ELECTRON TRANSITIONS IN ANTIMONY-RICH BISMUTH-ANTIMONY ALLOYS IN STRONG MAGNETIC FIELDS

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An investigation was made of the magnetoresistance of Bi-Sb semiconducting alloys containing 11.5–22 at.% Sb. The magnetoresistance was determined at 4.2°K for all the principal orientations of the magnetic field (up to 700 kOe) and of the current relative to the crystallographic axes. The temperature dependences of the resistivity were used to deduce the dependence of the energy gap of the alloys on the concentration of Sb. A new type of electron transition from the semiconducting to the metallic state, was found to be associated with an upward shift of a hole extremum H in the spectrum of Sb in a magnetic field. This transition was observed for all the principal orientations of the magnetic field, which indicated the special nature of the spectrum at the H extremum. On the basis of these results, it was concluded that the spin splitting of holes at the H extremum exceeded, for small sections of the constant-energy surfaces, the orbit splitting. An increase in the magnetic field parallel to the binary axis produced a complex sequence of electron transitions (semiconductor-"quasimetal"-semiconductor-metal), associated with shifts of the energy band extrema typical of the Bi and Sb spectra.

MAGNETIC-field-induced electron transitions of the semiconductor-metal, metal-semiconductor, and semiconductor-"quasimetal"-semiconductor type have been investigated in Bi-Sb alloys in the range of Sb concentrations up to 15 at.%, at which the alloys transform monotonically from the metallic to the semiconducting phase.[1-5]

It seemed of great interest to investigate Bi-Sb alloys in strong magnetic fields in that range of Sb concentrations in which the energy band structure typical of Bi is replaced by the structure of Sb. In this range, one would expect new types of electron transition associated with the shifts, in a magnetic field, of those band extrema which are typical of the energy spectrum of Sb. Such an investigation is reported in the present paper. It was carried out on Bi-Sb alloys containing 11.5–22 at.% of antimony, which were subjected to pulsed magnetic fields up to 700 kOe at liquid helium temperature.

ENERGY SPECTRUM OF BISMUTH-ANTIMONY ALLOYS

We may regard it as established that the change from the Bi to the Sb spectrum in Bi-Sb alloys occurs, in the first approximation, in the following manner (Fig. 1).

The Fermi surface of Bi consists of a single hole ellipsoid of revolution, which is elongated along the trigonal axis and located at the T extremum, and three triaxial strongly anisotropic electron ellipsoids at the L_S extremum. The short axes of the electron ellipsoids coincide with the binary axes of the crystal and the long axes make an angle of ~6° with the basal plane. The dispersion law for holes is quadratic (in the first approximation) whereas that for electrons is nonquadratic and described by the Lax-Cohen formula. The overlap of the T and L_S extrema is ~39 meV. The L_a extremum lies $E_g \approx 15$ meV below the L_S extremum, but they are located at the same point in the phase space. In the case of bismuth, all these extrema lie below the Fermi level and are completely filled with electrons. However, experiments on doped p-type samples of Bi show that the constant-energy surfaces at the L_a extremum are close in shape to the surfaces at the L_S extremum. They represent three triaxial ellipsoids whose long axes make an angle of ~8° with the basal plane. The dispersion law for holes at the L_a extremum is nonquadratic, like the dispersion law for electrons at the L_S extremum.

The most convenient approach to the shifts of the extrema in the energy spectra of Bi-Sb alloys is to consider them relative to the value of the energy E at the point L (the center of the pseudohexagonal face of the Brillouin zone) and assume that this value is constant.

