Dragging of electron-hole drops by phonons in longitudinal quantizing magnetic fields

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We have observed a magnetoacoustic effect in the dragging of electron-hole drops in germanium by long-wave acoustic phonons.

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The model of dragging of electron-hole drops (EHD) in germanium by a stream of nonequilibrium phonons produced in the course of nonradiative Auger recombination in the carriers in the EHD was proposed and considered in detail in[1,2]. Arguments favoring the assumption that the principal mechanism of this dragging is absorption of long-wave acoustic phonons in the drops were advanced in[3,4]. These phonons, having a wave vector $q \approx 2k_F$ and an energy $\hbar qs \approx kT$ (s is the speed of sound) can be intensively radiated by EHD, since the drop temperature T_e differs from the crystal-lattice temperature T_0.[5] The heating of the drops is due to the fact that an appreciable fraction of the energy of the Auger particles will be transferred to the electrons and holes inside the drop, inasmuch as the Auger-electron energy-relaxation time is of the same order in scattering by carriers and by optical phonons.[3]

A direct consequence of the mechanism of EHD dragging by the long-wave acoustic phonons emitted by the drops is the possibility of observing the magnetoacoustic effect as the drops move in longitudinal quantizing magnetic fields.

We consider the electron component of the dragging force produced for an EHD in germanium[1)] by phonons propagating along the magnetic-field direction (the z axis). In the quantizing magnetic field ($\hbar\omega_c \gg kT$) this force can be represented (for the planar case and per electron-hole pair) in the form[1,6]

$$F_2 = \frac{d_z^2\, a m_z m_c \omega_c}{(2\pi)^4 h^3 \rho s n_0} \sum_n \int \hbar q_z N(q_z) \left[f_n\left(\frac{q_z}{2} - \frac{m_z s}{\hbar}\right) - f_n\left(\frac{q_z}{2} + \frac{m_z s}{\hbar}\right)\right] d^3 q$$

$$\approx \frac{d_z^2\, a m_z m_c \omega_c}{(2\pi)^4 \hbar^3 \rho s n_0} \frac{\partial \epsilon}{\partial t} \frac{1}{s^2} \sum_n \left[f\left(k_F^n - \frac{m_z s}{\hbar}\right) - f\left(k_F^n + \frac{m_z s}{\hbar}\right)\right]. \qquad (1)$$

Here d_z is the deformation potential along the z axis, m_c and m_z are the cyclotron and state-density masses for the electrons, ω_c is the cyclotron frequency, a is the number of electron valleys, ρ is the density of the crystal, s is the speed of sound, n_0 is the EHD density, $N(q_z)$ is the concentration of the nonequilibrium phonons, f is the Fermi function,

$$k_F^n=(1/\hbar)\sqrt{2m_z[\epsilon-(n+\tfrac{1}{2})\hbar\omega_c]},\ \partial\epsilon/\partial t$$

is the phonon-energy flux density, and n is the number of the Landau band. In the derivation of (1) it was assumed that one could neglect the electron-phonon scattering in a direction perpendicular to the field, and consequently, $q\approx q_z\approx 2k_F$ and $\hbar qs\approx kT$. The expression for the energy flux density of the phonons from the drops can be written, accurate to a factor of the order of unity, in the form

$$\frac{\partial\epsilon}{\partial t}=\frac{k(T_e-T_0)}{\tau_\epsilon}\bar{n}l\approx\frac{k(T_e-T_0)}{\tau_p}\frac{m_z s^2}{kT_0}\bar{n}l=\bar{n}l\frac{\Delta T}{T_0}\frac{m_z s^2}{\tau_p},\qquad(2)$$

where $\bar{n}$ is the average concentration of the electron-hole drops in an excited region of the crystal having a dimension l, while τ_ϵ and τ_p are the electron relaxation times with respect to energy and momentum, respectively. Using for the dragging force expression (1) and taking (2) into account, we obtain for the drop drift velocity the relation[2)]

$$v_z=\frac{F_z\tau_p}{(m_e+m_h)}=\frac{\bar{n}}{n_0}l\frac{d_z^2a}{(2\pi)^4\hbar^3\rho s}\frac{m_z^2m_e}{(m_e+m_h)}\frac{\Delta T}{T_0}$$
$$\times\omega_c\sum_n\frac{\mathrm{sh}\left(\frac{\hbar s k_F^n}{kT_e}\right)}{\mathrm{ch}\left(\frac{m_z s^2}{2kT_e}\right)+\mathrm{ch}\left(\frac{\hbar s k_F^n}{kT_e}\right)}.\qquad(3)$$

Analysis of (3) shows that the EHD velocity is an oscillating function of the magnetic field and, as seen from the preceding analysis, these oscillations are due to oscillations of the dragging force.

