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ACOUSTIC PHONON EMISSION BY TWO DIMENSIONAL PLASMONS *

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ABSTRACT

Acoustic wave emission of the two dimensional plasmons in a semiconductor or superconductor microstructure is investigated by using the phenomenological deformation potential within the jellium model. The plasmons are excited by the external electromagnetic (e.m.) field. The power conversion coefficient of e.m. energy into acoustic wave energy is also estimated. It is shown, the coherent transformation has a sharp resonance at the plasmon frequency of the two dimensional electron gas (2DEG). The incoherent transformation of the e.m. energy is generated by ohmic dissipation of 2DEG. The method proposed for coherent phonon beam generation can be very effective for high mobility 2DEG and for thin superconducting layers if the plasmon frequency ω is smaller than the superconducting gap 2Δ.

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1. Introduction

The 2D plasmon is a well known excitation of 2DEG in Si inversion layers and GaAs-AL_xGa_{1-x}As heterojunctions (see the review by Ando et al [1]). Recently there has been a considerable interest in the study of light scattering from free carriers in multiple quantum wells, heterostructures and heterojunction superlattices [2-5]. Investigations of the interaction between 2DEG and acoustic phonons is now another rich field of activity. A general review in this area is given by Challis et al [6].

The aim of the present paper is to investigate theoretically the phonon channel of the decay of plasmons excited by an externally applied e.m. field. This effect may be useful for the coherent phonon conversion of e.m. waves into acoustic waves. This method for coherent phonon generation was for the first time proposed by Krasheninnikov, Sultanov and Chaplik (KSC) [7] (c.f. [8]). KSC considered only the low frequency case for which the phonon wavelength λ_{ph} is larger than the thickness of the electron layer d. KSC concluded that although this coherent conversion has a very low efficiency, one can observe it experimentally. Description of appropriate experimental techniques for phonon detection is given in [9,10].

In the following section 2, a brief description of the model structure is outlined for the present analysis. Section 3 present a formal theory of plasma waves. The acoustic emission is described in section 4, where an expression for the power conversion coefficient (PCC) is also obtained. Section 5 contains the results and a brief discussion. Finally, the main conclusions are also given in this section.

2. Model

We consider here a simplified model with only one filled 2D subzone. Fig.1 shows the structure similar to the one described by Allen et al [11] and Batke et al [12]. In the GaAs layer the electrons move freely with an effective mass m. But in the z-direction they are confined by the large potential barrier of $Al_xGa_{1-x}As$. The electron wave function is approximated in the flat-band model [13] by

$$\psi_o(z) = \begin{cases} (2/d)^{1/2}\cos(\pi z/d) & \text{for } -d/2 < z < d/2 \\ 0 & \text{for } |z| > d/2. \end{cases} \tag{1}$$

The instantaneous volume density of electrons is

$$n(r,t) = n(\rho,t)\, n_o(z), \tag{2}$$

where: $n_o(z) = |\psi_o(z)|^2, \quad r \equiv (\rho,z), \quad \rho \equiv (x,y),$

$$n(\rho,t) = n + \delta n(\rho,t). \tag{3}$$

Here $n(\rho,t)$ is the instantaneous electronic density per unite area, n is the equilibrium electron number per unit area and $\delta n(\rho,t)$ is the excess electron number per unit area induced by the external e.m. field. For simplification, we shall take the background dielectric constant ε to be identical for GaAs and $Al_xGa_{1-x}As$.

3. 2D plasmons

We briefly describe below the dispersion relation and the decay of plasmons excited in 2DEG. The plasma waves are a self-consistent motion of electrons in which the fluctuation of electronic density creates variation of the electric potential, and the variation of the potential causes variation of the electronic density.