When the concentration of Sb is increased, the L_S and L_a extrema approach each other. When the concentration of antimony is $c_{Sb1} \sim 4.5\%$ (we shall use atomic percent throughout), the energy gap between these extrema reaches its minimum value and the extrema ex-

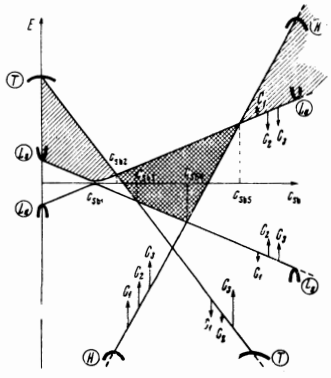

FIG. 1. Changes in the energy spectrum of Bi-Sb alloys due to increasing concentration of Sb. The arrows show the directions of the shifts of the extrema in a magnetic field. Simple hatching is used to indicate the overlap regions and cross hatching to indicate the energy gap.

change their wave functions ("reflection" of extrema). When the Sb concentration is increased still further, the value of the gap E_g increases, reaching ~100 meV for Sb. The linear nature of the shift of the L_s and L_a extrema is probably a rough approximation, which is valid only in the tight-binding model. Actually, the rate of increase of E_g with increasing concentration of Sb slows down in the region of large concentrations of antimony and this gives E_g ~ 100 meV for Sb.

The T extremum shifts downward. Consequently, the band overlap decreases and vanishes at $c_{Sb_2} \sim 7\%$. We can see that, even if the dependence of the position of the T extremum on c_{Sb} is linear, the dependence of the overlap on c_{Sb} is not linear.

At concentrations above ~7% Sb, a gap appears in the spectrum, which is retained up to $c_{Sb_5} \sim 22\%$. Initially, the gap represents the energy interval between the L_a and T extrema and it increases rapidly with increasing S_b. When the L_s extremum intersects the T extremum at $c_{Sb_3} \sim 9\%$ (after the "reflection" the L_s and L_a extrema interchange their positions), the rate of increase of the gap with increasing c_{Sb} slows down and then represents the relative divergence of the L_a and L_s extrema (in this range of concentrations, the gap is equal to E_g).

Finally, at $c_{Sb_4} \approx 17\%$, the gap begins to decrease rapidly; it vanishes at $c_{Sb_5} \sim 22\%$. At c_{Sb_5}, the spectrum again has an overlap and this increases with further rise in the concentration of antimony, reaching ~200 meV, which is typical of pure Sb. We can thus assume that the spectrum of alloys with $c_{Sb} > 22\%$ is basically the same as that of pure Sb and a further increase in the concentration of antimony simply increases monotonically the overlap and the gap E_g. This is supported by the fact that extrapolation of the shifts of the H and L_a extrema to $c_{Sb} = 100\%$ gives an overlap of ~250 meV. Therefore, the rapid reduction of the gap in the range $17\% < c_{Sb} < 22\%$ may be attributed to an upward shift of the H extremum at which six hole ellipsoids are located in pure Sb. We cannot say definitely whether this extremum exists in the spectrum of Bi or whether it appears in the spectra of alloys at some value of the concentration of Sb.

The electron "ellipsoids" L_s and L_a of Bi and Sb are located at the same points in the Brillouin zone, and they differ only (in spite of a change in volume by a factor of more than 200) in the value of the anisotropy (the anisotropy of Sb is ~2.5 times weaker) and in the angle with respect to the basal plane (this angle is ~4° for Sb and 6° for Bi). Therefore, we may assume that the constant-energy surfaces of holes at the H extremum of Bi-Sb semiconducting alloys differ little from the hole "ellipsoids" at the H extremum of Sb, i.e., they are surfaces which are similar in shape to the triaxial ellipsoids whose second longest axis is directed along the binary axis of the crystal, and whose longest axis makes an angle of ~36° with the basal plane.

The values of the gap ΔE in the range $12\% < c_{Sb} < 22\%$ were determined in our investigation from the temperature dependences of the electrical resistivity in the absence of a magnetic field, using the formula $\rho(T) = \rho_0 \exp(\Delta E/2kT)$, which is valid for intrinsic semiconductors on condition that the carrier mobilities depend on temperature as $T^{-3/2}$. The results of this determination were as follows:

c_{Sb}, at.%:	12.0	15.6	15.9	16.6	20.2	20.4	22.0
ΔE, meV:	15.7	19.5	19.2	19.0	10.0	9.0	2.1

CHANGES IN THE ENERGY SPECTRUM OF BISMUTH-ANTIMONY ALLOYS IN STRONG MAGNETIC FIELDS

The available information on the changes in the energy spectrum of alloys in a magnetic field is restricted to the range of antimony concentrations up to ~15 at.% Sb.

