$$\frac{\partial n}{\partial t} = \alpha \frac{\partial^2 \ln n}{\partial z^2}, \qquad \alpha = \frac{0{,}91\, T^{5/2}}{M^{1/2} k^2 \Lambda e^4}, \tag{5}$$

where e is the electron charge and Λ the Coulomb logarithm. For an initial condition in the form $n = n_0(1 + z^2/a^2)^{-1}$ the solution of Eq. (5) is

$$n = n_0(1 + 2\alpha t/a^2 n_0)[z^2/a^2 + (1 + 2\alpha t/a^2 n_0)^2]^{-1}.$$

QUANTUM SIZE-EFFECT SEMIMETAL-SEMICONDUCTOR TRANSITION IN ULTRATHIN BISMUTH FILMS

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A semimetal-semiconductor transition in films with decreasing thickness was theoretically predicted in [1, 2]. If the film potential is approximated by a square well, then this transition in bismuth films should occur at thicknesses $L_t \sim 300$ Å for textured samples [3] and $L_t \sim 200$ Å for non-textured samples [4].

Textured Bi films were investigated down to a thickness L ∿ 170 Å [5, 6], but no semimetal-semiconductor transition was observed. The shift of the red absorption edge in Bi films [7] is no evidence of a transition, owing to the large temperature smearing (T = 300°K). The indicated existence of a transition in cleaved $Bi_8Te_7S_5$ [8] cannot be regarded as convincing, since the carrier concentration was not determined in the cited paper, and the resistance does not increase as $T \to 0$.

The absence of a transition down to a thickness 170 Å is apparently connected with the inaccuracy of the film-potential model. Allowance for the electron interaction should lead to a lowering of the film levels, i.e., to a decrease of the expected L_t [9].

We have investigated the thickness dependences of the conductivity σ, of the Hall coefficient R, and of the magnetoresistance $\Delta\rho/\rho_0$ in ultrathin Bi films at T = 4.2°K, for the purpose of observing the semimetal-semiconductor transition. We used for the measurements non-textured polycrystalline films with thicknesses from 60 to 400 Å, obtained by electric explosion on glass substrates, using a previously described procedure [4]. The critical film thickness was decreased by using extremely high condensation rates (up to 10^3 μ/sec) [10]. The solidity of the films was determined by electron microscopy, and also by the absence of a sharp growth in the resistivity down to L ∿ 50 Å. The film thickness was determined photometrically by optical absorption, with absolute standardization by the interferometer method of bands of equal chromatic order [11], with accuracy ±5 Å. Measurements of σ, R, and $\Delta\rho/\rho_0$ were made by a null method, the sample was placed directly in the liquid helium, and the magnetic field intensity was 5000 Oe.

A decrease of the gap with decreasing L was not observed earlier [4], apparently because of the temperature smearing, which at temperatures 78 - 300°K is of the order of the band overlap in Bi, $\Delta = 4.3 \times 10^{-14}$ erg. At T = 4.2°K the temperature smearing is negligible.

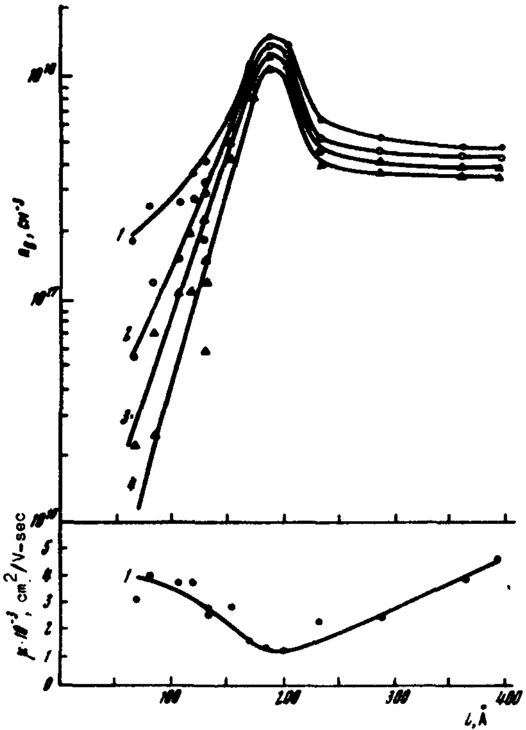

Fig. 1

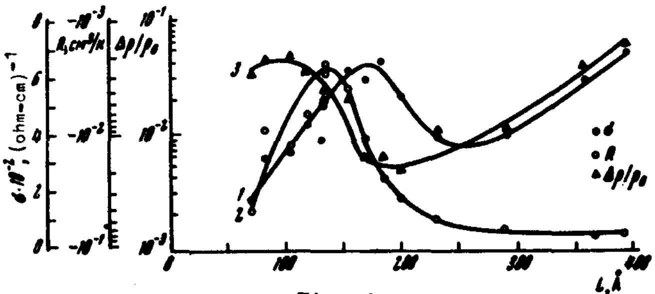

Fig. 2

Fig. 1. Dependence of the conductivity (1), the Hall coefficient (2), and the magnetoresistance (3) on the film thickness.

