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LETTER TO THE EDITOR

The screening of a potential distribution by a two-dimensional electron gas in a strong electromagnetic field

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Abstract. The influence of a very intense electromagnetic wave (EMW) on the penetration of a static electric field into a two-dimensional electron gas (2DEG) is considered. A static field is created by a charge distribution in the plane parallel to the 2DEG; the electric wavevector is parallel to the same plane. The distribution of the DC part of the potential behind the plane of the 2DEG is calculated for the two simplest cases, the sinusoidal charge distribution and the point charge. In the first case the amplitude of the sinusoidal potential is found to be an oscillating function of the wave amplitude. With increasing EMW intensity the 2DEG becomes 'electrically transparent', i.e. stops screening the static field and giving a contribution to the image potential.

The phenomenon of screening breakdown for the point charge (ion) field in semiconductors in the presence of an intense electromagnetic wave (EMW) was considered in [1, 2]. Screening breakdown takes place when a long-range part of the static potential appears that is proportional to the wave intensity when the latter is not quite so large.

In this Letter we consider a phenomenon of the same kind, i.e. the influence of an intense EMW on the penetration of the static electric field into a 2DEG. Such a problem would seem to be of interest since the charged impurities situated near the 2DEG play an important role in a number of phenomena [3].

Here screening breakdown of the form described above does not occur because the field of the point charge, penetrating into the 2DEG, has a long-range (dipole) form at distances that are large compared with the screening radius, even in the absence of an EMW. Nevertheless, as will be seen below, the influence of intense EMW on the penetration of a static electric field into a 2DEG turns out not to be negligible. As will be shown below, under the action of a strong high-frequency field the 2DEG becomes 'electrically transparent', and hence that the field that is formed by a static charge distribution outside the 2DEG penetrates into it.

Let the 2DEG occupy the plane $z = 0$ and divide the range $z > 0$ with dielectric constant ε_+ from the range $z < 0$ with the dielectric constant ε_-. The two-dimensional charge distribution $Q(\boldsymbol{\rho})$ is placed in the plane $z = h$ ($h \geqslant 0$). The EMW impinges on the 2DEG, the electric field of which is parallel to the plane of the 2DEG. We shall attempt to

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find the field created by a charge distribution in the presence of the 2DEG and the EMW in the form of a Fourier expansion

$$\varphi(\boldsymbol{\rho}, z, t) = \int \varphi(\boldsymbol{q}, z, t) \exp(\mathrm{i}\boldsymbol{q} \cdot \boldsymbol{\rho}) \frac{\mathrm{d}^2 \boldsymbol{q}}{(2\pi)^2}. \tag{1}$$

The Fourier component $\tilde{\varphi}(\boldsymbol{q}, z, t)$ is described by the equations

$$\partial^2 \varphi_+/\partial z^2 - q^2 \varphi_+ = -(4\pi/\varepsilon_+) Q(\boldsymbol{q}) \delta(z - h) \tag{2}$$

$$\partial^2 \varphi_-/\partial z^2 - q^2 \varphi_- = 0 \tag{3}$$

where $Q(\boldsymbol{q})$ is the Fourier component of the charge distribution and the + and − signs indicate $z > 0$ and $z < 0$.

With $z = 0$ the following boundary conditions are fulfilled:

$$(\varphi_+ - \varphi_-)|_{z=0} = 0 \tag{4}$$

$$\left(\varepsilon_+ \frac{\partial \varphi_+}{\partial z} - \varepsilon_- \frac{\partial \varphi_-}{\partial z}\right)\Bigg|_{z=0} = -4\pi e \sum_{\boldsymbol{p}} \langle a^+_{\boldsymbol{p}-\boldsymbol{q}} a_{\boldsymbol{p}} \rangle. \tag{5}$$

The right-hand side of (5) contains the Fourier component of the charge density of the 2DEG in terms of electron creation and annihilation operators ($\boldsymbol{p}$ is the two-dimensional crystal momentum of the electron, e is the elementary charge, and the angular brackets indicate the averaging with the density matrix of the 2DEG in the presence of an EMW).

The Fourier component of the partial density of the 2DEG $\langle a^+_{\boldsymbol{p}-\boldsymbol{q}} a_{\boldsymbol{p}} \rangle$ in the random-phase approximation is determined by the equation (see [1])

$$\{\partial \varphi/\partial t + \mathrm{i}[\varepsilon_{\boldsymbol{p}} - \varepsilon_{\boldsymbol{p}-\boldsymbol{q}} + (e/mc)\boldsymbol{q} \cdot \boldsymbol{A}(t)]\} \langle a^+_{\boldsymbol{p}-\boldsymbol{q}} a_{\boldsymbol{p}} \rangle = -\mathrm{i}e\varphi(\boldsymbol{q}, 0, t)(n_{\boldsymbol{p}-\boldsymbol{q}} - n_{\boldsymbol{p}}) \tag{6}$$

where the $n_{\boldsymbol{p}} = \langle a^+_{\boldsymbol{p}} a_{\boldsymbol{p}} \rangle$ are the occupation numbers of electron states in the 2DEG, m is the effective mass of an electron, c is the velocity of light, and $\boldsymbol{A}(t)$ is the vector potential of the EMW, related to the electric field strength of the wave, $\boldsymbol{E}(t) = \boldsymbol{E}_0 \sin \boldsymbol{\Omega} t$, by the relation $\boldsymbol{E}(t) = -\mathrm{d}\boldsymbol{A}/c\,\mathrm{d}t$.