The direction and the rate of shift of the extrema in a magnetic field are governed by the ratio of the spin and orbit masses of the carriers and by the values of these masses.[6] Therefore, the direction and rate of shift may be quite different for different orientations of the magnetic field. The nature of the shift of the extrema in magnetic fields oriented parallel to the trigonal (C_3), binary (C_2), and bisector (C_1) axes can be seen from Fig. 1. The arrows indicate the directions of the shifts. The lengths of the arrows are approximately proportional to the rates of the shifts. The subscripts C_1, C_2, and C_3 indicate the orientations of the field parallel to the C_1, C_2, and C_3 axes, respectively.

The T extremum shifts in a magnetic field independently of the L_s and L_a extrema because it lies at a different point in the phase space. The shifts of the L_s and L_a extrema are governed by the condition of non-

Table I

Sample No.	c_{Sb}, at.%	ρ (4.2 °K) / ρ (300 °K)	Orientation: field	Orientation: current	Sample No.	c_{Sb}, at.%	ρ (4.2 °K) / ρ (300 °K)	Orientation: field	Orientation: current
1	12.0	131	$H \parallel C_1$	$i \parallel C_1$	19	12.0	54	$H \parallel C_2$	$i \parallel C_2$
2	15.9	61	»	»	20	15.6	225	»	»
3	16.6	79	»	»	21	15.9	39	»	»
4	20.2	333	»	»	22	20.2	400	»	»
5	12.0	1810	»	$i \parallel C_2$	23	15.9	22	»	$i \parallel C_3$
6	15.6	112	»	»	24	20.2	660	»	»
7	15.9	65	»	»	25	12.0	82	$H \parallel C_3$	$i \parallel C_1$
8	16.6	33	»	»	26	15.9	38	»	»
9	20.2	58	»	»	27	16.6	80	»	»
10	20.4	426	»	»	28	20.2	346	»	»
11	22.0	2	»	»	29	12.0	1320	»	$i \parallel C_2$
12	15.9	22	»	$i \parallel C_3$	30	15.6	132	»	»
13	20.2	480	»	»	31	15.9	29	»	»
14	12.0	80	$H \parallel C_2$	$i \parallel C_1$	32	16.6	220	»	»
15	15.9	33	»	»	33	20.2	68	»	»
16	16.6	84	»	»	34	11.5	1920	»	$i \parallel C_3$
17	20.2	430	»	»	35	15.9	21	»	»
18	12.0	1550	»	$i \parallel C_2$	36	20.2	4000	»	»

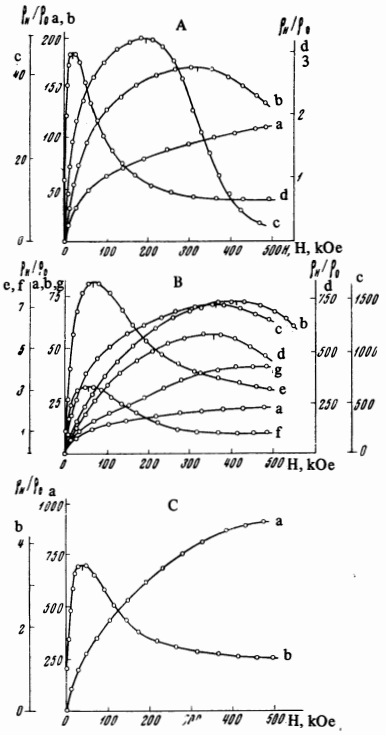

FIG. 2. Dependence of the magnetoresistance on the magnetic field $H \parallel C_1$. A–Orientation of the current $i \parallel C_1$ for samples with the following concentrations of Sb (at.%): a) 12 (No. 1); b) 15.9 (No. 2); c) 16.6 (No. 3); d) 20.2 (No. 4). B–Orientation of the current $i \parallel C_2$ for samples with the following concentrations of Sb (at.%): a) 12 (No. 5); b) 15.6 (No. 6); c) 15.9 (No. 7); d) 16.6 (No. 8); e) 20.2 (No. 9); f) 20.4 (No. 10); g) 22 (No. 11). C–Orientation of the current $i \parallel C_3$ for samples with the following concentrations of Sb (at.%): a) 15.9 (No. 12); b) 20.2 (No. 13).

intersection of the terms and, therefore, the L_s and L_a extrema approach each other, become reflected, and exchange their wave functions.[7,8] Evidently, the linear approximation for the interaction of the L_s and L_a extrema is only the zeroth approximation, since the dispersion law of the carriers at these extrema may change appreciably when the value of E_g changes.

