Spectral dependence of the magnetic oscillations of the luminescence intensity of the electron-hole condensate in pure Ge

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The magnetic oscillations of the intensity at different points of the LA-709 meV luminescence line from the electron-hole condensate (EHC) in pure Ge are investigated. The spectral pattern of oscillations obtained is explained in the framework of the "droplet" model. The magnetic oscillations of the spectral linewidth and of the characteristic EHC energies (the chemical potential and kinetic, exchange and correlation energies per pair of particles in the EHC) are calculated from the intensity oscillations at three points of the line.

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One of the ways of studying experimentally the properties of the electron-hole condensate (EHC) in semiconductors [1-3] is by the action of a strong magnetic field on the EHC. As shown by Keldysh and Silin [4], in a magnetic field there arises an oscillating correction to the equilibrium density of charge carriers in an electron-hole Fermi liquid, and this induces oscillations in the intensity of the radiative recombination (RR) of the EHC. Intensity oscillations of the integrated (over the spectrum) RR from the EHC in pure germanium have been observed previously [5,6].

In the present work the magnetic oscillations of the RR intensity at different points of the emission spectrum of the EHC are investigated. On the basis of the experimental data obtained, the dependences of the RR spectral linewidth and of the characteristic energies of the EHC in pure Ge on the magnetic field are calculated.

It is known that one can determine the characteristic energies of the EHC (the Fermi energy, binding energy, and so on) from the shape and spectral position of the luminescence lines from the EHC in the absence of a magnetic field [2,7,8]. At temperatures $T \to 0$ K, i.e., when the temperature-broadening of the Fermi level can be neglected, the chemical potential in the EHC, equal to the mean energy $\langle E_n \rangle$ per pair of particles, is determined by the short-wavelength edge E_h of the RR line of the EHC [7,8]. The total spectral linewidth ΔE is equal to the sum $E_F = E_F^e + E_F^h$ of the Fermi energies of the electrons and holes [2,9]. From the relation

$$\langle E_n \rangle = E_0 + \langle E_{kin} \rangle, \tag{1}$$

where $E_0 = E_{ex} + E_{cor}$ is the sum of the mean exchange and correlation energies and $\langle E_{kin} \rangle$ is the mean kinetic energy per pair of particles in the EHC, using the well-known expression $\langle E_{kin} \rangle = 3E_F/5$ we can obtain the energy E_0 defining the width of the forbidden band in the EHC. Application of a quantizing magnetic field complicates the determination of the characteristic energies of the EHC.

The experiments were performed at $T = 1.5$ K on samples of pure Ge with impurity concentration $\lesssim 10^{12}\ \text{cm}^{-3}$ with an applied magnetic field $H = 0$–32 kOe, produced by a superconducting solenoid. The field H was parallel to the [100] crystallographic axis of the samples. The nonequilibrium carriers were excited by a GaAs laser, which generated pulses of duration 2 μsec, at an off-duty factor of 0.2%. The luminous flux at the sample was ≈ 5 W/cm^2. The details of the experimental setup were described in [6,9]. The spectral gap width was ~ 1 meV.

The luminescence-intensity oscillations were studied at the maximum and along the edges of the line for RR with emission of a LA-phonon (709 meV) as a function of the delay time t between the exciting pulse and the detection. It was found that for sufficiently small delays ($t \lesssim 10\ \mu$sec) the relative amplitude of the intensity oscillations (i.e., the amplitude normalized to the magnitude of the intensity in zero magnetic field $H = 0$) is a minimum at the center of the line and increases toward the edges. Figure 1 shows the oscillations at three points of the LA-709 meV line at $t = 7\ \mu$sec. It can be seen that the oscillations at the maximum of the line are considerably smaller than those at the edges. This is explained by the fact that, according to the data of [6,9], as $t \to 0$ the relative amplitudes of the oscillations in the intensity of the integrated RR and of the RR spectral linewidth

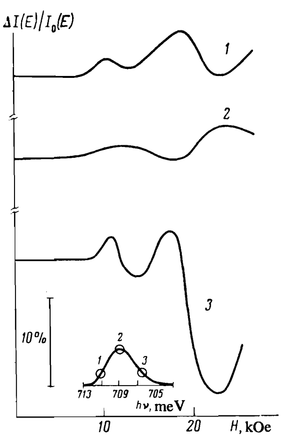

FIG. 1

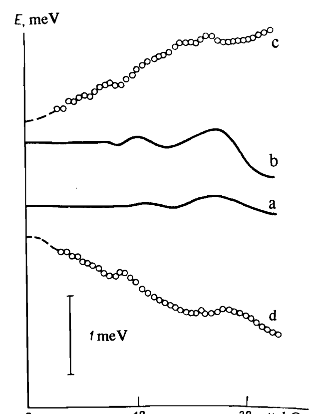

FIG. 2

FIG. 1. Magnetic oscillations of the intensity of the luminescence from the EHC in pure Ge at different points of the spectrum. T = 1.5 K. The curves 1, 2, 3 correspond to the points indicated on the spectral line. The delay time between the exciting pulse and the detection is 7 μsec. The error in the measurements is ±1.5%.

