A Resonant Terahertz Detector Utilizing a High Electron Mobility Transistor

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Abstract

We report on the implementation of a terahertz detector utilizing two-dimensional electronic fluid in a high electron mobility transistor. The device response is compared with the predictions of the hydrodynamic theory of electronic fluid. The results indicate the viscosity of electronic fluid might be larger than estimated previously. We also report on the unusual polarization dependence of the detector response.

I. Introduction

The terahertz detectors can be used in a wide variety of fields, including physics, chemistry, environmental monitoring, and defense applications (see, for example [1,2]). In this paper, we report on the novel High Electron Mobility Transistor (HEMT) terahertz detector.

Electrons in the channel of a short HEMT should behave as a two-dimensional (2D) electronic fluid rather than a 2D-electron gas [3, 4]. To the first order, this electronic fluid is described by the same equations as water in a shallow channel. Plasma waves (that are similar to shallow water waves) can propagate in this electronic fluid. The asymmetry of the boundary conditions at the source and the drain and the non-linearity related to the electric current (which is proportional to the product of the electron velocity and electron concentration) can be used for the detection of electromagnetic radiation at terahertz frequencies. This detector produces an open circuit *dc* voltage, U_{DS}, which is proportional to the intensity of the incoming terahertz radiation, with a resonance response to electromagnetic radiation at the plasma oscillation frequency. (A long channel FET has a non-resonant response to electromagnetic radiation and can be used as a broad band detector for frequencies up to several tens of terahertz [4].)

The resonant frequency can be tuned by the gate bias, which makes the electron fluid detector suitable for many applications involving far infrared spectroscopy for the detection of chemical and biological substances. We have demonstrated non-resonant detectors fabricated using AlGaAs/GaAs [5] and AlGaN/GaN HFETs [6] operating at frequencies below 20 GHz and, more recently, reported on the first implementation of the AlGaAs/GaAs terahertz HEMT detector [7, 8].

In this paper, we report on new experimental results for the HEMT detector (with the cutoff frequency of the order of 90 GHz or less) operating at 2.5 terahertz.

II. Experimental Procedure

The terahertz detector was fabricated using a *Fujitsu* FHR20X HEMT [9] mounted on a quartz substrate. The device was loaded into a custom-made cryostat. A CO_2-pumped far-infrared gas laser served as a source of 2.5 THz radiation. The polarized laser beam was chopped and focused on the sample as shown in Fig. 1. Fig. 1 also shows

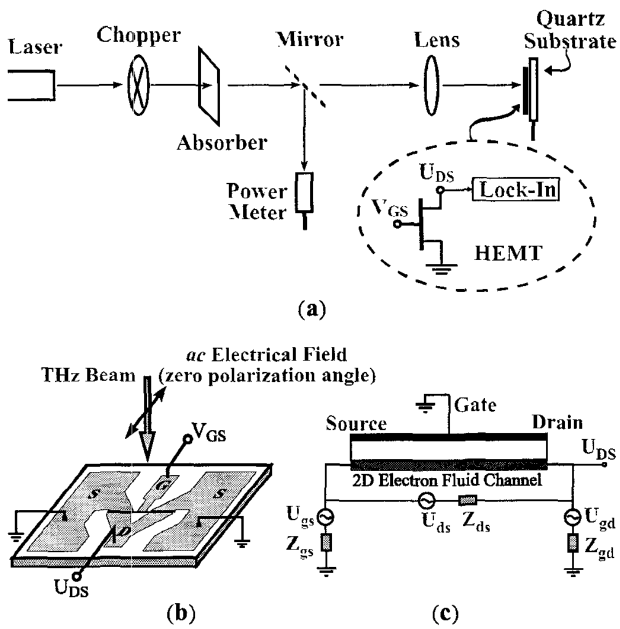

Fig. 1. (a) Measurement set-up. (b) HEMT layout; (c) *ac* equivalent circuit of a HEMT device operating in detector mode.