Within the linear response regime the plane wave potential

$$\delta\Phi(\rho,t) = \Phi_{q,\omega} \exp i(\mathbf{q}.\rho - \omega t) \tag{4}$$

induces plane wave variation of the electron density

$$\delta n(\rho,t) = n_{q,\omega} \exp i(\mathbf{q}.\rho - \omega t), \tag{5}$$

where $\mathbf{q} = (q_x, q_y)$ is the 2D wave vector , $\rho = (x,y)$ is the 2D position vector, ω is the frequency and t is the time. The Fourier coefficients of the electric potential and electron area density are related as

$$n_{\mathbf{q},\omega} = \Pi \; (e \; \Phi_{\mathbf{q},\omega}) \qquad (6)$$

where Π is the polarizability of 2DEG and e is the electron charge. The electron drift velocity $\mathbf{v} = (v_x, v_y)$ is also a plane wave

$$\mathbf{v}(\rho, t) = \mathbf{v}_{\mathbf{q},\omega} \exp \, i(\mathbf{q}\cdot\rho - \omega t). \qquad (7)$$

The conservation law

$$\partial \; \delta n(\rho, t)/\partial t = - \; n(\partial v_x/\partial x + \partial v_y/\partial y) \qquad (8)$$

gives the relation

$$n_{\mathbf{q},\omega} = n \; \mathbf{q}\cdot\mathbf{v}_{\mathbf{q},\omega} \;/\omega. \qquad (9)$$

This relation and the formula for the electric current $\mathbf{j} = ne\mathbf{v}$ give the connection between Π and the conductivity tensor $\underline{\sigma}$ (see for discussion [8])

$$\Pi = -i \;\; \mathbf{q}\cdot\underline{\sigma}\cdot\mathbf{q}/e^2\omega. \qquad (10)$$

The Drude formula for the conductivity

$$\sigma = \sigma_0/(1-i\omega\tau), \qquad \sigma_0 = e^2 n\tau/m \qquad (11)$$

goes to the Drude formula for the polarizability

$$\Pi = (nq^2/m\omega^2)/(1 + i/\omega\tau). \qquad (12)$$

Here τ is the relaxation time.

The Coulomb interaction between electrons renormalises the conductivity and polarizability as

$$\Pi^{ren} = \Pi/\varkappa, \qquad \sigma^{ren} = \sigma/\varkappa, \qquad (13)$$

where

$$\varkappa \equiv 1 - U\Pi. \qquad (14)$$

Here

$$U = 2\pi e^2/\varepsilon q, \qquad (15)$$

is the 2D Fourier-transformation of the Coulomb potential $e^2/\varepsilon|\rho|$.

One can obtain plasmon dispersion relation under the wave propagation condition $\omega\tau \gg 1$ by solving the dispersion relation

$$\varkappa(q,\omega) = 0. \qquad (16)$$

Explicitly, this gives

$$\omega_{pl}(q) = \left[2\pi e^2 nq/\varepsilon m\right]^{1/2} - i/2\tau. \qquad (17)$$

Here ω_{pl} is the plasmon frequency and $q = 2\pi/b$ (see fig.1) is the corresponding wave vector. The period of grating b determines the plasmon wavelength $\lambda_{pl} = b \gg d$. The perpendicular to the electronic layer magnetic field B_z changes the magnethoplasmon (mp) dispersion

$$\omega_{mp}^2 = \omega_{pl}^2 + \omega_c^2, \qquad \omega_c = eB_z/mc \qquad (18)$$

and in this way the frequency of the emited phonon.

The absorption coefficient A^* is defined as ratio of Ohmic dissipation power w_σ [1] and the power of incident e.m. wave w_{em}:

$$A^* = w_\sigma/w_{em}, \qquad (19)$$

$$w_\sigma = |E_{q\omega}|^2 \text{ Re } \sigma/2, \qquad (20)$$

$$w_{em} = c\ |E_{q\omega}|^2/8\pi. \qquad (21)$$

Here $E_{q\omega}$ is the amplitude of the e.m. wave, and the light velocity is denoted by c.

For the resonance frequency, i.e. $\omega = \text{Re } \omega_{pl}$ for the absorption coefficient we obtain

$$A^* = \begin{cases} 4\pi(\sigma_o\ /c) & \text{in the Gaussian units} \\ (4\pi\ 10^{-7})c\sigma_o & \text{in the SI units, } c/4\pi = 1/(377\Omega) \end{cases} . \qquad (22)$$

This formula is applicable for $A^* \ll 1$, but for estimation of an order of the effect, one can use it even if $A^* \simeq 1$. For a complete investigation it is necessary to solve an electrodynamic problem for diffraction and refraction for the real grating structure. We suppose that A^* is of an order of a relative change of the transmission coefficient [11], i.e. $A^* \simeq 10^{-2}$.