FIG. 2. Magnetic oscillations of the characteristic energies of the EHC in pure Ge (T = 1.5 K): a) oscillations of the mean energy $\langle E_n \rangle$ per pair of particles; b) oscillations of the width ΔE of the LA-709 meV line; c) oscillations of the mean kinetic energy $\langle E_{kin} \rangle$ per pair of particles; d) oscillations of the exchange and correlation energies $E_0 = E_{ex} + E_{cor}$. The points show the results of a calculation by formula (2).

can be assumed to be equal to the amplitude of the carrier-density oscillations in the EHC. But the intensity of the integrated RR is equal to the area under the curve of the spectral dependence of the RR of the EHC, i.e., it can, with sufficient accuracy, be represented in the form of a product of the spectral width with the intensity at the maximum of the line. Therefore, the intensity at the maximum should oscillate weakly at small values of t. As the delay time increases the amplitude of the intensity oscillations at any point in the spectrum varies linearly with the time t, i.e., displays a dependence analogous to that described in [6] for the intensity of the integrated RR.

As follows from the data of [9,10], in fields $H \lesssim 25$ kOe the LA-709 meV lineshape changes insignificantly, whereas in stronger fields a splitting of this line begins to appear [10]2). Therefore, assuming the lineshape to be unchanged for $H \lesssim 25$ kOe, we can calculate the spectral position of the line in this region of fields by using the intensity oscillations at three points in the spectrum. In fact, the intensity I(E) at any point of the line can be represented as a function of the outermost short-wavelength (E_h) and long-wavelength (E_l) points of the line and of the maximum intensity I_{max}:

$$I(E)=f(E_h,\ E_l,\ I_{max}).$$

E_h is defined as the short-wavelength edge of the line as $T \to 0$ K [7]. Using the intensity oscillations at the center and at two points on the edges of the line (Fig. 1), we have calculated the oscillations of E_h and E_l in a magnetic field. Figures 2a and 2b give the results of the calculation for E_h and for the linewidth $\Delta E = E_h - E_l$. The dependence of E_h on H determines the oscillations of the mean energy $\langle E_n \rangle$ per pair of particles in the EHC (i.e., the chemical potential) in a magnetic field.

The oscillations of ΔE characterize the behavior of the Fermi energy in a magnetic field and are in good agreement with the results of our previous paper [9]. Neglecting the quantization of the holes in fields $H < 25$ kOe [4,5,9] and using the expressions from [9], we can obtain a relation between the Fermi energy and the mean kinetic energy in a magnetic field for the EHC:

$$\langle E_{kin}\rangle = \langle E_{kin}\rangle + \langle E_{kin}^h\rangle = \varepsilon_F^e \sum_{n=0}^{n_{max}(s)} \sum_{s=0}^{1} \Big[\frac{1}{3}(1-nx-sy)^{3/2} + \Big(nx+sy+\frac{x+y}{2}\Big)(1-nx-sy)^{1/2} \Big] \Big/ \sum_{n=0}^{n_{max}(s)} \sum_{s=0}^{1} (1-nx-sy)^{1/2} + \frac{3}{5}\varepsilon_F^h, \quad (2)$$

where $x = \hbar\omega/\epsilon_F^e$, $y = \hbar\omega_s/\epsilon_F^e$, ϵ_F^e and ϵ_F^h are the electron and hole Fermi energies, measured from the lowest Landau levels, ω is the cyclotron frequency of the electrons for the given direction of H, $\omega_s = m_i\omega/m_s$, m_i is the cyclotron effective mass of the electron, $m_s = 2m_i/g_i$, m_0 is the free-electron mass, and g_i is the electron g-factor for the given direction.

From (2), putting $\epsilon_F^e \approx 0.4\Delta E$ and $\epsilon_F^h \approx 0.6\Delta E$ [8], we calculate the oscillations of $\langle E_{kin}\rangle$ and, substituting this into (1), obtain the oscillations of the energy $E_0 = E_{ex} + E_{cor}$ (Figs. 2c and 2d). The complex character of these oscillations is connected with the fact that both the redistribution of the density of states over the energies (as a result of the movement of the Landau levels in the magnetic field) and the oscillations of the equilibrium carrier density simultaneously affect $\langle E_{kin}\rangle$ and E_0. This also follows from the results of the work of Keldysh and Silin [4], in which it was shown that the phases of the oscillations of the kinetic and exchange energies and of the carrier density in the EHC in a magnetic field do not coincide. In order of magnitude, the oscillations of E_0 agree with their estimates [4] (~3% of the EHC binding energy ≈ 2.5 meV for H = 10 kOe).

Earlier, spectral investigations of the intensity oscillations of the EHC RR were carried out in Si [11], in which it was also observed that the amplitude of the oscillations at the center of the line is smaller than at the short-wavelength edge.

Thus, we have studied the magnetic oscillations of the emission intensity at different points of the luminescence line of the EHC in pure Ge. The results obtained are well explained in the framework of the "droplet" model. The magnetic oscillations of the spectral linewidth and of the characteristic EHC energies are calculated from the intensity oscillations at three points of the line.

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2)In our experiments the splitting of the LA-709 meV line was observed for $H > 25$ kOe, i.e., in weaker fields than those reported by Alekseev et al. [10] ($H > 40$ kOe).

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236