INTERACTION OF DRIFTING ELECTRONS WITH A REMOTE DIPOLE

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This article is devoted to the study of the interaction of drifting two-dimensional electrons and a remote molecule. The interaction of the two-dimensional electron gas (2DEG) with a remote dipole at three possible orientations of the latter is considered. The dispersion equation for joint oscillations of the 2DEG and a dipole is deduced, and the analytical and numerical studies of this equation are executed. For the orientations of the dipole perpendicularly to an applied electric field, the effect of a damping of oscillations is observed, and, at the orientation of the dipole in parallel to the field, the effect of a growth of oscillations of the system can arise. Different dependences of the mobility on the field strength affect differently the dependence of the instability increment on the concentration of electrons, which is related to different mechanisms of instability.

1. Introduction

In the physics of nanostructures, the trend concerning the interaction of atoms, molecules, quantum dots, or nanoparticles with plasmons in various structures is intensively developed in recent years. In particular, the interaction of a molecule and a metallic nanoparticle was considered in [1], the interaction of a metal-type nanoparticle with a plane dielectric surface was studied in [2], the physical properties of Au nanoparticles on the surface of a semiconductor were analyzed in [3], *etc.* Moreover, the effect of a semiconductor or a dielectric on the emissive properties of atoms, molecules, or nanoparticles excited by an external radiation was considered in [4]. In this case, the current carriers in a semiconductor were assumed to be equilibrium.

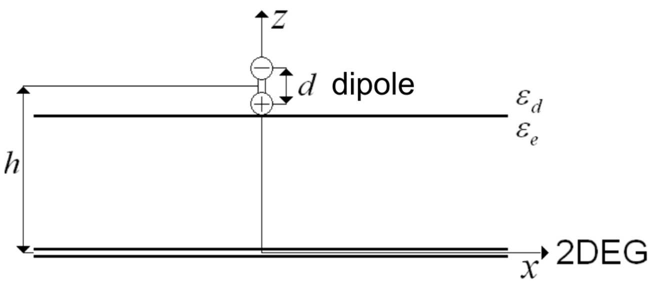

Fig. 1. Location of a dipole relative to the 2DEG. The y axis is perpendicular to the figure plane. The 2DEG is separated from the dipole by a dielectric (spacer)

In the present work, we pose the problem on the excitation of oscillations of a remote atom, molecule, quantum dot, or nanoparticle by collective oscillations of drifting nonequilibrium current carriers in a quantum well. To this end, we consider the interaction of drifting two-dimensional electrons with a remote dipole. In Section 2, we develop a model and construct the basic equations for the posed problem. Using the oscillator equation for a dipole, the equations for the current density in the drift-diffusion approximation, the equation of continuity for the electron subsystem, and the Poisson equation, we obtain an equation allowing us to renormalize the frequency of joint oscillations of the 2DEG and a dipole. In Section 3, we discuss the interaction of the two-dimensional electron gas with a remote dipole in the case where the mobility of electrons is independent of the field. The obtained equation is studied analytically in some approximation and numerically. We analyze the dependence of the real and imaginary parts of the frequency on a parameter related to an applied field at various temperatures and concentrations of the 2DEG. In Section 4, we present the results of studies of the interaction of the 2DEG with a remote dipole in the case of the negative differential conduction. The dependences of the real and imaginary parts of the frequency on the field strength at fixed temperatures and concentrations of the 2DEG are constructed. The work is completed by conclusions and the discussion of results.

2. Model and Basic Equations

Let the plane $z = 0$ be occupied by a 2DEG which is infinitely spread along the x and y axes in a medium with dielectric permittivity ε_e (see Fig. 1). Electrons are in a quantum well, and their motion along the z axis is bounded (see, e.g., [5]). Two oppositely charged ions with a reduced mass m^* and charges $\pm e^*$ form an electric dipole which is located at the point $x = 0$, $y = 0$, $z = h$ in a medium with dielectric permittivity ε_d.

In order to describe oscillations of the dipole, we use the oscillator equation for relative displacements $d(t)$ of the negative and positive ions forming this dipole,

$$\ddot{d} + \gamma\dot{d} + \omega_0^2 d = -\frac{e^*}{m^*}\,\boldsymbol{\xi}\cdot[\mathbf{E}-\mathbf{E}_d]|_{x=0,y=0,z=h}\,, \quad (1)$$

where γ – the damping factor of oscillations of the dipole, ω_0 – its cyclic eigenfrequency, $\boldsymbol{\xi} = (\xi_x, \xi_y, \xi_z)$ – a unit vector directed along the dipole, $\mathbf{E}(x, y, z, t)$ – the total electric field, and $\mathbf{E}_d(x, y, z, t)$ – the field created only by the dipole. From the total field at the point, where the dipole is located, we subtract the field $\mathbf{E}_d(x, y, z, t)$ at the same point in order to exclude the self-interaction of the dipole.

We consider the electron subsystem in the drift-diffusion approximation, which impose certain limitations on the free-path length λ and the free-path time τ of the electrons. The quantity λ must be much less than all characteristic spatial sizes of the system, and the time τ must be much less than all characteristic time intervals. In addition, this model sets some conditions for the wave vectors k and the frequencies ω of waves which can be considered in the problem:

$$k\lambda \ll 1, \quad \omega\tau \ll 1. \quad (2)$$

Within the proposed model, the current density $\mathbf{j}(x, y, t)$ satisfies the equation

$$\mathbf{j} = en\mu_E\,\mathbf{E}|_{z=0} + \boldsymbol{\nabla}_\parallel(Den), \quad (3)$$

where $e, n(x, y, t)$, and $\mu_E(E)$ mean the charge ($e > 0$), surface concentration, and mobility of electrons, respectively. In the present work, we use the index $\parallel$ for quantities and differential operators referred only to the plane $z = 0$. For example, the Laplace operator in the plane $z = 0$ is denoted as $\Delta_\parallel = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2}$. The Laplace operator in bulk is $\Delta = \Delta_\parallel + \dfrac{\partial^2}{\partial z^2}$.

Equation (3) should be supplemented also by the equation of continuity

$$-e\dot{n} + (\nabla_\parallel \cdot \mathbf{j}) = 0 \quad (4)$$

and by the Poisson equation for the total field strength

$$(\boldsymbol{\nabla}\cdot(\kappa\mathbf{E})) = -4\pi e(n - n_0)\delta(z) +$$

$$+4\pi e^* d(\boldsymbol{\xi}\cdot\boldsymbol{\nabla})\delta(x)\delta(y)\delta(z - h), \quad (5)$$

where n_0 – the equilibrium surface concentration of charge carriers, $\kappa = \varepsilon_e\theta(h - z) + \varepsilon_d\theta(z - h)$ – the dielectric permittivity of the medium, $\theta(h - z)$ – the Heaviside function. Thus, ε_e – the dielectric permittivity of the medium for $z \in (-\infty, h)$, and ε_d – the dielectric permittivity of the medium for $z \in [h, +\infty)$. It is assumed that the dielectric permittivity of a spacer is the same as that of the film, in which the 2DEG is positioned. The last term of Eq. (5) can be obtained, if we expand the densities of positive and negative ion charges in a Taylor series at $h \gg d$.

