# Nonequilibrium metallic state in the alloys $Pb_{1-x}Sn_xTe(In)$

B. A. Akimov, N. B. Brandt, S. A. Bogoslovskiĭ, L. I. Ryabova, and S. M. Chudinov
*M. V. Lomonosov Moscow State University*

(Submitted 18 October 1978)

Piz'ma Zh. Eksp. Teor. Fiz. **29**, No. 1, 11–14 (5 January 1979)

We found that in the alloys $Pb_{1-x}Sn_xTe + 0.5$ at.% In at temperatures below 20 K in a quantizing magnetic field processes involving flow of carriers between the indium level and conduction band are long-term (of the order of several hours). This characteristic permits the attainment of metallic phases in a system with a Fermi surface slowly shrinking with time.

PACS numbers: 71.25.Hc, 71.25.Tn, 71.55.Dp, 72.15.Gd

1. It is known that an external pressure may be used to induce dielectric-dielectric transitions in the alloys $Pb_{1-x}Sn_xTe + 0.5$ at% In ($0.22 \lesssim x \lesssim 0.28$) at $T = 4.2$ K.[1,2] In the dielectric state, the impurity level In [3] lies within the forbidden band $\epsilon_{gL}$, and the carrier concentration in the $L$-bands is dependent only on heat generation and may attain very low values $\sim 10^2$ cm$^{-3}$. The converging and inversion of the $L$-bands under pressure in the range $p_1(x) < p < p_2(x)$ for $x < 0.26$ leads to the overlapping of the indium level and the conduction band (Fig. 1a), and for $x \gtrsim 0.26$, the valence band. The

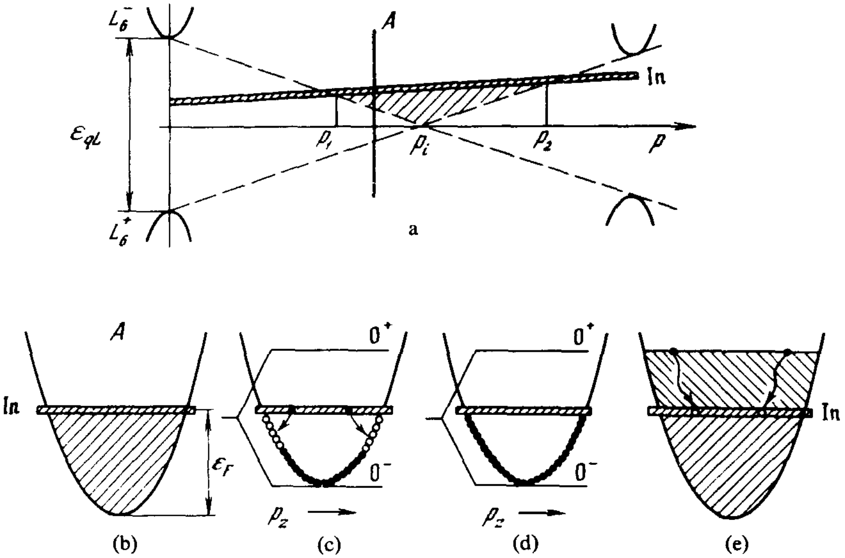

FIG. 1. Energy diagrams showing a production cycle of nonequilibrium metal.

