ANOMALIES OF LONGITUDINAL RESISTANCE OF SEMICONDUCTING Bi-Sb ALLOYS IN MAGNETIC FIELDS UP TO 500 kOe AT LIQUID-HELIUM TEMPERATURE

N. B. Brandt, E. A. Svistova, Yu. G. Kashirskii, and L. V. Lyn'ko
Physics Department, Moscow State University
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1. The possible existence of various types of electronic phase transitions connected with qualitative changes in the electron energy spectrum, in a magnetic field H, was considered in [1]. One transition of this type, that of a semiconductor (which is dielectric at T = 0°K) into a metal in a magnetic field, was observed in [2] and investigated in detail in [3]. Transformation of a semiconductor into a metal was observed in an alloy system at Sb concentrations 8.5 - 16 at.% with the magnetic field oriented parallel to the trigonal axis, and was revealed by the abrupt rise of the electric conductivity of the samples in a transverse magnetic field, accompanied by the appearance of a metallic dependence of the resistance on the temperature. When the field was oriented perpendicular to the trigonal axis, the transverse magnetoresistance of the samples increased continuously in the magnetic field, without showing a tendency to decrease.

We deemed it of interest to see how the electronic transitions are manifest in the components of the longitudinal magnetoresistance tensor, when the masking effect of the strong increase of the resistance in the field should be much weaker and the phenomena connected with the change of the carrier density should become more strongly pronounced.

2. We report here the results of an investigation of the longitudinal magnetoresistance of single-crystal semiconducting Bi-Sb alloys with antimony concentrations 8.8, 8.9, and 10.5 at.% in a magnetic field up to 500 kOe at liquid-helium temperature. The electric resistance of the investigated samples increased by 100 - 1000 times when cooled from 300 to 4.2°K (at H = 0).

Typical plots of the longitudinal resistance against the field at T = 4.2°K are shown in Figs. 1 and 2. When the field and the current are oriented parallel to the bisector axis (Fig. 1) the resistance increases monotonically in the magnetic field, the character of the dependence of ρ on H changing with increasing concentration of Sb, viz., the strong increase of ρ with increasing field, observed in the samples with concentrations 8.8 and 8.9 at.% Sb (curves 1 and 2, respectively), gives way at larger Sb concentrations to a tendency to saturation (10.5 at.% - curve

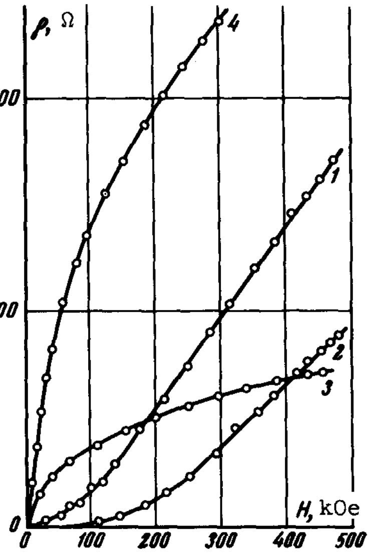

Fig. 1

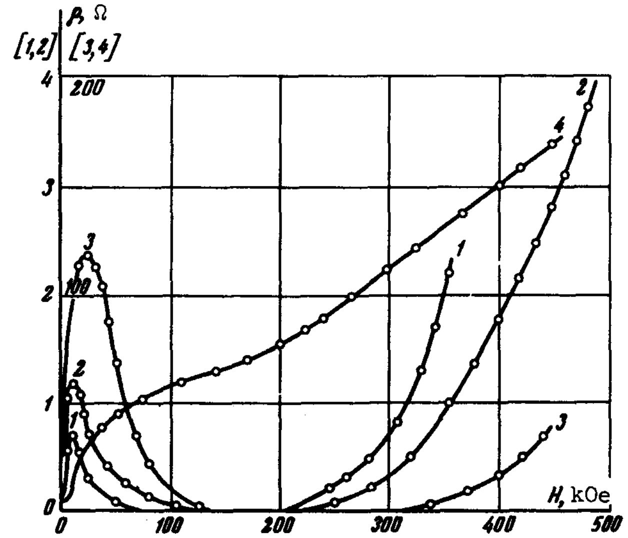

Fig. 2. Plot of ρ against H for samples $Bi_{91.2}$-$Sb_{8.8}$ (curve 1), $Bi_{91.1}$-$Sb_{8.9}$ (curve 2), and $Bi_{89.5}$-$Sb_{10.5}$ (curve 3) with H parallel to the current and to the binary axis, and $Bi_{89.5}Sb_{10.5}$ (curve 4) with H parallel to the binary axis and i parallel to the bisector axis; T = 4.2°K.

