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# *EXCITATION OF CONSTANT POTENTIAL DIFFERENCES BY A MICROWAVE FIELD IN BISMUTH*

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Constant potential differences (of the order of a microvolt) produced in bismuth single crystals at helium temperatures by a microwave field (with a power of the order of a milliwatt) and a stationary magnetic field are investigated. It is found that two emf's are produced in bismuth samples: 1) a Nernst emf resulting from sample heating by the microwave currents and 2) a "radio emf" due to magnetoplasma microwaves propagating in bismuth in the presence of a sufficiently strong magnetic field (of the order of several kilogauss). Some possibilities of studying radio-emf's in metals are discussed.

BUCHSBAUM and Smith[1] observed the occurrence, under the influence of a microwave field, of a constant potential difference in a single crystal of bismuth cooled to helium temperature and placed in a constant magnetic field. It was assumed that the reason for the appearance of the dc emf lies in the action exerted on the carriers by the plasma wave excited in the bismuth. The present study was aimed at investigating the nature of this effect.

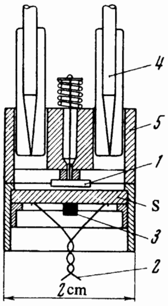

FIG. 1. Strip resonator. S–sample, 1–strip, 2–leads, 3–thermometer, 4–coaxial connecting lines, 5–cylindrical housing of resonator.

## EXPERIMENT

The experiments were performed on Bi single crystals grown in dismountable quartz molds.[2] The quality of the samples was characterized by the parameter $\omega\tau \sim 30-40$. The trigonal axes $C_3$ of the samples (disks of 17.8 mm diameter and 1 mm thickness) were oriented parallel to the normal of the flat surface. The sample was placed in a strip resonator[3] operating at 21.5 GHz (Fig. 1) in such a way that straight-line microwave currents **I**, parallel either to the binary axis $C_2$ or to the bisector axis $C_1$, were excited on the sample surface facing the interior of the resonator. Copper leads 0.1 mm in diameter were welded by capacitor discharge to the opposite outer side of the sample; the dimensions of the contacts were approximately equal to the wire cross section.

The potential difference U across the contacts was measured by a dc microvoltmeter (F-116), the output signal of which was fed to the Y coordinate of a two-coordinate recorder. The X coordinate of the recorder was controlled by the voltage from a Hall pickup measuring the magnetic field H (up to 10 kOe), applied parallel to the flat surface of the sample.

The resonator with the sample was placed either directly in liquid helium or in a volume insulated from the helium bath and containing helium gas for heat exchange (~0.5 Torr). The measurements were performed in the temperature range 4.2–1.3°K. The microwave source was a klystron.

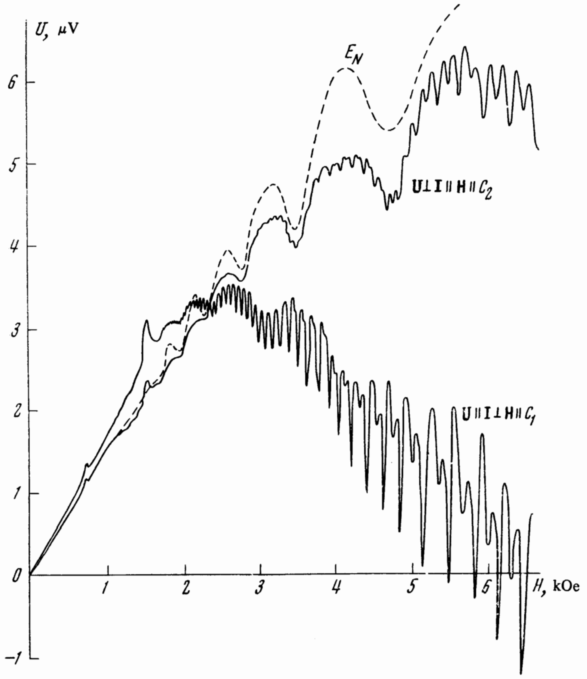

FIG. 2. Plot of the potential difference U(H) excited in the sample by the action of the microwave field. The dashed curve is a plot of the Nernst potential difference $E_N$ excited by heating of the sample. Temperature 1.3°K, the $C_3$ axis is parallel to the normal to the surface of the sample.

A sample plot of the U(H) signal in a direction perpendicular to H, when the signal is maximal, is shown in Fig. 2. The signal is antisymmetrical in the field, is proportional to the microwave power (within the limits

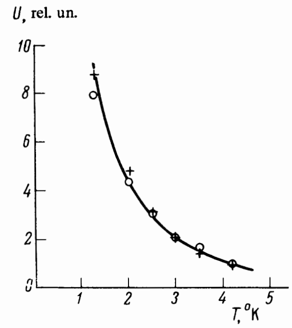

FIG. 3. Temperature dependence of the emf at H = 1 kOe: O–U, +–$E_N$; solid curve–calculation of $E_N$ from the data of [4,5].

