Magnetic oscillations of the half-width of the luminescence line of electron-hole drops in pure germanium

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Magnetic oscillations of the half-width of the radiative recombination (the LA 709-meV) line of electron-hole drops in germanium were observed. It is shown that the observed oscillations can be attributed to oscillations of the carrier density ρ_H in the drops. A relation is derived between dE_F/E_F and $d\rho_H/\rho_H$ and is used to calculate, with allowance for the oscillations of ρ_H, the dependence of the line half-width ΔE on the magnetic field. The calculated curve is in good agreement with the experimental data.

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As was observed experimentally [1], the total intensity of recombination radiation from electron-hole drops (EHD) in germanium oscillates in a magnetic field. Keldysh and Silin [2] have shown that application of a magnetic field produces oscillating increments to the free energy and to the equilibrium carrier density in the EHD. In [3,4], pulsed excitation and pulsed registration of the signal of the integrated (over the spectrum) radiative recombination (IRC) in germanium was used and made it possible to investigate the kinetics of the IRC oscillations, to determine the oscillations of the equilibrium carrier density ρ_H in EHD in a magnetic field, and to estimate the quantum yield.

It is known that in the absence of a magnetic field the shape of the EHD radiative-recombination spectral line is connected with the Fermi energy, $E_F \propto \rho^{2/3}$, from which it follows that it is possible to estimate the carrier density from the line shape. [5] When a magnetic field is applied, the connection between E_F and ρ_H becomes more complicated, and it was therefore of interest to investigate the EHD line shape as a function of the magnetic field.

We have investigated experimentally the radiative-recombination line shape of EHD with emission of an LA phonon (709 meV) in magnetic fields up to 32 kOe. The experiments were performed on samples of pure n-type germanium ($N_D \approx 10^{12}$ cm^{-3}) measuring $5 \times 5 \times 0.3$ mm, placed in a superconducting solenoid at a liquid-helium temperature T = 1.5°K. The magnetic field was parallel to the [100] crystallographic axis of the samples. The nonequilibrium carriers were generated with a pulsed GaAs laser of ~10 W power in pulse of 2 μsec duration and a repetition frequency 1 kHz. To avoid overheating, the laser power was distributed over the entire sample surface (≈ 0.2 cm²). The radiation from the samples was analyzed with an MDR-2 monochromator and registered with a pulsed germanium photodiode with operating time ~1 μsec. To increase the signal/noise ratio, strobing integration with strobe-pulse duration 2 μsec was used.

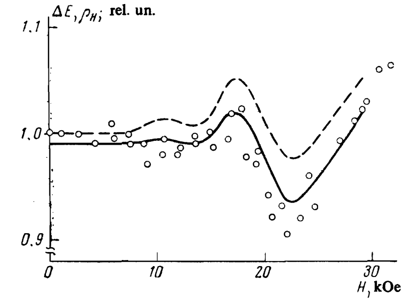
The figure shows the experimental half-width of the 709 meV LA line, i.e., the spectral line width measured at the 0.5 level, as a function of the maximum intensity I_{max}. An oscillatory effect was observed: the half-width of the EHD radiated-recombination line (the 709-meV LA line) oscillates in a magnetic field. The measurements were performed with a delay time t = 10 μsec between the excitation pulse and the instant of registration. As shown in [4], at this delay time the radiated-recombination line intensity is maximal and oscillates little in a magnetic field.

At zero temperature and in the absence of a magnetic field the spectral width of the EHD radiative-recombination line is equal to the sum of the Fermi energies for the electrons and holes ($E_F^e + E_F^h$). When a magnetic field is applied, the total line width is determined by the sum of the energy gaps between the Fermi level and the corresponding lowest Landau level for the electrons and holes. Since $kT \ll E_F$ under experimental conditions, we can neglect the temperature spread of the Fermi level.

Let us analyze the dependence of the Fermi energy in a magnetic field on the carrier density. According to Keldysh and Silin, [2] the main contribution to the oscillations in the magnetic-field region considered in this paper should be due to electrons, and the contribution of the holes can be neglected; this follows also from the anisotropic dependence of the oscillations [1] on the direction of the magnetic field H relative to the crystallographic axes. The dominant contribution of the electrons to the oscillations is connected with the fact that for the same field, up to 30 kOe, the holes have a larger number of Landau levels than the electrons, and therefore they make a smaller contribution to the EHD oscillations. [6] It can be assumed that the following expression holds for holes in this range of fields:

$$\frac{dE_F^h}{E_F^h} \Big/ \frac{d\rho_H}{\rho_H} \approx \frac{2}{3}. \qquad (1)$$

We consider the system of electrons in EHD. The density of states $\nu_H(E, s)$ for the electrons in a magnetic field, in the case of anisotropic valleys [7], can be written in the form [8]



Half-width of the EHD radiative-recombination line (709 MeV LA line) and equilibrium carrier density in EHD vs. the magnetic field; circles—experimental, solid curve—calculated half-width, dashed—carrier density in EHD. [4]

$$\nu_H(E,s)=\sum_{i=1}^{\eta}\frac{\hbar\omega_i m^{1/2}}{2\sqrt{2}\pi^2\hbar^3}\sum_{s=\pm1}\sum_{n=0}^{n_{max}(s)}[E-(n+1/2)\hbar\omega_i-1/2 g_i s\mu_B H]^{-1/2}, \quad (2)$$

where $\mu_B = e\hbar/m_0c$ is the Bohr magneton; m_0 is the mass of the free electron, m is the mass of the density of states; $\omega_i = eH/m_ic$, m_i and g_i are the cyclotron frequency, the cyclotron mass, and the g-factor of the electrons in the i-th valley for a given magnetic-field direction; s is the spin number, n is the number of the Landau level, and E is the energy.