Let $\mathbf{E}_0$ and n_0 be the applied external field strength and the equilibrium surface concentration of electrons, let the field $\mathbf{E}_0$ be directed in parallel to the x axis, and let $\widetilde{\mathbf{E}}(x, y, z, t)$ and $\widetilde{n}(x, y, t)$ be small deviations from the corresponding equilibrium values such that $\mathbf{E}(x, y, z, t) = \mathbf{E_0} + \widetilde{\mathbf{E}}(x, y, z, t)$ and $n(x, y, t) = n_0 + \widetilde{n}(x, y, t)$. Then

$$E = \sqrt{E_0^2 + 2(\mathbf{E_0}\cdot\widetilde{\mathbf{E}}) + \widetilde{E}^2} \simeq E_0 + s(E_0)(\mathbf{e}_x\cdot\widetilde{\mathbf{E}}), \quad (6)$$

where, by definition, the sign

$$s(E_0) = \begin{cases} 1, & E_0 \geq 0, \\ -1, & E_0 < 0. \end{cases}$$

It is assumed that the mobility $\mu_E(E)$ depends on the modulus of the total field. With regard for (6), it is possible to show that, at small deviations from the equilibrium field,

$$\mu_E(E) \simeq \mu_E(E_0 + s(E_0)(\mathbf{e}_x\cdot\widetilde{\mathbf{E}})) \simeq \mu_E(E_0) +$$

$$+\frac{\partial\mu_E(E_0)}{\partial E_0}s(E_0)(\mathbf{e}_x\cdot\widetilde{\mathbf{E}}) = \mu_0 + \mu_0' s(E_0)(\mathbf{e}_x\cdot\widetilde{\mathbf{E}}). \quad (7)$$

We represent small deviations in the form $\widetilde{\mathbf{E}}(x, y, z, t) = \mathbf{E}_1(x, y, z)e^{-i\omega t}$ and $\widetilde{n}(x, y, t) = n_1(x, y)e^{-i\omega t}$. The field $\mathbf{E}_1(x, y, z)$ is connected with the potential $\varphi(x, y, z)$ by the relation $\mathbf{E}_1 = -\boldsymbol{\nabla}\varphi$. Since the Poisson equation (5) is linear, any linear combination of its solutions is also its solution. This means that a solution of this equation can be sought in the form

$$\varphi(x, y, z) = \varphi_e(x, y, z) + \varphi_d(x, y, z), \quad (8)$$

where $\varphi_e(x, y, z)$ – the potential of electrons screened by the dipole, and $\varphi_d(x, y, z)$ – the potential of the dipole. Thus, denoting $A_d(\omega) = \omega^2 - \omega_0^2 + i\gamma\omega$, we obtain the following system of equations:

$$\begin{cases} d = -\dfrac{e^*}{m^*}(\boldsymbol{\xi}\cdot\boldsymbol{\nabla})\ \dfrac{\varphi_e}{A_d(\omega)}\Big|_{x=0,y=0,z=h}, \\ \kappa\Delta\varphi_d - (\varepsilon_e-\varepsilon_d)\delta(z-h)\dfrac{\partial\varphi_d}{\partial z} = \\ -4\pi e^* d(\boldsymbol{\xi}\cdot\boldsymbol{\nabla})\delta(x)\delta(y)\delta(z-h), \\ \kappa\Delta\varphi_e - (\varepsilon_e-\varepsilon_d)\delta(z-h)\dfrac{\partial\varphi_e}{\partial z} = 4\pi e n_1\delta(z), \\ i\omega n_1 - n_0\Big[\mu_0\Delta_\parallel(\varphi_e+\varphi_d)+\mu_0' s(E_0)E_0\dfrac{\partial^2}{\partial x^2}(\varphi_e+\varphi_d)\Big]\Big|_{z=0} - \\ -\mu_0(\mathbf{E}_0\cdot\boldsymbol{\nabla}_\parallel n_1) + D\Delta_\parallel n_1 = 0. \end{cases} \tag{9}$$

Solutions of the equation

$$A_d(\omega) = \omega^2 - \omega_0^2 + i\gamma\omega = 0 \tag{10}$$

give the eigenfrequency and the damping of the dipole.

The potential of the dipole $\varphi_d(x,y,z)$ is a solution of the second equation of system (9) and takes the form

$$\varphi_d = -\frac{2e^* d}{\varepsilon_e+\varepsilon_d}\frac{\xi_x x + \xi_y y + \xi_z(z-h)}{(x^2+y^2+(z-h)^2)^{\frac{3}{2}}}. \tag{11}$$

For the sake of brevity, it is convenient to introduce $\psi = \varphi_d|_{z=0}$. Since relation (8) allowed us to separate Eq. (5) into the second and third equations of system (9), we can perform the Fourier transformation

$$\varphi_e(\mathbf{r},z) = \int d^2k\,\varphi_k(z)\,e^{i\mathbf{kr}}, \quad n_1(\mathbf{r}) = \int d^2k\,n_k\,e^{i\mathbf{kr}}$$

and

$$\psi(\mathbf{r}) = \int d^2k\,\psi_k\,e^{i\mathbf{kr}},$$

where

$$\mathbf{r} = (x,y), \quad \mathbf{k} = (k_x,k_y), \quad \int d^2k \equiv \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y.$$

The quantities $\varphi_k(z)$, n_k, and ψ_k are, respectively, the Fourier-transforms of the potential of electrons screened by the dipole, surface concentration, and potential of the dipole at the point $z=0$. Then the Poisson equation for $\varphi_k(z)$ from system (9) and the necessary boundary conditions take the form

$$\begin{cases} \dfrac{d^2\varphi_k}{dz^2} - k^2\varphi_k = 0, \\ \varphi_k|_{z\to\pm\infty} \to 0, \\ \varphi_k|_{z=0+\varepsilon} = \varphi_k|_{z=0-\varepsilon}, \\ \varphi_k|_{z=h+\varepsilon} = \varphi_k|_{z=h-\varepsilon}, \\ \dfrac{d\varphi_k}{dz}\Big|_{z=0+\varepsilon} - \dfrac{d\varphi_k}{dz}\Big|_{z=0-\varepsilon} = \dfrac{4\pi e n_k}{\varepsilon_e}, \\ \varepsilon_d\ \dfrac{d\varphi_k}{dz}\Big|_{z=h+\varepsilon} - \varepsilon_e\ \dfrac{d\varphi_k}{dz}\Big|_{z=h-\varepsilon} = (\varepsilon_e-\varepsilon_d)\ \dfrac{d\varphi_k}{dz}\Big|_{z=h}, \end{cases} \tag{12}$$

where $\varepsilon \to +0$.

By performing the Fourier transformation and solving system (12), we obtain

$$\begin{cases} d = \dfrac{2\pi e}{\varepsilon_d}\dfrac{e^*}{m^* A_d(\omega)}\displaystyle\int d^2k\left(i\frac{\boldsymbol{\xi}_\parallel\mathbf{k}}{k} - \xi_z\right)e^{-kh}n_k, \\ \psi_k = \dfrac{e^* d}{\pi(\varepsilon_e+\varepsilon_d)}\left(i\dfrac{\boldsymbol{\xi}_\parallel\mathbf{k}}{k} + \xi_z\right)e^{-kh}, \\ \varphi_k = -\dfrac{2\pi e n_k}{\varepsilon_e k}\left(1+\dfrac{\varepsilon_e-\varepsilon_d}{\varepsilon_d}e^{-2kh}\right)e^{kz}, z\in(-\infty,0], \\ \varphi_k = -\dfrac{2\pi e n_k}{\varepsilon_e k}\left(e^{-kz}+\dfrac{\varepsilon_e-\varepsilon_d}{\varepsilon_d}e^{kz-2kh}\right), z\in[0,h], \\ \varphi_k = -\dfrac{2\pi e n_k}{\varepsilon_d k}e^{-kz}, z\in[h,+\infty), \\ i\omega n_k + n_0\big[\mu_0 k^2(\varphi_k+\psi_k)+\mu_0' s(E_0)k_x^2(\varphi_k+\psi_k)\big]\big|_{z=0} - \\ -i\mu_0 E_0 k_x n_k - Dk^2 n_k = 0. \end{cases} \tag{13}$$

