Terahertz Detector Utilizing Two-Dimensional Electronic Fluid

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***Abstract*—We report on the first implementation of a terahertz detector utilizing two-dimensional (2-D) electronic fluid in a high electron mobility transistor (HEMT) operating at 2.5 THz. The terahertz radiation induced a dc drain-to-source voltage proportional to the radiation intensity. The measured dependencies of the detector responsivity on the gate bias are in good agreement with the gate bias dependence of the normalized responsivity predicted by the detector theory. This result shows the potential for developing a new family of electronics devices—plasma wave electronics devices—operating at terahertz frequencies.**

***Index Terms*—HEMT, plasma wave electronics, terahertz detector.**

I. Introduction

THE terahertz detector technology has many applications in radio astronomy, industry and defense (see, e.g., [1], [2]). However, these applications have been hampered by the difficulties of generating and detecting far infrared radiation. The primary semiconductor device used as a detector is the submicron GaAs Schottky diode. As the size of these devices is scaled down to a quarter of a micron and the doping level increased to 10^{18} cm^{-3} the operating frequency of these devices has reached the terahertz range. However, the responsivity of terahertz Schottky diode detectors tends to be modest, typically on the order of 100–1000 V/W.

Our theory has predicted that electrons in a HEMT channel might behave as a two-dimensional (2-D) electronic fluid rather than a 2D-electron gas (2DEG) [3], [4]. This electronic fluid is described by the same equations as water in a shallow channel. Wave propagation in the electronic fluid can be used as the basis for a new generation of millimeter and submillimeter-wave devices—a FET emitting far infrared radiation, an electronic flute, a detector, and a mixer [4], [5]. These devices—referred to as "plasma wave electronics devices"—should be able to push three-terminal-device operation into a terahertz frequency range, which is much higher than has been possible for conventional transit-time-limited regimes of operation.

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As discussed in [5], a FET has a resonance response at the plasma wave frequency. The width of the resonance curve is determined by the inverse momentum relaxation time. The asymmetry of the boundary conditions at the source and the drain and the nonlinearity related to the electric current (which proportional to the product of the electron velocity and electron concentration) lead to the resonance detection and mixing of electromagnetic radiation at terahertz frequencies. This detector produces an open circuit dc voltage, $U_{\rm ds}$, which is proportional to the intensity of the incoming terahertz radiation.

Such 2-D electronic fluid detector can operate in two different modes [4]: a resonant mode with an extremely high predicted peak responsivity (up to 10^6 V/W) for devices with high electron mobility, and a nonresonant mode. The resonant frequency can be tuned by the gate bias, which would make the electron fluid detector suitable for many applications involving far infrared spectroscopy. We have demonstrated such nonresonant detectors fabricated using AlGaAs/GaAs [6] and AlGaN/GaN HFET's [7] operating at frequencies below 20 GHz.

In this letter, we report on experimental results for a HEMT detector operating at 2.5 terahertz, which is much higher than the cutoff frequency (on the order of 90 GHz).

II. Experimental Procedure

The terahertz detector is fabricated using a *Fujitsu* FHR20X HEMT [8] mounted on a quartz substrate. A CO_2-pumped far-infrared gas laser served as a source of 2.5-THz radiation. The laser beam was chopped and focused on the sample with the electric field polarization oriented in the drain-to-source direction. As a response, the dc drain voltage $U_{\rm DS}$ was measured using lock-in technique. The detector was tuned by a dc gate bias $V_{\rm GS}$.

The device characteristics were measured and simulated using the HEMT model implemented in AIM-Spice [9] (Fig. 1). The parameters were extracted from measured dc characteristics and from the elements of the small-signal microwave equivalent circuit. The threshold voltage, V_T, is close to -0.2 V with an effective field effect mobility, μ_e, of 2500 cm^2/Vs. The effective gate length $L_{\rm eff}$ is close to 0.18 μm.

III. Equivalent Circuit

The inset in Fig. 2 shows the detector equivalent circuit. Impedances $Z_{\rm gs}$, $Z_{\rm gd}$, and $Z_{\rm ds}$ depend on the device design.

