Relaxation time of the interband scattering of L_s holes in the alloy p-$Bi_{0.88}Sb_{0.12}$

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The relaxation times have been determined for the interband and intraband scattering of carriers ($\tau_{\text{interb}}/\tau_{\text{intrab}} \simeq 0.2$) in the alloy p-$Bi_{0.85}Sb_{0.12}$. These results were found through an analysis of certain anomalies in the behavior of the thermoelectric power [$\alpha_{22}(E_{FL})$] and the resistivity [$(\rho_{22}(E_{FL})$]. These anomalies are caused by an interband scattering of carriers by the ground hole band L_s into a heavy hole band Σ upon a topological electronic transition. The analysis is also based on the behavior of $|\alpha_{22}(E_{FL})|$ and $\rho_{22}(E_{FL})$ in the absence of this topological electronic transition in the alloy n-$Bi_{0.88}Sb_{0.12}$, in which the L_a conduction band is the mirror image of the L_s valence band.

In the valence band of $Bi_{1-x}Sb_x$ ($0 \leqslant x \leqslant 0.15$) alloys, the extrema corresponding to light holes (L_s) and heavy holes (Σ) are close together along the energy scale. The stage is thus set for a topological electronic transition when the alloy is doped with an acceptor impurity (Sn). In this case the Fermi level of the L_s band begins to pass through the Σ band also.[1,2] The anomalies which arise on plots of the thermoelectric power and the resistivity versus the Fermi energy of the L_s holes in the course of the topological electronic transition were utilized in Refs. 1 and 2 to determine the energy position of the heavy hole band, Σ. According to the theoretical analysis of the topological electronic transition carried out in Refs. 1 and 3, the anomalous behavior of the thermal emf and the resistivity during this transition occurs because a new scattering channel opens up for the majority charge carriers: interband (or intervalley) scattering. This conclusion agrees with the conclusions reached in experimental studies.[1,2,4] An analysis[4] of the Dingle temperature for n-type $Bi_{0.9}Sb_{0.1}$ in experiments on uniaxial compression has yielded an estimate of the ratio of relaxation times for intervalley scattering ($L_a^{1,2} \rightleftarrows L_a^3$), τ_{interv}, and intravalley scattering, τ_{intrav}, of electrons in L_a^i valleys: $0.8 \leqslant \tau_{\text{intrav}}^{-1}/\tau_{\text{interv}}^{-1} \leqslant 3.3$. In the present paper we calculate the relaxation times of interband and intraband scattering (τ_{interb} and τ_{intrab}, respectively) of charge carriers for the case of a valence band. This calculation is made by comparing the results on the thermoelectric power and the resistivity in n-type and p-type $Bi_{0.88}Sb_{0.12}$ for identical Fermi energies of the L_s holes and the L_a electrons.

1. The components of the thermoelectric power, $\alpha_{22}(E_{FL})$, and the resistivity, $\rho_{22}(E_{FL})$, in n-type and p-type alloys ($\mathbf{j} \| \nabla \mathbf{T} \| c_1$) with a carrier Fermi energy $1 < E_{FL} < 30$ meV were measured over a broad temperature range (2–100 K) on single-crystal samples. These samples were rectangular parallelepipeds with dimensions $\sim 3 \times 3 \times 30$ mm. Figure 1 shows the thermoelectric power $\alpha_{22}(E_{FL})$ (line *1*, which becomes line *2* at $E_{FL} > 15$ meV) and the resistivity $\rho_{22}(E_{FL})$ (line *3*, which becomes line *4* at $E_{FL} > 15$ meV) versus the Fermi energy E_{FL} for the light L_s holes of the alloy