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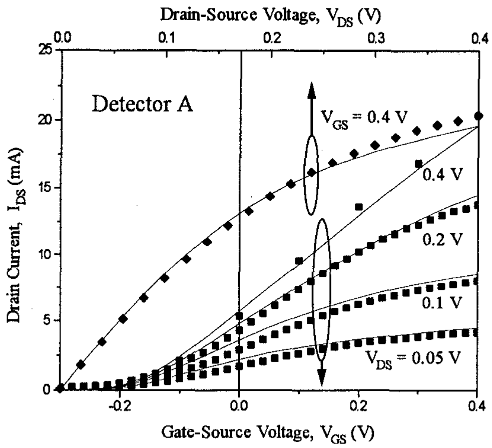

Fig. 2. Measured (symbols) and simulated (solid lines) device characteristics of *Fujitsu* FHR20X HEMT (used in detector A). Simulation parameters: gate length, *L*, of 0.17 μm, threshold voltage of -0.2 V, mobility of 2500 cm^2/Vs, gate width, *W*, of 100 μm, gate-to-channel spacing of 18 nm, saturation velocity of $1.6x10^5$ m/s, maximum sheet charge density of $1.2x10^{12}$ cm^{-2}, source and drain series resistances of 2.8 Ω each.

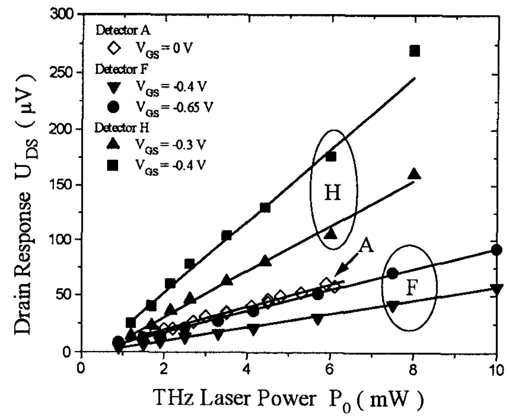

Fig. 3. Detector response versus laser power for detectors A, F and H. The linear relationship (solid line) confirms that the HEMT operates as a square-law detector, as predicted by the theory.

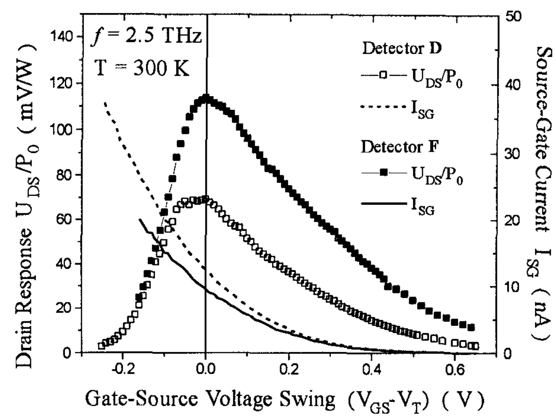

Fig. 4. Responsivity versus gate bias swing for detectors D and F at room temperature. Solid and dashed lines show source-gate currents as functions of gate voltage swing.

the detector layout. The terahertz radiation was polarized. As shown in Fig. 1b, we define that the polarization angle as zero if the electric field polarization is oriented in the drain-to-source direction.

The open circuit *dc* drain voltage, U_{DS} (that appeared in response to the THz radiation), was measured using lock-in technique. The detector was tuned by a *dc* gate bias, V_{GS}. A small-signal equivalent circuit of the detector shown in Fig. 1c was discussed in [7].

The measured device characteristics were simulated using the HEMT model implemented in AIM-Spice [10] (see Fig. 2). The parameters were extracted from the measured *dc* characteristics and from the elements of the small-signal microwave equivalent circuit given in [9]. For the HEMT used for detector A, the threshold voltage, V_T, was close to -0.2 V with the effective field effect mobility, μ_e, of 2,500 cm^2/Vs. The estimated effective gate length, L_{eff} = 0.17 μm. Several other HEMTs used for the terahertz detectors had similar parameters (see Section III).

III. Results and Discussion

The devices operated at 2.5 THz, which is about 30 times higher than the transistor cutoff frequency. As predicted by the terahertz detector theory [4], the radiation induces a *dc* drain-to-source voltage, U_{DS}. For laser power levels below 10 mW, the measured responsivity was independent of the radiation intensity (i.e., U_{DS} is proportional to the radiation intensity, see Fig. 3). This is in agreement with the detector theory [4].

For V_{GS} > 0.5 V, the detector becomes unstable because of the forward gate current flow. Fig. 4 shows the gate bias dependence of the detector responsivity. The responsivity increases with decreasing gate voltage swing above the threshold voltage (when $U_o = (V_{GS} - V_T) > 0$) and decreases when $U_o < 0$. The detector theory in [4] is only valid $U_o > 0$. Fig. 4 also shows the gate bias dependence of the source-to-gate currents. These currents were very small for the relevant gate biases (on the order of nA).

