ANOMALIES OF THE MAGNETORESISTANCE IN Bi–Sb *SEMICONDUCTING ALLOYS IN STRONG MAGNETIC FIELDS AT LOW TEMPERATURES*

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Systematic investigations of the longitudinal and transverse magnetoresistances of Bi–Sb semiconducting alloys were carried out for Sb concentrations from 8.8 to 16 at.% in magnetic fields up to 500 kOe and at temperatures from 4.2 to 10°K, using the principal orientations of the magnetic field and of the measuring current relative to the crystallographic axes. It was found that the dependences of the transverse and longitudinal magnetoresistances on the field were basically different when the magnetic field was oriented along the trigonal, binary, or bisector axes. It was assumed that the differences were due to three types of phenomenon: a semiconductor–metal transition caused by the overlap of the extrema L_1 and T; a transition to the "quasimetallic" state due to the L_1 and L_2 extrema approaching each other; and a decrease of the carrier density due to an increase of the gap between the valence and conduction bands.

WE have reported earlier[1-3] the discovery of a transition of Bi–Sb alloys from the semiconducting to the metallic state in a magnetic field at liquid helium temperature, due to an overlap of the L_1 and T extrema (Fig. 1), and the anomalous behavior of the longitudinal magnetoresistance of these alloys when the extrema L_1 and L_2, located at the same point in the phase space, approach each other.

The present paper reports the results of systematic investigations of the transverse and longitudinal magnetoresistances of Bi–Sb alloys in the concentration range c = 8.8–15.8 at.% Sb in magnetic fields up to 500 kOe, using the principal orientations of the magnetic field and of the electric current relative to the crystallographic axes of a sample.

The data about the investigated samples are presented in a table.

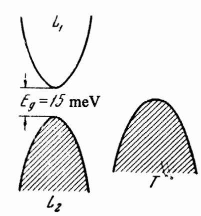


FIG. 1. Energy spectrum of Bi–Sb semiconducting alloys.

RESULTS OF MEASUREMENTS

1. Magnetoresistance in a Field Parallel to a Trigonal Axis

The dependences of the transverse and longitudinal resistances of the samples on the field at 4.2°K are shown in Figs. 2 and 3.

Sample No.	Concentration of Sb, at. %	$\rho_{4.2K}$*/$\rho_{300°K}$	Magnetic field direction	Measuring current direction	Sample No.	Concentration of Sb, at. %	$\rho_{4,2°K}$*/$\rho_{300°K}$	Magnetic field direction	Measuring current direction
1	8.8	43	$\mathbf{H}\parallel C_3$	$\mathbf{i}\parallel C_1$**	24	12	1810	$\mathbf{H}\parallel C_1$	$\mathbf{i}\parallel C_2$
2	8.9	145	»	»	25	15.8	33	»	»
3	9.1	6	»	»	26	8.8	29	»	$\mathbf{i}\parallel C_1$
4	10.5	690	»	»	27	8.9	25	»	»
5	12	82	»	»	28	9.1	6	»	»
6	15.8	80	»	»	29	10.5	175	»	$\mathbf{i}\parallel C_1$
7	15.8	40	»	»	30	12	131	»	»
8	8.8	24	»	$\mathbf{i}\parallel C_2$	31	15.8	79	»	»
9	8.9	45	»	»	32	8.8	21	$\mathbf{H}\parallel C_2$	$\mathbf{i}\parallel C_2$
10	9.1	215	»	»	33	8.9	59	»	»
11	10.5	122	»	»	34	9.1	7,3	»	»
12	12	1320	»	»	35	10.5	245	»	»
13	15,8	220	»	»	36	12	1550	»	»
14	8.9	25	»	$\mathbf{i}\parallel C_3$	37	15.8	51	»	»
15	10.5	118	»	»	38	8.8	35	»	$\mathbf{i}\parallel C_1$
16	10.5	107	»	»	39	8.9	135	»	»
17	11.5	1920	»	»	40	9.1	20	»	»
18***	9.1		»	»	41	10.5	720	»	»
19***	12.0		»	»	42	12	80	»	»
20	8.8	24	$\mathbf{H}\parallel C_1$	$\mathbf{i}\parallel C_2$	43	15.8	84	»	»
21	8.9	45	»	»	44	8.8	43	»	»
22	9.1	15	»	»	45	8.9	88	$\mathbf{H}\parallel C_2$	$\mathbf{i}\parallel C_2$
23	10.5	118	»	»					

*The ratio of the resistance of a sample at 4.2°K ($\rho_{4.2°K}$) and the resistance at 300°K ($\rho_{300°K}$) represents the quality of the sample and affects strongly the magnitude of the magnetoresistance. [2]