4. Acoustic emission

The variation of electron density caused by plasmons interacts with the lattice. This has been taken into account through a phenomenological deformation potential within the jellium model.

In the jellium model the lagrangian density $\mathcal{L}$ for the lattice motion including electron phonon interaction is given by

$$\mathcal{L} = \tfrac{1}{2}\rho_o \dot{u}^2 - \tfrac{1}{2}K(\nabla.u)^2 - \Xi\, n(r,t)\, \nabla.u. \tag{23}$$

Here Ξ is the deformation potential, K is the elastic constant, ρ_o and u are the mass density and lattice displacement vector, respectively.

Using the principle of action, one obtains the equation of motion

$$\rho_o\left[\partial^2/\partial t^2 - s^2\nabla^2\right]u = -\,\Xi\,\nabla n(r,t), \tag{24}$$

where $s = (K/\rho_o)^{1/2}$ is the sound velocity.

For the electron density variation

$$\delta n(r,t) = n_{q,\omega}\, n_o(z)\cos(q.\rho - \omega t) \tag{25}$$

the solution of the equation of motion is

$$u_z(r,t) = (\Xi/2K)\, n_{q,\omega}\, |\chi(\beta d)|\cos(q.\rho+\beta|z|-\omega t), \tag{26}$$

$$u_x(r,t) = u_y(r,t) = 0,$$

where $\beta = \omega/s$ is the wave vector of the acoustic phonon and $\lambda_{ph} = 2\pi/\beta$ is the phonon wavelength. One can verify that the displacement u of the lattice is practically normal to the 2DEG $(x-y)$ layer for $\omega/q \gg s$, $\chi(\beta d)$ is the form-factor of electron density distribution in the z-direction perpendicular to the layer

$$\chi(\beta d) \equiv \int_{-\infty}^{+\infty} n_o(z)\exp(i\beta z). \tag{27}$$

In the flat-band model (1) this is simplified to [14]

$$\chi(\gamma) = [\sin(\gamma)/\gamma] \,/\, [1 - (\gamma/\pi)^2], \tag{28}$$

where $\gamma = \beta d/2 = \pi d/\lambda_{ph}$.

The power per unit area of the emitted acoustic wave is given by

$$w_{ac} = 2\,\langle \rho_o \dot{u}^2/2\rangle\, s, \tag{25}$$

where ⟨⟩ denotes time-average. Substitution of (26) here gives

$$w_{ac} = (1/4)\ \rho_o\ (\Xi/K)^2\ |n_{q,\omega}|^2\ |\chi(\beta d)|^2\ \omega^2\ s. \tag{30}$$

Here, a multiplication factor of 2 is included, which takes into account the two sides of the layer. Let us compare the acoustic power w_{ac} with ohmic dissipation per unit area w_σ. The ohmic power is given by

$$w_\sigma = \langle n\ F.v\rangle, \tag{31}$$

where $F=-(m/\tau)v$ is the friction force per electron, and $v(\rho,t)$ is the drift velocity. Substituting here (9) and (25) we obtain for the final expression

$$w_\sigma = (m/\tau)(n/2)(\omega/qn)^2 |n_{q,\omega}|^2. \tag{32}$$

The power ratio P^* defined as

$$P^* = w_{ac} / w_\sigma, \tag{33}$$

is roughly speaking (for $P^* \ll 1$) the probability of phonon decay of 2D plasmon. Formulae (30) and (32) give the final result

$$P^* = P_o\ |\chi(\beta d)|^2, \qquad P_o = \tau\ n\ (\Xi\ q)^2\ /\ 2\ s^3\ \rho_o\ m. \tag{34}$$

The power conversion coefficient (PCC) P^* of e.m. energy into the acoustic wave is

$$C^* = A^*\ P^*. \tag{35}$$

(Probability of phonon a generation is the probability of a photon absorption by the plasmon multiplied by the phonon decay probability of a plasmon.)

