Experimental observation of magnetodipole resonances in electron-hole drops in germanium

V. I. Gavrilenko, V. L. Kononenko, T. S. Mandel'shtam, V. N. Murzin, and S. A. Saunin

P. N. Lebedev Physics Institute, USSR Academy of Sciences

(Submitted June 8, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 2, 102–106 (20 July 1977)

Magnetodipole resonant absorption in electron-hole drops (EHD) was experimentally observed for the first time in germanium at submillimeter wavelengths ($\lambda = 0.6 - 1.35$ mm). A study of the observed phenomenon led to a direct measurement of the effective masses of the electrons in the EHD. The dimensions of the drops and the change of their shape in a magnetic field are determined.

PACS numbers: 71.35.+z, 71.25.Jd, 76.90.+d

The deviation of the electron and hole masses in electron-hole drops (EHD) from the masses of the free carriers in Ge, due to the collective multiparticle excitation of the system, is one of the fundamental features of the condensed phase of excitons in Ge.[1] However, the use of ordinary methods such as cyclotron resonance (CR), which yielded the basic information on the band parameters of most semiconductors, to investigate EHD is made difficult by the hybridization of the cyclotron and plasma oscillations on account of the high density of the condensate and the limited dimensions of the drops ($r \ll \lambda_0$).[1–4] At the same time, the spectra of the magnetoplasma resonance (MPR) at cyclotron frequencies contain, in principle, information not only on the characteristics of the carriers in the EHD, but also on other properties of the condensed phase.

In the present investigation of the optical properties of EHD at cyclotron carrier frequencies and at $H=0$ to 30 kOe (submillimeter waves) we have observed for the first time resonance absorption lines due to the interaction of the EHD with the magnetic field of the electromagnetic wave (magnetodipole resonance MPR). Study of the observed phenomenon by the most direct method has made it possible to measure the effective masses of the electrons in the EHD, and to determine the dimensions and the change in the shape of the drops in a constant magnetic field.

The investigations were carried out in the range $\lambda = 0.6$–1.35 mm with a backward-wave-tube spectrometer[1] with the crystal excited by intense light from a cw YAG:Nd^{3+} laser ($\lambda = 1.06$ μm, $P_{max} \sim 3$ W). The optically induced change in the transmission of pure Ge($N_A \sim 10^{12}$ cm^{-3}) at 4.2–1.7 K was measured by a differential method at the orientations $\mathbf{H} \parallel [111]$ and $\mathbf{H} \parallel [110]$ with $H=0$ to 30 kOe.

Figure 1 shows typical absorption spectra measured at 4.2 and 1.8 K. It is seen that with decreasing temperature, when the condensed phase of excitons is produced, there will appear in the spectra, besides the CR lines of the free

© 1978 American Institute of Physics

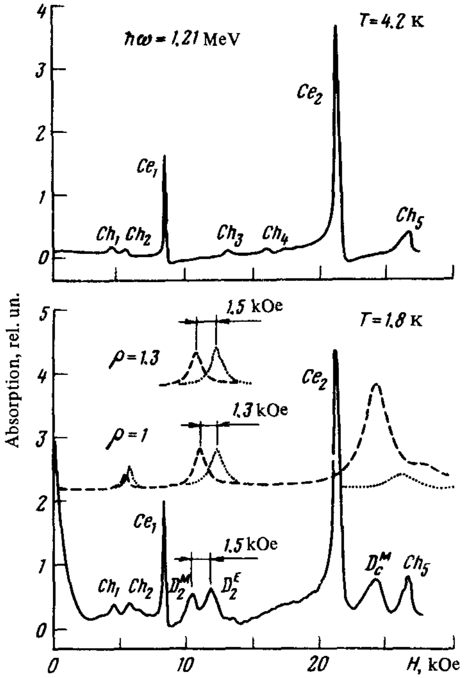

FIG. 1. MPR spectra in EHD in germanium. The solid lines show the experimental data at **H** ∥ [111], the dashed and dotted lines show the respective results of the calculation of the magnetodipole and electrodipole absorption for a spherical ($\rho = 1$) and oblate ($\rho = 1.3$) EHD.

electrons (Ce_1—Ce_2) and holes (Ch_1—Ch_5) new broader lines D_2^M, D_2^E, and D_C^M. All are connected with the formation of EHD in Ge. However, whereas D_2^E has been thoroughly studied at shorter wavelengths and is determined by the electrodipole (ED) absorption mechanism,[1] the two others cannot be attributed to this mechanism, primarily because of their spectral position. In addition, their intensity has a different dependence on the frequency than in the case of ED absorption (Fig. 2).

