the focus (FWHM approx. 600 μm). We determine voltage responsivity via Eq. 1.

$$R_V = \alpha_{\text{LIA}} \cdot \frac{\Delta U_{\text{DS,LIA}}}{P_{\text{THz}}} = \frac{\Delta U_{\text{DS}}}{P_{\text{THz}}} \quad (1)$$

Where $\alpha_{\text{LIA}} = \pi/\sqrt{2}$ relates the detector’s rectified signal ΔU_{DS} to the magnitude read from lock-in amplifier. Optical Noise-Equivalent-Power (NEP) relates experimental noise spectral-density to R_V via Eq. 2.

$$\text{NEP}_{\text{opt}} = \frac{V_N}{R_V} = \frac{P_{\text{THz}}}{\text{SNR} \cdot \sqrt{\Delta f}} \quad (2)$$

At the same time, it relates the available terahertz power to the resulting signal-to-noise ratio for a given measurement bandwidth Δf . For TeraFETs in unbiased Source-Drain condition, it was shown in that the dominant noise contribution is Johnson Nyquist thermal noise.

$$V_N = \sqrt{4k_B T R_{\text{DS}}} \quad (3)$$

Following Eq. 3, the relevant detector noise density is strongly dependent on detector temperature T and its Drain-Source

¹ 9 MHz transmission was successfully tested, but it is above f_{-3dB}

Resistance R_{DS} . However, for our detectors we usually determine V_N experimentally using a lock-in amplifier and show $NEP_{opt,exp}$ (related to experimental noise density) and $NEP_{opt,JN}$ (relating to Eq. 3).

III. RESULTS

As shown in Fig. 1., a relative $\times 1.5$ increase in responsivity was seen at the most sensitive gate bias around 0.55 V as the temperature reduced from 300 K to 77 K. In addition, due to the reduced thermal noise (Johnson–Nyquist) contribution arising from the transistor channel, the system’s noise spectral density decreased by a factor of ~ 1.5 down to $0.4 \mu W/\sqrt{Hz}$ at LN_2 -temperature. This results in a relative improvement of NEP by a factor of ~ 2.3 , comparable with available literature for LN_2 -cooled TeraFETs operating at 600 GHz [4].

IV. SUMMARY

The realized compact LN_2 -cooled TeraFET detector system shows potential for future sensing applications in the 2.8 THz to 3.5 THz band (e.g., power or gas sensing experiments benefiting from available bandwidth) in the laboratory or field environment (e.g., satellite instrumentation). The optical NEP (only referenced to the incident power (here: 400 μW , no area normalization) was determined to be $NEP_{opt,exp,RT} = 2 \text{ nW}/\sqrt{Hz}$ at room temperature and $NEP_{opt,exp,LN2} = 0.8 \text{ nW}/\sqrt{Hz}$ at LN_2 -temperature. Relating to pure Johnson–Nyquist noise, we find $NEP_{opt,JN,RT} = 1.35 \text{ nW}/\sqrt{Hz}$ and $NEP_{opt,JN,LN2} = 430 \text{ pW}/\sqrt{Hz}$. The lower room-temperature sensitivity compared to [2] is related to the detector chip’s IV-characteristic (cp. Fig. 1), as we found in recent studies. By applying a detector with similar IV-characteristics to [2], we found $NEP_{opt,exp,LN2} = 438 \text{ pW}/\sqrt{Hz}$ and $NEP_{opt,JN,LN2} = 192 \text{ pW}/\sqrt{Hz}$. (available power approx. 2.06 mW). The reason for this difference is mainly attributed to the theoretical prediction of the noise-level via Eq.3 and our experimental noise characterization of the full system. One should note, that $NEP_{opt,exp,LN2}$ describes the full-system’s optical NEP (TeraFET at 77 K, Amplifiers at room-temperature). In our experiment, we see a maximum SNR of approx. 64 dB for 100 ms integration time, which agrees well with the calculated NEP (see Eq. 2).

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DATA AVAILABILITY

The data associated with this paper are openly available from the Zenodo Data Repository <https://doi.org/10.5281/zenodo.15125821>

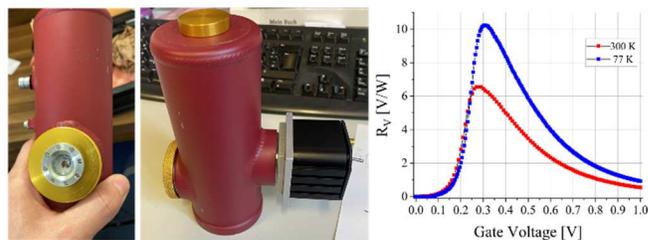


Fig. 2. Photographs of the realized compact liquid nitrogen (LN_2)-cooled detector system. Front View: optical access to the TeraFET detector is shown. Side View: LN_2 access from top of the dewar, with shielded electronics compartment visible. Right: Experimental detector voltage responsivity R_V (System’s Responsivity corrected by Gain-factor 100) as function of applied TeraFET gate potential, using a 2.85-THz QCL source with a 50% duty-cycle modulated at 2 kHz both at 300 K and at 77 K.

AUTHOR CONTRIBUTIONS

J. Holstein: Investigation (lead), Methodology, Visualization, Writing original draft; A. Hof: Investigation; N. K. North: Investigation; S. Kondawar: Investigation; M. Salih: Investigation; Investigation; L. Li: Investigation, Resources; E. H. Linfield: Conceptualization, Funding Acquisition; J. R. Freeman: Conceptualization, Funding Acquisition; A. Valavanis: Conceptualization, Methodology, Investigation, Funding Acquisition, Supervision, Writing Review and Editing; A. Lisauskas: Conceptualization, Methodology, Funding Acquisition, Supervision; H. G. Roskos: Conceptualization, Methodology, Funding Acquisition, Supervision, Writing

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