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Effect of magnetic field on the terahertz radiation detection in high electron mobility transistors*

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In this paper, we make a theoretical investigation of the plasma-wave instability mechanism in a two-dimensional electron fluid in a high electron mobility transistor (HEMT) driven by the terahertz radiation in the presence of a perpendicular magnetic field. It is found that the resonant peaks of the gate-to-source/drain admittances and detection responsivity depend on the strength of the external magnetic field. Such phenomena can be used to produce a desired effect by adjusting the intensity of the magnetic field.

Keywords: terahertz radiation, magnetic field, HEMT

PACC: 5265, 5240D

1. Introduction

There are a number of approaches to the generation of terahertz (THz) radiation, and one of the promising approaches is associated with optical techniques.[1−11] Recently THz generation in a high electron mobility transistor (HEMT) has been studied.[12−26] Plasma waves in HEMT follow a linear dispersion law, which is similar to sound waves, and the transistor channel acts as a resonance cavity for plasma waves that can reach THz frequencies. When a direct current flows through a HEMT, the steady state can become unstable against the generation of high-frequency plasma waves (Dyahonov–Shur instability), leading to the emission of electromagnetic radiations at plasma wave frequencies. Such a phenomenon can be used for generation, detection, mixing, and frequency multiplication of THz radiation.

The purpose of this paper is to study the influence of a perpendicular magnetic field applied on the current instability mechanism in a HEMT channel. We develop an analytical device model for a HEMT affected by the incoming terahertz radiation. Using this model, we calculate the frequency-dependent admittance and responsivity of this device as a function of the structural parameters, gate voltage and external magnetic field. The obtained results demonstrate that an applied magnetic field can substantially modify the current instability in the HEMT channel.

The rest of the paper is organized as follows. In Section 2, we present the equations of the model. In Section 3, using these equations, we deal with the frequency-dependent HEMT gate-to-source/drain admittance and the detection responsivity, and we present the corresponding numerical results. Finally, in Section 4, we present a brief discussion about the results, and draw the main conclusions.

2. Basic equations of the physical model

A schematic diagram of the HEMT structure under consideration is shown in Fig.1. An external magnetic field B_0 is applied in the $+z$-direction. This field is uniform in space and constant in time. It is assumed that the bias gate voltage and the structural parameters are chosen to provide an effective electron injection from the channel into the gate layer via either tunnelling through the top of the barrier or thermionic

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emission over such a barrier.

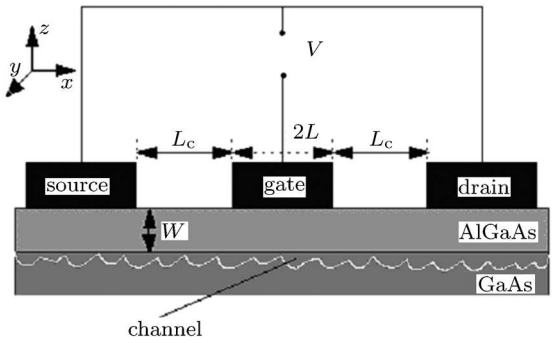


Fig.1. Schematic diagram of the HEMT structure.

We use a hydrodynamic electron model, which includes continuity equation and Euler equation. The linearized versions of the continuity equation with the electron sheet concentration $\Sigma(x,t) = \Sigma_0 + \delta\Sigma_\omega(x)\exp(-\mathrm{i}\omega t)$, the electron velocity along the channel $u(x,t) = u_0 + \delta u_\omega \exp(-\mathrm{i}\omega t)$ and electric potential of the 2D channel $\varphi(x,t) = \varphi_0 + \delta\varphi_\omega \exp(-\mathrm{i}\omega t)$, where subscript 0 denotes the steady-state values and subscript ω represents the signal frequency, can be presented in the following form:[16−19]

$$\frac{\partial \Sigma}{\partial t} + \Sigma_0 \nabla \boldsymbol{u} = \frac{j}{e}, \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u} + \nu\boldsymbol{u} = \frac{e}{m}(\nabla\varphi + \boldsymbol{u}\times\boldsymbol{B}_0), \tag{2}$$

where e is the electron charge, m is the electron mass, ν is the electron collision frequency, and $j = j(\xi)$ is the density of the electron leakage current from the channel into the gate, with $\xi = -4\pi e\Sigma/\varepsilon$ and the dielectric constant ε.

