SURFACE IMPEDANCE OF BISMUTH AT LARGE ELECTROMAGNETIC-WAVE AMPLITUDES

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It has been observed that at helium temperatures and alternating electromagnetic-field amplitudes above a certain critical value there exists a magnetic-field region in which bismuth samples can have several stable states characterized by different dependences of the derivatives of the real and imaginary parts of the surface impedance on the magnetic field.

We report here the results of preliminary experiments on the dependence of the derivatives of the surface impedance of bismuth on the magnetic field H at large electromagnetic-wave amplitudes.

The experiments were performed on disks of 18 mm diameter and thickness d = 0.25 - 0.6 mm. The normal to the disk plane made an angle of 3° with the trigonal axis. The electron mean free path in the metal was such that the radio-frequency size effect could be easily registered.

The samples were placed inside an inductance coil placed in one of the arms of a double-T bridge. Voltage from a radio-frequency generator was fed to the bridge input, and the output signal was fed to a standard demodulation circuit, with a narrow-band amplifier and a synchronous detector (see, e.g., [1]). The measurement setup made it possible to register the derivatives of the real and imaginary parts of the surface of the impedanqe of the metal with respect to the magnetic field ($\partial R/\partial H = f(H)$ and $\partial X/\partial H = f(H)$). It must be noted, however, that the signs of the derivatives were not watched in our experiments.

The electromagnetic-field amplitude was determined from the voltage on the inductance coil and equaled $H^{\sim} = 0.4\pi nU/\omega L$, where L is the inductance of the coil with the sample, n is the number of coil turns per unit length, and ω is the frequency. The experiments were performed at $H^{\sim} \leq 10$ Oe. The maximum temperature rise of the sample relative to the helium bath was of the order of 0.2°K. The constant magnetic field was parallel to the plane of the sample. The magnetic-field orientation relative to the crystallographic axes of the sample was set more precisely by observing the lines of the radio-frequency size effect.

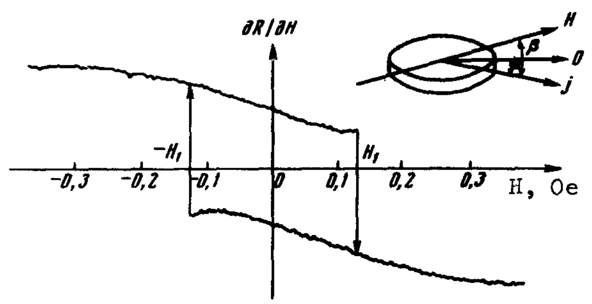

Fig. 1. Sample plot of the derivative of the real part of the surface impedance of bismuth vs. the magnetic field. H = 6.3 Oe, $\alpha = -12°$, $\beta = 25°$, d = 0.4 mm, helium-bath temperature 1.3°K. The angles are defined in the upper right corner (C_1 is the bisector axis making a minimum angle with the direction of the high-frequency current j).

It was observed that at helium temperatures and large values of $H^{\sim}$ there exists a region of magnetic fields $-H_1 < H < H_1$ in which the bismuth can have several stable states characterized by different dependences of the derivatives of the real and imaginary parts of the surface impedance on the magnetic field. In the simplest case there are two such states (Fig. 1). The transition from one state to another occurs jumpwise at definite values of the magnetic field (H_1 and $-H_1$ in Fig. 1). Special experiments have established that not only the derivatives, but also the imaginary and real parts of the surface impedance themselves change jumpwise at the transition. In the general case there exists in the region $-H_1 < H < H_1$ a set of states, each of which is stable in a certain interval of magnetic fields (Fig. 2).

The width of the region $-H_1 < H < H_1$ in which several stable states exist is determined by the following parameters: the value of $H^{\sim}$, the orientations of the constant magnetic and alternating electromagnetic fields relative to the sample crystallographic axes, and the temperature. H_1 is independent of the alternating field frequency in the frequency range in which this could be verified (0.3 - 1.7 MHz).

At a fixed direction of the vector $\vec{H}$, the region with several stable states exists if the amplitude of the alternating field $H^{\sim}$ exceeds a critical value H_c ($H_1 = 0$ at $H^{\sim} \leq H_c$), and further increase of $H^{\sim}$ broadens this region. The critical amplitude of the alternating field increases with increasing sample temperature ($H_c^{\sim}(4.2°K)/H_c^{\sim}(1.5°K) \simeq 2$). The dependence of H_c on the direction of the constant magnetic field is shown in Fig. 3.

In a zero magnetic field and at $H^{\sim} > H_c^{\sim}$, the bismuth samples can be in one more (unstable) state. When a small magnetic field $H < H_1$ is applied, a transition to one of the stable states takes place. The sample can be returned to the initial unstable state only by decreasing the alternating field to a value $H^{\sim} < H_c^{\sim}$.

