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Current instability and plasma waves generation in ungated two-dimensional electron layers

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We predict instability of the steady state with a direct current for an ungated two-dimensional (2D) electron layer. This instability caused by the current flow is similar to the "shallow water" instability in the gated 2D electron gas [see M. Dyakonov and M. S. Shur, Phys. Rev. Lett. **71**, 2465 (1993)]. The mathematics of the problem correspond to "deep water" solutions for plasma waves. Just like in the "shallow water" case, this instability occurs when the boundary conditions correspond to zero ac voltage at the source and zero ac current at the drain. Such boundary conditions can be realized using either an external circuit or a depleted region at the drain. For the same device dimensions and electron mobility, the plasma wave generated in an ungated 2D device has a much higher frequency and, as a consequence, a much higher resonance quality factor, which makes the ungated devices promising for applications in resonant terahertz detectors. [DOI: 10.1063/1.2042547]

The instability[1] and excitation[2] of plasma waves in short-channel field effect transistors lead to the emission[3,4] and nonresonant[5,6] and resonant tunable detection[7,8] of terahertz radiation, respectively. In a gated two-dimensional electron gas (2DEG), these waves are similar to "shallow water" waves. In an ungated 2DEL, their dispersion relation is the same as for "deep water" waves. Recently, new approaches based on resonant photomixing[9–11] using resonant tunneling structures[12] and 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.

The resonant frequencies of plasma oscillations are much higher for ungated structures.[14] Therefore, the condition of the undamped plasma oscillations ($\omega\tau \gg 1$, where ω is the plasma frequency and τ is the relevant collision time) is easier to achieve.[13–15] In this letter, 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 two-dimensional 2DEG for asymmetrical boundary conditions

We will use the hydrodynamic approach, which is valid 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. We will first neglect scattering by impurities and phonons, assuming that the corresponding mean-free path is larger than the device length. In this case, the Euler equation is given by

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = \frac{e}{m}\frac{\partial \varphi}{\partial x}. \tag{1}$$

It has to be solved together with the continuity equation

$$\frac{\partial n}{\partial t} + \frac{\partial (nv)}{\partial x} = 0, \tag{2}$$

where n is the 2DEG density, v is the average electron velocity, the x axis is perpendicular to the source and drain contacts in the 2DEG plane, 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 corresponds to $\varphi=0$, a uniform electron density n_0, and drift velocity $v_0=-j/en_0$. To explore the stability of this steady state, we put $n=n_0+n_1$, $v=v_0+v_1$ [where n_1, v_1, $\varphi\sim\exp(-i\omega t+ikx)$], and linearize Eqs. (1) and (2) with respect to n_1 and v_1. Then, we find

$$(\omega - kv_0)n_1 = kn_0v_1,$$

$$(\omega - kv_0)v_1 = -\frac{e}{m}k\varphi. \tag{3}$$

For an infinite ungated two-dimensional (2D) electron system,

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

where ϵ is the background dielectric constant. (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.) From Eqs. (3) and (4),

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$$\omega = kv_0 + \sqrt{2a|k|}, \quad a = \frac{\pi n_0 e^2}{\epsilon m}, \tag{5}$$

which is analogous to the dispersion relation for deep water waves in hydrodynamics. When the Doppler shift is small ($|kv_0| \ll \omega$):

$$k_1 = \frac{\omega^2}{2a}\left(1 - \frac{v_0}{s}\right), \quad k_2 = -\frac{\omega^2}{2a}\left(1 + \frac{v_0}{s}\right), \quad s = \frac{a}{\omega} = \frac{\pi n_0 e^2}{\epsilon m \omega}, \tag{6}$$

$$\frac{n_1}{n_0} = \frac{A}{\omega - k_1 v_0}\exp(ik_1 x) + \frac{B}{\omega - k_2 v_0}\exp(ik_2 x), \tag{7}$$

