NEW MECHANISM OF ACOUSTO-OPTICAL INTERACTION IN PIEZOSEMICONDUCTING CRYSTALS

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A sound wave propagating in a crystal produces a space-time modulation of the dielectric constant

$$\epsilon(\omega, x, t) = \epsilon_0 + \delta\epsilon \exp(iqx - i\Omega t), \qquad (1)$$

where ε_0 is the dielectric constant in the absence of the sound wave $\{\vec{q},\Omega\}$. This modulation is usually regarded as a consequence of the dependence of the lattice part of ε on the elastic deformation. It is physically obvious, however, that modulation of the electronic part of the dielectric constant has a singularity in the region of optical frequencies close to the boundary frequency ($\hbar\omega \approx E_g$). It is this singularity which gives rise to the proposed mechanism of light scattering by acoustic waves in semiconductors having a strong electron-phonon interaction. This mechanism is based on the scattering of light by a stimulated electron-density wave induced by the sound, and is apparently most effective in piezosemiconductors.

Let us estimate the amplitude $\delta\varepsilon_{el}$ of the modulation due to an electron wave. We use the following expression for the part of the dielectric constant corresponding to the contribution of the conduction electrons [1]:

$$\delta\epsilon_{el} \approx \frac{4\pi e^2\hbar^2}{mTE_g}\left(\frac{m_c}{m^*}\right)^{3/2} n_e G(\xi), \qquad (2)$$

$$G(\xi) = 1 - \xi/\sqrt{\pi}[1 - \Phi(\xi)]\ell^{\xi^2}.$$

Here $\xi = [(m^*/m_c)(E_g - \hbar\omega/T)]^{1/2}$, $\Phi(\xi)$ is the probability integral, n_e is the amplitude of the stimulated plasma wave, and E_g is the width of the forbidden band. Expression (2) was obtained for the non-degenerate electron gas under the condition $E_g - \hbar\omega >> h\alpha$ ($h\alpha$ is the broadening of the dispersion curve), i.e., in a frequency range for which the absorption of the light is still small, but the frequency dispersion $\delta\varepsilon$ is already appreciable. The amplitude n_e of the plasma wave is expressed linearly in terms of the deformation amplitude qu. The coefficient of proportionality of n_e to qu depends significantly on the ratio of the electron mean free path ℓ to the length of the sound wave. In semiconductors of the A_2B_6 type (e.g., CdS), in which $q\ell << 1$, the expression for n_e takes the form [2]

$$n_e = \frac{4\pi\beta}{\epsilon_{\parallel} v_s}\mu N_e \frac{qu}{(1 - v_d/v_s) + i\frac{\omega_M}{\Omega}(1 + q^2 r_D^2)}, \qquad (3)$$

where β is the piezoelectric modulus, v_s the speed of sound, $\varepsilon_{\parallel}$ the longitudinal dielectric constant, μ the mobility, r_D the Debye radius, $\omega_M = 4\pi e\mu N_e/\varepsilon_{\parallel}$ the Maxwellian frequency, and $v_d = \mu E_0$ the drift velocity of the electrons in an external field E_0. To compensate for the viscous losses, it is necessary to apply to the crystal a field E_0 stronger than the threshold value ($v_d > v_s$) [2]. The maximum value of $\Delta\varepsilon_{el}$ is reached in this case at $qr_D = 1$, $|v_d/v_s - 1| = (\omega_M/\Omega)(1 + q^2 r_D^2)$, and is equal to

$$\delta\epsilon_{el}\big|_{max} = \frac{\pi\sqrt{2}e\hbar^2}{mTE_g}\left(\frac{m_c}{m^*}\right)^{3/2}\beta q u G(\xi). \tag{4}$$

In narrow-band crystals with low effective mass (e.g., InSb), where $q\ell \gg 1$ as a rule, the expression for the plasma-wave amplitude is [3]

$$n_e = \frac{\beta q}{e}\,\frac{qu}{1 + q^2 r_D^2/2} \tag{5}$$

and the maximum of $\delta\varepsilon_{el}$ is reached at $qr_D = \sqrt{2}$.

It is seen from (4) that the considered mechanism of acousto-optical interaction is quite sensitive to the frequency of the light wave, and is significant in a narrow frequency region near the edge of the band. With increasing acoustic flux, the electron-density wave ceases to be sinusoidal [4, 5]. The resultant nonlinearity ($|n_e|/N_e \sim 1$) leads to saturation of the mechanism in question [5], and the presence of intense harmonics in the plasma wave complicates the scattering picture.