The region $-H_1 < H < H_1$ is not the only one with several stable states. Phenomena similar to those described above are observed in the angle interval $-30° < \gamma < 30°$ at $H_2(\gamma) < H < H_3(\gamma)$, where $\gamma = \beta - \alpha$ (see Fig. 2).

In our opinion, the results can be explained as follows. It is known that a closed direct current can be excited in a conductor irradiated by radio waves in the presence of an external magnetic field. Such a current was observed in bismuth exposed to microwaves [2]. One of the causes of the closed direct

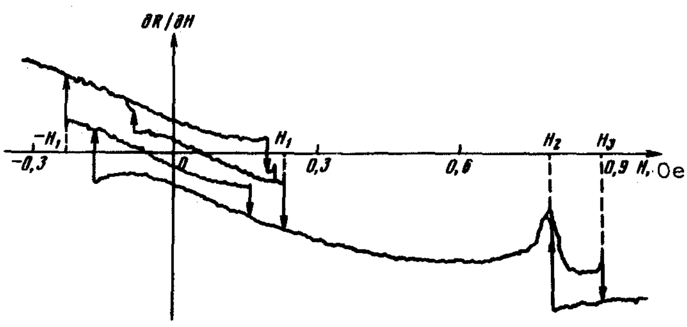

Fig. 2

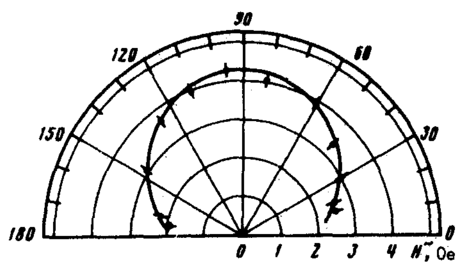

Fig. 3

Fig. 2. Plot of $\partial R/\partial H = f(H)$ at $H^{\sim} = 7.3$ Oe, $\alpha = -1°$, $\beta = 14°$, and $d = 0.4$ mm. Helium-bath temperature 1.3°K.

Fig. 3. Dependence of $H_c^{\sim}$ on the angle between the direction of the constant magnetic field and the high-frequency currents. Sample of thickness $d = 0.4$ mm at $\alpha = 5°$.

current may be modulation of the conductivity by the field's own magnetic field which is superimposed on the external magnetic field. The direct current is then proportional to the square of the alternating-field amplitude.

The closed electric field produces in turn a constant magnetic field, so that the magnetic field in the sample is a sum of the external field and the field produced by the rectified current. At large radio-wave amplitudes it may turn out that when the external magnetic field is turned off the dc does not vanish, since the magnetic field produced by the rectified current itself suffices for the detection. In other words, at alternating field amplitudes above a certain critical value, the metal can exist, even without an external magnetic field, in a "current" state such that a closed direct current flows in the sample. In a zero external magnetic field there are two equivalent "current" states that differ in the direction of the rectified current. Depending on the direction of the "priming" external magnetic field, the sample can be in either of these states.

The foregoing analysis explains many features of the observed phenomena, such as the presence of at least two stable states, the independence of the loop width of the frequency, and the increase of $H_c^{\sim}$ with rising temperature. At the same time, the experimentally observed curves are much more complicated than called for by the model (Fig. 2). The proposed model, however, explains in principle the existence and the large number of states as being due, for example, to anisotropy of the magnetoresistance or to the breakup of the sample into domains. The loop in strong fields (Fig. 2) may be due to a change in the phase relations between the high-frequency currents and the alternating magnetic field. (The amplitude of the rectified current is proportional to the cosine of the phase angle, and the phase shift itself is determined by the total magnetic field, i.e., by the sum of the external field and the magnetic field produced by the rectified current.)

To prove the validity of the proposed model it is necessary to observe directly the magnetic field produced by the closed direct current.

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[1] A. Loesche, Nuclear Induction (Russ. transl.), IIL, 1963.
[2] M.S. Khaikin and S.G. Semenchinskii, ZhETF Pis. Red. 15, 81 (1972) [JETP Lett. 15, 55 (1972)].

RESONANT ABSORPTION BY ELECTRONS LOCALIZED ON DONOR PAIRS IN COMPENSATED n-InSb

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A model of the molecular hydrogen ion H_2^+ is proposed for an analysis of the energy levels of the localized electrons in compensated semiconductors. The measured absorption coefficients of n-InSb at 1.6 - 4.2°K are explained within the framework of the proposed model.

Shklovskii and Efros [1] have developed a model of the electric conductivity of weakly doped, $N_d a^{*3} \ll 1$ ($N_d^{1/3} a^* \ll 1$), and strongly compensated ($1 - K \ll 1$) semiconductors (N_d is the donor concentration, a* is the Bohr radius of