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CURRENT INSTABILITY AND PLASMA WAVE GENERATION IN UNGATED TWO DIMENSIONAL ELECTRON LAYERS

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We show that the steady state with a dc current in ungated 2D electron gas might exhibit an instability related to asymmetrical boundary conditions, which is similar to the "shallow water" instability in the gated 2D electron gas. The mathematics of the problem corresponds to "deep water" solutions for plasma waves. In the ideal case, the boundary conditions should correspond to zero ac voltage at the source and zero ac current at the drain, similar to the conditions for instability in a field effect transistor. Such boundary conditions can be realized using several different device configurations. For similar device dimensions, the plasma wave generated in an ungated 2D device will have much higher frequency compared to that in gated devices.

Keywords: plasma waves; two-dimensional electrons.

1. Introduction

Contributions Plasma waves are the oscillations of electron density in space and time, and their properties depend on the electron density and on the dimensions and geometry of the electronic system. Plasma waves in a two dimensional electron gas (2DEG) propagate with a much larger velocity than the electron drift velocity (pushing the frequency into the terahertz range for submicron devices), and a short channel field effect transistor, where electrons experience few collisions, serves as a resonant cavity for the plasma waves. The instability [1] and excitation [2] of plasma waves in short channel field effect transistors lead to the emission [3,4] and non-resonant [5,6] and resonant tunable detection[7,8] of terahertz radiation, respectively. In a gated 2DEG, these waves are similar to "shallow water" waves, whereas in an ungated 2DEG, their dispersion relation is the same as for "deep water" waves. Recently, new approaches based on resonant photomixing [9],[10],[11] using resonant tunneling structures[12], and using transit-time effects[13] have been proposed to increase the efficiency of the terahertz radiation by field effect transistors operating in a plasma wave electronics regime.

An analysis of the ungated 2DEG shows that the resonant frequencies of plasma oscillations are much higher.[14] Therefore, the condition of the undamped plasma oscillations ($\omega_p\tau \gg 1$, where ω_p is the plasma frequency and τ is the relevant collision time) is easier to achieve. This is confirmed by the calculations of the device impedance in [14],[15]. In this paper, we show that the current instability and resulting plasma wave generation similar to that for the field effect transistor should also occur in an ungated 2DEG provided certain boundary conditions are imposed.

2. Basic Equations

As in our previous work [1], we will use the hydrodynamic description of the electron motion. The hydrodynamic approach is strictly appropriate when the mean free path for electron-electron collisions is smaller than both the device length, and the mean free path for collisions with impurities and phonons. However, it gives qualitatively correct results even if those conditions are not fulfilled (as it is the case at low temperature when the electron-electron collisions are suppressed because of the Pauli principle). We will also neglect scattering by impurities and phonons, assuming that the corresponding mean free path is larger than the device length.

The continuity equation is given by

$$\frac{\partial n}{\partial t} + \frac{\partial (nv)}{\partial x} = 0, \tag{1}$$

where n is the 2DEG density, v is the average electron velocity, and the x axis is perpendicular to the source and drain contacts in the 2DEG plane.

Neglecting scattering, we write down the Euler equation as follows:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = \frac{e}{m}\frac{\partial \varphi}{\partial x}, \tag{2}$$

where the electronic charge is $-e$, m is the electron effective mass, and φ is the potential, so that the electric field is $-\partial\varphi/\partial x$.

The steady-state solution (in the absence of electron scattering) corresponds to $\varphi = 0$, a uniform electron density n_0, and drift velocity v_0 related to the fixed current density $j = -en_0v_0$. We now explore the stability of this steady state by looking at the time evolution of a small fluctuation superimposed on the steady-state solution.

