Electron-electron interaction in thin bismuth films

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The temperature dependence of quantum corrections to conductivity, which are due to the weak localization (WL) of electrons and electron-electron interaction (EEI), has been studied for thin Bi films. A change of the total quantum correction has been determined as well as the components related to WL and EEI under the action of an electric field associated with a high-density current flowing through the film. The quantum corrections are found to decrease with an increase in the current during electron overheating. However, the change in the quantum correction related to EEI is caused not only by the heating but also by a change in the electron interaction. This effect is considered together with a similar effect that shows itself as a change in the contribution of quantum corrections to the Bi-film magnetoresistance under the action of an electric field.

I. THE GOAL OF INVESTIGATION

It was found in Ref. 1 that in thin Bi films (~ 100 Å) the magnetic-field dependence of quantum corrections to the conductivity, which are related to the effects of weak electron localization[2-4] (WL) and the electron-electron interaction (EEI),[5-9] change considerably as the density of the current flowing through the film increases. With a weak current the quantum correction to the magnetoconductivity is only dependent on the WL effect.[1,10] With a strong current ($\sim 10^2-10^4$ A cm^{-2}, which corresponds to an electric-field strength 0.1–60 V cm^{-1}) the shape of the magnetoresistance (MR) curves changes:[1] a maximum appears that is shifted toward low magnetic fields as the current increases, and, negative MR is observed. The correct allowance for the electron heating shows that this is not the only factor influencing the localization correction: the magnetoconductivity also contains a contribution from the component related to the EEI. It is found that this correction increases with the electric field, which indicates that the interaction constant λ_H^D grows as the electron energy increases.

The finding in Ref. 1 calls for an independent check of the conclusion about the influence of the energy of the electrons in Bi films on the nature of their interaction. In addition to the magnetoconductivity, the EEI, along with WL, influences quantum corrections to the temperature dependence of the conductivity. The corresponding interaction constant λ_T^D responsible for the temperature variation of the quantum correction to the EEI in a diffusion channel is not identical with λ_H^D, but it should also be sensitive to the electron energy if the effect mentioned exists.

This work was restrictively aimed at studying the influence of the electric field excited by a strong current upon the temperature behavior of the quantum corrections to the conductivity of thin Bi films (below referred to as localization or Coulomb corrections). The central methodical problem arising on approaching this goal requires correct separation of the WL and EEI effects in the total quantum correction to the temperature dependence of the film conductivity. Here the technique that was tried in Ref. 11 may be used: the temperature variations of the film conductivity are compared in zero and strong magnetic fields. In the latter case the localization correction is suppressed. The shape of the localization correction may be found using another independent procedure: calculation from the data for the phase-electron relaxation time τ_φ by the formulas given below.

There may be two reasons for the influence of a strong electric field on each of the quantum corrections. (i) Variations of the quantum corrections may be caused by the rising temperature of the electrons (the electron overheating effect[12,13]) or by the rising temperature of the electrons and phonons (Joule heating). (ii) A direct influence of the electric field on the quantum correction is possible. The direct influence of the electric field upon the WL effect is discussed in the literature,[14-17] but related theoretical concepts are inconsistent. There is a qualitative interpretation of the electric-field effect on the Coulomb correction,[18] but a rigorous theory is so far lacking.

The influence of the electron-overheating effect can be determined accurately if the shape of the temperature dependence is known for the electron-phonon relaxation time $\tau_{e\text{-ph}}$ for the objects studied.

Thus the problem set must be solved in three steps: (i) find the dependence $\tau_{e\text{-ph}}(T)$, (ii) separate the WL and EEI effects, and (iii) separate the influence of the rising electron temperature upon each of the quantum corrections.

II. BASIC RELATIONS

The temperature dependence of the thin-film resistance is a sum of several components:

$$R(T)=R_0+R_{e\text{-ph}}(T)+\Delta R_T^L+\Delta R_T^C , \quad (1)$$

where R_0 is the residual resistance dependent on the elastic relaxation processes, $R_{e\text{-ph}}(T)$ is the ordinary ("classical") electron-phonon resistance, and ΔR_T^L and ΔR_T^C are

the resistance variations due to quantum interference of the WL and EEI effects.

