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Interaction of electron-hole drops in germanium with constant and alternating magnetic fields

A. S. Kaminskiĭ, Ya. E. Pokrovskiĭ, and A. E. Zhidkov

Institute of Radio Engineering and Electronics, USSR Academy of Sciences
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The absorption of the energy of an alternating magnetic field as a result of excitation of eddy currents in electron-hole drops (EHD) in germanium is investigated. The mobility of the carriers in the EHD is determined from the dependence of the absorption on the intenstity of the constant magnetic field. It is shown that at impurity concentrations larger than 10^{14} cm^{-3} the mobility is determined by impurity scattering. Quantitative agreement is obtained between the absolute value of the absorption and the results of the calculation that takes into account the skin effect in EHD. It is observed that the ablation of large EHD in a constant magnetic field depends substantially on the mobility. It is shown that the ablation of EHD and the saturation of this effect in strong magnetic fields is a natural manifestation of the recombination magnetism of the EHD.

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1. INTRODUCTION

Even though electron-hole drops (EHD) in germanium have been investigated systematically since 1969, there were until recently no reliable experimental data whatever on the conductivity of EHD and on the mobility of the electrons and holes inside the drops. The reason is that the EHD are surrounded by a cloud of free carriers that determined both the dc and the alternating (microwave) conductivity of the crystal up to concentrations $\approx 10^{17}$ cm^{-3}, at which flow-through (percolation) conductivity via a chain of EHD appears. However, when such large carrier densities are produced, the crystal is bound to be overheated[1] and the results of measurements in this region can hardly describe the conductivity of the condensed phase. By way the example we can cite the results of[1,2], with which the results of earlier investigations[3,4] agree in the region of moderate excitation levels. It follows from[1,2] that at electron and hole densities in the samples 2×10^{17} cm^{-3}, which is the value of the density in EHD, the conductivity reaches only $2\times10^{3}\Omega^{-1}$cm^{-1}, while the mobility reaches 3×10^{4} cm^2/V-sec. In[5] we have shown that the mobility of the carriers in the drops can be determined from the dependence of the absorption of the energy of the alternating magnetic fields, due to excitation of eddy currents in the EHD, on the intensity of the constant magnetic field. In the present paper we investigate in further detail the investigation of EHD with alternating and constant magnetic fields.

2. EXPERIMENTAL PROCEDURE

To investigate the losses in the frequency range 8–30 MHz, we used commercial apparatus of the Sh1-1 type to measure the induction of the constant magnetic field by means of nuclear magnetic resonance. The germanium samples were placed in the inductance coil, of the tank circuit of the apparatus, with quality vactor $Q_L = 50$, and were excited either by radiation pulses from a nitrogen laser at a wavelength 0.337 μm, duration 40 nsec, and energy 10^{-5} J, or else by radiation from an argon laser of power up to 200 mW, interrupted at a frequency of 320 Hz. Photoexcitation changed the Q of the tank circuit and produced a modulation ΔU of the RF voltage. The low-frequency component of the signal was detected, amplified, and fed to an oscilloscope. The modulation depth $\Delta U/U$ was determined from the ratio of the signal produced by the illumination to the signal U produced in the system when the lasing was stopped.

To produce large EHD, the germanium samples were subjected to inhomogeneous compression in liquid he-

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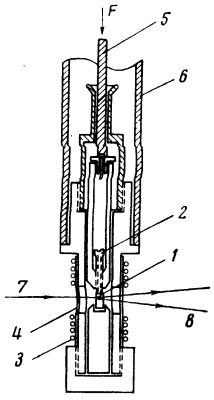

FIG. 1. Setup for the investigation of RF absorption and for the production of inhomogeneous deformation in germanium: 1—sample, 2—caprone screw, 3—high-frequency coil, 4—brass screen, 5—rod to transmit the deforming force and internal conductor of coaxial lead-in, 6, 7—exciting radiation, 8—recombination radiation.

lium (Fig. 1). The inhomogeneous deformation in sample 1 was produced with a caprone screw, the calibrated force F on which was transmitted by a rod 5, which served simultaneously as the internal conductor of a coaxial RF lead-in 6. The alternating magnetic field was excited in a two-section coil 3 with an effective volume $V_L = 1$ cm^3. To eliminate the influence of the RF electric field, a slotted brass-foil screen 4 was placed between the coil and the sample, and had windows for the entrance of the exciting radiation 7 and for the exit of the recombination radiation 8. All the parts of the apparatus were mounted on a dismountable teflon block.