Since the drain current was zero (*dc* open circuit at the

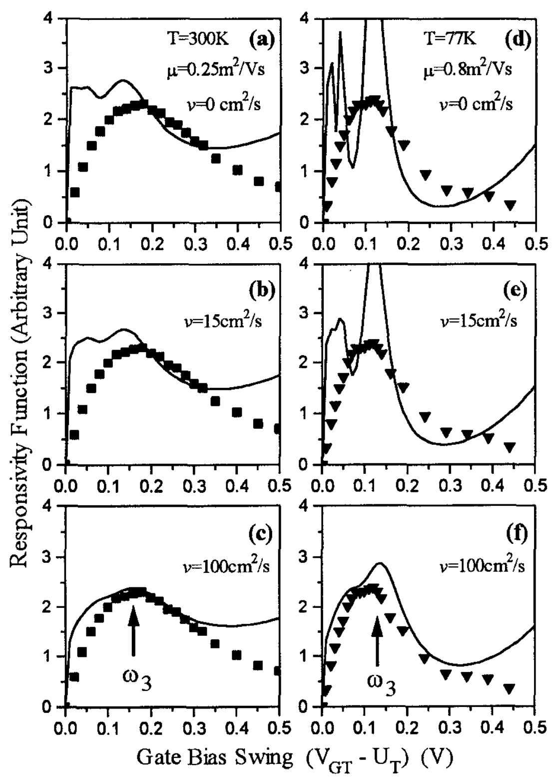

Fig. 5. Measured (symbols) and simulated (solid lines) gate bias dependencies of responsivity function of detector G at 300K (left figures) and 77 K (right figures) and f = 2.5 THz. The parameters used for these calculations are $L = 0.17$ µm; $\mu = 0.25$ m^2/V.s for (a)-(c) and $\mu = 0.8$ m^2/V.s for (d)-(f); and three values of the viscosity of the electron fluid, ν, of 0, 15, and 100 cm^2/s. The peaks correspond to the third harmonic of the surface plasma frequency, ω_3.

drain), and the gate current in the measurement range was very small, the heating effect should be entirely independent of the gate bias. Hence, it could not have been responsible for the measured gate-bias dependent responsivity.

Also, as shown in Fig. 4, the gate current increases monotonously with decreasing gate bias swing, while the detector response reach a peak near the threshold. Hence, the detector response could not be explained by the response of the Schottky gate.

The responsivity of the detector at 2.5 THz was much lower than estimated in [4] (values on the order of 600 V/W were expected, depending on the viscosity of the 2D electronic fluid). However, this can be expected since only a very small fraction of the laser radiation is coupled into the device.

Fig. 5 shows the gate bias dependence of the responsivity function measured for detector G at 77K and 300K. The solid lines are calculated using the detector theory developed in [4], and normalized to the measured data.

The detector responsivity should exhibit resonant peaks at the surface plasma wave frequencies in a HEMT channel [4]. The width of these peaks depends on quality factor, Q, which, in turn, depends on the electron mobility and on the viscosity of the electronic fluid. The resonant frequency of the detector is equal to $f_o = [e(V_{GS} - V_T)/m_e]^{1/2}/(4L)$, where m_e is the effective mass. For a HEMT with $L_{eff} = 0.17$ µm, μ_e = 0.25 m^2/V-s, V_T = - 0.2 V, and for V_{GS} < 0.5 V, f_o = 2.38 $(V_{GS} - V_T)^{0.5}$ (THz) and the highest quality factor is close to 0.7. Therefore the resonant peak at the fundamental frequency cannot be observed at 2.5 THz. However, as seen from the Fig. 5, the predicted shape of the responsivity curves is reproduced correctly. The peak at $(V_{GT} - V_T)$ = 0.14 V (77K) corresponds to the resonant frequency of 0.82 GHz. Hence, for this bias, the 2.5 GHz laser frequency is close to the third harmonic of the plasma wave resonance.

Even though the shape of the responsivity dependence on the gate bias is consistent with the theoretical predictions, we did not observe the expected increase in responsivity at cryogenic temperatures related to a higher electron mobility (see Fig. 5a and 5d). Possibly, the responsivity is more strongly limited by the viscosity of the electronic fluid, which might have been underestimated in [4]. The effect of the viscosity is illustrated in Fig. 5. As can be seen from the comparison of Fig. 5c and Fig. 5d, the values of the mobility play a relatively minor role in determining the responsivity at 2.5 THz for ν = 100 cm^2/s.

