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OBSERVATION OF TRANSFORMATION OF A SEMICONDUCTOR INTO A METAL IN A MAGNETIC FIELD

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1. It was shown in [1] that a transition from the metallic state to the semiconducing state (dielectric at 0°K), or conversely the transformation of a semiconductor (dielectric) into a metal, depending on the ratio of the spin and cyclotron effective carrier masses, can be observed in substances having an even number of electrons per unit cell if the magnetic field is strong enough.

These effects are easiest to observe in objects with small band overlap or with small energy gap between bands. The metals with minimum overlap are bismuth and antimony. Neither, however, goes over into the dielectric state in a magnetic field: In bismuth the band overlap increases in the field, owing to the small spin carrier mass [2], and in antimony the attainable fields (H = 450 kOe) are insufficient for a transition into the ultraquantum region [3]. From this point of view, special interest is attached to the system of Bi-Sb solid solutions in the concentration range from 0 to ~10 at.% Sb. When the antimony concentration increases, the band overlap decreases and vanishes at ~5 at.% Sb, after which an energy gap is produced in the Bi-Sb spectrum [4,5].

2. The investigation of the solid solutions at concentrations 0 - 5 at.% Sb * shows that the overlap increases in a magnetic field, i.e., the picture is similar to that in bismuth. It was therefore to be expected that if the antimony content exceeds 5 at.%, when a gap appears, the gap will decrease in strong magnetic fields and will vanish at a certain critical value H_{cr}, so that the semiconducting alloy will go over into the metallic state.

3. We present here the results of an investigation of the magnetoresistance of single-crystal samples of Bi-Sb with antimony concentrations ~5, ~9, and ~12 at.%, in magnetic fields up to 420 kOe at liquid helium temperatures, and in different crystallographic orientations. The measurement procedure is similar to that described in [2]. The samples had the form of parallelepipeds with dimensions ~2 x 0.3 x 0.3 mm.

Measurement of the temperature dependence of the electric resistance at H = 0 has revealed also a semiconductor dependence for samples of all compositions. A slight increase of the resistance with decreasing temperature of the $Bi_{95}Sb_5$ samples ($\rho_{4.2°K}/\rho_{300°K}$ = 3.5) indicates that no noticeable energy gap has yet been produced. In the $Bi_{91}Sb_9$ and $Bi_{88}Sb_{12}$ samples a strong increase of resistance, of the semiconductor type, is observed ($\rho_{4.2°K}/\rho_{300°K}$ = 107 for $Bi_{91}Sb_9$ and $\rho_{4.2°K}/\rho_{300°K}$ = 220 for $Bi_{88}Sb_{12}$). The near-exponential character of the dependence in the temperature region 30 - 120°K makes it possible to estimate the size of the energy gap ΔE of alloys of this composition. The values of ΔE in three investigated $Bi_{91}Sb_9$ samples are approximately equal at ~17 meV. The corresponding band structure is shown in Fig. 1c.

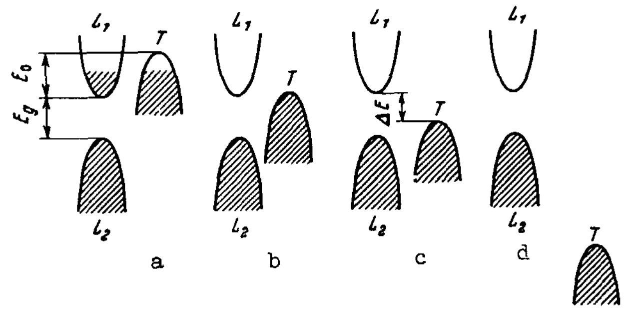

Fig. 1. Band structure for: a - pure Bi, b - $Bi_{95}Sb_5$, c - $Bi_{91}Sb_9$, d - $Bi_{88}Sb_{12}$.

According to [6], the extremum of T of the $Bi_{88}Sb_{12}$ alloy is much lower than L_2. Therefore the exponential growth of the resistance of alloys having this concentration is connected with the gap E_g between the extrema of L_1 and L_2, and does not determine the position of the maximum T in Fig. 1d.