Solving equation (6) using zero-field initial conditions, substituting the result into (5) and then solving equations (2) and (3) using the matching conditions (4) and (5), we obtain for the DC part of the potential when $z < 0$

$$\varphi_-(\boldsymbol{q}, z) = \frac{\Omega}{2\pi} \int_0^{2\pi/\Omega} \tilde{\varphi}(\boldsymbol{q}, z, t)\,\mathrm{d}t = \frac{4\pi Q(\boldsymbol{q})}{q} \exp[-q(h - z)]$$
$$\times \sum_{n=-\infty}^{\infty} \mathcal{J}_n^2(\boldsymbol{a}, \boldsymbol{q})(\varepsilon_+ + \varepsilon_- - \Pi(\boldsymbol{q}, n\Omega))^{-1}. \tag{7}$$

Here $\boldsymbol{a} = e\boldsymbol{E}_0/m\Omega^2$ is the oscillation amplitude of the electron in the field of the EMW, $\mathcal{J}_n(x)$ is the Bessel function of the real argument and

$$\Pi(\boldsymbol{q}, \omega) = \frac{4\pi e^2}{q} \sum_{\boldsymbol{p}} \frac{n_{\boldsymbol{p}+\boldsymbol{q}} - n_{\boldsymbol{p}}}{\varepsilon_{\boldsymbol{p}+\boldsymbol{q}} - \varepsilon_{\boldsymbol{p}} - \omega} \tag{8}$$

is the polarisation function of the 2DEG ($\hbar = 1$).

Formula (7) takes a simpler form when $\Omega \gg \omega_0$, $q \ll \bar{p}$, where ω_0 is the frequency of the plasmons of the 2DEG and $\bar{p}$ is a typical value of the crystal momentum of the electrons. In that case

$$\Pi(\boldsymbol{q}, n\Omega) \simeq \begin{cases} -(\varepsilon_+ + \varepsilon_-)\kappa/q & n = 0 \\ 0 & n \neq 0 \end{cases} \tag{9}$$

where $\kappa = 4\pi e^2 N_s/[(\varepsilon_+ + \varepsilon_-)k_B T]$ is the reciprocal of the screening length, and N_s is the density of the 2DEG. Formula (7) takes the form

$$\varphi(\boldsymbol{q}, z) = [4\pi Q(\boldsymbol{q})/(\varepsilon_+ + \varepsilon_-)q] \exp[-q(h - z)]\{1 - [\kappa/(q + \kappa)]\mathscr{J}_0^2(\boldsymbol{a}, \boldsymbol{q})\}. \tag{10}$$

We confine ourselves to the two simplest (but, probably, the most important) cases: (i) a one-dimensional sinusoidal charge distribution; (ii) a point charge.

(i) Let the density of the charge distribution be $Q(\boldsymbol{\rho}) = \sigma_0 \cos kx$ and $\boldsymbol{a} = \{a, 0, 0\}$. Then the potential distribution is described by the expression

$$\varphi_-(x, z) = [4\pi\sigma_0 \cos kx/(\varepsilon_+ + \varepsilon_-)k] \exp[-k(h - z)]\{1 - [\kappa/(k + \kappa)]\mathscr{J}_0^2(a, k)\}. \tag{11}$$

The screening breakdown may be described by the relation

$$\eta_a \equiv \varphi_-(x, z)|_{a\neq 0}/\varphi_-(x, z)|_{a=0} = 1 + (\kappa/k)(1 - \mathscr{J}_0^2(a, k)). \tag{12}$$

It follows from (11) and (12) that in the strong electromagnetic field ($a \gtrsim k^{-1}$) the amplitude of the potential turns out to be an oscillating function of the amplitude of the EMW. When $\kappa \gg k \sim a^{-1}$ or $(k\kappa)^{-1/2} \ll a \ll k^{-1}$ we have $\eta_a \gg 1$.

(ii) When $Q(\boldsymbol{\rho}) = Q_0\delta(\boldsymbol{\rho})$

$$\varphi_-(\boldsymbol{\rho}, z) = \frac{Q_0}{\pi(\varepsilon_+ + \varepsilon_-)} \int \frac{d^2\boldsymbol{q}}{q} \exp[-i\boldsymbol{q}\cdot\boldsymbol{\rho} - q(h - z)] \left(1 - \frac{\kappa}{q + \kappa}\mathscr{J}_0^2(\boldsymbol{a}, \boldsymbol{q})\right). \tag{13}$$

This integral is not expressed in terms of known functions. It is seen, however, that in the limiting case $a/(h - z) \gg 1$ the 2DEG does not screen the point charge. In particular, for $\kappa(h - z) \gg 1$

$$\eta_\infty = \kappa[\rho^2 + (h - z)^2]/(h - z) \gg 1. \tag{14}$$

Similarly the potential φ_+ is calculated in the range $z > 0$, where the charge distribution is placed. In the case of a point charge the screening breakdown that occurs on switching on the strong electromagnetic field is indicated by the disappearance of the 2DEG contribution to the image potential (see [4]). The consequence of this may be, in particular, a change in the adsorptive properties of thin films where there is intense electromagnetic irradiation (for example, under laser annealing conditions).

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