For a magnetic field directed along the [100] axis, all four valleys are equivalent. Since[2] $g_i \approx 1.7$, we neglect the spin splitting for the case $n \geq 1$. Introducing new symbols

$$\mathscr{E}_F^e=E_F^e-\hbar\omega_i/2, \quad x=\hbar\omega_i/\mathscr{E}_F^e, \quad (3)$$

we obtain an expression for the carrier density ρ_H in EHD in a magnetic field:

$$\rho_H=\frac{4\cdot 2^{1/2}m^{3/2}}{\pi^2\hbar^3}x(\mathscr{E}_F^e)^{3/2}\sum_{n=0}^{n_{max}}(1-nx)^{1/2}. \quad (4)$$

We obtain next an expression for the ratio of the logarithmic derivatives of $\mathscr{E}_F^e$ and ρ_H:

$$\frac{d\mathscr{E}_F^e}{\mathscr{E}_F^e}\Big/\frac{d\rho_H}{\rho_H}=2\sum_{n=0}^{n_{max}}(1-nx)^{1/2}\Big/\sum_{n=0}^{n_{max}}\frac{1}{(1-nx)^{1/2}}. \quad (5)$$

As follows from (5), when the n-th Landau level crosses the Fermi level (nx = 1) the position of the Fermi level does not depend on the density, and is determined by the position of this Landau level. The half-width of the EHD radiative-recombination line in the magnetic field ΔE, is proportional to[2)] $\mathscr{E}_F^e + \mathscr{E}_F^h$. Using relations (1) and (5), we can obtain an expression for the logarithmic derivative of the line half-width of the function of the density ρ_H in a magnetic field

$$\frac{d(\Delta E)}{\Delta E}=\left\{\frac{\mathscr{E}_F^e}{\mathscr{E}_F^e+\mathscr{E}_F^h}\cdot 2\sum_{n=0}^{n_{max}}(1-nx)^{1/2}\Big/\sum_{n=0}^{n_{max}}\frac{1}{(1-nx)^{1/2}}+\frac{\mathscr{E}_F^h}{\mathscr{E}_F^e+\mathscr{E}_F^h}\frac{2}{3}\right\}\frac{d\rho_H}{\rho_H} \quad (6)$$

From (6) and from the experimental data for the oscillations of the carrier density in EHD in a magnetic field[4], we calculated by an iteration method, the oscillations of the half-width of the EHD radiative-recombination line. For fields in which n = 0 we took into account the spin splitting of the last electronic Landau level. The calculation was based on formula (6), except that m_i was replaced by the spin mass $m_s = 2m_0/g_i$. The figure showed a plot of ρ_H against the magnetic field[4] and the plot, calculated on its basis, of the line half-width ΔE on H for $m/m_i = 0.22/0.13$.[2] The circles denote the experimental values dependence of the half-width of the 709-meV LA line as a function of the magnetic field. It is seen from the comparison that the character of the oscillations of ΔE is well described by the calculated curve.

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[2)]The oscillations of the spectral line width measured at the level $0.25I_{max}$ have the same relative magnitude as the oscillations of the line half-width. It can therefore be assumed that the oscillations of the half-width are equivalent to the oscillations of the total spectral width of the line.

[1] V. S. Bagaev, T. I. Galkina, N. A. Penin, V. B. Stopachinskiĭ, and M. N. Churaeva, Pis'ma Zh. Eksp. Teor. Fiz. **16**, 120 (1972) [JETP Lett. **16**, 83 (1972)].

[2] L. V. Keldysh and A. P. Silin, Fiz. Tverd Tela **15**, 1532 (1973) [Sov. Phys. Solid State **15**, 1026 (1973)].

[3] V. B. Ginodman, P. S. Gladkov, B. G. Zhurkin, N. A. Kazakov, and N. A. Penin, Preprint Phys. Inst. Acad. Sci. SSSR, No. 90 (1974).

[4] K. V. Betsler, B. G. Zhurkin, and A. L. Karuzskiĭ, Solid State Commun., in press.

[5] Thomas K. Lo, Solid State Commun. **15**, 1231 (1974); Gordon A. Thomas, T. M. Rice, and J. C. Hensel, Phys. Rev. Lett. **33**, 219 (1974); Ja. E. Pokrovsky, Phys. Status Solidi [a] **11**, 385 (1972); R. W. Martin and R. Sauer, Phys. Status Solidi [b] **62**, 443 (1974).

[6] A. S. Alekseev, V. S. Bagaev, T. I. Galkina, O. V. Gogolin, N. A. Penin, A. N. Semenov, and V. B. Stopachinskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **12**, 203 (1970) [JETP Lett. **12**, 140 (1970)]; Tr. Fiz. Inst. Akad. Nauk SSSR **67**, 109 (1973).

[7] M. Blackman, Proc. R. Soc. **116**, 1 (1938).

[8] N. B. Brandt, S. M. Chudinov, Élektronnaya struktura metallov (Electron Structure of Metals), Moscow State University Press, 1973, p. 189. B. M. Askerov, Kineticheskie éffekty v poluprovodnikakh (Kinetic Effects in Semiconductors), Nauka, 1970, p. 175.

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117