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SEMICONDUCTOR - "QUASIMETAL" - SEMICONDUCTOR TRANSITION IN $Bi_{1-x}Sb_x$ ALLOYS UNDER THE INFLUENCE OF PRESSURE

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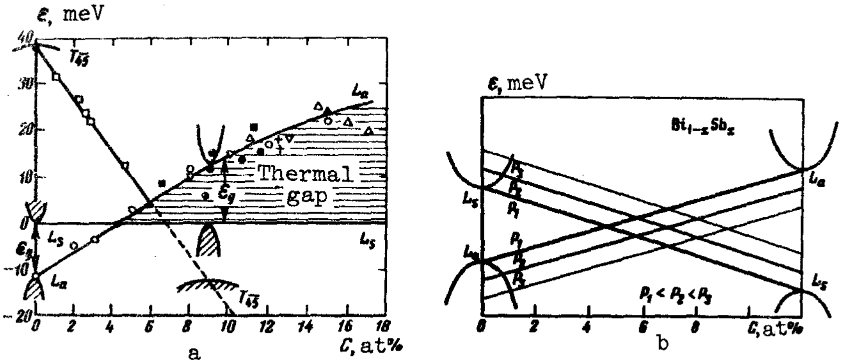
1. We investigated the influence of the pressure p ($0 \leq p \leq 20$ kbar) on the energy spectrum of $Bi_{1-x}Sb_x$ alloys with $0 < x \leq 0.15$ by measuring the galvanomagnetic characteristics in both extremely weak magnetic fields and in strong magnetic fields H in the temperature interval 1.5 - 300°K.

2. In the $Bi_{1-x}Sb_x$ alloys (at $x > 0.05$) we observed a transition under the influence of the pressure p (at $H = 0$) from the superconducting state into a new state (called "quasimetallic") characterized by anomalously small values of the energy gap ϵ_g and of the effective carrier masses. The transition is the result of the coming together, under the influence of the pressure, of the terms L_a and L_s (the notation is from [1]), which determine at $p = 1$ bar and $x > 0.05$ the bottom of the conduction band and the top of the valence band at the point L of the reduced Brillouin zone, respectively.

3. The change of the structure of the energy spectrum of the $Bi_{1-x}Sb_x$ alloys with increasing x under atmospheric pressure occurs in the following manner (Fig. 1a). The top of the valence band in T (the term T_{45} [1]) drops relative to the term L_s (of the bottom of



a

b

Fig. 1. a) Structure of energy spectrum of $Bi_{1-x}Sb_x$ alloys vs. the antimony concentration x at atmospheric pressure: o - [2], ● - [8], ▲ - [4], △ - [5], ▽ - [6], + - [7], □ and ▣ - present data. b) Qualitative plot of energy ϵ of the terms L_s and L_a vs. pressure p in $Bi_{1-x}Sb_x$ alloys with different x.

the conduction band in L at $x < 0.05$), so that the terms T_{45} and L_a intersect when $x \sim 0.065$. At the same time, the terms L_s and L_a come closer together [1-3], and the gap ϵ_g between them becomes minimal at $x \sim 0.05$. When $x > 0.05$, the terms L_s and L_a exchange places, and the gap ϵ_g increases with increasing x.

4. An investigation of the temperature dependences of the components of the galvanomagnetic tensor of the $Bi_{1-x}Sb_x$ alloys (at $\mu H \ll 1$, where μ is the average carrier mobility) in the range $0 \leq p \leq 20$ kbar has shown that under the influence of p the top of the valence band in T shifted downward relative to the term L_s at a rate, practically independent of x, $\sim 1.35 \times 10^{-6}$ eV/bar. For semimetallic $Bi_{1-x}Sb_x$ alloys with $x < 0.06$, we determined the critical pressures of the transition into the semiconducting phase, and from them the energy of the band overlap at $p = 1$ bar (Fig. 1a). It was established that at $x > 0.05$ the gap ϵ_g first decreases with increasing pressure p (at a rate $\partial\epsilon_g/\partial p = -2.6 \times 10^{-6}$ eV/bar), becomes minimal at a certain $p = p^*$ that depends on x, and then increases with increasing p. Thus, for alloys with $x > 0.05$, the terms L_a and L_s again change places under the influence of the pressure. The region of the "quasimetallic" state lies near p^*, and the inverse "quasimetal" - semiconductor transition occurs when $p > p^*$. The qualitative pressure dependence of the energies of the terms L_s and L_a at equal x is shown in Fig. 1b.