To do this, we put $n = n_0 + n_1$, $v = v_0 + v_1$, and we linearize Eqs. (1) and (2) with respect to n_1 and v_1. We search the solutions of the linearized equations in the form: n_1, v_1, $\varphi \sim exp(-i\omega t + ikx)$. Then we find

$$(\omega - kv_0)n_1 = kn_0v_1, \tag{3}$$

$$(\omega - kv_0)v_1 = -\frac{e}{m}k\varphi.$$

We now need an equation relating the potential φ to the charge density, $-en_1$, and it is this relation that makes the difference between the case of a gated electron gas, which we considered previously, [1] and the ungated case with which we are concerned now. For an infinite ungated 2D electron system, we have

$$\varphi = -\frac{2\pi e n_1}{|k|\varepsilon}, \tag{4}$$

where ε is the background dielectric constant. In a finite device, Eq. (4) is not accurate and the potential generally depends on the type of contacts. However, numerical calculations [15],[16] show that the finite-size effect on the plasma waves is in a relatively small frequency shift, which depends on the contact geometry. Thus it appears that we can use Eq. (4) even for a finite device and still correctly reproduce all qualitative results.

From Eqs. (3) and (4), we obtain the dispersion relation for the plasma waves

$$\omega = kv_0 + \sqrt{2a|k|},$$

$$a = \frac{\pi n_0 e^2}{\varepsilon m}. \tag{5}$$

For $v_0 = 0$, Eq. (5) yields the usual dispersion relation for plasma waves in an ungated 2DEG:

$$\omega = \sqrt{\frac{2\pi n_0 e^2}{\varepsilon m}|k|}, \tag{6}$$

which is analogous to the dispersion relation for deep water waves in hydrodynamics. The term kv_0 in Eq. (5) represents the Doppler shift of the frequency due to the flow of the electron fluid with the drift velocity v_0. Thus the velocities of plasma waves propagating upstream and down stream are different. In what follows we will consider the Doppler shift small: $|kv_0| << \omega$. Under this condition the two values of the wave vector corresponding to a given frequency ω can be written as follows:

$$k_1 = \frac{\omega^2}{2a}\left(1 - \frac{v_0}{s}\right), \quad k_2 = -\frac{\omega^2}{2a}\left(1 + \frac{v_0}{s}\right), \quad s = \frac{a}{\omega} = \frac{\pi n_0 e^2}{\varepsilon m \omega}. \tag{7}$$

Here $s = d\omega/dk$ is the group velocity of plasma waves with a frequency ω, which can be calculated by using Eq. (6). The ratio v_0/s is considered as small.

We can now write down the following solution of Eq. (3):

$$\frac{n_1}{n_0} = \frac{A}{\omega - k_1 v_0}\exp(ik_1 x) + \frac{B}{\omega - k_2 v_0}\exp(ik_2 x) \tag{8}$$

$$v_1 = \frac{A}{k_1}\exp(ik_1 x) + \frac{B}{k_2}\exp(ik_2 x),$$

where A and B are constants to be determined from the boundary conditions. As mentioned above, Eqs. (8) are exact for an infinite 2D plane but are only approximate for a real finite device.

3. Boundary conditions

We assume the same boundary conditions that we have studied in Ref. 1, which correspond to zero *ac* potential at the source and zero *ac* current at the drain:

$$n_1(0)=0, \tag{9}$$

$$n_0 v_1(L) + v_0 n_1(L) = 0, \tag{10}$$

where L is the distance between the source and drain contacts. The combination $n_0 v_1 + v_0 n_1$ is obviously proportional to the *ac* part of the total current $j=-env$, since $n=n_0+n_1$, $v=v_0+v_1$.

These boundary conditions can be realized by grounding the source either directly or via very large capacitance presenting a short at plasma wave frequencies and by attaching the drain to the power supply via an inductance that presents an open circuit at plasma wave frequencies The required boundary condition at the drain can be also obtained by depleting the 2D electrons close to the drain using a heterodimensional Schottky contact at the drain [17] or using a gated section at the drain (see Fig. 1.) A conventional field effect transistor can also support ungated plasma waves in the ungated regions.

