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Room temperature imaging at 1.63 and 2.54 THz with field effect transistor detectors

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GaAs nanometric field effect-transistors are used for room temperature single-pixel imaging using radiation frequencies above 1 THz. Images obtained in transmission mode at 1.63 THz are recorded using transistors operating in a photovoltaic mode with spatial resolution of 300 μm and voltage sensitivity of about 8 mV/W. A reduction in response with increasing frequency was observed and mitigated by the application of a source-drain current, leading to the demonstration of imaging at up to 2.54 THz. © *2010 American Institute of Physics*. [doi:10.1063/1.3463414]

I. INTRODUCTION

Terahertz (THz) electromagnetic waves (0.1–10 THz), located at the gap between microwaves and infrared waves, are useful for a wide range of applications. THz waves have the capability to penetrate various materials such as plastics, paper, wood, etc., and can thus serve as a powerful instrument in security systems. Generally, conventional THz imaging systems are based on an optoelectronic approach, i.e., femtosecond lasers and related optical components.[1] Such systems are rather bulky, require precise optical alignment and are therefore not very convenient for direct implementation. During the last 10 years, novel emitters like quantum cascade lasers (QCLs),[2,3] QCL based intracavity mixers,[4] plasma wave based emitters/sources[5] and detectors based on plasma waves,[6] microbolometers,[7] or bow-tie diodes[8] have been developed, opening a way to reduce the size and cost of THz imaging systems. The interest in field effect transistors (FETs) operating in THz range started at the beginning of 1990s with the pioneering theoretical work of Dyakonov and Shur[9] who predicted that a steady current flow in a FET channel can become unstable leading to the generation of the plasma waves and the emission of the electromagnetic radiation at THz frequencies. Further works showed that the nonlinear properties of the two-dimensional (2D) plasma in the transistor channel can be used for detection and mixing of THz radiation.[10]

The plasma wave related detection process is based on the rectification of THz currents induced by the incident radiation within the transistor channel. The rectification takes place due to a nonlinear response of the gated two dimensional electron gas. As a result, a photoresponse appears in the form of a dc voltage between source and drain which is proportional to the incident radiation intensity (i.e., a photovoltaic effect).[10] Some asymmetry between the source and drain is needed to induce such a voltage. There may be various sources of such asymmetry, of which one is the difference in the source-gate and drain-gate capacitances. Another possibility is the inherent asymmetry in channeling the incoming radiation (e.g., arising either from the use of special antennas, or from the asymmetric design of the source and drain contacts).

Veksler *et al.*[11] studied the influence of direct current on the detection of sub-THz and THz radiation in gated 2D structures, developing a theory of the current-driven detection both for the resonant and nonresonant case. They have shown that indeed, the increase in amplitude of the detected signal can be achieved when applying a dc current flow along the channel. More information about the current status of THz detection and emission using FETs can be found in Refs. 14 and 15. Recently, it was shown that at room temperature, a GaAs nanometric FET can be used as an efficient broadband detector for sub-THz (0.6 THz) imaging.[12] An attempt to reach THz frequencies was reported by El Fatimy *et al.*[13] who used a broadband THz photoconductive antenna as a source and THz time domain spectroscopy technique for detection. However, until now there have been no images obtained for frequencies significantly higher than above 1 THz. Imaging at frequencies above 1 THz is important because of increased spatial resolution and possibilities of chemical recognition.

In this paper, we present 2D images obtained at 1.63 THz and 2.54 THz in continuous wave (cw) mode using a GaAs FET operating at room temperature. We also study two approaches to record the images. In the first one the FET operates in a purely photovoltaic mode, in the second approach a dc drain-to-source current is applied in order to improve the contrast of the image.

