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Resonance excitation of hypersound by two-dimensional plasmons

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The feasibility of exciting superhigh-frequency acoustic waves by means of piezoelectric coupling to two-dimensional plasma waves is demonstrated. The cases of two-dimensional plasmons on the free boundary of a crystal and in the inversion layer of a metal-dielectric-semiconductor structure are considered. The effect of a magnetic field on plasmon damping and hypersound generation is elucidated.

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In our previous paper,[1] we drew attention to the possibility of resonance interaction between a two-dimensional plasma wave and a surface piezoacoustic wave if the plasma layer is organized on the surface of the piezocrystal. This may be a metal-dielectric-semiconductor (MDS) structure on a piezoelectric semiconductor, or a thin film of a semimetal or a semiconductor sputtered onto a piezocrystalline substrate.[1)] It was shown that there exists in the system in question a specific two-dimensional-plasmon damping mechanism (besides the collision and Landau-damping mechanisms) stemming from the emission of acoustic waves into the body of the piezoelectric substrate. Thus, a two-dimensional plasma wave can serve as a source for the generation of sound with frequency equal to the plasma frequency ω_p. This quantity is determined by the formula[5]

$$\omega_p^2=4\pi e^2N_sk/m(\varepsilon+\varepsilon_D\operatorname{cth}k\Delta),\quad \omega_p\gg kv_0, \tag{1}$$

where N_s is the surface charge density in the inversion layer; k is the plasmon wave vector; $\varepsilon,\varepsilon_D$ are the permittivities of the semiconductor and the dielectric of the MDS structure; Δ is the thickness of the dielectric, e, m, v_0 are the charge, effective mass, and Fermi velocity of the electron. In the cited experiments,[2-4] $N_s \sim 10^{12}$ cm^{-2}, $m=0.2m_0$, and $k\sim 2\times10^4$ cm^{-1}; then $\omega_p \sim 6\times10^{12}$ sec^{-1}.

In the present paper we present the results of the solution of the nonhomogeneous problem of coupled plasma-acoustic vibrations, i.e., we find the acoustic field in the piezocrystal for a given "extraneous" electric field on its surface. Such a formulation corresponds to the scheme of the experiments described in Refs. 2–4: onto the metallic electrode of the MDS structure falls electromagnetic radiation of frequency ω, and the transmittance of the electrode is modulated with a spatial period of $2\pi/k$. If the quantities ω, k, and N_s are connected by the relation (1), then a two-dimensional plasma wave arises in the system. For the indicated values of N_s and k, the phase velocity of the plasmon is much greater than the velocity, s, of sound. Therefore, it follows from the phase-matching conditions that the wave vector, **q**, of the emitted wave is almost perpendicular to the surface, so that its component along the direction of propagation of the plasmon is equal to k (see Fig. 1). We also investigate the effect of a magnetic field, and show that, besides the obvious change in the dispersion law, the value of the decrement of the plasma waves becomes appreciably magnetic-field dependent.

Let us first consider the simplest case: $\varepsilon_D=1$, $k\Delta\to\infty$, i.e., the plasma layer is located on the free surface of a piezocrystal. The crystal has the symmetry C_{6v}, the hexagonal axis lies in the plane of the surface, the plasmon wave vector is perpendicular to the C_6

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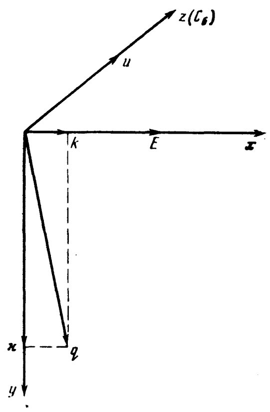

FIG. 1.

axis, and the acoustic wave is polarized along this axis. The system of equations describing the free plasma-acoustic vibrations is given in Ref. 1. This system includes the equation of motion of the piezocrystal, the Poisson equation, as well as a relation connecting the nonequilibrium correction to charge density in the plasma layer with the electric field of the wave. In the homogeneous problem under consideration here, the last relation should contain the inducing force $eEe^{i(kx-\omega t)}$, where E is the electric vector of the extraneous field ($\mathbf{E}\|\mathbf{k}$). As a result, we find the amplitude of the acoustic vibrations in the crystal:

$$u=\frac{\beta\omega_p^2E}{\rho s^2}\left\{(i\gamma k-\varkappa)\left[\omega^2-\omega_p^2\left(1-\frac{i}{\omega\tau}\right)\right]-\frac{i\varepsilon\gamma k\omega^2}{\varepsilon+1}\right\}^{-1},\quad \varkappa^2=\omega^2/s^2-k^2, \tag{2}$$

where ρ is the crystal density, β is the piezoelectric modulus, γ is the electromechanical coupling constant, and τ is the relaxation time of the electrons of the plasma layer.

