1, 1138 (1968)]; Phys. Stat. Sol. 22, 333 (1967).

SECOND HARMONIC GENERATION IN BISMUTH IN THE MICROWAVE BAND

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A number of investigations (see, for example, [1] have been devoted to the reflection of light from the surface of a metal with emission of the second harmonic, excited by a current $\vec{j}$ which is nonlinearly (quadratically) connected with the fields $\vec{E}$ and $\vec{H}$ (for isotropic media with an inversion center)

$$\mathbf{j} = \sigma\mathbf{E} + \alpha[\mathbf{E}\,\mathbf{H}] + \beta\mathbf{E}\,\mathrm{div}\,\mathbf{E}\ . \tag{1}$$

It is shown in [1] that in the optical band both the conduction electrons and the bound electrons contribute to the nonlinear constants α and β. On the other hand, the nonlinear properties of metals have been traditionally investigated in galvanomagnetic experiments. The nonlinear connection between the current and sufficiently weak fields is usually written in the form [2]

$$E_i = \rho_{ij}\,i_j + \epsilon_{ijk}\,i_j R_{km} H_m + \rho_{ijmn} i_j H_m H_n \tag{2}$$

(here ϵ_{ijk} is a unit antisymmetrical tensor). The second term of (2) describes the Hall effect. In the case of alternating fields, second harmonic generation and the detection effect are connected with this term. The third term is connected with the magnetoresistance. It is of interest to investigate the nonlinear properties of a metal in the microwave band. Unlike the optical band, the principal role is played here by the free carriers, and furthermore the last term in (1) is negligible. Unlike the static case, temporal and spatial dispersion can play a role here.

We have investigated experimentally second-harmonic generation in bismuth in the microwave band. Bismuth was chosen because its carrier density is low; this leads to a larger Hall constant than in other metals and to a better penetration of the field into the metal.

The experiment was performed at room temperature. A bismuth single crystal grown by the method described in [3] was placed at the bottom of a two-mode copper resonator. The resonator was excited in the E_{010} mode by a powerful microwave generator (10 kW) at a frequency of 9200 MHz. The use of short pulses (10^{-6} sec) prevents heating of the sample. The resonator dimensions were chosen such that the H_{111} mode had the second-harmonic frequency, i.e., 18400 MHz. The bismuth crystal in the form of a disc (diameter 17.8 mm) with mirror-finished flat surfaces was secured to the resonator with a conducting adhesive.

Let us consider the nonlinear current given by (2):

$$\mathbf{j} = [\mathbf{E}\,\hat{\alpha}\,\mathbf{H}]. \tag{3}$$

For bismuth, if X_1 and X_3 are the binary and trigonal axes, respectively,

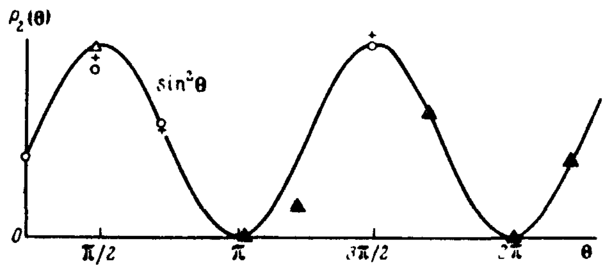

Fig. 1

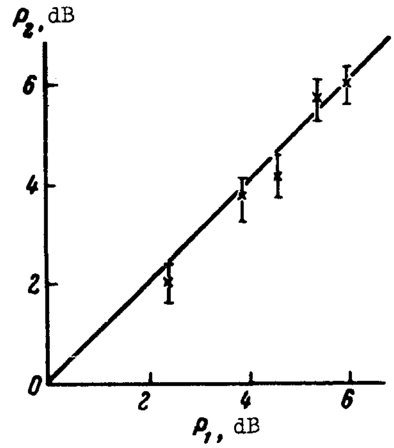

Fig. 2

$$\alpha_{11} = \alpha_{22} = -R_{11}/\rho_{22}\rho_{33} >> \alpha_{33} = -R_{33}/\rho_{11}^2$$

