Magnetization wave induced by second-sound wave in bismuth

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When a thermal pulse is pased through a bismuth sample in a longitudinal magnetic field $H_{\parallel}$ at liquid-helium temperature, a diamagnetic wave arises. This effect is attributed to a spatially nonuniform perturbation of a magnetized electron-hole plasma in the bismuth.

For the measurements we used long samples with the shape of a parallelepiped and a resistance ratio $\gamma = \rho_{300\text{K}} / \rho_{4.2\text{K}} = 900$–$950$. The procedures for synthesizing the samples and providing thermal insulation are described in Ref. 1. The cross-sectional area was about 1 cm^2, and the length was 10 cm. The longitudinal axis was parallel to the crystallographic C_1, C_2, and C_3 axes. The range of the carriers under the experimental conditions (the temperature of the liquid-helium bath was $T = 1.3$ K) was on the order of the transverse dimension of the sample. Figure 1 shows the experimental geometry. Thermal pulses of length τ with a power amplitude W were excited by a generator G and a bifilar electric heater made of wire 0.05 mm in diameter, of an alloy equivalent to Manganin, and cemented to an end of the sample. The voltage pulse which appeared in coils K_i (each consisting of 10 turns of PÉV0.06 wire) were amplified by amplifier A and displayed on oscilloscope O. Figure 2 shows a typical shape of a pulse; t is the time, reckoned from the middle of the generator pulse, at which the maximum value A is reached. When the polarity of $H_{\parallel}$ is changed, the pulse changes sign without any change in shape. Using some specially devised alternating fields $\tilde{H}_{\parallel}$, we found that a pulse of this sort can be formed in the measuring coils by changing the magnetic flux through the coils produced by a field which bucks the applied field (diamagnetic sign). The measurements showed that for this coil and a fixed $H_{\parallel}$, at least for τ between 2 and several μs and for W up to 0.1 W, the relation $A \sim \tau W$ holds,

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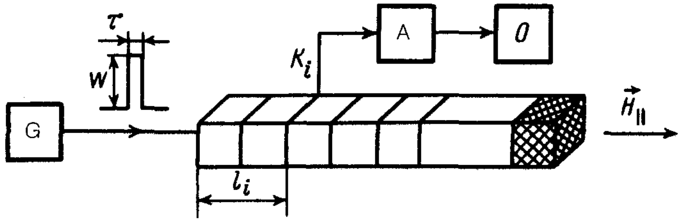

FIG. 1.

and the shape of the pulse does not change. Under these conditions the amplitude falls off with increasing l in accordance with $A \sim \exp(-l/l_0)$, where $l_0 = 1.8$ cm, and t does not change for a given coil. Figure 2 shows the dependence $t(l)$ measured for a sample with an axis $\| C_2$. We see that the dependence is linear; i.e., the propagation of the pulse is characterized by a constant velocity v. Experiments on samples with a longitudinal axis $\| C_1$, C_3 revealed that v does not depend on the orientation of the samples, within an error of 5%, and has the value 0.95×10^5 cm/s.

The following mechanism might be proposed for this effect. When the thermal pulse is applied, a second-sound wave is excited in the sample. It propagates along the sample and creates in the electron-hole plasma an electrically neutral wave of the charge-carrier density. If we assume that as a result of the interaction of phonons with the boundaries, the average directed velocity of the phonons along the sample, v_p, is lower near the surface than in the middle of the sample (Fig. 3a), then we see that in a transverse layer of the sample with an elevated charge-carrier density a decompensation of Larmor orbits occurs near the boundaries, and a closed magnetization current I arises (Fig. 3b). The magnetic field of this current, h, is directed opposite the applied field in the sample.

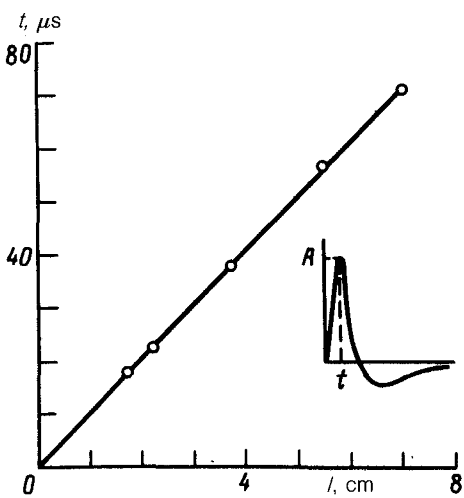

FIG. 2. Shape of the observed pulse. Dependence of the pulse arrival time t on the position of the detection coil.

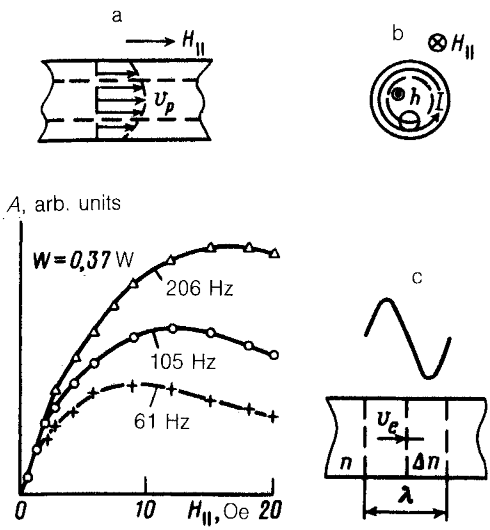

FIG. 3. Wave amplitude versus the applied magnetic field, measured at a fixed amplitude of the thermal power, W, for various frequencies.

