

Terahertz Electronics for Sensing Applications

Michael Shur
Center for Integrated Electronics
Rensselaer Polytechnic Institute
Troy, NY 12180, USA
shurm@rpi.edu

Abstract— Terahertz sensing is used for detection of hidden objects, explosives and biological and chemical hazardous agents, and for applications in radio astronomy, space research, biology and medicine. Emerging THz transistor sensing technology uses the rectification of electron density oscillations in short channel Si CMOS and FIN FETs and III-V and III-N High Electron Mobility Transistors (HEMTs). Such plasma wave electronics detectors might be tunable by applied bias voltage and can be modulated at very high frequencies. Using synchronized THz plasmonic transistor arrays is expected to improve performance of THz electronic detectors by orders of magnitude.

I. INTRODUCTION

Terahertz electronics could greatly expand applications of terahertz technology for sensing and imaging with big reductions in cost, system size, and power consumption compared to terahertz photonics systems. Plasmonic FET THz detectors have potential for outperforming other types of THz electronic detectors if the problems related to coupling and matching of THz radiation to the device, FET parasitics, interplay of contacts and ballistic transport in short channel structures, and high field properties of resonant and overdamped plasma waves will be understood and solved.

II. TERAHERTZ SENSING

A. Applications

Figure 1 lists frequency ranges for THz sensing applications.

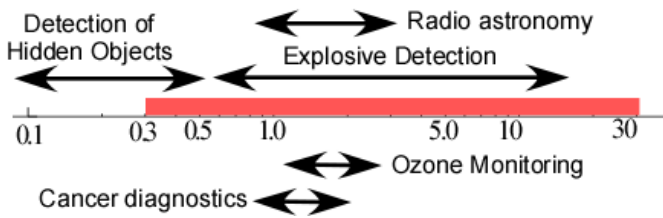


Fig. 1. THz sensing applications

This work is supported by the NSF under the auspices of I/UCRC “CONNECTION ONE” at RPI.

B. THz detectors

The bolometer (invented in 1878 by Samuel Pierpont Langley) was the first device capable of sensing THz radiation. Table 1 summarizes the characteristics of modern THz detectors.

TABLE I. TERAHERTZ DETECTORS

THz detector	Spectral range (THz)	Operating temperature (K)	Noise equivalent Power (W/Hz ^{1/2})
Si Bolometer ¹	0.1-150	0.3 – 4.2	2.4×10 ⁻¹⁶ (@ 0.3K) 10 ⁻¹³ (@4.2 K)
Pyroelectric ²	0.1 - 30	240 - 350	10 ⁻¹⁰
Golay Cell ³	0.3 - 15	300	10 ⁻¹⁰
Hot Electron Bolometer ¹	0.1 - 70	4.2	3×10 ⁻¹³ - 10 ⁻¹⁰
Schottky Diodes ⁴	0.1 - 3	300	10 ⁻¹⁰ - 10 ⁻¹²
Si CMOS ⁵	0.3*	300	10 ⁻¹¹
Si CMOS heterodyne ⁶	0.65*	300	8×10 ⁻¹⁴
Si FINFET ⁷	0.2-2.5*	300	10 ⁻⁷

*it is expected to operate up to and above 10 THz with re-design

In this paper, we will focus on THz electronics and, in particular, on emerging plasmonic detectors that have promise of using mainstream silicon CMOS based technology for THz applications.

C. THz plasmonic detectors

As was predicted in ⁸, plasma waves (which are oscillations of the electron density) in the channels of short field effect transistors (FETs) might be unstable in a certain range of the FET currents and such short channel FETs could be used as sources and detectors of THz radiation.^{9,10}

Dependent upon the incident THz frequency, semiconductor momentum relaxation time, radiation damping, and device dimension, the detection can be resonant (when the FET channel serves as a resonant cavity for the plasma waves) and non-resonant (when plasma waves are

overdamped and the detection under bias is determined by the device nonlinear current voltage and capacitance-voltage characteristics. Resonant detection takes place when $\omega\tau \gg 1$ and $s\tau/L \gg 1$, where ω and τ are the angular frequency of the incident radiation and the plasmon lifetime time respectively, s is the plasma wave velocity and L is the FET channel length. The plasma wave velocity is $s = (q V_{gt}/m)^{1/2}$, where q is the electronic charge, m is the electron effective mass and $V_{gt} = V_{gs} - V_t$ is the gate voltage swing, and V_t is the threshold voltage. Such resonant detectors are tunable by the gate bias. For $\omega\tau \gg 1$ but $s\tau/L \ll 1$, or for $\omega\tau \ll 1$, detection is non-resonant, (broadband).