5. Results, discussion and conclusions

Let us take for estimation typical parameters for GaAs 2DEG (see [5]):

$n = 7\times10^{11} cm^{-2}$, $b = 1\mu$, $\mu = \sigma_o/ne = 5\ m^2/Vs$,

$\lambda_{pl}^{-1} = 10000\ cm^{-1}$, $\varepsilon = 12.5$, $\Xi = 16$ eV, $d = 260A$

$\rho_o = 5.3\ g/cm^3$, $s = 5$ km/s, $m = 0.065\ m_e$, (36)

where m_e is the free electron mass. For these parameters we obtain:

$\tau = 1.84\times10^{-12}$ s, $\hbar/2\tau = 0.179$ meV, $\omega_{pl} = 6.1$ meV,

$\omega\tau = 17$, $v_{pl} \equiv \omega/q = 1480$ km/s, $Ma \equiv v_{pl}/s = 300$,

$P_o = 2.14\times10^{-2}$, $A^* \simeq 10^{-2}$, $\lambda_{ph} = 35$ Å,

$$|\chi|^2 \simeq 10^{-5}, \quad \gamma = 23, \quad C^* \simeq 10^{-8}. \tag{37}$$

This estimation for PCC is in agreement with KSC.

In order to increase the PCC it is necessary to use layers with higher mobility ($P_o \propto \tau \propto \mu \propto \sigma_o$ (30)). There is remarkable success in this direction [15], GaAs structures with mobility of $\mu = 5\times10^6$ cm^2/V s [16]. However, the most important ingredient for PCC increasing is the 2DEG form-factor (28) (see also [6])

$$|\chi(\gamma)|^2 \propto (\lambda_{ph}/d)^6 \qquad \text{for} \quad \lambda_{ph} \ll d. \tag{38}$$

We hope that contemporary molecular beam epitaxy (MBE) can give narrow 2DEG with high mobility for which the PCC can be comparable with the PCC = -64 db of the quartz piezoelectric surface (reported by Grill and Weis [17]).

Completely different can be the case of a thin (d = 500 Å) high temperature superconducting layer [18]. In case of the absence of ohmic dissipation and for coherent e.m. excitation the considered method for transformation will give practically a phonon laser. In layers like those with thickness lower than the London penetration depth λ_L it is also possible to propagate 2D plasma waves [19] if the frequency ω_{pl} is lower than the superconducting gap 2Δ. In this case $n_o(z) = 1/d$, $n = dn^{3d}$ and

$$\chi(\beta d) = \sin(\gamma)/\gamma, \tag{39}$$

$$|\chi(\gamma)|^2 \propto (\lambda_{ph}/d)^2 \qquad \text{for} \quad \lambda_{ph} \ll d. \tag{40}$$

Here n^{3d} is the volume Cooper pair density. The different power coefficient in (40) in comparison with (38) is caused by sharp jump of the density of carriers at the surface of the superconducting layer. In dispersion relation (17) in this case it is necessary only to perform the replacement

$$e^2 n^{3d}/m = L^{-1} = c^2 d/4\pi\lambda_L^2, \tag{41}$$

where the kinetic inductance L is an experimental measurable quantity [18]. In spite of much lower deformation potential for the $YBa_2Cu_3O_8$ (because of weak binding between different CuO layers), the absence of ohmic dissipation makes these layers an ideal system for coherent phonon generation. The performed analysis remains valid also for strongly anisotropic material. In this case s is the sound velocity in the z-direction and Ξ is the interaction constant in the lagrangian density

$$\mathcal{L} = \ldots -n(r,t)\left[\Xi\partial u_z/\partial z + \Xi_{CuO}(\partial u_x/\partial x+\partial u_y/\partial y)\right]/2. \tag{42}$$

One can expect that $\Xi_{CuO}\simeq 1eV$ and $\Xi\simeq(m_{CuO}/m_c)\Xi_{CuO}$, with Cooper pair mass in the CuO planes m_{CuO} and in the perpendicular c-direction m_c. Due to extremely strong mass anisotropy in $Bi_2Sr_2CaCu_2O_8$ [20], one came to the conclusion that for this material the 2D plasmon resonance would be extremely sharp.

