Plasma effects in lateral Schottky junction tunneling
transit-time terahertz oscillator

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Abstract. We study the plasma oscillations in a two-dimensional electron channel with a reverse-biased Schottky junction. Using the developed model we show that the negative dynamic conductivity of the Schottky junction associated with the tunneling injection and electron-transit-time effect can result in the self-excitation of plasma oscillations (plasma instability) in the quasineutral portion of the channel serving as a resonant cavity. The spectrum of plasma oscillations and the conditions of their self-excitation are expressed via the structure parameters. The instability can be used in a novel diode device - lateral Schottky junction tunneling transit-time terahertz oscillator.
1. Introduction
Two-dimension electron gas (2DEG) systems with sufficiently high mobility of electrons confined in the lateral directions can serve as resonant cavities for electron plasma waves in different devices. As proposed [1, 2], the resonant plasma effects in gated 2DEG systems similar to high-electron mobility transistors can be used for detection, frequency multiplication and generation of terahertz (THz) radiation. The generation of THz radiation can be associated with the self-excitation of plasma oscillations due to different mechanisms of instability of the steady-state current flow, for instance, the instability caused by the plasma waves reflection from the drain edge of the gated channel (Dyakonov-Shur instability) [3], negative dynamic conductivity of the gate layer [4, 5] (owing to the resonant-tunneling through this layer or the electron transit-time effect). The self-excitation of plasma oscillations is also possible due to the features of strongly inelastic electron scattering on polar optical phonons (see, for example, early and recent papers [6, 7, 8, 9]). The plasma oscillations excitation in the structures similar to high-electron mobility transistors can be realized by optical signals [10, 11]. The observation of THz emission from high-electron mobility transistors associated with plasma instability was reported recently [12, 13]. The instability of a steady-state electron flow in the transistor channel is attributed to the plasma waves reflection from the drain edge of the gated channel (Dyakonov-Shur instability) [3] (see also, recent papers [14, 15]). The THz emission from high-electron mobility transistors due to resonant excitation of plasma oscillations by laser beams with close photon frequencies was demonstrated as well [16]. In this paper, we consider a diode device based on a heterostructure with a 2DEG channel and two different contacts to the latter. One contact is assumed to be Ohmic, while another one forms a lateral Schottky junction (see, for example, [17]). The latter serves as a tunneling injector of electrons from the contact into the 2DEG channel. In fact, the device under consideration is a tunneling Schottky diode with a 2DEG channel as the diode base and resonant cavity. A schematic view of the device structures under consideration and their band diagram are shown in Fig. 1. We shall refer to the device in question as a lateral Schottky diode (LSD). The use of the lateral tunneling Schottky junction provides at least the following advantages: (1) easy fabrication and high electron mobility in the 2DEG channel, (2) high electric field at the tunneling barrier due to the special feature of the electric field distribution, and (3) low capacitance of the depletion region.

The LSDs in question can be fabricated using heterostructures based on different III-V materials or nitrides.

2. Device model and its equations
We consider the LSD structures of two types shown in Figs. 1(a) and 1(b): (a) with a lateral strip-like metal contact (2−2 Schottky junction) and (b) with a bulk metal contact (3−2 Schottky junction). For simplicity, it is assumed that the 2DEG channel is sandwiched between the two regions with the same dielectric constant $\varepsilon$. The spatial dependence of the potential energy of electrons in the depletion region of the 2DEG channel under the reverse bias voltage (see Fig. 1(c)) is given by the following formulae:

$$U_{2-2}(x) = \frac{e(V + V_0)}{\pi} \left[ \cos^{-1}\left(\frac{2x}{l} - 1\right) - \sqrt{1 - \left(\frac{2x}{l} - 1\right)^2} \right]$$ (1)

for the strip-like metal contact, and

$$U_{3-2}(x) = \frac{e(V + V_0)}{\pi} \left[ 2 \tan^{-1}\left(\frac{\sqrt{l^2 - x^2}}{x}\right) + \frac{x}{l} \ln\left(\frac{l - \sqrt{l^2 - x^2}}{l + \sqrt{l^2 - x^2}}\right) \right]$$ (2)

for the bulk metal contact [18]. Here $l$ is the length of the depletion region which is given by $l = [\varepsilon(V + V_0)/\pi^2e\Sigma_d] = l_{2-2}$ and $l = [\varepsilon(V + V_0)/4\pi e\Sigma_d] = l_{3-2}$ for the 2−2 and 3−2 Schottky
Figure 1. Schematic view of (a) LSD structures with strip-like and (b) bulk Schottky metal contacts and (c) the band diagram.

