Quantum oscillations of the intensity of induced radiation of an electron-hole liquid in CdS crystals

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A new method is used to observe oscillations of the intensity of recombination radiation of an electron-hole liquid (EHL) in a magnetic field at helium temperatures. In this method the oscillations are observed in induced radiation. The period of the oscillations in the reciprocal field is used to estimate the Fermi energies of the carriers and the equilibrium density of the *e*-*h* pairs in the EHL, namely $n_0 \sim 10^{18}$ cm^{-3}.

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It was shown in[1] for the first time that in CdS crystals the excitons and nonequilibrium carriers of sufficiently high density condense at low temperatures into an electron-hole liquid. The energy of the ground state of the EHL in CdS lies 12 meV deeper than the lowest exciton term A_T, and the equilibrium density of the e-h pairs in the liquid phase amounts to $n_0 \sim 10^{18}$ cm^{-3}. This condensation was confirmed experimentally in subsequent studies.[2,3] The unexpectedly high stability of EHL in a straight-band semiconductor such as CdS can be explained as being the consequence of the strong polar interaction of the carriers with the longitudinal optical phonons (the polaron effect).[4,5]

We have investigated the recombination radiation of the EHL in a strong magnetic field H. When H is applied, the carrier motion in the EHL, which is a degenerate two-component Fermi system, becomes quantized. Recognizing that the number of Landau levels under the Fermi surface, as well as the very distributions in the states, are periodic in the reciprocal field, it is natural to expect the radiation intensity to oscillate with changing H at fixed frequencies within the limits of the EHL band.

We used for the investigations high-purity crystals with electrically active impurity concentration $n_{d,a} \lesssim 10^{15}$ cm^{-3}. The measurements were performed with the samples placed in superfluid helium at $T = 1.4$ °K. The method of excitation, the optical projecting system, and the registration system were identical with those described in[1]. To obtain the spontaneous recombination spectra, crossed diaphragms were used to cut out only the central part of the excitation spot, which was projected directly on the input slit of the spectrometer. The EHL laser emission spectra were registered when the stimulated-emission light scattered by one of the ends of the crystals was gathered onto the entrance slot. We note that the resonator was made up of the natural end faces of the crystal (insert in Fig. 1).

The corresponding spectra are shown in Fig. 1. The stimulated-emission spectrum shows a mode structure (see also Fig. 2), which corresponds to axial modes of the resonator and can vary depending on the choice of the resonator

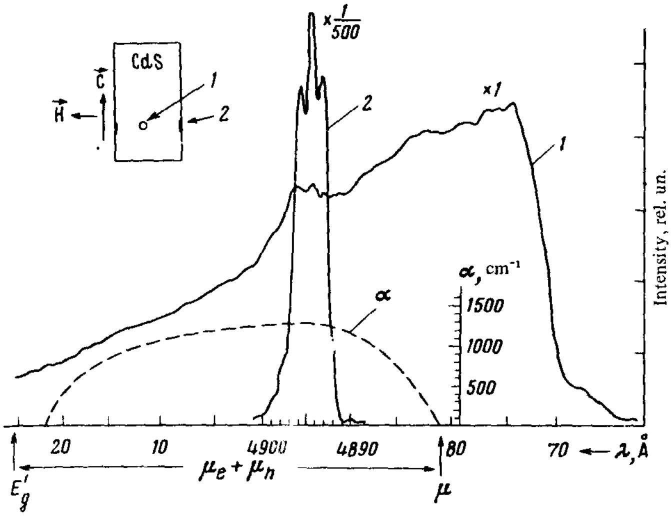

FIG. 1. Spectra of spontaneous (1) and induced (2) recombination of EHL at 2MW/cm^2 pumping. The dashed curve (a) shows the spectrum of the gain of the EHL corresponding to this pumping, taken from[1]. The insert on the upper left shows the geometry of the excitation: 1—excitation spot, 2—sections of end faces making up the resonator.

(cf. Figs. 1 and 2). The "violet" boundary of the gain spectrum coincides with the chemical potential μ of the EHL per e-h pair, its width is determined by the sum $\mu_e+\mu_h$ of the Fermi quasi-levels of the electrons and holes, while the

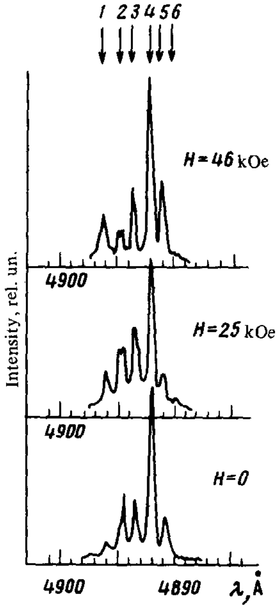

FIG. 2. Lasing mode structure corresponding to the chosen resonator at different values of the magnetic field H.

