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THE INFLUENCE OF HYDROSTATIC COMPRESSION ON
THE MAGNETORESISTIVE EFFECTS IN BISMUTH AND ITS ALLOY. I

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Many papers have dealt with investigations of the magnetoresistive properties of metals. Recently Bobrikov has made a systematic study of the magnetoresistive properties of pure metals /1-4/. Utilizing the findings of theoretical papers /5-6/, Bobrikov gives figures for the density of conduction electrons in several pure metals, calculated from measurements of the Hall effect and from the change of electrical resistivity within a magnetic field.

The comments previously expressed by us on the influence of the density of conduction electrons on the nature of the shift of the critical temperature of superconductors under elastic deformation /7-8/ made a study of the influence of all-round compression on the electron concentration an interesting topic. With this in mind, we measured the Hall effect and the change in electrical resistivity of bismuth and of some compounds of bismuth with other nonsuperconductive metals within magnetic field, and also investigated the temperature dependence of their electrical conductivity in the compressed and uncompressed states. The present paper reports the results of our investigation of bismuth.

To the best of our knowledge, no one else has yet investigated the influence of pressure on magnetoresistive properties in the low-temperature region, so that this may be interesting in itself.

The magnetoresistive phenomena were investigated in single-crystal specimens of bismuth of varying purity, most of them in the shape of a sphere.

This specimen shape was a convenient one, since it ensured a minimum of irreversible changes due to possible deformation of the specimen. The lead-ins were flash-welded to the specimen.

In studying the behavior of the specimens under pressure, we employed the method suggested by Lazarev and co-workers /9/, which we had used successfully in our earlier researches. All measurements were made throughout a wide temperature range: from 1.5 to 300°K. The curve of electrical resistivity vs. temperature in a zero magnetic field was plotted after warming up the apparatus, which had previously been chilled by liquid hydrogen or helium. It usually took 5 to 6 hours to warm the apparatus from 14 to 1273°K, which enabled us to measure resistance with sufficient accuracy. Temperature was measured with a copper-constantan thermo-couple, welded to the outer wall of the bomb facing the midpoint of the specimen.

Fourteen specimens were used in our investigation of bismuth. The specimens were made of Hilger bismuth 99.9996% pure, without preliminary recrystallization, as well as a bismuth containing 0.02% lead. Some of the latter specimens were purified by preliminary recrystallization. Figure 1 gives the curves of the ratio of the Hall field to the electric field in the direction of the current, E_y/E_x , and of the electric resistance r , both as functions of the magnetic field H , at a temperature of 20.4°K for a bismuth specimen containing 0.02% lead. Analogous data for the bismuth specimen No. 14 of the same degree of purity, at a temperature of 4.2°K and at two different orientations within the field are given in Fig. 2. As a rule, all-round compression of the specimens produced no change in the shape of the rotation graph. The anisotropy of the specimens, characterized by the ratio of the minimum to the maximum resistance within a constant magnetic field, decreased reversibly by 7-10%, in all-round compression.

When we measured the Hall effect in one of the Hilger bismuth specimens at liquid helium temperatures, we found a slight oscillation of the Hall