Germanium samples with different impurity concentrations N and different exciton lifetimes τ_{exc} at 4 K (see Table I) were usually parallelepipeds measuring 4×3.8×2.5 mm. Most investigations were carried out on samples with lateral faces lying in the planes (111) and $(\bar{2}11)$, and with bases in the $(0\bar{1}1)$ planes. When such samples were deformed in the [111] directions, a single large EHD drop was produced in them.[6] In samples whose faces were in the (100) plane and the

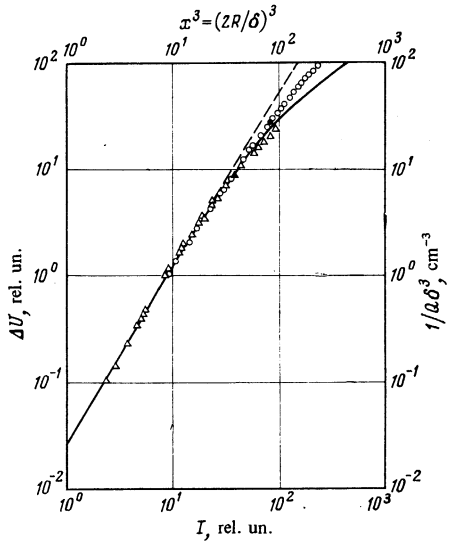

FIG. 2. Dependence of the RF absorption ΔU on the recombination-radiation intensity I at $F \parallel [111]$ and 1.8 K: ○—for sample 5, △—for sample 3; ●, ▲—points at which the absolute values of R and $\Delta U/U$ were measured. The dependence of $1/Q\delta^3$ on x^3 (solid line) was calculated in accordance with (2), (3), and (5).

TABLE I. Principal parameters of germanium sample and mobility in EHD at 1.8 K.

Sample	Type of conductivity	N, cm^{-3}	τ_{exc}, μsec	Mobility, cm^2/V-sec	
				Large EHD	Small EHD
1	n	$8\cdot10^{14}$		$6\cdot10^4$	
2	p	$2\cdot10^{14}$	6	$1.9\cdot10^5$	
3	p	$1.5\cdot10^{14}$	16	$2.2\cdot10^5$	
4	p	$2.6\cdot10^{11}$	20	$6.7\cdot10^5$	$2\cdot10^6$
5	p	$2\cdot10^{10}$	16	$6.7\cdot10^5$	$2\cdot10^6$

deformation was in the [010] direction, four large EHD were produced.[6] In some cases we used cylindrical samples with bases in the (100) planes, deformed in the [011] direction. The samples were chemically etched to produce a mirror-finish surface.

To determine the shape of the dimensions of the large EHD, the image of the samples was focused, with twelve-fold magnification, on the plane of a screen with opening 0.2 mm, mounted in front of the photosensitive element of a cooled photoresistor based on p-Ge doped with copper.[7] By moving the receiver, we could scan the image of the EHD in its recombination radiation. Usually the scanning was carried out along the EHD axes in the horizontal and vertical planes. The spatial distribution of the recombination radiation of the large EHD was recorded with the aid of an x-y recorder. The resolution of the system was ≈ 20 μm. The integrated intensity of the recombination radiation was registered with a germanium photodiode, on which a reduced image of the EHD was focused. The constant magnetic field with intensity up to 13 kOe was produced with an electromagnetic in a direction perpendicular to the axis of the inductance coil 3.