A transition from ΔR_T^L and ΔR_T^C to the corresponding quantum corrections to the conductivity obtained in the theory of WL and EEI effects[2-9] is possible, taking into account the relative smallness of these corrections via the relation $-\Delta\sigma=\Delta R/(RR_\square)$, where $R_\square$ is the resistance per film square.

The quantum corrections to the thin-film conductivity related to the WL and EEI effects are seen at low temperatures ($\lesssim 20$ K), and disappear as the temperature rises. In a two-dimensional (2D) case the localization correction is[3,4]

$$\Delta\sigma_T^L=-\frac{e^2}{2\pi^2\hbar}\ln\frac{\tau_\varphi}{\tau}\ , \tag{2}$$

where τ_φ is the relaxation time of the wave-function phase of the electrons, and τ is the elastic relaxation time of the electrons. If the time τ_φ which corresponds to the inelastic electron relaxation can be approximated by the power function $\tau_\varphi \propto T^{-p}$, then Eq. (2) is usually as follows:

$$\Delta\sigma_T^L=\frac{e^2}{2\pi^2\hbar}p\ln T\tau\ . \tag{3}$$

With a strong spin-orbit interaction during the impurity scattering of electrons, the factor $-\frac{1}{2}$ appears in Eqs. (2) and (3), and the localization correction changes its sign. The same is true for the magnetic-field localization correction $\Delta\sigma_H^L$ (see below). The anomalous positive MR observed in the Bi films suggest that at helium temperatures the localization correction to the conductivity corresponds to the case of strong spin-orbit scattering ($\tau_\varphi \gg \tau_{so}$).

The quantum correction related to the EEI in the 2D case is[5,9]

$$\Delta\sigma_T^C=\frac{e^2}{2\pi^2\hbar}\lambda_T^D\ln T\tau\ , \tag{4}$$

where λ_T^D is the effective constant of interaction of electrons with a small difference in their momenta (the diffusion channel of interaction). The total quantum correction to the temperature dependence of the Bi film conductivity is

$$\Delta\sigma_T=\Delta\sigma_T^L+\Delta\sigma_T^C=\frac{e^2}{2\pi^2\hbar}[-\tfrac{1}{2}p\ln T\tau+\lambda_T^D\ln T\tau]\ . \tag{5}$$

The temperature dependences of quantum corrections are usually analyzed using the minimum resistance $R(T)$ (for the Bi films $T_{min}\sim 5$ K). In practice the correction contribution can occur even above the minimum resistance. This implies that the considered value of $-\Delta\sigma=\Delta R_T/(RR_\square)$ (where $\Delta R_T=R_T-R_{min}$) is smaller than the true value. An analysis of the temperature dependences of corrections and estimation of p and λ_T^D by (3) and (4) allow the measurement of ΔR_T from the minimum resistance, but this method may be unfavorable for separation of the localization correction from the total quantum one. We proceed from the assumption that the temperature at which the current effect on the shape of the temperature dependence of resistance disappears is just the temperature at which the quantum corrections vanish themselves. By this criterion and the estimations made for the Bi films, the temperature at which the quantum corrections become vanishingly small ranges between 15 and 20 K.

For a magnetic field perpendicular to the film plane, the variation of the conductivity in the WL effect can be described, in the general case, by the quantum correction of the form[6]

$$\Delta\sigma_H^L=\frac{e^2}{2\pi^2\hbar}\left\{\tfrac{3}{2}f_2\left[\frac{4eHD}{\hbar c}\tau_\varphi^*\right]-\tfrac{1}{2}f_2\left[\frac{4eHD}{\hbar c}\tau_\varphi\right]\right\}\ , \tag{6}$$

where D is the diffusion coefficient of electrons,

$$(\tau_\varphi^*)^{-1}=(\tau_{\varphi 0})^{-1}+\tfrac{4}{3}(\tau_{so})^{-1}+\tfrac{2}{3}(\tau_s)^{-1}\ ,$$

$$\tau_\varphi^{-1}=\tau_{\varphi 0}^{-1}+2\tau_s^{-1},\quad f_2(X)=\ln X+\Psi\left[\tfrac{1}{2}+\frac{1}{X}\right]\ ,$$

Ψ is the logarithmic derivative of the Γ function, τ_{so} is the spin-orbit interaction time for elastic electron scattering by an impurity, and τ_s is the time of spin-spin scattering of electrons (it may be neglected in the absence of magnetic impurities).

