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Implementation of a multi-element detector consisting of an 8×8 network of patch-antenna-coupled TeraFETs for gas spectroscopy with THz-QCLs

J. Holstein[1], M. Horbury[2], N. North[2], H. Godden[2], A. Krysl,[1] A. Lisauskas[1,3], L. H. Li[2], A. Valavanis[2], J. R. Freeman[2], E. H. Linfield[2], H. G. Roskos[1]

[1]Physikalisches Institut, Goethe University Frankfurt, 60438 Frankfurt am Main, Germany

[2]School of Electronic and Electrical Engineering, University of Leeds, United Kingdom

[3]Institute of Applied Electrodynamics and Telecommunications, Vilnius University, Lithuania

Abstract — **Monolithically integrated, antenna-coupled field-effect transistors (TeraFETs) are known as sensitive detectors, which can be designed to work properly over the entire THz range (0.1-10 THz). In this work, we present a new multi-element THz detector design. It employs 8×8 monolithically integrated patch-antenna-coupled TeraFETs fabricated in a commercial 65-nm CMOS process. In contrast to conventional detector matrices, where each TeraFET represents a pixel, here the entire TeraFET network serves as a single pixel, combining the output signals of all elements in a parallel read-out circuit. The matrix approach offers two advantages: A larger effective detector area, which makes beam alignment easier, and a significantly reduced electrical resistance down to approx. 300 Ω at the working bias point, leading not only to a reduction in detector noise but also to an increase in modulation bandwidth, which improves the time resolution of measurements of dynamical processes. We demonstrate applicability of the detector for laboratory methanol gas spectroscopy at 3.4 THz with a quantum cascade laser (QCL) applied as a radiation source.**

I. INTRODUCTION

The THz frequency range of the electromagnetic spectrum sees continuously growing research activities which lead to the development of a variety of promising technologies and applications. In the last decades, many possible applications could not be implemented, or existing ones not be improved, due to the unavailability of sufficiently powerful detectors and sources. One of the established applications is gas spectroscopy in the frequency range above 2 THz, where spectral fingerprints of important atmospheric gases (e.g. CH_4) are located [1]. Here, advances on both the side of the radiation sources and the detectors promise more compact, cost-effective and sensitive measurement systems. In this report, we focus on progress enabled by TeraFETs used as detectors at frequencies above 1 THz [2-5]. The radiation source of choice for this type of gas spectroscopy are quantum cascade lasers (QCLs) [6]. A few years ago, we reported the use of TeraFETs for power monitoring of QCL local oscillators in heterodyne measurement systems [7]. Here, we extend their application to radiation power detection at 3.4 THz in a spectroscopy system. For this purpose, we have developed a novel multi-element detector layout, which is discussed in this work, while spectroscopic aspects are covered in another presentation at this conference [8].

II. DETECTOR IMPLEMENTATION

Depending on the application at hand, TeraFETs can either be designed with narrow-band or broadband antenna [2-5]. Here, as we intend to focus on gas spectroscopy over a narrow frequency region around 3.4 THz, we present a detector where

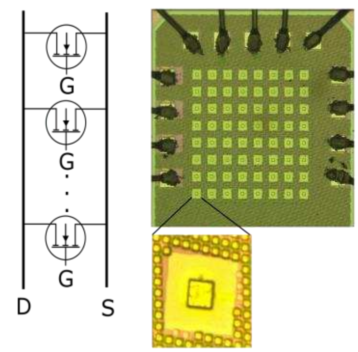

Fig. 1. Left: Visualization of the 8×8 detector circuit combining 64 patch-antenna-coupled TeraFETs in a parallel readout circuit. Right, top: Photograph of wire-bonded detector array. Right, bottom: Photograph of a single TeraFET element of the array, resonant at 3.4 THz.

the individual TeraFETs have a patch antenna (see Fig. 1). Such an antenna provides a higher antenna impedance compared to many other antenna structures [2], which helps to reduce the mismatch to the FET's channel impedance (typical channel resistance of several kΩ) for good radiation power coupling to the FET. As individual patch-coupled TeraFETs (SP) have a relatively small effective antenna area, they are well-suited for imaging applications [9], however, this property is a disadvantage for other applications because of the small power-collecting area which cannot be compensated readily by the use of a substrate lens. In the case of broadband TeraFET detectors, which typically have a bow-tie, log-periodic or spiral antenna integrated, one injects the THz radiation from the backside of the chip through a substrate lens. With patch-antenna-coupled TeraFETs, this approach is not possible because of the antenna's buried metallic ground-plane. While we have developed a front-side substrate-lensing technique for this challenge [10], we explore here the substrate-lens-free multi-element enhancement of the radiation coupling efficiency. A motivation for this approach is that it brings about an easier beam alignment to the detector, and that it increases detector speed by significantly reducing detector resistance. As presented in [8] at this conference, a 3-dB modulation bandwidth of 500 kHz could already be achieved by the application of the presented detector. The 8×8-elements detector presented here covers an area of 0.6×0.6 mm^2 which allows to collect almost full radiation power stored in the QCL's laser beam focused with an off-axis paraboloidal mirror (see inset of Fig. 2).