So far, the room terahertz detection observed in silicon FETs has been non-resonant, (although at gate lengths sufficiently short and high enough frequency, room temperature resonant detection in silicon may be possible¹¹). Resonant detection was observed in InGaAs HEMTs (see, for example, ¹²⁻¹³ and AlGaIn/GaN HEMTs.¹⁴ AlGaIn/GaN plasmonic detectors recently demonstrated superior performance.¹⁵

Broadband THz detection using short channel FETs can be used in a wide temperature range^{9,16}. In this regime, a THz signal excites plasma waves decaying while propagating from channel boundaries. The characteristic decay length,^{17,18,19}

$$L_o = \sqrt{\frac{V_{gs} - V_T}{2\pi\mu f}},$$

determines the spatial resolution of such detectors when used for proximity sensors (see, for example,²⁰) and could reach a nanometer resolution (see Fig. 2).

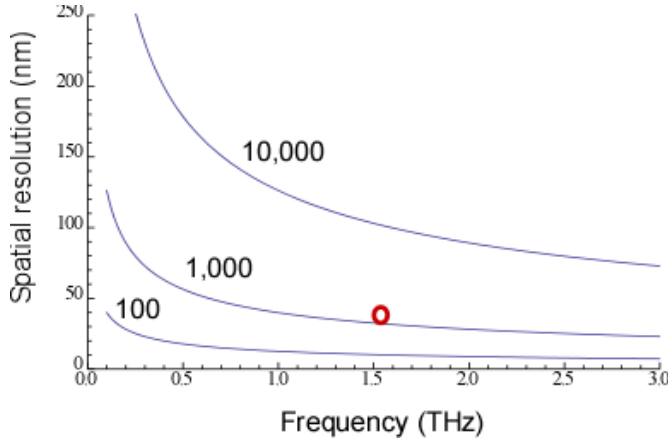


Fig. 2: Estimated spatial resolution of broadband plasmonic FET detector. The numbers next to the curves are the values of the low field mobility in $\text{cm}^2/\text{V}\cdot\text{s}$. The dot corresponds to the estimated resolution for THz detectors reported in ⁷

The predicted and measured responsivities are quite high (see Figs. 3 and 4) and could be enhanced by biasing transistor close or even deep in the saturation regime due the increased non-linearity.^{21,18,19}

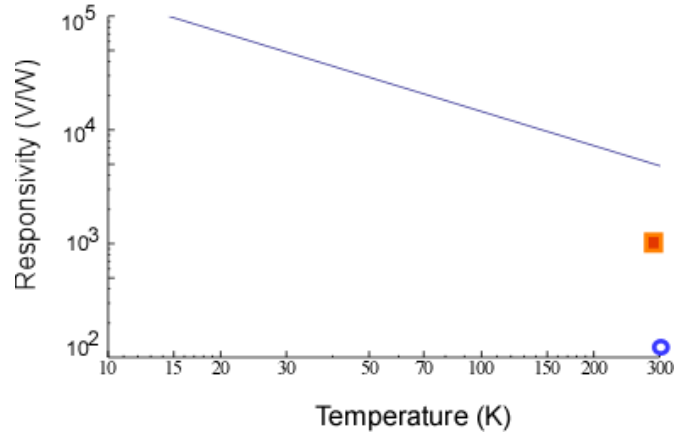


Fig. 3. Maximum responsivity of Si broadband plasmonic FET detectors (assuming perfect coupling) for zero drain current. Symbols correspond to the responsivities measured for Si FIN FETs at zero current and close to saturation.⁷

