Quantum oscillations of Bi and alloy BiSb magnetoresistance in magnetic fields up to 33 T

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Abstract

The special quantum oscillations of bismuth magnetoresistance have been considered. In contrast to Shubnikov-de Haas (SdH) oscillations observed at temperature less than 4K, the oscillations were detected in the temperature range 6-65 K and were referred to as "high-temperature" oscillations (HTO). The results of joint studies of SdH oscillations and HTO of the magnetoresistance for pure Bi and alloy $Bi_{1-x}Sb_x$ (x=2.6 at.%) in stationary magnetic field up to 33 T are presented. It was found that SdH oscillations and HTO reached its quantum limit at the same value of magnetic field. The analysis of the experimental data verified one of two alternative models of HTO.

Key words: bismuth; magnetoresistance; quantum limit

A new type of quantum oscillations of static conductivity of bismuth in a magnetic field has been considered. These oscillations are periodic in reciprocal magnetic field and are characterized by a frequency higher than that of Shubnikov-de Haas (SdH) oscillations. In contrast to SdH oscillations observed at temperature $T \leq 4\ K$, the oscillations were detected in the temperature range 6-65K and were referred to as "high-temperature" oscillations (HTO)[1]. HTO are investigated on bismuth samples of various quality, in compensated alloys $Bi_{1-x}Sb_x$ and in not compensated alloys $Bi_{1-x}(Sb,Te,\ Sn)_x$. The thermo-emf HTO in a magnetic field has also been studied. HTO differ basically from SdH oscillations in peculiar temperature dependence: the HTO amplitude rapidly attains its peak value at $T \approx (10-12)K$ and then decreases slowly upon heating. It was found [2] that the existence of a peak on the HTO amplitude temperature dependence is determined by frequency intergroup electron-hole transitions associated with inelastic scattering by acoustic phonons. The characteristic feature of HTO distinguishing them from other quantum oscillations in a magnetic field is the independence of the HTO frequency F of the Fermi energy ϵ_F. It was found that $F^{HTO} \propto \epsilon_F^e + \epsilon_F^h = \epsilon_p$ (ϵ_F^e and ϵ_F^h are the Fermi energy of electrons and holes and ϵ_p is of the energy bands overlapping region).

Recently two alternative models tried to explain qualitatively of the HTO nature.

1. HTO emerge due to the electron-hole transitions near the boundaries of the energy bands [3]. Every time the Landau subband extremum for the hole (electron) band of the spectrum appears near the bottom of the conduction (valence) band, the collision frequency suffers a discontinuity because the density of electron states below the bottom of the conduction band is equal to zero. Authors [3] suppose that in the temperature region $T << \epsilon_F/k_B$ the number of unoccupied states below the Fermi level (and the number of occupied states above ϵ_F) is not exponentially small but one is determined by the broadening of the energy levels due to relaxation processes (both elastic and inelastic).

2. Oscillations of conductivity are a result of electron-hole transitions close to a Fermi level [4]. The necessary condition for HTO appearance is that the effective electron and hole masses must be commensurable ($km_e^* = k'm_h^*$ with integers k and k'). In this case the appropriate extrema of electron and hole

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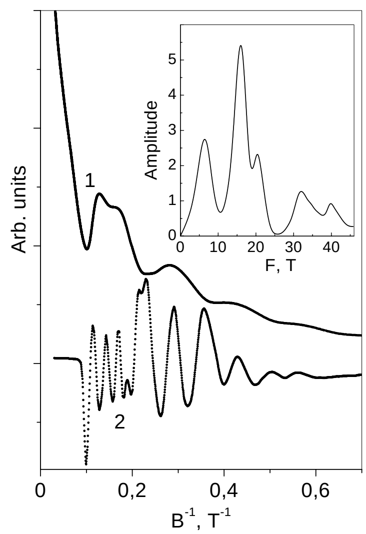

Fig. 1. Dependences of $\rho_{yx}(1/B)$ in bismuth at 4.3 K (curve 1) and $\rho''_{yx}(1/B)$ at 15 K (curve 2), $\mathbf{B} \parallel C_3$. In the insert: frequency spectrum of oscillations at 15 K.

Landau subbands have a simultaneous tangent in the vicinity of the Fermi level.