II. TECHNOLOGY AND EXPERIMENTAL SET UP

The images were taken in the transmission mode at 1.63 and 2.54 THz. As a radiation source a cw CO_2 laser pumped molecular THz laser emitting radiation with output power of about 2 mW was used. The laser beam was divided into two parts with a mylar beam-splitter. One part of the beam was used to monitor relative changes in THz output power with a pyroelectric detector, and the second part was focused onto

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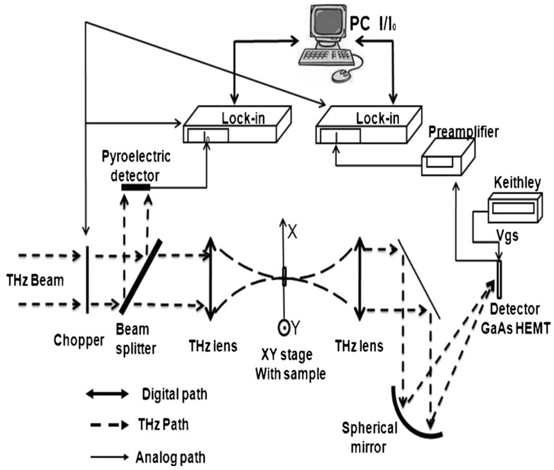

FIG. 1. Experimental set-up for imaging in transmission mode with a cw molecular laser source.

the object to be imaged by a high-density polyethylene (HDPE) lens (Fig. 1). The object was moved in a plane perpendicular to THz beam axis using an XY-axis motor translation stage. The optical system approaches the diffraction limit and the Gaussian shaped THz beam spot in the focal plane of the first HDPE lens has a radius of 275 μm at frequency of 1.63 THz. The beam transmitted through the object and second HDPE lens is focused onto the GaAs FET detector by a spherical mirror which produces a spot onto the FET detector with a radius of around 300 μm. The transistor pad dimensions were 450 by 350 μm (i.e., smaller than the beam size), the gate length and width were 250 nm and 200 μm, respectively, (see the inset of Fig. 2) and the room temperature electron mobility in the transistor channel was around 8500 cm^2/V s. The FET operated without any spatial coupling antennas. Radiation was coupled to the transistor only via the contact pads and/or the connecting wires. The laser beam intensity was modulated by a mechanical chopper (160 Hz). The FET detector photoresponse between source and drain contacts was amplified and measured by a standard lock-in technique. The GaAs FET detector was biased with a gate to source dc-voltage source and in some experiments also with a dc-drain to source current. The typical current voltage characteristics are shown in Fig. 2.

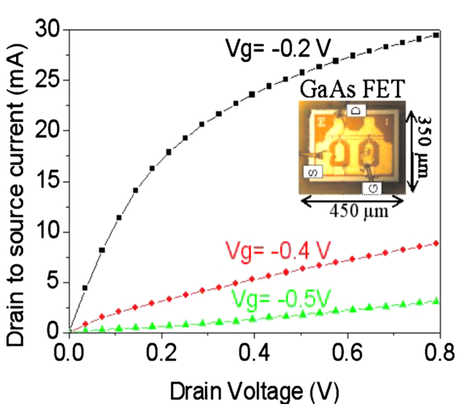

FIG. 2. (Color online) Current-voltage characteristics at room temperature for different values of gate voltage (−0.2, −0.4, and −0.5 V). Inset: layout of GaAs FET transistor used in the experiment.

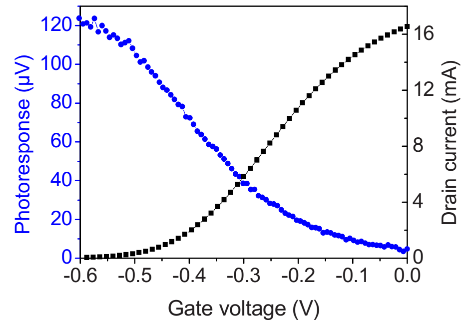

FIG. 3. (Color online) Photoresponse of GaAs FET at 1.63 THz as a function of gate voltage V_g (left blue curve) and transfer characteristic at drain voltage $V_d=0.1$ V (right black curve).

