Odd Harmonic Responses in Two-Dimensional AlGaAs/GaAs HEMT Devices Due to Plasma Wave Interaction

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Abstract. Plasma waves are oscillations of electron density in time and space, and in deep submicron field effect transistors, typical plasma frequencies, ω_p, lie in the terahertz (THz) range and do not involve any quantum transitions. Hence, using plasma wave excitation for detection and/or generation of THz oscillations is a very promising approach. In this paper, the investigation of plasma wave interaction between the plasma waves propagating in a short-channel High-Electron-Mobility Transistor (HEMT) and the radiated electromagnetic waves was carried out. Experimentally, we have demonstrated the detection of the terahertz (THz) radiation by an AlGaAs/GaAs HEMT up to third harmonic at room temperature and their resonant responses show very good agreement with the calculated results.

Keywords: surface plasma wave, non-drifting plasma, THz device, GaAs, HEMT.
PACS: 52.35.g plasma wave

INTRODUCTION

Since the last decade, the study on terahertz (THz) devices and their applications in radio astronomy, industry and defense have recently been processing rapidly [1], but the terahertz band is still considered as an unexplored region in the sense that no practical integrated device technology exists. New operating principles should be introduced for the real applications in THz region since the transit-time effect is so severe in this frequency range for conventional devices. One possibility is to utilize plasma wave interaction in semiconductor. Recently, Dyakonov and Shur proposed a new THz device utilizing the plasma resonance effect of highly dense two-dimensional conduction electrons in the field-effect transistor (FET) channel [2-4]. Some motivated experimental studies on the plasma resonant effect in HEMTs and /or similar FETs have also been reported [5-7]. We call this kind of device hereafter as a plasma wave device.

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Dyakonov and Shur proposed that the reduction of semiconductor device feature sizes results in a greatly increased electron density in the device channel. As a consequence, the critical device dimensions are becoming comparable to or even smaller than a mean free pass for electron collisions with impurities or phonons. At the same time, this reduction of device feature sizes results in a greatly increased electron density in the device channel, hence, electron–electron collisions become dominant, and electrons in an FET channel should behave as a two-dimensional (2D) electron fluid. In this situation, the 2D electrons behave as a fluid, and they can be described by hydrodynamic equations and coincide with the hydrodynamic equations for shallow water [2].

According to their theory, this plasma wave device does not rely upon transit-time carrier transport but upon electronic polarization so that it can operate up to THz region. They demonstrated that the resonance frequency of this plasma wave device can be controlled by the gate voltage, which results in a possibility of frequency-tunable THz detector [8] which makes it suitable for many applications involving far infrared spectroscopy for the detection of chemical and biological substances. This detector produces an open circuit dc voltage, which is proportional to the intensity of the incoming terahertz radiation with a resonance response to electromagnetic radiation at the plasma oscillation frequency. In addition, plasma waves are oscillations of electron density in time and space, and in deep submicron FET, typical plasma frequencies lie in the THz range and do not involve any quantum transition. Hence, plasma wave excitation is a very promising approach for detection and/or generation of THz oscillation.

Besides of the above plasma wave interaction of non-drifting carrier concept, recently, we have also successfully demonstrated the existence of plasma wave interaction between the drifting carriers in two-dimensional electron gas (2DEG) AlGaAs/GaAs HEMT and electromagnetic waves propagating in interdigital slow wave circuit both theoretically and experimentally [9-12].

In this paper, we present the investigation of plasma wave interaction between the plasma waves of non-drifting carriers propagating in a short-channel HEMT and the radiated electromagnetic waves. Experimentally, we have demonstrated the detection of the terahertz (THz) radiation by an AlGaAs/GaAs HEMT up to third harmonic at room temperature and their resonant responses show very good agreement with the calculated results.

FUNDAMENTAL OF PLASMA WAVE DEVICES

In this paper we will discuss the harmonics response in conventional three terminal two-dimensional AlGaAs/GaAs high electron mobility transistor (HEMT) structure. Figure 1 depicts the schematic cross section of a plasma wave device and its structure has no difference from those of normal HEMT device. The plasma waves in this kind of gated structure are described by a linear dispersion law,

$$\omega(k) = sk \tag{1}$$

Here, s is the plasma wave velocity that depends on the carrier density, and k is the wave vector.