The formula (2) pertains to the case $\omega\tau\gg1$ (in the published experiments on silicon at liquid-helium temperatures, $\omega\tau\sim6$–10). Under resonance conditions $\omega\approx\omega_p$, and then, taking into account the fact that $\omega\gg sk$, i.e., that $\kappa\approx\omega/s$, we obtain

$$u_{\rm res}=\frac{i\beta E}{\rho s^2}\left[\frac{1}{s\tau}+\frac{\varepsilon\gamma k}{\varepsilon+1}\right]^{-1}. \tag{3}$$

The two terms in the square brackets in (3) correspond to two plasma-damping mechanisms: due to the collisions of the electrons and due to the emission of acoustic waves. In the already published experiments the first mechanism turns out to be dominant, i.e., the condition $\gamma sk\tau\ll1$ is fulfilled. The sound intensity, $P_{\rm res}$, is given in this case by the formula

$$P_{\rm res}=s(\omega\tau)^2(\beta^2/\rho s^2)E^2. \tag{4}$$

For CdS, when $\omega\tau\sim10$ and the intensity of the electromagnetic wave acting on the plasma is of the order of $1/\text{W/cm}^2$, we have $P_{\rm res}\sim10^{-4}$ W/cm². The limiting value of the sound intensity for a given k is attained when $\gamma sk\tau\gg1$:

$$P_{max}=\left(\frac{\omega}{k}\frac{\varepsilon+1}{\varepsilon\gamma}\right)^2\frac{\beta^2E^2}{\rho s^3}. \tag{5}$$

In a magnetic field H perpendicular to the plasma layer, the emission of hypersound with the frequency of the magnetoplasmon, $\omega_{\rm mp}=(\omega_p^2(k)+\omega_H^2)^{1/2}$, where $\omega_H=eH/mc$ is the cyclotron frequency, is possible. If we experiment not with an inversion channel, but with a film sputtered onto a piezocrystal, then in this case N_S is given, but can be adjusted to the resonance value by changing the magnetic field. Allowance for the magnetic field can be carried out within the framework of the kinetic-equation method for the nonequilibrium correction to the charge density in the plasma layer. The corresponding formulas in the general case are quite unwieldy (see, for example, Ref. 6—the generalization to the two-dimensional case is quite trivial). Therefore, we shall give the final result, indicating beforehand the region of its applicability.

First, let us assume that the condition for the absence of geometric resonances is fulfilled, i.e., that $\omega_H\gg kv_0$. For the above-indicated parameters of the two-dimensional plasma, $v_0\sim10^7$ cm/sec, and in the most important magnetic-field region, where $\omega_H\sim\omega_p$, we find that $kv_0/\omega_H\sim0.03$. Secondly, we can, for all reasonable values of the magnetic-field intensity, neglect that contribution to the current which arises as a result of the difference between the thermodynamic-equilibrium distribution of the electrons and the distribution that is an equilibrium distribution in the local coordinate system fixed to the vibrating lattice. This neglect is legitimate if $\beta H/\rho s^2\ll ck\tau$, which corresponds, under the conditions in question, to the requirement that $H\ll10^8$ Oe. The computations in the case when $\omega_{\rm mp}\tau\gg1$ yield for the decrement of the magnetoplasmon the following formula:

$$\operatorname{Im}\omega=-\frac{1}{\tau}\left(1-\frac{\omega_p^2}{2\omega_{mp}^2}\right)-\frac{\varepsilon\gamma sk}{2(\varepsilon+1)}\frac{\omega_p^2}{\omega_{mp}^2}. \tag{6}$$

Thus, the collision part of the decrement slowly increases with increasing magnetic-field intensity (from $1/2\tau$ to $1/\tau$), while the decrement due to sound emission [the second term in (6)] decreases like ω_H^{-2} in the region $\omega_H\gg\omega_p$. Assuming, as before, that the collision damping is dominant, we obtain for $\omega=\omega_{mp}$ a formula for P that coincides with (4) with τ replaced by $\tau(1+2\omega_H^2/\omega_p^2)^{-1}$.

