The effect of quantum corrections on the resistance of thin bismuth films

A. K. Savchenko, V. N. Lutskiĭ, and A. S. Rylik
Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR

(Submitted 31 July 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **34**, No. 6, 367–371 (20 September 1981)

A logarithmic increase of the resistance of thin Bi films resulting from a decrease in temperature, as well as a logarithmic dependence of the magnetoresistance on the magnetic field have been observed. The obtained results are in agreement with theory, in which the quantum corrections for the conductivity, with allowance for the interelectronic interaction, are examined.

PACS numbers: 73.60.Dt

Theoretical studies, in which the quantum corrections for the resistance of thin metallic films are analyzed, have been published in recent years.[1-3] It was shown in Refs. 1 and 2 that electron-wave interference due to scattering by impurities leads to an anomalous increase of the resistance with decreasing temperature ("localization" theory). An anlogous result has been obtained in an alternative theory[2] ("interaction" theory), in which the interaction between electrons due to scattering by impurities was taken into account.

Both theories yield the same logarithmic law for the increase of resistance in films with decreasing temperature T:

$$\frac{\Delta R_{\square}}{R_{\square}^2} = -\frac{\alpha p}{2}\,\frac{e^2}{\pi^2\hbar}\ln T, \tag{1}$$

where $R_{\square}$ is the resistance of a square-shaped film.

In the localization theory the parameter $\alpha \sim 1$, and the parameter p, which is determined by the inelastic-scattering mechanism ($\tau_{in} \sim T^{-p}$), is in the range 2–3. In the interaction theory $\alpha p \sim 1$ and can be less than unity if there is a strong shielding: $k_F/\mu \ll 1$ (k_F is the wave number of electrons, and μ is the reciprocal-shielding length).

The effect of magnetic field on quantum corrections for the conductivity was analyzed in Ref. 4, in which the difference between the theories mentioned above was shown in a plot of the anomalous magnetoresistance vs the magnetic field: Except for certain specific cases, it is negative in the localization theory and positive in the interaction theory.

A logarithmic increase of the resistance of thin metallic films with decreasing temperature T has been reported in several experimental studies (Ref. 5, for example); this increase was attributed by the authors of these studies to electron localization. This explanation has been confirmed by the detection of a negative magnetoresistance.[5] The dominant role of interelectronic interaction in metallic films was mentioned in Ref. 6.

Our goal in this letter is to investigate the effect of quantum corrections on the resistance of thin bismuth films. It would be useful to analyze the indicated effects in a semimetal with specific characteristics (two types of current carriers, low Fermi energy, strong spin-orbit interaction, large dielectric constant). Low current-carrier density (large $R_\square$), moreover, implies that the effects are large.

The bismuth films were produced by thermal sputtering on a mica substrate in a low vacuum (10^{-5} Torr) at room temperature. The distance between the potential leads was 10 mm, the film width was 0.5 mm, and the film thickness was 50-500 Å. The resistance of the samples was measured by using the compensation method with a 20-Hz alternating current, which provided a sensitivity of 10^{-5}: The resistance of

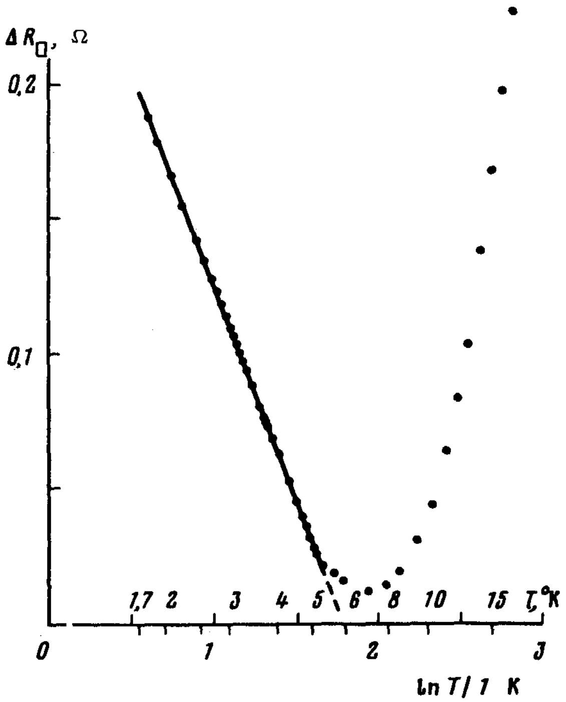

FIG. 1. Temperature dependence of the resistance of a bismuth film ($R_\square = 148\ \Omega$ at $T = 4.2$ K).

