Collision-controlled scattering of light by free electrons in semiconductors and the influence exerted on it by an electric field

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We observed and investigated the spectrum of light scattering by free electrons in CdS under conditions when the mean free path is shorter than the wavelength of the light. The observed dependence on the concentration and on the scattering angle agrees with the theoretical predictions (Gantsevich *et al*., Sov. Phys. JETP **30**, 276 (1970) and in "Light Scattering in Solids", edited by M. Balcanskii, Paris, 1971, page 94). A Doppler shift of the spectrum in an electric field was observed.

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We report here the observation, for the first time ever, of light scattering by free electrons in a semiconductor under conditions of frequent collisions ($ql<1,\kappa l<1$, $\mathbf{q}$ is the change of the wave vector of the light by the scattering, $1/\kappa$ is the Debye radius, and l is the electron mean free path). Under these conditions the light is scattered by "hydrodynamic" fluctuations of the electron density, and the scattering spectrum should have a Lorentzian shape[1]

$$\frac{P_s}{P_i}=\frac{1}{\pi a}+\frac{b}{1+\omega^2/a^2}\Delta O. \qquad (1)$$

Here P_i is the power of the incident light of frequency ω_i; P_s is the power of the scattered light of frequency $\omega_s=\omega_i+\omega$; ΔO is the solid angle. The half-width a is determined by the damping of the fluctuations on account of the diffusion D and the electric conductivity

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$$\sigma : a = q^2 D + \frac{4\pi\sigma}{\epsilon} \equiv (q^2 + \kappa^2) D,$$

where ϵ is the dielectric constant of the lattice; the quantity b determined the scattered-light power integrated over the frequencies:

$$b = (e^2/m^* c^2)^2 (\vec{\epsilon}_i \vec{\epsilon}_s)^2 v_0 n_0 q^2/(q^2 + \kappa^2),$$

where e and m^* are the charge and effective mass of the electron; n_0 is the concentration; v_0 is the scattering volume; ϵ_s and ϵ_i are the polarization vectors of the scattered and incident light.

The setup consisted of a pulsed ($\tau_p \sim 250$ nsec) xenon laser [we used the yellow ($\lambda_y = 595$ nm) and green ($\lambda_g = 539$ nm) lasing lines], a double monochromator, and a pulsed differential recording system with digital storage.

The electron density in the investigated CdS single crystals was low and independent of the illumination by the λ_y line. The electrons were pumped into the conduction band from the impurity levels only by the λ_g line.

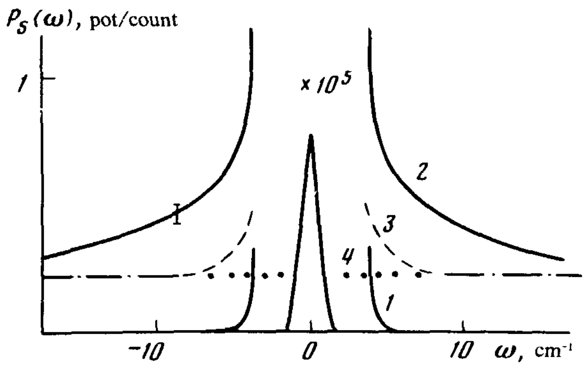

FIG. 1. Spectrum of light scattered by CdS sample No. B-1 near the yellow line $\lambda_y = 595$ nm, $T = 300$ K, (1)—$z(xx)y$, $n_0 = 10^{14}$ cm^{-3}; (2) and (3)—$z(xx)y$ and $z(yx)y$ respectively, with simultaneous illumination by the green line ($n_0 = 10^{16}$ cm^{-3}); (4)—luminescence of crystal due to green line only.

Figure 1 shows the scattering spectra near λ_y. When the single crystal was illuminated by only this line, the electron density did not exceed 10^{14} cm^{-3} and the spectrum (curve 1) was close to the instrumental function. On the other hand, wings were observed in the scattering spectrum (curve 2) when the sample was illuminated at the same time by the λ_g line, which increased the density to 10^{16} cm^{-3}. Curve 4, obtained by illuminating the sample with only λ_g, shows the absence of singularities near λ_y. Study of the spatial-polarization characteristics has shown that the observed scattering has a dipole character (cf. curves 2 and 3).

Similar wings were observed also in scattering by λ_g, and vanished when the photoconductivity vanished. The latter took place in certain samples after a slight lowering of the temperature (from 300 to 220 K), when the band shift made the quantum energy insufficient to transfer the electrons to the conduction band.

These scattering singularities prove that the scattering is in fact by the free electrons. In all our experiments, the observed line shape is splendidly approximated by a Lorentzian with half-width 14, 8, or 2.5 cm^{-1} (± 1 cm^{-1}) for scattering angles θ equal to 180, 90, or 30°, respectively. The mobility μ in the samples at room temperature was 250–300 cm^2/V-sec, and hence $l \sim 8 \times 10^{-7}$ cm. Since $q_{max} = 6 \times 10^5$ cm^{-1} and $\kappa \sim 2.5 \times 10^5$ cm^{-1}, it follows that $ql < 0.5$, $\kappa l < 0.2$, and consequently the regime realized in the experiment should be precisely of the collision type described by formula (1), with a half width a at $n_0 = 10^{16}$ cm^{-3} equal to 15 cm^{-1} (180°), 8.5 cm^{-1} (90°), and 3 cm^{-1} (30°), in agreement with experiment. An estimate of the integrated cross section per electron, obtained from the experiment, is several times larger than the Thomson cross section $(e^2/m^*c^2)^2$, apparently as a result of the resonant character of the scattering.