5. The semiconductor - "quasimetal" transition is accompanied by a sharp increase of the carrier mobility in the semiconducting $Bi_{1-x}Sb_x$ alloys (of both p and n type), this being due to the strong decrease of the effective masses of the electrons and holes in L - extrema as $\epsilon_g \to 0$. At the same time, the resistivities decrease and the coefficients of transverse

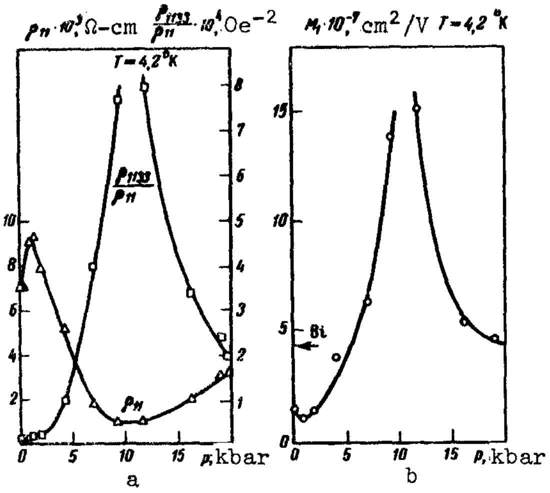


Fig. 2. a) Resistivity ρ_{11} (current parallel to binary axis) and transverse magnetoresistance coefficient $\rho_{11,33}/\rho_{11}$ (field H parallel to trigonal axis) of $Bi_{85}Sb_{15}$ alloy vs. pressure p at T = 4.2°K. b) Electron mobility μ_1 (along the binary axis) of $Bi_{85}Sb_{15}$ alloy (n-type, $N \cong 1 \times 10^{14}$ cm^{-3}) vs. pressure p at T = 4.2°K.

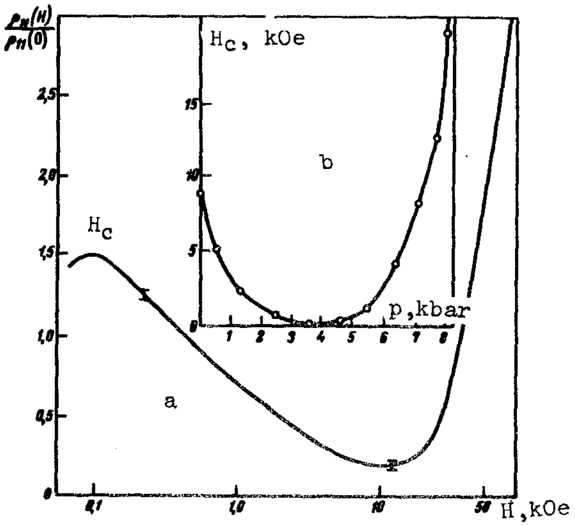


Fig. 3. a) Resistivity $\rho_{11}(H)$, measured along the binary axis in a longitudinal magnetic field H, of $Bi_{91.1}Sb_{8.9}$ alloy vs. H at a pressure $p \cong p^*$ and T = 4.2°K ($p^* \approx 3.2$ kbar). b) Critical field H_c of $Bi_{91.1}Sb_{8.9}$ alloy vs. pressure p at T = 4.2°K.

magnetoresistance increase sharply (Fig. 2a). The magnetic-field region where the condition $\mu H \ll 1$ is satisfied narrows down at $p = p^*$ from 20 - 30 Oe ($p = 1$ bar) to 1 - 2 Oe, from which it follows that at $p = p^*$ the carrier mobilities in the investigated alloys greatly exceed the mobility in pure bismuth [9]. Figure 2b shows the pressure dependence of the electron mobility in L, for an alloy with $x = 0.15$ (n-type), as calculated from the components of the galvanomagnetic tensor.

6. The approach and "reflection" of the extrema at the point L in the $Bi_{1-x}Sb_x$ alloys was observed also in strong magnetic fields (semiconductor - "quasimetal" - semiconductor transitions in a magnetic field) [3]. The longitudinal magnetoresistance passed in this case through a maximum (in a field $H = H_c$), dropped to a value much lower than the value at $H = 0$, and then increased exponentially. The fields required to observe transitions of this type at $\epsilon_g \approx 6$ meV were of the order of 200 - 300 kOe. By applying pressure, it was possible to obtain semiconducting $Bi_{1-x}Sb_x$ with very small ϵ_g and to effect transitions of the indicated type in constant fields of several dozen kOe. Figure 3 shows by way of an example a plot of the longitudinal magnetoresistance against H for $Bi_{1-x}Sb_x$ alloys with $x = 0.089$ at a pressure $p \sim p^*$ and a plot of H_c against p. We see that with increasing p H_c passes through a minimum, thus indicating directly the approach and "reflection" of the bands in L under the influence of the pressure. The character of the obtained relations is in splendid correlation with the results obtained in pulsed fields [3], and is convincing proof of the correctness of their interpretation.

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ELECTRON ENERGY LEVELS AT Z > 137

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As is well known, the solution of the Dirac equation in the field of a point charge Ze is mathematically correct only if $Z < 137$. The energy of the lower level of the discrete spectrum ($n = 1$, $j = 1/2$) is

$$\epsilon_0 = \sqrt{1 - \alpha^2} \qquad (\alpha = Ze^2 = Z/137, \quad \hbar = c = m = 1). \tag{1}$$

ϵ_0 reaches zero when $\alpha = 1$, and the continuation of formula (1) to the region $\alpha > 1$ leads to imaginary values of ϵ_0. When $\alpha > 1$ it is therefore necessary to take into account the finite dimensions of the nucleus. Such a formulation of the problem belongs to Pomeranchuk and Smorodinskii [1], who gave a correct description (from the qualitative point of view) of