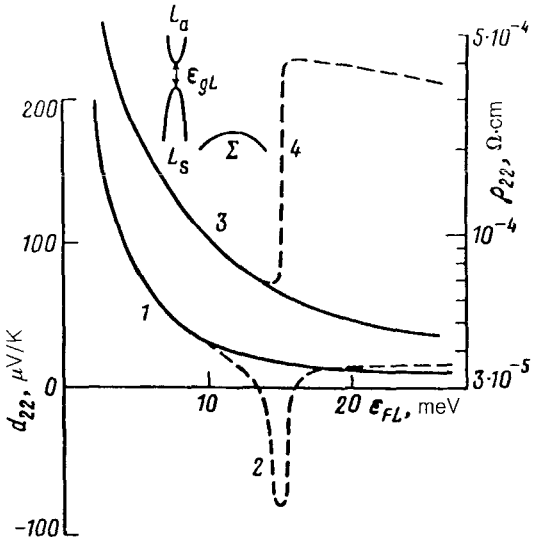

FIG. 1. The thermoelectric power α_{22} at $T = 12$ K and the resistivity ρ_{22} at $T = 4$ K for n-type and p-type $Bi_{0.88}Sb_{0.12}$ ($\mathbf{j} \| \nabla \mathbf{T} \| c_1$) versus the Fermi energy E_{FL}. 1—The absolute value of the thermoelectric power, $|\alpha_{22}^n(E_{FL})|$ for the alloy n-$Bi_{0.88}Sb_{0.12}$ (solid line); 2—the thermoelectric power $\alpha_{22}^p(E_{FL})$ for the alloy p-$Bi_{0.88}Sb_{0.12}$ ($\alpha_{22}^p(E_{FL}) \simeq |\alpha_{22}^n(E_{FL})|$ at $E_{FL} < 15$ meV); 3, 4—the resistivity for the alloy n-$Bi_{0.88}Sb_{0.12}$ (solid line) and for the alloy p-$Bi_{0.88}Sb_{0.12}$ (dashed line, $\rho_{22}^p(E_{FL}) \simeq \rho_{22}^n(E_{FL})$ at $E_{FL} < 15$ meV). Shown at the top is an energy diagram of the L_a, L_s, Σ extrema for the semiconducting alloy $Bi_{0.88}Sb_{0.12}$ with an energy gap $E_{gL} \simeq 17.2$ meV.

p-$Bi_{0.88}Sb_{0.12}$. We are also reporting data on the behavior of the absolute value of the thermoelectric power, $|\alpha_{22}(E_{FL})|$ (solid line *1*), and the resistivity $\rho_{22}(E_{FL})$ (solid line *3*) of the alloy n-$Bi_{0.88}Sb_{0.12}$ for the case in which only the electrons of the L_a band participate in transport processes. The L_a and L_s zones in the n-type and p-type $Bi_{0.88}Sb_{0.12}$ can be regarded as approximately mirror images of each other, with a small mass of the density of states at the bottom of the conduction band, $m_{dL}(0) \simeq 0.036m_0$. For the heavy hole band, on the other hand, we have $\Sigma m_{d\Sigma} \simeq 0.9m_0$. Figure 1 also shows an energy diagram of the arrangement of the L_a, L_s, and Σ extrema in the alloy. In the n-type $Bi_{0.88}Sb_{0.12}$ alloys (doped with a donor impurity, Te) the Fermi level lies in the L_a conduction band. In the p-type alloys (doped with an acceptor impurity, Sn), the Fermi level is in the L_s valence band or passes through both the valence subbands, L_s and Σ. The energy separation of the edges of the L_s and Σ bands in the alloy $Bi_{0.88}Sb_{0.12}$ is $E_0 \simeq 15.5$ meV.

2. The data on $|\alpha_{22}(E_{FL})|$ and $\rho_{22}(E_{FL})$ in the n-type and p-type alloys at energies below 15 meV conform to a common curve as a function of the energy. A pronounced difference is observed near the energy $E_{FL} \sim 15$ meV. In the alloy n-$Bi_{0.88}Sb_{0.12}$, the thermoelectric power satisfies $|\alpha_{22}(E_{FL})| \sim k_0T/E_{FL}$, and the resistivity continues to decrease monotonically, without any structural features. In the alloy p-$Bi_{0.88}Sb_{0.12}$, a topological electronic transition is observed near $E_{FL} \simeq 15$ meV. This transition results in an anomalous increase in the resistivity, by a factor ~ 6,

while the thermoelectric power changes sign, from positive to negative, within $\sim k_0 T$. Later, at $E_{FL} > 15$ meV, it goes back to approximately its original value. In the region of the transition the absolute value of the anomaly in the thermoelectric power, $|\Delta\alpha|$, is greater than the thermoelectric power before the transition: $|\Delta\alpha|/|\alpha_{22}| \simeq 5$.

