Thermomagnetic waves in bismuth

V. N. Kopylov

Institute of Solid State Physics, USSR Academy of Sciences
(Submitted 20 June 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 3, 131–135 (5 August 1978)

The propagation of thermodynamic waves in bismuth, predicted by Gurevich and Gel'mont in 1964 [Sov. Phys. JETP **24**, 124 (1967)], has been observed.

PACS numbers: 72.55.+s, 72.15.He

The passage of a sound-frequency signal through a bismuth sample in the presence of a temperature gradient was investigated in the experiment. The bismuth single crystal was grown by the Czochralski method. The sample cross section area was 2–2.5 cm^2. A heater was secured to the upper part of the sample. Two pairs of transmitting coils connected to an acoustic generator were placed in the middle part. On the lower end face of the sample was placed a receiving coil, the signal from which was fed to an automatic recorder through a broadband amplifier and a synchronous detector. The coils and the sample were surrounded by a lead screen. The lateral surface of the sample was coated with a layer of wax to reduce the heat transfer. The output signal could be plotted as a function of the generator and of the current through the heater that produced the temperature gradient.

Figure 1 shows plots of the output signal U_{out} against the heater current at various temperatures T of the helium bath. It is seen that there is no signal at small currents. An oscillating signal appears and grows with increasing current; the instant of onset of the signal shifts towards larger currents with increasing temperature. At $T \approx 4.12$ K there is practically no signal at attainable temperature gradients. It is also seen that the period of the observed oscillations changes with changing frequency and current. The signal amplitude is maximal at $T \approx 1.94$ K and decreases in either direction with changing T.

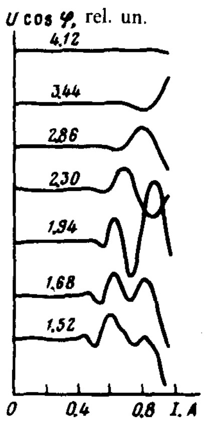

FIG. 1. Dependence of U_{out} on the current of a heater producing a gradient: the numbers on the curve indicate the helium bath temperature in K, $f = 225$ Hz.

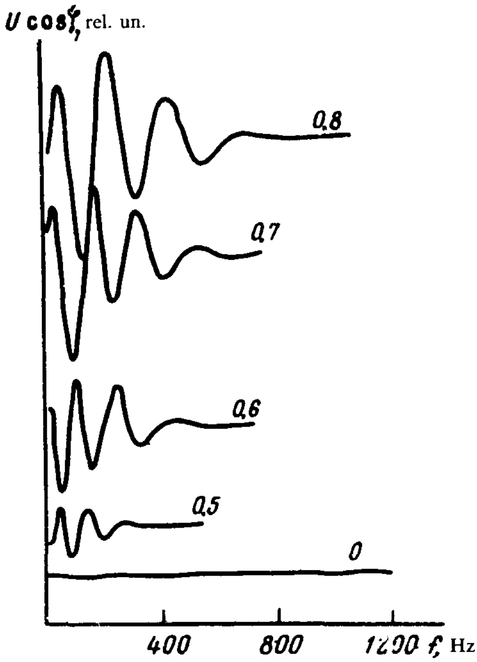

FIG. 2. Frequency dependence of U_{out} at the different heater currents marked on the curves: $T \approx 2.0$ K.

Figure 2 shows the frequency dependences of the signal at various values of I. It is seen that the signal amplitude decreases with increasing frequency. With increasing I, the signal amplitude increases and the signal vanishes at a higher frequency.

Figure 3 shows typical frequency dependences of the signal at various distances

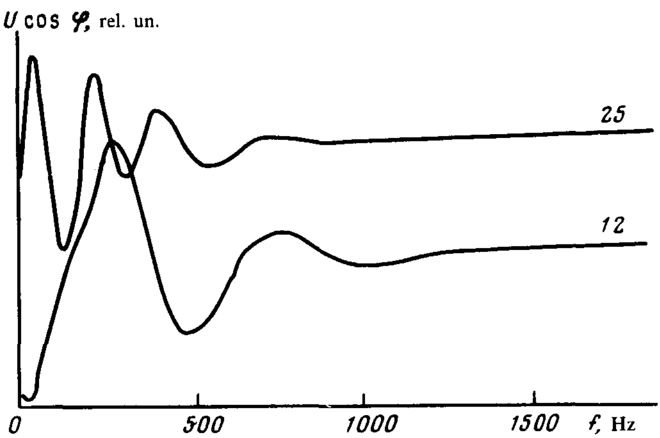

FIG. 3. Frequency dependence of U_{out} at different distances between the coils (marked in mm on the curves).

between the receiving and transmitting coils. It is seen that when the distance between coils increases the period of the oscillations, the amplitude, and the upper frequency at which oscillations can still be observed all decrease. In addition, it turned out that when the upper coil was connected to the amplifier input and the lower coil to the generator there was no signal, i.e., the signal flow was asymmetrical.

