# Terahertz Imaging and Broadband Wireless Communication Using Plasma Oscillations in Nanometer Field Effect Transistors

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**Abstract— An overview of recent results concerning THz detection related to plasma nonlinearities in nanometer field effect transistors is presented. In particular nonlinearity and dynamic range of these detectors are discussed. We present also results on THz detection by Graphene field effect transistors. As a conclusion, we will show one of the first real world application of the FET THz detectors: a demonstrator of the imager developed for fast postal security imaging and wireless communication at carrier frequency above 300GHz.**

## I. INTRODUCTION

We present an overview of some recent results concerning THz detection related to plasma nonlinearities in nanometer field effect transistors [1, 2]. The subjects were selected in a way to show physics related limitations and advantages rather than purely technological or engineering improvements of nanometer Field Effect transistors (FETs) working as Terahertz detectors. We address the basic physics related problems like temperature dependence of the response [3], helicity sensitive detection [4] and nonlinear/saturation response at high incident power [5].

We present also the results on graphene based THz detectors [6-8] and first results on new THz detectors based on Si junction-less FETs [9]. The results will be discussed in view of the physical and technical limitations of Field Effect Transistors based THz detectors in view of their application for linear scanners [10].

## II. DYNAMIC RANGE

Use Terahertz power dependence of the photoresponse of field effect transistors, operating at frequencies from 0.1 to 3 THz for incident radiation power density up to 100 kW/cm2 was studied for Si metal–oxide–semiconductor field-effect transistors and InGaAs high electron mobility transistors. The photoresponse increased linearly with increasing radiation intensity up to the kW/cm2 range. Nonlinearity followed by saturation of the photoresponse was observed for all investigated field effect transistors for intensities above several kW/cm2 – see Fig. 1. The observed photoresponse nonlinearity is explained by the saturation of the transistor channel current. The theoretical model of terahertz field effect transistor photoresponse at high intensity was developed. The model explains quantitatively experimental data both in linear and nonlinear (saturation) range. Our results show that dynamic range of field effect transistors is very high and can extend over more than six orders of magnitudes of power densities (from ~ 0.5 mW/cm2 to ~ 5 kW/cm2).

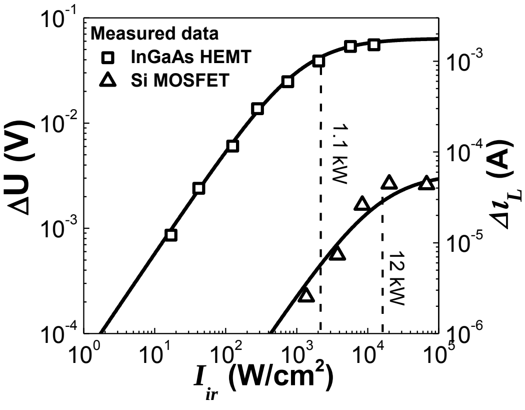

Fig. 1 Voltage and current generated by THz radiation. Saturation region is clearly visible. Solid lines are results of calculations [5]

## III. GRAPHENE PLASMA THZ DETECTORS

Graphene, a one/two-atom-thick planar sheet of a honeycomb carbon crystal is a unique material with superior properties. The unusual gapless band structure of graphene with linear energy spectra for electrons and holes may lead to giant carrier mobility at room temperature and broadband flat optical response. In combination with huge thermal conductivity, these properties make graphene very appealing for electronics and sensor applications, including terahertz applications. Review of recent achievement on graphene based terahertz devices can be found in [11].

Exfoliated on Si/SO2 single and double layer graphene flakes were used to fabricate top gate transistors. Log-periodic circular-toothed antennas at source and gate were used to couple 0.3 THz radiation. A 35 nm thick HfO2 layer was used as the gate dielectric. The channel length was 7-10 µm, while the gate length was 200 – 300 nm. Fig. 2 shows the responsivity as a function of gate voltage. The specific feature of these dependencies is the change of the sign of the response at the charge neutrality (Dirac) voltage. Similar results were obtained at higher frequencies up to 3.11 THz for back-gated graphene transistors [8].

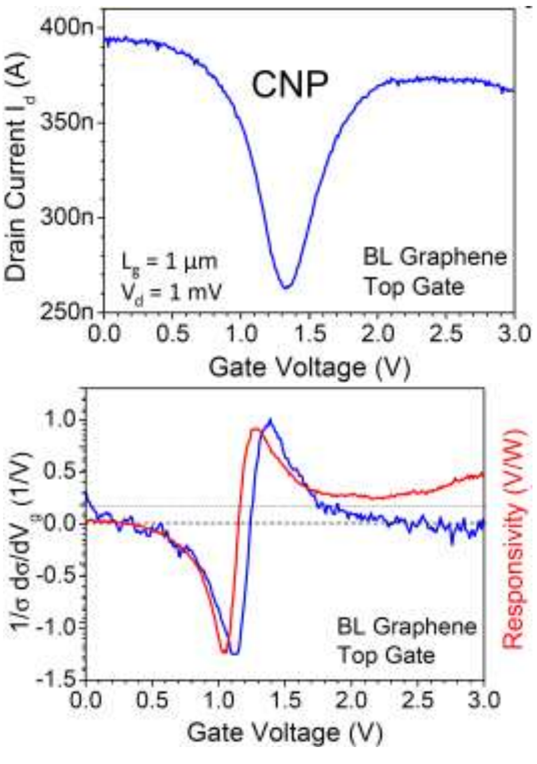

Fig. 2 The conductivity and responsivity as a function of gate voltage. The specific feature of these dependencies is the change of the sign of the THz response at the charge neutrality (CNP) point [6, 7].