3. EDDY CURRENTS IN EHD

The power W absorbed by a homogeneous sphere of radius R with conductivity σ in an alternating magnetic field of frequency ω and intensity H is determined by the imaginary part of the magnetic polarizability α'' and is given, according to[8],

$$W = {}^1/_2 \cdot {}^4/_3 \pi R^3 \omega \alpha'' H^2, \tag{1}$$

$$\alpha'' = -\frac{9}{4\pi}\frac{1}{x^2}\left(1 - \frac{x}{2}\frac{\operatorname{sh} x + \sin x}{\operatorname{ch} x - \cos x}\right) \tag{2}$$

where $x = 2R/\delta$ is a dimensionless parameter, and $\delta = c/(2\pi\sigma\omega)^{1/2}$ is the depth of the skin layer. If a sample containing a condensed phase of volume V is placed in an inductance coil with an effective volume V_L, then the loss in the tank circuit to the eddy currents introduced by the EHD can be expressed in terms of the loss Q:

$$Q^{-1} = 4\pi V \alpha''/V_L. \tag{3}$$

For small EHD, when $x \lesssim 1$ (neglect to the skin effect) we have

$$\frac{1}{Q} = \frac{2\pi}{5}\frac{V}{V_L}\frac{\sigma\omega R^2}{c^2}. \tag{4}$$

At low losses, the depth of modulation of the RF signal is

$$\Delta U/U=Q_L/Q, \tag{5}$$

where Q_L is the quality factor of the tank circuit.

When comparing the results of the absolute measurements with expressions (2) and (3), it is convenient to use the universal dependence of the losses on the dimensionless parameter x, the value of which is determined by the dimension of the EHD and by their conducitivity. For a single EHD, this dependence can be obtained by replacing the EHD volume by the quantity $V=\frac{1}{6}\pi x^3\delta^3$. In this case the quantity $1/Q\delta^3$, which characterizes the loss due to the excitation of the eddy currents in the EHD, depends only on x. Neglecting the skin effect, this dependence acquires the simple form

$$\frac{1}{Q\delta^3}=\frac{\pi}{120V_L}x^5. \tag{6}$$

On the other hand, the experimentally measured intensity I of the recombination radiation of the EHD is proportional to its volume, and therefore it follows from (6) that the RF absorption is $1/Q\delta^3\sim I^{5/3}$. Allowance for the skin effect leads to a somewhat more complicated dependence of $1/Q\delta^3$ on x^3, represented in absolute units by the solid line in Fig. 2.

The influence of a constant magnetic field of intensity H_0 on the absorption was taken into account by us in the expression for the conductivity

$$\sigma=\frac{\sigma_0}{1+(\mu H_0/c)^2} \tag{7}$$

where

$$\sigma_0=e^2n_0\left(\frac{\tau_e}{m_e}+\frac{\tau_h}{m_h}\right), \tag{8}$$

m_e and m_h are the effective masses of the electrons and holes, n_0 is their concentration in the EHD, τ_e and τ_h are the relaxation times of their momenta, μ is the mobility in the EHD and is assumed to be the same for the carriers of both signs, owing to the equality of the electron and hole densities. Neglecting the skin effect, it follows from (4) and (7) that in strong magnetic fields ($\mu H_0/c\gg 1$) the absorption should decrease like H_0^{-2}. A decrease of the absorption to one-half corresponds to $\mu H_0/c=1$, which makes it possible to determine readily the mobility of the carriers in the EHD.

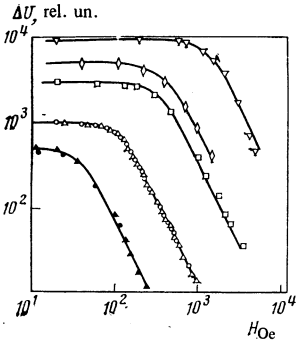

FIG. 3. Dependence of the RF absorption ΔU on the intensity H_0 of the constant magnetic field at 1.8 K, at an argon-laser excitation power 30—70 mW, and at an alternating magnetic field frequency 17 MHz. ▽—sample 1, $F\parallel[111]$, $H_0\parallel[\bar{2}11]$, 1 EHD; ◇—sample 2, $F\parallel[111]$, $H_0\parallel[\bar{2}11]$, 1 EHD; □—sample 3, $F\parallel[111]$, $H_0\parallel[\bar{2}11]$, 1 EHD; ○—sample 4, $F\parallel[100]$, $H_0\parallel[010]$, 4 EHD; △—sample 5, $F\parallel[111]$, $H_0\parallel[\bar{2}11]$, 1 EHD; ●—sample 4, $F=0$, $H_0\parallel[010]$, small EHD; ▲—sample 5, $F=0$, $H_0\parallel[\bar{2}11]$, small EHD.

