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Spin-Orbit Effects in Thin Bismuth Films

Yuri KOMNIK[1], Vladimir ANDRIEVSKII[1], and Igor BERKUTOV[1,2]

[1] *B.I. Verkin Institute for Low Temperature Physics and Engineering, Kharkov, Ukraine 61103*
[2] *Department of Physics, Faculty of Science, Kyushu University, 4-2-1 Popponmatsu, Fukuoka, Japan 810-8560*

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The magnetic field dependences of the resistance of thin bismuth films with a thickness of 100 – 700 Å were measured at different temperatures (1.5 – 77 K) in perpendicular and parallel magnetic fields and analyzed. The behavior of the quantum corrections to conductivity caused by the weak localization and electron-electron interaction effects is determined. In the perpendicular magnetic field, the spin-orbit interaction time τ_{so} tends to increase with the film thickness, thereby indicating that surface scattering is dominant in the spin-orbit processes. In the parallel magnetic field, τ_{so} increases considerably with the magnetic field. It is assumed that the strong spin-orbit electron interaction occurs due to the existence of a potential gradient near the metal surface and the parallel magnetic fields regulates the spin orientation of electrons and changes the character of spin scattering.

KEYWORDS: Bismuth, Thin films, Weak localization, Spin-orbit interaction

1. Introduction

Experimental investigations show that the spin-orbit interaction time τ_{so} in thin films is shorter than that in bulk metals, which induces an intensive spin-orbital process. Studies of Mg films [1)] and Au films[2)] have shown that the probabilities of spin flip caused by surface scattering are one or two orders of magnitude higher those for bulk.

Thus, the enhancements in the spin-orbit interaction under the surface scattering of electrons can be due to the gradient of the inner crystalline potential near the metal surface. Since the time inversion of the spin-related symmetry invariance dos not occur during the motion of the electron toward the surface and on its reflection from it, the description of the electron reflection from the surface should include the term related to the spin-orbital interaction (SOI). The aim of this study is to investigate the influence of the magnetic field on the spin-orbit interaction process in thin bismuth (Bi) films.

2. Experimental results and discussion

Film samples (100 – 700 Å) were prepared by the high-vacuum (5×10^{-6} Hg mm) condensation of a atomic Bi beam onto a substrate (glass, mica) at room temperature and above. The films had textures with the C_3-axis oriented along the normal to the film plane. We analyzed the change of the film resistance in perpendicular and parallel magnetic fields at $T = 1.5 – 77$ K.

The magnetoresistance (MR) curves of the Bi films taken in the perpendicular magnetic field (Fig. 1a) exhibit the effect of weak electron localization[3)] (WL) in the case of a strong SOI. The manifestation of this effect is the positive sign of the MR and the logarithmic saturation in the MR carves in the region of high magnetic fields (see below). The amplitude of the MR variation decreases as the film thickness L and T increase.

In the parallel magnetic field, the MR exhibits an extremely wide variety of behavior patterns. The curve shapes of the MR change with L and T. The MR of the films with $L = 250 – 400$ Å is negative at high T, but with lowering temperature ($T < 10$ K) it show maximum (Fig. 1b). The temperature of the transition to the negative

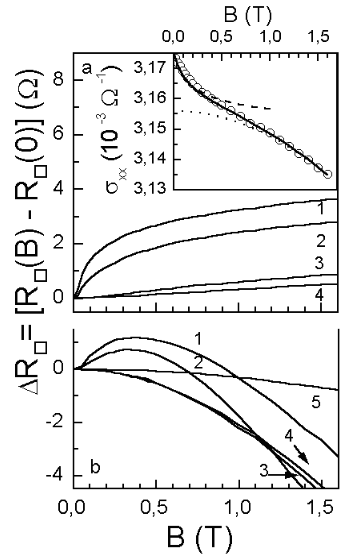

Fig. 1. Variations of the resistance of a Bi film with a thickness of 380 Å in (a) perpendicular and (b) parallel magnetic fields at different temperatures (K) of (1) 2; (2) 4.2; (3) 14; (4) 20 and (5) 77. Inset: Description of the experimental data (points) of a Bi film with a thickness of 400 Å at 4.2 K in the perpendicular magnetic field by Eq. (1) (solid line). The dotted curve shows the Drude contribution to the magnetoconductivity. The dashed curve shows the WL-related quantum correction.

