Galvanomagnetic waves in bismuth

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We observed propagation of galvanomagnetic waves in bismuth predicted by Morozov and Shubin in 1964.

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The experimental study involved the propagation of an audio signal through a bismuth sample concurrently with transmission of direct current.

The bismuth single crystal was Czochralski-grown. The average cross-section of a sample was 2.2 cm^2. Superconducting leads were soldered to the upper and lower parts of a sample. Coils surrounded by lead screens were placed at the upper portion (on a lateral surface) and the lower end of the sample. Either coil could serve as a receiver while the other served as a transmitter. The output signal from the receiving coil was coupled through a broadband amplifier and synchronous detector to a recorder input.

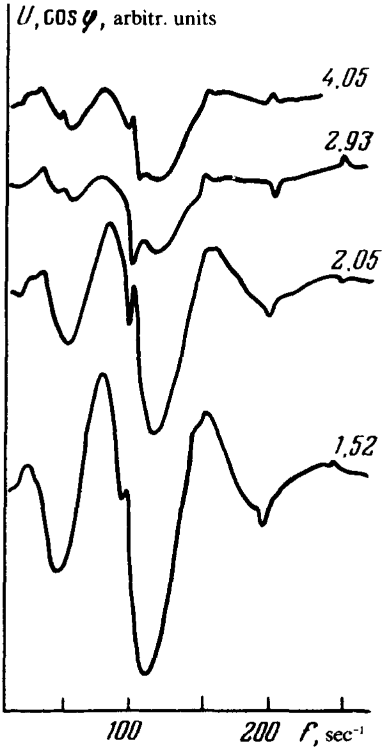

FIG. 1. Dependence of output signal on frequency for different helium-bath temperatures (in degrees K) designated by numbers by the curves.

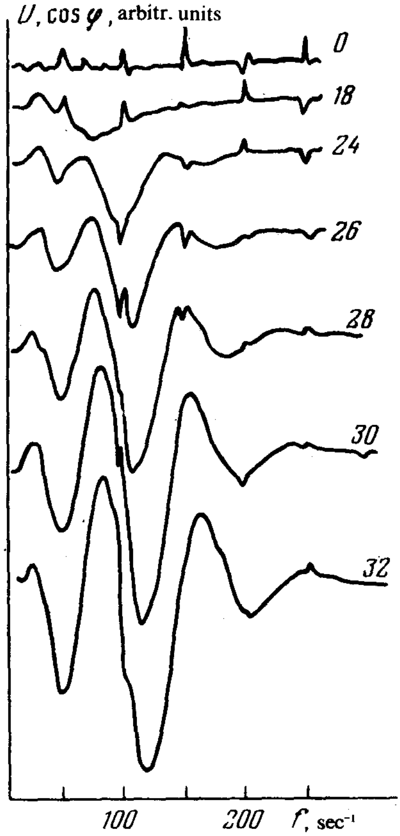

FIG. 2. Frequency dependence of signal for different currents (in A) in a sample designated by numbers by the curves. $T = 1.4$ K.

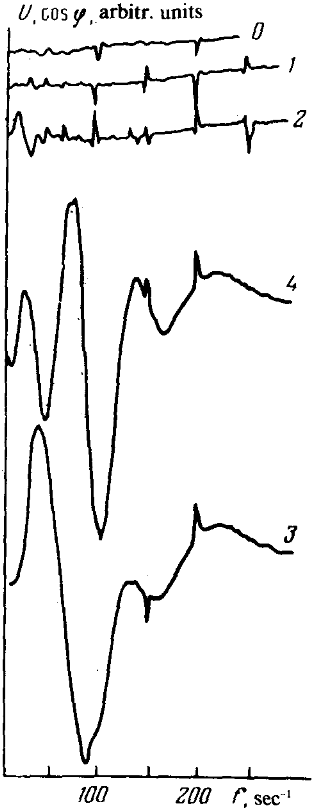

FIG. 3. Signal at different different directions of propagation of signal and current in a sample. Curves 0—$I = 0$. Curves 1–4—$I = 25$ A. $T = 1.4$ K.

The transmitting coil was connected to an audio oscillator whose frequency could be changed at a given rate.

Figure 1 shows recorded output signals at different temperatures of the helium bath. The direct current flowing through a sample I was 30 A. The positive side of a source was connected to the upper lead while the lower coil acted as a transmitter.

As can be seen, the amplitude of oscillating signal increases with a decreasing temperature, and oscillations are evident well into higher frequencies. Moreover, the period of frequency oscillations is relatively independent of frequency and helium-bath temperature.

Figure 2 shows frequency functions of a signal at different values of I, the hook-up arrangement between source and sample, and for the coils being the same.