Figure 3 shows the dependence of the RF absorption on the intensity H_0 of the constant magnetic field, for a number of germanium samples, both in the absence of deformation, when the absorption was determined by the interaction of the alternating magnetic field with the cloud of small EHD, and in the case of inhomogeneous deformation, when large EHD were produced in the samples. The solid lines in the figure correspond to the dependence of σ on H_0 as calculated in accordance with (6) by choosing the optimal values of the mobility μ (see Table I).

The maximum carrier mobility in the EHD, $\mu=2\times10^6$ cm^2/V-sec, was observed in the purest samples of undeformed germanium. This exceeds by approximately two orders of magnitude the experimental values obtained in[1-4]. In doped germanium with impurity concentration $N\gtrsim10^{14}$ cm^{-3}, the absorption at 1.8 K in the absence of deformation did not exceed the noise level, thus indicating a strong decrease of the mobility in the shallow EHD as a result of scattering by impurities. In the case of inhomogeneous deformation of the pure germanium samples, when a single EHD drop was produced in them, the mobility decreased to approximately one-third. This decrease of mobility is due to the change in the carrier density n_0 in the EHD, from 2.4×10^{17} cm^{-3} in the undeformed germanium to 6.2×10^{16} cm^{-3} following compression in the [111] direction.[6] The decrease of the mobility in the degenerate electron-hole plasma with decreasing concentration agrees with the calculation results given in[9]. A detailed comparison of the experimental mobilities obtained by us with[9] is hardly useful, since the calculation was carried out for the case of isotropic effective masses.

In doped germanium with impurity concentration $N\gtrsim10^{14}$ cm^{-3}, the mobility in the large EHD decreased approximately in proportion to N. Thus, $\mu=6\times10^4$ cm^2/V-sec for the sample with $N=8\times10^{14}$ cm^{-3}. A simple estimate shows (see, e.g.,[10]) that even if μ in this sample is determined completely by scattering by neutral impurities, the mobility should be equal to 1.5×10^5 cm^2/V-sec, which agrees in order of magnitude with experiment.

According to[9], one should expect a substantial increase of the mobility in the EHD with decreasing temperature. In the case of large EHD, however, their dimensions, and consequently also the RF absorption due to the excitation of eddy currents, depend strongly on the focusing of the exciting radiation. Self-focusing at a temperature above 2.17 K is made difficult by the boiling of the liquid helium. We note that improvement of the focusing, by making the helium superfluid, would increase the absorption by approximately one order of magnitude. In the temperature interval 2.17–1.8 K, the absorption and mobility in large EHD has increased

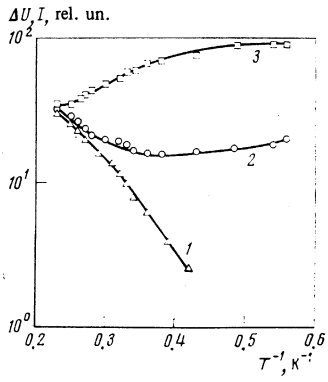

FIG. 4. Temperature dependence of RF absorption ΔU in samples 3 (1) and 4 (2) and of the intensity I of the recombination radiation (3) in the absence of deformation at an excitation power 100 mW.

noticeably. But the temperature interval in which such measurements are possible was too narrow, so that it was impossible to obtain quantitative information on the temperature dependence of the mobility in large EHD. In the case of small EHD, the dimensions of which depend to a lesser degree on the excitation conditions, the investigation of the temperature dependence of the absorption was made complicated by the presence of free carriers outside the EHD.

