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Spectrum of plasma oscillations in a slot diode with a two-dimensional electron channel

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1. Introduction

Plasma oscillations in heterostructures akin to a high-electron mobility transistor (HEMT) and some others with a two-dimensional (2D) electron channel under the gate contact can be used for the detection, frequency multiplication, and generation of terahertz radiation [1,2]). Since the electron mobility in a 2D channel can be rather high and, therefore, the collision frequency of electrons with impurities can be very small, the quality factor of 2D plasma oscillations can markedly exceed that in bulk systems. Different devices utilizing the excitation of plasma oscillations in 2D systems have been proposed and extensively studied both theoretically and experimentally (see the review paper [2] and references therein as well as recent publications [3-7]). In this communication, we report the results of strict calculations of the spectrum of plasma oscillations in a slot diode structure with a 2D electron channel and strip-like short circuited contacts. We show that the plasma frequencies deviate from the "quantized" square-root spectrum of 2D plasmons in uniform electron systems.

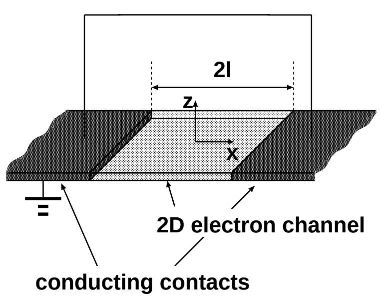

Figure 1: Schematic view of the structure.

2. Equation of the model

As in ref. [8], we use a hydrodynamic electron transport model, which includes continuity equation and the Euler equation. The linearized versions of the continuity equation and the Euler equation for the ac components of the electron sheet concentration $\Sigma(x,t) = \Sigma_\omega(x)\exp(-i\omega t)$ and the electron velocity along the channel $u(x,t) = u_\omega(x)\exp(-i\omega t)$, where ω is the signal frequency, can be presented in the following form (see ref. [1] and subsequent ones, in particular, ref. [8]):

$$i\omega\Sigma_\omega = \Sigma_0\frac{\partial u_\omega}{\partial x}, \qquad (\nu - i\omega)u_\omega = \frac{e}{m}\frac{\partial\varphi_\omega}{\partial x}\bigg|_{z=0}. \tag{1}$$

The ac self-consistent electric potential $\varphi(x,z,t) = \varphi_\omega(x,z)\exp(-i\omega t)$ obeys the two-dimensional Poisson equation

$$\frac{\partial^2\varphi_\omega}{\partial x^2} + \frac{\partial^2\varphi_\omega}{\partial z^2} = \left(\frac{4\pi e}{æ}\right)\Sigma_\omega\,\delta(z). \tag{2}$$

Here $e = |e|$, m, and ν are the electron charge, effective mass, and collision frequency, respectively, Σ_0 is the steady-state value of the electron sheet concentration in the channel, which is determined by the doping (and/or by polarization and piezoelectric charges in nitride semiconductors), æ is the dielectric constant (which is assumed to be equal in the regions below and above the channel), and $\delta(z)$ is the Dirac delta function. The directions z and x are perpendicular to and in the channel plane, respectively (see Fig. 1).

Equations (1) and (2) can be reduced to the following:

$$\frac{\partial^2\varphi_\omega}{\partial x^2} + \frac{\partial^2\varphi_\omega}{\partial z^2} = \left[\frac{4\pi e^2\Sigma_0}{mæ\omega(\omega + i\nu)}\right]\frac{\partial^2\varphi_\omega}{\partial x^2}\,\delta(z). \tag{3}$$

For the highly conducting contacts, the boundary conditions can be presented as $\varphi_\omega|_{|x|\geq l,\, z=0} = 0$. We shall assume that the contacts are Ohmic. In this case, electrons can freely pass through their edges ($x = \pm l$). As a result, the hydrodynamic equations do not imply additional boundary conditions for the potential at the points $x = \pm l$. Equation (3) with the boundary conditions lead to the following equation for the ac potential in the 2D channel:

$$\varphi_\omega(x) = -\frac{2}{q_\omega}\int_{-l}^{+l} d\,x' G(x/l, x'/l)\frac{\partial^2\varphi_\omega(x')}{\partial\,x^2}. \tag{4}$$

Here $q_\omega = \dfrac{mæ\omega(\omega + i\nu)}{2\pi e^2\Sigma_0}$ and (see, for example, ref. [9])

$$G(\xi,\xi') = \frac{1}{2\pi}Re\,\ln\left\{\frac{\sin[(\cos^{-1}\xi + \cos^{-1}\xi')/2]}{\sin[(\cos^{-1}\xi - \cos^{-1}\xi')/2]}\right\} \tag{5}$$

is the function which is obtained from the Green function of 2D Poisson's equation with the pertinent boundary conditions.