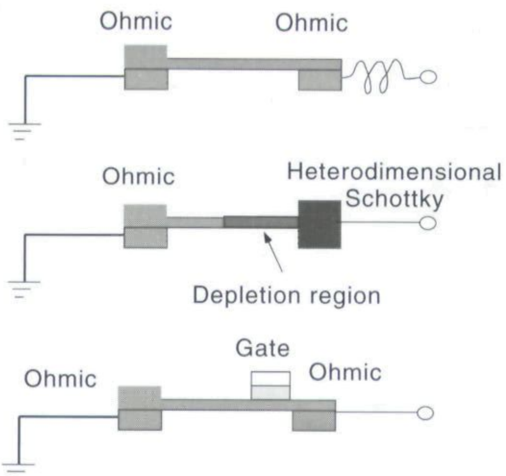

Figure 1. Device configurations for excitation of ungated plasma waves

4. Plasma wave instability

Using boundary conditions given by Eqs. (9) and (10) , we obtain from Eqs. (8):

$$\frac{A}{\omega-k_1 v_0}+\frac{B}{\omega-k_2 v_0}=0 \quad , \tag{11}$$

$$A\left(\frac{1}{\omega-k_1 v_0}+\frac{1}{k_1 v_0}\right)\exp(ik_1 L)+B\left(\frac{1}{\omega-k_2 v_0}+\frac{1}{k_2 v_0}\right)\exp(ik_1 L)=0 \quad . \tag{12}$$

From these equations, we obtain

$$\frac{k_1}{k_2}=\exp[i(k_1-k_2)L] \quad , \tag{13}$$

where k_1 and k_2 are given by Eq. (7). This equation allows us to find the complex frequency $\omega=\omega'+i\omega''$, and the sign of the imaginary part will determine the stability of the steady state. Note that Eq. (13), as well as Eqs. (11) and (12) are exactly the same as for the case of a gated 2DEG studied previously. The difference lies only in the dependence of the wave vectors k_1 and k_2 on ω, which is determined by the relation between the potential and the charge density in the 2D plane.

Using Eqs. (7) and (13) and the condition of a small Doppler shift, $v_0/s << 1$, we obtain

$$\omega'=\pi\sqrt{\frac{n_0 e^2}{\varepsilon m L}(2l-1)} \quad , l=1, 2, 3 \ldots \tag{14}$$

$$\omega''=\frac{v_0}{L} \quad . \tag{15}$$

Equation (14) gives the frequencies of small signal plasma modes, which are given by Eq. (6) for the values of k determined by the boundary conditions and equal to $(\pi/2L)(2l-1)$. For our boundary conditions the fundamental mode (l=1) corresponds to $\lambda/4 = L$, where $\lambda= 2\pi/k$ is the plasma wavelength.

All of these modes are unstable ($\omega''>0$), and the increment of the amplitude growth is given by Eq. (15). Interestingly, in the limit of small drift velocities $v_0/s << 1$, this increment is exactly the same as the one found previously [1] for the case of a gated 2DEG. In the presence of collisions, Eq. (15) becomes

$$\omega''=\frac{v_o}{L}-\frac{1}{2\tau} \tag{15a}$$

Here, τ is the momentum relaxation time, Hence, in the presence of collisions there is an instability threshold $v_o/L = 1/(2\tau)$.

The ratio of plasma wave frequency for the ungated 2DEG to that of the gated 2DEG, which is given by

$$\left(\frac{L\varepsilon}{\pi d}\right)^{1/2} >> 1 \quad , \tag{16}$$

where ε is the dielectric constant of the gate insulating layer for the gated 2DEG and the gate length L is always larger that the gate-to-channel separation, d. Figure 2 compares the frequency dependence on the gate voltage for the gated devices with the plasma frequency for ungated devices.