The temperature dependence of the absorption in pure and doped germanium in the absence of deformation is represented in Fig. 4. The formation of small EHD was indicated by the increase of the intensity of the characteristic recombination radiation with decreasing temperature. It is seen from the figure, however, that in doped germanium the absorption decreased exponentially with decreasing temperature. The activation energy of this process, ≈ 1.35 meV, is close to the thermal energy of the evaporation of the electrons and holes from the EHD (1.4 meV).[11] We can therefore conclude that in doped germanium the absorption by free carriers predominates in the entire presented temperature interval. In pure germanium, the absorption decreased negligibly with decreasing temperature, and then again increased. This difference can be understood by recognizing that in pure germanium the mobility of the carriers in the EHD is much higher than in doped germanium, and therefore absorption due to the eddy currents in the EHD begins to predominate already at relatively high temperatures, when there are still many free carriers in the sample.

Figure 2 shows the dependence of the RF absorption on the recombination-radiation intensity I at 1.8 K for two samples with different impurity contents. It is seen from the figure that in a wide range of photoexcitation intensity, the absorption increases like $I^{5/3}$ (dashed line in the figure), in accordance with (6), and only at large dimensions of the EHD does it deviate from this relation because of the influence of the skin effect. At the points marked by the dark symbols in Fig. 2, we measured the absolute values of the depth of modulation $\Delta U/U$ and of the EHD radius R by scanning their image (Fig. 5). Then, using the values of the mobility μ (see Table I) and $n_0 = 6.2\times10^{16}$ cm^{-3}, we calculated the conductivity σ_0, the depth of the skin layer δ, and the parameter x. The values obtained in this manner were substituted in expressions (2) and (3) to determine the absolute value of $1/Q\delta^3$. It is seen from Fig. 2 that the measured and calculated values are in good agreement, although the value of the parameter x was determined from other independent experiments. This has made it possible to carry out an absolute "normalization" of the entire dependence of the absorption on the recombination-radiation intensity to the universal relation $1/Q\delta^3 = f(x^3)$, shown in Fig. 2 by the solid line. It can be concluded from Fig. 2 that relations (2) and (3) describe quantitatively the energy absorption of the alternating magnetic field as a result of excitation of the eddy currents in the EHD.

4. CHANGE OF SHAPE OF LARGE EHD IN A CONSTANT MAGNETIC FIELD

The change of the shape of a drop of magnetic liquid in a constant magnetic field is determined both by the physical nature of the magnetism and by the shape of the potential well in which the drop is localized. In[12,13] it was observed that large EHD are flattened in the direction of the magnetic field. This phenomenon has been attributed to a manifestation of recombination magnetism of the EHD.[14] The recombination magnetization of EHD is proportional to the carrier mobility inside the drops. One should therefore expect the EHD deformation in a constant magnetic field in pure and doped germanium will proceed in different manners. To verify this assumption, we used the influence of the doping of the germanium on the deformation of the EHD in a magnetic field.

Figure 5 shows the spatial distribution of the intensity of recombination radiation of a large EHD in pure germanium in the absence of a magnetic field and in a field $H_0 = 10$ kOe, obtained by scanning the EHD image along (a axis) and across (b axis) the direction of the magnetic field. The method of determining the EHD dimensions a_0, a_H, b_0, and b_H is clear from the figure. It is seen that an appreciable flattening of the EHD takes place in a magnetic field. The change in the shape of the drops can be characterized by the quantity $a_0 b_H / b_0 a_H$, whose dependence on the magnetic field intensity H_0 for pure and doped germanium is shown on Fig. 6. It is seen from the figure that the ablation of the EHD begins after a certain magnetic field intensity is reached, then increases rapidly and reaches saturation in fields 5–10

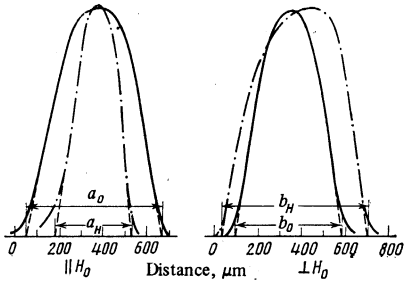

FIG. 5. Spatial distribution of the radiation of a large EHD in sample 5 at 1.8 K for $H_0 = 0$ and $H_0 = 10$ kOe, obtained by scanning in directions parallel and perpendicular to H_0; $F \parallel [111]$, $H_0 \parallel [\bar{2}11]$.

