1. INTRODUCTION

The plasma instability and the related self-excitation of plasma oscillations in two dimensional (2D) structures can lead to the generation of the terahertz (THz) radiation \[1\]. This effect was reported in many theoretical and experimental papers \[2-5\] (see also the references therein). The 2D structures with the graphene channel (G-channel) have advantages compared with those based on the standard materials. The high-energy ballistic electrons (BEs) \[6-12\] injected into the G-channel lead to an effective Coulomb drag of the quasi-equilibrium carriers \[13-17\] strongly affecting the device characteristics. As demonstrated recently \[18, 19\], the Coulomb interaction of the injected BEs with the quasi-equilibrium electrons (QEs) results in the dragged electrons (DEs) in the gated G-channel of the $n^+\text{-}i\text{-}n^+$ graphene field effect transistors (GFETs) and the dragged holes (DH) in the $p^+\text{-}i\text{-}n^+$ graphene tunneling transistors (GTTs) \[20\]. The drag effect is associated with the linearity of the electron and hole energy-momentum relations in G-channels and followed from the specifics of the kinematics of the carrier pair collisions \[21, 22\] and can enable the plasma instability associated with the internal current amplification \[14\].

In this paper, we analyze the high-frequency characteristics of the $n^+\text{-}i\text{-}n^+$ G-channel structures with the gated n-region (called as the GFETs) and with the ungated n-region, to which we refer to as the graphene lateral diodes (GLDs). The Coulomb drag in the GFETs and GLDs was considered recently \[17\]. We now use the distributed (waveguide) model of the electron plasma in the n-regions instead of the previous model based on the equivalent circuits with the lumped capacitance and kinetic inductance of these regions. The lumped-element model describes well the fundamental plasmonic resonance in the GFETs and GLDs. However, the consideration of the resonance harmonics and the analysis of GLDs require the distributed model. The electron viscosity can substantially affect the plasma resonances, especially for higher harmonics. Accounting for the viscosity also requires using the distributive model. A substantial distinction of the plasma oscillations spectra in the gated and ungated channels \[24-27\] leads to markedly different characteristics of the GFETs and GLDs despite a similarity of the drag effect in these devices. In particular, the plasmonic resonances in the GLDs can correspond to markedly higher frequencies compared to the GFETs with the same n-region length.

Below we calculate the frequency-dependent impedance of the GFETs and GLDs as a function of the structural characteristics. We demonstrate that the real part of the impedance can be negative in the THz frequency range where the impedance imaginary part changes sign. This corresponds to the plasma instability and the self-excitation of THz plasma oscillations \[28\] enabling the THz radiation emission using a pertinent antenna. We calculate the growth rate of the self-excited plasma oscillation as a function of the drag factor and the device structural parameters.

The paper is organized as follows. In Sec. 2, we discuss the GFET and GLD device model describing the BE and QE transport and the role of DEs. In Sec. 3, we derive the spatial distribution of the ac potential in GFETs and calculate their frequency-dependent impedance. Section 4 deals with the calculation of the GLD frequency-dependent impedance using the 2D Poisson equation for the spatial distribution of the ac potential. Using the obtained expression for the frequency-dependent impedance, we analyze the instability of the steady-state current flow in the GFETs (the plasma instability toward the self-excitation of the coupled oscillation of the potential and the electron density) and find the instability conditions and the oscillations growth rate. In Sec. 5, the results of the distributed device model are compared with those using a lumped circuit model.
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Sec. 6 we summarize the main conclusions.

FIG. 1. Schematic view of GFET and GLD circuit with an antenna (R_A is the antenna radiation resistance).

We also comment on the role of the GLD contacts. In Sec. 6 we summarize the main conclusions.

2. DEVICE MODEL

Figure 1 shows the schematical views of the GFET and GLD under consideration. The n-region in the GFET is electrostatically induced by the gate voltage V_g > 0. The formation of the n-region in the GDs is due to the remote donor doping. Such a selective doping can provide the electron densities sufficient for the effective interaction with the BEs injected from the n^+ -source contact region via the i-region and for the pronounced plasmonic response without marked sacrificing of the QE mobility. Similar devices can be implemented using the p^+ -i-p^+ structures and using G-multilayer gated and selectively doped structures with a commensurate improvements in performance. The GFETs and GLDs under consideration are forward biased by the source-drain dc voltage V_0. It is assumed that the conditions of the ballistic transport of the injected BEs and the effective transfer of the BE momentum to the QEs are fulfilled. This primarily implies that the lengths, l_i and l_n, of the i- and n-regions, respectively, are not too large (in the μm range or somewhat smaller, see [17, 18] for details), providing sufficiently large Coulomb drag factor b (b ≥ 1).