Without a dipole ($d=0$, $\psi_k=0$), four last formulas of system (13) yield the dispersion equation for oscillations of the 2DEG

$$A_e(\omega,k) = i\omega - i\mu_0 E_0 k_x - M(k) - Dk^2 = 0, \tag{14}$$

where

$$M(k) = \frac{2\pi e n_0}{\varepsilon_e k}\left(1+\frac{\varepsilon_e-\varepsilon_d}{\varepsilon_d}e^{-2kh}\right)B(k)$$

and

$$B(k) = (\mu_0 k^2 + \mu_0' s(E_0)E_0 k_x^2).$$

The second term of Eq. (14) is related to the drift of charge carriers, the third term concerns the Maxwellian relaxation time and the conduction, and the fourth term describes the diffusion. Thus, the solution of Eq. (14) gives the spectrum $\omega(k)$ of elementary excitations of the 2DEG at the drift-diffusion motion of electrons. If $\mu_0' \geq 0$, then $M(k) > 0$, and the damping of oscillations occurs in the system, because $\mathrm{Im}(\omega) < 0$. But if the quantity $M(k)$ changes its sign (due to the change of the sign of μ_0') and becomes greater in modulus than Dk^2, then the damping of oscillations is changed by the exponential growth of oscillations which can be bounded only by nonlinear effects. We note that the quantity $M(k)$ includes the factor $\left(1 + ((\varepsilon_e - \varepsilon_d)/\varepsilon_d)\, e^{-2kh}\right)$ which is equal to 1 if $\varepsilon_e = \varepsilon_d$, is less than 1 if $\varepsilon_e < \varepsilon_d$, and is more than 1 if $\varepsilon_e > \varepsilon_d$. Hence, if a specimen is positioned in the medium with a sufficiently high dielectric permittivity, it is possible to decrease the value of $M(k)$ and, by this, to decrease the energy losses of electrons.

In the presence of a dipole, system (13) yields the integral equation for n_k:

$$n_k = -\frac{2en_0}{\varepsilon_d}\frac{e^{*2}B(k)\left(i\frac{\boldsymbol{\xi}_\parallel \mathbf{k}}{k} + \xi_z\right)e^{-kh}}{m^*(\varepsilon_e+\varepsilon_d)A_d(\omega)A_e(\omega,k)}\times$$

$$\times\int d^2k'\left(i\frac{\boldsymbol{\xi}_\parallel \mathbf{k}'}{k'} - \xi_z\right)e^{-k'h}n_{k'}. \quad (15)$$

Equation (15) is integral with a separable kernel. Here, we put the kernel part which is independent of k' outside of the integral symbol. Using this equation, we can perform the limiting passage to the noninteracting dipole and 2DEG. Indeed, as $h \to +\infty$, the potential will be bounded, if $A_e(\omega,k)A_d(\omega) \to 0$, and this will give Eqs. (10) and (14) describing the noninteracting systems.

We can show that, to within an arbitrary constant C, the solution of Eq. (15) takes the form

$$n_k = -C\frac{2en_0}{\varepsilon_d}\frac{e^{*2}B(k)\left(i\frac{\boldsymbol{\xi}_\parallel \mathbf{k}}{k} + \xi_z\right)e^{-kh}}{m^*(\varepsilon_e+\varepsilon_d)A_d(\omega)A_e(\omega,k)}, \quad (16)$$

under condition that the equality

$$1 = \frac{2en_0}{\varepsilon_d}\frac{e^{*2}}{m^*(\varepsilon_e+\varepsilon_d)A_d(\omega)}\int d^2k\frac{B(k)\left[\left(\frac{\boldsymbol{\xi}_\parallel \mathbf{k}}{k}\right)^2 - \xi_z^2\right]e^{-2kh}}{A_e(\omega,k)} \quad (17)$$

is satisfied. Equation (17) is a condition for the existence of nontrivial solutions of Eq. (15). We will formally call it the dispersion equation. In the absence of the translational symmetry, the solutions of the transcendental equation (17) (the eigenfrequency of oscillations of the system) do not depend on the wave vector. In what follows, we will pay the main attention to the analysis of this equation.

We consider a model which describes the interaction of a dipole with the two-dimensional electron gas at three possible orientations of the dipole. Using the oscillator equation for the dipole, the equation for the current density in the drift-diffusion approximation, the equation of continuity for electrons, and the Poisson equation, we obtain the dispersion equation for the physical system under study. This dispersion equation gives information about the renormalization of the frequency and the damping of the dipole at its interaction with the two-dimensional electron gas.

3. Calculations and Analysis of Dispersion Curves in the case of Steady Mobility

In this section, we consider the simplest solutions of the dispersion equation (17) in the case where the mobility μ_0 is independent of the field. Then Eq. (17) takes the form

$$(\Omega^2 - 1 + i\Omega\Gamma) = \Omega_{\mathrm{int}}\times$$
$$\times\int_0^{2\pi}d\theta\int_0^{\infty}dk\frac{k^3e^{-k}\left(\xi_x^2\cos^2\theta + \xi_y^2\sin^2\theta + \xi_z^2\right)}{i\Omega - i\Omega_{\mathrm{dr}}k\cos\theta - M_\tau\left(1+\frac{\varepsilon_e-\varepsilon_d}{\varepsilon_d}e^{-k}\right)k - D_\tau k^2}. \quad (18)$$

In order to obtain (18) from Eq. (17), it is necessary to set $\mu_0' = 0$ and to pass to dimensionless variables, by denoting

$$\Omega = \frac{\omega}{\omega_0}, \quad \Gamma = \frac{\gamma}{\omega_0}, \quad \Omega_{\mathrm{int}} = \frac{2e^{*2}en_0\mu_0}{\varepsilon_d(\varepsilon_e+\varepsilon_d)m^*(2h)^4\omega_0^3},$$

$$\Omega_{\mathrm{dr}} = \frac{\mu_0 E_0}{2\omega_0 h}, \quad M_\tau = \frac{\pi e n_0 \mu_0}{\varepsilon_e \omega_0 h}.$$

We assume that the diffusion coefficient D does not depend on the field and is connected with the mobility by the Einstein relation at $E_0 = 0$. Therefore,

$$D_\tau = \frac{D}{(2h)^2\omega_0} = \frac{k_{\mathrm{B}}T}{e}\frac{\mu_0}{(2h)^2\omega_0}.$$

The quantity Ω_{int} is responsible for the interaction of the dipole with the 2DEG. We denote $\kappa^{*2} = \frac{\varepsilon_d(\varepsilon_e+\varepsilon_d)}{2}$. Then Ω_{int} can be rewritten in terms of the interaction energy of the electron gas with the dipole, if we carry out the corresponding multiplication and division by the certain quantities:

$$\Omega_{\mathrm{int}} = \frac{e^{*2}en_0\mu_0}{\kappa^{*2}m^*(2h)^4\omega_0^3} = \frac{(ee^*d)^2}{\kappa^{*2}(2h)^4}\frac{n_0\mu_0}{2e\omega_0 W_k^d},$$

where e^{*d} – the dipole moment, $W_k^d = (m^* d^2 \omega_0^2)/2$ – the kinetic energy of the dipole. Then we apply the Einstein relation and get

$$\Omega_{\rm int} = \frac{W_c^{e-d}}{W_k^d} \frac{W_c^{e-d}}{k_{\rm B}T} \frac{n_0 D}{2\omega_0},$$

where

$$W_c^{e-d} = \frac{(ee^* d)}{\kappa^* (2h)^2}$$

– the energy of the Coulomb interaction of the electron gas with the dipole. Since $N = n_0 \pi (2h)^2$ is the mean number of electrons in a circle with radius $2h$, and the diffusion time of the damping of a perturbation is $\tau_D = (2h)^2/D$, we can finally write

$$\Omega_{\rm int} = \frac{1}{2\pi} \frac{W_c^{e-d} N}{W_k^d} \frac{W_c^{e-d} N}{k_{\rm B}TN} \frac{1}{\omega_0 \tau_D}. \qquad (19)$$

Thus, we get that the interaction parameter $\Omega_{\rm int}$ is the ratio of the square of the energy of the Coulomb interaction of N electrons of the 2DEG with the dipole to the kinetic energy of the dipole multiplied by the kinetic energy of N electrons $k_{\rm B}T$, the frequency of the dipole, and the diffusion time of the damping of a perturbation.

