Intervalley scattering in bismuth–antimony alloys at 4.2 K

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A sharp decrease in the Dingle temperature has been observed during uniaxial compression in the alloy $Bi_{0.9}Sb_{0.1}$ along the bisector axis. This decrease occurs because the intervalley scattering mechanism turns off upon the transition from a three-valley electron spectrum to a single-valley electron spectrum in the course of the deformation.

In pure bismuth, intervalley transitions are mediated by acoustic phonons with an energy of 40 K. Their component of the scattering falls off exponentially with the temperature, and at 4.2 K the ratio of the relaxation time for intervalley transitions, $\tau_{\rm inter}$, to the momentum relaxation time $\tau_{\rm intra}$ (the momentum relaxation time is associated with intravalley scattering) is $\tau_{\rm inter}/\tau_{\rm intra} \cong 100$. In impure samples and in bismuth–antimony alloys, one can expect $\tau_{\rm inter} \sim \tau_{\rm intra}$ in scattering by neutral impurities (Sb) or point defects even at 4.2 K (Ref. 1). Indirect support for this expectation comes from, for example, the anomalies observed in Ref. 2 on the temperature and concentration dependence of the thermoelectric power and the resistance of tin-doped $Bi_{1-x}Sb_x$ $(0.12 < x < 0.135)$ alloys. Those anomalies are explained under the assumption that there is a finite probability for interband (and therefore intervalley) scattering by neutral antimony impurities even at 4.2 K. In the present study we have succeeded, for the first time, in observing a sharp decrease in the Dingle temperature T_D during uniaxial compression along the bisector (C_1) axis of samples of $Bi_{0.9}Sb_{0.1} + 10^{-4}$ at. % Te due to the turn-off of the intervalley scattering mechanism as a result of a transition from a three-valley electron spectrum to a single-valley spectrum in the course of the deformation.

The energy spectrum of the alloy $Bi_{0.9}Sb_{0.1}$ is determined by three equivalent electron valleys in L, which are separated from corresponding L extrema of the valence band by a direct energy gap $E_{gl} = 14$ meV. The addition of the donor impurity Te results in a slight filling of the electron L extrema with a total electron density $n_e \cong 2\times 10^{16}$ cm^{-3}. Uniaxial compression along C_1 leads to a nonequivalent separation of L_i valleys and to a complete flow of charge carriers to the L_1 extremum at a certain value of the strain ϵ_k (Fig. 1a). At $\epsilon > \epsilon_k$, the energy spectrum becomes a single-valley spectrum.[3]

The Shubnikov–de Haas oscillations were studied as a function of the minimum cross section $S_{\min}$ of the electron "ellipsoid" of the Fermi surface at the L_1 extremum during compression to a strain level $\epsilon \approx 0.3\%$. From the temperature dependence of the oscillation amplitude of the first harmonic,

$$A \sim TH^{-1/2} \exp(-\alpha T_D/H) \sinh^{-1}(\alpha T/H),$$

where $\alpha = 1.469(m_c/m_0)\times 10^5$ G^{-1}, and T_D is the Dingle temperature, we determined the change in the minimum cyclotron mass $m_c^{\min}$ with the strain (Fig. 1b). From this information we can in turn calculate the corresponding change in $T_D(\epsilon)$. Figure 2a shows a series of linear plots of $\ln[AH^{1/2}\sinh(\alpha T/H)]$ versus $1/H$ for various strain levels. The slope of these plots directly yields αT_D.

