Change of carrier density in electron-hole drops in germanium in a magnetic field

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The shape of the electron-hole drops (EHD) in a magnetic field is considered. It is shown that the presence of recombination magnetization leads to a new mechanism of EHD instability when the drop dimensions increase. The magnetoplasma absorption spectra are used to obtain the first quantitative information on the increase of the EHD particle density in germanium, from 2.2×10^{17} to 3.9×10^{17} cm^{-3}, in fields $H \parallel$ [111] up to 40 kOe.

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The study of plasma resonance in a system of electron-hole drops (EHD) makes it possible to follow directly the concentration of the particles in the electron-hole liquid, both under ordinary conditions[1] and when subjected to various external actions, particularly in a magnetic field. These data are of fundamental significance for the understanding of the nature and properties of the condensed state of excitons. An important problem in the quantitative interpretation of the magnetoplasma-resonance (MPR) spectra in EHD is, however, the determination of the shape of the drops in the magnetic field. This question, which is also of independent interest, has heretofore not been considered.

In this paper we analyze the shape of EHD in a magnetic field as a function of the ratio of the surface-tension forces to the ponderomotive forces due to the recombination magnetization of EHD. It is shown that with increasing drop dimensions the presence of recombination magnetization leads to a new mechanism of EHD instability. Quantitative information on the change of the EHD particle density in magnetic fields $H \parallel$ [111] up to 40 kOe is obtained for the first time from the MPR spectra, on the basis of a theory that takes into account the change of the EHD in a magnetic field.

It can be shown that for any drop other than spherical, say an ellipsoid of revolution about $\mathbf{H} \parallel$ [100] or $\mathbf{H} \parallel$ [111], the spectral dependence of the magnetoplasma absorption of the EHD is of the form

$$a(\omega) \sim \omega \, \mathrm{Im} \left\{ \frac{\tilde{\epsilon} - 1}{4\pi + L(\tilde{\epsilon} - 1)} \right\} . \tag{1}$$

Here $\tilde{\epsilon}(\omega)$ is the ratio of the dielectric constants of the EHD material and of the germanium lattice, [2] while L is the EHD depolarizing factor in the direction of the electric field of the wave, and characterizes the effect of the drop shape on the magnetoplasma resonance. In the absence of inhomogeneous deformations in the crystal, the shape of an EHD situated in a magnetic field is determined by the balance between the surface-tension energy and the recombination-magnetization energy, [3] the latter being proportional to the area of the drop cross section perpendicular to $\mathbf{H}$ (the contribution of the magnetization connected with
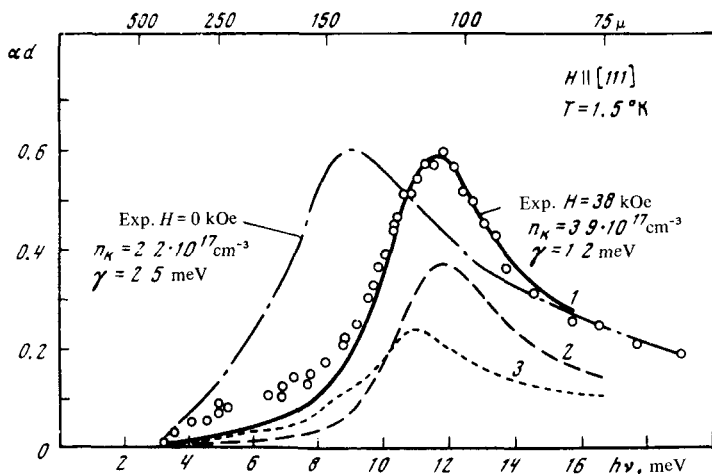
FIG. 1. Absorption spectra of EHD in germanium, measured at $H = 0$ and 38 kOe, and the theoretical curves calculated for $H = 38$ kOe (1—combined curve for linear polarization, 2 and 3—for left- and right-hand circular polarizations of the radiation).