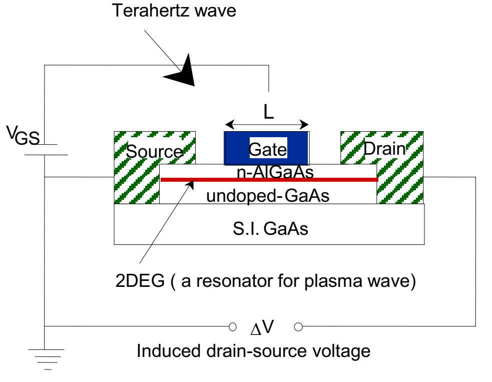

FIGURE 1. Schematic cross-sectional structure of plasma wave device under study.

The velocity of the plasma waves, s, is typically on the order of 10^8 cm/s, which is much larger than the drift velocity of the electrons in the HEMT channel. A HEMT, biased by the gate-to-source voltage and subject to electromagnetic radiation, can develop a constant drain-to-source voltage, which has a resonant dependence on the radiation frequency $f = \omega / 2\pi$ with maxima at the plasma frequency $f_p = \omega_p / 2\mu$ where μ is the mobility. The plasma waves velocity depend on the carrier density, n_s, in the channel capacitance per unit area C, $s = (e^2 n_s/mC)^{½}$, where e is the electron charge and m is the electron effective mass.

In the gradual channel approximation, the carrier density in the channel is related to the gate voltage as $n_s = CV_0/e$. V_0 is the gate to channel voltage swing that is defined as $V_0 = V_{GS} - V_{TH}$, where V_{GS} is the gate voltage and V_{TH} is the threshold voltage. In this case the fundamental plasma frequency, f_0 can be expressed by an approximate relation

$$f_0 = \frac{\omega_0}{2\mu} = \frac{n}{4L}\sqrt{\frac{eU_0}{m}} \quad (2)$$

where $n/4$ is the numerical constant correspond to the boundary condition, and n = 1,3,5…. ., L is the gate length of a device. This relation leads to two important consequences: (i) a sufficiently short (sub-micron) HEMT can operate as a THz detector, and (ii) the frequency of this detector can be tuned by the gate voltage.

EXPERIMENTAL STUDY

Since the last decade, the theoretical and experimental works dealing with plasma waves in HEMTs and their applications for sources and detectors operating in millimeter and sub-millimeter range have been intensively studied [1-8]. In this work, we demonstrate the implementation of the n-AlGaAs/GaAs HEMT as a THz detector where the devices operated at 2.5 THz which is about 30 times higher than the transistor cut-off frequency operating on transit-time basis. Figure 2 shows the THz measurement setup. In this study, CO_2 pumped CH_3OH laser which served as a THz source of 2.5 THz radiation was used. In this setup, chopper and lock-in amplifier were not used. The laser beam was focused on the sample with the electric field polarization oriented in the drain-to-source direction. The induced drain-to-source voltage, ΔV as illustrated in Fig. 1 was measured using Agilent semiconductor parameter analyzer. The power of radiated THz beam is 2mW. The measurement of THz detection was carried out at room temperature.

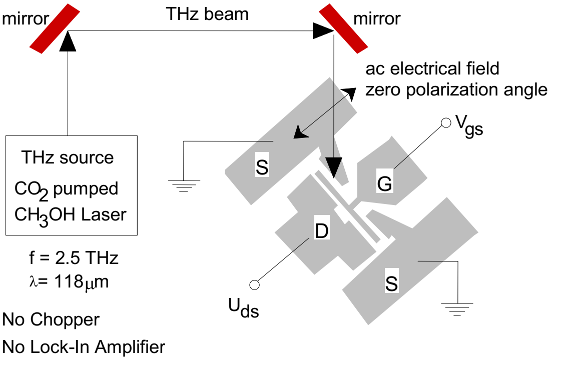

FIGURE 2. Measurement setup for THz detection.

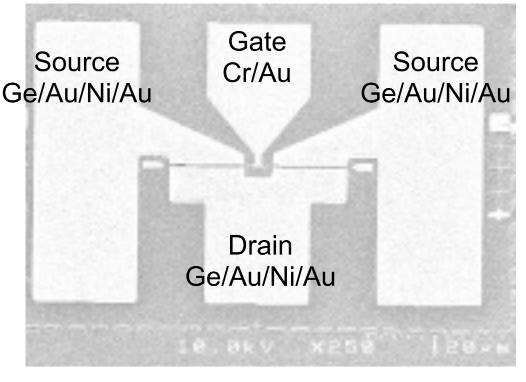

FIGURE 3. Fabricated device layout (top view).