It is natural to attribute the presence of the oscillations to the propagation of low-frequency weakly damped waves in the sample. With changing wavelength, the phase of the signal in the receiving coil changes, and it is this which leads to the appearance of the oscillating voltage at the output of the synchronous detector. The only waves that can propagate, in our opinion, under our conditions are thermomagnetic waves (TMW), which were predicted theoretically in[1].

According to[1], the TMW dispersion law is given by

$$\omega = -\alpha_1 c\,(\nabla T\,\mathbf{k}) - i\rho c^2 k^2/4\pi\,, \tag{1}$$

where ω is the cyclic frequency, c is the speed of light in vacuum, α_1 is the Nernst-Ettingshausen coeficient, $\mathbf{k}$ is the wave vector, and ρ is the resistivity.

The condition for weak damping is a large ratio of the real and imaginary parts, which can be attained by decreasing k. In the case of weak damping, the dispersion relation can be written in the form

$$k(\omega) \equiv k_1(\omega) + ik_2(\omega) \approx \frac{\omega}{c\alpha_1|\nabla T|}\left(1 + i\omega\frac{\rho}{4\pi(\alpha_1\nabla T)^2}\right)\,. \tag{2}$$

If the current in the transmitting coil is independent of frequency, then the emf induced in the receiving coil is $E \sim ie^{ik_1d}(\omega e^{-k_2d})$ where d is the distance between coils. The factor in the parentheses determines the amplitude of the received signal, while the second factor represents the phase.

It was possible to compare the periods of the oscillations of the curves corresponding to different currents in Fig. 2. It was found that the period of the frequency oscillations is nearly constant within the limits of each curve, while the ratio of the periods for the different curves is close to the ratio of the squared currents. This fact can be easily interpreted. The frequency periodicity of the signal means that the phase $\phi = k_1d$ of the signal is linear in frequency. With increasing I the oscillations becomes less frequent (the corresponding period is $\propto I^2$), i.e., the phase k_1d varies more slowly with frequency. Hence $k \sim \omega/I^2 \sim \omega/\nabla T$. The experimental confirmation of the dispersion law is important evidence that the model of the phenomenon is correct.

Figure 2 shows the increase of the damping with increasing f and with decreasing T, as follows from (2). When the distance d increases the signal decreases and vanishes at a lower frequency, while the period of the oscillations decreases in proportion to $1/d$ (Fig. 3), This is caused by the increased damping and by the larger phase shift k_1d with increasing d.

The measured relations enable us to determine from experiment the real and imaginary parts of the wave vector as a function of frequency, phase velocity, and wave damping, and hence such parameters of the metal as α_1 and ρ. Such estimates were made for the upper curve of Fig. 2. The values of ∇T were determined from the known power and the known coefficient of thermal conductivity.[2] At $\nabla T \approx 0.2$–0.25 K/cm the wave velocity turned out to be 370 cm/sec at 100 Hz and decreased by 30% following an eightfold increase. Estimates yield $\alpha_1 \approx 6 \times 10^{-8}$ cgs esu and $\rho \approx 2.5 \times 10^{-19}$ cgs esu; these agree in order of magnitude with the results of[2,3].

Further evidence of the correctness of the interpretation of the observed phenomenon is provided by the unilateral propagation of the TMW (the wave propagates counter to ∇T), which follows from (1), and the fact that the best wave passage is observed at $T \approx 2$ K. The latter is due to the presence of a maximum on the $\alpha_1(T)$ curve at $T = 3.5$ K [3] and to the decreases of the thermal conductivity and of the resistance with decreasing temperature in this region, which should shift the maximum of the effect to temperatures lower then $T(\alpha_{1\,max})$.

The aggregate of the observed regularities demonstrates unambiguously, in our opinion, that we have observed in the experiment propagation of thermomagnetic waves.

The author is deeply grateful to E.P. Vol'skiĭ for suggesting the problem and for a number of valuable remarks, I.N. Zhilyaev for supplying a perfect bismuth single crystal, and to V.F. Gantmakher, L.E. Gurevich, B.L. Gel'mont, and V.T. Petrashov for a discussion of the results.

[1]E.L. Gurevich and B.L. Gel'mont, Zh. Eksp. Teor. Fiz. **51**, 183 (1966) [Sov. Phys. JETP **24**, 124 (1967)].
[2]V.N. Kopylov and L.P. Mezhov-Deglin, *ibid.* **65**, 720 (1973) [**38**, 357 (1974)].
[3]I. Ya. Korenblit, M.E. Kuznetsov, and S.S. Shalyt, *ibid.* **56**, 3 (1969) [**29**, 1 (1969)].