Considering that the net source-drain voltage comprises the signal component V = V_0 + δVω exp(−iωt) with δVω and ω being the signal amplitude and frequency, respectively, we obtain:

\[ \delta J_{BE}^ω = \frac{\sigma_i \delta \phi_ω}{l_i}, \quad \delta J_{QE}^ω = \sigma_n \frac{i\nu_n}{(\omega + i\nu_n)} \int dx \delta \phi_ω. \] (1)

Here the density of the BE ac current across the i-region (−l_i ≤ x ≤ 0) and the density of the QE ac current in the n-region (0 ≤ x ≤ l_n), respectively, \( \sigma_i = \kappa v_F/2\pi \) is the conductivity of the i-region (disregarding the BE transit-time delay), \( \sigma_n = (e^2/\mu_n/\pi h^2) \) is the n-region Drude dc conductivity, \( \kappa \) is the effective dielectric constant of the media surrounding the G-channel, \( v_F \approx 10^8 \text{ cm/s} \) is the characteristic electron velocity in G-channels, \( \tau_n \) is the QE momentum relaxation time (\( \nu_n = 1/\tau_n \) represents the frequency of the QE collisions with impurities and acoustical phonons), μ_n and Σ_n are the QE Fermi energy and density with \( \mu_n \approx h v_F \sqrt{2\pi n}, \) e is the electron charge, h is the Planck constant, and \( \delta \phi_ω = \delta \phi_ω(x, y)|_{y=0} \) expresses the ac potential spatial distribution along the axis x directed in the G-channel plane (y = 0) with x = −l_i and x = l_n corresponding to the coordinate of the n^+ -source and drain region, respectively. The frequency dependence of the ac conductance reflects the kinetic inductance of the QE system.

The DE ac current is given by [17, 18]

\[ \delta J_{DE}^ω = b\Lambda \delta J_{BE}^ω, \] (2)

where b is the drag factor [16, 18], \( \Lambda = d J_{DE}^ω/d J_{BE}^ω \), \( J_{BE}^ω = \sigma_i \nu_0/\nu_n \) is the dc bias current, and \( \Phi_0 \) is the dc potential at x = 0 corresponding to the bias voltage V_0.

3. GFET IMPEDANCE SPECTRAL CHARACTERISTICS

The standard procedure of reducing of the general system of electron plasma hydrodynamic equations coupled with the 2D Poisson equation [29, 32] using in the gradual channel approximation [33] yields the spatial distribution of the ac potential \( \delta \phi_ω = \delta \psi_ω(x, y)|_{y=0} \), where \( \delta \psi(x, y) \) is the potential around the n-region of the G-channel (y = 0), by the following equation (see, for example, [29]):

\[ \frac{d^2 \delta \psi_ω}{dx^2} + \frac{\omega(\omega + i\nu_n)}{s^2} (\delta \phi_ω - \delta V_ω) = 0 \] (3)

with the boundary conditions at the edges of the n-region: \( \delta \phi_ω|_{x=0} = l_i \delta J_{BE}^ω/\sigma_i \) and \( \delta \phi_ω|_{x=l_n} = -\delta V_ω, \delta J_{BE}^ω \) coincides with the net ac terminal current. These boundary conditions are valid for all devices under consideration. The plasma velocity in the gated n-region is given by \( s = \sqrt{4e^2 \mu_n d/\pi \hbar^2} \) with d ≪ l_n being the thickness of the layer separating the gate and the n-region of the channel. In reality, the electron fluid viscosity (see also [34, 36]) can strongly affect the electron dynamics, resulting in a strong damping of the plasma resonances, particularly, affecting the higher resonances, their height and widths [1, 34]. This is due to the deviation of the ac potential and electron density spatial distributions from a linear function. To account for the viscosity effect, we put in Eq. (3) \( \nu_n = \nu_n + \sqrt{4e^2 \mu_n d/\pi \hbar^2} \) where h is the QE viscosity and \( k = \omega/s \) is the plasma wave number. Considering that for the characteristic plasma frequency \( \Omega^{\text{GFET}} \) one obtains \( \Omega^{\text{GFET}}/s = \pi/2l_n \), we set \( \nu_n = \nu_n + \sqrt{4e^2 \mu_n d/\pi \hbar^2} (\omega/\Omega^{\text{GFET}})^2 \). It is worth mention
that both the electron drag and the elevated electron viscosity in G-channels originate from the specifics of the Coulomb interaction of the 2D electrons with the linear dispersion law.