As shown in Fig. 3, we fabricated a n-AlGaAs/GaAs HEMT device with a gate length of 0.16 μm and width of 64 μm using conventional electron beam lithography and lift off techniques. The layer structure of the fabricated device is illustrated in Fig. 1. The source-drain distance is 2 μm so that the total ungated region length is 1.84 μm. The gate is almost at the center of the source and drain. Alloy of Cr/Au was used for Schottky-gate electrode, while Ge/Au/Ni/Au was used for source and drain ohmic contacts. From Hall measurement at room temperature, the mobility of AlGaAs/GaAs wafer is 7480 cm^2/Vs.

RESULTS AND DISCUSSION

At first, the measurement of current-voltage characteristics was carried out. Figure 4(a) shows the measured I_{DS} versus V_{DS} characteristics and Fig. 4(b) the measured I_{DS} versus V_{GS} where I_{DS} is the drain-source current, V_{DS} is the drain-source voltage and V_{GS} is the gate voltage. From both characteristics, the transconductance, g_m, of the device and its threshold voltage, V_{TH} are estimated to be around 94 mS/mm and -1.3 V, respectively.

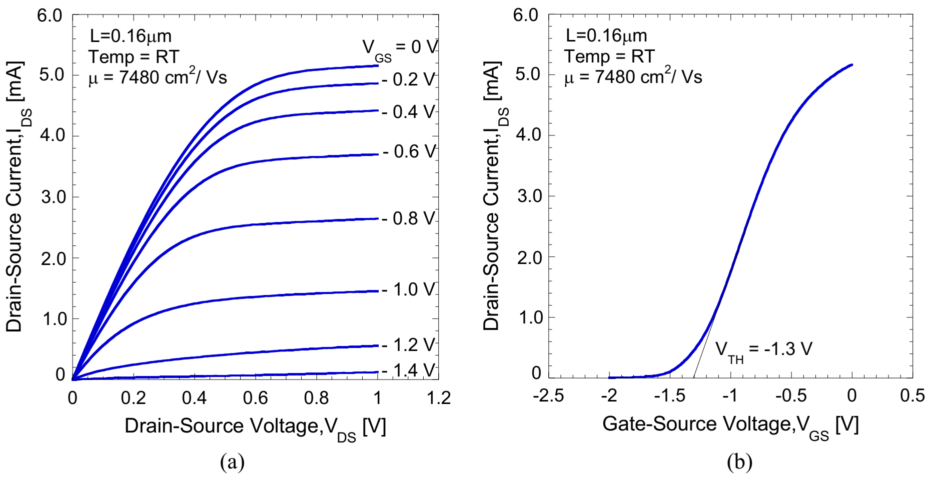

FIGURE 4. (a) Measured I_{DS} vs. V_{DS} and (b) measured I_{DS} vs. V_{GS}.

During the radiation, the gate voltages were changed and the induced drain-to-source voltage was measured. Figure 5 shows the measured drain response in the unit of mV/W. The measured response was not smooth because the measurement was done at room temperature and our system was not supported by the lock-in amplifier which is normally used as reported by other groups [5-7]. The responses seem to be resulted from the plasma wave interactions which are well supported by the theoretical calculation presented in Figs. 6(a) and 6(b). Two peaks can be clearly seen in the Fig. 5. The first peak is resonated at -0.4 V and the second peak is resonated at -1.2 V which are corresponding to the first and third harmonic, respectively. From these results, it can be understood that the third harmonic response occurred at the value of gate voltage which is very close to the threshold voltage.

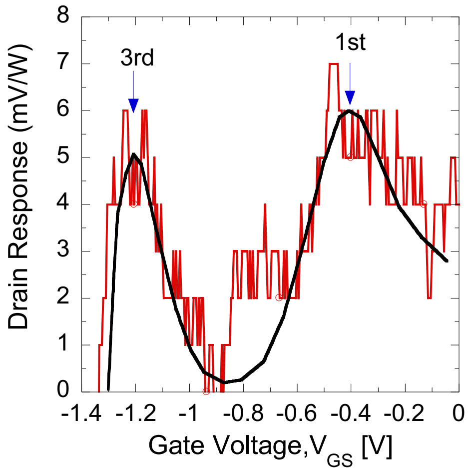

FIGURE 5. Measured drain response as a function of gate voltage. The arrow shows the peaks of the resonance occur at the 1st and 3rd harmonics correspond to the gate voltage.