MR tends to increase with L.

It is likely that the intricate variations of the MR are mainly connected with the contribution of quantum interference effects WL and interaction of electrons (EEI). The EEI correction contributes to the T dependence of the film resistance and is independent of B at $\omega_c \tau \ll 1$ (ω_c is the cyclotron frequency and τ is the elastic scattering time). Similarly, we can exclude the classical size effect as it can never occur in such thin films at $l \leq L$ (l is the electron mean free path). Thus, the WL effect is the determining factor in the transformation of the MR curves of Bi films. The WL-induced change of the MR sign occurs during the transition from the strong SOI to the weak SOI.

The WL-related corrections to the conductivity of thin films vary according to the following relations: in the perpendicular magnetic field,[4)]

$$\Delta\sigma_{\perp}^{WL} = \frac{e^2}{2\pi^2\hbar}\left[\frac{3}{2}f_2\left(\alpha\tau_{\varphi}^{*}\right) - \frac{1}{2}f_2\left(\alpha\tau_{\varphi}\right)\right], \quad (1)$$

and in the parallel magnetic field,[5)]

$$\Delta\sigma_{\parallel}^{WL} = \frac{e^2}{2\pi^2\hbar}\left[\frac{3}{2}\ln\left(\beta\tau_{\varphi}^{*}+1\right) - \frac{1}{2}\ln\left(\beta\tau_{\varphi}+1\right)\right], \quad (2)$$

where $f_2(x) = \ln x + \Psi(1/2 + 1/x)$, Ψ is the logarithmic derivative of the Γ-function, $\alpha = 4BD/\hbar$, $\beta = L^2e^2B^2D/3\hbar^2$, D is the diffusion coefficient,[6)] $(\tau_{\varphi}^{*})^{-1} = \tau_{\varphi}^{-1} + (4/3)\tau_{so}^{-1}$, τ_{φ} is the phase relaxation time, and τ_{so} is the time of spin relaxation determined by the elastic SOI. Eqs. (1) and (2) refer to the diffusion regime.

The transformation from the correction to resistance to the correction to conductivity can be achieved using the relation $\Delta\sigma = -[R_{\square}(B) - R_{\square}(0)]/[R_{\square}(B)\,R_{\square}(0)]$, where $R_{\square}$ is the resistance per square of the film. The WL correction is obtained after the subtraction of the classical (Drude) conductivity ($\sigma^D(B) = \sigma_0^D/(1 + \mu^2B^2)$, μ is the mobility) from the experimental dependence $\sigma(B)$. The dependences $\Delta\sigma^{WL}(B)$ were analyzes according to Eqs. (1) and (2). The matching procedure was performed using τ_{φ} and τ_{so} as fitting parameters. The theoretical curve provides a very good description of all experimental results obtained in the perpendicular magnetic field (see Fig. 1a (inset)). It is found that at $T = 4.2$ K, τ_{so} is an order of magnitude smaller than τ_{φ}. As T rises, τ_{φ} decreases as $\tau_{\varphi} \propto T^{-1}$ in the range of 2 – 4.2 K (dominant electron-electron scattering) and then as $\tau_{\varphi} \propto T^{-2}$ (dominant electron-phonon scattering). When the film thickness increases, τ_{so} tends to grow, while τ_{φ} remains practically invariant and the difference between these times reduces.

The transformation of the MR curves in the parallel field can be explained by assuming that τ_{so} increases with the magnetic field strength. Evidently, the curve with the maximum MR can appear only when τ_{φ} and τ_{so} approach each other and the MR is negative at $\tau_{so} > \tau_{\varphi}$. But, Eq. (2), which assumes that τ_{φ} and τ_{so} are independent of B, (in contrast to the case of the perpendicular field) cannot describe the dependences $\Delta\sigma^{WL}(B)$. If we base the calculation on τ_{φ} and τ_{so} obtained in the perpendicular magnetic field, the calculated curve describes only a small initial part of the dependence $\Delta\sigma^{WL}(B)$ and then runs sharply to the region of negative $\Delta\sigma^{WL}$ (Fig. 2, curve 1). We believe that τ_{φ} unaffected by a weak parallel magnetic field. It appears that τ_{so} increases in the region of weak B (Fig. 2). By increasing τ_{so}, we can obtain $\Delta\sigma^{WL}$ in the subsequent small parts of the curve τ_{so} up to $B \leq 0.5$ T (Fig. 2, curves 2–6). However, in higher fields the variation of τ_{so} becomes saturated or lower τ_{so} values are required in some cases (Fig. 2, inset).