We have the following evidence that a thermal pulse creates a second-sound wave in our samples. First, it was shown in Ref. 2 that a hydrodynamic situation arises in high-quality bismuth samples of sufficient purity. Second, v is close to the average velocity of all of the phonon modes ($\bar{c}$) divided by $\sqrt{3}$ (according to the theory for the isotropic case, the second-sound velocity is $v_2 = c\sqrt{3}$). For bismuth the values of $\bar{c}/\sqrt{3}$ for directions in the basal plane and transverse with respect to it are 1.0×10^5 and 0.8×10^5 cm/s, respectively. Third, additional experiments on samples with a longitudinal axis ($\parallel C_3$) showed that the propagation of a pulse is not of a diffusion nature, since a pulse reflected from the far end of the sample is observed, and in the case of a sinusoidal excitation of the wave one observes a maximum amplitude at the resonant frequency. As the length of the sample is changed, the resonant frequency shifts correspondingly. Note also that in this picture of the effect the ballistic phonon modes would not excite a current since their velocity would be identical along a cross section of the sample.

Let us discuss the part of the effect involving the current. Figure 3 shows an $A(H_{\parallel})$ dependence in the case of a sinusoidal excitation of a wave, measured at a fixed W at various frequencies f. The dependence on $H_{\parallel}$ can be explained at a qualitative level as follows: If it is assumed that I is excited in a thin surface layer of thickness d, then at small values of $H_{\parallel}$ the size of a Larmor orbit with radius r is large in comparison with d, and the conribution to I is proportional to the part of the Larmor orbit which decreases in the layer, i.e., $\sim\sqrt{d/r} \sim \sqrt{H_{\parallel}}$. With increasing $H_{\parallel}$, as r becomes comparable to d, the current goes through a maximum and then falls off, since the transverse irregularity decreases at the size r. The shift of the $A(H_{\parallel})$ maximum with f may be due to the imposition of a skin effect, since the expression for the depth of the skin layer contains the frequency and the resistance; the latter depends strongly on the field near 10 Oe.

The following calibration gives an idea of the magnitude of the effect. When we generated $\bar{H}_{\parallel}$ at a frequency of 105 Hz with an amplitude of 0.08 Oe, an amplitude corresponding to the maximum in Fig. 3 was induced in the coils for $f = 105$ Hz. Let us find an order-of-magnitude estimate of the maximum current I which can be produced in the sample according to our model and the experimental values of f and $H_{\parallel}$ (Fig. 3). We assume that a second-sound wave with a length λ and a frequency $f = v_2/\lambda$ is excited at the end of the sample by a thermal power with an amplitude W and propagates along the sample (Fig. 3c). Over a wavelength, a gradient of the charge-carrier drift velocity v_e arises because of phonon-electron drag. This gradient gives rise to an excess density Δn of charge carriers in comparison with the equilibrium value n. Assuming that Δn forms as a result of transport out of a region of the sample where v_e is large into a region where it is low, while the oppositely directed transport of the density excess occurs at the Fermi velocity v_F, and using the dynamic-equilibrium condition $nv_e = \Delta n v_F$, we find $\Delta n = n(v_e/v_F)$. We can estimate a typical value of v_e. Let us assume that the energy of the second-sound wave (over a period) is $\mathscr{E} \approx W/f = W\lambda/v_2$. Correspondingly, the momentum of the wave is $p = \mathscr{E}/v_2$. We assume that all of the momentum over a period is transferred to the charge carriers; we then have $v_e = p/M$, where M is the mass of charge carriers in a volume of $(1\ \text{cm}^2)\cdot\lambda$. We also need to note that at f on the order of 100 Hz the relation $\lambda \gg l_0$ holds, so as $\mathscr{E}$ we need to use a quantity which is no greater than $\mathscr{E} \approx Wl_0/v_2$. We then find the following estimate of Δn: $\Delta n = nWl_0/Mv_F v_2^2$. Let us assume that, as a result of the interaction of phonons with the boundaries, a gradient in Δn arises along the cross section of the sample and that Δn falls off to zero at the boundary. In the field $H_{\parallel}$, because of the decompensation of Larmor orbits near the boundary, a magnetization current I arises. If we assume that the gradient of Δn is at a maximum near the surface, we conclude that I is dominated by charge carriers at a distance equal to the Larmor radius r. For Bi with $H_{\parallel} \approx 10$ Oe we would have $r \approx 10^{-1}$ cm. Since l_0 is on the order of 1 cm, we assume that I is formed near the surface in a cross-sectional area $rl_0 \approx 10^{-1}$ cm^2. Also assuming $I = \Delta n e v_F r l_0$, and substituting the corresponding values, we find $I/W \approx 10$ A/W *at* $f = 100$ Hz.

Narayanamurty and Dynes[3] have reported observing second sound in bismuth in samples with $\gamma = 200$–400. They also reported a value $v_2 = 0.78 \times 10^5$ cm/s, which does not agree with that found in the present study. Since this discrepancy cannot be explained on the basis of experimental errors, we carried out measurements on samples with $\gamma = 400$. We found that under the same experimental conditions the amplitude of the observed pulse decays much more rapidly and the position of the maximum corresponds to a time which is substantially greater (by a factor ≈ 3). These observations are evidence of a diffusion regime.

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