The various directions and rates of shift of the extrema in a magnetic field, shown in Fig. 1, have led to the discovery of the following electron transitions, which are accompanied by basic changes in the energy spectrum:

a) a transition from the semiconducting to the metallic state ($H \parallel C_3$, $8\% < c_{Sb} < 9.5\%$; the L_a and T extrema overlap);[1,2]

b) a transition from the metallic to the semiconducting state ($H \parallel C_2$, $4.5\% < c_{Sb} < 7\%$; the overlap of the T and L_s extrema disappears);[7]

c) a transition from the semiconducting state to a special state known as "quasimetallic," and from the "quasimetallic" back to the semiconducting state ($H \parallel C_2$, $8\% < c_{Sb} < 15\%$; the approach and the reflection of the L_a and L_s extrema);[3,4]

d) a semiconductor-"quasimetal"-metal transition ($H \parallel C_3$, $9.5\% < c_{Sb} < 15\%$; the approach and the reflection of the L_a and L_s extrema followed by an overlap of the T and L_s extrema).[3,4]

The investigations described below enabled us to determine the nature of the shift of the H extremum in the range $17\% < c_{Sb} < 22\%$ and to observe the electron transitions associated with the shift of this extremum in a magnetic field.

RESULTS OF MEASUREMENTS

Strong magnetic fields were produced by a pulse generator, similar to that described in[9]. Intermediate temperatures were established using a device described in[10]. Table I lists the properties of the investigated samples. The compositions were determined by the neutron-activation method to within 0.3 at.%. The ratio of the resistivity at 4.2°K to that at room temperature was used as a criterion of the quality of our samples.[1]

1. Magnetoresistance in a Field Parallel to the Bisector Axis

Figure 2 shows the dependences of the relative change in the resistance ρ_H/ρ_0 on the magnetic field $H \parallel C_1$ for the principal directions of the current i with respect to the crystallographic axes. When the field is parallel to the current, $i \parallel H$ (Fig. 2a), the magnetoresistance of the sample with 12% Sb increases monotonically and that of the samples with 15.9, 16.6, and 20.2% Sb reaches a maximum at some value of the magnetic field H_c and then begins to fall. The magnetoresistance of the sample with 20.2 at.% Sb falls to a certain constant value, which is lower than that in the absence of a magnetic field ρ_0. The position of the maximum shifts toward weaker fields when the concentration of Sb is increased.

When the field is perpendicular to the current, $i \perp H$, and the current is parallel to the binary axis (Fig. 2b), the sample with 12% Sb again exhibits a monotonic rise of the magnetoresistance, whereas the samples with 15.6, 15.9, 16.6, 20.2 and 20.4% Sb exhibit dependences in which the magnetoresistance passes through a maximum at $H = H_c$ and then falls. The value of H_c decreases with increasing concentration of Sb. When the current is oriented along the trigonal axis (Fig. 2c), the sample with 15.9% Sb shows a tendency to saturation and the sample with 20.2% exhibits a maximum and a reduction in the magnetoresistance.

Monotonic dependences of the longitudinal and transverse magnetoresistances are reported in[1,4] for the semiconducting Bi-Sb alloys with up to 12% Sb. The longitudinal effect was found to be of the same order of magnitude as the transverse magnetoresistance, which was attributed to an increase in the energy gap (divergence of the L_a and L_s extrema) in a magnetic field. The samples with higher concentrations of Sb were reported to exhibit a decrease in the longitudinal and transverse magnetoresistances, which was evidently a consequence of the upward shift of the hole extremum H and of the appearance of an overlap of the L_a and H extrema in a magnetic field. This explanation is supported by the correlation between the values of H_c (i.e., the values of the magnetic field in which the magnetoresistance reaches its maximum) and of the gap between the L_a and H extrema of Bi-Sb alloys: the field H_c weakens as the energy gap decreases.