Solving Eq. (3) with the boundary conditions under consideration, we obtain

\[
\delta \phi_\omega - \delta V_\omega = (\delta \phi_\omega |_{x=0} - \delta V_\omega) \left[ \cos \left( \frac{\gamma_{GFET}^\omega x}{l_n} \right) - \frac{\cos(\gamma_{GFET}^\omega)}{\sin(\gamma_{GFET}^\omega)} \sin \left( \frac{\gamma_{GFET}^\omega x}{l_n} \right) \right].
\]  

(4)
In Eq. (4),

\[ \gamma_{\omega}^{GFET} = \frac{\pi \sqrt{\omega(\omega + i\nu_n)}}{2Q^{GFET}}, \]  

(5)

where the plasma frequency is given by

\[ \Omega^{GFET} = \frac{e}{\hbar} \sqrt{\frac{\pi^2 \mu_d}{\kappa l_n^2}} \propto \sqrt{\frac{d}{l_n^2}}. \]  

(6)

Substituting \( \delta \phi_\omega \) from Eq. (4) into Eq. (1), equalizing \( \delta J_{\omega}^{BE} \) and \( (\delta J_{\omega}^{DE} + \delta J_{\omega}^{QFET})_{x=0} \) (i.e., using the Kirchhoff’s circuit law), and accounting for the antenna radiation resistance \( R_A \), we arrive at the following expression for the GFET impedances \( Z_{\omega}^{GFET} = \delta V_\omega / \delta J_\omega + R_A \):

\[ \frac{Z_{\omega}^{GFET}}{R_i} = -i \left( 1 - bA \right) (\omega + i\nu_n) \tan(\gamma_{\omega}^{GFET}) \eta + 1 + \rho_A. \]  

(7)

Here \( H \) is the device size in the z-direction perpendicular to the source-drain current direction (device width), \( R_i = l_i / \hbar \sigma_i \) is the i-region resistance, \( \rho_A = R_A / R_i \), \( \eta = R_i / R_n \) is the ratio of the n-region and i-region resistances with \( R_n = l_n / \hbar \sigma_n \), so that \( \eta = \hbar \sigma_n / l_i \sigma_i \). In the absence of the electron drag at \( \omega \) tending to zero, \( Z_{\omega}^{GFET} \) tends to \( Z_{\omega}^{GFET} = R_n + R_i + R_A \).

Using the properties of the trigonometric functions [27], the GFET impedance given by Eq. (7) can be presented in the form explicitly expressing its resonant behavior:

\[ \frac{Z_{\omega}^{GFET}}{R_i} = -i \left( 1 - bA \right) (\omega + i\nu_n) \tan(\gamma_{\omega}^{GFET}) \eta + 1 + \rho_A \times \sum_{m=1}^{\infty} \frac{(2m-1)^2(\Omega^{GFET})^2}{\omega^2 - (\gamma_{\omega}^{GFET})^2 - \nu_n^2} + 1 + \rho_A. \]  

(8)

As follows from Eq. (7) and more clearly seen from Eq. (8), when \( \Omega^{GFET} \gg \nu_n \), the real part of the GFET impedance \( \Re Z_{\omega}^{GFET} \) as a function of the signal frequency \( \omega \) exhibits the resonant peaks. The resonant frequencies \( \omega_{2m-1} \), where \( m = 1, 2, 3, \ldots \) is the resonance index, are given by

\[ \omega_{2m-1} \simeq (2m - 1) \sqrt{(\Omega^{GFET})^2 - \rho_n^2}. \]  

(9)

For the height of the resonant peak we obtain

\[ \left| \Re Z_{\omega}^{GFET} / R_i \right| = \frac{8}{\pi^2} \frac{(1 - bA)}{\eta} \left( \frac{\Omega^{GFET}}{\nu_n} \right)^2 + 1 + \rho_A. \]  

(10)