E and H are the microwave fields of fundamental frequency in the metal. The current with frequency 2ω is an extraneous current exciting the H_{111} mode. For effective excitation of the second harmonic it is necessary that the extraneous current have a tangential component defined by the tangential components of the fields of frequency ω. This is possible because of the anisotropy of $\hat{\alpha}$. The sample had the following orientation: the binary axis was in the plane of the sample, and the trigonal axis made an angle of 45° with the normal to the surface. To calculate the second-harmonic field in the resonator, we used the formulas for the excitation of a resonator by an extraneous current (see, for example, [4]), and the natural modes of the resonator, with allowance for the field in the metal, were determined approximately with the aid of the boundary conditions of M. A. Leontovich. The second-harmonic power leaving the resonator is given by

$$P_2 = A Q_1^2 Q_2 P_1^2 R_{11}^2 \sigma \sin^2\theta . \qquad (4)$$

Here P_1 and P_2 are the powers at the frequencies ω and 2ω, Q_i is the loaded Q of both modes, σ is the conductivity of the bismuth, $A = 1.1 \times 10^{-5}$ (absolute units) is a factor that takes into account the geometry of the resonator, and θ is the angle between the projection of the trigonal axis on the plane of the sample and the magnetic field of the H_{111} mode in the center of the sample. Formula (4) was obtained for the case of resonance and of matching on both modes, and neglecting the anisotropy of the surface impedance of the sample. Rotation of the sample in the resonator revealed good agreement between the angular dependence of the second-harmonic power and the $\sin^2\theta$ law (Fig. 1). The qudratic dependence of the second-harmonic power on the fundamental-frequency power is also well satisfied (Fig. 2). The constant R_{11} was estimated from formula (4). At P_1 = 6.3 kW, $Q_1 \sim Q_2 \sim 1400$, $P_2 = 7.5 \times 10^{-5}$ W, and $\alpha \sim 10^{16}$ absolute units, we get $R_{11} = (2.5 \pm 1.2) \times 10^{-20}$ absolute units.

It is known that at room temperature the electron mean free path in bismuth, δ, at 10^{10} Hz ($\ell \sim 3\mu k$ [5]). However, this does not affect the value of the surface impedance of bismuth. The value of R_{11} measured by us likewise does not differ from the static value. Nonetheless, authors of papers on magnetoresistance [6, 7] note the presence of a strong dispersion in the microwave band.

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[1] N. Bloembergen, R. K. Chang, S. S. Jha, and C. H. Lee, Phys. Rev. 174, 813 (1968).
[2] T. Okada, J. Phys. Sos. Japan, 12, 1327 (1957).
[3] V. F. Gantmakher and Yu. V. Sharvin, PTE No. 6, 115 (1963).
[4] L. A. Vainshtein, Elektromagnitnye volny (Electromagnetic Waves), M., 1957.
[5] A. B. Pippard and R. G. Chambers, Proc. Phys. Sos., A, 65, 955 (1952).
[6] C. W. Heaps, Phys. Rev., 80, 892 (1950).
[7] D. E. Clark and J. G. Assenheim, British Journ. Appl. Phys., 11, 35 (1960).

CRITICAL THICKNESS OF IRON FILMS

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In one of our earlier investigations [1] we observed the existence of a new allotropic modification in iron films obtained by low-temperature condensation. This modification is transformed jumpwise into α - Fe when the films are heated to 40°K (Fig. 1). It was shown recently by electron diffraction [2] that the new allotropic modification observed in extremely non-equilibrium iron films is amorphous iron. A very sharp drop of resistance is observed also when films of the rare-earth element ytterbium, obtained by condensation on a substrate cooled with liquid helium [3], is annealed to 14°K. This drop of the electric resistance is also connected with the transition of the ytterbium from new non-equilibrium phase into the usual modification. It was shown further that ytterbium retains the new phase when annealed to 14°K in films of thickness below critical (∼ 3000 Å). When the ytterbium films reach the thickness 3000 A during the course of condensation, they change jumpwise into the usual

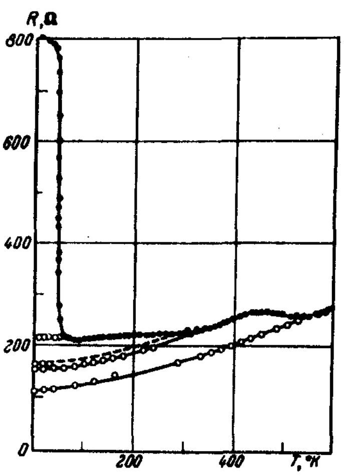

Fig. 1. Resistance vs. temperature for iron film ∼50 Å thick; • - irreversible variation of resistance upon annealing, o - reversible variation of resistance of annealed film.

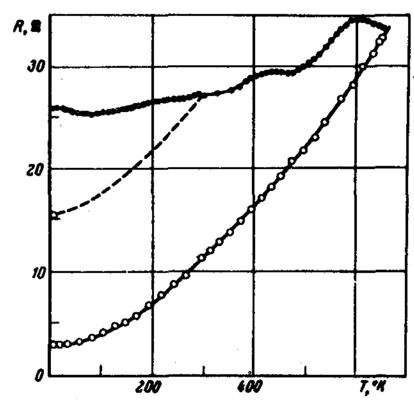

Fig. 2. The same as Fig. 1, but for ∼600 Å film.