0021-3640/79/010009-04$00.60

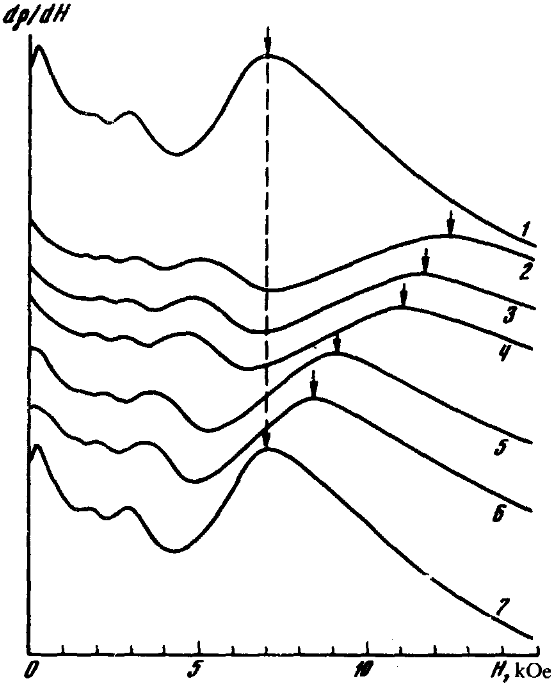

FIG. 2. Recorded oscillations $\partial\rho/\partial H$ for the alloy $Pb_{0.75}Sn_{0.25}Te + 0.5$ at% In at $p = 5.4$ kbar, H|| ⟨100⟩ corresponding to equilibrium (1,7) and nonequilibrium (2–6) states (see text).

Fermi energy of the resultant metal attains a maximum at the point of inversion of bands $p = p_i$.

2. In this work we examine the oscillatory and galvanomagnetic effects in the alloys $Pb_{1-x}Sn_xTe + 0.5$ at% In ($0.22 \lesssim x \lesssim 0.28$) under pressures of up to 18 kbar and in magnetic fields up to 60 kOe and the temperature range 2–50 K. The experimental results are given for the case of an alloy with $x = 0.25$.

Figure 1b shows the energy diagram of an alloy with $x = 0.25$ which is one of the sections (vertical line) of the diagram in Fig. 1a. It shows the respective positions of the conduction band and impurity level at $p = 5.4$ kbar, $T = 4.2$ K and $H = 0$.[11] The carrier concentration in the conduction band under these conditions is $n_0 \approx 4 \times 10^{15}$ cm$^{-3}$. The energy required to overlap the impurity level with the conduction band is comparable to $\epsilon_F \approx 10$ meV. The energy gap $\epsilon_{gL} \approx 20$ meV (valence band not shown in the figure); the effective carrier $g$-factor in the band $\tilde{g} \approx 1.9$.[11] At $T = 2$ K and $H < 10$ kOe the alloy exhibits Shubnikov-deHaas oscillations (S-deH) (Fig. 2, curve 1).

3. At $T \gtrsim 20$ K, the nature of dependence of the Hall potential difference $U_x$ on the magnetic field at H||⟨100⟩ (Fig. 3a, curve 3) agrees with theoretical calculations which take the following circumstances into account. The quantizing of a spectrum in a strong magnetic field occurs only for the electrons in the conduction band since the effective carrier mobility along the impurity level at concentrations of $N_{\mathrm{In}} \sim 10^{19}$ cm$^{-3}$ is $\nu \sim 10^{-5}$ cm$^2$/W. sec. The position of an individual level remains fixed with respect to the center of the forbidden band. Beyond the ultra-quantum limit $H_{\mathrm{uql}}$ of the magnetic fields the last $0^-$ Landau sub-band remains below the Fermi level. The number of states

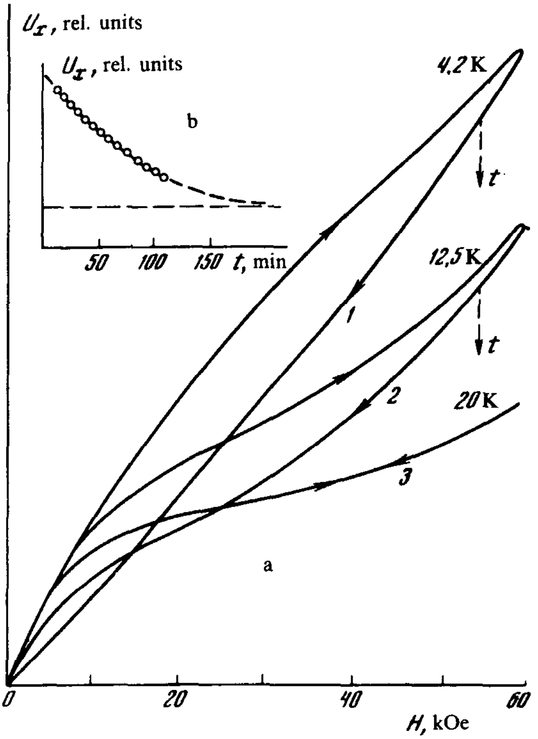

FIG. 3. a—Automatic recording of a function $U_x(H)$ for the alloy $Pb_{0.75}Sn_{0.25}Te$ + 0.5 at% In at $p = 5.4$ kbar, $\mathbf{H} \| \langle 100 \rangle$ and various temperatures; b—temporal dependence of $U_x$ at $H = 60$ kOe, $T = 2$ K.