The resonant peaks are pronounced if \( (\Omega^{GFET}/\nu_n)^2 \gg 1 \). Since \( \Omega^{GFET} \propto l_n^{-1} \) and \( R_i \propto l_n \nu_n \), the latter inequality can be satisfied when the product \( l_n \nu_n \) is sufficiently small. A marked increase in \( \nu_n \) with increasing peaks index \( m \) associated with the viscosity effect, results in relatively small height of these peaks. Assuming that \( h = 250 - 500 \) cm\(^2\)/s (see the estimates for the electron viscosity [34]) and \( l_n = 0.5 \) \( \mu \)m, for the quantity \( \nu_n = h(\pi^2/4l^2_n) \simeq 0.25 - 0.5 \) ps\(^{-1}\). Using Eq. (8), at \( \nu_n = 0.75 \) ps\(^{-1}\) \( h = 250 \) cm\(^2\)/s for the ratio of the fundamental \( (m = 1) \) peak height and the next peak \( (m = 2) \) height we obtain \( \sim 9 \).

Figure 2 shows the spectral characteristics of the normalized real and imaginary parts of the GFET impedance, \( \Re Z_{\omega}^{GFET}/R_i \) and \( \Im Z_{\omega}^{GFET}/R_i \), calculated using Eq. (7) for different values of the plasma frequencies \( \Omega^{GFET} \) and the electron viscosity \( h \). We assumed that \( \mu_n = 25 \) meV, \( l_n = 0.5 \mu \)m, \( l_n/l_i = 5 \), \( d = 0.05 \mu \)m, \( \kappa = 4 \) and 6, \( \eta = 6.1 \) and - 9.2, \( \nu_n = 0.75 \) ps\(^{-1}\), \( h = 250 - 500 \) cm\(^2\)/s, \( \rho_A = 1 \), and \( bA = 0.5 \). The latter parameters correspond to \( b = 0.25 \) and \( J_{\omega}^{BE} = 1.41 \) A/cm and can be related to the GFETs at room temperature [17]. One can see from Fig. 2(a) that the impedance real part exhibits a series of the markedly damping resonant peaks.

Figure 3 shows thereal and imaginary parts of the GFET frequency-dependent impedance normalized by \( R_i \) under the condition of relatively strong drag effect \( (bA > 1) \). Other parameters are the same as for Fig. 2. One can see that at chosen parameters near the plasma resonances (fundamental) with the frequencies \( \omega_1/2\pi = \Omega^{GFET}/2\pi = 1.073 \) THz and \( \omega_1/2\pi = \Omega^{GFET}/2\pi = 0.876 \) THz the GFET impedance is negative. The impedance imaginary part changes sign at the resonant frequency, i.e., in the range where \( \Re Z_{\omega}^{GFET} < 0 \) (around of the above resonant frequencies). However, the latter takes place only for the fundamental plasma resonance due to a strong damping associated with the viscosity.

As pointed out previously [18–20], such a situation implies the possibility of the plasma instability (see below), i.e., the self-excitation of the plasma oscillations (see, for example, [28]).

4. TWO-DIMENSIONAL POTENTIAL DISTRIBUTION IN GLD AND ITS IMPEDANCE

The potential distribution \( \delta \psi_\omega(x, y) \) around the n-layer in the GLD is governed by the 2D Poisson equation in the following form [29–32]:

\[ \frac{\partial^2 \delta \psi_\omega}{\partial x^2} + \frac{\partial^2 \delta \psi_\omega}{\partial y^2} = \frac{s^2}{\omega(\omega + i\nu_n)} \frac{\partial^2 \delta \psi_\omega}{\partial x^2} \cdot \delta(y), \]  

(11)

where \( \delta(y) \) is the Dirac delta-function describing thinness of the G-channel. Solving Eq. (11) considering that \( \delta \psi_\omega(x, y) = \delta \varphi_\omega(x) \exp(-\gamma_\omega^{GLD} |y|/l_n) \), and accounting for the specifics of the current induced in the blade-like conducting electrodes [39], for the n-region admittance we obtain [30].
where \( t_i = R_i C_l \simeq (\kappa R_i/2\pi) L_i = l_i/v_W \). When \( b\Lambda \) and \( \omega \) tend to zero, \( Y_\omega \) and \( Z^{G^{LD}} \) tend to \( Z_0^{G^{LD}} = R_n + R_l + R_A \). In the high-frequency limit, \( Z_\omega^{G^{LD}} \simeq R_l + R_A + i/\omega C_l \simeq R_l + R_A \).