3. Note that the sign of the thermoelectric power at a nonzero temperature, $\alpha \sim \langle (E - E_{FT})\tau \rangle$, in a conductor is determined by the relation between the contributions from the charge carriers which occupy states as the result of a temperature-induced smearing of $k_0 T$ above and below the Fermi surface. The sign of α far from the topological electronic transition is determined by the circumstance that charge carriers above the Fermi surface make a large contribution to the thermoelectric power. For a hole conductor, this contribution would be positive, while for an electron conductor it would be negative; these are the results that are seen experimentally. As the Fermi level approaches the edge of the new cavity, the carriers above the Fermi surface become involved in interband scattering. The relaxation time for these charge carriers decreases, while that for the carriers below the Fermi surface remains the same. The result is the anomalous change in the sign of the thermoelectric power.[3] With a further increase in E_{FL}, the thermoelectric power exhibits the normal behavior, since all the carriers, both below and above the Fermi surface, experience an interband scattering. In the case at hand, the absolute values of the thermoelectric power for the n-type and p-type $Bi_{0.88}Sb_{0.12}$ differ only slightly for $15 < E_{FL} < 20$ meV (Fig. 1). At the beginning of the topological transition, the thermoelectric power of the p-type alloy is dominated by the light L_s holes, since for these holes we have $\sigma_L \gg \sigma_\Sigma$ and $\alpha = (\alpha_L \sigma_L + \alpha_\Sigma \sigma_\Sigma)/(\sigma_L + \sigma_\Sigma) \simeq \alpha_L$, where α_i and σ_i are the partial values of the thermoelectric power and of the conductivity for light holes (L_s) and heavy holes (Σ). With increasing density of heavy holes ($E_{FL} > 20$ meV), σ_Σ increases and their contribution to the thermoelectric power and to the resistivity becomes significant. Accordingly, the value of the thermoelectric power for the p-type alloy at $E_{FL} > 20$ meV found experimentally is slightly larger than that for the n-type alloy, and the resistivity decreases.

4. We should also point out that the resistivity in the p-type alloy remains anomalously large at $E_{FL} > 15$ meV, since interband scattering continues to limit the conductivity of the charge carriers. While the majority carriers in the alloy p-$Bi_{0.88}Sb_{0.12}$ (light holes, L_s) undergo interband and intraband scattering during the topological transition ($\tau^{-1} = \tau_{\text{intrab}}^{-1} + \tau_{\text{interb}}^{-1}$), the L_a electrons in the alloy n-$Bi_{0.88}Sb_{0.12}$ experience only an intraband scattering. We assume that the relaxation time for the intraband scattering of the light L_s holes in the p-type alloy upon the topological transition remains equal to the relaxation time for the intraband scattering of L_α electrons in the n-type alloy, as at $E_{FL} < 15$ meV. We can work from the value of the resistivity $\rho = m_{dL}(E_{FL})\tau^{-1}/ne^2$ in the n-type and p-type alloys at $E_{FL} \geqslant 15.5$ meV to calculate the relaxation times for interband and intraband scattering: $\tau_{\text{intrab}}^{-1} = \rho_{22}^n ne^2/m_{dL}(E_{FL})$ and $\tau_{\text{interb}}^{-1} = \rho_{22}^p pe^2/m_{dL}(E_{FL}) - \tau_{\text{intrab}}^{-1}$. Here $m_{dL}(E_{FL}) = m_{dL}(0)(1 + 2E_{FL}/E_{gL})$. The mass of the density of electron states at the bottom of the conduction band, $m_{dL}(0) = 3^{2/3}(m_1 m_2 m_3)^{1/3} \simeq 0.036 m_0$, was determined from the parameters of the electron energy spectrum of the alloy $Bi_{0.88}Sb_{0.12}$ (Ref. 5): $E_{FL}/E_{gL}((1 + 2\hbar^2(3\pi^2 n)^{2/3}/m_{dL}(0)E_{gL})^{1/2} - 1)/2$. For $E_{FL} = 16$ meV, a calculation yields $\tau_{\text{intrab}}^{-1} \simeq 2.8 \times 10^{10}$ s^{-1} and $\tau_{\text{interb}}^{-1} \simeq 1.6 \times 10^{11}$ s^{-1}. The relaxation

time for the interband scattering of charge carriers can also be estimated from the value of the thermoelectric power in the vicinity of the topological transition.[3] According to Ref. 3, we have $|\Delta\alpha|/|\alpha_{22}| \sim (E_0/h\cdot\tau_{\text{interb}}^{-1})^{1/2}$, where E_0 is the energy separation of the edges of the L_s and Σ bands. The values found for the relaxation time of the interband scattering from the anomaly in the thermoelectric power and from that in the resistivity are in fairly good agreement.

In summary, a comparison of the results found on *n*-type and *p*-type $Bi_{0.88}Sb_{0.12}$ shows that an interband scattering of light and heavy holes ($L_s \rightleftarrows \Sigma$) inside the valence band near the topological electronic transition plays an important role for transport phenomena. These results can be used to determine the corresponding relaxation times for interband and intraband scattering of L_s holes. We find a ratio $\tau_{\text{interb}}/\tau_{\text{intrab}} \simeq 0.2$.

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