The new resonances can be attributed to magnetodipole (MD) interaction of the wave with the EHD ($r \ll \lambda_0$). In the Mie theory, this interaction is represented by the second term in the expansion in the small parameter $(2\pi r/\lambda_0)^2$, where r/λ_0 is the ratio of the drop radius to the length of the electromagnetic wave in the crystal. For EHD in Ge in a constant magnetic field and in the Faraday configuration $\mathbf{E}_\omega$, $\mathbf{H}_\omega \perp \mathbf{H}$ the ED and MD absorption are described by the expression[3–5]

$$a_\pm \sim \omega \left\{ \mathrm{Im}\,\frac{\tilde{\epsilon}_\pm - 1}{\tilde{\epsilon}_\pm + 2} + \frac{1}{30}\left(\frac{2\pi r}{\lambda_0}\right)^2 \mathrm{Im}\,\tilde{\epsilon}_\pm^{\mathrm{eff}} \right\}, \text{where } \tilde{\epsilon}_\pm^{\mathrm{eff}} = \frac{2\tilde{\epsilon}_\pm \tilde{\epsilon}_\parallel}{\tilde{\epsilon}_\pm + \tilde{\epsilon}_\parallel}. \qquad (1)$$

Here $\tilde{\epsilon}$ is the relative dielectric constant of the EHD in Ge.[3] The subscripts ± correspond to two circular (hole and electron) polarizations of the electromagnetic wave, and $\tilde{\epsilon}_\parallel$ is the longitudinal constant of the dielectric constant of the EHD. Although the MD absorption in the far infrared is much weaker than

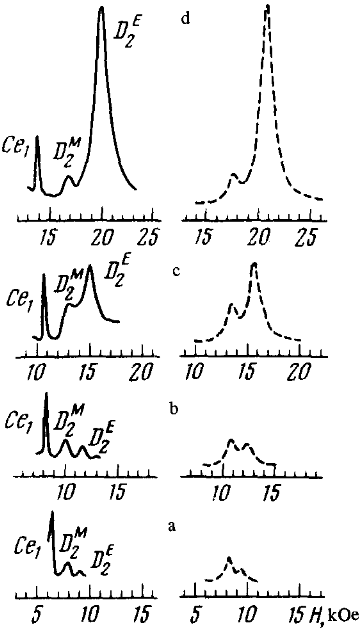

FIG. 2. Measured (solid lines) and calculated (dashed) spectra of MPR in EHD in germanium at H∥[111] and different frequencies $\hbar\omega$: a—0.92 meV, b—1.20 meV, c—1.54 meV, d—2.03 meV. The calculations were performed according to (3) for oblate drops: a—$r^{\rm eff}=2.8$ μm, $\rho=1.2$; b—$r^{\rm eff}=2.8$ μm, $\rho=1.3$; c—$r^{\rm eff}=2.2$ μm, $\rho=1.4$; d—$r^{\rm eff}=1.6$ μm, $\rho=1.7$.

the ED absorption, it decreases more slowly with increasing wavelength, and can become predominant at $\lambda > 500$ μm (owing to the frequency dependence of $\epsilon(\omega)$). As seen from Fig. 1, which shows the MPR spectra in EHD in Ge calculated according to (1), the position of the observed new lines is satisfactorily explained by the MD absorption mechanism (D_2^M and D_C^M).

A most important and nontrivial feature of the observed MD absorption is that if the ellipsoid of the effective mass of any type of carrier is inclined to H, then the resonant MD absorption in EHD takes place exactly at the cyclotron frequency of these carriers (see (1)). It is easily seen that observation of such resonances permits a direct measurement of the effective masses of electrons in the EHD, without resorting to complex calculations that call for taking into account the valence band of Ge in a magnetic field.[1,4] At orientations H∥[111] and H∥[110], these cyclotron replicas are the lines D_C^M (Fig. 1). From the positions of these lines as obtained by us in the experiment we determined, using the known formulas for the cyclotron frequencies of the electron s in Ge, the transverse $m_t^{\rm EHD}$ and the longitudinal $m_t^{\rm EHD}$ effective masses of the electrons in the EHD:

$$m_t^{\rm EHD} = (1.15 \pm 0.02)\, m_t; \qquad m_l^{\rm EHD} = (1.0 \pm 0.2) m_l. \tag{2}$$

As follows from (1), the MHD absorption, in contrast to ED absorption is determined not simply by the volume of the condensed phase, but depends most strongly on the drop radius and is therefore more sensitive to a change in their form. This makes it possible to obtain information on the EHD dimensions from the ratio of the intensities of the MD and ED lines in the measured spectra.