For the Bi films, the second term in Eq. (6) is determining because of the strong spin-orbit interaction. When the temperature rises ($T>4$ K) and τ_φ thus decreasing brings τ_φ and τ_{so} [in the studied Bi films $\tau_{so}\lesssim 10^{-13}$ s (Ref. 1)] closer, the first term may also contribute.

It is found[1] that with an increase in the current density the component of the quantum correction related to the EEI contributes to the magnetoresistance of Bi films. In the diffusion channel of the interaction this correction is[8]

$$\Delta\sigma_H^{CD}=-\frac{e^2}{2\pi^2\hbar}\lambda_H^D g_2(h),\quad h=\frac{g\mu_B H}{k_B T}\ ,$$

$$g_2(h)=\int_0^\infty d\Omega\frac{d^2}{d\Omega^2}[\Omega N(\Omega)]\ln\left[1-\frac{h^2}{\Omega^2}\right]\ , \tag{7}$$

$$g_2(h)=\begin{cases}0.084h^2, & h\ll 1\\ \ln(h/1.3), & h\gg 1,\end{cases}$$

where g is the Lande factor of conduction electrons, and μ_B is the Bohr magneton.

III. EXPERIMENTAL PROCEDURE

The experimental samples were thin bismuth films prepared by condensing a molecular Bi beam (the Bi purity is 99.9999) in a vacuum ($\sim 10^{-6}$ torr) onto a room-temperature substrate. The samples were narrow strips (60 μm wide) with whiskers to measure resistance by the four-probe method. The electron microscopic data show that films of thickness $\gtrsim 100$ Å were homogeneous and continuous. The electron diffraction analysis revealed a texture with the trigonal axis C_3 normal to the substrate. The measurement was carried out at temperatures rang-

ing between 1.5 and 20 K (at $T \leq 4.2$ K the sample was immersed in liquid helium) in magnetic fields up to 55 kG. The current through the sample was varied from 10 to 300 μA, and the applied electric field corresponding to the maximum current was as high as 18 V cm^{-1}.

To produce electron overheating in the Bi films, we used calcite as a substrate. The electron overheating is realized with a high acoustic coupling of the film-substrate (or film-surroundings) boundary. This is provided by the closeness of the acoustic impedances $Z = \bar{p}s/\cos\vartheta$ for these substances ($\bar{p}$ is the density, s is the sound velocity, and ϑ is the angle of sound wave incidence or transmission). Bismuth and calcite have close $\bar{p}s$ values, and this permits us to believe that the acoustic coupling is adequate [for bismuth: $\bar{p}=9.80$ g cm^{-3}, $s_l = 2.18\times10^5$ cm s^{-1}, and $s_t = 1.1\times10^5$ cm s^{-1};[19] for calcite: $\bar{p}=3.72$ g cm^{-3}, $s_l = 6.75\times10^5$ cm s^{-1}, and $s_t = 3.48\times10^5$ cm s^{-1} (Ref. 20)]. In this case for a high-density current through the film, the phonons emitted by the heated electrons escape from the film without reabsorption (it is essential that the film thickness be lower than the phonon-electron relaxation length). As a result, the temperature of the phonons T_{ph} in the film remains almost unchanged, and coincides with that of the substrate (or surroundings), and the electron system state can be described by the Fermi distribution function with an effective temperature T_e that differs from T_{ph}. The temperature T_e is determined by the energy balance condition for the electron system.