**C_1 is the bisector axis; C_2 is the binary axis; C_3 is the trigonal axis.

***The magnetoresistance of samples Nos. 18 and 19 were measured in a constant field.

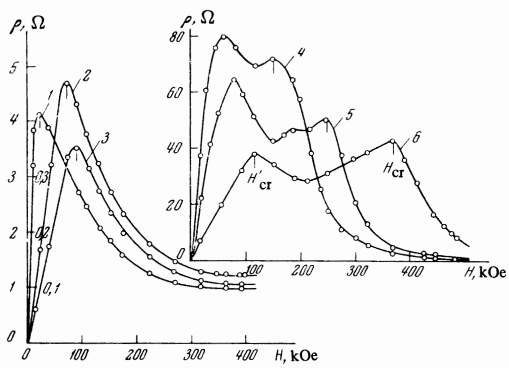


FIG. 2. Dependences of the transverse resistance on the magnetic field for the orientations $H \| C_3$, $i \| C_1$. 1) 8.8 at.% Sb (sample No. 1); 2) 8.9 at.% Sb (No. 2); 3) 9.1 at.% Sb (No. 3); 4) 10.5 at.% Sb (No. 4); 5) 12 at.% Sb (No. 5) 6) 15.8 at.% Sb (No. 6). In the dependences shown at lower left the ordinate scale for curves 1 and 2 is given on the left of the ordinate axis, and that for curve 3 on the right.

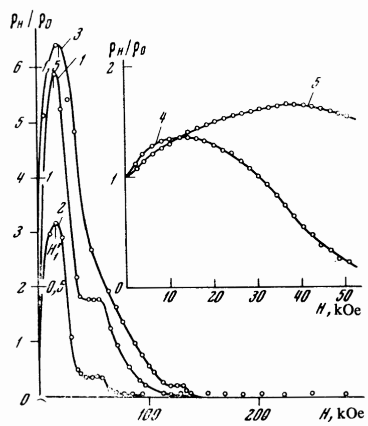


FIG. 3. Dependences of the relative change in the longitudinal resistance, ρ_H/ρ_0 on the magnetic field for the orientation $H \| i \| C_3$. 1) 10.5 at.% Sb (sample No. 15); 2) 10.5 at.% Sb (No. 16); 3) 11.5 at.% Sb (No. 17); 4) 9.1 at.% Sb (No. 18); 5) 12 at.% Sb (No. 19). In the dependences shown at lower left, the ordinate scale for curves 1 and 2 is given on the left of the ordinate axis and that for curve 3 on the right.

The transverse magnetoresistance increases in weak fields, passes (depending on the alloy composition) through one or two maxima, and then decreases rapidly in fields $H > H_{cr}$. The semiconducting nature of the temperature dependence of the resistance in fields $H < H_{cr}$ changes to the metal-type dependence in $H > H_{cr}(c)$.

The nature of the magnetoresistance dependences is governed mainly by the orientation of the magnetic field and is affected weakly by the orientation of the measuring current relative to the crystallographic axes (Fig. 4). Some shift to the left of the maxima (at $H = H_{cr}(c)$ in the $\rho(H)$ curves, observed when the current is oriented parallel to a binary axis, may be due to the anisotropy of the constant-energy surfaces of Bi–Sb and a consequent change in the contribution of these surfaces to electrical conduction when the orientation of the current is altered. We must also bear in mind that the sharp-

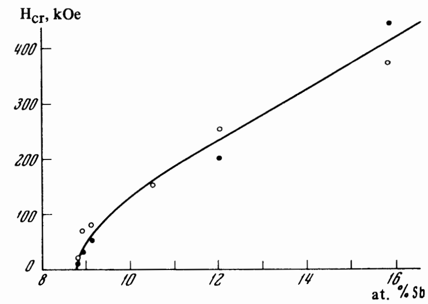


FIG. 4. Dependences of the fields H_{cr} on the concentration of antimony: ○ – $H \| C_3$, $i \| C_1$; ● – $H \| C_3$, $i \| C_2$.

ness of a maximum and the magnitude of the subsequent fall of the resistance are governed, to a considerable degree, by the quality of the samples[2], and, therefore, in different samples of the same composition, the positions of the maxima may be different.