III. RESULTS AND DISCUSSION

We performed detection measurements with a range of applied gate voltages (from 0 to −0.6 V) in order to optimise the sensitivity of the THz detector element. The results are shown in Fig. 3. The right side of Fig. 3 presents the transfer characteristic. The threshold voltage V_{th} is about −0.45 V. The left side shows the room temperature photoresponse at 1.63 THz as a function of V_g. As can be seen, the transistor photoresponse is gate voltage dependent. The optimal THz detection bias conditions were achieved when the gate voltage was close to V_{th} where the signal to noise ratio is optimum. The responsivity of a detector, R_V, is defined as the ratio between the voltage induced by radiation on the detector and the incident power, P_i

$$R_V = \frac{\Delta U}{P_i} = \frac{\Delta U}{A\dfrac{P_{\text{laser}}}{\pi r^2}},$$

where ΔU is the photoresponse signal, P_{laser} is the laser power (~1 mW at the transistor), A is the transistor area (0.157 mm^2), and r is the spot radius on the transistor (300 μm). For $V_g=-0.5$ V the $\Delta U=4.3$ μV (106 μV with amplification of 25 times), corresponding to a sensitivity of about 8 mV/W.

One of the advantages of the detection using FETs is the possibility to optimise the detector's sensitivity by applying a dc source to drain current. Using this method, Teppe *et al.*[16] demonstrated an increase in sensitivity by two orders of magnitude at 300 K. The photoconductive response of the GaAs FET as a function of drain to source current for 1.63 THz at room temperature is shown in Fig. 4. These results clearly show that the measured response increases with applied drain to source current by more than one order of magnitude (as compared with the response values given in Fig. 3). We measured the photoresponse with applied drain current up to 30 mA, but to avoid damaging the transistor we have chose a working point at 200 μA far from the saturation region. For this current and $V_g=-0.5$ V the photoresponse was enhanced by a factor of 8 (see the arrow in Fig. 4).

Using this GaAs FET, we have performed raster scan transmission imaging of a metallic cross (in air). The FET response was registered as a function of the position at $V_g \approx -0.5$ V and $I_{ds}=0$ A, as shown in Fig. 5(a). The units are

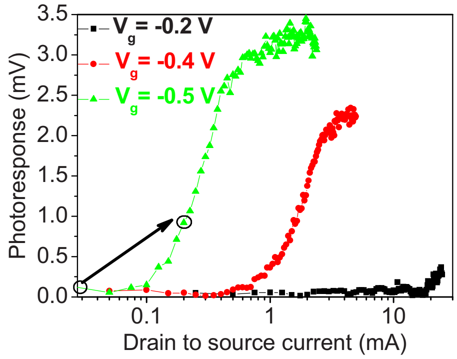

FIG. 4. (Color online) Photoresponse of GaAs FET as a function of drain to source current for different gate voltage values (−0.2, −0.4, and −0.5 V).

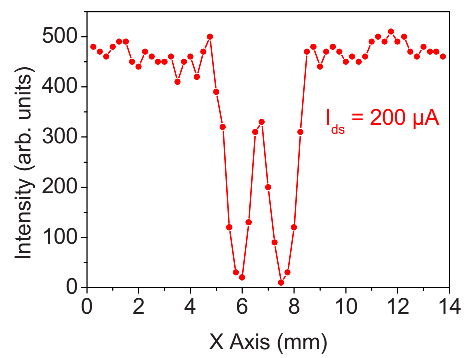

FIG. 6. (Color online) Signal position profile along the marked red line of Fig. 5(b) with $I_{ds}=200$ μA.

relative as the photoresponse was normalized by the pyroelectric reference signal. We obtain a 14.0×19.0 mm^2 image, consisting of 56×77 pixels with integration time T_c of 50 ms. The imaging speed is limited only by XY mechanical stage motion. These parameters clearly show the possibility of using GaAs FETs for room temperature focal plane arrays in THz video rate imaging systems with video rate of at least 20 frames per second. Increasing the radiation frequency