From the equation of thermal balance under the electron overheating condition, we can derive the following expression:[16]

$$(k_B T_e)^2 = (k_B T_{ph})^2 + \frac{6}{\pi^2}(eE)^2 D\tau_{e\text{-ph}} . \quad (8)$$

This relation is suitable because, like Eq. (6) for the localization quantum correction to magnetic conductivity, it involves the diffusion coefficient of electrons D as the only characteristic of the substance. It was calculated from $D = \frac{1}{3}v_F^2\tau$, where the elastic relaxation time of electrons τ is defined by the film conductivity.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

(1) The temperature dependence of the phase relaxation time τ_φ can be found from experimental data for the film resistance variation in the magnetic field at different temperatures and currents using Eq. (6). The solid lines in Fig. 1 show experimental dependences $\Delta\sigma(\ln H)$ for a sample 125 Å thick at different temperatures, and a current of 10 μA (to the left) and at different currents at $T = 1.6$ K (to the right). Light circles show the calculated curves for the localization correction [according to Eq. (6)], fitted to the experimental curves taken at estimated τ_φ and τ_{so}. A small contribution of the "ordinary" magnetoresistance $\Delta\rho/\rho = \mu^2H^2$ was preliminarily subtracted from the experimental record, which for this particular sample corresponds to the mobility $\mu = 100$ cm^2 V^{-1} s^{-1} averaged for two types of charge carriers.

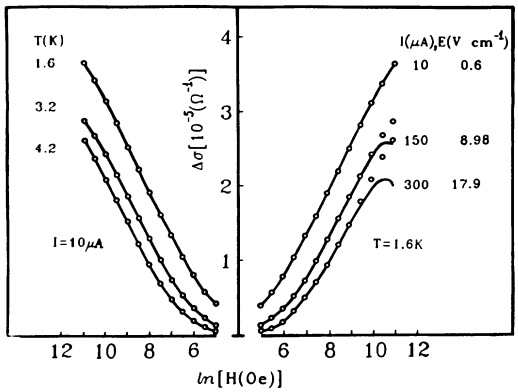

FIG. 1. Dependences of correction to magnetoresistance $\Delta\sigma$ upon the perpendicular magnetic-field strength for a 125-Å-thick Bi film at different temperatures and currents through the sample. Light symbols show the curves calculated by Eq. (6) found at τ_φ and τ_{so} times. Left: 10 μA; 1.6, 3.2, and 4.2 K; $\tau_\varphi = 4.55\times10^{-11}$, 1.71×10^{-11}, and 9.42×10^{-12} s, respectively; $\tau_{so} = (2.5\pm0.5)\times10^{-14}$ s for the range 1.6–4.2 K. Right: 1.6 K; 10, 150, and 300 μA; $\tau_\varphi = 4.55\times10^{-11}$, 1.67×10^{-11}, and 9.09×10^{-12} s.

For samples of smaller thickness ($\lesssim 100$ Å) this contribution is practically unobserved. It should be noted that at a highly increasing current the fitting region of experimental and calculated curves is limited by the region of weak magnetic fields ($H < 10$ kOe) since in high fields the contribution of the component related to the electron-electron interaction emerges.[1] Since the computer-based accuracy of the fitting parameter $D\tau_\varphi$ is high in comparison with the experimental curve and the one calculated by Eq. (6), the accuracy of τ_φ is thus sufficiently high too, and the systematic error may be connected with the estimate of D. It is shown below that this error is excluded from our calculation.

The results for $D\tau_\varphi$ of the 125-Å-thick sample are shown in Fig. 2 (bottom left). The diffusion coefficient D was estimated to be ≈ 20 cm^2 s^{-1} for this sample.

The time τ_φ was calculated taking into account the data of Ref. 1, in which the contribution of the EEI-related correction to the magnetic resistance of Bi films at strong currents was detected. In this context the currents and magnetic fields were used, where the magnetic resistance is dependent only on the localization correction (6).

The dependence $\tau_\varphi(T)$ for a small current reflects the contribution of two main mechanisms of the inelastic electron relaxation: electron-electron and electron-phonon interactions. The first mechanism predominates at lower temperatures and is described by the dependence $\tau_{ee}^{-1} \propto T$ for disordered metals.[7] The second mechanism operates at higher temperatures, and gives a stronger dependence of τ_φ on T: $\tau_\varphi^{-1} \propto T^2$ in this particular case. The decrease in τ_φ in Fig. 2 as the current grows should be taken as a manifestation of the electron overheating effect.