junction, respectively (see [18, 19, 20], where the depletion region length in the 2DEG channel in similar structures was calculated), \( V \) and \( V_0 \) are the applied and built-in voltages (\( V > 0 \) for the reverse-biased Schottky junction), \( \Sigma_d \) is the sheet concentration of donors in the channel or somewhat above it (so that the 2DEG and donor layer are separated by a spacer), and \( e \) is the electron charge. The value of \( l_{2-2} \) which follows from equation (1) differs from that obtained previously [20] for a 2DEG channel at the interface between a dielectric with \( \varepsilon \gg 1 \) and air (\( \varepsilon = 1 \)) by factor 2.

The linearized hydrodynamic equations for 2DEG in the quasineutral portion of the channel (where the dc electron sheet concentration \( \Sigma_0 \approx \Sigma_d \)) coupled with the two-dimensional Poisson equation can be reduced to the following equation for the self-consistent ac potential, \( \psi_\omega(x, z, t) = \psi_\omega(x, z) \exp(-i \omega t) \), at the signal frequency \( \omega \) [21, 22]:

\[
\frac{\partial^2 \psi_\omega}{\partial x^2} + \frac{\partial^2 \psi_\omega}{\partial z^2} = \left[ \frac{4\pi e^2 \Sigma_d}{m \varepsilon \omega (\omega + i \nu)} \right] \frac{\partial^2 \psi_\omega}{\partial x^2} \delta(z). \tag{3}
\]

Here \( m \) is the electron effective mass and \( \nu \) is the collision frequency of electrons (with impurities and phonons) in the channel. In the case of structures (a) and (b), the boundary condition at \( x = L \), where \( L \) is the length of the 2DEG channel, corresponds to the fixed potential \( \psi_\omega(x, z)|_{x=L} \) at the Ohmic contact. The boundary condition at \( x = l \) can be determined taking into account that the electrons injected into the transit region and propagating in it (\( 0 < x < l \)) induce the ac current, \( J_\omega \), in the quasi-neutral section of the channel primarily in the vicinity of the edge of this section. This corresponds to the partition of the device into two sections (connected at \( x = l \)): the lateral tunneling Schottky junction with the admittance \( Y_\omega \) and the 2DEG channel. In this case, taking into account that \( J_\omega = Y_\omega \psi|x=l \) one can arrive at the following boundary conditions for the ac potential at \( x = L \) and \( x = l \):

\[
\psi_\omega(x, z)|_{x=L, z=0} = 0, \quad Y_\omega \psi|x=l, z=0 = -i \frac{e^2 \Sigma_d}{m(\omega - i \nu)} \frac{\partial \psi}{\partial x}|_{x=l, z=0}. \tag{4}
\]