We present estimates for $\delta\varepsilon_{el}$: in CdS crystals ($E_g = 2.4$ eV, $\beta = 9 \times 10^4$ cgs esu) at $T = 78°K$, $q = 1.5(2\pi/\lambda_{opt}) \approx 5.7 \times 10^5$ cm^{-1} (λ_{opt} is the length of the light wave in the medium), $E_g - \hbar\omega \sim 10^{-2}$ eV, and acoustic flux density $S = 1$ W/cm^2 we obtain for $|\delta\varepsilon_{el}|$ the value 3×10^{-5}. In the case of n-InSb ($E_g = 0.23$ eV, $\beta = 2.1 \times 10^4$ cgs esu), $q \approx 1.3 \times 10^5$ cm^{-1}, and the same values of T, S, and $E_g - \hbar\omega$ we obtain $|\delta\varepsilon_{el}| = 10^{-5}$.

For frequencies close to the edge, $\hbar\omega \lesssim E_g$, there exists in addition to the mechanism considered above also another mechanism that competes with it and is likewise based on modulation of the electronic part of the dielectric constant by the sound. The point is that when a sound wave passes through the crystal, the width of the forbidden band $\delta E_g = \Lambda qu$ becomes modulated (Λ is the deformation-potential constant), and accordingly there is modulation of the part of the dielectric constant corresponding to the contribution of the valence electrons [1]:

$$\delta\epsilon_{def} = \frac{4e^2}{\pi\hbar}\,\frac{m^*}{m}\,\frac{\sqrt{2m^*E_v}}{E_g^2}\left[1 + \frac{\pi}{4}\,\frac{E_g}{\sqrt{E_v(E_g - \hbar\omega)}}\right]\Lambda q u, \tag{6}$$

where E_v is the width of the valence band. Just as above, it is assumed here that $E_g - \hbar\omega \gg \hbar\alpha$. The first term in (6), which does not depend on ω, describes the electronic contribution to the elasto-optical constant far from the edge frequency. The second term becomes decisive at $E_g - \hbar\omega \ll (\pi/4)^2(E_g^2/E_v)$. The presence of a root singularity in $\delta\varepsilon_{def}$ means that when $h\omega$ is sufficiently close to E_g the effectiveness of the acousto-optical interaction $M_2 = (\delta\varepsilon)^2/4\varepsilon_0 S$ [6] can increase appreciably. For example, for CdS crystals ($\Lambda \sim 3$ eV, $E_v \approx 10$ eV) this term becomes decisive at $E_g - \hbar\omega \approx 0.4$ eV, and for $E_g - \hbar\omega \approx 10^{-2}$ eV the amplitude $\delta\varepsilon_{def}$ is equal to 5×10^{-5}. In the case of n-InSb ($\Lambda \approx 6$ eV, $E_v \sim 10$ eV), the second term is small up to $E_g - \hbar\omega \sim \hbar\alpha$ and does not lead to a root singularity of the elasto-optical constant.

Let us compare the effectivenesses of the two mechanisms. Assuming $\beta \sim e/a_0^2$ and $\Lambda \sim (\hbar^2/ma_0^2)$ (a_0 is the lattice constant), we obtain an order-of-magnitude estimate of the ratio

$$\left|\frac{\delta\epsilon_{el}}{\delta\epsilon_{def}}\right| \sim \frac{m}{m^*}\,\frac{\lambda_T}{r_D}\sqrt{\frac{E_g - \hbar\omega}{T}}\left(\lambda_T = \frac{\hbar}{m^* v_T}\right). \qquad (7)$$

Near the boundary frequency ($E_g - \hbar\omega \sim T$), the effectivenesses turn out to be of the same order. In particular, for CdS this ratio is of the order of 0.6. According to estimates for CdS, the acousto-optical effectiveness near the edge of the band is equal to $M_2 \simeq 10^{-16}\ \sec^2 g^{-1}$ and exceeds by one order of magnitude the values of M_2 obtained in experiment far from the edge of the band [6]. The estimates have a qualitative character, since in the anisotropic medium the contribution made to the scattering by any particular mechanism depends strongly on the crystal orientation.

In conclusion we note that the acousto-optical effectiveness of the electronic mechanism depends strongly on the concentration of the conduction electrons. In photosemiconductors (CdS, CdSe), application of infrared illumination makes it possible to control the conduction-electron density [7], and this, in turn, makes it possible to control effectively the scattering and diffraction of light in such crystals.

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ROLE OF STIMULATED COMPTON SCATTERING IN THE INTERACTION OF LASER RADIATION WITH A SUPERDENSE PLASMA

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Recently, much hope has been placed in the possibility of obtaining a controlled thermonuclear reaction by fast adiabatic compression of thermonuclear matter heated with a laser [1]. We wish to call attention to one circumstance that must be taken into account both in the theoretical description of different models of fast heating of a superdense plasma by laser radiation and in their practical realization. We have in mind the possibility of strong reflection of the laser radiation from the heated plasma due to the stimulated Compton scattering of light by the plasma electrons. As is well known, in such a process the gasdynamic expansion of the hot plasma leads to formation of a plasma corona around the dense part, in which the plasma, with varying density gradient, moves in a direction opposite to the laser beam. Our earlier experimental and theoretical investigations [2] have shown that in the presence of a