The longitudinal magnetoresistance was measured in constant[1)] as well as in pulsed fields. The dependence of the longitudinal resistance on the field oriented along a trigonal axis has the following features. The resistance increases in weak fields, passes through a maximum, decreases to a constant value, and then again falls rapidly in a field close to $H_{cr}(c)$ for the transverse magnetoresistance (Fig. 3). The low value of the longitudinal resistance of the samples in fields oriented parallel to a trigonal axis prevented us, because of the limitations of the sensitivity of the method, from detecting a second fall of the resistance at $H \sim H_{cr}(c)$ in all the investigated samples.

2. Magnetoresistance in a Field Parallel to a Binary Axis

In magnetic fields of this orientation, the transverse resistance rises strongly in weak fields but eventually this rise slows down so that the $\rho(H)$ curves exhibit a plateau, which is followed by a second strong rise. In the strongest magnetic fields employed, the dependences $\rho(H)$ exhibit a tendency fo saturation, which appears more clearly in the alloys with higher antimony concentrations (Fig. 5). Samples containing 15.8 at.% Sb have $\rho(H)$ curves which pass through a maximum but the resistance of these samples remains higher than ρ_0 (the resistance in H = 0) even in the strongest fields.

The resistance in a longitudinal field increases rapidly at first, reaches its maximum at $H = H_1(c)$, falls to values within the limits of the experimental error, which is ± 0.1 Ω, and remains constant up to a field $H_2(c)$, above which the resistance again increases with the field (Fig. 6). When the concentration of antimony is increased, the maximum and the second rise in the $\rho(H)$ curves are shifted in the direction of stronger fields. The second rise is shifted more strongly than the maximum so that a sample with 15.8 at.% Sb shows no second rise of the resistance in fields up to 500 kOe.

It should be mentioned that the shape of the curves

1)We take this opportunity to thank Yu. P. Gaĭdukov for carrying out these measurements.

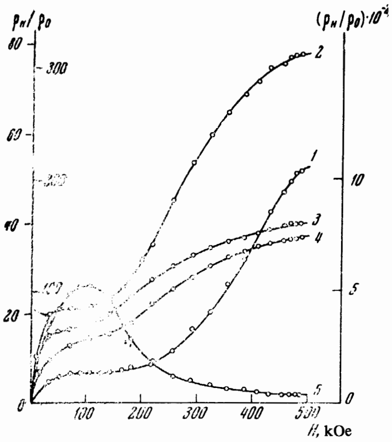


FIG. 5. Dependences of the relative change in the transverse resistance ρ_H/ρ_0 on the magnetic field for the orientations $H \| C_2$, $i \| C_1$. 1) 8.8 at.% Sb (sample No. 38); 2) 8.9 at.% Sb (No. 39); 3) 10.5 at.% Sb (No. 41); 4) 12 at.% Sb (No. 42); 5) 15.8 at.% Sb (No. 43). The left-hand ordinate axis gives the scales for curves 2 and 3 (indicated on the left of this axis) and for curve 5 (on the right); the right-hand ordinate axis gives the scale for curves 1 and 4.

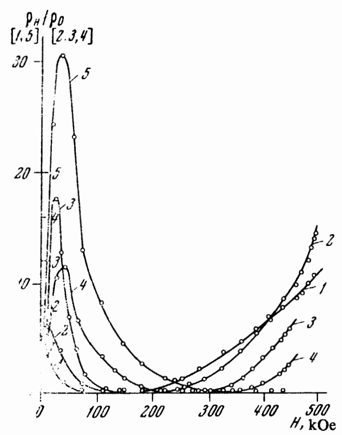


FIG. 6. Dependences of the relative change in the longitudinal resistance ρ_H/ρ_0 on the magnetic fieldfor the orientation $H \| i \| C_2$. 1) 8.8 at.% Sb (sample No. 32); 2) 8.9 at.% Sb (No. 33); 3) 10.5 at.% Sb (No. 35); 4) 12 at.% Sb (No. 36); 5) 15.8 at.% Sb (No. 37). The ordinate scale for curves 1 and 5 is given on the left and that for curves 2, 3, and 4 is given on the right.

obtained is very sensitive to the orientation of a sample relative to the magnetic field. A deviation of the field direction by $\sim 10^\circ$ from the binary axis (the direction of the current) produces a strong shift and broadening of the maximum in the $\rho(H)$ curve and destroys the rise of the resistance in strong fields (Fig. 7).

When the temperature is increased, the magnitude of the maximum in the $\rho(H)$ curves decreases and the second rise shifts in the direction of stronger fields (Fig. 8).