Thus, the experimental data fit well the formula (1), which describes light scattering by fluctuations of the electron density. This is as it should be, since CdS is a single-valley semiconductor with a weak spin-orbit coupling and small nonparabolicity, so that the other known mechanisms[2] of light scattering by conduction electrons do not play any role in it. Nor was a noticeable contribution made to the observed spectrum by the generation-recombination noise,[3] as is evidenced by the dependence of the line half-width on **q** and by the fact that the spectrum did not vary from sample to sample.

We investigated the influence of a strong electric field **E** on the scattering spectrum. Figure 2 shows the difference scattering spectra for $E = 15$ kV/cm,

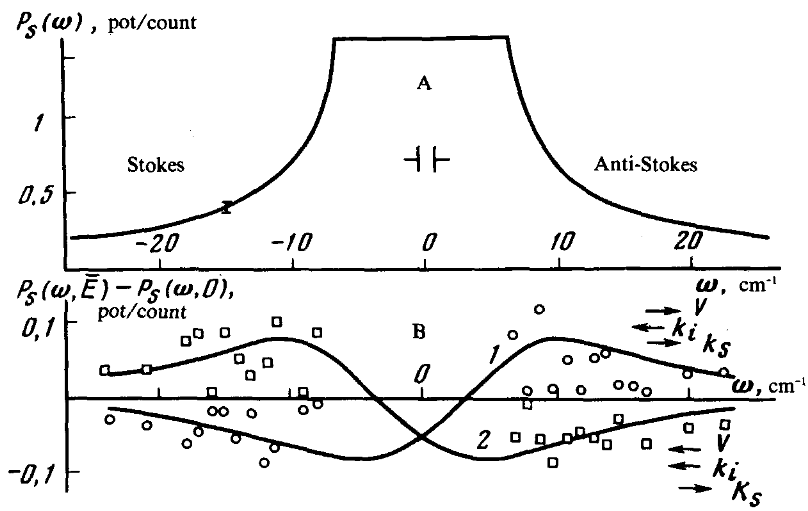

FIG. 2. Effective electric field on the spectrum of the scattering of CdS sample No. A-20, $y(zz)\bar{y}$, $\lambda_g = 539$ nm, $T = 300$ K, $n_0 = 10^{16}$ cm^{-3}. A—spectrum without field, B—difference between the scattering spectra with a field of 15 kV/cm and without a field, (1)—calculated difference spectrum for 65% of electrons trapped by the sound and 35% drifting with velocity $\mathbf{V} = \mu \mathbf{E}$, with **V** antiparallel to the wave vector $\mathbf{k}_i$ of the incident light; ●—experimental points; (2)—calculated spectrum at **V** parallel to $\mathbf{k}_i$; □—experimental points.

$\mathbf{E} \| \mathbf{q}(\theta=180°)$. The Doppler shift due to the drift of the electron system is clearly seen and depends on the field intensity.

The observed shift of the spectrum, however, is not described by formula (1) with ω replaced by $\omega-\mathbf{q}\cdot\mathbf{V}$, where $\mathbf{V}$ is the drift velocity (see[1]). This disparity is due to the enhancement of the acoustic noise by the electron drift. Qualitatively, the results of the experiment can be understood by using the motion of the electrons trapped by the noise flux and moving with sound velocity V_s, and the untrapped electrons that drift with velocity $V=\mu E \gg V_s$. The scattering line contour can then be represented as a superposition of two Lorentzians shifted respectively by $\mathbf{q}\cdot\mathbf{V}_s$ and $\mathbf{q}\cdot\mathbf{V}$, with weights corresponding to the fraction of the trapped and free electrons [Fig. 2(b)], as estimated from the kink on the current-voltage characteristics.

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[1]S.V. Gantsevich, V.L. Gurevich, and R. Katilyus, Zh. Eksp. Teor. Fiz. **57**, 503 (1969) [Sov. Phys. JETP **30**, 276 (1970)]; S.V. Gantsevich, V.L. Gurevich, V.D. Kagan, and R. Katilius, in Light Scattering in Solids, ed. by M. Balcanski, Paris, 1971, p. 94.

[2]P.M. Platzman and P.A. Wolff, Waves and Interactions in Solid State Plasmas, Academic, 1972. M.V. Klein, in: Light Scattering in Solids, ed. by M. Cardona, Berlin, 1975, p. 147; A. Mooradian, in Laser Handbook, ed. by F.T. Arecchi, Amsterdam, 1972, vol. 2, p. 1409.

[3]A.G. Aronov, Fiz. Tverd. Tela (Leningrad) **11**, 2219 (1969) [Sov. Phys. Solid State **11**, 1791 (1970)].