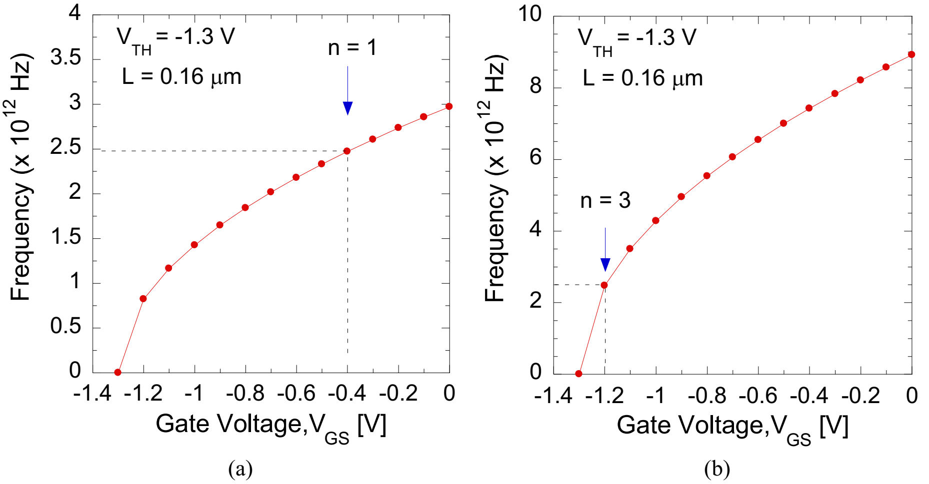

FIGURE 6. Calculated resonant frequency as a function of gate voltage. (a) 1st harmonic, and (b) 3rd harmonic. Arrow shows the gate voltage at the frequency of 2.5 THz.

We estimated that it was about 10% to the threshold voltage where our device will completely close at voltage slightly larger than -1.4 V as shown in Fig. 4 (I-V characteristics). As presented in [5] by Shur's group, the fundamental response was observed at V_{GS} of -0.42 V which is also very close to the threshold voltage, V_{TH}, of -0.47 V or about 10% to the threshold voltage. In addition, since our device has quite large threshold voltage, this makes the observation of third harmonic response possible. As stated in previous section, the gate length of our device is 0.16 μm and the mobility of our AlGaAs/GaAs sample is 7480 cm^2/Vs at room temperature. The resonant response reported by Shur's group [5] was measured at 8 K. The mobility of their device at 10 K was ~7000 cm^2/Vs and the gate length was 0.15 μm. Those parameters are very close to the parameters of our device. Therefore, it is possible to observe the resonant response at room temperature if the mobility is above 7000 cm^2/Vs.

Dyakonov and Shur [13,14] reported that the resonant frequencies of plasma oscillations are much higher for ungated structures. Therefore, the current instability and plasma waves generation is easier to achieve. According to the calculation presented in [13], a much higher frequency for ungated devices results in a much higher quality factor, ωt, for detecting electromagnetic radiation. The total of ungated region length of our device is 1.84 μm and referring to the calculation presented in ref. [13], the ωt value is in the vicinity of 10.

The simulation based on the proposed theory [3] and briefly described in previous section, was carried out to confirm those resonant peaks. Because of the nonlinear properties of the electron fluid and the asymmetry in the boundary conditions, a HEMT biased only by the gate-to-source voltage, and subjected to an electromagnetic radiation develops a constant drain-to-source voltage, which has a resonance dependence on the radiation frequency with maxima at the plasma oscillation frequency and its odd harmonics (n = 1, 3, 5, ……) as being demonstrated in [8].

Using the fabricated device parameters, and the Eq. (2), the dependences of various frequencies and the gate voltages for the first and third harmonics were calculated. The results of calculated resonant frequency as a function of gate voltage for first harmonic and third harmonic are shown in Fig. 6(a) and 6(b), respectively. For the first harmonic, the resonance of 2.5 THz is predicted to occur at gate voltage of -0.4 V while for the third harmonic the resonance is predicted to occur at -1.2 V. These results show very good agreement with the experimental one as shown in Fig. 5. Hence, the existence of plasma wave interaction was observed experimentally at room temperature up to third harmonic. The measurement techniques can be approved by using lock-in amplifier.

CONCLUSION

The existence of plasma wave interaction was observed experimentally at room temperature in conventional HEMT device. It was shown that plasma waves propagating in a short channel HEMT have a resonant response to electromagnetic radiation where the resonance occurs at certain gate voltages for the odd harmonics. Hence, the conventional HEMT device can be used as tunable THz detector operating in the THz region.

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