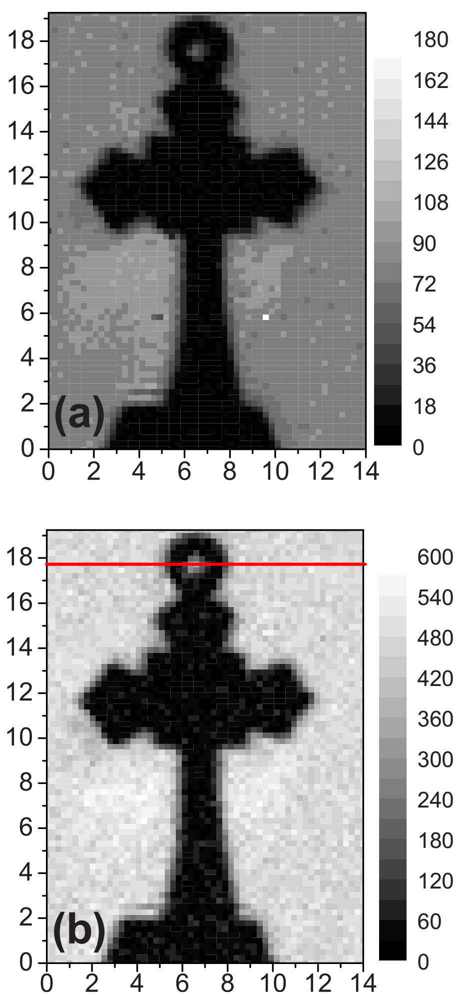

FIG. 5. (Color online) Two 1.63 THz images of a metallic cross in transmission mode at room temperature: (a) without drain to source current and (b) with applied drain-source current $I_{ds}=200$ μA. The red line indicates pin-hole area.

above 1 THz allows the narrowing of the probe beam radius. The focal THz spot measured at 1.63 THz had a radius of about 300 μm, i.e., half the width compared with the probe beam measured for 0.6 THz imaging.[12] The increased spatial resolution represents one of the main advantages of imaging with frequencies above 1 THz.

The effect of a dc drain to source current, I_{ds}, on the THz imaging performance is illustrated in Fig. 5. Here we show two images of the same metallic cross for $I_{ds}=0$ A [Fig. 5(a)] and $I_{ds}=200$ μA [Fig. 5(b)]. Comparison of these two images shows that applying a current allows receiving higher quality images. This is due to the increased detector responsivity ($R_v\approx 8$ mV/W at $I_{ds}=0$ μA and ≈ 61 mV/W at $I_{ds}=200$ μA). The cross section of the intensity profile in the object pin-hole area is shown in Fig. 6. The result demonstrates the identification a 1 mm hole, demonstrating the image resolution.

Figure 7 shows transmission images of the metallic cross and a 7 mm diameter tablet. Objects were imaged at 1.63 THz, both were concealed in a paper envelope. Both objects are clearly identifiable, with a contrast in excess of 150. This shows that room temperature GaAs FETs can be efficiently used for postal security imaging systems, at radiation frequencies above 1 THz with a useful resolution (300 μm).

Finally, it is interesting to explore the frequency limit at which GaAs FETs can still be used for imaging purposes. With this aim we have studied the same transistor under illumination of 2.54 THz radiation. The operation in photovoltaic mode gave relatively poor signal to noise ratio. To improve the situation we applied a drain-to-source current of $I_{ds}=200$ μA. The result is shown in Fig. 8. It clearly demonstrates that room temperature imaging at 2.54 THz using GaAs FETs is possible. The use of a specially designed antennas to couple the 2.54 THz radiation to the transistor channel, or the implementation of the FETs into a detector array[17] would potentially improve the signal to noise ratio and thus take advantage of the improved spatial resolution.

The application of a drain-source current increases the responsivity but it can also be a source of additional noise. Therefore we have measured the noise of the GaAs FET as a function of I_{ds}. The measurements were performed at 0.3 THz frequency radiation with a modulation frequency of $\sim$163 Hz. The effect of increasing I_{ds} is shown in Fig. 9(a), where the noise equivalent power (NEP) is plotted as a func-