Figure 4 shows the spectral characteristics of the GLD impedance calculated using Eq. (16) for GLDs with different resonant plasma frequencies (due to different \( k \)) at different values of the drag parameter \( b\Lambda \) \((b\Lambda > 1)\) assuming that \( \mu_n = 25 \text{ meV}, \ l_n = 1.0 \ \mu \text{m}, \ l_n/l_i = 10, \ \kappa = 4 - 6, \ \eta = 6.1 - 9.2, \ \tau_n = 0.75 \text{ ps}^{-1}, \ \rho_A = 1, \) and \( h = 1000 \text{ cm}^2/\text{s} \). The n-region length is chosen to be as twice as larger than that in Fig. 3 related to the GFETs. Nevertheless, the values of GLD characteristic plasma frequency \( \Omega_\omega^{G^{LD}} \) are larger than the frequency \( \Omega_{G^{DET}}^{G^{LD}} \) due to the difference of these frequencies dependences on \( l_n \) and \( d \). It also assumed that in GLD the viscosity is four times larger to provide the same value of \( \tau_n \) as for the GLD.

As seen from Fig. 4, at sufficiently large \( b\Lambda \) the impedance real part \( \text{Re } Z_\omega^{G^{LD}} \) exhibits deep minima at certain frequencies. In the first minima \( \text{Re } Z_\omega^{G^{LD}} \lt 0 \). The second minimum \( \text{Re } Z_\omega^{G^{LD}} \) is small being, nevertheless, positive. The latter is attributed to a relatively strong plasma oscillation damping due to the viscosity effect. The frequency dependences, including the magnitudes in the minima, shown in Figs. 4(a) and 4(b) appears to be rather similar, except for the values of the frequencies \( \omega_1/2\pi \) and \( \omega_2/2\pi \) corresponding to the Re \( Z_\omega^{G^{LD}} \) minima. These frequencies, \( \omega_1/2\pi \simeq 1.3 \text{ THz} \) and \( \omega_2/2\pi \simeq 2.9 \text{ THz} \) [for the GLD with \( \Omega_\omega^{G^{LD}}/2\pi = 2.71 \text{ THz} \), see Fig. 4(a)] and to the minima
\(\omega_1/2\pi \simeq 1.2\) THz and \(\omega_2/2\pi \simeq 2.35\) THz [for the GLD with \(\Omega_{GLD}^G/2\pi = 2.21\) THz, see Fig. 4(b)], are smaller than the pertinent values of the characteristic frequencies \(\Omega_{GLD}^G/2\pi\) and \(3\Omega_{GLD}^G/2\pi\). This can be explained by a substantial contribution of the GLD geometrical capacitance to the plasma resonances. Such a capacitance increases the net capacitance in comparison with the electron capacitance of the n-region (which determines \(\Omega_{GLD}\)). As in the GFETs, the impedance imaginary part \(\text{Im} \ Z_n^G\) changes its sign at the frequencies corresponding to the real part minima. Generally, the spectral characteristics of \(Z_n^G\) are qualitatively similar to those of the GFETs. However, there are the following distinctions: (a) the GLD characteristic and the resonant frequencies are larger than those of the GFETs for the same n-region length, (b) the resonant frequencies in the GLDs are markedly smaller than the characteristic frequencies (while in the GFETs these frequencies are rather close to each other), and (c) the resonant peaks in the GLDs are affected by the viscosity effect for a lesser degree. Indeed, the plots in Fig. 4, are akin to the possibilities of the plasma instability, i.e., the plasma instability takes place. When \(\nu_n < \Omega_{GFET}^G\), inequality (19) can be satisfied at much smaller \(bA\) than required for the GFET source-drain characteristics of the S-type [17]. Considering that \(bA \simeq 4\pi e l_i J_{th}^{BE}/\kappa v_W \mu_n\) [17], inequality (18) can be presented as

\[
J_{th}^{BE} > J_{th}^{BE} = J_{th}^{BE} \left[ 1 + \frac{\pi^2 \eta(1 + \rho_A)}{8} \left( \frac{\nu_n}{\Omega_{GFET}^G} \right)^2 \right],
\]

where

\[
J_{th}^{BE} = \left( \frac{\kappa v_W \mu_n}{4\pi e l_i} \right).
\]