As the carriers overflow to the L_1 extremum (Fig. 1a), the cross section $S_{\min}$ of the L_1 "ellipsoid" and the cyclotron masses m_c at this cross section increase up to the point ϵ_k and then stabilize (Figs. 1b and 2b). The Fermi level E_F at L_1 for the typical sample to which the results in Figs. 1 and 2 correspond increases from 8.4 to

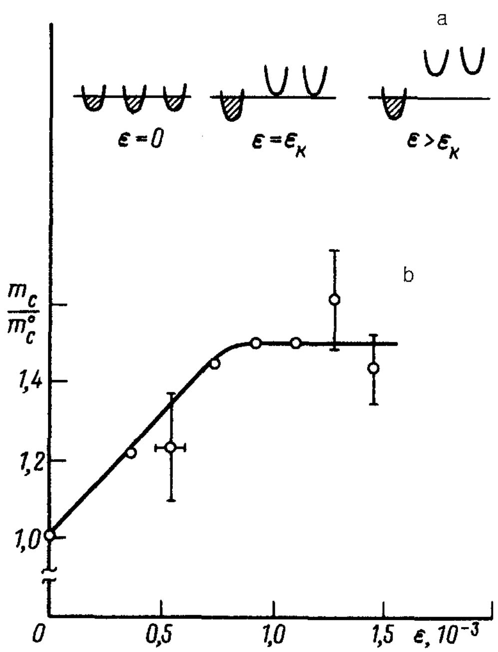

FIG. 1. a—Shift of the electronic extrema of $Bi_{0.9}Sb_{0.1}$ (Te) during compression along the C_1 axis; b—change in the cyclotron mass at the minimum cross section with the strain.

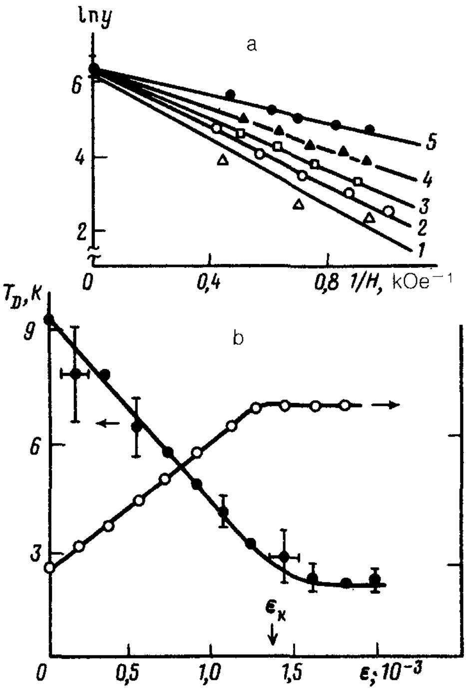

FIG. 2. a—Dingle plots for various compressional strain levels. *1*—$e = 0$; *2*—0.7×10^{-3}; *3*—0.9×10^{-3}; *4*—1.5×10^{-3}; *5*—1.8×10^{-3} b—Dingle temperature (scale at left) and relative size of the maximum cross section of the Fermi surface (scale at right) versus the compressional strain level.

15.8 meV. During the compression T_D drops sharply (Fig. 2b): $T_D(0)/T_D(\epsilon_k) = 4.2$ [$T_D(0)$ is the Dingle temperature in the absence of deformation, and $T_D(\epsilon_k)$ is the value after the transition to a single-valley spectrum].

The Dingle temperature $T_D = \hbar/(2\pi k \tau_D)$ (τ_D is a characteristic relaxation time and k is the Boltzmann constant) determines the broadening of the Landau levels due to the carrier scattering by impurities and lattice defects. The scattering probability $1/\tau_D$ which is proportional to the Dingle temperature, is the average over the extremal orbit of the Fermi surface, normal to the direction of magnetic field **H**. In the scattering of free electrons by a screened Coulomb potential, the scattering probability $1/\tau_\rho$, determined by the resistivity ρ, is related to $1/\tau_D$ by[4]

$$\tau_D / \tau_\rho = (u-1)\{ \frac{1}{2}(u+1)\ln[(u+1)/(u-1)] - 1 \}, \qquad (1)$$

where $u = 1 + q^2/(2k_F^2)$, $1/q$ is the screening length, and k_F is the Fermi radius ($0 < \tau_D/\tau_\rho < 1$, and τ_D/τ_ρ decreases with increasing k_F). This relation reflects the predominance of a large-angle scattering in the resistivity. This relation holds for metals with a nearly spherical Fermi surface, and in the case of $Bi_{1-x}Sb_x$ it can be used only for a limiting estimate. Under the assumption that the relation $\tau_D/\tau_\rho < 1$, always holds because of the pronounced sensitivity of τ_D to small-angle scattering, and under the assumption that the decrease in this ratio with increasing Fermi surface, which follows from (1), always occurs in the case of an anisotropic dispersion law, we find the inequality