~0.01–1 mW), and increases with decreasing temperature (Fig. 3). As shown below, the observed potential difference U is the result of excitation of two emf's in the sample: 1) a Nernst emf due to heating of the sample by the microwave current (the transverse Nernst–Ettinghausen effect), and 2) a "radio emf" due to the action of the magnetoplasma microwaves propagating with small damping in the sample if the magnetic field applied to it is large enough.

## THE NERNST EMF

In magnetic fields $0 \lesssim H < 1.5$ kOe, the observed emf U is proportional to H, and its behavior is in full qualitative agreement with the properties of the Nernst emf*

$$\mathbf{E}_N = Q_N[\mathbf{H}\cdot\nabla T],$$

where $Q_N$ is the Nernst coefficient, and the temperature gradient is $\nabla T = \mathbf{S}/\lambda$, where S is the heat flux and λ the thermal conductivity. To verify that U is a Nernst emf, the following experiment was performed. To monitor the temperature gradient ∇T in the sample, a germanium thermometer was fastened to the outer surface of the sample (Fig. 1) between the contacts; this thermometer measured the heat rise of the sample relative to the helium bath. At a power dissipation in the resonator ~ 0.1 mW, the heat rise was ~0.1°K and consequently ∇T was of the order of $10^{-4}$ deg/mm. (Obviously, a direct measurement of such a small value of ∇T is impossible, since any thermometer placed on the side of the sample facing the resonator would be appreciably heated by the microwave field.)

By replacing the resonator strip with a wire-wound electric heater of the same shape, it was possible to observe the Nernst emf $E_N$, which exceeded U by ~ 30% at equal readings of the thermometer. This should be regarded as equality of $E_N$ and U, when account is taken of the difference between the conditions under which the sample becomes heated by the heater and by the microwave currents. In the latter case, a fraction (~ 10%) of the microwave radiation is leaked through the imperfect contact between the sample and the housing of the resonator and heats the outside of the sample and the thermometer on it. This leads to a decrease of ∇T at a given heat rise of the thermometer.

As seen from Fig. 3, the U(T) dependence coincides with the $E_N(T)$ dependences obtained in the experiment and calculated on the basis of individual measurements of $Q_N(T)$ and λ(T).[4,5]

Thus, at $0 < H \lesssim 1.5$ kOe, the observed emf U is the Nernst emf $E_N$ induced in the sample as a result of its heating by the microwave currents.[1)] The $E_N(H)$ dependence exhibits the following two features:

1. At $H_1 \approx 1.6$ kOe and $H_2 \approx 0.8$ kOe, the U(H) plots exhibit peaks (Fig. 2) whose positions coincide with the values of the fields of the cyclotron resonances of the first and second orders on holes with mass $m^*/m_e = 0.210$.[8] These variations of U are apparently a secondary consequence of the change of the heating of the sample by the microwave currents during the cyclotron resonance.

2. At $H \gtrsim 1.5$ kOe, the function U(H) oscillates with an amplitude that increases with the field (Fig. 2); the oscillations are periodic as a function of $H^{-1}$ and have a period $\Delta H^{-1} \approx 0.07 \times 10^{-3}$ Oe$^{-1}$ (at $H \parallel C_2$), coinciding with the period of the de Haas–Van Alphen quantum oscillations for the electron ellipsoid of the Fermi surface of bismuth.[9] The fact that U(H) is antisymmetrical in H means that the U(H) oscillations are a consequence of the quantum oscillations of $Q_N$ (and not of λ, the dependence of which on H is symmetrical), which were noted earlier by Grenier, Reynolds, and Sybert.[10]

## RADIO EMF

In the magnetic-field region $H \gtrsim 2$ kOe, one can see on the U(H) plot oscillations with amplitude that increases with increasing field (Fig. 2), which are periodic in $H^{-1}$. Their period coincides with the period of the variation of the surface resistance of a bismuth sample in which standing magnetoplasma microwaves are excited.[11] As is well known,[12] magnetoplasma waves are excited with maximum efficiency when the microwave currents **I** in the sample flow perpendicular to the field **H**, and quite weakly when $\mathbf{I} \parallel \mathbf{H}$. Accordingly, the difference between U(H) and $E_N(H)$, and the amplitude of the U(H) oscillations, are relatively small when $\mathbf{I} \parallel \mathbf{H}$ and are quite appreciable when $\mathbf{I} \perp \mathbf{H}$, as is seen from Fig. 2. (Experiment has shown that a change of the crystallographic direction in the basal plane in which U(H) is measured has little effect on the value of U.) A particularly important circumstance is that U(H) reverses sign in sufficiently strong fields (the attainable negative values of U increase with increasing H in the region $6.5 < H < 10$ kOe, which was investigated experimentally but is not represented in Fig. 2). Obviously, any change in the conditions of the heating of the sample by the microwave radiation incident on it from the resonator can only change the absolute magnitude of the gradient ∇T, but not its direction, and consequently can change only the magnitude of $E_N(H)$, but not its sign.