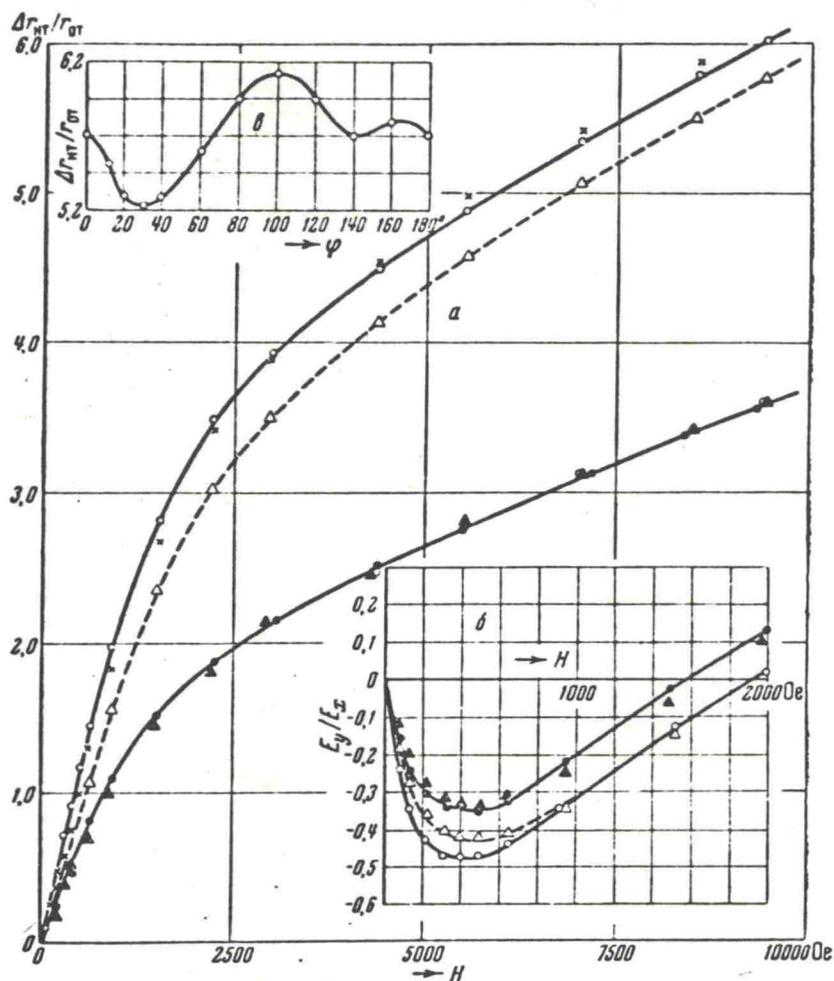


Fig. 1. Specimen Bi No. 8_{II}; $T = 20.4^\circ\text{K}$; $\phi = 28^\circ$; a - resistance vs. field; $\underline{\epsilon}$ - E_y/E_x vs. field; $\underline{\delta}$ - graph of rotation in a field of $H = 7000$ oersteds. \circ - specimen before application of pressure; \bullet - ~ 1500 atm pressure; \times - pressure removed; \blacktriangle - ~ 1500 atm pressure re-applied; \triangle - after removal of reapplied pressure.

e.m.f. An analogous phenomenon has been noted in References /10-12/. Not only did this oscillation of the Hall e.m.f. not vanish under all-round compression, but rather it increased somewhat, and its period changed.¹

1. A detailed report on the results of our investigation of the influence of all-round compression on pure bismuth will be published in the near future.