Clearly, as I increases so does the signal amplitude, and the point at which the signal disappears moves up with frequency. In addition to this, the period and number of oscillations increase with a growth in I.

Figure 3 shows recorded signals for several different possible ways of coupling a sample to a d. c. source and of coils to amplifier and oscillator.

Curve *0* corresponds to an open-circuit case, i.e., when no current flows through a sample. This curve is identical in both cases within noise-level accuracy, i.e., when either upper or lower coil is transmitting. Curves *1* and *3* correspond to a case when the positive side of a d. c. source is connected to the lower end of sample; moreover, the lower coil was transmitting in the case of curve *1* and the upper coil for curve *3*. In the case of curves *2* and *4*, the positive side of a source was connected to the upper lead, but in the case of curve *2* the upper coil was transmitting, and for curve *4*—the lower.

All the curves indicate that a signal was recorded in a receiving coil for two out of four possible methods of coupling the coils to a sample.

It may be concluded from these recordings that signals propagate through a sample only in a direction counter to the current flow in the same sample (from minus to plus), i.e., signal propagation is asymmetric. The occurrence of oscillations must naturally be associated with propagation of low-frequency weakly-attenuation electromagnetic waves in a sample. A change in the wavelength affects the phase of a signal in the receiving coil, which leads to the occurrence of an oscillating voltage at the output of a synchronous detector. The only waves, in our opinion, that may propagate under our conditions, are those predicted theoretically by Morozov and Shubin.[1]

In the absence of an external magnetic field, we shall call these waves galvanomagnetic (GMW) since a possibility of their propagation depends on the Hall effet that leads to interaction of direct current in a sample with the magnetic field of a wave. The GMW dispersion equation is obtained by the simultaneous solution of Maxwell's equations and the mass equation, and may be expressed as follows:

$$\omega \equiv \omega_1 + i\omega_2 = (\mathbf{j}\mathbf{k})/ne - i\rho c^2 k^2/4\pi, \qquad (1)$$

where ω is the circular frequency, c is the speed of light in vacuum, $\mathbf{j}$ is the direct current density, $\mathbf{k}$ is the wave vector, n is the carrier concentration, e is the carrier charge, and ρ is the resistivity. In the case of two types of carriers, the real part of the dispersion equation is as follows:

$$((\mathbf{j}_1/n_1e_1 + \mathbf{j}_2/n_2e_2)\mathbf{k}) = ((\mathbf{v}_1 + \mathbf{v}_2)\mathbf{k}),$$

where subscripts 1 and 2 denote different carriers and v is the carrier drift velocity.

If the carriers are characterized by unlike signs and mobilities and like concentrations, the real part of the dispersion equation is nontrivial, thus permitting the observation of GMWs in Bi in which, according to Gurevich and Ioffe,[2] electron mobility at helium temperatures is an order of magnitude higher than hole mobility. Therefore, we shall neglect holes from consideration. It appears of interest to calculate the real and imaginary parts of the dispersion equation by means of Eq. (1) and under our experimental conditions. The wavelength may be made comparable to the size of a sample and, therefore, we shall assume $k = 3$ cm^{-1}, $v = 280$ cm/sec, and $\rho = 10^{-19}$ CGSE units.[3] This yields $\omega_1 = 830$ sec^{-1} and $\omega_2 = -100$ sec^{-1}. Thus, propagation of waves with frequencies of the order of 100 Hz is possible. The results shown in Fig. 2

indicate that as the current grows, the signal phase $\phi = kr$ (at a fixed frequency) decreases approximately inversely proportionally to current in direct confirmation of the dispersion law.

The curves in Fig. 2—which correspond to 30 and 24 A currents—were used to calculate wave velocities of 250 and 207 cm/sec, respectively. The electron drift velocities were 280 and 225 cm/sec, respectively. The good quantitative agreement between these data offers, in our opinion, a strong argument in favor of the correctness of our interpretation of the phenomenon. The second important argument is the unidirectional propagation of waves which, under our conditions, move in the same direction as the bulk of current carriers, as was predicted by theory.

The fact that a temperature decrease results in a growth of signal amplitude and practically no change in its phase (Fig. 1) is apparently associated with theoretical predictions that assign ρ—which falls off with a temperature decrease—to the imaginary part, while the real part remains independent of the temperature.

All the experimental data clearly prove that propagation of a new type of waves—galvanomagnetic waves—was observed. These waves substantially differ from those observed earlier in the presence of the carrier drift in bismuth[5] by the fact that both GMWs and, the recently identified, thermo-magnetic waves[6] may propagate in a metal in the absence of an external magnetic field.

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