Fig. 6 shows the detector response as a function of the angle between the *ac* electric field and the source-to-drain direction (the electric field is in the device plane). The theory developed in [4] applies to the case when this angle is zero, and we expected the angle dependence of the responsivity to be a cosine function. However, the measured responsivity is even higher for the polarization angle of 90 degrees. This result might be explained as follows. When the polarization angle is equal to 90°, i.e., the electrical field is along the gate (vertical to the drain-to-source direction), the 2D-electron concentration in the channel becomes a function of the position. As the second order effect, this causes the periodic modulation of the threshold voltage. Hence, the total output *dc* signal can be found from the equivalent circuit shown as an insert to Fig. 6, where $U_{DS1} = R_1(FL\cos\theta)^2$, $U_{DS2} = R_2(FW\sin\theta)^4$, W is the gate width, F is amplitude of the electrical field, R_1 and R_2 are constants that depend on frequency and gate bias. Fig. 6 shows the comparison of the measured polarization dependence with the predictions of this model. The agreement is fairly good but more detailed

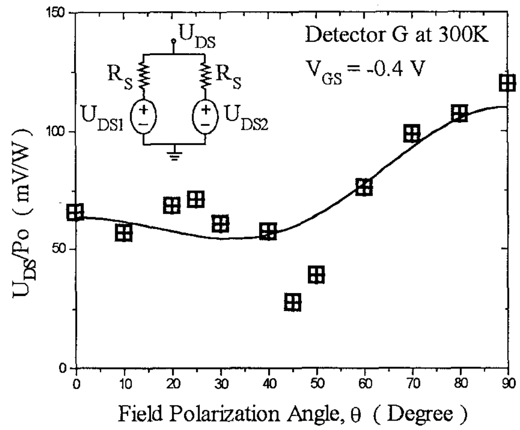

Fig. 6. Polarization dependence of detector responsivity. Solid line shows $R = U_{DS}/P_0 = R_0(\cos^2\theta+\alpha\sin^4\theta)$ for α = 1.74 and R_0 =63.2.

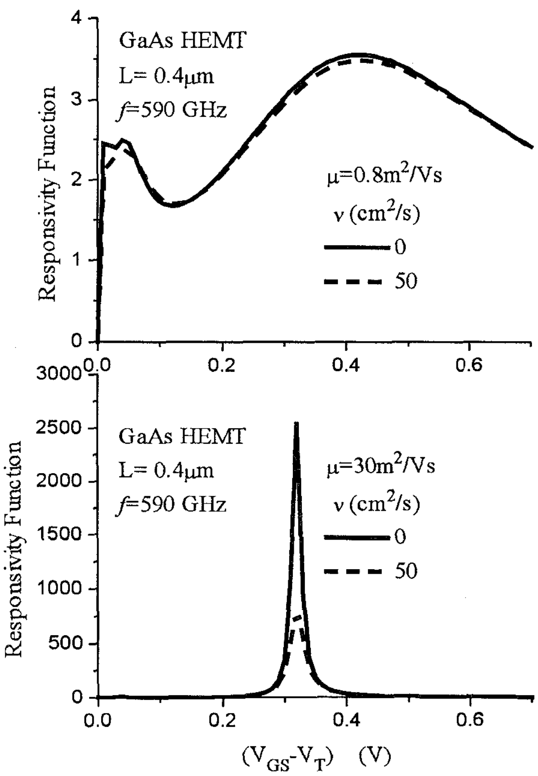

Fig. 7 Expected responsivity function for resonance HEMT detector with gate length of 0.4 μm.

experimental and theoretical studies are needed in order to check the validity of this model.

Based on the estimated range of the electron viscosity, we can now propose an improved detector design that should allow us to observe a more pronounced resonance peak and to estimate more accurately the electron fluid viscosity. The key features of this design are a higher mobility and a longer gate, which decreases the effect of the viscosity. Fig. 7 shows the expected responses.

V. Conclusion

We demonstrated a resonant terahertz detector utilizing two-dimensional electronic fluid in a HEMT operating at 2.5 THz. The terahertz radiation induced a *dc* drain-to-source voltage. Our experimental results confirm many features of the theoretical predictions but also pose many questions. Our results demonstrate a high potential for the applications of plasma electronics devices in terahertz technology.

Acknowledgment

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