The absence of a jump in the temperature dependences $D\tau_\varphi$ and quantum correction $\Delta\sigma_T$ (see below) at the tem-

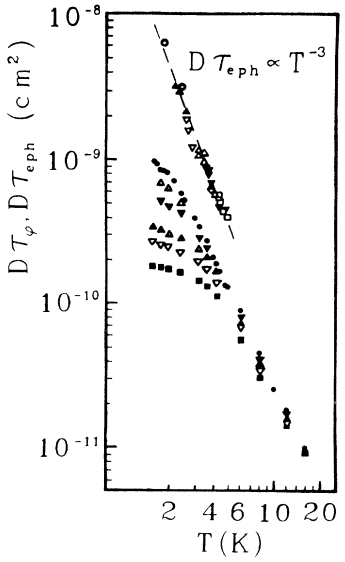

FIG. 2. The temperature dependences $D\tau_{\varphi}$ found from the MR of a 125-Å-thick Bi film according to expression (6), and the temperature dependence $D\tau_{e\text{-ph}}$ found from the electron overheating effect at different values of current (in μA): ●—10; ○—20; △▲—40; ▼▽—80; ▲△—150; ▽▼—200; ■□—300.

perature of helium transformation into the superfluid state ($T_{\lambda} \approx 2.18$ K) is indicative of the electron overheating effect in Bi films on calcite at the above current conditions. Such a jump is inevitable when the acoustic film-substrate coupling is poor (e.g., in Bi on mica[12]) and the phonon escape from the film provides partially liquid helium. These capabilities are different in He I and He II.

The quantum correction to the magnetic conductivity of the film, and hence τ_{φ}, decreases with current due to the rising electron temperature, which affects the values of these characteristics essentially. The comparison of τ_{φ} values observed at a certain preassigned current and the initial temperature T_{ph}, with the equal values on the "equilibrium" curve $\tau_{\varphi}(T)$ corresponding to the minimum current, may give information about the electron temperature T_e. Then $D\tau_{e\text{-ph}}$ can be calculated from Eq. (8).

The obtained dependence $D\tau_{e\text{-ph}}$ is shown in Fig. 2 (top); it can be presented in an analytical form:

$$(D\tau_{e\text{-ph}})^{-1} = 2.44 \times 10^{7} T^{3} . \quad (9)$$

The analysis of the dependences $\tau_{e\text{-ph}}(T)$ for several thin $\gtrsim$100-Å-thick Bi films shows that they practically agree for films of different thicknesses and are insensitive to changes in the electron mean free path l. This fact and the analytical form of the dependence $\tau_{e\text{-ph}}(T)$ [Eq. (9)] (see also Refs. 12 and 13) suggest that the results obtained for $\tau_{e\text{-ph}}$ in >100-Å-thick Bi films in the range 2–4 K refer to the 3D case of the electron-phonon interaction in the "pure limit," where the inequality $q_{ph} l > 1$ (q_{ph} is the wave vector of the thermal phonon) is met.[21,22]

(2) Each of the components may be separated from the measured total quantum correction to the temperature dependence of the film conductivity [Eq. (5)], proceeding from the following experimental feasibility.[11] It is known that a comparatively weak magnetic field can destroy localization, since the electron wave function assumes an additional phase in the magnetic field, and this disturbs the interference. The corresponding magnetic field $H_0^L = \hbar c / 4eD\tau_{\varphi}$ at $D \approx 20$ cm^{2}s^{-1} and $\tau_{\varphi} \approx 10^{-11}$ s at 4 K is estimated to be $H_0^L \approx 90$ Oe. On plotting the temperature-film resistance dependence in the magnetic field $H \gg H_0^L$, the temperature behavior of the EEI-related quantum correction can be separated out. This correction for Bi films appears to be larger than the total one, since the localization correction $\Delta\sigma_T^L$ has the minus sign. The latter can be found as the difference between the total quantum correction and the Coulomb one. This calculation of $\Delta\sigma_T^L$ and the plot of the temperature dependence of this magnitude at different currents were performed in the magnetic fields of 7.7 and 55 kG. The slight distinction between the dependences obtained is due to the WL effect, whose contribution is not removed completely in the first case; in the second case there is a contribution from the EEI effect which shows up in a strong magnetic field at large currents. It is difficult to take this contribution into account accurately in the total magnetoresistance of films. In our plotting procedures we used $\Delta R_T = R_T - R_{16\,K}$ to change over from the temperature variation of resistance to the quantum correction to the film conductivity.