It follows from the foregoing that reversal of the sign of U(H) is evidence of the appearance in the sample, besides $E_N$, of one additional emf—the "radio

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*$[\mathbf{H}\cdot\nabla T] \equiv \mathbf{H} \times \nabla T$.

[1)] Buchsbaum and Smith[1] have stated that the emf observed by them cannot be a consequence of the heating of the sample, since it did not change when the liquid helium in which the sample was immersed became superfluid. This is a misunderstanding: the sample can be heated by the existence of the Kapitza temperature jump on the boundary between the solid sample and the liquid helium. The thermal resistance of the boundary is large—approximately $10^4$ times larger than the thermal resistance of bismuth—and does not experience a jump at the λ point[7].

emf" produced by the action of the microwaves propagating in bismuth to which a sufficiently strong magnetic field is applied. This phenomenon is observed even more clearly when measurements are made with a thinner sample (0.2 mm thick): the amplitude of the oscillations of the radio emf in it are larger by one order of magnitude than in Fig. 2, and greatly exceeds the value of the Nernst emf. This is obviously due to the fact that in a thin sample the measurement of the radio emf is performed at a smaller distance from the plane of excitation of the magnetoplasma waves (i.e., from the sample surface facing the resonator), and at a larger Q of the resonance of the standing waves in the sample, and consequently at a larger energy density in the electromagnetic field of the waves. Experiment has shown that the radio emf is proportional to the power of the microwave field irradiating the sample.

The dependence of the radio emf on the energy density of the wave field should lead to a decrease in its value with increasing distance into the interior of the sample from the wave excitation plane, owing to the damping of the waves. Owing to the inhomogeneity of the radio emf inside the sample, there should exist in the sample a closed electric current due to this emf, and this current can apparently be revealed by its magnetic field outside the sample. The presence of this current should influence the results of the measurement of U: in this case U is a sum of the radio emf and of the voltage drop in the surface layer of the sample between the measuring contacts.

The radio emf should apparently exist in a metal when the electromagnetic wave propagating in it attenuates rapidly, i.e., in the case of the usual skin effect. The radio emf should then be maximal on the metal surface exposed to the microwave radiation, and attenuate in the interior of the metal in the skin layer together with the electromagnetic field. Accordingly, an attempt to observe the radio emf on the exterior side of a tin sample 1 mm thick (at a noise level $5 \times 10^{-9}$ V) yielded no affirmative result.

At the same time, it is necessary to discuss the possibility of observing the radio emf on the illuminated surface of the sample. If the radio emf is excited in a thin skin layer of a relatively thick sample, then the currents produced by it are short-circuited in the interior of the sample, which has a negligibly small resistance compared with the resistance of the skin layer. This means that the radio emf acts under short-circuit conditions and the potential difference between arbitrary points of the skin layer should be equal to zero. The existence of short-circuited currents produced by this emf in the interior of the method can be revealed by their magnetic field.

Mention should be made of another case of appearance of a radio emf, which was observed by Carter and Libchaber[13] in an InSb sample: a constant voltage was produced along the direction of the constant magnetic field under the influence of microwave helicons propagating in the same direction.

Seeking the causes of the appearance of the radio emf, Buchsbaum and Smith[1] drew attention to the fact that electrons moving on helical trajectories along a constant magnetic field may drift in the perpendicular direction under the action of a microwave field that attenuates toward the interior of the metal. However, no nonlinearity capable of explaining the appearance of a constant emf is discerned in the proposed mechanism.

In discussing the possible mechanisms of the currents of constant emf's in a metal under the influence of a microwave field, attention should be paid to the role of the pressure of the electromagnetic wave on the conduction electrons. Indeed, in an inhomogeneous alternating field E, the charged particles are acted upon by a potential average force proportional to $\nabla |E|^2$.[14] This should lead to the appearance of an emf directed into the interior of the metal parallel to the wave vector of the wave propagating in it. Such an emf undoubtedly exists, but an estimate shows that it is very small compared with the radio emf observed in the experiments described above. An estimate of the possible effect of electron superheating also gives a value smaller by several orders of magnitude than that observed.[15]

The most likely mechanism is the occurrence of the radio emf as a result of transfer of momentum to the electrons from the wave propagating in the conductor. Such a mechanism of occurrence of radio emf was considered by Barlow[16] and in greater detail by Gurevich and Rumyantsev.[17] In this case, however, an estimate of the expected radio emf turns out to be smaller by 2–3 orders of magnitude than that measured in the experiment.

The phenomenon of excitation of radio emf in metals is undoubtedly worthy of further experimental and theoretical study.

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239