the paramagnetic and diamagnetic susceptibilities of the carriers can be neglected). In a magnetic field, the EHD surface-tension coefficient becomes anisotropic as a result of the anisotropy of the Bohr radius. This leads to a relative decrease of the energy per unit area of the EHD surface parallel to **H**, and helps stretch out the drops along the field. The forces acting on the recombination fluxes in EHD in a magnetic field, to the contrary, tend to spread the drop in a plane perpendicular to **H**. Taking into account the anisotropy of the surface tension of the EHD, we can express, in analogy with[*], the shape-dependent increment to the total energy of the EHD in the form

$$\Delta E = \left[2\pi\sigma_\perp \left(\sqrt{\zeta} + \frac{\ln(\sqrt{\zeta} + \sqrt{\zeta x^2 - 1})}{x\sqrt{\zeta x^2 - 1}} \right) - f(H) V \right] x^{2/3} \left(\frac{3V}{4\pi} \right)^{2/3} \tag{2}$$

$$f(H) = \frac{n_k m}{30 \tau_0 \tau} \frac{(\omega_c \tau)^2}{1 + (\omega_0 \tau)^2} \left[1 + \frac{3}{8} \frac{\eta \tau}{n_k m} \left(\frac{4\pi}{3V} \right)^{2/3} \right]^{-1}$$

Here $\zeta(\sigma_\parallel/\sigma_\perp)$ is the square of the ratio of the coefficients of the surface tension of the EHD for surfaces with normals parallel and perpendicular to **H**, $x = b/a$, is the ratio of the semiaxes of the ellipsoid, $V = 4\pi ab^2/3$ is the volume of the drop, n_k is the carrier density in the EHD, $\tau_0 \approx 2 \times 10^{-5}$ sec is their lifetime in the EHD, $\tau \approx 10^{-11}$ sec is the carrier momentum relaxation time, [5] $\eta \approx 10^{-7}$ g-cm^{-1} sec^{-1} is the viscous-friction coefficient, [6] $m \approx 10^{-28}$ g is the effective mass, and $\omega_c = eH/mc$ is the cyclotron frequency. The expression for $f(H)$ differs from that in[3] in that account is taken of the saturation of the recombination magnetization, in accordance with[7], as well as of the viscous friction inside the EHD. The equilibrium shape of the drop is determined by the condition $\partial \Delta E/\partial x = 0$ at constant V and H.

It can be seen from (2) that, first, the stretching action of the recombination magnetization forces increases with increasing EHD dimensions. Second, in a magnetic field, the presence of recombination magnetization leads to an instability of drops with dimensions exceeding a certain critical value. At $f(H)V > 2\pi\sigma_1$, the ponderomotive forces acting on the circular recombination fluxes inside the EHD stretch the drop into a film $(x \to \infty, \Delta E \to \infty)$, and ultimately break it up into smaller droplets. The critical EHD dimensions

$$R_{cr} = \left(\frac{3V}{4\pi}\right)^{1/3} = \left[\frac{45\,\sigma_{\shortparallel}(1+\omega_c^2\tau^2)}{\dfrac{n_k m}{\tau_0 \tau}\,\omega_c^2\tau^2}\left(1+\frac{3}{8}\,\frac{\eta\tau}{n_k m R_{cr}^2}\right)\right]^{1/3} \tag{3}$$

in the case of germanium at $H = 40$ kOe amount to $R_{cr} \approx 5\,\mu$ (without allowance for the recombination-magnetization saturation) and $R_{cr} \approx 30\,\mu$ (with allowance for this saturation), i.e., they turn out to be approximately of the same order as the critical EHD dimensions determined by the phonon wind. [8] In the presence of uniform deformations, when the phonon wind is greatly weakened, [8] the recombination magnetization can apparently become the principal factor that limits the dimensions of the EHD in a magnetic field.

