Resonant frequency response of plasma wave detectors

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(Received 10 March 2006; accepted 7 October 2006; published online 22 November 2006)

Resonant behavior in the frequency dependent responsivity of a high electron mobility transistor based plasma wave detector from 0.1 to 6 GHz is clearly demonstrated at $T=0.3$ to 4 K. By independently determining the frequency dependent power coupling, the authors are able to measure the absolute responsivity of the device. Clear peaks in the responsivity are observed at 2.0 and 4.4 GHz. At elevated temperatures up to 20 K, the resonant behavior vanishes due to increased phonon scattering. Taken collectively these experiments provide strong evidence that plasma wave rectification is the dominant mechanism of device response. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2393023]

The terahertz frequency spectrum falls between microwave and infrared frequencies. Submicron GaAs Schottky diodes or bolometers have been used to date as broadband terahertz detectors. Plasma wave detectors, based on resonant behavior of a gated two-dimensional electron gas, have recently been introduced as a potentially selective and tunable terahertz solid state detector.[1] Compared with transit time limited conventional field effect transistor devices, plasma wave devices can detect[2–5] and emit[6] terahertz frequency signals and so may have many applications in materials characterization, medicine, military, and biological applications.[7,8] However, to date no frequency dependent studies of such devices in the resonant regime have been carried out, due to the difficulty in characterizing power coupling at terahertz frequencies. In this study, we perform a "scale model" study of plasma wave detectors at microwave frequencies, allowing us to quantitatively test device performance over a broad range of frequencies (0.1–6 GHz).

A plasma wave in a two-dimensional system is a collective mode in which the charge density oscillates in time and space. We recently probed these capacitively[9] and also through Ohmic contacts[10–12] in high electron mobility transistor (HEMT) based devices made of ultrahigh mobility GaAs material at cryogenic temperatures. Dyakonov and Shur have developed a theory for the use of such a HEMT in the ballistic limit (in the sense that the operation frequency ω is greater than the scattering frequency $1/\tau$) as a detector of microwave and terahertz radiations.[1] For rectification of an ac voltage (i.e., detection), three conditions must be satisfied: (1) an ac voltage is applied to the gate, (2) the source is grounded at both ac and dc, and (3) the drain is an open circuit at ac, i.e., no ac current flows through the drain. Under these conditions, at resonant frequencies given by $f=nv_p/4L_{\text{gate}}$ (with v_p the plasma wave velocity) and its odd harmonics, a dc voltage develops at the drain, hence the device performs as a detector. Such a device is named a plasma wave detector. In this letter we realize such a device, and test its responsivity as a function of power, frequency, and temperature.

The necessary frequency condition $\omega\tau > 1$ for resonant plasma wave behavior requires frequencies greater than 500 GHz for most semiconductor materials (Si, GaAs, InP, and GaN) at room temperature. At cryogenic temperatures, higher mobilities μ can be attained. Since $\mu = e\tau/m$, this allows for larger values of τ and hence resonant plasma behavior at lower frequencies. In our studies, $\mu=3\times10^6$ cm^2/V s, so that resonant plasma wave behavior can be observed at microwave frequencies. Thus, by utilizing ultrahigh mobility material in combination with straightforward microwave frequency measurement tools, we are able to quantitatively test the frequency, power, and temperature dependence of plasma wave responsivity.

The significance of these studies is as follows. In this work, we clearly demonstrate resonant frequency response in a plasma wave detector. Prior studies,[2–6] although significant and pioneering in their own right, have been performed at typically only one frequency, leaving open the possibility that the measured response was due to a mechanism other than plasma wave rectification. Additionally, many previous studies have been in the nonresonant regime. In contrast, our systematic and thorough studies clearly demonstrate scaling of resonant device response with frequency, temperature, and power that strongly suggest plasma wave rectification as the dominant mechanism of response.

The plasma wave detector is fabricated from a GaAs/AlGaAs modulation doped single quantum well grown by molecular beam epitaxy. Device fabrication was presented in detail in our recent paper,[12] and is briefly summarized here. After molecular beam epitaxy growth, a mesa is defined by wet etching. Rapid annealing at 440 °C follows after Ni/Ge/Au/Ni/Au Ohmic metallization (80:270:540:140:2000 Å). Ti/Au (300:3000 Å) metallization is used to form the gate in order to have low sheet resistance for the leads to both the gate and source. After illumination with a red light-emitting diode, the mobilities based on dc measurements of samples from the same wafer are 13×10^6 and 6×10^6 cm^2/V s at 0.3 and 4 K, respectively. The measured electron density of the fabricated plasma wave detector at $T=0.3$ K and $V_{\text{gate}}=0.25$ V is 1.3×10^{11}/cm^2.