in this sub-band increases proportionally to $\hbar\omega p_z$ ($\hbar\omega$—cyclotron frequency), resulting in a flow of carriers from the impurity level into sub-band $0^-$. The process of flow into the freed states is shown schematically in Fig. 1c. Increased electron concentration at $H > H_{\text{uql}}$, leads to a discontinuity in the dependence of $U_x$ on $H$ at $H = H_{\text{uql}}$ and a much slower growth of the function in the magnetic field at $H > H_{\text{uql}}$ for $\tilde{g} \approx 1.9$.

The situation changes materially when the temperature drops below $T = T_0 \approx 20$ K. The functions $U_x$ ($H$) exhibit hysteresis (curves 1 and 2 in Fig. 3a) as the field is applied and removed (at a rate 8 kOe/min), which is associated with the fact that the value of $U_x$, at a fixed value of field, slowly decreases with time to an equilibrium value (Fig. 3b). Long-term relaxations in a strong field are observed for all alloys under consideration. The relaxation $\tau$ decreases to $\lesssim 1$ sec as the pressure or temperature increase to $\leqslant 15$ kbar and $T = T_0 \approx 20$ K, respectively (the characteristic temperature $T = T_0$ also decreases with pressure). In weak fields $H \ll H_{\text{uql}}$ (without pre-application of the field) the hysteresis is nonexistent.

The combined results definitely indicate that the observed effects are associated with the process of carrier flow between the impurity level and conduction band, requiring times which, for reasons unclear to us, attain very large values at low temperatures.

4. The effect of long-term carrier flow may be used to produce a nonequilibrium metallic state. At a fixed applied magnetic field $H > H_{\text{uql}}$ the flow process (lasting several hours at $T = 2$ K) may be accelerated by means of a short (~3 min) tempera-

ture surge: 2 K→20 K→2 K. This "freezes" the equilibrium state in the field (Fig. 1d). Since the reverse flow process is also protracted, the concentration $n_H > n_0$ is almost preserved and the Fermi level in the conduction band increases when the field is applied quickly (~3 min) and the temperature fixed at $T = 2$ K (Fig. 1e). Calculations show that at $H = 60$ kOe $n_H \approx 2n_0$. Under these conditions the system is in nonequilibrium and the Fermi surface slowly shrinks. Curve 2 in Fig. 2 corresponds to the initial recording of the S-deH oscillations after completion of the procedures described above. The oscillation period (for curve 2) corresponds to a concentration $n^* \approx 2n_0$. Curves 3–6 were recorded within 5, 10, 30 and 60 min., respectively. The displacement of the oscillation extrema into the region of weaker fields is evident and corresponds to temporal shrinking of the Fermi surface. Curve 7 is a repetition of curve 1 and was obtained after a rapid heating of a sample from 2 K→20 K at $H = 0$, the sample returning to the original equilibrium state (2 K). Thus, production of a nonequilibrium state is a fully reversible cycle.

Clearly, dimensions of a nonequilibrium Fermi surface that is shrinking with time depend, other things being equal, on the magnitude of the applied magnetic field, and may be made very large (in a range up to $n^* \sim N_{\mathrm{In}} \sim 10^{19}$ cm$^{-3}$).

[1] B.A. Akimov, N.B. Brandt, L.I. Ryabova, and S.M. Chudinov, J. de Physique. Colloque C6, suppl. an No. 8 **39**, 1079 (1978).

[2] B.A. Akimov, R.S. Vadkhva, V.P. Zlomanov, L.I. Ryabova, and S.M. Chudinov, Fiz. Tekh. Poluprovodn. **11**, 1077 (1977) [Sov. Phys. Semicond. **11**, 637 (1977)].

[3] A.A. Averkin, V.I. Kaĭdanov, and R.B. Mel'nik, ibid. **5**, 91 (1971) [**5**, 75 (1971)].