On the other hand, the τ_{φ} values obtained from the localization correction to the film magnetoresistance permit calculation of $\Delta\sigma_T^L$ by Eq. (2), and thus provide another method of deriving information about the temperature behavior of the localization correction. The results of such calculations are shown in Fig. 3. The general pictures of $\Delta\sigma_T^L$ variations with temperature at different currents as obtained by either of the two methods are identical, and the absolute values of the localization correction calculated from τ_{φ} are only ~10% higher than those obtained by the first method in the magnetic field 7.7 kG, and practically coincide with those

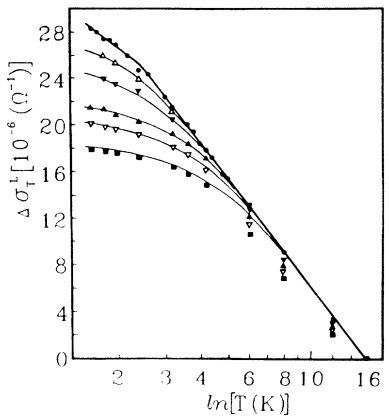

FIG. 3. The temperature variation in the quantum correction related to the weak electron localization at different values of current (in μA): ●—10; △—40; ▼—80; ▲—150; ▽—200; ■—300.

taken in the magnetic field 55 kG. Figure 3 shows the localization correction to the temperature dependence of the Bi film conductivity separated with sufficient accuracy from the total quantum correction.

It should be noted that the localization correction reproduced the temperature behavior of τ_φ, including the change from the exponential dependence $\tau_\varphi^{-1} \propto T$ to $\tau_\varphi^{-1} \propto T^2$. It follows that the commonly used Eq. (3) does not work in a wide temperature range, since p is not constant.

Finally, the points in Fig. 4 show the temperature variation of the Coulomb correction to the Bi film conductivity at different currents. A decrease in the values of localization and Coulomb corrections with increasing current is, first of all, connected with the increasing electron temperature.

(3) Let us consider the expected variation of the quantum corrections due to the electron overheating. The dependence $D\tau_{e\text{-ph}}(T)$ obtained is sufficient to solve the problem.

Proceeding from Eq. (9) and using Eq. (8) for $T_{\rm ph}$ at given T_e values in the "equilibrium" curve $\Delta\sigma_T(\ln T)$, the problem inverse to searching for $D\tau_{e\text{-ph}}$ can be solved, i.e., the expected variation of the $\Delta\sigma_T(\ln T)$ shapes due to electron overheating can be restored at different currents. The results of such calculations are shown in Figs. 3 and 4 (solid lines).

For the localization correction, the calculated curves agree essentially with experimental ones. It follows that within the experimental accuracy no direct influence of the electric field on the localization correction is observed (at least, in the electric fields applied; the higher-density currents, in our opinion, would violate the conditions of electron overheating; as a result, signs of the Joule heating appear).

This conclusion does not support the assumptions made earlier[14,15] about the possible influence of the electric field on WL, but agrees well with the following statement:[4] since the electric field does not break time-reversal invariance, the electric field also has no influence on the WL. It is found[16,17] that only the electron overheating may be responsible for the localization correction variations in the electric field.

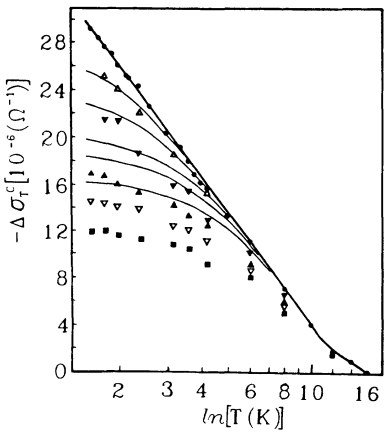

FIG. 4. The variation with the temperature of the quantum correction related to EEI at different values of current (in μA): ●—10; △—40; ▼—80; ▲—150; ▽—200; ■—300.