For small amplitudes of the incoming signals, the ac component of the electron sheet concentration in the channel can be expressed in terms of φ_ω as follows:[18]

$$\Sigma_\omega = -\frac{\varepsilon}{4\pi e W} c_\omega \varphi_\omega, \tag{3}$$

where $c_\omega = [1 + \mathrm{i}\nu_t/\omega - \mathrm{i}\nu_t f(\omega\tau_\mathrm{d})/\omega]^{-1}$, and $f(\omega\tau_\mathrm{d}) = [\exp(\mathrm{i}\omega\tau_\mathrm{d}) - 1]/(\mathrm{i}\omega\tau_\mathrm{d})$.

Using Eqs.(1), (2), and (3), we can obtain the following equation for φ_ω in the region beneath the gate ($|x| \le L$):

$$\frac{\mathrm{d}^2\delta\varphi_\omega}{\mathrm{d}x^2} + \frac{s^{-2}(\omega+\mathrm{i}\nu)(-\nu^2+\omega^2-e^2B_0^2/m^2+2\mathrm{i}\nu\omega)c_\omega\delta\varphi_\omega}{\omega + i\nu} = 0, \tag{4}$$

where $s = (4\pi e^2\Sigma_0 W/\varepsilon m)^{1/2} = (eV_0/m)^{1/2}$ is the plasma wave velocity.

The boundary condition can be taken in the following form:[18]

$$\delta\varphi_\omega\Big|_{x=\pm L} = \delta V_\omega \mp L_\omega \frac{\mathrm{d}\delta\varphi_\omega}{\mathrm{d}x}\Big|_{x=\pm L}, \tag{5}$$

where $L_\omega = L_\mathrm{c}(\Sigma_0/\Sigma_{0\mathrm{c}})(\nu_\mathrm{c} - \mathrm{i}\omega)/(\nu - \mathrm{i}\omega)$, $\Sigma_{0\mathrm{c}}$ and ν_c are the electron sheet concentration and the electron collision frequency in the contact regions.

Using Eq.(4) with the boundary condition (5), we obtain

$$\delta\varphi_\omega = \delta V_\omega \frac{\cos(\pi\alpha_\omega x/2L)}{\cos(\pi\alpha_\omega/2) - (\pi\alpha_\omega L_\omega/2L)\sin(\pi\alpha_\omega/2)}, \tag{6}$$

where

$$\alpha_\omega^2 = \frac{c_\omega(\omega+\mathrm{i}\nu_t)(-\nu^2+\omega^2-e^2B_0^2/m^2+2\mathrm{i}\nu\omega)}{\Omega^2(\omega+\mathrm{i}\nu)}. \tag{7}$$

Here, $\Omega = \pi(eV_0/m)^{1/2}/(2L)$ is the characteristic fundamental resonant plasma frequency.

3. Calculation of the admittance and the detection responsivity

The net ac current (per unit length) is given by

$$\delta J_\omega = \left(\sigma - \mathrm{i}\frac{\omega\varepsilon}{4\pi}\right)\frac{c_\omega}{W}\int\limits_{-L}^{L}\mathrm{d}x\delta\varphi_\omega. \tag{8}$$

Figure 2 shows the frequency dependences of the real and imaginary parts of the admittance $\delta J_\omega/\delta V_\omega$ with different intensities of external magnetic field. The parameters used in Fig.2 are chosen as follows: $L = 0.25\,\mu$m, $W = 0.05\,\mu$m, $\nu_{\mathrm{QW}} = 1\times10^{13}\,\mathrm{s}^{-1}$, $\upsilon_{\mathrm{d}} = 1\times10^{7}\,$cm/s, $L_{\mathrm{c}} = 0\,\mu$m, $L_\omega = L_{\mathrm{c}}$ (i.e. $\Sigma_{0\mathrm{c}} = \Sigma_0$ and $\nu_{\mathrm{c}} = \nu$), $\upsilon_{\mathrm{d}} = 1\times10^{7}\,$cm/s, $V_0 = 0.75\,$V, and $\nu = 1\times10^{12}\,\mathrm{s}^{-1}$. One can see that with the intensity of the external magnetic field increasing, the peaks of the admittance have a blue shift, and their heights decrease as well.