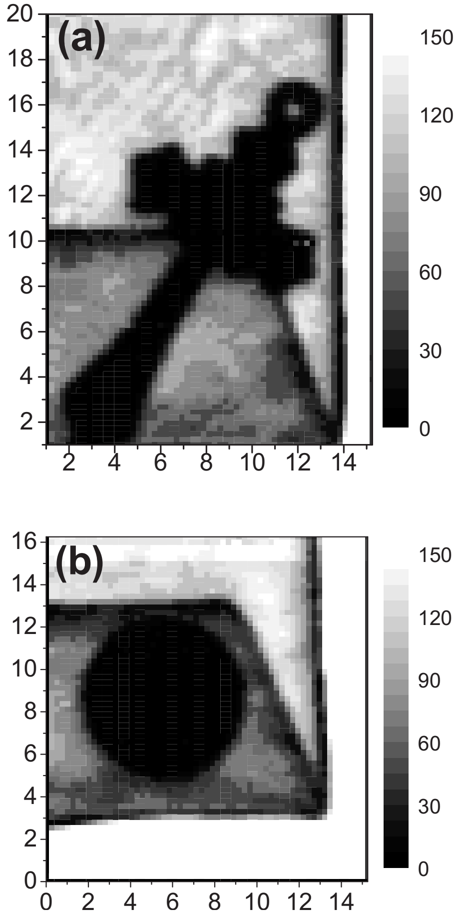

FIG. 7. 1.63 THz images ($I_{ds}=0$) in transmission mode at room temperature of two objects placed into a paper envelope: (a) the metallic cross and (b) a 7 mm medical tablet.

tion of drain-to-source current for different gate voltage. First, one can see that without current, the NEP is relatively low, i.e., of the order of 10 $nW/Hz^{0.5}$. Second, the increase in I_{ds} up to the saturation part of photo response [see Fig. 9(b)], increases the NEP by a factor about 2 up to 18 $nW/Hz^{0.5}$. We would like to mention that the increase in the NEP was smaller than the gain in the responsivity. Therefore application of current leads to better imaging conditions.

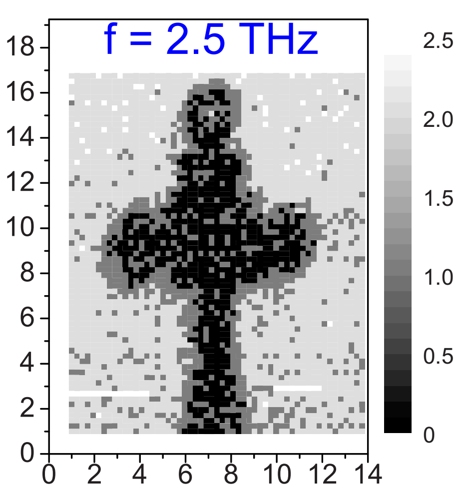

FIG. 8. (Color online) 2.54 THz image of metallic cross places in air in transmission mode at room temperature with $I_{ds}=200$ μA

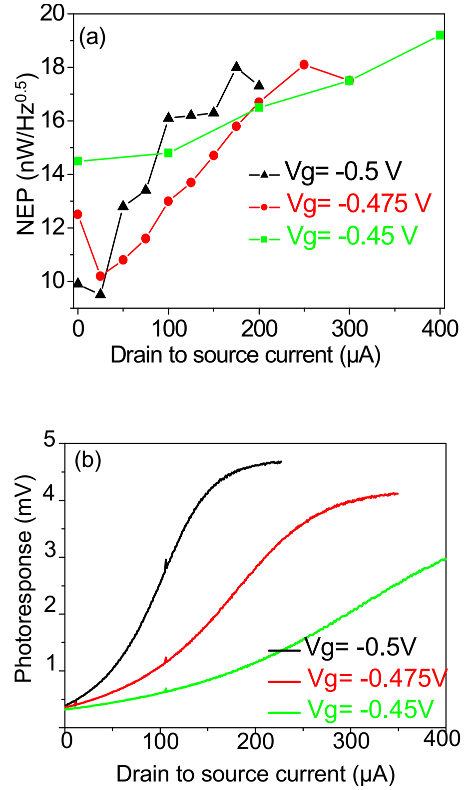

FIG. 9. (Color online) NEP (a) and photoresponse (b) of GaAs FET as a function of drain to source current for different gate voltages (−0.5, −0.475, and −0.45 V).

IV. CONCLUSIONS

In summary, GaAs FETs were investigated as room temperature THz detectors in imaging system at frequencies of 1.63 and 2.54 THz. At 1.63 THz, imaging with a resolution of around 300 μm was demonstrated. The application of drain-to-source current increased the detector's sensitivity with moderate noise increase, thus, improving the image quality. Initial results at 2.54 THz were also obtained. The resolution, contrast and acquisition rate obtained proves the suitability of the FET-based system as the basis of room temperature real time imaging cameras for frequencies above 1 THz.

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