the sample was ~1 mV.

The films whose resistance range was 100-5000 Ω were measured. The resistance of all the samples increased with decreasing temperature in the temperature range $T = 1.7$-8 K. (An increase of the resistance in bismuth films at low temperatures was reported in Ref. 7.) The increase in resistance observed by us can be approximated by the logarithmic law (Fig. 1). Note that the resistance minimum has been observed in films of thickness $d \lesssim 400$ Å. The logarithmic dependence is replaced by a stronger dependence in thicker samples when the temperature is raised. The specific characteristics of bismuth films, which have a complex $R(T)$ dependence in the region $T > 8$ K, presumably manifest themselves in this case.[7]

The anomalous increase of the resistance ΔR of films in the region $T = 1.7$-6 K turned out to be proportional to the square of the film resistance $R_{\square}^2$ within the entire investigated range of $R_{\square}$ values. This fact does not make it possible to explain the increase in resistance in terms of the condo effect. The parameter αp, which was determined from a comparison of experimental dependences with expression (1), is equal to 0.6 ∓ 0.15.

The magnetoresistance of films in a magnetic field H perpendicular to the film plane has a positive sign. The $\Delta R(H)$ curve has a logarithmic part for thin (~ 100 Å) films in small fields H. (Because of the increase of the mobility of current carriers, the usual magnetoresistance $\Delta R \sim H^2$ is dominant in thicker films within the entire range of fields.) A comparison of experimental curves with the theoretical curves for the case of interacting electrons[4] showed a good agreement between them (Fig. 2). In the comparison we used the expression

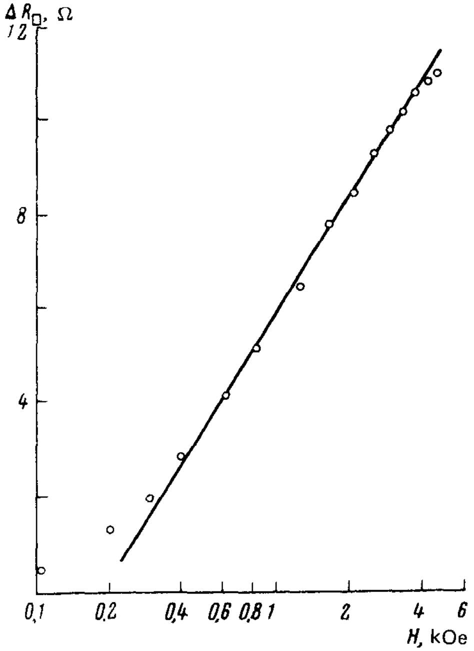

FIG. 2. Variation of the resistance of a bismuth film in a magnetic field perpendicular to the film surface ($R_{\square} = 1.27$ kΩ at $T = 1.8$ K).