$$T_D(0)/T_D(\epsilon_k)=\tau_D(\epsilon_k)/\tau_D(0)\leqslant\tau_\rho(\epsilon_k)/\tau_\rho(0), \quad (2)$$

where the strain interval $0<\epsilon<\epsilon_k$ corresponds to the increase in E_F from 8.4 to 15.8 meV observed in the present experiments. While at $\epsilon=0$ there is only an intravalley scattering, which is determined primarily by scattering by an ionized impurity $(1/\tau_\rho\approx 1/\tau_{\rm ion})$ in $Bi_{1-x}Sb_x$ at 4.2 K according to Refs. 5 and 6, we have $\tau_\rho(\epsilon_k)/\tau_\rho(0)=3.2$ at the point of the carrier overflow to the L_1 extremum in view of the known energy dependence $\tau_{\rm ion}\sim[m^*(E_F)]^{1/2}E_F^{3/2}\Phi(E_F)$ [$\Phi(E_F)$ is a slowly varying function]. This is an "upper estimate" of $\tau_\rho(E_F)$, since the introduction of energy-independent scattering processes $(1/\tau_\rho=1/\tau_{\rm ion}+1/\tau_0)$ will only reduce the ratio $\tau_\rho(\epsilon_k)/\tau_\rho(0)$. In view of inequality (2), one might assert that the increase in the electron energy upon the overflow into one valley could not explain the increase $T_D(0)/T_D(\epsilon_k)=4.2$.

To reconcile the results with the experimental results, we are left with the assumption that at $\epsilon=0$ there is an intervalley scattering mechanism, which fades away as the $L_{2,3}$ valleys "escape" above the Fermi level at $\epsilon>\epsilon_k$ (Fig. 1a). In this case, at a zero strain we would have $1/\tau_\rho=1/\tau_{\rm intra}+1/\tau_{\rm inter}$, where $1/\tau_{\rm intra}=1/\tau_{\rm ion}+1/\tau_0$ is determined by the value of $1/\tau_{\rm ion}$ (Refs. 5 and 6) [scattering by phonons can be ignored at $T\leqslant 4.2$ K, since the relation $(\rho_{4.2}-\rho_{1.5})/\rho_{4.2}\sim 10^{-2}$ holds for the test samples]. According to inequality (2), we have $\tau_\rho(\epsilon_k)/\tau_\rho(0)=[1/\tau_{\rm intra}(0)+1/\tau_{\rm inter}(0)]/[1/\tau_{\rm intra}(\epsilon_k)]\geqslant 4.2$. For the most probable relation between $1/\tau_0$ and $1/\tau_{\rm ion}$, which would lie in the interval[6] $0\leqslant 1/\tau_0\leqslant 0.5/\tau_{\rm ion}$, the relation between the intravalley and intervalley scattering processes at $\epsilon=0$ is $0.8\leqslant(1/\tau_{\rm intra})/(1/\tau_{\rm inter})\leqslant 3.3$.

To the best of our knowledge, this estimate is the first direct evidence in favor of a significant role of intervalley transitions in Bi–Sb alloys at 4.2 K. This piece of evidence should be taken into account in calculations of the kinetic characteristics in these alloys. In addition to the data of Ref. 5, however, there is other evidence for the existence of such transitions: the observation of an anomalous thermoelectric power in these $Bi_{0.9}Sb_{0.1}$ (Te) alloys during topological electron Lifshitz transitions corresponding to the "nucleation of a new cavity of the Fermi surface,"[7] since the structural feature in the thermoelectric power in this case is formed by electrons from other regions of the Fermi surface.[8] In other words, an intervalley scattering is assumed at the outset. This fact is also indicated by the calculations of Ref. 9.

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