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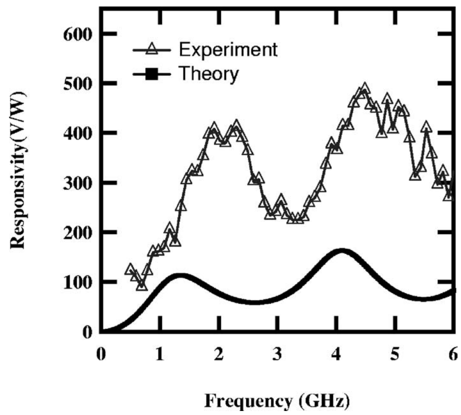

FIG. 1. Measured responsivity at 4 K.

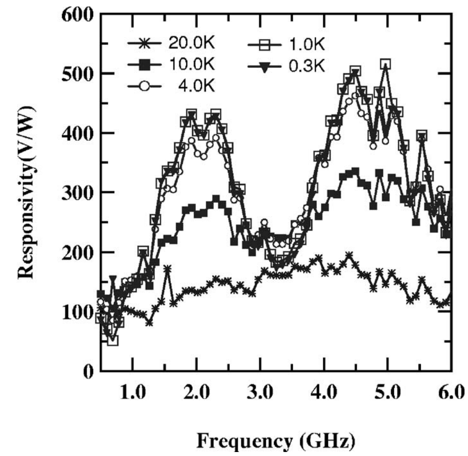

FIG. 2. Measured responsivity vs frequency for plasma wave detector at different temperatures. The curves at 0.3 and 1 K overlap closely.

An integrated long, narrow thin-film resistor ($\sim$1 kΩ) is used as the electrode to contact the drain at dc, in order to measure the induced dc voltage when an ac signal is applied to the gate. Since the electrode resistance is much higher than the 50 Ω microwave system and since the capacitance of the narrow lead is small, it becomes a broadband open at microwave frequencies, a necessary condition for plasma wave rectification. For the ac measurement, the sample is mounted at the end of a 50 Ω matched microstrip line. The gate is connected to the end of the microstrip with In solder. The source is grounded at both ac and dc. An ac voltage is applied to the gate, which is amplitude modulated with a semiconductor switch. We measure the synchronous induced drain-to-source voltage (V_{ds}) using a lock-in analyzer. By varying the frequency of the microwave source, we thus measure the responsivity as a function of frequency.

In our experiments, there is some rf loss from the microwave generator to the terminals of the device. These were independently determined by measuring the loss of the coax in a separate experiment. The source contact resistance ($R_{\text{source-contact}}$) is estimated to be 19 Ω based on the dc mobility and electron density. This constitutes an additional loss of about 3.50 dB, since the microwave power will get absorbed in this contact resistance. The total loss is the sum of the coaxial cable loss and $R_{\text{source-contact}}$ power loss.

The total loss is only mildly dependent on frequency, and cannot explain the resonant behavior we observe. In addition, the power actually absorbed by the device from the microwave system varied between 80% and 90% of the incident power over the entire band (1–6 GHz) without resonance, so that the frequency dependent impedance matching to the device cannot explains the resonant frequency dependence we observe.

In Fig. 1, we plot the measured responsivity as a function of frequency, taken at T=4 K and V_{gate}=0.25 V. We also plot the predicted curve from Ref. 1, using the parameters appropriate for our sample (V_{th}=−0.32 V). In our experiments, resonances are clearly observed in the responsivity. This is the central result of this letter. The absolute value of the responsivity is within a factor of 4 of the predicted value. At present it is not clear if this is a calibration uncertainty or a bonafide discrepancy with theory; we discuss possible reasons for the latter in the conclusions.

We now discuss the location of the peaks in frequency. The responsivity is predicted to show resonant behavior at the fundamental frequency ($f_0=v_p/4L_{gate}$) and its odd harmonics. The fundamental frequency (f_0) can be expressed by the relation

$$f = \frac{s}{4L_{\text{gate}}} = \frac{1}{4L_{\text{gate}}}\sqrt{\frac{ne^2 d}{m^* \varepsilon}}, \tag{1}$$

where L_{gate} is the gate length (180 μm for our samples), n the measured electron density ($1.3\times10^{11}/\text{cm}^2$), ε the dielectric constant ($12\times8.85\times10^{-12}$ F/m), m^* the effective mass ($0.067\times9.11\times10^{-31}$ kg), and d the distance from gate to the channel (1900 Å). In Eq. (1), there are no free parameters. Therefore, the locations of the peaks in frequency are predicted to be slightly lower than the observed peaks. Although there is a discrepancy between the location of the peaks, resonant behavior is clearly observed. In addition, by varying the two-dimensional electron gas 2DEG density (by varying the gate voltage), we observe a clear trend in the location of the peaks with changing density, consistent with Eq. (1).