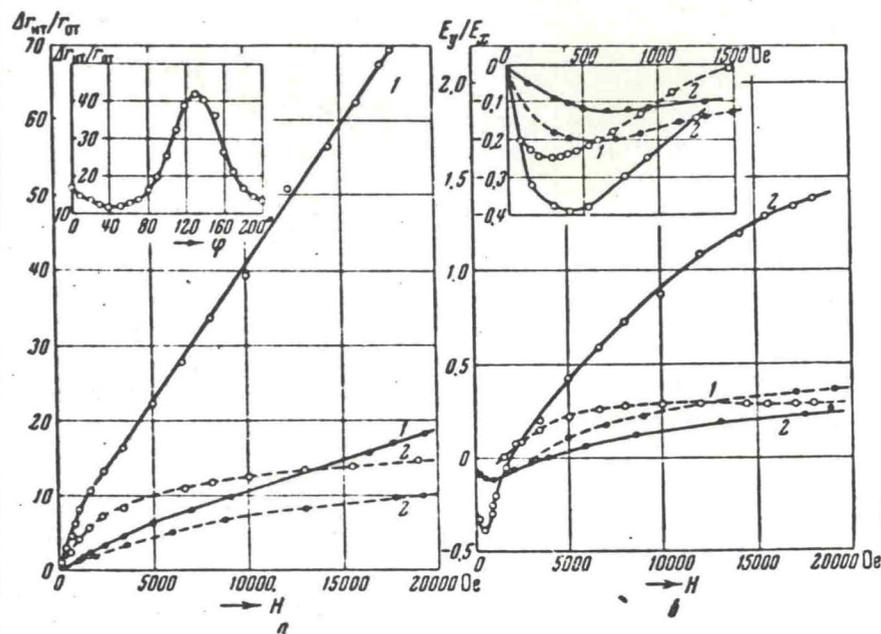


Fig. 2. Specimen Bi No. 14: $T = 4.2^\circ\text{K}$; a - resistance vs. field and graph of rotation in a field of $H = 10,000$ oersteds; b - E_y/E_x vs. field; 1 - $\varphi = 122^\circ$; 2 - $\varphi = 32^\circ$; o - specimen without pressure; ● - 1500 atm pressure.

In our investigation of the temperature dependence of electrical resistivity in bismuth containing 0.02% lead, we found that in four specimens, all-round compression to 1500 kg/cm^2 produces a maximum on the curve of $r(T)$ in the temperature region near $30\text{--}40^\circ\text{K}$ (Fig. 3). Of these four specimens, Bi No. 7, No. 8, and No. 14 were spherical in shape, while the specimen Bi No. 8_{II} was in the shape of a cylinder 3 mm in diameter and 12 mm long. In all these specimens the current direction was approximately perpendicular to the major axis. This phenomenon is apparently absent for other orientations. The unlabeled dashed curve in Fig. 3 shows the variation of electrical resistivity with temperature in a specimen subjected to a pressure of about 1500 kg/cm^2 , with the current flowing parallel to the major axis.

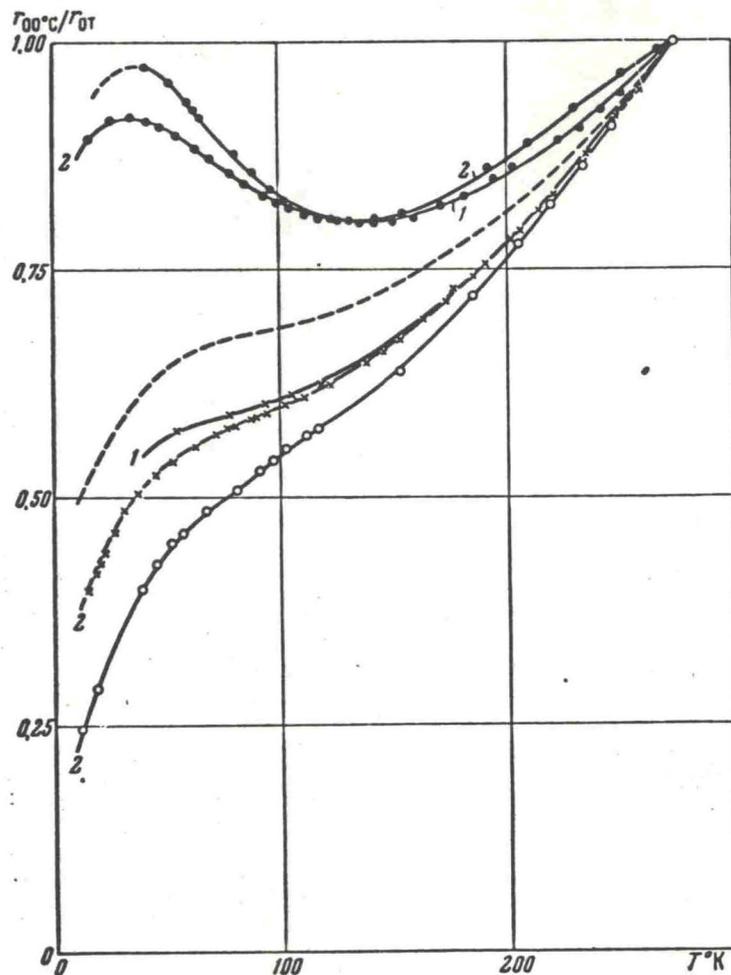


Fig. 3. Temperature dependence of the electrical resistivity of bismuth containing 0.02% Pb. 1 - Bi No. 14; 2 - Bi. No. 8; o - specimens not under pressure; • - pressure ~ 1500 atm; x - after pressure has been removed.