More complex dependences arise in the case of the MDS structure because of waveguide effects in the dielectric film. In the frequency dependence $P(\omega)$, there arises a new characteristic dimension $\delta\omega=\pi s_D/\Delta$, where s_D is the velocity of sound in the dielectric of the MDS structure. By taking $\Delta\sim10^{-5}$ cm, $\tau\sim10^{-12}$ sec, we can verify that $\tau\delta\omega\ll1$. Consequently, there arise inside the $P(\omega)$ peak of width $1/\tau$ a series of resonances with period $\pi s_D/\Delta$:

$$P(\omega)=sE^2\left(\frac{\beta^2}{\rho s^2}\right)\left[1+\left(\frac{\rho_Ds_D}{\rho s}\right)^2\operatorname{tg}^2\frac{\omega\Delta}{s_D}\right]^{-1}\left[\left(\frac{\omega^2}{\omega_p^2}-1\right)^2+\frac{1}{\omega^2\tau^2}\right]^{-1},$$

where ρ_D is the density of the dielectric. The acoustic-wave intensity inside the dielectric itself if proportional to

$$\left[\frac{\cos^2\omega\Delta}{s_D}+\left(\frac{\rho_Ds_D}{\rho s}\right)^2\frac{\sin^2\omega\Delta}{s_D}\right]^{-1}.$$

When $\omega\Delta/s_D$ is equal to a half-integral number, the elastic wave is entirely localized in the dielectric layer (an effect which is similar to the quarter-wave-plate effect).

The considered geometry of the problem is not the only one in which the excitation of sound by two-dimensional plasmons is possible. For example, in a cut perpendicular to the C_6 axis, a plasmon excites a bipartial acoustic wave: longitudinal and shear. For both components the parallel component of the wave vector is equal to k. The resultant wave vector lies in the plane containing the normal to the surface and the direction of the vector **k**. The absolute values of the wave vectors for each wave are, to within $(ks/\omega)^2 \ll 1$, equal to ω/s_l and ω/s_t, where s_l and s_t are the velocities of the longitudinal and shear waves propagating along the C axis. Another example is the (100) cut of a cubic crystal. If **k** is directed along the [010] axis, then the plasmon excites a shear wave propagating in a direction almost perpendicular to the crystal surface. In all these cases the order of magnitude of the acoustic-wave intensity can be estimated from the formula (4), although the exact value is determined by more complex combinations of the piezoelectric modulus and the elastic constants.

In conclusion, let us emphasize the important role played by the plasma layer in the effect under consideration. In principle, an electromagnetic wave is capable of exciting piezocrystal vibrations in the absence of a plasma, but because of the clearly nonresonant character of the excitation, the effect will be quite weak. In our case the plasma layer plays the role of a resonator, in which the amplitude of the electric field pumping the crystal lattice is greater by a factor of $\omega\tau$ than the amplitude of the field of the incident electromagnetic wave.

A second important circumstance is the spatial inhomogeneity of the considered system: the electrons are localized on the surface, while the electric field attenuates with decrement k as we go into the crystal. Therefore, the y component of the momentum is not conserved, and the emission of sound with any value of $\varkappa$ (see Fig. 1) becomes kinematically possible. The phase-matching conditions are selected from these values of $\varkappa = (\omega^2/s^2 - k^2)^{1/2}$. Since $\varkappa \approx \omega/s \gg k$, the distant Fourier component of the plasma-wave field turns out to be important. Accordingly, the imaginary part of the frequency is smaller than the real part by a factor of $\varkappa/k$ (see Ref. 1, formula (24); naturally, if $\gamma \ll 1$, then an additional smallness–interaction weakness arises).

In the analogous homogeneous three-dimensional problem (the interaction of three-dimensional plasmons with piezoacoustic waves) the dispersion law also contains a region where the group velocity of the plasma wave is higher than the sound velocity. Nevertheless, no plasmon damping connected with the piezoelectric effect occurs, and, consequently, acoustic waves are not (at least in the linear theory) emitted. The only consequence of the interaction of the plasma oscillations with the piezoelastic vibrations is that the coefficient attached to k^2 in the dispersion law for three-dimensional plasmons gets to be slightly renormalized. The reason is that, in the spatially homogeneous problem, the electric field of the monochromatic plasma wave contains a single Fourier component corresponding to the momentum **k**, and this is not compatible with the conditions for phase matching.

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[1)]At present we know of several experiments [2-4] in which two-dimensional plasmons have been observed, but these investigations pertain to silicon MDS structures, in which the piezoelectric effect does not occur.

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