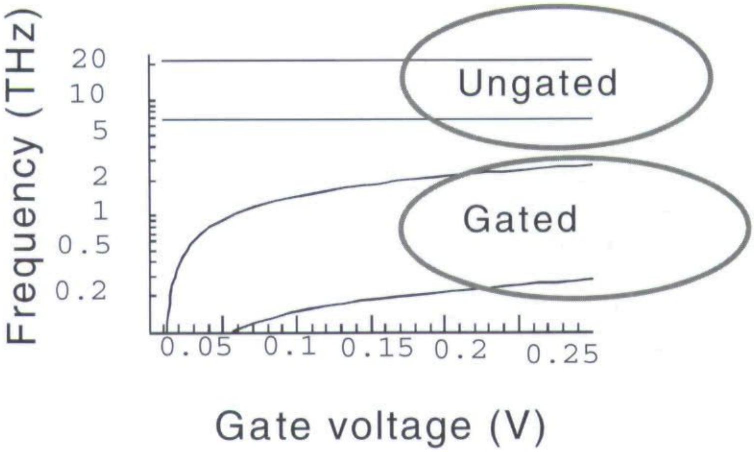

Fig. 2. Plasma frequency versus gate voltage for the gated and ungated devices. Parameters used in the calculations: electron effective mass 0.042 m_o, electron velocity $2x10^5$ m/s; electron concentration 10^{12} cm^{-2}. Top curves for 0.1 micron long channels, bottom curves are for 1 micron channels.

For a field effect transistor, a situation corresponding to such instability occurs in the gate-to-drain region. In the recent paper by Knap et al, [3] the emission caused by the plasma waves had a maximum corresponding to the plasma frequencies in the gated region. However, the emission also had place at much higher frequencies that might correspond to the plasma waves excited in the drain-to gate ungated section of the device. Figure 3 shows the calculated instability increment for the gated and ungated devices.

A higher plasma frequency, ω, for ungated devices results in a much higher quality factor, $\omega\tau$, for detecting electromagnetic radiation as illustrated by Figure 4. This makes ungated devices to be very promising for the resonant detection of the plasma radiation.

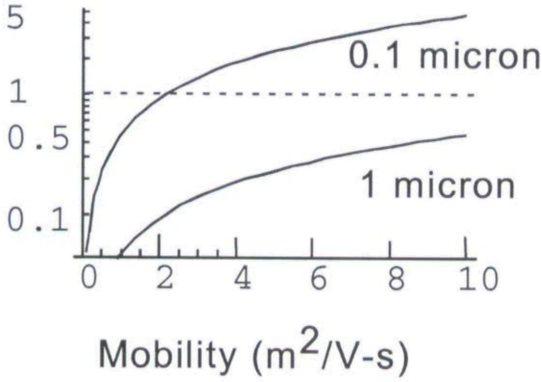

Figure 3. Calculated ratio $v_o/(2L\tau)$ versus electron mobility. The values exceeding unity correspond to the instability regime.

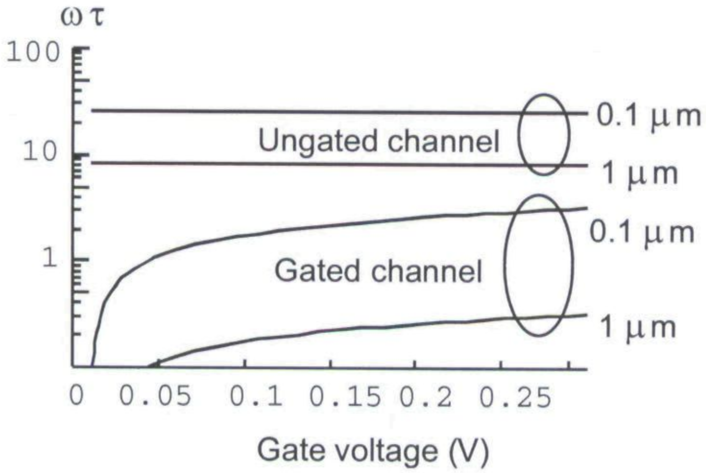

Figure 4. Calculated plasma resonance quality factor for the gated and ungated devices versus device length for electron mobility 0.8 m^2/V-s. Top curves for 0.1 micron long channels, bottom curves are for 1 micron channels.

5. Conclusions

The steady state with a *dc* current in ungated 2D electron gas with asymmetrical boundary conditions might exhibit instability against spontaneous generation of plasma oscillations at terahertz frequencies. This instability is similar to the current instability that we predicted previously for the gated 2D electron gas. The required asymmetrical boundary conditions can be realized in a heterodimensional diode or in an ungated drain-to-gate section of a field effect transistor. For similar device dimensions, the generated plasma oscillations should have much higher frequencies compared to those in gated devices, which is very promising for the resonant detection of the terahertz radiation by ungated plasma waves.

6. Acknowledgments

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