When we compare the data obtained for pure bismuth in our own experiments as well as in the experiments of other authors /13, 14/ with the findings of our investigation of bismuth containing 0.02% lead, we note the following. Whereas electrical resistivity varies almost as the square of the magnetic field intensity in pure bismuth, the analogous curve for bismuth containing a trace of lead exhibits a tendency toward saturation. Moreover, the curve of E_y/E_x vs. H

changes sign in the same field region where the function $r(h)$ exhibits a point of inversion.

No maximum on the $r(T)$ curve is found in the purer specimens of bismuth. It is not impossible, however, that such a maximum may be found even in these specimens at sufficiently high pressures. A maximum on the $r(T)$ curve has been observed in Reference /15/, which made a study of the temperature dependence of electrical resistivity in bismuth containing various percentages of lead. When we compare our findings on the size of this maximum with the data in Reference /15/, we may conclude that all-round compression of the specimen to a pressure of about 1500 kg/cm^2 is equivalent to a change in the concentration of the lead trace from 0.02% to 0.15%. It should be noted, however, that a maximum of the same size, due to impurities, is located in the region of higher temperatures (about 80°K).

It may be that the occurrence of a maximum on the curve showing the variation of electrical resistivity with temperature, produced by pressure, is due to a change in the concentration of conduction electrons under compression. It is difficult to utilize the two-band theory to evaluate the concentration and mobility of the electrons that participate in conductivity for bismuth, as the presence of even slight impurities, such as a trace of lead, results in a substantial departure of the E_y/E_x vs. H and $r(H)$ functions from those that might be expected for models containing an equal number of electrons and "holes" ($n_1 = n_2$). When the lead content of the bismuth is as much as 0.02%, it is more likely that we are dealing with a case where $n_1 \neq n_2$ and, although the change in the functions E_y/E_x vs. H and $r(H)$ under all-round compression is an indication

of a considerable change in mobility and electron concentration caused by pressure, experiments in much stronger magnetic fields are required to determine the magnitude of these changes. Still, if, in evaluating the change of electron concentration and mobility under all-round compression, utilizing the findings for the purest bismuth and considering it as a case of two-band conductivity with an equal number of current carriers in each band, we find that all-round compression lowers the mobility and the concentration of the current carriers. It is quite likely that this may explain the increase in electrical conductivity in bismuth under all-round compression at room temperatures, observed by Bridgman /16/.

The change in the mobility of the conduction electrons and in their concentration under the influence of all-round compression, produced, apparently, by slight changes in the lattice parameters, justifies the assumption that temperature changes of the lattice parameters may produce similar results. Thus, in addition to the changes in the concentration of current carriers in bismuth at temperatures that are higher than the degeneration temperature of the electron gas, i.e. above 70-140°K, noted previously /17/, we may expect a change in the electron concentration in bismuth, related to a decrease in the lattice parameters when chilled. If this hypothesis is correct, it might explain the discrepancy between the curves of the variation of bismuth's resistivity with the strength of the effective magnetic field, $H(r_{00^\circ C}/r_{OT})$, (see References /3,4/), obtained at different temperatures, inasmuch as Köhler's diagram /18/ made no allowance for a change in the number of current carriers with temperature.

For the same reasons, the magnetoresistive properties of bismuths

different purities cannot be compared, since, here, in addition to the changes in mean free path due to the impurities, there may be a very great change in the electron concentration. Hence, the substantial discrepancy between the curves of Hall constant vs. magnetic field intensity, found in Reference /10/, and the curves of $\Delta r_{HT}/r_{OT}$ vs. $H (r_{00^\circ C}/r_{OT})$ in Reference /3/ for different bismuth specimens.

It is quite possible that the variation of electron concentrations with pressure and the variation of electron concentration with temperature that is related thereto may be present in other metals and alloys, in addition to bismuth.

It should be noted that the oscillations of the Hall effect, which persist under all-round compression, are grounds for assuming that it is possible to investigate the influence of all-round compression on the de Haas and Alfvén effects. This presupposition becomes more likely, when we bear in mind the findings reported in References /10/12/, which note the correlation between the Hall e.m.f. and susceptibility in bismuth.

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