Using equations (3) and (4), we arrive at the following dispersion equation for the oscillations of the self-consistent potential and, hence, the electron density, i.e., plasma oscillations in the
device under consideration:
\[-\frac{4\pi}{\alpha\omega} Y_\omega \tan[q_\omega(L - l)] = 1, \tag{5}\]
where the signal frequency $\omega$ and the wave number $q_\omega$ are related as $q_\omega = (m_s/2\pi e^2 \Sigma_d)\omega/(\omega + i\nu)$. The Schottky junction admittance is presented as $Y_\omega = -i\omega C + G_\omega$, where $C$ is the geometrical capacitance of the depletion region in LSD per unit length in the in-plane direction (parallel to the edge of the quasi-neutral section of the channel): $C \approx [(\nu/2\pi^2) \ln(4\pi^2 e^2 \Sigma_d L/\alpha\nu)(V + V_0)] = (\nu/2\pi^2) \ln(4L/l_{SC}) = C_{2-2}$ for structure (a) and $C \approx [(\nu/2\pi^2) \ln(8\pi^2 e \Sigma_d L/\alpha\nu)(V + V_0)] = (\nu/2\pi^2) \ln(2\pi L/l_{SC}) = C_{1-2}$ for structure (b). The term $G_\omega$ is associated with the ac current created by the electrons injected from the Schottky contact and propagating in the depletion region. This term is given by $G_\omega = (\mu_0 l_0 f_0 dxg(x) \exp(i\omega x/v))$, where $v$ is the electron drift velocity in the depletion region. The dc differential conductivity of the tunnel barrier $G_0$ is determined by the spatial distribution of the dc potential, which in turn is determined by the channel donor concentration $\Sigma_d$, the bias voltage $V$, and the height of the Schottky barrier $eV_0$. Function $g(x)$ determining the contribution of electrons propagating in the depletion region to the current induced in the metal contact and the channel depends, as follows from Shockley-Ramo’s theorem, on their shape. Assumption that $\nu = v_s$, where $v_s$ is the electron saturation velocity, one obtains $G_{\omega} = G_0 \exp(i\omega \tau_\Sigma/2) J_0(\omega \tau_\Sigma/2)$ and $G_{\omega} = G_0 [J_0(\omega \tau_\Sigma) + iH_0(\omega \tau_\Sigma)]$ for structures (a) and (b), respectively. Here, $\tau_\Sigma = l/v$ is the characteristic electron transit time across the depletion region, $J_0(\theta)$ and $H_0(\theta)$ are the Bessel and Struve functions.

3. Dispersion equation for plasma oscillations and their spectra
As follows from equation (5), the dispersion equation for plasma oscillations in LSDs with structure (a) can be obtained in the following form:
\[\cot \left[ \frac{\pi \omega ( \omega + i\nu )}{\Omega_p^2} \right] = c - \frac{g_t}{\omega} \sin \left( \frac{\pi \omega}{\Omega_t} \right) \cdot J_0 \left( \frac{\pi \omega}{\Omega_t} \right) + \frac{g_t}{\omega} \cos \left( \frac{\pi \omega}{\Omega_t} \right) \cdot J_0 \left( \frac{\pi \omega}{\Omega_t} \right), \tag{6}\]
Here $\Omega_p = (2\pi^2 e^2 \Sigma_d/\max(L - l))$ and $\Omega_t = 2\pi/\tau_\Sigma$ are the characteristic plasma and transit frequencies, respectively, $c = (4\pi/\alpha)C$, and $g_t = (4\pi/\alpha)G_0$. Assuming that $\Sigma_d = 10^{12}$ cm$^{-2}$, $L = 1$ $\mu$m ($L \gg l$), and $m = 6 \times 10^{-29}$ g and $\alpha = 12$, we obtain $\Omega_p/2\pi \approx 1.55$ THz. The quantity $\Omega_t/2\pi$ falls into the THz range if the electron transit time $\tau_\Sigma \leq 1$ ps. For $v_s = (1 - 2) \times 10^7$ cm/s, the latter inequality satisfies at $l \leq 0.1 - 0.2$ $\mu$m.

In the THz range of frequencies, one can assume that $\nu \ll \omega$. Apart from this in such a range, the second and third terms in the right-hand side of equation (6) can be considered as small perturbations. Considering this, one can find the following expression for the complex frequencies of the plasma modes, $\omega = \omega_k$, with different indices $k = 0, 1, 2, 3, \ldots$:
\[\omega_k \simeq \Omega_k - \frac{i}{2} \left[ \nu + \frac{g_t}{\Omega_k} \cos \left( \frac{\pi \Omega_k}{\Omega_t} \right) \cdot J_0 \left( \frac{\pi \Omega_k}{\Omega_t} \right) \right], \tag{7}\]
where $\Omega_k = \sqrt{\Omega_p/\nu + \cot^{-1} c/\pi}$ and $\zeta_k = \pi(1 + c^2)\zeta_k^2 = (1 + c^2)(\pi k + \cot^{-1} c)$.