For typical parameters \(\kappa = 4 - 6, \ l_i = 0.1\ \mu m, \ l_n = 0.5\ \mu m, \ d = 5 \times 10^{-6}\ \text{cm}, \ \mu_n = 25\ \text{meV}, \ \nu_n = 1\ \text{ps}^{-1}, \ \text{and} \ \rho_A = 1\), we arrive at the following estimates: \(\eta \simeq 6 - 9, \ \Omega_{GFET}^G/2\pi = 0.87 - 1.08\ \text{THz}, \ \text{and} \ J_{th}^{BE} \simeq (130 - 190)\ \text{mA/cm}.\) The latter values of the threshold dc current are markedly smaller than that at which the emission of optical phonons by the BEs (affecting the GFET characteristics) becomes essential \([J_0 = \kappa v_W h \omega_0/2\pi e l_i \simeq (1410 - 2115)\ \text{mA/cm}, \ \text{where} \ h\omega_0 \simeq 200\ \text{meV}\) is the optical phonon energy [16, 18].

The electron viscosity leads to a strong damping of the higher plasma oscillation harmonics. This results in larger values of \(bA\) and \(J_{th}^{BE}\) (because of a larger \(\nu_n\)) and complicates (or prevents) the appearance of the plasma instability with the self-excitation of these harmonics.

4. PLASMA INSTABILITY

We focus below of the instability in the GFETs since the spectral characteristics of the GFET and GLD impedance are qualitatively similar (negative real part and changing sign imaginary part), both corresponding to the possibility of the plasma instability.

To find the conditions of the plasma instability in the GFETs, the frequency of the self-excited modes \(\omega'\), and their growth rate \(\omega''\) corresponding to the plasma instability in the GFETs, we use the dispersion equation governing the plasma oscillation in the following form:

\[
\omega''(\omega'' + \omega') + 2\omega' = 0.\]

Invoking Eq. (7) and setting Re \(Z_{GFET}^{GFET} \omega' + \omega'' = 0\) and Im \(Z_{GFET}^{GFET} \omega' + \omega'' = 0\), for the growth rate of the fundamental plasma mode we find

\[
\omega'' \simeq -\frac{\nu_n}{2} \left[ 1 + \frac{8}{\pi^2 \eta(1 + \rho_A)} \left( \frac{\Omega_{GFET}^G}{\nu_n} \right)^2 \right].
\]

If \(bA < 1\) (no electron drag or a weak electron drag), Eq. (17) yields \(\omega'' < 0\). This corresponds to the damping of the plasma oscillations with the frequency \(\simeq \Omega_{GFET}^G\).

5. COMMENTS

Distributed model versus lumped-element model

Compare the GFET impedance calculated using the lumped capacitance and inductance model with that obtained above. The latter is given by (in the present notations) [18]

\[
\frac{Z_n}{R_i} = \frac{(1 - bA)}{\eta(1 + f_{\omega})} \left( \frac{\omega^2 + \nu_n^2}{\nu_n^2} \right) + 1 + \rho_A,
\]

where \(f_{\omega} = (\omega/\nu_n)/[2(\Omega_{GFET}^G)^2 - \omega^2 - \nu_n^2]/[2(\Omega_{GFET}^G)^2 - \omega^2 - \nu_n^2]^2\) with \(\Omega_{GFET}^G\), which differs from \(\Omega_{GFET}^G\) given by Eq. (6) by
a factor of $\sqrt{2/\pi}$. This is because the distributed model accounts for a deviation of the ac potential distribution in the n-region from a linear distribution (in contrast to the lumped-element model). Equation (21) yields the resonant peak height equal to the fundamental resonant peak ($m = 1$) height described by Eq. (10). However, the main distinction in the spectral characteristics of the GFET impedance calculated by the distributed and lumped-element models is that the former can describe a multiple peak structure.

Effect of the side contacts shape on the plasma resonances in GLDs

Equations (12) - (14) correspond to the case of the GLDs with the blade-like side contacts. If the thickness of the side contacts in the GLDs, $D > l_i + l_n \approx l_n$ (the GLDs with bulk contacts), we have to account for the features of the displacement current induced by the carriers between the source and drain (bulk) contacts. In this case, for the n-region admittance we obtain [compare with Eq. (12)]

$$Y_n = i\left(\frac{\sigma_n v_n}{\omega + iv_n} - \omega C_b\right).$$

We estimate the capacitance $C_b$ as $C_b \sim (\kappa/4\pi)\mathcal{L}_b$ with $\mathcal{L}_b \sim D/l_n$. In the case under consideration, Eqs. (15) and (22) lead to the following formula for $Z_{\omega \text{GLD}}$

$$\frac{Z_{\omega \text{GLD}}}{R_i} = -i\frac{(1 - b\Delta)}{\omega t_i \mathcal{L}_b + \frac{4\pi \sigma_n v_n}{(\mathcal{L}_b)\kappa l_n(\omega + iv_n)}} + 1 + \rho_A \quad \quad (23)$$