The quantity $\Omega_{\rm dr}$ is related to the drift of electrons and is proportional of the electric field strength. The quantities M_τ and D_τ are related, respectively, to the Maxwellian relaxation time and the duration of the diffusion damping and are responsible for dissipation processes in the 2DEG. If we fix all the above-mentioned quantities and choose a certain orientation of the dipole, a solution of Eq. (18) is the eigenfrequency of oscillations of the system.

As distinct from the other quantities which are present in Eq. (18), $\Omega_{\rm dr}$ can vary in a sufficiently wide range, because it depends on the applied field E_0. Therefore, Eq. (18) will be considered as an implicit dependence of Ω on $\Omega_{\rm dr}$, all the rest parameters being fixed. In this case, the frequency is complex-valued. We denote $\Omega = \Omega' + i\Omega''$.

In the case of a weak coupling ($\Omega_{\rm int} \to 0$), the real part is formed by the frequency of the dipole and a small addition to its frequency, and the imaginary part is determined by the damping of the dipole ($\frac{\Gamma}{2}$, since Γ enters only into the right-hand side of the dispersion equation), and by a small addition to this damping. Therefore, it is convenient to introduce corrections to the real part of the frequency of the dipole (to one in the dimensionless variables) and to a half-damping Γ of oscillations of the dipole in the following way:

$$R_d(\Omega_{\rm dr}) = \Omega'(\Omega_{\rm dr}) - 1, \qquad (20)$$
$$I_d(\Omega_{\rm dr}) = \Omega''(\Omega_{\rm dr}) + \frac{\Gamma}{2}.$$

In what follows, we will use these corrections, since they present all the necessary information about oscillations of the system composed from the dipole and the 2DEG.

The exact solutions of Eq. (18) can be determined only by numerical methods. Nevertheless, we can construct some approximate analytical solutions. Let us consider a partial case where the electric field is zero: $E_0 = 0$. We now multiply and divide the integrand in Eq. (18) by the expression which is complex conjugate to the denominator and equate separately the real parts, as well as separately the imaginary parts, of the equation. Then we get that the correction $I_d(\Omega_{\rm dr})$ is strictly negative:

$$I_d = -\frac{\Omega_{\rm int}}{2} \int_0^{2\pi} d\theta \int_0^\infty k^3 e^{-k} \times$$
$$\times \frac{\left(\xi_x^2 \cos^2\theta + \xi_y^2 \sin^2\theta + \xi_z^2\right) dk}{(D_\tau k^2 + M_\tau\left(1 + \frac{\varepsilon_e + \varepsilon_d}{\varepsilon_d} e^{-k}\right) k - \Omega'')^2 + (\Omega')^2} < 0. \qquad (21)$$

We now consider another limiting case of strong fields ($\Omega_{\rm dr} \gg 1$). After the integration with respect to θ on the right-hand side of Eq. (18), we can apply the approximation $\Omega_{\rm dr} \gg 1$ and then integrate with respect to k. The approximate analytical solution for sufficiently strong fields takes the form

$$\begin{cases} R_d = -2\pi\Omega_{\rm int}\left[\dfrac{\xi_y^2 + \xi_z^2}{\Omega_{\rm dr}} + \left(\xi_x^2 - \xi_y^2\right) \dfrac{M_\tau (9\varepsilon_d - \varepsilon_e) + 24 D_\tau}{8\Omega_{\rm dr}^2}\right], \\ I_d = \dfrac{2\pi\Omega_{\rm int}\left(\xi_x^2 - \xi_y^2\right)}{\Omega_{\rm dr}^2}. \end{cases} \qquad (22)$$

It is seen from this solution that the addition to the real part of the frequency of the dipole is negative. The addition to the damping of the dipole can be positive (the growth of oscillations) for the orientation of the dipole in parallel to the field ($\xi_x = 1,\ \xi_y = 0,\ \xi_z = 0$). Such an addition is always negative (the damping of oscillations) at the orientation along the y or z axis. Thus, at the orientation of the dipole in parallel to the field, it is possible to excite oscillations of the dipole by the drift of electrons. For the growth of oscillations of the system, it is necessary that the contribution to I_d due to the drift component (parameter $\Omega_{\rm dr}$) be greater than the total contribution of both the diffusion damping time and the Maxwellian relaxation time to I_d. Moreover, the system will be unstable, if the correction to I_d is greater than the damping of the dipole Γ.

Using formulas (21) and (22), we may make conclusions about a structure of the function $I_d(\Omega_{\rm dr})$. For example, at the orientation of the dipole in parallel to the field, we have $I_d < 0$ at low fields and $I_d > 0$ at high fields; it is a decreasing function of the parameter $\Omega_{\rm dr}$. Hence, the function $I_d(\Omega_{\rm dr})$ will cross the axis $\Omega_{\rm dr}$ at some point. Then it will attain a maximum (at least one maximum), and it will decrease further as $1/\Omega_{\rm dr}^2$. It follows from formula (22) that the correction R_d tends asymptotically to zero at high fields.

For numerical studies of Eq. (18), we have to consider specific materials and parameters. These parameters should be chosen such that inequalities (2) be satisfied. To illustrate the solutions of Eq. (18), we consider a quantum well on the basis of GaN (with the wurtzite structure) with the dielectric permittivity $\varepsilon_e = 5.35$ and the mobility $\mu_0 = 500$ cm^2/(V·s). We chose this material, because it is characterized by a comparatively low mobility, which is required to satisfy inequalities (2). The parameters of GaN are taken from [6, 7]. The other parameters related to the 2DEG will be indicated additionally in the course of the analysis.

Knowing the mobility μ_0, we can estimate the free-path time of an electron if its effective mass $m_e = 0.2m_0$, where m_0 is the free electron mass. We obtain that the free-path time $\tau = \frac{m_e}{e}\mu_0 = 5.7 \times 10^{-14}$ s. Then the free-path length of an electron can be estimated as $\lambda = \sqrt{\frac{2k_{\rm B}T}{m_e}}\tau$, where $k_{\rm B}$ is the Boltzmann constant. The characteristic size of the system h corresponds to the wave vector k of the order of $\frac{1}{h}$. Then inequalities (2) can be written in the form

$$\sqrt{\frac{2k_{\rm B}T}{m_e}}\frac{\tau}{h} < 1, \quad \omega_0 < \frac{1}{\tau}. \tag{23}$$

The estimate of the free-path time of an electron for the chosen material indicates that the frequency of oscillations of the dipole belongs to a subterahertz range of frequencies or is close to a frequency of 1 THz. As such a dipole, we can consider heavy organic molecules [11–13], many-electron quantum dots [14], whose characteristic frequencies fall just in this range, or other artificially produced systems with a sufficiently large dipole moment and sufficiently low frequencies of oscillations. By taking a heavy organic molecule as a dipole, we accept that the charge e^* is equal to the electron charge and the reduced mass $m^* = 2000m_0$. We note that the necessity to consider low frequencies or low mobility of electrons is related only to the boundedness of the model under consideration, i.e., to inequalities (23). The physical effects considered in this work will be probably observed also in the high-frequency region of oscillations.