Figure 3 shows schematically possible shifts of the bands in a magnetic field $H \parallel C_1$ for various concentra-

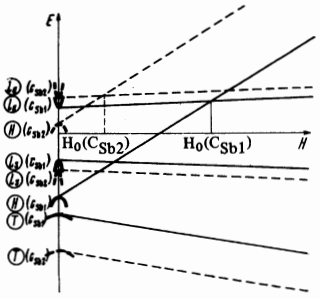

FIG. 3. Shifts of the energy bands of Bi-Sb alloys in a magnetic field $\mathbf{H} \parallel C_1$ for two different concentrations of Sb: $c_{Sb1} < c_{Sb2}$.

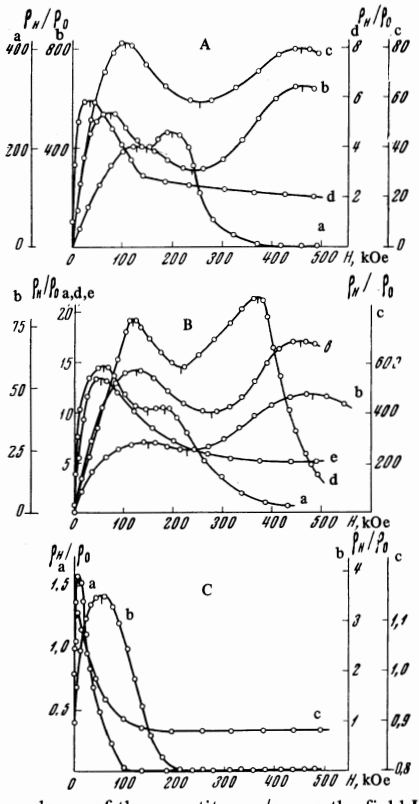

FIG. 4. Dependence of the quantity ρ_H/ρ_0 on the field $\mathbf{H} \parallel C_3$. A–Orientation of the current $\mathbf{i} \parallel C_1$ for samples with the following concentrations of Sb (at.%): a) 12 (No. 25); b) 15.9 (No. 26); c) 16.6 (No. 27); d) 20.2 (No. 28). B–Orientation of the current $\mathbf{i} \parallel C_2$ for samples with the following concentrations of Sb (at.%): a) 12 (No. 29); b) 15.6 (No. 30); c) 15.9 (No. 31); d) 16.6 (No. 32); e) 20.2 (No. 33). C–Orientation of the current $\mathbf{i} \parallel C_3$ for samples with the following concentrations of Sb (at.%): a) 11.5 (No. 34); b) 15.9 (No. 35); c) 20.2 (No. 36).

tions of Sb. Unfortunately, the magnetoresistance data cannot be used to determine the exact value of the magnetic field H_0 in which the band overlap begins. The value of H_c depends on the quality of a sample and on the orientation of the current with respect to the applied magnetic field: it can be used only in qualitative comparisons of the dependences $\rho(H)$ obtained for different concentrations of Sb.

2. MAGNETORESISTANCE IN A FIELD PARALLEL TO THE TRIGONAL AXIS

Figure 4 gives the results of measurements of the magnetoresistance in a magnetic field parallel to the trigonal axis. When the field is parallel to the current,

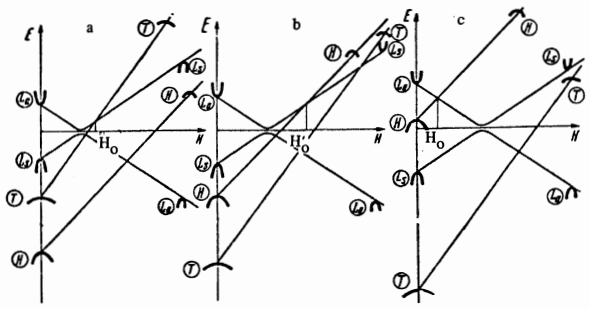

FIG. 5. Shifts of the energy bands of Bi-Sb alloys in a magnetic field $\mathbf{H} \parallel C_3$ for three different concentrations of Sb: c_{Sb} (a) $< c_{Sb}$ (b) $< c_{Sb}$ (c).

