Plasma waves Terahertz detection by field effect transistor in Quantinzing magnetic fields

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Abstract. Detection of THz radiation by a Field Effect Transistor InGaAs/InAlAs transistor was investigated at 4.2 K as a function of the magnetic field and gate voltage. We observed oscillations of the photovoltaic signal analogous to Shubnikov-de Haas oscillations, as well as their strong enhancement at the cyclotron resonance conditions. The results are successfully quantitatively described within the frame of a recent theory, taking into account a new source of nonlinearity related to Shubnikov-de Haas effect. We show that the detection is due to gated plasmon.

1. Introduction

The exploitation of nonlinear properties of the 2D plasma in Field Effect Transistors (FETs) channel is a promising approach proposed by M. Dyakonov and M. Shur [1], [2] as a new route to create compact solid state high frequency devices. These FETs can be used as terahertz (THz) resonant [3] and selective detectors at cryogenic temperatures, as well as broadband detectors at room temperature [4]. These transistors were found to have competitive Noise Equivalent Power in comparison with other kinds of commercially available detectors [5]. Detection of THz radiation by Si-CMOS based transistors was also demonstrated and already reported in many application systems such as THz cameras [6]. The detection signal results from the rectification of THz currents induced by the incident radiation in the transistor channel. The rectification takes place due to a nonlinear response of the gated 2DEG to the radiation. The main source of nonlinearity, explored until now, were changes in conductivity due to radiation-induced modulation of the carrier density in the channel. Nevertheless, in high magnetic fields the oscillatory effects like Shubnikov-de Haas (SdH) oscillations and cyclotron resonance (CR) can take place and have influence on the rectification related photovoltaic response.

The purpose of this work is to clarify the physical mechanism of Shubnikov de Haas (SdH) oscillations and Cyclotron Resonance (CR) related detection by FETs. We investigate the THz response in the transistor of a simple architecture, with the gate covering the major part of the channel. Fig 1 shows the transfers characteristics of the FET at different values of the drain voltage (0.1 V and 0.2 V) obtained at 4.2 K. In this simplified structure (see the inset of Fig 1), the effect of the gate bias on the observed signal can be clearly established and the results can be compared with the recent theory [7].
2. Results and discussion
Experiments were carried out on a pseudomorphic InGaAs/InAlAs HEMT. The measurements were performed with an optically pumped molecular CH3OH laser. The radiation of frequency 2.5 THz. The photoconductivity signal was measured using the standard lock-in technique. Two types of experiments were performed. First, the detection signal was measured as a function of the gate voltage \( V_g \) at fixed magnetic field \( B \). Second, the magnetic field was swept at a fixed gate voltage. The results are shown in Figs. 2 - 3. In both kinds of experiments the photoresponse was found to be periodic in \( B^{-1} \), i.e., it showed Shubnikov - de Haas oscillations. Its periodicity versus \( V_g \) and \( 1/B \) clearly indicates that the oscillations are related to the crossing between the Fermi level and the Landau levels (analogous to the SdH effect). Additionally, a strong enhancement of the signal is observed in magnetic fields close to cyclotron resonance magnetic field \( B_c \approx 4.5 \) T.

![Figure 1. Transfert characteristics at different values of the drain voltage (0.1 V and 0.2 V) obtained at 4.4 K. The inset shows a schematic of the transistor geometry.](image)

Fig. 2 shows experimental results of detection signal as a function of the gate voltage at different values of \( B/B_c \) (0.44, 0.88, 1, 1.55). One can notice that the amplitude of oscillations grows as the magnetic field increases. This can be understood in terms of an increase of a nonlinearity related to SdH oscillations as described in Ref [7] and [8]. In the post-cyclotron resonance region \( (B > B_c) \), the oscillations of the signal are damped. This can be qualitatively explained by considering the plasma wave dispersion law in the magnetic field: 
\[
k = \frac{(\omega^2 - \omega_c^2)^{1/2}}{s},
\]
where \( s = \left( eU_0/m^* \right)^{1/2} \) is the plasma wave velocity at \( B = 0 \), where \( U_0 = V_g - V_{th} \) is the gate voltage swing, \( V_{th} \) is the threshold voltage, \( m^* \) is the effective mass and \( e \) the electron charge. For \( \omega_c > \omega \) the plasma wave vector becomes imaginary, plasma waves cannot propagate, and one can expect a reduction of the signal, as evidenced in Fig. 2.

Not only the oscillation amplitude of the signal, but also its background grows with \( B \). One can clearly see in Fig.2 that this background has it’s maximum close to the CR condition. This enhancement can also be explained within the model in Ref [7].

Fig. 3 shows the measured magnetic field dependence for fixed gate voltage (fixed electron density). Fig. 3a corresponds to a relatively high value of electron density in the channel, for which one can see strong oscillatory behavior of the photovoltaic signal. Fig. 3b corresponds
Figure 2. Experimental results of photoresponse at 2.5 THz as a function of the gate voltage for different values of the magnetic field at T = 4.2 K. Values of B/Bc are indicated.

Figure 3. Figure a - Experimental photoresponse as a function of the magnetic field for higher values of the electron density (Vg = 0 V ) at 4.2 K. b - Same as in a for 3a lower carrier density (Vg = -0.125 V)

Figure 4. Electron density extracted from experimental curves at different values of gate voltage
to a lower value of electron density in the channel with a very weak oscillations signature. For \( B > B_c \) the oscillation amplitude decreases (see Fig. 3a). This behavior is quite consistency with the results shown in Fig. 2, and is also described by the theory [7]. The strong dependence of the photoresponse on the gate voltage (see Fig 3a and Fig 3b) indicates that the rectification takes place in the gated part of the transistor channel.

The Fourier transform of the oscillations (of the photovoltage resulting from THz radiation) allowed us to extract electron density that participate in detection process. Indeed the carrier density is related to the period of SdH oscillations \( \Delta(1/B) \) by, \( n = \frac{e}{\pi \hbar} \Delta(1/B) \). Fig 4 shows values of electron density extracted from experimental curves at different values of gate voltage. One can clearly see that this density shift with the gate voltage. This result confirms that the detection signal is induced in the gated part of the channel.

3. Conclusion

In conclusion, we have performed magnetic field studies of plasma wave related detection in InGaAs/InAlAs field effect transistor. We observe oscillatory behavior of the photovoltaic signal, similar to Shubnikov-de Haas oscillations, as well as a strong enhancement of the signal at the cyclotron resonance conditions. The experimental data are quantitatively reproduced by a theoretical model [7]. Our results clearly show that the detection mechanism is related to the THz rectification by nonlinearities of the plasma in the transistor channel.

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