To illustrate the solutions of the dispersion equation, we chose the distance from the 2DEG to the dipole h and the cyclic frequency of the dipole ω_0 as follows: $h = 2 \times 10^{-6}$ cm and $\omega_0 = 2\pi \times 10^{12}$ 1/s (which corresponds to a frequency of 1 THz). Let the medium, where the dipole is positioned, be vacuum with $\varepsilon_d = 1$. Then the first inequality in (23) can be satisfied at sufficiently low temperatures. On the other hand, the model under study is valid for the nondegenerate charge carriers. The second inequality in (23) is satisfied at the above-indicated mobility.

In Fig. 2,*a*, we present the dependence of the correction R_d on the parameter $\Omega_{\rm dr}$ at the orientation of the dipole in parallel to the x axis. It is seen from this figure that the larger the concentration (at a fixed temperature), the greater the effect of a renormalization of the real part of the frequency. Moreover, the higher the temperature (at a fixed concentration of electrons), the less the effect of a renormalization of the real part of the frequency.

In Fig. 2,*b*, we show the dependence of the correction I_d on the parameter $\Omega_{\rm dr}$ at the orientation of the dipole in parallel to the x axis. For example, let us consider the curve constructed at $n_0 = 10^{10}$ cm^{-2} and a temperature of 300 K. In this case, the sign of the imaginary part of the frequency changes, if $\Omega_{\rm dr} \simeq 0.75$. The value of the field strength E_0 corresponding to this value of the parameter $\Omega_{\rm dr}$ is $E_0 \simeq 37.7$ kV/cm. As is known [7], the drift velocity of electrons, as a function of the electric field strength applied to GaN, reaches the maximum at fields of about 100–150 kV/cm. Since the imaginary part of the frequency changes the sign, the system becomes unstable, and oscillations of this system increase.

As seen from Fig. 2,*b*, the greater the concentration of current carriers (M_τ), the greater the role of dissipations in the 2DEG, the greater the fields, at which the sign of Im(Ω) changes, and the less the maximum value of the instability increment. As the diffusion coefficient increases with the temperature, the instability increment must decreases. But, at certain values of the parameters and at the orientation of the dipole in parallel to the field, we observe the tendency to an increase of oscillations in the system due to the drift of electrons. The analysis of formula (14) indicates that the maximum

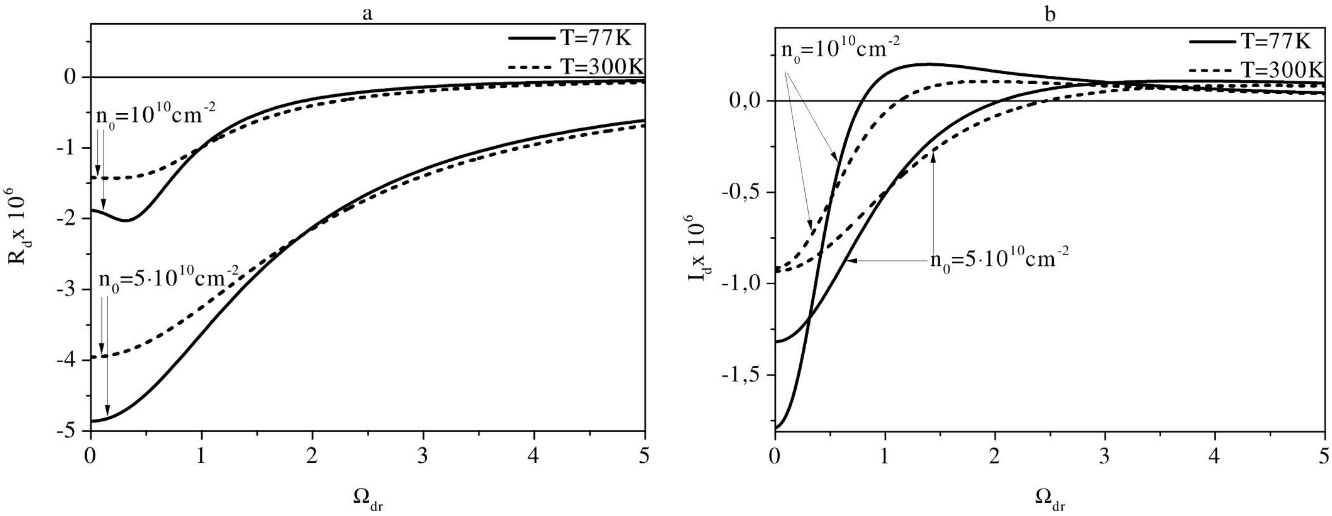

Fig. 2. Corrections R_d (a) and I_d (b) versus the parameter $\Omega_{\rm dr}$ at the orientation of the dipole in parallel to the x axis at various temperatures and concentrations of electrons

contribution to a growth of oscillations can be given by waves propagating in parallel to the field. The dipole interacts with all collective excitations of the 2DEG, but the system can be unstable due to the interaction with waves propagating along the field.

By considering the instability increment as a function of the parameter $\Omega_{\rm dr}$, it is easy to see that, in each separate case (or at a fixed concentration and a fixed temperature), there exists some critical value of $\Omega^c_{\rm dr}$ such that $\mathrm{Im}(\Omega) < 0$ on the left from it and $\mathrm{Im}(\Omega) > 0$ on the right. This point, $\Omega^c_{\rm dr}$, is a point, at which $\mathrm{Im}(\Omega(\Omega_{\rm dr})) = 0$. Its position depends on the concentration and the temperature. Therefore, one can control its position, by varying the temperature and the concentration of electrons.

At the orientation of the dipole perpendicularly to the field, formulas (21) and (22) indicate that oscillations of the system must decay in the course of time. Therefore, as an example, it is sufficient to consider any single case: for example, let the dipole be oriented in parallel to the z axis.

In Fig. 3, we give the corrections R_d and I_d versus the parameter $\Omega_{\rm dr}$ at the orientation of the dipole in parallel to the z axis. Due to the orientation of the dipole perpendicularly to the field, the effect of the damping of oscillations of the system increases (approximately twice at low fields) as compared with the case where the dipole is oriented along the x axis. It is also seen that the higher the concentration and the less the temperature, the greater the effect of a renormalization of the frequency of joint oscillations of the dipole and the 2DEG.

At the orientation of the dipole perpendicularly to the field, we observe the electron-induced effect of the damping of oscillations. At the orientation of the dipole in parallel to the field at low fields, the effect of the damping of oscillations of the system is also revealed. But, at sufficiently intense fields, the imaginary part of the frequency changes its sign, i.e., there exists the tendency for the system to become unstable. The performed numerical studies of Eq. (18) agree qualitatively with formulas (21) and (22). It is shown that the critical field, at which the sign of the imaginary part of the frequency changes, decreases, as the influence of dissipation processes decreases.