An alternative conclusion has been made about the correction related to the EEI (Fig. 4). It can be seen that in the growing electric field the Coulomb correction decreases more sharply than is expected during electron overheating. This discrepancy increases with the current and may far exceed (by at least an order of magnitude) the possible error of calculations. The proper consideration of the Coulomb correction variation caused by the electric field[18] brings only slight changes in to the calculations.

The discrepancy between the computed and experimental temperature dependences of the Coulomb corrections suggests that the interaction constant λ_T^D in Eq. (4) decreases with the growing electric field. This change can be found by introducing into Eq. (4) a scale factor eliminating the above discrepancy. The following values have been obtained for λ_T^D variations: 1.0, 0.95, 0.83, 0.8, and 0.75 at $E \leq 1$ V cm^{-1}, $E = 4.7$ V cm^{-1} (at 80-μA current), $E = 8.45$ V cm^{-1} (at 150 μA), $E = 12$ V cm^{-1} (at 200 μA), and $E = 18$ V cm^{-1} (at 300 μA), respectively.

Thus the influence of an electric field on the magnetic-field variation of quantum corrections to the Bi film conductivity revealed in Ref. 1 has received further support through the analysis of the temperature-dependent Coulomb correction. However, under the action of an electric field, the corresponding interaction constants λ_H^D and λ_T^D behave in different ways: In Ref. 1 the absolute value of λ_H^D increased from an infinitesimal value up to $\lesssim 0.5$ for the field of 40 V cm^{-1}; in this work λ_T^D decreased with the growing electric field as compared with the initial value equal to 1. This apparent discrepancy may be explained qualitatively; however, the emerging problem requires a more careful theoretical approach. The qualitative considerations are as follows.

According to the theory of electron-electron interaction in disordered metals,[5,6] the interaction constants defining the quantum correction values are estimated by summing over all particle-hole and particle-particle interaction processes of the exchange and Hartree types. In the approximation of screened Coulomb interaction, these components can be expressed in terms of a single constant F averaged over angular amplitudes of the electron interaction with small momenta. In the case of strong spin-orbit scattering ($\tau_\varphi \gg T_{\rm so}$), the interaction constant λ_T^D defining the quantum correction to the temperature dependence of conductivity may be expressed as[9]

$$1 - \tfrac{3}{4}F \quad \text{at } H < H_s\,, \tag{10a}$$

$$1 - \tfrac{1}{4}F \quad \text{at } H > H_s\,, \tag{10b}$$

where

$$H_s = \frac{\pi k_B T}{g\mu_B}\,.$$

The interaction constant λ_H^D which defines the magnetic-field-induced change of the quantum correction in the diffusion channel is equal to $F/2$.[8]

As is known for bismuth,[23] the g factors are equal to 17 for electrons and to 134 for holes (if $H \| C_3$). The corresponding values for the field H_s are 27.5 and 3.5 kG at $T = 10$ K. It seems reasonable to suggest that the contribution of the Coulomb correction to the magnetoresistance in the fields ranging from 10 to 40 kG at high currents appears to be due to the interaction occurring both in the electron and hole valleys; for the λ_H^D expression (10b) can be used.

In the framework of the above consideration, the changes in λ_H^D and λ_T^D with the electric field should be regarded as resulting from the constant F increasing from the minimum initial value (for wear screening) in the absence of electron overheating to the value approaching unity (for strong screening) at the increasing energy of charge carriers. Explanations of this conclusion presents some difficulties, therefore, additional considerations can be put forward. The interaction constants contain[9] an additional component $\lambda_{e\text{-ph}}$ accounting for the interaction mechanism related to the virtual phonon exchange. With the proper choice of the component sign corresponding to attraction, the experimental results in Ref. 1 and this work can be described qualitatively by the variation of just this component with the growing of E, while the constant F is small over the whole range of electric fields. The growth of the component $\lambda_{e\text{-ph}}$ with increasing electric field may be connected, for example, with the mechanism considered in Ref. 24, which shows that the electron-electron interaction via virtual phonons enhances appreciably under the condition of the electron drift because the frequency of the virtual phonons attains the Doppler shift.

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