3. Magnetoresistance in a Field Parallel to a Bisector Axis

In fields of this orientation, all the investigated samples (with the exception of an alloy containing 15.8 at.% Sb) exhibit a monotonic rise of the transverse and longitudinal magnetoresistances (Figs. 9 and 10). As the concentration of Sb is increased, the magnetoresistance tends to saturation and this tendency becomes stronger for both directions of the current. The alloy with 15.8 at.% Sb has $\rho(H)$ dependences with a maximum at $H \sim 250$ kOe in a longitudinal field (the current is parallel to the bisector axis) and at $H \sim 350$ kOe in a transverse magnetic field (the current is parallel to the binary axis).

When the field is oriented along the bisector axis, an

FIG. 7. Dependences of the relative change in the longitudinal resistance ρ_H/ρ_0 on the magnetic field for a sample with 8.8 at.% Sb (No. 32), for $H \| i \| C_2$ (curve 1) and for H turned by 10° from C_2 toward C_3 (curve 2).

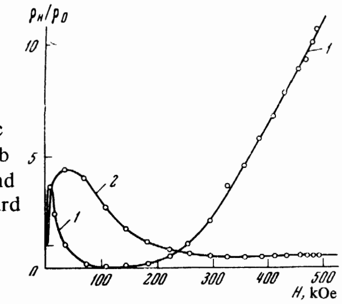
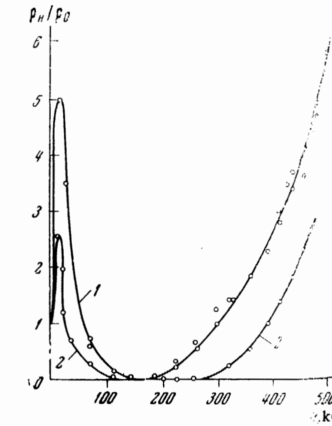


FIG. 8. Dependences of the relative change in the longitudinal resistance ρ_H/ρ_0 on the magnetic field for the orientation $H \| i \| C_2$. 1) T = 4.2°K; 2) T = 10°K. Curves 1 and 2 apply to sample No. 45.



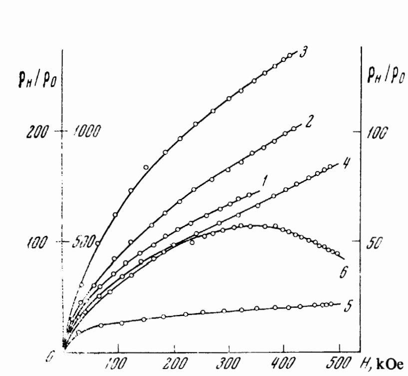


FIG. 9. Dependences of the relative change in the transverse resistance ρ_H/ρ_0 on the magnetic field for the orientations $H \| C_1$, $i \| C_2$. 1) 8.8 at.% Sb (sample No. 20); 2) 8.9 at.% Sb (No. 21); 3) 9.1 at.% Sb (No. 22); 4) 10.5 at.% Sb (No. 23); 5) 12 at.% Sb (No. 24); 6) 15.8 at.% Sb (No. 25). The left-hand ordinate axis gives the scales for curves 1 and 2 (indicated on the left of this axis) and for curves 3 and 6 (on the right); the right-hand ordinate axis gives the scales for curves 4 and 5.

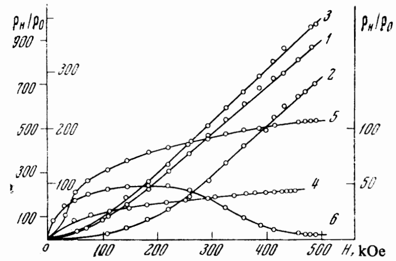


FIG. 10. Dependences of the relative change in the longitudinal resistance ρ_H/ρ_0 on the magnetic field for the orientation H||i||C_1. 1) 8.8 at.% Sb (sample No. 26); 2) 8.9 at.% Sb (No. 27); 3) 9.1 at.% Sb (No. 28) 4) 10.5 at.% Sb (No. 29); 5) 12 at.% Sb (No. 30); 6) 15.8 at.% Sb (No. 31). The left-hand ordinate axis gives the scales for curves 1 and 3 (indicated on the left of this axis) and for curve 2 (on the right); the right-hand ordinate axis gives the scales for curves 4, 5, and 6.

unusually strong rise of the resistance is observed in a longitudinal magnetic field (the longitudinal effect becomes of the same order of magnitude as the transverse magnetoresistance).

DISCUSSION OF RESULTS

I. The reported results show that the following three phenomena take place in semiconducting Bi—Sb alloys in magnetic fields.