4. Calculations and Analysis of Dispersion Curves in the Case of the Krëmer Mobility

The dispersion equation (17) is deduced in a rather general form for any mobility. Therefore, for each specific physical situation, we need to indicate or calculate the dependence of the mobility on the field. In this section, we consider the mobility within the Krëmer model [8]. As for the interaction of the 2DEG with the dipole under the negative differential conduction, we use the model proposed to explain the Gunn effect [9, 10].

Thus, the drift velocity $V_{\rm dr}(E_0)$ in the Krëmer model takes the form

$$v_{\rm dr}(f) = \frac{1+\frac{1+5b}{3-b}}{1+b}\frac{1+bf^4}{1+\frac{1+5b}{3-b}f^4}f,, \qquad (24)$$

where $v_{\rm dr}(f) = V_{\rm dr}(E_0)/v_m$ and $f = E_0/E_m$ are, respectively, the dimensionless drift velocity and the applied

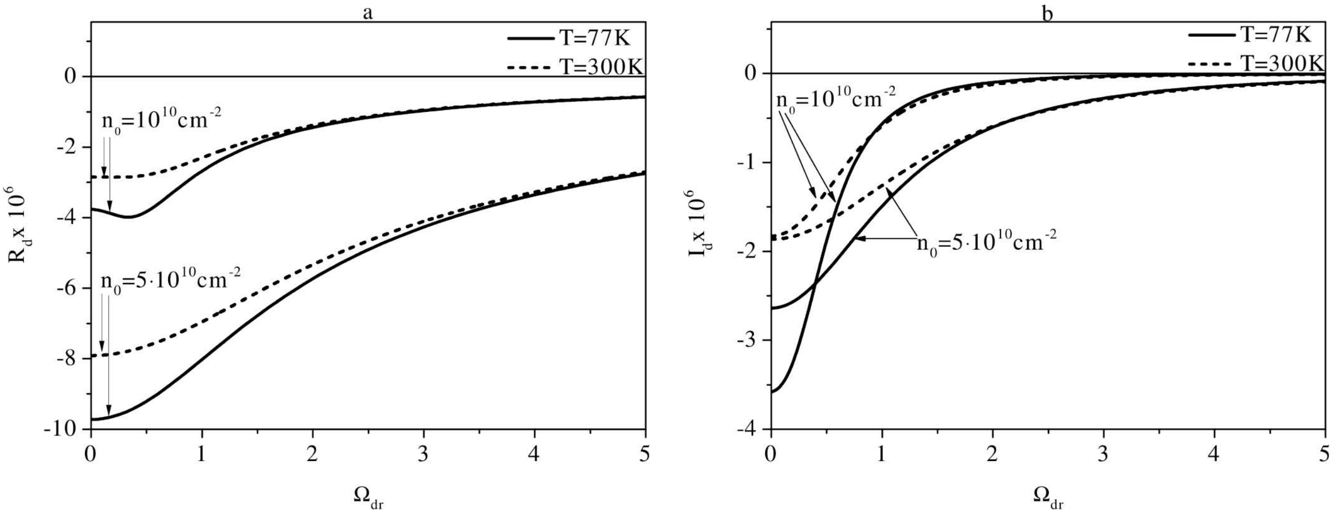

Fig. 3. Corrections R_d (*a*) and I_d (*b*) versus the parameter $\Omega_{\rm dr}$ at the orientation of the dipole in parallel to the z axis at various temperatures and concentrations of electrons

field strength. The quantity $v_m = \mu_m E_m$ is the maximum value of the drift velocity of electrons $V_{\rm dr}$, and E_m and μ_m are the field strength and the mobility corresponding to v_m. The less the parameter $b > 0$, the greater the region where the drift velocity decreases, and the stronger the manifestation of the Gunn effect. It is easy to verify that $v_{\rm dr}|_{f=1} = 1$ and $\frac{dv_{\rm dr}}{df}\big|_{f=1} = v'_{\rm dr} = 0$. The dependence of the drift velocity of electrons $v_{\rm dr}$ on the field f is shown in Fig. 4.

In this section, the dispersion equation is obviously different from Eq. (18), since $\mu'_0 \neq 0$. It is convenient to pass to somewhat other dimensionless variables as compared with those in the previous section. Then the dispersion equation (17) takes the following form:

$$(\Omega^2 - 1 + i\Omega\Gamma) = \overline{\Omega}_{\rm int} \int\limits_0^{2\pi} d\theta \int\limits_0^{\infty} dk k^3 e^{-k} \times$$

$$\times \frac{\left(\mu + \mu' f \cos^2\theta\right)\left(\xi_x^2 \cos^2\theta + \xi_y^2 \sin^2\theta + \xi_z^2\right)}{\overline{A_e}(\Omega, k)}, \qquad (25)$$

where

$$\overline{A_e}(\Omega, k) = i\Omega - i\overline{\Omega}_{\rm dr}\mu f k \cos\theta - \overline{M}(k) - \overline{D}_\tau k^2$$

and

$$\overline{M}(k) = \overline{M}_\tau k \left(1 + \frac{\varepsilon_e - \varepsilon_d}{\varepsilon_d} e^{-k}\right)\left(\mu + \mu' f \cos^2\theta\right).$$

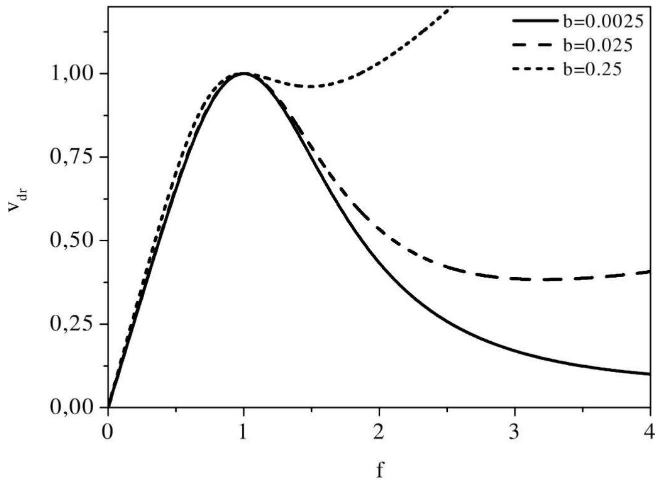

Fig. 4. Dependence of the drift velocity of electrons on the field at various values of the parameter b in the Krëmer model [8]

We denote

$$\Omega = \frac{\omega}{\omega_0}, \quad \Gamma = \frac{\gamma}{\omega_0}, \quad \overline{\Omega}_{\rm int} = \frac{e^{*2} e n_0 \mu_m}{\varepsilon_d(\varepsilon_e + \varepsilon_d) m^* (2h)^4 \omega_0^3},$$

$$\overline{\Omega}_{\rm dr} = \frac{\mu_m E_m}{2\omega_0 h}, \quad \overline{M}_\tau = \frac{\pi e n_0 \mu_m}{\varepsilon_e \omega_0 h}, \quad \overline{D}_\tau = \frac{k_{\rm B} T}{e} \frac{\mu_m}{(2h)^2 \omega_0},$$

$$\mu' = \frac{d\mu(f)}{df}, \quad v'_{\rm dr} = \frac{dv_{\rm dr}(f)}{df}.$$

We note that, in this section, the parameter $\overline{\Omega}_{\rm dr}$ does not depend on the field E_0. Equation (25) can be considered as an implicit function $\Omega(f)$.