In the LSD structures with bulk Schottky contacts (structure (b)), one can get the dispersion equation for plasma oscillations similar to Eq. (6) but with different dependence of the right-hand side on $\omega/\Omega_t$. The obtained dispersion equation yields (instead of equation (7))
\[\omega_k \simeq \Omega_k - \frac{i}{2} \left[ \nu + \frac{g_t}{\Omega_k} \cdot J_0 \left( \frac{2\pi \Omega_k}{\Omega_t} \right) \right], \tag{8}\]
As follows from the above formulae, the plasma frequencies $\Omega_k$ are mainly determined by the electron dc concentration in the quasi-neutral portion of the 2DEG channel $\Sigma_0 \simeq \Sigma_d$, its length
(L – l), and the mode index k. Since l depends on the bias voltage V, Ω_k is voltage-tuned. Some dependence of Ω_k on the capacitance of the Schottky junction also leads to an additional dependece of Ω_k on V. Figure 2(a) demonstrates the variations of the depletion and tunneling lengths, l and l_t, in the Schottky junction with changing bias voltage. The voltage dependences of the frequency of the fundamental mode of plasma oscillations Re ω_0 = Ω_0 in LSDs with a GaAs channel and strip-like metal contacts at different values of the built-in voltage (having different heights of the Schottky barrier) calculated using equation (6) and taking into account equation (1) and the pertinent formulae for the Schottky junction capacitance are shown in Fig. 2(b). The voltage dependences of the increment of plasma oscillations (Im ω_0) calculated assuming that the electron mobility in the channel is equal to μ = 1.3 × 10^6 cm^2/Vs at T = 4.2K are shown in Fig. 2(b) as well.

As follows from equations (7) and (8), the plasma oscillations increment can be positive at certain structural parameters and bias voltages. This corresponds to plasma oscillation instability, i.e., self-excitation of the plasma oscillations. The pertinent conditions of the instability in question can be presented as

\[ \nu + \frac{g_t}{\zeta_k} \cos \left( \frac{\pi \Omega_k}{\Omega_t} \right) \cdot J_0 \left( \frac{\pi \Omega_k}{\Omega_t} \right) < 0, \quad \nu + \frac{g_t}{\zeta_k} \cdot J_0 \left( \frac{2\pi \Omega_k}{\Omega_t} \right) < 0 \]  

(9)

for structures (a) and (b), respectively. Since the differential tunneling conductivity of the Schottky barrier is positive, i.e., g_t > 0, inequalities (9) can be satisfied only at such ratios of the plasma and transit frequencies that the second terms in these inequalities are negative. Taking into account the values of functions cos θ J_0(θ) and J_0(2θ) in their minima, one can present the above conditions of instability in the folowing form:

\[ \frac{g_t}{\nu} > Q_k, \]  

(10)

where Q_k > 1 are some numbers increasing with k. These numbers are determined by ζ_k and the modulus of function cos θ J_0(θ) or function J_0(2θ) at their minima. At the first minima, one has cos θ · J_0(θ) ≃ −0.094 and J_0(θ) ≃ −0.400, so that Q_k ≃ 10.6ζ_k and Q_k ≃ 2.5ζ_k for the devices with strip-like and bulk metal contacts, respectively. Inequality (10) implies that the plasma instability is possible in LSD with sufficiently small collision frequency ν, i.e., with sufficiently high mobility of electrons in the device channel. As seen from Fig. 2(b), the condition of instability can be satisfied at least for the fundamental mode in LSDs with strip-like contacts.

4. Conclusions

We have developed a device model for LSDs. Using this model we have found the spectra of the plasma oscillations in such devices and the conditions of the self-excitation of these oscillations (plasma instability) due to the negative dynamic conductivity of the lateral tunneling Schottky junction associated with the electron-transit time effect. We have demonstrated that the self-excitation of plasma oscillations in the terahertz range of frequencies in LSDs with GaAs channel with high-electron mobility is feasible.

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Figure 2. Depletion region length and tunneling length (a) and fundamental frequency of plasma oscillations and their increment (b) vs bias voltage.

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