$\mathbf{i} \parallel \mathbf{H}$ (Fig. 4c), the magnetoresistance of the samples with 11.5 and 15.9% Sb passes through a maximum and then falls to a very small value, which lies within the limits of the experimental error. The position of the maximum shifts in the direction of stronger fields when the concentration of Sb is increased. The sample with 20.2% Sb has a maximum in fields weaker than those corresponding to the maxima exhibited by the samples with 11.5 and 15.9% Sb. Then, the magnetoresistance of the sample with 20.2% Sb falls to a constant value close to ρ_0. When the field is perpendicular to the current, $\mathbf{i} \perp \mathbf{H}$ (Figs. 4a and 4b), the dependences of the magnetoresistance of the samples with 12, 15.6, 15.9, and 16.6% Sb have a characteristic double-peak form: the magnetoresistance increases, passes through its first maximum, falls to a minimum, increases again, passes through a second maximum (in a field H_c), and falls again. The sample with 20.2% Sb has only one maximum in a field H_c whose value is less than those of the fields at which the first maximum is reached by the other samples; then, the magnetoresistance of the sample with 20.2% Sb falls to a constant value, which is larger than ρ_0. When the concentration of Sb is increased, the positions of the first maxima and minima of the magnetoresistance tend to shift toward stronger fields and the value of H_c increases at first (for concentrations of Sb < 15%) and then decreases (for $c_{Sb} > 15\%$).

The nature of the dependences of the magnetoresistance on the magnetic field and the changes caused by an increase in the concentration of Sb may be explained as follows (Fig. 5). The first maxima and minima in the transverse magnetoresistance curves of the samples with 12, 15.6, 15.9, and 16.6% Sb, and the maxima and the fall to very low values of the longitudinal magnetoresistance of the samples with 11.5 and 15.9% Sb are due to the approach and the subsequent reflection of the L_a and L_s extrema (the semiconductor-"quasimetal"-semiconductor transition).[4] This effect appears most clearly in a parallel field, whereas in a transverse field it is masked by a strong reduction in the carrier mobility. When the concentration of Sb is increased still further, the L_a and L_s extrema diverge and, therefore, the singularities of the magnetoresistance appear at higher fields. The positions of the second maxima, which are followed by falls of the magnetoresistance, are governed by the overlap of the extrema T and L_s (the semiconductor-metal transition) in the case of the samples with $c_{Sb} < 15\%$. When the concentration of Sb is increased, the T extremum shifts downward and the

overlap occurs at higher fields, so that H_c increases. The subsequent decrease of H_c with increasing concentration of Sb (when $c_{Sb} > 15\%$) is evidently due to the upward shift of the H extremum and the appearance of an overlap between the L_s (L_a) and H extrema: the gap between these extrema decreases with increasing concentration of Sb. Beginning from some concentration of antimony, the overlap of the L_a and H extrema appears earlier than the "quasimetallic" state (because of the approach of the L_a and L_s extrema) and the $\rho(H)$ curves exhibit only one maximum (the sample with 20.2% Sb). The appearance of an overlap between the L_s and T or L_s and H extrema explains the absence of a second rise of the magnetoresistance of the samples with 11.5 and 15.9% Sb in a longitudinal field after the reflection of the L_a and L_s extrema.