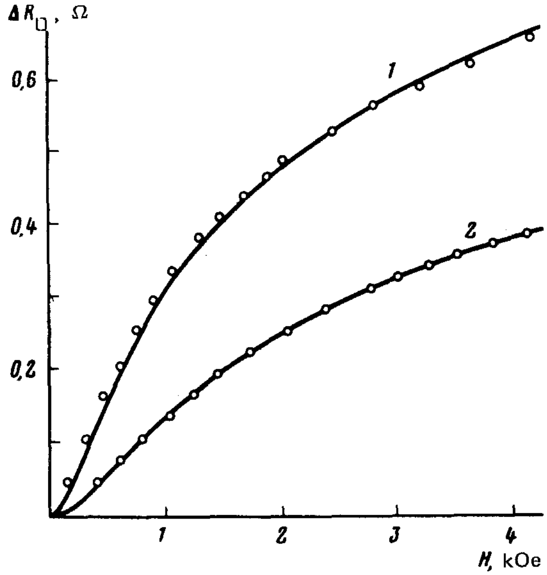

FIG. 3. Variation of the resistance of a bismuth film ($R_\square = 174$ Ω at 4.2 K) in a parallel magnetic field (1–1.74 K, 2–4.2 K).

$$\Delta R_\square = g(T)\,\frac{R_\square^2 e^2}{2\pi^2\hbar}\ln\left(\frac{2DeH}{\pi ckT}\right) \tag{2}$$

with two adjustable parameters: $g(T)$ is the electron-electron interaction constant, and D is the diffusion coefficient. The calculated values $g \sim 0.2$ and $D \sim 10^2$ cm$^2\cdot$sec^{-1} are reasonable for the films under investigation.

A paper,[8] in which the effect of the magnetic field H, parallel to the plane of the film, on the quantum corrections was analyzed, was published recently. A measurement of $\Delta R(H)$ dependences for $H \parallel I$ and $H \perp I$ (I is the direction of current) revealed anomalous logarithmic sections (Fig. 3) which were predicted theoretically.[8] The magnitude of the effect is the same for both field directions with respect to the current. The value of H, in the vicinity of which a transition from a logarithmic dependence to a stronger dependence is observed, is determined by the film thickness and corresponds to the condition $d \approx L_H$ (L_H is the magnetic length). The mentioned peculiarities of the $\Delta R(H)$ curves correspond to those predicted theoretically.[8]

A quantitative comparison (Fig. 3) of the experimental curves with the expression

$$\Delta R_\square = g(T)\,R_\square^2\,\frac{e^2}{2\pi^2\hbar}\ln\left(\frac{d^2}{12}\,\frac{D}{kT}\,\frac{e^2H^2}{c^2\hbar} + 1\right)$$

for the case of interacting electrons[8] yields the values 0.2-0.3 for the $g(T)$ parameter. These values correlate well with the value of g for the field perpendicular to the film. The values of D in this case turn out to be too high. This result requires additional explanation.

In summary, we can assume that the effects observed in this study are attributable to the predominant influence of interelectronic interaction.

The authors are grateful to V. A. Volkov and D. E. Khmel’nitskiĭ for a useful discussion of the problems under consideration.

1. E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979).
2. L. P. Gor’kov, A. I. Larkin, and D. E. Khmel’nitskiĭ, Pis’ma Zh. Eksp. Teor. Fiz. **30**, 248 (1979) [JETP Lett. **30**, 228 (1979)].
3. B. L. Al’tshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).
4. B. L. Al’tshuler, A. G. Aronov, A. I. Larkin, and D. E. Khmel’nitskiĭ, Zh. Eksp. Teor. Fiz. **81**, 8 (1981) [Sov. Phys. JETP (to be published)].
5. L. Van den Dries, C. Van Haesendonck, Y. Bruynseraede, and G. Deutscher, Phys. Rev Lett. **46**, 565 (1981).
6. M. E. Gershenzon and V. N. Gubankov, Pis’ma Zh. Eksp. Teor. Fiz. **34**, 32 (1981) [JETP Lett. **34**, 30 (1981)].
7. Yu. F. Komnik, B. I. Bukhshtab, Yu. V. Nikitin, and V. V. Andrievskiĭ, Zh. Eksp. Teor. Fiz. **60**, 669 (1971) [Sov. Phys. JETP **33**, 364 (1971)].
8. B. L. Al’tshuler and A. G. Aronov, Pis’ma Zh. Eksp. Teor. Fiz. **33**, 515 (1981) [JETP Lett. **33**, 499 (1981)].

Translated by S. J. Amoretty
Edited by Robert T. Beyer