It seems that for final conclusions concerning the HTO physical nature it is necessary to a set of joint measurements of SdH hole oscillations and hole HTO in a Bi and alloy BiSb in strong magnetic fields up to 30-40 T. SdH hole oscillations reached its quantum limit when magnetic fields is so high. Under these conditions according to the hole HTO behavior it will be possible to obtain the appropriate conclusions on their nature.

The measurements of SdH oscillations and HTO were made in stationary magnetic fields up to 33 T on pure Bi and alloy $Bi_{1-X}Sb_X$ (x =2.6 at.%) samples under the conditions when $I \parallel C_1$ (or C_2), $B \perp C_1$ (or C_2) (I is the current; C_3, C_2 and C_1 - trigonal, binary and bisector crystallographic axes, respectively). Both diagonal, ρ_{ii}, and nondiagonal, ρ_{ik}, components of the tensor were measured. All measurements were taken using low frequency ac techniques. The experimental results on Bi sample for SdH oscillations (4.3 K) and HTO (20 K) are presented in Fig.1. In the temperatures 4 - 15 K SdH oscillations prevail in the dependencies ρ_{ik}(H), while HTO dominate above ≈15 K.

In the Fig. 1 we can see dependence of $\rho_{yx}(B^{-1})$ at 4.3 K (curve 1) and $\rho''_{yx}(B^{-1})$ at 15 K (curve 2) received on the bismuth sample when magnetic field align with trigonal crystallographic axes, $B \parallel C_3$. The SdH oscillations period as a function of the inverse magnetic field is $P_h^{SdH} = 0.155\ T^{-1}$ (or frequency is $F_h^{SdH} = 6.45$ T). This value corresponds to the area of the extremal section of the hole Fermi surface. Fourier analysis of oscillations on curve 2 indicates the presence SdH periods for holes $P_h^{SdH} = 0.155\ T^{-1}$ as well as HTO periods $P_1^{HTO} = 0.062\ T^{-1}$ ($F_1^{HTO} = 16$ T) and $P_2^{HTO} = 0.051\ T^{-1}$ ($F_2^{HTO} = 19.8$ T) (see frequency spectrum of oscillations in inset to Fig.1). The frequency of oscillations also displays second harmonics of fundamental frequencies $2F_1^{HTO} = 32$ T and $2F_2^{HTO} = 39.6$ T. The occurence of the second HTO harmonic is easily seen in the curve 2 in Fig. 1: beginning with $B \approx 4.3$ T the HTO frequency increases by a factor of two.

In the experiments under consideration the quantum limit $\hbar\Omega_c > \epsilon_F^e$ (or ϵ_F^h) at high magnetic fields is realized for different ratio between spectral parameters of electrons and holes in bismuth and $Bi_{1-X}Sb_X$. While for $\mathbf{B}$ oriented in the vicinity of C_3 the electron Fermi energy increases and Fermi energy of holes decreases with increasing magnetic field, for $\mathbf{B}$ oriented in the vicinity of C_2 this is directly opposite. In all cases the last HTO minimum coincides with the quantum limit magnetic field B_{QL} for the SdH oscillations. This behavior of HTO is typical of the oscillation mechanism proposed in [4]. According to [4], the HTO are nominally the SdH oscillations but with due regard for interband transitions nearby the Fermi level followed by a change of sign of the effective mass. In this case it is reasonable that the quantum limit for SdH oscillations of both electrons and holes is bound to show itself also in HTO in the same way. It is particularly remarkable that the last minimum of HTO, which are a collective electron-hole effect, coincides with field B_{QL} of either electrons or holes depending on experimental conditions. At the same time, the model proposed in [3] predicts observable HTO until the condition $\hbar\Omega_c > \epsilon_F^e + \epsilon_F^h$ is fulfilled. It is evident that this condition corresponds to magnetic fields much higher than that observed in the present paper.

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References

[1] Yu. A. Bogod, Vit. B. Krasovitsky, and S. A. Mironov, Sov.Phys. JETP **51,** (1980) 554.

[2] Yu. A. Bogod, and Vit. B. Krasovitsky, Sov. J. Low Temp. Phys. **16,** (1990) 527.

[3] Yu. A. Bogod, Sov. J. Low Temp. Phys. **12,** (1986) 569.

[4] V. M. Polianovskii, Ukr. Fiz. Zh. **34,** (1989) 459.