The 8×8-element detector consists of individual TeraFET elements connected in a parallel circuit (see Fig. 1) which forms a ladder structure, with the single elements representing the rungs of the ladder. The individual TeraFETs were designed with the help of CST Microwave Studio and ADS (Advanced Design System) for lowest NEP performance. The chosen FET channel length is 60 nm and the width 200 nm, the dimension of each patch is 15×15 μm^2 with a simulated directivity of 8 dBi in the direction of beam incidence. The TeraFET array was fabricated at TSMC (Taiwan Semiconductor Manufacturing Company) with a 65-nm CMOS process. Finally, the detector was mounted and wire-bonded on a PCB-based read-out circuit, the detector's output signal was fed to an operational amplifier with a gain of 100 and a GBWP of 45 MHz. At the optimal gate bias potential, the array detector exhibits an ohmic resistance of about 300 Ω which is by a factor of 64 smaller than that of the individual TeraFETs. This results in a reduction of Johnson-Nyquist noise, the dominant noise source of TeraFETs, by a factor of eight compared to a single TeraFET. At the same time, system's responsivity is decreasing, as each element sees less of the (distributed) power. Due to these aspects, we expect the system's NEP to be increased by a factor of eight to ten compared to the single patch detector. For the single patch detector, we determined a cross-sectional NEP, as defined in [11], of 106 $\frac{\mathrm{pW}}{\sqrt{\mathrm{Hz}}}$ at $\nu_{QCL} = 3.4$ THz which leads to an expected NEP of the array detector on the order of 1 $\frac{\mathrm{nW}}{\sqrt{\mathrm{Hz}}}$ which is currently not reached in experiment, due to additional electronic noise sources and the experimental beam shape. Despite the pure detector figures of merit, the data quality in spectroscopy applications is improved compared to a single TeraFET (without substrate lens) due to the larger effective antenna area and the higher stability against fluctuations of the beam position. This important finding for spectroscopy applications will be confirmed by the results of the experiment presented in the following.

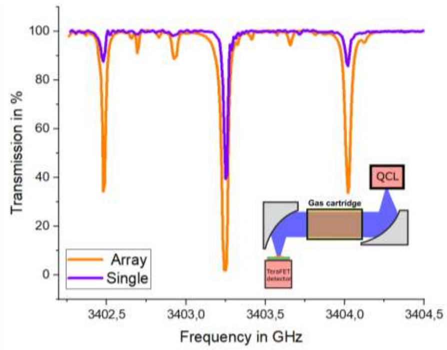

Fig. 2. Transmission spectrum of methanol gas around 3.4 THz, recorded either with a single TeraFET (purple line) or an 8×8-element detector (orange line), both without substrate lens. Despite an expected lower device responsivity, the data quality of the transmission spectra obtained with the array is increased because of the better power collection efficiency and the reduced noise level. Several weak absorption lines are resolvable. Inset: Schematic of the experimental setup.

III. Spectroscopic measurements

The detector module was mounted with a QCL in the measurement setup, which is schematically shown in the inset of Fig. 2. The QCL provided an emission-line at ν_{QCL} while showing a 100 MHz linewidth and an output power of $P_{THz} = 3.6\,\mathrm{mW}$. Spectroscopic transmission measurements were performed with methanol gas in a cartridge as the substance under test. The orange line in Fig. 2 displays measured spectra obtained with the multi-element detector as a power detector. The measurements were repeated with an individual substrate-lens-free TeraFET as detector (see purple line in Fig. 2). It captured only about 10% of the incoming QCL radiation due to the small effective antenna area. The spectrum measured with the multi-element detector clearly shows less noise and more pronounced absorption signatures. It resolves weak absorption lines of the methanol which were not or only weakly visible with the single TeraFET.

IV. Summary

We have presented a multi-element 3.4-THz power detector consisting of a parallel network of 8×8 TeraFETs. The detector has an enlarged effective area and a reduced noise floor compared with individual TeraFETs without substrate lens. We have demonstrated application of the detector in transmission measurements of methanol gas over a narrow frequency band around 3.4 THz, enabled by a THz-QCL. Besides an easy beam alignment, the multi-element detector allowed for a good signal stability with regards to misalignment and vibrations. The significantly decreased ohmic resistance provides great potential for modulation bandwidths in the upper MHz-range when employed with a large-bandwidth amplifier. This feature will be exploited in the future for time-resolved spectroscopy of dynamical gas-phase processes on the nanosecond-scale.

Acknowledgments

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Data availability

The data that support the findings of this study are available from the corresponding author, JH, upon reasonable request.

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