3). At larger Sb concentrations and at this orientation, the transverse magnetoresistance increases monotonically in the magnetic field, revealing a tendency to saturation (Fig. 1, curve 4 - 8.8 at.% Sb).

The most surprising are the ρ(H) plots when the field and the current are parallel to the crystal binary axis. At this orientation, the resistance first increases rapidly with the field, passes through a maximum, drops to a value lower than at H = 0, remains constant in a certain field interval, and then again begins to increase. When the Sb density increases, the maximum of the resistance shifts weakly towards the stronger fields; the start of the second growth of the resistance in the magnetic field shifts towards the stronger fields much more rapidly.

The transverse magnetoresistance curves obtained at this magnetic-field orientation reveal (unlike the field orientation parallel to the bisector axis) an irregularity consisting in a decrease in the growth rate of the resistance in a certain field interval (Fig. 2, curve 4).

3. As shown in [3], the sharp increase of the transverse magnetoresistance when H is oriented parallel to the trigonal axis is due to the fact that the extrema of T and L_1 (Fig. 3), which lie at different points of the Brillouin zone, overlap in a magnetic field. The observed overlap continues to increase with increasing field, as a result of which the continuous increase of the carrier density compensates for the usual increase of the resistance in a transverse field.

A different picture should be observed when the extrema of L_1 and L_2, which are located one under the other in the Brillouin zone, come closer together. The character of the changes occurring in the spectrum when the extrema of L_1 and L_2 come closer together is not quite clear. It can be expected, however, that as a result of the condition for the non-intersection of the energy levels the band overlap can occur in this case only as a result of their bending, so that the carrier density will increase slowly and perhaps irregularly) with increasing magnetic field intensity.

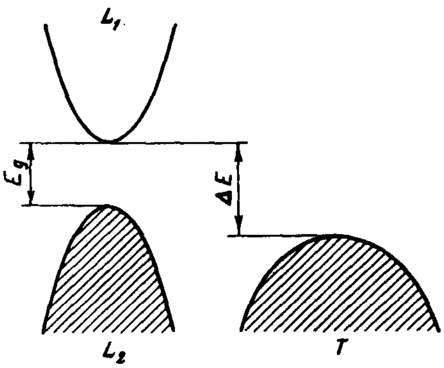

Fig. 3. Energy spectrum of semiconducting Bi-Sb alloys.

When the field is oriented parallel to the bisector axis, the extrema of L_1 and T apparently shift very little in the magnetic field, so that the gap ΔE remains practically constant in fields up to 400 kOe [3]. We note that at this orientation the downward shift of L_1 should be maximal, owing to the minimum values of the orbital and spin effective masses [4]. Thus, when the field is oriented along the binary axis the anomalies observed on the longitudinal magnetoresistance curves are apparently connected essentially with the shift of the extrema of L_2. Since the cyclotron masses of the holes in L_2 are small, a slight excess of the spin splitting over the orbital one is sufficient to shift the extrema of L_2 rapidly upward when H is parallel to the binary axis. The rate of displacement of the extrema of L_1 and L_2 relative to each other can change in a magnetic field, since the effective carrier masses in L_1 and L_2 change when the gap E_g changes. The gap E_g increases slightly in Bi-Sb alloys. A weak dependence of E_g on the Sb concentration corresponds to a weak shift of the maximum on the $\rho(H)$ curves to the right on going to alloys with a larger Sb content.

It can therefore be assumed that the appearance of a maximum on the $\rho(H)$ curves when H is parallel to the binary axis, followed by a strong decrease of the resistance, is connected with the occurrence of a peculiar overlap of the extrema of L_1 and L_2. When this overlap increases in the magnetic field, the ratio of the spin and orbital masses can change. It is not excluded that the secondary increase of the resistance in strong magnetic fields is connected with the divergence of the extrema of L_1 and L_2 as a result of such a change.

The absence of similar anomalies on the longitudinal magnetoresistance curve (in fields up to 500 kOe) when H is parallel to the bisector axis indicates that at this orientation the spin splitting of the levels in L_2 does not exceed the orbital splitting, or else exceeds it very little.

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