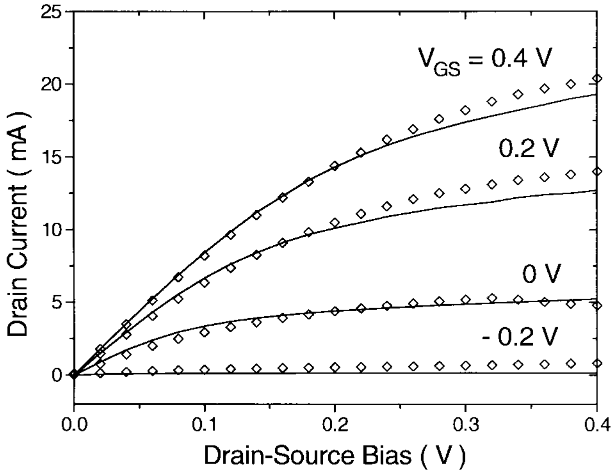

Fig. 1. The measured (symbols) device characteristics of the *Fujitsu* FHR20X HEMT. $V_{\rm GS}$ is the gate-source bias. The solid lines are simulated using AIM-Spice with the following parameters: gate length of 0.18 μm, threshold voltage of -0.2 V, and mobility of 2500 cm^2/Vs, gate width of 100 μm, gate-to-channel spacing of 18 nm, saturation velocity of 1.6×10^5 m/s, maximum sheet charge density of 1.2×10^{12} cm^{-2}, source and drain series resistances of 2.8 Ω.

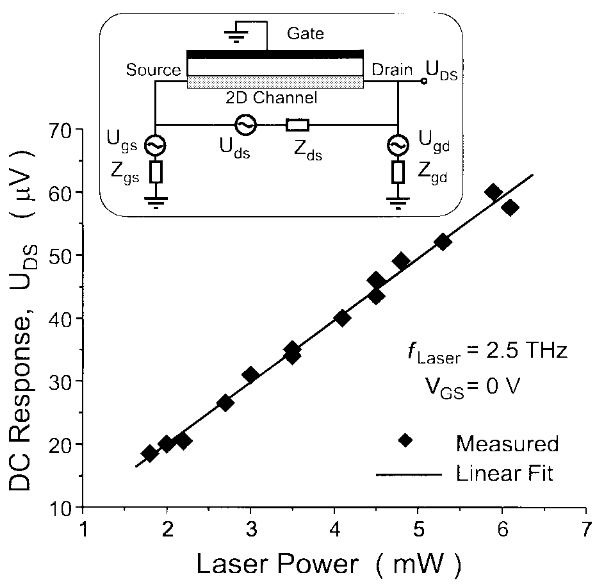

Fig. 2. The detector response—dc drain-source voltage $U_{\rm DS}$ versus laser power measured (symbols) at zero gate bias. The linear relationship (solid line) confirms that the HEMT operates as a square-law detector, as predicted by the theory. Inset: ac equivalent circuit of a HEMT device operating in detector mode.

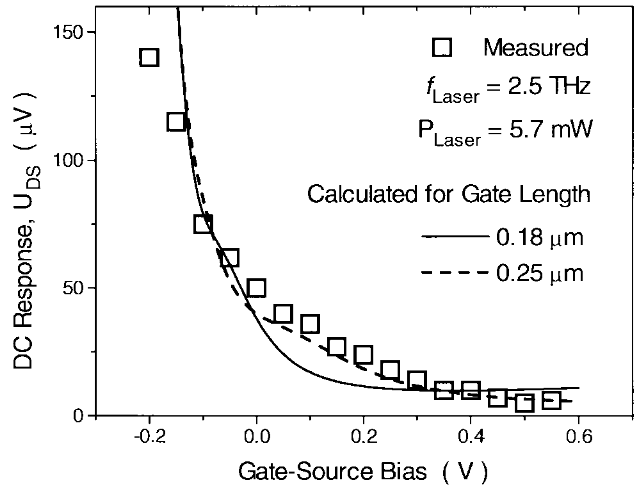

Fig. 3. Gate bias dependence of the detector response $U_{\rm DS}$ measured (symbols) at the frequency of 2.5 THz. The solid and dashed lines are predicted by the theory using the same parameters as in Fig. 1 and normalized for comparison.

