Recombination magnetism of electron-hole drops

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We estimate the magnetic moment of electron-hole drops, which is produced in a magnetic field as a result of the recombination flow of carriers from the surface into the interior of the drops. The interaction of this moment with the alternating magnetic field leads to a characteristic resonant absorption.

Recombination of carriers inside electron-hole drops (EHD)[1] leads to the appearance of a flow of electrons and holes from the surface into the interior of the drops. In the case of stationary excitation, this current can be estimated from the continuity equation

$$\operatorname{div}(n_0 \mathbf{v}_r) = -n_0/\tau_0 . \quad (1)$$

Here n_0 is the concentration, $\mathbf{v}_r$ is the radial component of the electron and hole velocity, and τ_0 is the EHD lifetime. Assuming that the concentration n_0 varies very little, we can obtain from (1)

$$\mathbf{v}_r = -\mathbf{r}/3\tau_0 , \quad (2)$$

where **r** is a radius vector with origin at the center of the EHD.

In a homogeneous magnetic field $\mathbf{H}_0$ directed along the z axis, the electrons and holes moving from the periphery to the center of the EHD are acted upon by a Lorentz force that causes the electrons and holes to rotate relative to the z axis in opposite directions. These circular currents of the carriers produce in the EHD a magnetic moment **M** directed along z. The motion of these currents can be described by the equations

$$\begin{aligned} &\frac{en_0}{c}[\mathbf{v}_h \times \mathbf{H}_0] + F_h = 0, \\ &-\frac{en_0}{c}[\mathbf{v}_e \times \mathbf{H}_0] + \mathbf{F}_e = 0 . \end{aligned} \quad (3)$$

Here $\mathbf{v}_h$ and $\mathbf{v}_e$ are the velocities of the currents, and $\mathbf{F}_h$ and $\mathbf{F}_k$ are the friction forces of the holes and electrons, respectively. Assuming that electron-hole scattering predominates in the EHD, and that the interaction with the crystal lattice is negligible, we can put

$$\mathbf{F}_h = -\mathbf{F}_e = -[\mathbf{r} \times \vec{\omega}_h - \vec{\omega}_e]\frac{m_h n_0}{\tau_h} \quad (4)$$

Here $\vec{\omega}_h$ and $\vec{\omega}_e$ are the angular velocities of the holes and electron subsystems, m_h and m_e are the effective masses, and τ_h and τ_e are the hole and electron momentum relaxation times. From (3) and (4) it follows that

$$\vec{\omega}_h - \vec{\omega}_e = \frac{1}{3\tau_0}\,\frac{eH_0}{c}\,\frac{\tau}{m}; \qquad \frac{m}{\tau} = \frac{m_e}{\tau_e} = \frac{m_h}{\tau_h} . \quad (5)$$

The EHD magnetic moment produced by the total circular current of the electrons and holes is equal

$$M = \frac{en_0 R^2}{5c}(\omega_h - \omega_e)V = \frac{n_0 e^2 H_0 R^2}{15c^2}\,\frac{\tau}{m}\,\frac{V}{\tau_0} , \quad (6)$$

where R is the radius of the drop and $V = 4\pi R^3/3$ is its volume.

If the EHD is acted upon not only by a constant field but also by a weak alternating magnetic field $H\cos\omega t$ perpendicular to $\mathbf{H}_0$, then the magnetic moment **M** of the EHD will be inclined periodically from the direction of $\mathbf{H}_0$ through an angle θ. The equation of the EHD oscillations can be written in the form

$$I\frac{d^2\theta}{dt^2} + \frac{I}{\tau_L}\frac{d\theta}{dt} + MH_0\theta = MH\cos\omega t . \quad (7)$$

Here $I = (2/5)(m_e + m_h)n_0 R^2 V$ is the moment of inertia of the drop. The damping coefficient $\lambda = 1/2\tau_L$ may turn out to be quite small if the electron and hole subsystems oscillate as a unit and the damping is determined by the interaction with the crystal lattice. This assumption is likely, for owing to the finite compressibility of the electron-hole liquid the magnetic field H_0 should cause a certain increase in the carrier density in the EHD from the poles towards the equator. Therefore independent shifts of the electron and hole subsystems should lead to the appearance of space charge and of electrostatic forces that prevent such a shift. Introducing the notation $\omega_0^2 = MH_0/I$ and $\epsilon = (\omega_0^2 - \omega^2)/2\omega$, we obtain from (7) the power absorbed by the EHD:

$$W(\omega) = \left(\frac{M^2H^2}{4I}\right)\left[\frac{\lambda}{(\epsilon^2 + \lambda^2)}\right] , \tag{8}$$

which yields under resonance conditions ($\omega = \omega_0$)

$$W(\omega_0) = \frac{M^2\tau_L}{2I} H^2. \tag{9}$$

To estimate the expected effect, we used several EHD parameters typical of germanium,[1] and put $m_e \approx 1 \times 10^{-28}$ g, $m_h \approx 3\times10^{-28}$ g, $R \approx 10^{-3}$ cm, $n_0 \approx 2\times10^{17}$ cm^{-3}, and $\tau_0 \approx 2\times10^{-5}$ sec. The momentum relaxation time τ for a degenerate electron-hole gas can be estimated from[2] and turns out to be of the order of 3×10^{-10} sec at 2 °K. The characteristic time of the lattice scattering of the EHD, $\tau_L \approx 10^{-8}$ sec, was obtained in[3].

Let us compare the recombination susceptibility $\chi_p = (1/V)(\partial M/\partial H_0)$ of the EHD with the susceptibility of a degenerate electron gas. The Pauli paramagnetic susceptibility was given by the relation[4] $\chi_P = n_0\beta^2/\phi$, where $\beta \approx 10^{-20}$ erg/G is the Bohr magneton, and $\phi \approx 3$ meV is the Fermi energy in the EHD.[1] Substituting the characteristic parameters in (6), we obtain $\chi_p/\chi_P \approx 50$. It appears that the recombination susceptibility can exceed also the diamagnetic susceptibility of a degenerate plasma.

The frequency of the resonant absorption is

$$\omega_0 = \frac{eH_0}{c\,[2m(m_e + m_h)]^{1/2}} \sqrt{\frac{\tau}{3\tau_0}} . \tag{10}$$

It is seen from (10) that the resonant absorption can be observed either at low frequencies, or else in stronger magnetic fields and cyclotron absorption, inasmuch as $\tau \ll \tau_0$. Thus, at $\omega_0 \approx 6\times10^8$ sec^{-1} the resonances set in at $H_0 \approx 6\times10^3$ Oe. Since the damping should be determined in this case by the lattice relaxation time τ_L, corresponding to $\omega_0\tau_L \gg 1$, the resonance should be quite distinct. Hopefully, an experimental investigation of the resonant absorption of EHD will make it possible to determine both τ_L, from the width of the resonant peak, and the characteristic electron-hole scattering time inside the drops, from the position of the resonant peak.

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