Figures 2 and 3 show the relative variation of the resistance in a magnetic field for bismuth-antimony alloys of three different

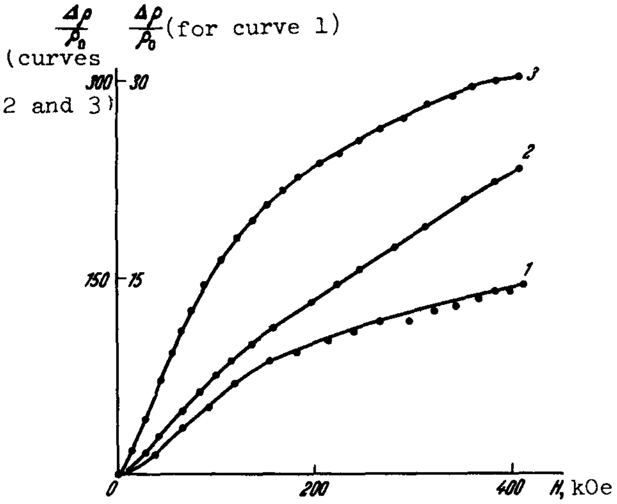

Fig. 2. Relative change of electric resistance vs. magnetic field at T = 4.2°K for the following samples: 1 - $Bi_{88}Sb_{12}$, H parallel to the trigonal axis, $\rho_{4.2°K}/\rho_{300°K}$ = 220; 2 - $Bi_{95}Sb_5$, H parallel to the bisector axis, $\rho_{4.2°K}/\rho_{300°K}$ = 3.5; 3 - $Bi_{95}Sb_5$, H parallel to trigonal axis, $\rho_{4.2°K}/\rho_{300°K}$ = 3.5.

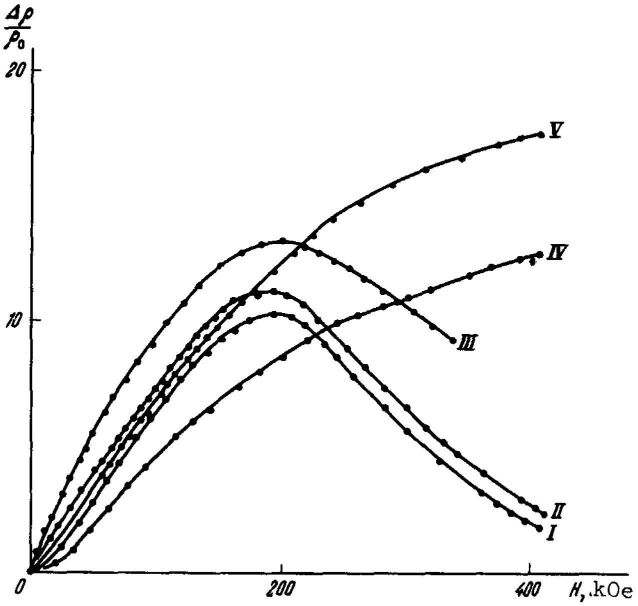

Fig. 3. Relative change of electric resistance vs. magnetic field at T = 4.2°K for the following samples: I - H parallel to trigonal axis, $\rho_{4.2°K}/\rho_{300°K}$ = 122; II - H parallel to trigonal axis, $\rho_{4.2°K}/\rho_{300°K}$ = 91; III - H parallel to trigonal axis, $\rho_{4.2°K}/\rho_{300°K}$ = 50; IV - H parallel to bisector axis, $\rho_{4.2°K}/\rho_{300°K}$ = 91; V - H parallel to bisector axis, $\rho_{4.2°K}/\rho_{300°K}$ = 122.

compositions at field orientations parallel to the trigonal and bisector axes. In all three investigated $Bi_{91}Sb_9$ samples, a sharp decrease of the resistance is observed in fields exceeding 200 kOe and oriented parallel to the trigonal axis.

No decrease in resistance was observed in fields up to 420 kOe parallel to the bisector axis. Nor was such a decrease observed in the $Bi_{95}Sb_5$ and $Bi_{88}Sb_{12}$ alloys.

4. The cause of the sharp increase of the electric conductivity, leading to a drop in resistance of the $Bi_{91}Sb_9$ alloy when the magnetic field is parallel to the trigonal axis, is the overlapping of the L_1 and T bands. At this field orientation, the spin splitting of the Landau levels of the bismuth holes is approximately double the orbital splitting.

The drop in resistance indicates that the spin splitting remains larger than the orbital splitting in the case of Bi-Sb alloys in the investigated range of concentrations.

As a result, the top of the T band is raised in a magnetic field by an amount

$$\Delta E_T = [-\frac{1}{2}\frac{|e|\hbar}{m_h^* c} \pm \frac{1}{2}\frac{|e|\hbar}{m_{hs}^* c}]\,H,$$

where m_h^* is the cyclotron *effective mass of the hole and* m_{hs}^* is the spin effective mass of the hole. For electrons in bismuth, with the magnetic field parallel to the trigonal axis, the spin splitting is smaller than the orbital splitting. If this relation is maintained also in bismuth-antimony alloys, then the bottom of the L_1 band rises in the field by an amount

$$\Delta E_{L_1} = [\frac{1}{2}\frac{|e|\hbar}{m_e^* c} - \frac{1}{2}\frac{|e|\hbar}{m_{es}^* c}]\,H,$$

where m_e^* is the cyclotron effective mass of the electrons and m_{es}^* is the spin effective mass of the electrons.