Preliminary experimental data on the presence of the magnetoacoustic effect in the dragging of drops in germanium are given in[3]. These experiments, however, were performed under conditions when the quantitative characteristics of the effects could be greatly distorted by the influence of phonon fluxes reflected from opposite faces of the sample. To prevent this phenomenon we used in the present study an experimental geometry such that the dimension of the sample along the drop-motion direction was much larger than the mean free path of the EHD (see Fig. 1). Samples in the form of parallelepipeds $0.5\times0.5\times1.0$ cm were cut from pure germanium and placed inside a superconducting solenoid. The drop detectors were p-n junction[10] placed on one of the lateral faces of the sample at a distance ≈ 0.1 cm from the forward face from which the crystal was excited. The excitation was produced by pulses of duration 1 μsec and frequency 400 Hz from a GaAs laser of 15 W power. The dimensions of the excitation region were 0.2×0.2 cm. In the experiments we measured the time of delay of the arrival of the EHD at the contacts relative to the instant of excitation, as a function of the longitudinal magnetic field at a constant excitation level. Figure 1 shows the results of the measurements for different orientations of the magnetic field relative to the crystal axes. The dashed curve shows the velocity oscillations calculated from formula

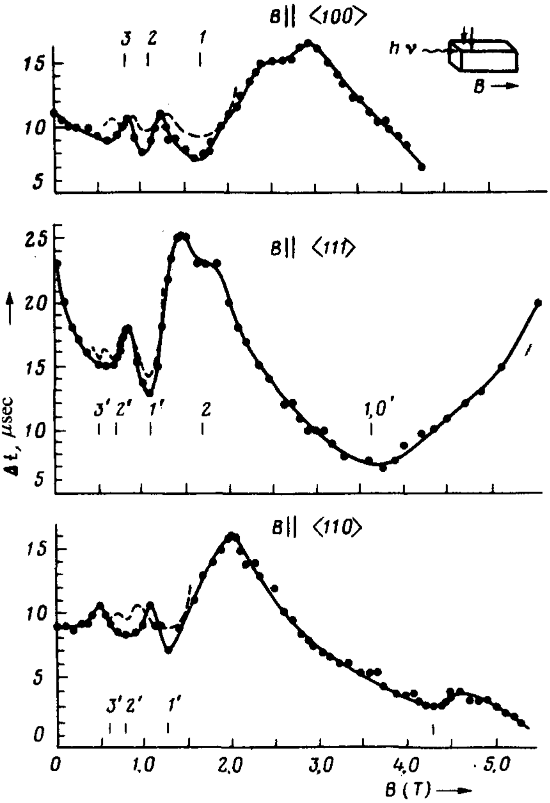

FIG. 1. Delay of arrival of EHD at the contacts relative to the instant of excitation vs the magnetic field. Solid curve—experiment, dashed—calculation. Excitation power density $P=150\ W/\mathrm{cm}^2$, $T_0=1.8$ K. The numbers mark the Landau bands of the electrons responsible for the corresponding minima of the delay time (the primed numbers mark the "easy" bands). The experimental and calculated curves are made coincident at the point of the maximum between the oscillations $n=1$, (1′) and 2(2′).

(3). For the orientations $\mathbf{B}\|\langle 111\rangle$ and $\mathbf{B}\|\langle 110\rangle$ we took into account the contribution of only the "easy" Landau bands, which have a minimal value of m_c and a maximal m_z. In accord with the anisotropy of the deformation potential of the electrons in germanum,[7,11] we took into account for the orientations $\mathbf{B}\|\langle 100\rangle$ and $\mathbf{B}\|\langle 110\rangle$ only the interaction with the transverse phonons, and for the $\mathbf{B}\|\langle 111\rangle$ orientation only the interaction with the longitudinal phonons. It was also assumed that the position of the Fermi level of the electrons does not depend on the magnetic field and is at 2.5 meV.[5] Expression (3), in view of the approximate character of its derivation, cannot provide a complete quantitative description of the experimental results. As seen from Fig. 1, however, the calculation accounts well both for the positions of the minima of the delay time (the maximum of the velocity) and for their relative magnitude, if it is recognized that oscillations with $n>2$ for the orientation $\mathbf{B}\|\langle 100\rangle$ and $n>1$ for the remaining cases cannot be resolved experimentally. We note that formula (3) gives the correct order of magnitude of the drop velocity if we substitute in these formula parameters typical of germanium and the values $\bar{n}\approx 2\times 10^{15}$ cm^{-3}, $l\approx 0.1$ cm, $T=1.8$ K and $\Delta T\approx 0.1$ K[5] which correspond to the experimental conditions.[5] The description of the behavior of the drop velocity in fields stronger than $2T$ calls for allowance for the dependence of the principal parameters of the EHD on the magnetic field, and also of the contribution of the holes to the dragging effect.

We note in conclusion that observation of the magnetoacoustic effect proves that the drops are dragged by the long-wave acoustic phonons emitted by the EHD.

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1) The deformation potential of the electrons in germanium is larger than that of the holes,[7] so that the contribution of the latter to the dragging effect can be neglected in first-order approximation.

2) In the derivation of (3) it was assumed that τ_p does not depend on the EHD velocity. This is true if $v \ll kT_e/2\hbar k_F^n \approx \hbar qs/2\hbar k_F^n \approx s$.[8,9]

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