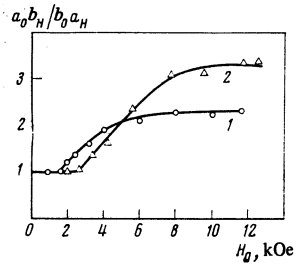

FIG. 6. Dependence of the paramater a_0b_H/b_0a_H, which characterizes the change in the shape of a large EHD, on the magnetic field intensity H_0 at 1.8 K, $F \parallel [111]$, $H_0 \parallel [\bar{2}11]$: 1—sample 5, 2—sample 3.

kOe. In doped germanium, both the start of the ablation and its saturation take place in stronger magnetic fields. However, in the satuaration region the ablation in doped germanium is stronger than in pure germanium. Such a difference was observed by us both at $F \parallel [111]$, $H_0 \parallel [\bar{2}11]$, and at $F \parallel [011]$, $H_0 \parallel [0\bar{1}1]$.

It should also be noted that the production of large EHD in doped germanium is possible only in the case of sharp focusing of the exciting radiation on the sample in the immediate vicinity of the region in which a potential well or EHD was produced under inhomogeneous deformation. The large EHD are provided with electrons and holes mainly as a result of arrival of small drops excited from the surface of the sample.[6] Owing to the decrease of their mobility in the doped germanium, the mean free path of the small drops should be much smaller than in pure germanium, so that the supply to the large EHD is hindered when the distance to the excitation region is increased.

The ablation of the large EHD was observed at any orientation of the magnetic field relative to the crystallographic axes of the germanium, including also the direction [100], which is equivalent for the valleys of the conduction band. However, the magnitude of the effect depended substantially on the experimental conditions—on the direction of the deforming force, on the orientation of the potential wells produced by the deformation relative to the magnetic field, on the slopes of the "walls" of the potential wells, and on the position of the excitation region. The ablation was minimal when the deforming force was directed along the [100] axis and four strongly localized potential wells were produced in the crystal.[6] The reproducibility of the results of the experiments for each experimental geometry was good.

A general quantitative calculation of the change in the shape of the EHD in a magnetic field is complicated, since it calls for taking into account the true shape of the potential well in which the EHD is localized, the surface tension which depends on the magnetic field, the inhomogeneity of the EHD supply, the change in the EHD volume with changing shape, etc. An attempt at such a calculation was made in[15]. There, however, just as in[13], a factor analogous to the expression for the transverse magnetoresistance (6) was introduced without justification into the expression for the magnetic moment, in order to explain the saturation of the EHD deformation. We shall show that even if the surface tension and the interaction of the EHD with the potential well produced by the deformation are neglected, the ablation and its saturation are a natural consequence of the very recombination character of the EHD magnetism.

Indeed, for an ellipsoid of revolution with semiaxis a along the magnetic field H_0 and semiaxis b in the perpendicular direction, the magnetic moment $\mathbf{M}$ due to the recombination flux inside the EHD can be written in the form

$$\mathbf{M}=\mathbf{H}_0\frac{e^2n_0}{5c^2\tau_0}\frac{\tau}{m}V\frac{ab^2}{2a+b} \tag{9}$$

where $V=\frac{4}{3}\pi ab^2$ is the volume of the ellipsoid, τ_0 is the EHD lifetime, $\tau/m=\tau_e/m_e=\tau_h/m_h$, m_e and m_h are the effective masses and τ_e and τ_h are the momentum relaxation times of the electrons and holes in the EHD. If it assumed that the EHD volume remains unchanged in the magnetic field ($ab^2=\text{const}$), then expression (9) reaches a maximum at $b/a=4$. Since the energy in the magnetic field is

$$E=-{}^1/_2\mathbf{M}\mathbf{H}_0, \tag{10}$$

it reaches the maximum at the same value of b/a, corresponding to the saturation of the ablation. Thus, even the very redistribution of the recombination flux inside the EHD as a result of the decrease in its shape in a magnetic field leads to the saturation effect. This result seems natural, for as $b/a\to\infty$ (film) the recombination flux does not produce a component normal to the magnetic field, and does not lead to appearance of recombination magnetism.