1. **Overlap of the L_1 and T extrema.** This is accompanied by a strong increase of the electrical conductivity and the appearance of the metal-type temperature dependence of the resistance in fields $H > H_{cr}(c)$. The amount of the overlap of the L_1 and T extrema, located at different points in the phase space, continues to increase in fields $H > H_{cr}$; a strong rise of the carrier density reduces appreciably both the transverse and longitudinal magnetoresistances. This effect—the transformation of a semiconductor into a metal in a magnetic field—is observed when the magnetic field is oriented parallel to the trigonal axes of the samples. An increase of the value of $H_{cr}(c)$, observed when the concentration of Sb is increased (Fig. 2), is in good agreement with an increase of the energy gap between L_1 and T in the original alloys.

2. **Approach of the L_1 and L_2 extrema, located at the same point in the phase space.** Since the extrema cannot intersect (there is a theorem on the non-crossing of terms), their approach produces a much weaker rise of the carrier density than the overlap of the L_1 and T extrema. It is possible that the approach of the L_1 and L_2 extrema produces a special state in which the alloys are neither metals nor semiconductors. This state with the zero overlap of the bands may be called arbitrarily the "quasimetallic" state. Such a state appears in magnetic fields oriented parallel to the trigonal and binary axes. Since the carrier density does not increase very greatly due to transition to the "quasimetallic" state, this transition can be recorded clearly only in measurements of the longitudinal resistance in a magnetic field when the change in the carrier mobility in the field is relatively small and the resultant increase in the carrier density is sufficient for the appearance of the maxima in the ρ(H) cufves. In transverse fields, the transition is masked by a strong reduction in the carrier mobility.

The values of the fields at which the L_1 and L_2 extrema approach each other are very similar for magnetic fields oriented parallel to the trigonal and binary axes.

When the field is oriented parallel to the trigonal axes of semiconducting Bi—Sb alloys, the L_1 and L_2 extrema approach each other first and this results in the first fall of the longitudinal magnetoresistance (Fig. 3) at $H = H_1'(c)$ and the formation of the "quasimetallic" state. Further increase of the field intensity produces an overlap of the L_1 and T extrema, resulting in a transition of the alloys to the metallic state.

It is possible that the appearance of the first maxima at $H_{cr}'(c)$ in the transverse magnetoresistance curves (Fig. 2) of alloys with $c > 10$ at.% Sb is associated with the formation of the "quasimetallic" state. The appearance of these maxima at fields higher than H_1' may be due to the fact that the fields H_1' correspond to the beginning of an appreciable rise in the carrier density when the L_1 and L_2 extrema approach each other, while the fields $H_{cr}'(c)$ correspond to an appreciable change in the transverse magnetoresistance, which is observed only after a sufficiently strong rise in the carrier density.

When the field is oriented parallel to a binary axis, the L_1 and T extrema do not overlap, at least in fields up to 500 kOe. In fields $H = H_1(c)$, the approach of L_1 and L_2 produces the "quasimetallic" state. This results in a plateau in the dependence of the transverse resistance on the field. It is possible that a further increase of the field may increase the gap between the L_1 and L_2 extrema because of a change of the parameters of carriers in these extrema, which may account for the further rise of the transverse resistance as well as the appearance of a rising branch of the longitudinal magnetoresistance. The shift of the rising branch of the longitudinal magnetoresistance in the direction of stronger fields at higher temperatures may be explained on this basis by assuming thermal generation of carriers crossing the gap between the L_1 and L_2 extrema so that when the gap between L_1 and L_2 increases, the carrier density decreases more slowly at higher than at lower temperatures. The possibility of an increase in the gap between the L_1 and L_2 extrema after their approach in a magnetic field has been considered by Baraff.[5]

3. **Increase in the gap between the valence and conduction bands in a magnetic field.** An increase in the gap between these bands should be accompanied by a reduction in the carrier density (because of the weaker thermal excitation of carriers and a reduction of the overlap of the band "tails"[4]) and an additional increase in the electrical resistance in a magnetic field. This effect is evidently observed when the field is oriented parallel to a bisector axis and is manifested by an anomalously strong rise of the longitudinal magnetoresistance.

II. Qualitative changes in the nature of the field dependences of the transverse and longitudinal magnetoresistances due to an increase in the concentration of Sb (Figs. 5, 9, and 10), together with the nonlinear nature of the dependences of the fields H_{cr} and H_1 on the concentration of antimony, indicate appreciable changes in the basic parameters of the carriers in Bi–Sb alloys. In view of this, it would be very interesting to investigate the strong-field galvanomagnetic effects of Bi–Sb alloys with higher concentrations of Sb.

We take this opportunity to express our deep gratitude to G. I. Ivanov for kindly supplying the high-quality samples.

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