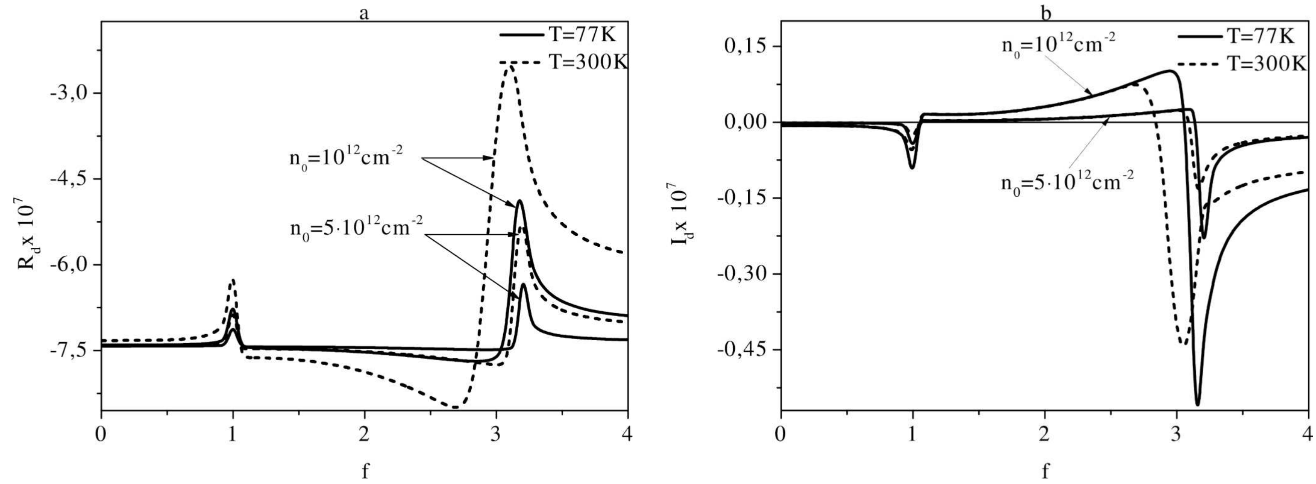

Fig. 5. Corrections R_d (a) and I_d (b) versus the field f at the orientation of the dipole in parallel to the x axis at various temperatures and concentrations of electrons

Exact solutions of Eq. (25) can be determined only by numerical methods. But we can obtain approximate analytical formulas describing the dependence of the corrections R_d and I_d on the field on linear segments of the drift velocity ($v'_{\rm dr} > 0$). For simplicity, let us consider the case where $\varepsilon_e = \varepsilon_d$. We will analyze three possible situations in the approximation $\overline{D}_\tau/\overline{M}_\tau \ll 1$.

If the dipole is directed in parallel to the x axis ($\xi_x = 1, \xi_y = 0, \xi_z = 0$), then

$$\begin{cases} R_d = -R_0^{x,y} - \dfrac{\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau^2}\dfrac{\left(12\overline{D}_\tau - \Gamma\right)\left(\mu - \sqrt{\mu v'_{\rm dr}}\right)}{1 - R_0^{x,y}\sqrt{\mu v'_{\rm dr}}\,(\mu - v'_{\rm dr})}, \\ I_d = -\dfrac{\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau^2}\left(\dfrac{\mu}{(\mu - v'_{\rm dr})\sqrt{\mu v'_{\rm dr}}} - \dfrac{1}{\mu - v'_{\rm dr}}\right), \end{cases} \tag{26}$$

where $R_0^{x,y} = 1 - \sqrt{1 - \frac{\Gamma^2}{4} - \frac{2\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau}}$.

If the dipole is directed in parallel to the y axis ($\xi_x = 0, \xi_y = 1, \xi_z = 0$), we have

$$\begin{cases} R_d = -R_0^{x,y} - \dfrac{\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau^2}\dfrac{\left(12\overline{D}_\tau - \Gamma\right)\left(\sqrt{\mu v'_{\rm dr}} - v'_{\rm dr}\right)}{1 - R_0^{x,y}\sqrt{\mu v'_{\rm dr}}\,(\mu - v'_{\rm dr})}, \\ I_d = -\dfrac{\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau^2}\left(\dfrac{1}{\mu - v'_{\rm dr}} - \dfrac{v'_{\rm dr}}{(\mu - v'_{\rm dr})\sqrt{\mu v'_{\rm dr}}}\right). \end{cases} \tag{27}$$

If the dipole is directed in parallel to the z axis ($\xi_x = 0, \xi_y = 0, \xi_z = 1$), then

$$\begin{cases} R_d = -R_0^{z} - \dfrac{\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau^2}\dfrac{\left(12\overline{D}_\tau - \Gamma\right)}{1 - R_0^{z}\sqrt{\mu v'_{\rm dr}}}, \\ I_d = -\dfrac{\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau^2}\dfrac{1}{\sqrt{\mu v'_{\rm dr}}}, \end{cases} \tag{28}$$

where $R_0^{z} = 1 - \sqrt{1 - \frac{\Gamma^2}{4} - \frac{8\pi\overline{\Omega}_{\rm int}}{\overline{M}_\tau}}$.

For example, consider the case where the dipole is oriented along the x axis. Then formula (26) implies that, if $f = 0$, the addition to the frequency of the dipole is negative, because $(\pi\overline{\Omega}_{\rm int})/\overline{M}_\tau > 0$. Then, as the field increases, this addition decreases. This formula indicates also that, for sufficiently low fields, the imaginary part of the frequency is negative.

Below, we present the results of numerical studies of Eq. (25). In the previous case, we chose GaN as a material for the quantum well. If the drift velocity is set by the Krëmer model, it is convenient to choose a GaAs-based quantum well, since the significantly lower fields are required for GaAs to attain the maximum of the drift velocity. We take the following characteristic value of the parameter μ_m for the GaAs-based quantum well [15]: $\mu_m \simeq 6667$ cm^2/(V·s). Then, for the field $E_m = 3$ kV/cm, the drift velocity attains the maximum value $V_d = 2 \times 10^7$ cm/s. As is known [5], at fields of the order of E_m, the free-path time of electrons is about 0.1 ps. Therefore, inequalities (2) are satisfied if $\omega_0 = 2\pi \times 10^{12}$ 1/s, and the distance $h = 3 \times 10^{-6}$ cm. If $b = 0,025$, then the drift velocity decreases in the interval $f \in$ (1-3.21) (see Fig. 4). The dielectric permittivity of GaAs $\varepsilon_e = 10.89$, and the dipole is positioned in vacuum: $\varepsilon_d = 1$.

In Fig. 5, we give the dependence of the corrections R_d and I_d on the field strength f at the orientation of the dipole in parallel to the x axis. The function $R_d(f)$ has two local maxima which approach each other, as the coefficient of diffusion increases. The addition to the frequency of the dipole is negative for all parameters under