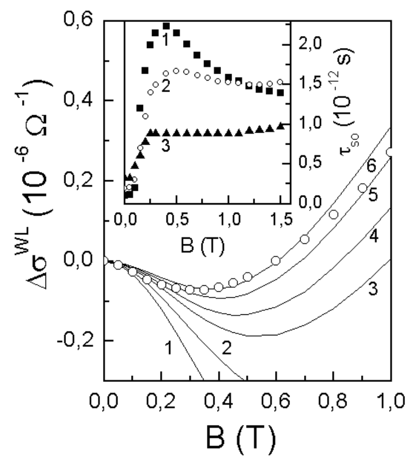

Fig. 2. Description of localization variation of a Bi film with a thickness of 380 Å at 4.2 K in a parallel magnetic field (solid line) at $\tau_{\varphi} = 4.6\times10^{-12}$ s and varying τ_{so}: (1) 2×10^{-13} s, (2) 7×10^{-13} s, (3) 1.1×10^{-12} s, (4) 1.3×10^{-12} s, (5) 1.52×10^{-12} s and (6) 1.67×10^{-12} s. The circles show the experimental data. Inset: Magnetic field variation of τ_{so} at T (K): (1) 2, (2) 4.2, and (3) 20.

The reason for the growth of τ_{so} in the parallel magnetic field is as follows. In the absence of the magnetic field, the Hamiltonian of the SOI suggests that near the surface, the electron spin (or the spin precession axis) rotates in parallel to the crystal surface. The spins are oriented parallel to the surface, but they are chaotic in the azimuth direction. The spin relaxation has a diffusion character and it is described by the Dyakonov-Perel mechanism (DP).[7)] Magnetic field oriented parallel to the film surface tends to order the spin orientation of the electrons interacting with the surface. It is necessary to take into account the Zeeman interaction. The combined effect of the SOI and Zeeman splitting changes the intensity of spin-orbit scattering during electron reflection from the surface. In a system with ordered spin polarization, the spin relaxation ceases to be diffusive and differs from the DP mechanism. In Ref. 8, the evolution of spin density in a system with local spin polarization (e.g., a quantum well in a GaAs-type semiconductor) has been studied as a function of the coordinate and the time in magnetic fields parallel to the quantum well. It 1s shown[8)] that τ_{so} increases due to the influence of the parallel magnetic field. The DP mechanism of spin relaxation operating in a disordered spin system gives way to a new evolutionary mechanism of spin relaxation under the condition of spin polarization.

3. Conclusion

Thus, the detected increase in the time of the SOI τ_{so} in thin Bi films with increasing strength of the parallel magnetic field can be interpreted as a transition from the DP diffusion mechanism of spin relaxation to a new evolutionary-type spin relaxation in a system with partially ordered spin orientation, which appears due to the parallel magnetic field.

1) P. E. Lindelof and S. Wang: Phys. Rev. B **33** (1986) 1478.
2) B. I. Belevtsev, Yu. F. Komnik, and E. Yu. Beliayev: Phys. Rev. B **58** (1998) 8079.
3) P. A. Lee and T. V. Ramakrishnan: Rev. Mod. Phys. **53** (1985) 287.
4) B. L. Altshuler, A.G. Aronov, A. I. Larkin, and D. E. Khmel'nitskii: JETP **54** (1981) 411.
5) B. L. Altshuler and A. G. Aronov: JETP Lett. **33** (1981) 499.
6) Yu. F. Komnik, E. I. Bukhshtab, Yu. V. Nikitin, and V. V. Andrievskii: JETP **33** (1971) 364.
7) M. I. Dyakonov and V. I. Perel: JETP **33** (1971) 1053.
8) V. A. Froltsov: Phys. Rev. B **64** (2001) 045311.