3. MAGNETORESISTANCE IN A FIELD PARALLEL TO THE BINARY AXIS

Figure 6 shows the results of our measurements of the magnetoresistance in a field parallel to the binary axis. When the field is parallel to the current (Fig. 6b), the magnetoresistance of the samples containing 12, 15.6, and 15.9% Sb passes through a maximum and then falls to a value which lies within the limits of the experimental error (±0.1 Ω). The sample with 12% Sb exhibits a second rise of its magnetoresistance, whereas the samples with 15.6 and 15.9% Sb retain a very low

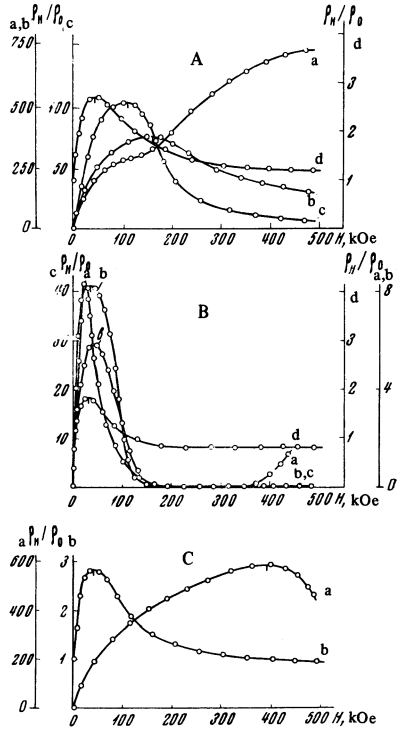

FIG. 6. Dependence of the quantity ρ_H/ρ_0 on the field $\mathbf{H} \parallel C_2$. A–Orientation of the current $\mathbf{i} \parallel C_1$ for samples with the following concentrations of Sb (at.%): a) 12 (No. 14); b) 15.9 (No. 15); c) 16.6 (No. 16); d) 20.2 (No. 17). B–Orientation of the current $\mathbf{i} \parallel C_2$ for samples with the following concentrations of Sb (at.%): a) 12 (No. 18); b) 15.6 (No. 20); c) 15.9 (No. 21); d) 20.2 (No. 22). C–Orientation of the current $\mathbf{i} \parallel C_3$ for samples with the following concentrations of Sb (at.%): a) 15.9 (No. 23); b) 20.2 (No. 24).

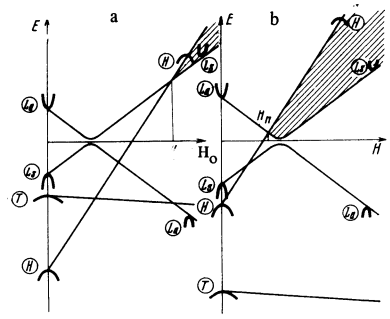

FIG. 7. Shifts of the energy bands of Bi-Sb alloys in a magnetic field $\mathbf{H} \parallel C_2$ for two different concentrations of Sb: c_{Sb} (a) $< c_{Sb}$ (b).

value of ρ_H right up to the strongest field employed. The position of the magnetoresistance maximum shifts toward stronger fields when the concentration of Sb is increased. The sample with 20.2% Sb has a maximum followed by a decline of the magnetoresistance to a constant value close to ρ_0; this maximum is reached in a field H_c which is less than the corresponding fields for the samples with 15.6 and 15.9% Sb.

When the field is perpendicular to the current (Figs. 6a and 6c), the magnetoresistance of the sample with 12% Sb first increases, then slows down to form a plateau; this is followed by a second rise and saturation in strong fields. The samples with 15.9, 16.6, and 20.2% Sb exhibit a maximum of the magnetoresistance at H_c, which is followed by a fall to constant values larger than ρ_0. When the concentration of Sb is increased, the position of the maximum shifts in the direction of weaker fields.

In this orientation of the magnetic field, the T extremum shifts gradually downward and the L_a and L_s extrema approach each other and are reflected, as in the $\mathbf{H} \parallel C_3$ case. This explains the plateau exhibited by the transverse magnetoresistance of the sample with 12% Sb, as well as the maximum and the fall to very low values of the longitudinal magnetoresistance of the samples with 12, 15.6, and 15.9% Sb (the semiconductor-"quasimetal"-transition) and also the shift of this maximum in the direction of stronger fields (because the gap between the L_a and L_s extrema widens with increasing concentration of Sb). The second rise of the longitudinal magnetoresistance of the sample with 12% Sb is due to an increase in the gap between the L_s and L_a extrema after their reflection (the "quasimetal"-semiconductor transition). The appearance of a maximum and the fall of the magnetoresistance of the samples with 15.9, 16.6, and 20.2% Sb in a transverse field and of the sample with 20.2% Sb in a longitudinal field, as well as the shift of this maximum toward weaker fields with increasing concentration of Sb, are a consequence of the approach and overlap of the L_a and H extrema. This approach and overlap explains also the absence of a second rise of the longitudinal magnetoresistance of the samples with 15.6 and 15.9% Sb. The possible shifts of the band in a field $\mathbf{H} \parallel C_2$ are shown schematically in Fig. 7 for two different concentrations of Sb.