Fig. 2. Dependence of the concentration n_b and of the mobility μ on the thickness L at: $1 - n = p$, $2 - n_s = 3 \times 10^{11}$ cm^{-2}, $3 - n_s = 5 \times 10^{11}$ cm^{-2}, $4 - n_s = 10^{12}$ cm^{-2}. Owing to the small difference between μ_n and μ_p, one curve is given for μ.

The results of the measurements are shown in Fig. 1. An important factor is the growth of $|R|$ with decreasing thickness, starting with L = 140 Å. This was not observed in [4], because of the high temperature; no such thicknesses were attained in other investigations of the quantum size effect. We note also the considerable value of $\Delta\rho/\rho_0$, which (see below) is connected with the relatively high mobilities μ_n and μ_p.

From the measured values of σ, R, and $\Delta\rho/\rho_0$ it is possible to calculate the concentrations n and p and the mobilities from the formulas in (1), by assuming some hypothesis concerning the connection between n and p:

$$n\mu_n + p\mu_p = \frac{\sigma}{e}, \quad n\mu_n^2 - p\mu_p^2 = R\sigma^2, \qquad (1)$$

$$n\mu_n^3 + p\mu_p^3 = \sigma\left\{\frac{\Delta\rho c^2}{\rho_0 H^2} + (R\sigma)^2\right\}.$$

In thin films it is necessary to take into account the influence of the surface levels on the carrier concentration. The absence of the field effect, however, did not make it possible to determine the surface concentration n_s.

The results of calculations by formulas (1), under the assumption n = p, corresponding to an "ideal" semimetal in the absence of or under complete compensation of the surface states, is shown in Fig. 2. We see that the bulk concentration of the carriers n_b decreases with decreasing thickness, starting with L ∿ 180 Å, this being due to the transition of the Bi films into the semiconducting state. The thickness interval ΔL within which n_b decreases by a factor e is ∿50 Å. As already noted, the temperature smearing is small here and ΔL is determined by the broadening of the levels (by the smoothing of the state-density function) resulting from the carrier scattering. The value of μ leads to ΔL of the same order.

We also calculated n_b under the assumption that $n = p(n_s/L)$ (Fig. 2). At reasonable values of n_b, the character of the $n_b(L)$ dependence remains unchanged, the decrease of n_b begins at the same thickness L ∿ 180 Å, and only ΔL varies.

The presence of the transition is evidenced indirectly also by the μ(L) dependence. The increase of μ starting with L ∿ 200 Å is apparently due to the decrease of the scattering with decreasing concentration of the charged scatterers. Thus, from the $n_b(L)$ dependence, and also from μ(L), it follows that a semimetal-semiconductor transition occurs in Bi films at L_t ∿ 180 Å. This is somewhat less than the thickness calculated theoretically from the square-well model, owing, as noted above, to the inaccuracy of the model.

An interesting feature of the $n_b(L)$ dependence is the growth of n_b when L changes from 250 to 180 Å. A similar rise was observed in [6]. At $n_s \neq 0$, the maximum on the $n_b(L)$ curve decreases somewhat, but does not vanish (Fig. 2). It is difficult to explain satisfactorily this sharp growth of n_b at present, but it may be connected with the contribution of the surface states. For "thick" films (L > 300 Å) far from the transition point L_t, the value of the concentration n_b coincides with those given by others [6, 12].

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[1] V.N. Lutskii, ZhETF Pis. Red. 2, 391 (1965) [JETP Lett. 2, 245 (1965)].
[2] V.B. Sandomirskii, Zh. Eksp. Teor. Fiz. 52, 158 (1967) [Sov. Phys.-JETP 25, 101 (1967)].
[3] I. Gol'dfarb and B.A. Tavger, Fiz. Tverd. Tela 11, 1517 (1969) [Sov. Phys.-Solid State 11, 1231 (1969)].
[4] V.I. Petrosyan, V.N. Molin, E.I. Dagman, B.A. Tavger, P.A. Skripkina, and L.N. Aleksandrov, Fiz. Met. Metallov. 31, 725 (1971).
[5] V.N. Lutskii, Phys. Status Solidi (a) 1, 199 (1970).
[6] Yu.F. Komnik, E.I. Bukhshtab, Yu.B. Nikitin, and V.V. Andrievskii, Zh. Eksp. Teor. Fiz. 60, 669 (1971) [Sov. Phys.-JETP 33, 364 (1971)].
[7] V.N. Lutskii and L.A. Kulik, ZhETF Pis. Red. 8, 3 (1968) [JETP Lett. 8, 1 (1968)].
[8] R. Schemmel and H. Soonpaa, Solid State Comm. 6, 10 (1968).
[9] B.A. Tavger and V.Ya. Demikhovskii, Usp. Fiz. Nauk 96, 61 (1968) [Sov. Phys.-Usp. 11, 644 (1969)].
[10] L.N. Alexandrov, E.I. Dagman, V.I. Petrosyan, P.A. Skripkina, and V.I. Zelevinskaya, Thin Solid Films 6, 1 (1970).
[11] H.F. Bennet and J.M. Bennet, Translation in: Fizika tonkikh plenok (Physics of Thin Films), Vol. 4, Mir, 1970.
[12] V.N. Lutskii, Abstract of Doctoral Dissertation, Leningrad, 1970.

THERMODYNAMICS OF THE MELTING OF ARGON

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We describe here the results of measurements of the volume of argon in the vicinity of the melting point in the temperature region from 197.78 to 323.15°K.