They correspond to a capacitive response. $Z_{\rm gs}$ is small compared to $Z_{\rm gd}$ in order to minimize the Miller effect, also much smaller than $Z_{\rm ds}$. If $Z_{\rm gs}$ is small enough to be approximated by a short circuit, and $Z_{\rm gd}$ and $Z_{\rm ds}$ are sufficiently large to act as open circuits, the equivalent circuit reduces to that proposed in [4]. The equivalent sources $U_{\rm gs}$, $U_{\rm gd}$, and $U_{\rm ds}$ are determined by the polarization and the orientation of the laser beam. They are proportional to the square root of the radiation intensity and depend on the coupling of the radiation to the device.

The coupling of the electromagnetic radiation should roughly correspond to the scheme considered in [4], because of the asymmetrical design of the HEMT used in this study. In this case, $Z_{\rm gs} \to 0$, $Z_{\rm gd} \to \infty$, $Z_{\rm ds} \to \infty$, only $U_{\rm gs}$ is important, and the problem reduces to that considered in [4]. In this letter, we compare the measured data to the theory developed in [4]. The qualitative dependencies of the detector responsivity on the gate voltage swing and frequency are similar for different boundary conditions. A detailed analysis of the boundary conditions on the detector performance will be published elsewhere.

IV. Results and Discussion

The device operates at a frequency of 2.5 THz, which is about 30 times higher than the transistor cutoff frequency. In agreement with the predictions of the terahertz detector theory [4], the radiation induces a dc drain-to-source voltage $U_{\rm DS}$. For laser power levels below 7 mW in total, the measured responsivity is independent of radiation amplitude and $U_{\rm DS}$ is proportional to the radiation intensity as shown in Fig. 2.

The detector responsivity is measured for the gate bias from its threshold voltage of -0.2 V to a maximum voltage of 0.55 V. If $V_{\rm GS} > 0.55$ V, the detector becomes unstable since the gate-to-channel Schottky diode is turned on. Fig. 3 shows the gate bias dependence of the detector responsivity for the laser intensity of 5.7 mW. The responsivity increases at smaller gate voltage swings. The solid line is calculated using the detector theory developed in [4], and normalized to the measured data, using the same parameters as obtained in Section II and in Fig. 1. From our calculations reported in [4], we estimate that the predicted responsivity of the detector at 2.5 THz should be on the order of 600 V/W (depending on the viscosity of the 2-D electronic fluid). However, this responsivity is calculated for the radiation intensity coupled into the device with a maximum asymmetry in the boundary conditions. Since only a very small fraction of the laser radiation is coupled into the device, the ratio of the output voltage to the laser power is much smaller than the computed values of the responsivity.

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, i.e., $Q = \frac{\mu_e}{L}\sqrt{\frac{m_e}{e}(V_{\rm GS} - V_T)}$, where L is the gate length and m_e is the electron effective mass. The resonant frequency of the detector is given [4] as $f_0 = \frac{1}{4L}\sqrt{\frac{e}{m_e}(V_{\rm GS} - V_T)}$. For the HEMT with $L_{\rm eff} = 0.18\ \mu$m, $\mu_e = 0.25$ m^2/V.s, $V_T = -0.2$ V, and $V_{\rm GS} < 0.55$ V, the highest quality factor is close to 0.7. For $L = 0.25\ \mu$m, $f_0 = 1.62\ (V_{\rm GS} - V_T)^{0.5}$ (THz). Therefore the resonant peak at the fundamental frequency cannot be observed. However, as seen from the figure, the predicted shape of the responsivity curve is reproduced correctly. As expected, the shape changes at the gate bias of 0.08 V, which corresponds to $f_0 = 0.86$ THz. (At this gate bias, the laser frequency of 2.5 THz corresponds to the third harmonic of the plasma frequency.)

Therefore, the resonant peak cannot be observed. The observation of the resonant peak for our detector will require cryogenic measurements, which should allow us to increase the gate voltage and improve the quality factor. In devices with higher electron mobility or a shorter gate, it should be possible to see the resonant peaks in dependence of the responsivity on the gate bias.

V. Summary

We demonstrated the first terahertz detector utilizing 2-D electronic fluid in a HEMT operating at 2.5 THz. The terahertz radiation induced a dc drain-to-source voltage. The dependence of the detector responsivity on the gate bias is in good agreement with the theory.

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