$$v_1 = \frac{A}{k_1}\exp(ik_1 x) + \frac{B}{k_2}\exp(ik_2 x), \tag{8}$$

where $s = d\omega/dk$ is the group velocity of plasma waves, and A and B are constants to be determined from the boundary conditions. We assume the same boundary conditions, as in Ref. 1, which correspond to zero ac potential at the source and zero ac current at the drain:

$$n_1(0) = 0, \quad n_0 v_1(L) + v_0 n_1(L) = 0, \tag{9}$$

where L is the distance between the source and drain contacts. 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[16] or using a gated section at the drain. (In the latter case, the boundary conditions depend on and controlled by the gate-to-drain bias.) A conventional field effect transistor can also support ungated plasma waves in the ungated regions.

From the above equations, we obtain

$$\frac{k_1}{k_2} = \exp[i(k_1 - k_2)L], \tag{10}$$

where k_1 and k_2 are given by Eq. (6). Equation (10) 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. This equation is exactly the same as for the case of a gated 2DEG studied previously.[1] 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. (6) and (10) and the condition of a small Doppler shift, $v_0/s \ll 1$, we obtain

$$\omega' = \pi\sqrt{\frac{n_0 e^2}{\epsilon m L}}(2l - 1), \quad l = 1,2,3\ldots \tag{11}$$

$$\omega'' = \frac{v_0}{L}. \tag{12}$$

For our boundary conditions, the fundamental mode ($\ell = 1$) corresponds to $\lambda/4 = L$, where $\lambda = 2\pi/k$ is the plasma wavelength.

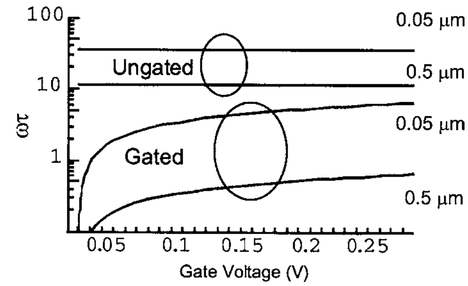

FIG. 1. Calculated plasma resonance quality factor for the gated and ungated devices vs device length for electron mobility 0.8 $m^2/V\,s$.

All of these modes are unstable ($\omega'' > 0$), and the increment of the amplitude growth is exactly the same as the one found previously[1] for the case of a gated 2DEG. In the presence of collisions, Eq. (12) becomes

$$\omega'' = \frac{v_o}{L} - \frac{1}{2\tau}. \tag{13}$$

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 plasma wave frequency for the ungated 2DEG is $(\epsilon L/\pi d)^{1/2}$ times larger than that for the gated 2DEG, where ϵ is the dielectric constant of the gate insulating layer for the gated 2DEG. For a 0.1 micron channel, the ungated plasma frequency for typical parameters of the 2DEG in InGaAs is close to 20 THz compared to the value between 0.2 to 2 THz (depending on the gate voltage swing) for the gated channel. (For this estimate, we assumed the electron effective mass 0.042 m_o, which is the effective mass of InGaAs lattice matched to InP, the electron velocity 2×10^5 m/s; and the electron concentration 10^{12}cm^{-2}.).

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.

A much higher frequency for ungated devices results in a much higher-quality factor, $\omega\tau$, for detecting electromagnetic radiation as illustrated by Fig. 1. This makes ungated devices very promising for the resonant detection of the plasma radiation.

The required asymmetrical boundary conditions can be realized using an external circuit, for example, by attaching an inductance to the drain side of the device and a grounding the source contact using a large capacitance (much larger then the effective capacitance of the 2D layer) or a small resistance. Also, a depletion layer at the drain (using a heterodimensional diode or a gated structure closer to the drain) allows achievement of a small ac current at the drain and also allows for tunable changes in the resonant plasma frequency.

In conclusion, the steady state with a dc current in high-mobility ungated 2DEL with asymmetrical boundary conditions might exhibit instability similar to that previously predicted for the gated 2DEG. For similar device dimensions, the ungated plasma oscillations have much higher frequencies compared to those in gated devices, which could be very useful for the resonant detection of the terahertz radiation by plasma waves.

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