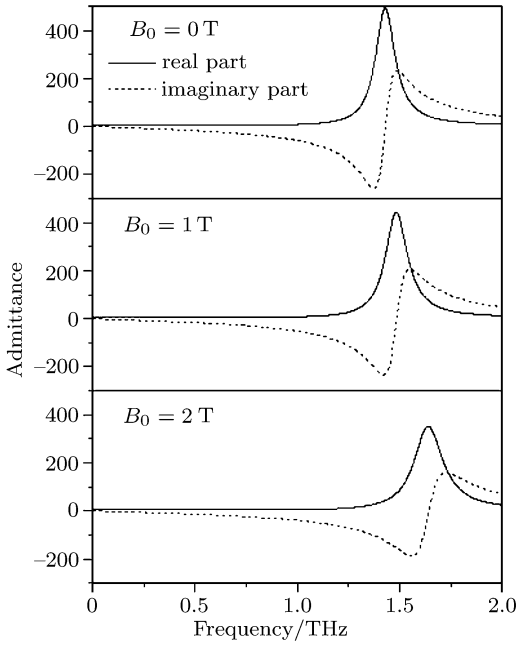


Fig.2. Real and imaginary parts of the HEMT gate-to-source/drain admittance versus signal frequency for different strengths of the magnetic fields (collision frequency is set as $\nu = 1\times10^{12}\,\mathrm{s}^{-1}$).

After averaging over the signal period we obtain the following expression for the current component induced by an incoming signal:[18]

$$\delta J_0 = \frac{\beta|c_\omega|^2}{2W^2}\int\limits_{-L}^{L}\mathrm{d}x|A_\omega(x)|^2, \tag{9}$$

where $|A_\omega(x)|$ is the absolute value of α_ω.

Figure 3 illustrates the frequency dependence of the responsivity associated with the nonlinear response $\delta J_0/\delta V_\omega^2$, of which the value is proportional to the rectified component of the current. The parameters used in Fig.3 are chosen $\varepsilon_0 = 0.1\,$eV corresponding to $V_t = 2.92\,$V. Other parameters are the same as those used in Fig.2. This figure clearly reveals that with the magnetic field increasing from $B_0 = 0$ to 2 T, the peaks of the detection responsivity have a blue shift by a factor of 15%, and their heights decrease by a factor of 65%.

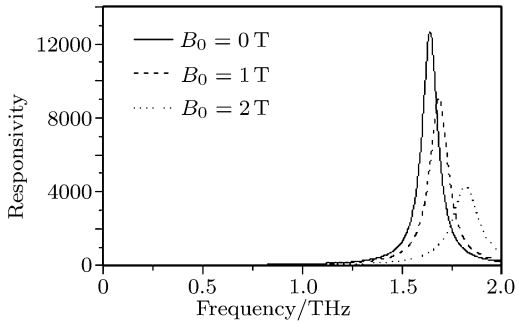


Fig.3. Detection responsivity versus signal frequency for different intensities of magnetic fields (collision frequency is set as $\nu = 1\times10^{12}\,\mathrm{s}^{-1}$, electron drift velocity across the gate layer $\upsilon_d = 1\times10^{7}\,$cm/s, voltage $V_0 = 1.0\,$V).

4. Conclusions

In summary, we calculate the gate-to-source/drain admittance and the detection responsivity of the HEMT as a function of the signal frequency in the presence of a perpendicular magnetic field. It is shown that with the intensity of the magnetic field increasing, the peaks of the admittance and the responsivity have a blue shift, which is attributed to the change in the resonant plasma frequency due to the variation of the electron concentration in the channel. Besides there are two mechanisms for suppressing the wave growth: one is the external friction associated with electron scattering by impurities and phonons and the other is the internal friction caused by the viscosity of the electron fluid. The increasing of the magnetic field can enhance these two mechanisms, consequentially the heights of the admittance peaks decrease. In order to produce the desired effect, we could adjust the strength of the magnetic field.

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