The model of the shifts of the energy bands in strong magnetic fields, used in our discussion, allows us to predict that the samples with $c_{Sb} < 15\%$ should exhibit

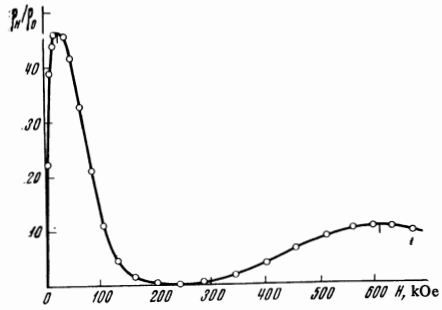

FIG. 8. Dependence of the quantity ρ_H/ρ_0 on the field for the $H \| i \| C_2$ orientation. Sample No. 19 with $c_{Sb} = 12\%$.

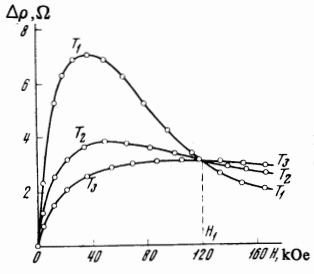

FIG. 9. Characteristic changes in the temperature dependence of the magnetoresistance due to the semiconductor-metal transition (sample with $c_{Sb} = 20.2$ at.%). $T_1 < T_2 < T_3$.

the following interesting sequence of electron transitions in $H \| C_2$: semiconductor-"quasimetal"-semiconductor-metal. Measurements designed to test this prediction were carried out on a sample with 12% Sb in fields up to 700 kOe.

Figure 8 shows the obtained dependence of the magnetoresistance on the magnetic field. We can see that the second rise of the magnetoresistance slows down in fields higher than 500 kOe, and that a second maximum appears at about 600 kOe. The second maximum and the subsequent fall of the magnetoresistance are a consequence of the transition from the semiconducting to the metallic state because of the appearance of an overlap between the L_S and H extrema, which is the final stage of the semiconductor-"quasimetal"-semiconductor transition resulting from the approach and the reflection of the L_a and L_S extrema.

Measurements of the magnetoresistance carried out at various temperatures (Fig. 9) confirm that the semiconductor-metal transition, associated with the appearance of an overlap between the L_a (L_S) and H extrema, occurs for all the principal orientations of the magnetic field. In the range of magnetic fields ($H < H_1$) in which these extrema are separated by a gap, the resistance falls as the temperature rises, which is a typical semiconductor property. In stronger fields ($H > H_1$), the resistance increases with rising temperature, which is typical of metals.

It must be mentioned that an overlap of the L_a (L_S) and H extrema is observed for all orientations of the magnetic field, in good agreement with the expected complex structure of the spectrum at the H extremum: the hole "ellipsoids" are inclined at large angles with respect to the basal plane and therefore only the near-central "ellipsoid" sections are active at all orientations of the field. The observation that the transitions associated with the shift of the H extremum are independent of the field orientation provides additional evidence of the similarity, at the H extremum, of the constant-energy surfaces of Bi-Sb alloys and of pure Sb, since the large inclination of the "ellipsoids" of Sb at the H extremum makes the hole surface practically "isotropic".

Since the H extremum shifts upward for all the principal directions of the magnetic field, we may conclude that—in the case of small sections—the spin splitting of the holes in a magnetic field exceeds the orbit splitting. Unfortunately, a quantitative analysis of the results is difficult to perform because the rate of shift of the H extremum in a magnetic field cannot be determined accurately.

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