Thus, EHD with small dimensions $(V \ll V_{cr})$ become stretched out along the magnetic field. With increasing drop volume (at constant H), owing to the flattening action of the recombination magnetization, the drops become spherical, and ultimately take the form of an oblate ellipsoid. We note that in ultrastrong magnetic fields, in view of the saturation of the recombination magnetization, the situation corresponds to the condition $V \ll V_{cr}$.

On the basis of the model developed here, which takes into account the shape of the EHD in a magnetic field, the MPR spectra of EHD in germanium[9] were used to determine the concentration of the particles in EHD in germanium at 1.5°K in magnetic fields $\mathbf{H} \parallel [111]$ up to 40 kOe. The calculation was performed for EHD with dimensions $\sim 1\,\mu$[9] with allowance for the quantum spectrum of the holes in germanium in a magnetic field[10] and with allowance for the renormalized values of the carriers masses in the EHD. [5] The drop shape was
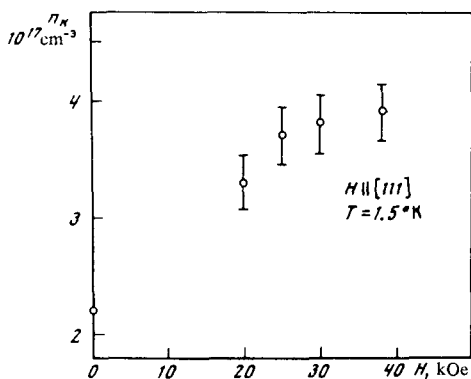

FIG. 2. Equilibrium concentration of the carriers in EHD in germanium vs. the magnetic field.

estimated on the basis of Eq. (2) and the calculations of[4]. Best agreement between theory and experiment was obtained by varying two parameters, the concentration n_k and the damping constant γ of the plasma oscillations (Fig. 1). As seen from Fig. 2, when the magnetic field is increased to 40 kOe the concentration of the particles in EHD in germanium increases from 2.2×10^{17} cm^{-3} (with allowance for the mass renormalization)[1] to 3.9×10^{17} cm^{-3}. The value of γ decreased in this case from 2.5 to 1 meV. So noticeable a change of n_k indicates that the tendency of the electron-hole liquid to become self-compressed in ultrastrong magnetic fields[11] begins to manifest itself already in fields on the order of 30—40 kOe.

[1]V. I. Gavrilenko, V. L. Kononenko, and V. N. Murzin, Fiz. Tverd. Tela **18**, 1753 (1976) [Sov. Phys. Solid State **18**, 1020 (1976)].
[2]V. L. Kononenko, Fiz. Tverd. Tela **17**, 3264 (1975) [Sov. Phys. Solid State **17**, 2146 (1975)].
[3]A. S. Kaminskiĭ and Ya. E. Pokrovskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 431 (1975) [JETP Lett. **21**, 197 (1975)].
[4]M. Morimoto, K. Shindo, and A. Morita, J. Phys. Soc. Jap. **41**, 91 (1976).
[5]V. I. Gavrilenko, V. L. Kononeko, T. S. Mandel'shtam, and V. N. Murzin, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 701 (1976) [JETP Lett. **23**, 645 (1976)].
[6]A. K. Kikoin and I. K. Kikoin, Mokekulyarnaya fizika (Molecular Physics), Nauka, 1976.
[7]J. P. Wolfe, J. E. Furneaux, and R. S. Markiewicz, Proc. Thirteenth Intern. Conf. on Physics of Semiconductors, Rome, 1976.
[8]L. V. Keldysh, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 100 (1976) [JETP Lett. **23**, 86 (1976)].
[9]V. N. Murzin, V. A. Zayats, and V. L. Kononenko, Fiz. Tverd. Tela **15**, 3634 (1973) [Sov. Phys. Solid State **15**, 2421 (1974)].
[10]J. C. Hensel and K. Suzuki, Phys. Rev. **B9**, 4219 (1974).
[11]L. V. Keldysh and T. A. Onishchenko, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 70 (1976) [JETP Lett. **24**, 59 (1976)].