Figure 1 shows, besides the experimental data, the ED and MD absorption spectra calculated for drops of 2.4 μm radius, which corresponds to the measured ratio of the intensities of the lines D_2^M and D_2^E. Comparison of the theory with experiment for another MD line, D_C^M, located in stronger magnetic fields, leads to the conclusion that the dimensions of the drops decrease under our conditions with increasing magnetic field. This is confirmed also by the data shown in Fig. 2. The observed effect is apparently due to the decrease of the carrier lifetimes in the EHD on account of the increase of the drop density in the magnetic field.[4]

As already noted, the MPR spectra calculated according to (1) are in satisfactory agreement with experiment. It can be noted, however, that the measured distance between the lines D_2^M and D_2^E (Fig. 1) is somewhat larger than calculated. This discrepancy cannot be explained within the framework of the developed model of MPR in EHD for Ge in the case of spherical drops. It can be shown by examining the electrodynamic interaction of a wave with an EHD in the form of an ellipsoid of revolution oblate or prolate in the H direction, that in this case the absorption is given by

$$\alpha_{\pm} \sim \omega\left\{\frac{4\pi}{3}\,\mathrm{Im}\,\frac{\tilde{\epsilon}_{\pm}-1}{4\pi+L(\tilde{\epsilon}_{\pm}-1)}+\frac{1}{30}\left(\frac{2\pi r^{\mathrm{eff}}}{\lambda_0}\right)^2\mathrm{Im}\,\tilde{\epsilon}_{\pm}^{\mathrm{eff}}\right\}, \tag{3}$$

where

$$\tilde{\epsilon}_{\pm}^{\mathrm{eff}}=\rho^{-4/3}\,\frac{2\tilde{\epsilon}_{\pm}\rho^2\tilde{\epsilon}_{\parallel}}{\tilde{\epsilon}_{\pm}+\rho^2\tilde{\epsilon}_{\parallel}}\,.$$

Here L is the depolarizing factor of the EHD, $\rho=a/b$ is the ratio of the transverse and longitudinal semiaxes of the ellipsoid, and $r^{\mathrm{eff}}=(a^2b)^{1/3}$. The results obtained in the present paper can be satisfactorily explained if it is assumed that application of the field causes the EHD to become oblate. As seen from Figs. 1 and 2, in fields $H=10$—20 kOe the oblateness of the drops increases from $\rho\sim1.2$ to $\rho\sim1.7$. The observed change of the shape of the drops in a magnetic field is apparently due to recombination magnetism of the EHD.[4,6]

In conclusion, we note the presence of an abrupt decrease in the absorption in fields up to 1.5 kOe at $T=1.8$ K (Fig. 1) is analogous to that observed in[2], and cannot be explained unequivocally at present. One cannot exclude the possibility that this decrease is due to a size effect in the EHD, inasmuch as in fields ~ 1 kOe the carrier cyclotron radius becomes comparable with the drop dimensions.

The authors thank V. D. Kopanev for help in the construction of the apparatus.

[1] V. I. Gavrilenko, V. L. Kononenko, T. S. Mandel'shtam, and V. N. Murzin, Pis'ma Zh. Eksp. Teor. Fiz. 23, 701 (1976) [JETP Lett. 23, 645 (1976)]; Dokl. Akad. Nauk SSSR 232, 802 (1977) [Sov. Phys. Dokl. 22, 82 (1977)].
[2] V. N. Murzin, V. A. Zayats, and V. L. Kononenko, Fiz. Tverd. Tela 15, 3634 (1973) [Sov. Phys. Solid State 15, 2421 (1974)].

[3] V. L. Kononenko, Fiz. Tverd. Tela **17**, 3264 (1975) [Sov. Phys. Solid State **17**, 2164 (1975)].

[4] V. L. Kononenko and V. N. Murzin, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 590 (1976) [JETP Lett. **24**, 548 (1976)]; Preprint FIAN No. 54, 1977.

[5] G. W. Ford, J. K. Furdyna, and S. A. Werner, Phys. Rev. B **12**, 1452 (1975).

[6] A. S. Kaminskiĭ and Ya. E. Pokrovskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 431 (1975) [JETP Lett. **21**, 197 (1975)].