The transition from an increasing resistance in a magnetic field to a decreasing one (at H ~ 200 kOe) corresponds to the vanishing of ΔE, i.e., to the condition

$$\Delta E_T = \Delta E + \Delta E_{L_1}\ .$$

The fact that the resistance does not drop when the field is parallel to the bisector axis agrees with the ratio of the spin and cyclotron masses at this orientation. The vanishing of the section with $\partial\rho/\partial H < 0$ for the $Bi_{88}Sb_{12}$ alloy in fields up to 420 kOe (Fig. 2) at the corresponding orientation of H is due to the strong increase of the gap ΔE (Fig. 1d) and indicates that the spin splitting of the holes at the extremum of L_2 is only slightly larger than the orbital splitting, if at all.

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* The results of an investigation of Bi-Sb alloys at concentrations from 0 to 5 at.% Sb will be published in the very near future.

INFLUENCE OF MAGNETIC FIELD ON THE THRESHOLD ABSORPTION OF JOSEPHSON RADIATION IN Sn-Pb TUNNEL JUNCTIONS *

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An investigation of the behavior of the maxima of the dV/dI characteristics of Josephson tunnel junctions [1-3] as a function of the magnetic field provides an answer to the question whether the observed structure of the dV/dI characteristics is due to Josephson electromagnetic radiation [1,3] or whether it is connected with many-particle tunneling processes [4]. In the former case a strong field dependence is expected, whereas the many-particle tunnel current is practically independent of the field. It was observed in [1] that in magnetic fields ~100 Oe the fine structure of the dV/dI characteristics of Sn-Pb junctions vanishes gradually, and Rochlin [3] observed no field dependence for Pb-Pb junctions.

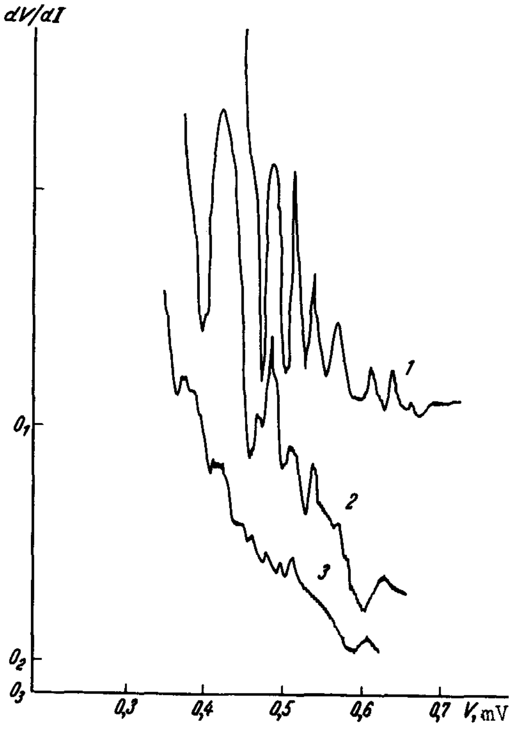

Fig. 1. dV/dI characteristics of Sn-Pb tunnel junctions at T = 1.7°K. 1) H = 21 Oe, 2) H = 52.5 Oe, 3) H = 84 Oe. The null point of the abscissa axis is shifted to the left. The null point of the ordinate axis is different for the different curves and is tagged with an appropriate number. The amplitude of the alternating modulating voltage V across the junction does not exceed 3 μV.

We present in this communication the results of a detailed investigation of the dependence of the **intensity of the minima of the group** Δ_{Sn} (see [1]) on a constant magnetic field parallel to the plane of the junction for two different Sn-Pb tunnel junctions. Figure 1 shows dV/dI characteristics plotted at different values of the magnetic field. It is clearly seen that the fine structure of the dV/dI characteristics near $\bar{\Delta}_{Sn} = 0.6$ meV vanishes gradually with increasing magnetic field, whereas the positions of the maxima on the V axis are practically independent of the field. It should be noted that the investigated junctions had very low resistivity ($\rho < 10^{-4}$ ohm-mm^2) and had a sufficiently homogeneous dielectric layer. The homogeneity of the oxide is apparently a necessary condition for the observation of a strong interaction