## IV. DIFFRACTIVE OPTICS AND POSTAL SCANNER

The active THz scanning systems present on the market require THz radiation source with specially adapted optics [2-4]. The first THz imaging systems were two axes raster scanning setups containing single point source and a single detector. They provided high quality images but the scanning time was relatively long, mainly limited by the speed of (XY) mechanical scanners. However, it appeared that to get the imaging speed acceptable for practical applications like postal security and on line nondestructive quality control so called linear scanners can be used. In these scanners the object moves on the transportation belt and the image is constructed line by line using linear multi-detector system. In principle the linear beam required in this case can be formed by a single rotating/vibrating mirror, but this imposes the speed limitations and long term mechanical stability of the system.

Recently diffractive elements that shape the illuminating divergent beam coming from the point-like source into a line segment in the given plane like shown in Fig. 3.

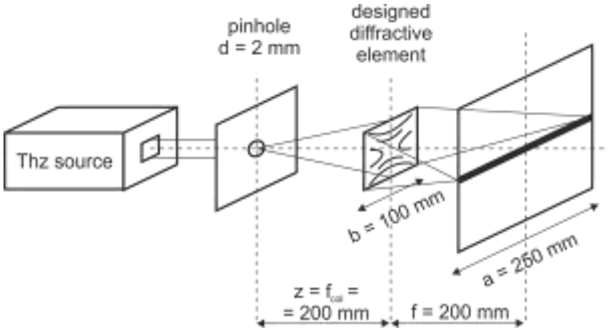

Fig. 3 Scheme of the optical system using diffractive elements that shape the illuminating divergent beam coming from the point-like source into a line segment in the given plane [10].

In particular the structure based on the cost efficient 3D printing technology was demonstrated. The structure was experimentally evaluated and applied in a fast on line imaging system operating at 0.3 THz atmospheric window, like shown in Fig 4.

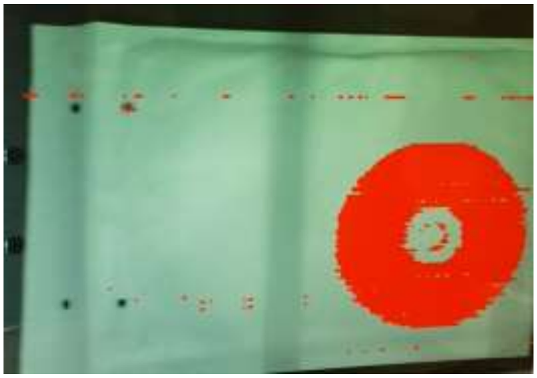

Fig. 4 The control monitor of the postal scanner. It shows a real time image of the envelope with CD disc inside. The envelope is moving on the control belt. Image is obtained by the fusion of the visible and 300 GHz images [12].

## IV. THz wireless communication

We would like to stress that both fast imaging and wireless communication require not only rectification of sub-THz signals with carrier frequency in the 300/600 GHz band but also very high modulation speeds and/or wide band operation. Standard FET-based THz detectors operate at a subthreshold range that is characterized by the high channel resistance (order of MOhms). Therefore the RC constant (with parasitic capacitances) limits their speed/bandwidth.

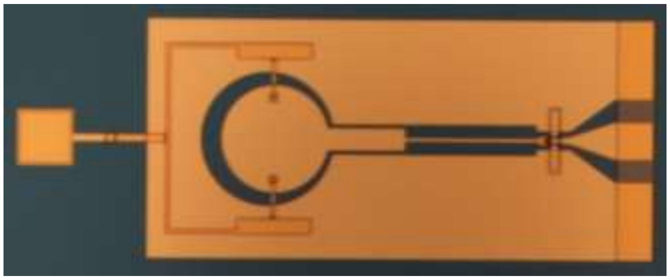

Fig. 5 Layout of plasma wave detector with slot ring antenna calculated for operation at 300GHz. This detectors were successfully used in broadband wireless communication experiments [13,14].

High modulation frequencies and wideband wireless communication require low channel resistance and therefore require special input /output impedance engineering.THz Wireless applications with plasma FET based receivers operating at sub-THz bands have been demonstrated, showing error free data rate up to 8.2 Gbits/s. [13,14].

## ACKNOWLEDGEMENTS

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