The very simple calculation presented above was carried out under the assumption that the velocity of the recombination flux on the internal surface of the EHD is constant. This can be satisfied only for a homogeneous flux of the electrons and holes to the outer surface of the drop. Under the experimental conditions, however, when the large EHD is localized in a potential well of complicated form, its supply can be quite inhomogeneous. This inhomogeneity should manifest itself particularly strongly in doped germanium, for owing to the low mobility of the small EHD the large drop is supplied predominantly along the shortest distance to the point of excitation, i.e., through the surface facing the region of excitation. The recombination flux in the EHD is then directed mainly perpendicular to the magnetic field even in the case of considerable ablation, and contributions to the recombination magnetization. The stronger maximum ablation of the EHD in doped germanium (Fig. 6) confirms this assumption.

We note in conclusion that the ablation of the EHD in a magnetic field cannot be a manifestation of diamagnetism or paramagnetism of a degenerate electron-hole plasma. Using the expression for the depolarization indices of an ellipsoid of revolution[8] of volume V and semiaxes a and b, having a small accentricity $\varepsilon^2=|b^2/a^2-1|$, we can express the change of the ellipsoid energy in the field H_0, due to the deviation of its shape from spherical, in the form

$$\Delta E = \pm \frac{4\pi V}{15} H_0^2 \chi^2 e^4, \qquad (11)$$

where the + and − signs correspond to ellipsoids prolate and oblate along H_0, while χ is the diamagnetic or paramagnetic susceptibility. It is seen from (11) that a drop of diamagnetic or paramagnetic liquid finds it energy-wise more convenient to become stretched along the magnetic field, whereas recombination magnetization leads to ablation of the EHD.

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Screening and localized impurity states in "optical" and exciton insulators

A. S. Aleksandrov and V. F. Elesin

Moscow Engineering Physical Institute
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We show that when a semiconductor (due to electron and hole pairing through a strong electromagnetic wave) or a semimetal (due to electron-hole Coulomb attraction) change into a dielectric state the nature of the charge screening changes considerably: in the ground state the screening radius becomes infinite, the static permittivity starts to depend on the intensity of the electromagnetic wave in a semiconductor and on the magnitude of the dielectric gap in a semimetal, and the point charge retains a Coulomb potential but with a smaller effective charge. The set of Bogolyubov equations which describes the impurity states in a semiconductor in a strong electromagnetic field and in a metal is reduced to the relativistic Dirac equations. We find as a result the wavefunctions and energies of the localized impurity states.

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In the field of a strong electromagnetic wave with a frequency in the region of the intrinsic absorption ($\omega_0 > E_g$) a semiconductor goes as the result of the appearance of an energy gap[1] over into a dielectric state[2–4] ("optical" insulator). It is natural to expect that at low temperatures the screening due to the transition into a new phase is changed considerably: electrons and holes bound by the electromagnetic wave into neutral pairs cannot move in the field of a test charge so that the screening radius becomes infinite. The calculations given below confirm this qualitative statement: the long-wavelength limit of the static permittivity turns out to be finite in the ground state and dependent on the magnitude of the "optical" gap $2\lambda = Ed$:

$$\varepsilon = \varepsilon_0 \left(1 + \frac{2}{3}\left(\frac{\omega_p}{2\lambda}\right)^2\right),$$

where ω_p is the plasma frequency of the free carriers, ε_0 takes into account the interband polarizability, E is the wave amplitude, and d the dipole moment of the interband transition.

In the short-wavelength region ($q\xi_0 \gg 1$, $\xi_0 = v_F/\lambda$ is the coherence length) the dielectric permittivity has the usual metallic character:

$$\varepsilon(0, q) = \varepsilon_0 (1 + (r_0 q)^{-2}),$$

where $r_0 = (8\pi N e^2/\varepsilon_0)^{-1/2}$ is the usual Debye radius; v_F

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