3. Results

The ac potential of the 2D channel is searched in the form of expansions over $\cos[\pi(2k-1)x/2l]$ and $\sin(\pi kx/l)$ with amplitudes s_k and a_k for symmetrical and asymmetrical modes of plasma oscillations. As a result, eq. (4) reduces to the following sets of equations:

$$\lambda_\omega s_k = \sum_{k'=1}^{\infty} \theta^s_{k,k'} s_{k'}, \qquad \lambda_\omega a_k = \sum_{'=1}^{\infty} \theta^a_{k,k'} a_{k'}, \qquad (6)$$

where $\lambda_\omega = \dfrac{m æ l \omega(\omega + i\nu)}{2\pi^2 e^2 \Sigma_0}$, and $\theta^s_{k,k'}$ and $\theta^a_{k,k'}$ are the matrix elements of function $G(\xi,\xi')$ calculated numerically.The calculation of the eigenvalues of matrices $\theta^s_{k,k'}$ and $\theta^a_{k,k'}$ was based on the replacement of these infinite matrices by the respective truncated matrices. Convergence of the computational procedure used was verified by the comparison of the eigenvalues calculated using the matrices of different size K. Using the obtained eigenvalues $\lambda_\omega = \lambda^s_n$ and $\lambda_\omega = \lambda^a_n$ of matrices $\theta^s_{k,k'}$ and $\theta^a_{k,k'}$, where $n = 1, 2, 3, ...$ is the mode index, we arrive at the following equations determining the plasma oscillation spectrum:

$$\omega(\omega + i\nu) = \Omega^2\lambda^s_n, \qquad \omega(\omega + i\nu) = \Omega^2\lambda^a_n. \qquad (7)$$

Here $\Omega = \sqrt{\dfrac{2\pi^2 e^2 \Sigma_0}{m æ l}}$ is the characteristic plasma frequency of 2D plasmons (with the wavenumber $q = \pi/l$). Assuming that $\Sigma_0 = 10^{12}$ cm^{-2}, $m = 6 \times 10^{-29}$ g, $æ = 12$, and $l = 0.25 - 1$ μm, one can get $\Omega/2\pi \simeq (0.714 - 1.428)$ THz.

Thus, the spectrum of plasma oscillations in a 2D channel with two contacts is determined by Ω and λ^s_n (or λ^a_n). The former is a function of the 2D electron system parameters (the electron concentration and effective mass as well as the spacing between contacts), while the dimensionless factors λ^s_n and λ^a_n are determined by the shape of the contacts. The shape of the contacts is taken in to account by the matrix elements of the specific Green function $G(\xi,\xi')$.

The obtained values of the plasma modes frequencies differ from those in a 2D electron channel with bulky contacts, i.e. when the ac potential obeys the boundary conditions $\varphi_\omega|_{|x|=l,\,z} = 0$. In this case, $Re\,\omega \simeq \Omega\sqrt{(2n-1)/2}$ and $Re\,\omega \simeq \Omega\sqrt{n}$ for symmetric and asymmetric modes, respectively. Figure 2 shows the real part of the plasma frequency $Re\omega/2\pi$ versus the mode index n. The dependence of the fundamental ($n = 1$) plasma s-mode vs the spacing between the edges of the strip-like contacts is shown in the inset. For comparison, the dependence of the real part of the plasma frequency on the mode index for a 2D electron channel obtained previously is also shown. One can see

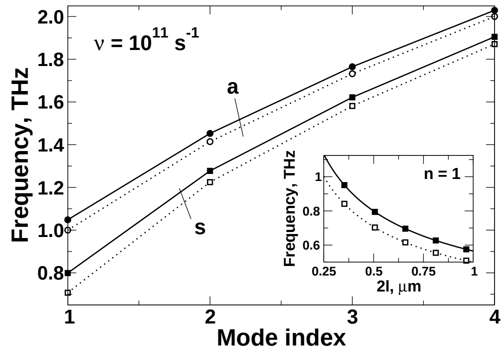

Figure 2: Plasma frequency $\mathrm{Re}\,\omega/2\pi$ of symmetric (s) and asymmetric (a) modes vs mode index n for $\Omega/2\pi = 1$ THz and $l = 0.25$ μm (solid line with filled markers). Inset shows the frequency of symmetric mode with $n = 1$ vs spacing $2l$. Dotted lines with open markers correspond to the data from ref. 8.

from Fig. 2 that the deviation of the plasma frequencies calculated above from those obtained using a simplified approach can be marked, particularly, for the fundamental mode (see the inset in Fig. 2)

4. Conclusions

In conclusion, we calculated the spectrum of plasma oscillations in a slot diode structure with a 2D electron channel and strip-like short circuited contacts. The obtained plasma frequencies deviate from the "quantized" square-root spectrum of 2D plasmons in uniform electron systems. This deviation is marked for the fundamental mode while it markedly decreases with increasing mode index. Using the approach developed, one can calculate the plasma oscillation spectrum of 2D systems with the contacts of arbitrary geometry.

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