Quantum oscillations of the longitudinal thermoelectromotive force (α_{33}) in bismuth

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Quantum oscillations in the longitudinal thermoelectromotive force α_{33} in bismuth and in the alloy $Bi_{97}Sb_3$ at $T = 7.7$ K are explained in terms of an interband scattering of L electrons into a quantized H hole band. The interband scattering parameter is evaluated.

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Galev *et al.*[1] have observed quantum oscillations of the longitudinal thermoelectromotive force (α_{33}) in bismuth and in the semimetallic alloy $Bi_{97}Sb_3$ at a frequency determined by the cyclotron mass of the holes. They attributed these oscillations to an oscillatory hole component of the overall thermoelectromotive force. However, the hole component of the conductivity along the particular observation direction involved (along the trigonal axis) is known to be negligible. In the present letter we wish to propose a different explanation for the experiments of Galev *et al.*[1]

In addition to participating directly in the transport processes in semimetals, the holes affect the transport coefficients by scattering the electrons. A substantial fraction of the electron scattering in bismuth is known to be interband scattering: the recombination of light (L) electrons and heavy (H) holes.[2] In quantizing magnetic fields, the oscillation of the hole-state density at the Fermi level and the associated oscillation of the electron relaxation time during scattering into the hole band should lead to corresponding oscillations in the kinetic coefficients. The oscillation should be particularly clear in the thermoelectromotive force, which, in the highly degenerate case, is the difference between two large quantities: the thermoelectromotive force of electrons with energies above the Fermi level and that of electrons below the Fermi level.

Interband scattering in a semimetal does not require an energy transfer, but it does require the transfer of a substantial momentum, corresponding in this case to the L-H distance in the Brillouin zone. The corresponding phonon has an energy of 43 K (Ref. 2) and cannot play any important role at the measurement temperature (7.7 K). The electron-hole recombination apparently involves scattering by an impurity. Lopez[2] has reported evidence for impurity scattering in bismuth.

Since the extrema of the valence and conduction bands lie at singularities of the Brillouin zone, the interband scattering is determined by the corresponding selection rules for the matrix elements. For impurity scattering, for example, we would have $\langle T_{45}^- | V_{\rm imp} | L_s \rangle = 0$, while for scattering by X acoustic phonons we would have $\langle T_{45}^- | V_{X\text{-ph}} | L_s \rangle \neq 0$. Since the condition $\zeta_n \gg E_g$ holds for intrinsic bismuth, these selection rules are not important.

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To describe the electron scattering, we assume that

$$\frac{1}{\tau} = \frac{2\pi}{\hbar} \{ |M_{LL}|^2 \rho_e + |M_{LH}|^2 \rho_h \}, \tag{1}$$

where M_{LL} and M_{LH} are the scattering matrix elements corresponding to intraband and interband scattering, respectively. We are ignoring the energy dependence of the matrix elements. In a quantizing magnetic field ($\mathbf{H} \| C^3$) we have

$$\rho_h = \frac{(2M_{\|})^{1/2} M_{\perp} \omega_c}{(2\pi\hbar)^2} \sum_{N=0}^{N_{max}} \left[(E_G - E) - \left(N + \frac{1}{2}\right)\hbar\omega_c \pm m_s g \mu_0 H \right]^{-1/2}, \tag{2}$$

where E_G is the semimetal energy gap, E is the electron energy, reckoned from the bottom of the band, and ω_c is the hole cyclotron frequency in a magnetic field directed along the trigonal axis. Spin splitting has essentially no effect on the results because the hole $g_{\rm eff}$ factor is approximately 4.[3]

The quantization of the electron orbits in the magnetic field is of secondary importance, for the following reason: Because of the relatively low state-density mass, the Fermi level corresponds to a relatively high-index Landau level, and the oscillation of the electron state density at the Fermi level is much less pronounced than the oscillation of the hole state density. For ρ_e we have used the customary expression for the state density in the Lex model. The parameters of the bismuth band structure were taken from Ref. 3.

We have ignored both the quantization of the electron orbits and the motion of the Fermi level in the magnetic field, so that our results do not apply to the extreme quantum limit; the calculations were accordingly carried out only for magnetic fields up to a certain limit ($H < 50$ kOe). The only adjustable parameter in the calculations was the ratio of scattering matrix elements, which determines the oscillation ampli-

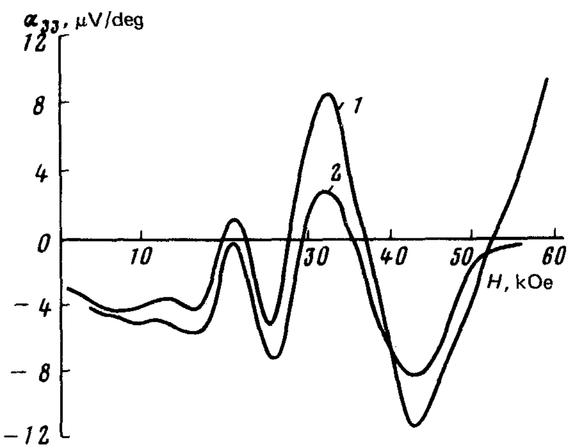

FIG. 1. Dependence of the thermoelectromotive force of bismuth (T = 7.7 K) on the longitudinal magnetic field $H \| C_3 \| \nabla T$. 1) Experimental; 2) calculated.

tude. The best agreement between the calculated and measured oscillation amplitudes was found with the ratio $|M_{LH}|2|M_{LL}|^2 \sim 0.08$. The results calculated for this value are shown in Fig. 1. The good agreement is convincing evidence that interband scattering is important in the quantum oscillations of the longitudinal thermoelectromotive force.

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