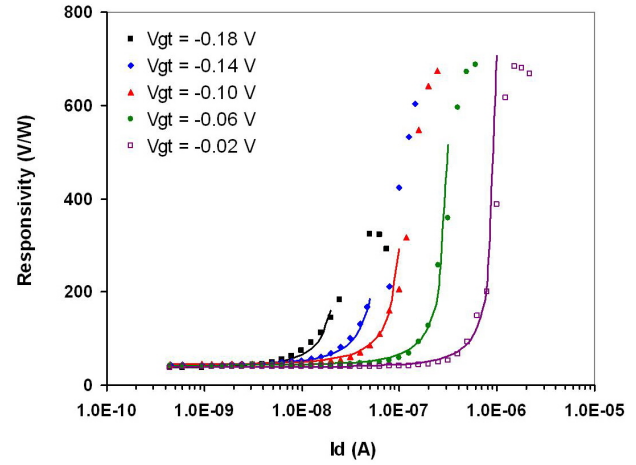


Fig. 4. 0.2 THz responsivity of 20 fin device with 40 nm width and 100 nm gate length. Symbols are measured data; lines are modeled responsivity.⁷

Parasitics, such as the gate series resistance, play a crucial role and have to be minimized.

Grating gate structures could be used to capture the entire THz beam and enhance coupling, and pronounced plasmon resonances were observed at elevated temperatures up to 170 K in grating gate structures due to strong coupling between incident THz radiation and plasmons using the grating gate with relatively narrow slits²² (see Fig. 5) as predicted in ²³. The absorbance approached its theoretical maximum $A = 0.5(1 - \sqrt{R_0})$, where $R_0 \approx 0.25$ is the reflectivity from a bare sapphire substrate, at temperature 120 K. The maximal absorption at the plasmon resonance is achieved when a half of the electron scattering rate becomes equal to the plasmon radiative decay rate.²⁴

Preliminary results on the THz detection using multiple transistors show big enhancement in responsivity.²⁵ Much greater improvements are expected from using plasmonic

transistor arrays^{26,23} due to a much better coupling of THz radiation. The FET array acts as a broadband antenna, and coupling increases proportionally to the number squared of the FET in the array because the plasmon mode is spread over the entire FET array.²⁴

Heterodyne plasma wave detection discussed in²⁷ allows for a significant reduction in NEP.^{6,28}

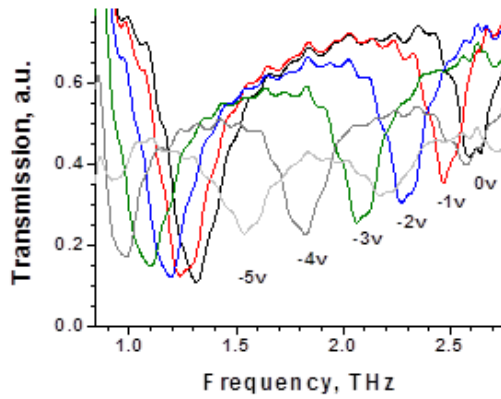
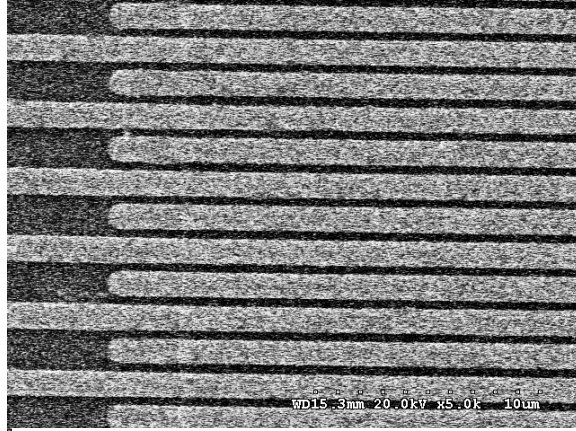


Figure 4. GaN-based 2D electron gas large area grating-gate HEMT structure on sapphire substrate. Electron concentration under the gates can be controlled by applying voltage on gate fingers. Terahertz beam had normal incidence and its polarization was perpendicular to the gate fingers. Experimental transmission spectra dependence on the gate voltage. Resolution is 0.1 THz. Temperature = 10 K.²⁶

Images obtained by moving the transistor with respect to the THz beam reveal coupling patterns of the THz radiation (Fig. 5²⁹). The resolution of such images could be as high as a few nanometers because the patterns are sensitive to the field distribution at the gate edges determining the boundary conditions for the electron density oscillations. Impressive THz images were obtained in^{30, 31}.