Hence $t_i \mathcal{L}_b \sim (l_i/v_0)(D/l_n) = t_i(D/l_n)$ and the plasma frequency in the GLDs with bulk contacts is given by

$$\omega_{n \text{GLD}} \approx \frac{e}{\hbar} \sqrt{\frac{4\mu_v}{\kappa l_n D}} \sim \frac{e}{\hbar} \sqrt{\frac{4\mu_v}{\kappa D}}.$$ 

Output THz power

To estimate the maximum output THz power, one can determine the variation $\delta \Lambda$ of the parameter $\Lambda$ and hence the swing of the dc bias current $\Delta J_{0 \text{BE}}$ corresponding to $\text{Re} \ Z_{\omega \text{GFET}} < 0$ (or $\text{Re} \ Z_{\omega \text{GLD}} < 0$). From Eqs. (7) we find

$$b\Delta \approx (b\Delta - 1) + \eta(\nu_n/\Omega_{\text{GFET}}^2)(1 + \rho_A).$$

At the parameters used for Fig. 3(a), we obtain $\eta(\nu_n/\Omega_{\text{GFET}}^2) \sim 0.2$. Considering that at $J_{0 \text{BE}}^\text{BE} \leq J_0$ (we disregard the case or relatively high dc bias current at which the optical phonon emission markedly affects the GFET (GLD) characteristics), $\Delta \Lambda = 2\Delta J_{0 \text{BE}}/J_0$, for $b\Delta = 2$ and $b\Delta = 3$ [as in Fig. 3(a)], from Eq. (25) we obtain $\Delta J_{0 \text{BE}}^\text{BE}/J_0 \approx 0.6 - 0.7$. Considering that at the above parameters $J_0 \approx 1.4 \ A/cm$ and for the GFET width $H = (10 - 14) \ \mu m$, $R_i = R_A \approx 100 - 140 \ \Omega m$, one can obtain $\Delta J_{0 \text{BE}}^\text{BE} \approx (0.85 - 1.4) \ mA$. In this case the maximum output THz power $P_{\omega \text{GFET}}$ at the frequency $\omega/2\pi = 1 \ THz$ is estimated as $P_{\omega} \approx 100 - 200 \ \mu W$. Similar estimates can be obtained for the GLDs.

6. CONCLUSIONS

Our calculations of the frequency dependendencies of the $n^+\text{-i-}n^+$ and GFETs and GLDs impedances accounting for the resonant response of the electron plasma in the n-regions, damping of the plasma oscillations due to the electron viscosity, and the Coulomb drag of the QEs by the injected BEs show that the impedance real part $\text{Re} \ Z_{\omega}$ in both GFETs and GLDs can be negative if the drag effect is sufficiently strong. Since in the frequency range, where $\text{Re} \ Z_{\omega} < 0$, $\text{Im} \ Z_{\omega}$ changes sign, i.e., turns zero at a certain THz signal frequency, the electron plasma can be unstable toward the self-excitation of the plasma oscillations (the effect of the plasma instability). This can enable the emission of the THz radiation. The electron viscosity can effectively suppress the higher plasma resonances, although this effect is weaker in the GLDs in comparison with the GFETs. The results related to the GFETs confirm the predictions obtained using a simplified model of the gated n-region as a plasmonic cavity except not accounting for the possibility of the plasma frequency harmonics self-excitation. We demonstrated that the GLDs with the ungated n-region formed by chemical selective doping can also exhibit the plasma instability and generation of the THz radiation. In these devices, the plasma resonant frequency and, hence, the frequency of the emitted THz radiation, can markedly exceed that in the GFETs for the same n-region length. The obtained results imply that the $n^+\text{-i-}n^+$ GFETs and GLDs can be used in novel THz radiation sources. A similar instability could also occur in $p^+\text{-}i-p^+$ (including the structures based on G-multilayers
with the carriers induced by the gate voltage or doping) and the p+-p-i-n+ single G-layer (i.e., GTTs [20]) or G-multilayer [41] structures with the Zener-Klein interband tunneling generation of ballistic carriers.

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