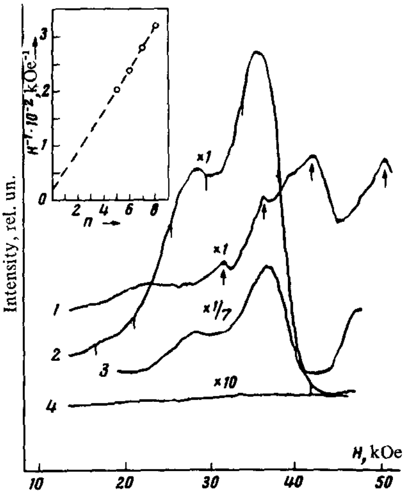

FIG. 3. Experimental plots of the EHL radiation intensity against H for two different modes within the limits of the EHL lasing band: curve 1—$\lambda = 4894.5$ Å, curves 2,3,4—$\lambda = 4892$ Å. Curve 2 and 3 correspond to pumps 0.3 and 1 MW/cm^2, respectively, while curve 4 corresponds to the spontaneous spectrum. The markers on curve 2 are from a calibrated Hall pickup. The upper insert shows the dependence of the number of the oscillations on H^{-1} for curve 1.

"red" boundary corresponds to the width E_g' of the forbidden band in accordance with the restructuring of the energy spectrum in the EHL.[1] The maxima of the spontaneous and stimulated recombination should coincide in energy only at $T = 0$. The observed difference between the spectral positions of these maxima is attributed by us to the heat rise of the electron system, which is estimated by us at $T_e \sim 30$ °K.

Figure 3 shows a plot of the radiation intensity against H (curve 4), measured at a wavelength $\lambda = 4892$ Å in the case of the spontaneous EHL recombination spectrum corresponding to Fig. 1. The radiation intensity increases monotonically with increasing H. No intensity oscillations were observed at any of the frequencies of the spontaneous spectrum within the limits of the realized accuracy (on the order of 2%).

It is easy to show, however, that the weak oscillatory dependence, if it does exist in principle in the spontaneous spectrum, can be greatly amplified in the case of stimulated emission. We note that the gain $\alpha(\hbar\omega)$ is connected with the intensity of the spontaneous emission $I_{sp}(\hbar\omega)$ of the electron-hole plasma in the following manner (see, e.g.,[1]):

$$\alpha(\hbar\omega) = \frac{\pi c^2 \hbar}{\kappa^2 \omega^2} \cdot r_{sp}(\hbar\omega)\left[1 - \exp\left\{\frac{\hbar\omega - E_g - \mu_e^T - \mu_h^T}{kT}\right\}\right],$$

where

$$r_{sp}(\hbar\omega) = \frac{4\kappa e^2 \omega}{m_0^2 \hbar c^3} \, |p|^2 I_{sp}(\hbar\omega)$$

is the rate of the spontaneous transitions per unit volume, per unit solid angle, and per unit energy interval, κ is the refractive index, and p is the momentum of the transition. The depth $(\Delta I/I)_{sp}$ of the oscillations at fixed frequencies within the limits of the spontaneous spectrum determines completely the gain oscillations, $(\Delta I/I)_{sp} \sim \Delta\alpha/\alpha$. The relative depth of the oscillations $(\Delta I/I)_{st}$ in the case of stimulated emission, when the conditions $\alpha l \gg 1$ and $\Delta\alpha l \ll 1$ are satisfied (l is the linear dimension of the excitation region), are increased by a factor αl in comparison with the spontaneous emission:

$$\left(\frac{\Delta I}{I}\right)_{st} \sim \left(\frac{\Delta a}{a}\right) a l \ .$$

In the case of lasing, the factor by which the depth of oscillations increase is much larger. Thus, the method of observing the oscillations in stimulated emission is quite effective, inasmuch as a "quantum amplifier" of sorts is realized in this case for the oscillation depth.

We have thus succeeded in experimentally observing a strong oscillatory dependence of the EHL radiation with changing magnetic field. Figure 2 shows the lasing spectra at different value of H. It is seen that when H is varied the spectrum structure corresponding to different axial modes remains constant with high accuracy, but the intensity of each mode changes in nonmonotonic fashion.

The dependence of the radiation intensity of the most intense axial mode ($\lambda = 4892$ Å) on H at different points is shown in Fig. 3 (curve 2, 3). As the pump is increased, a fact accompanied by an increase of the electron temperature, the depth of the oscillations decreases. It is important that when the pump is changed by a factor of 3 or more the period of the oscillations in the reciprocal field, estimated from measurements at a fixed mode, remains practically constant. Within the limits of the structure of the axial modes, which is governed by the resonator, the phases of the oscillations can be substantially different for the different modes (for example, curve 1 or Fig. 3 corresponds to $\lambda = 4894.5$ Å). However, the differences in the values of the reciprocal-field period do not exceed 30% for the different modes.

It is natural to assume that the observed oscillations of the intensity of the induced emission of the EHL in a magnetic field are of quantum origin. This is evidenced by the decrease of the depth of the oscillations with increasing temperature, and by the constancy of their periods in the reciprocal field, as well as by the linear dependence of the serial number of the oscillations on H^{-1}. Such a dependence, corresponding to curve 1, is shown in the insert of Fig. 3.

The observed period of the oscillations does not depend on the direction of the field **H** relative to the hexagonal crystal axis c. It is therefore natural to attribute it only to electrons whose mass is isotropic and equal to $m_e = 0.205 m_0$ (the mass of the holes is large and is strongly anisotropic, $m_h^{\parallel} = 5 m_0$ and $m_h^{\perp} = 0.7 m_0$).

From the period of the oscillations $A = (5 \pm 1.5) \times 10^{-3}$ kOe^{-1} we estimated directly the Fermi energy of the electrons $E_F^e = \hbar e / m_e c A = (12 \pm 3)$ meV and then the equilibrium concentration of the electron-hole pairs in the EHL, which turned out to be $n_0 \sim 10^{18}$ cm^{-3}.

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