We next discuss the absolute value of the responsivity: This value is close to the predicted theoretical value, and is comparable to most microwave detectors currently in use. However, theoretically this value will increase dramatically if the gate length is reduced, and the resonant frequency increased. This is clearly a subject for future work.

Finally, we discuss the resonance width. The scattering time determined from dc measurements of the mobility is approximately 230 ps. We find experimentally that a scattering time of 100 ps more accurately describes our resonant width observed in the responsivity. This may be due to reduced sample mobility as a result of processing, which is typical for these ultrahigh mobility samples. Thus, the resonance linewidth is consistent at least within a factor of 2 of the measured dc mobility.

In order to investigate the effect of the mobility on the linewidth more carefully, we measured the frequency dependent responsivity at several different temperatures. In Fig. 2, we plot the measured results. From this figure, it is clear that increasing the temperature from 0.3 to 20 K gradually increases the linewidth until the resonance disappears entirely. Note that the linewidths at 0.3 and 1 K are identical; this is consistent with the fact that the dc mobility is measured to be temperature independent in this range. In contrast, the dc mobility changes significantly between 10 and 20 K, which is reflected in the significant increase in linewidth measured in the microwave response. This clearly demonstrates the

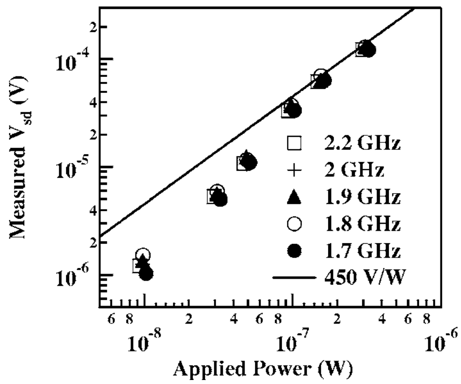

FIG. 3. Induced voltage vs rf power at $T=1$ K.

crossover from the resonant ($\omega\tau>1$) to the nonresonant ($\omega\tau<1$) regime of device operation, and provides even stronger evidence for plasma wave rectification as the mechanism of response.

In Fig. 3 we plot the power dependence of the induced voltage. The responsivity is shown to be linear for powers above 10^{-7} W. In most detectors, the detector voltage is linear below a certain threshold and saturates at higher powers. However, in our experiments, at low powers, the device response is sublinear, with an apparent power law of $V_{dc} \sim P_{rf}^{1.5}$. This behavior is currently not understood and emphasizes the necessity to always measure responsivity at a variety of power levels for any detector technology, as we have done here.

An important practical issue is the device noise equivalent power (NEP). In our experiments, we have applied a positive gate voltage in order to maximize the device mobility, hence responsivity. In HEMT devices this is known to cause excess $1/f$ noise, so we measured the voltage noise at the operating conditions and a typical chopping frequency (30 Hz). We found the noise voltage of both the device and measurement amplifier together (a Stanford Research Systems SRS 830 lock-in amplifier) to be 11 nV/Hz$^{1/2}$, and independent of the gate bias voltage. This indicates that there is no excess $1/f$ noise in our devices above that level due to the gate bias, which is reasonable given the large gate area of our devices. In addition, this implies an upper limit on the NEP (calculated) of 2×10^{-11} W/Hz$^{1/2}$. Clearly, this NEP does not justify cryogenic operation of plasma wave based microwave detectors, as lower NEPs are achievable at room temperature.[13] However, the goal of this work is to demonstrate the mechanism of plasma wave response, which has been achieved.

Most HEMT devices have submicron gate lengths and hence much larger $1/f$ noise. This is an important issue to consider in scaling down the gate length of plasma wave devices in order to increase the resonance frequency into the terahertz range. Therefore, $1/f$ noise will need to be carefully quantified in any future terahertz plasma wave devices, and may significantly degrade the NEP. Future devices operating at higher frequencies, applying a gate bias may not be necessary, since the device resonant Q and hence responsivity[1] will already be much larger than it is on our experiments.

Taken collectively these experiments provide strong evidence that plasma wave rectification is the dominant mechanism of device response. It should be noted that in prior theoretical work, the mobility was assumed to be constant (independent of gate voltage and density), whereas in our structures this is not the case. This may explain some of the minor discrepancies between theory and experiment, such as the difference between the absolute predicted and measured responsivity. Future work could include, e.g., device measurements at higher frequencies with such ultrahigh mobility samples, where responsivities of 10^7 V/W are predicted. This would be an improvement of four orders of magnitude over that measured in our "scale" models.

This work is supported by the National Science Foundation, Office of Naval Research, and the Army Research Office.

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