Such high sensitivity to the electrical conditions at the gate edge makes plasmonic FETs to be extremely sensitive to biological agents as shown in²⁰. Large changes in the THz response of plasmonic detectors loaded with solutions of globulin free bovine serum albumin (BSA), arginine and heparin were observed (compare Fig. 6 and 7). The same concentrations only very weakly affected the device transfer characteristics (see Fig. 7). Such change of the response

characteristics can be used to identify and quantify biological and chemical substances makes this device suitable for using as a building block of a biochip with integrated processing capabilities.

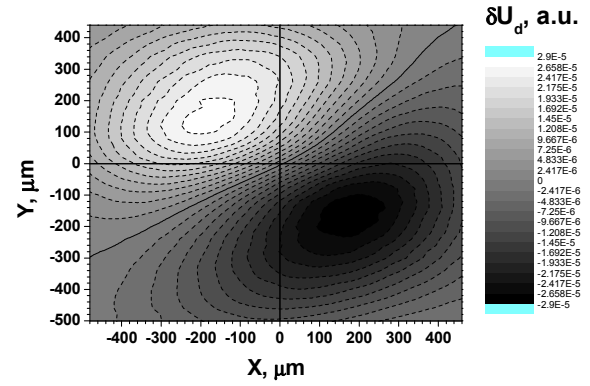


Fig. 5. THz image of a transistor, recorded as the dependence of the transistor response with its displacement in the focal plane in 5 μm steps. $f = 1.63$ THz; the polarization of THz radiation is perpendicular to the gate (vertical axis). (From²⁹)

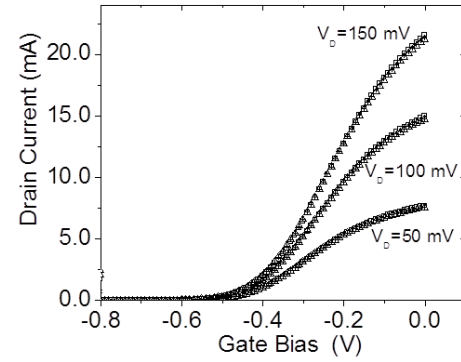


Fig. 6. Transfer characteristics of AlGaAs/GaAs HEMT plasmonic THz detectors before and after covered with biological specimens (marked by different symbols) (from²⁰).

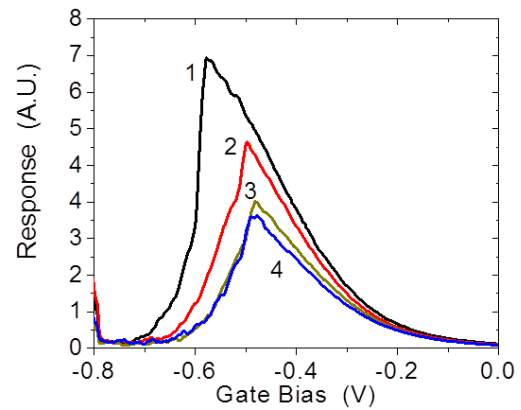


Fig. 7. THz response of plasmonic detector after covering with heparin solutions with different concentrations: 1) before biological specimen 2) 1mg/ml 3) 2mg/ml 4) 3mg/ml (from²⁰)

ACKNOWLEDGMENT

I am grateful to my colleagues Drs. M. Dyakonov, W. Knap, A. Muraviev, W. Stillman, D. Veksler, S. Rumyantsev, A. Dmitriev, V. Kachorovskii, F. Teppe, V. Ryzhii, V. Popov, T. Otsuji, and N. Pala, for their pioneering contributions to plasma wave THz electronics.

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