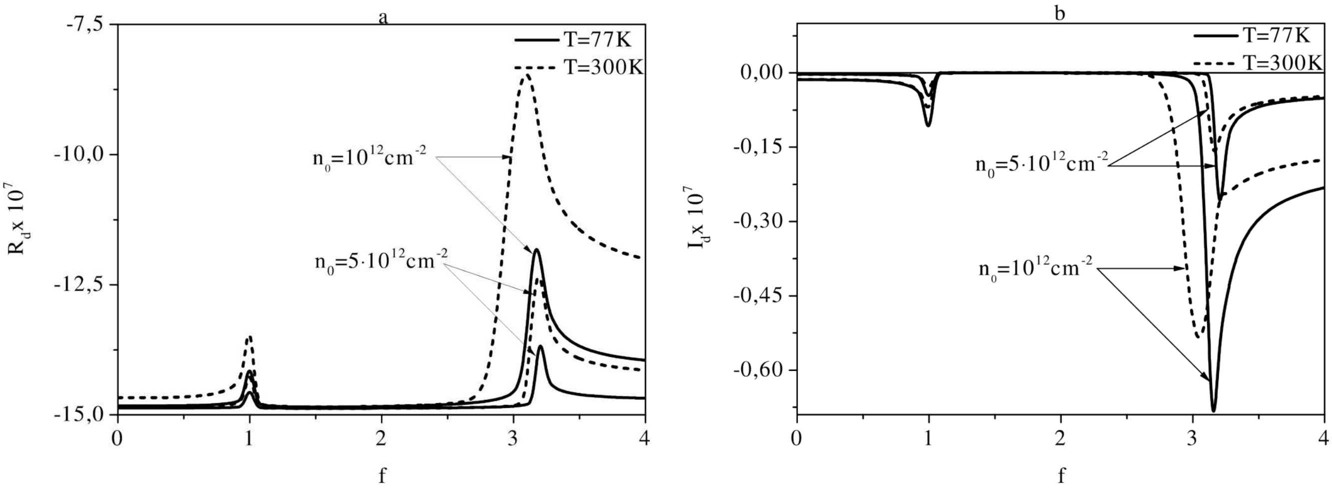

Fig. 6. Corrections R_d (a) and I_d (b) versus the field strength f at the orientation of the dipole in parallel to the z axis at various temperatures and concentrations of electrons

consideration, but the case where it can be positive at certain values of the parameters is not considered here.

As for the addition to the imaginary part of the frequency shown in Fig. 5,b, it can have different signs: it is negative in a rather wide interval of fields and is positive on a certain interval where the drift velocity decreases. The addition to the damping of the dipole can be positive, but it is not so in the whole region of fields which correspond to a decrease of the drift velocity. The interval of values of the field strengths, for which $I_d(f) > 0$, increases with decrease in the temperature. As the coefficient of diffusion increases, the instability increment decreases, since the diffusion hampers any increase of oscillations in such physical system. Nevertheless, at certain temperatures and concentrations of current carriers, the system becomes unstable, and the effect of a growth of oscillations in this system is observed. This instability is caused by the instability of the 2DEG itself. As was mentioned above, it follows from formula (14) that the maximum contribution to a growth of oscillations is made by those waves which propagate in parallel to the field. As the concentration of charge carriers increases, both effects of a renormalization of the frequency and the instability of the system are less remarkable, though the interval of values of the field strengths, for which the instability happens, increases with the concentration.

Like the previous section, the analytical consideration of the dispersion equation shows that if the dipole is oriented perpendicularly to the field, only the damping of oscillations is realized in the system. Therefore, we consider only the case where the dipole is oriented in parallel to the z axis. In Fig. 6, we present the dependences of the corrections R_d and I_d on the field strength f at the orientation of the dipole in parallel to the z axis. As seen from Fig. 6,b, only the damping of oscillations is possible in such a system, because $I_d(f) < 0$ for all fields.

Like the previous section, at the orientation of the dipole perpendicularly to the applied field, we observe the electron-induced effect of the damping of oscillations. At the orientation of the dipole in parallel to the field, the system can be unstable, which is related to the interaction of the dipole with waves which propagate in parallel to the applied field. As the concentration of charge carriers decreases, the effects of a renormalization of the frequency and the instability increment of the system increase, whereas the effect of a renormalization of the frequency becomes weaker, as the diffusion coefficient increases.

5. Conclusions

We have studied the interaction of a dipole with the two-dimensional electron gas at three possible orientations of the dipole. Using the oscillator equation for the dipole, the equations for the current density in the drift-diffusion approximation, the equation of continuity for electrons, and the Poisson equation, we have deduced the dispersion equation for the physical system under study. This dispersion equation gives information about a renormalization of the frequency and the damping of the dipole at its interaction with the two-dimensional electron gas.

We considered the case where the mobility is independent of the field. The corresponding dispersion equation is analyzed, and its approximate solutions are obtained. We have constructed the dependences of the corrections to the frequency as functions of a parameter which depends linearly on the field strength at various orientations of the dipole and various temperatures and concentrations of charge carriers.

The analysis of the dispersion equation shows that, at the orientation of the dipole in parallel to the field, the addition to the frequency of the dipole is negative and tends asymptotically to zero, as the field strength increases. The addition to the imaginary part of the frequency as a function of the field strength is negative, then it crosses the axis, reaches a maximum, and then decreases, by asymptotically approaching zero. At sufficiently high fields, the system can become unstable, and the effect of a growth of oscillations of this system can arise due to the drift of current carriers. If the dipole is parallel to the field, the instability increment decreases, as the temperature or the concentration of electrons increases. This happens, because the temperature and the concentration are responsible for the dissipation processes running in the 2DEG. We have shown also that, as the effect of dissipation processes decreases, the value of the field strength, at which the sign of the imaginary part of the frequency is changed, decreases.

If the dipole is oriented perpendicularly to the field, then the behavior of the real part of the frequency is similar to that of the same function at the orientation of the dipole in parallel to the field, but the imaginary part of the frequency is strictly less than zero. Therefore, at the orientation of the dipole perpendicularly to the field, we observe the damping of oscillations in the system.

We have also considered the case where the 2DEG is characterized by the negative differential conductance and interacts with the dipole. Within the Krëmer model for the drift velocity of charge carriers, we constructed the dependences of additions to the frequency of the dipole as functions of the field strength at various orientations of the dipole, temperatures, and concentrations of charge carriers.

It is shown that, at the orientation of the dipole in parallel to the field, the addition to the frequency of the dipole is negative in all the cases. The imaginary part of the frequency can possess different signs: it is negative in a rather wide interval of field strengths, and it is positive in a certain region of field strengths with the negative differential conductance. At certain temperatures and concentrations of current carriers, the system is unstable, and the effect of a growth of oscillations in this system can happen. Only at the orientation of the dipole in parallel to the field, the system can be unstable, which is related to the interaction of the dipole with waves propagating in parallel to the field. As the concentration of charge carriers decreases, both effects of a renormalization of the frequency and the instability of the system increase, whereas the effect of a renormalization of the frequency becomes weaker, as the diffusion coefficient increases.

If the dipole is oriented perpendicularly to the field, the addition to the frequency of the dipole is negative in all the cases. The addition to the damping of the dipole is strictly negative, and only the damping of oscillations is realized in such a system.

The common point of both cases under consideration (where $\mu' = 0$ or $\mu' \neq 0$) consists in that, at the orientation in parallel to the field,the instability and the growth of oscillations can happen in both systems, whereas two other orientations are characterized by the effect of the electron-induced damping of oscillations of the system.

The studied phenomena can be applied in molecular plasmonics and for the generation of subterahertz and terahertz emissions.

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ВЗАЄМОДІЯ ДРЕЙФУЮЧИХ ЕЛЕКТРОНІВ ІЗ ВІДДАЛЕНИМ ДИПОЛЕМ

С.М. Кухтарук

Р е з ю м е

Дану статтю присвячено дослідженню взаємодії дрейфуючих двовимірних електронів і віддаленої молекули. Для цього розглянуто взаємодію двовимірного електронного газу (2DEG) з віддаленим диполем при трьох можливих орієнтаціях останнього. Отримано дисперсійне рівняння для спільних коливань 2DEG та диполя. Проведено аналітичне та чисельне дослідження цього рівняння. Для орієнтацій диполя перпендикулярно до прикладеного електричного поля спостерігається ефект загасання коливань, а при орієнтації диполя паралельно полю може бути наявним ефект наростання коливань системи. Різна залежність рухливості від поля по-різному впливає на залежність інкременту нестійкості від концентрації електронів, що пов'язано з різними механізмами нестійкості.