For superconductors (and for semiconductors layers with high mobility $\sigma \ll c/4\pi$) the reflection coefficient is almost unit. The amplitude of the 2D current density $j=env$ can be estimated by the field intensity

$$E_{q\omega} \simeq (4\pi/c)env_{q\omega}. \tag{43}$$

After that using (9) we obtain for the amplitude of the variation of electron density

$$n_{q\omega} = cqE_{q\omega}/4\pi e\omega. \tag{44}$$

The substitution of this expression into (30) gives for this (w_σ=0) case

$$C^* = w_{ac}/\omega_{el} = (1/8\pi K)(c/s)(\chi q\Xi/e)^2 = c\Xi^2\chi^2q^2/8\pi\rho_0 s^3 e^2. \tag{45}$$

Of course it is only an order estimation. The general nonperturbative analysis of the theory of the 2D grating couplinng is given in [21]. We hope that the exact analysis will give a dimensionless multiplayer to C^*, something like 1/4 or 1/10, and the obtained estimations for C^* has a correct order.

In conclusion, we hope that a new coherent phonon spectroscopy of 2D plasmons will be developed in the near future, and an efficient method for conversion of the coherent emission of a FIR laser into sound will be practically an *Ersatz* phonon laser.

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Figure caption

Figure 1. Transformation of the electromagnetic field into sound (schematically; not to scale). The e.m. field E_ω receives momentum ($2\pi\hbar/b$) from the grating and excites plasmons which emit phonons [8].

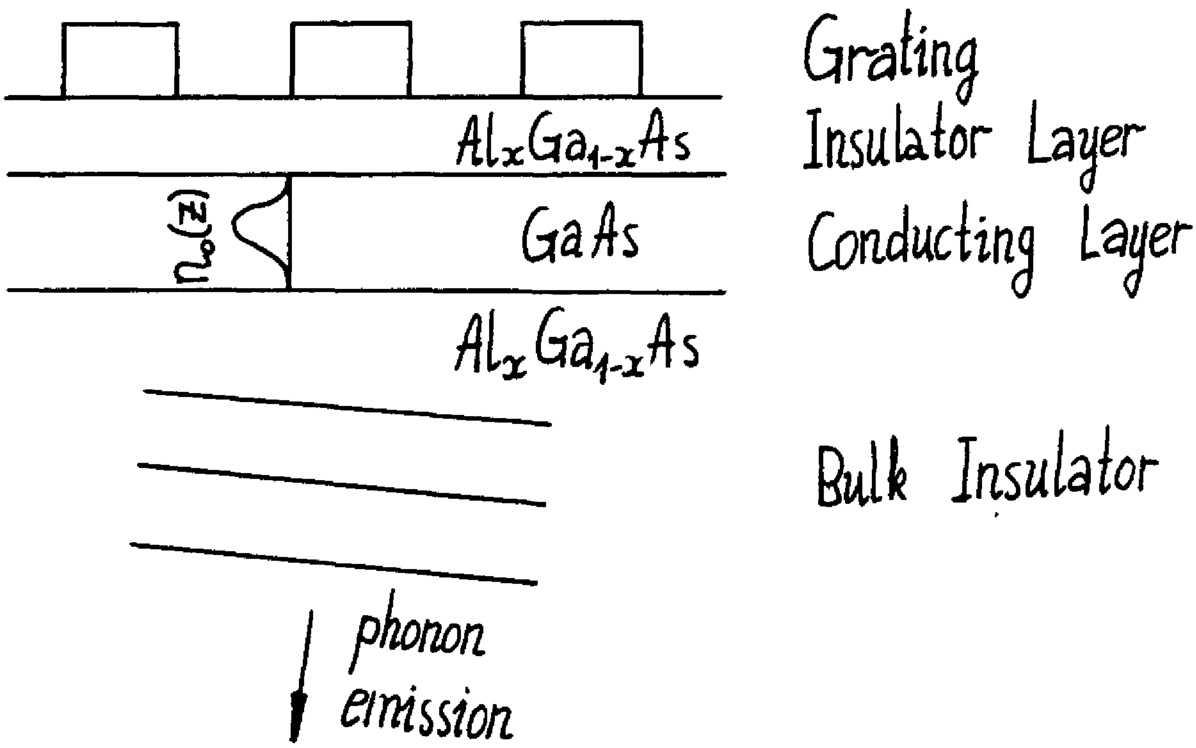

Fig.1

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