The Anti-Localization Effect in Bi Thin Films

F. Komori, S. Kobayashi and W. Sasaki

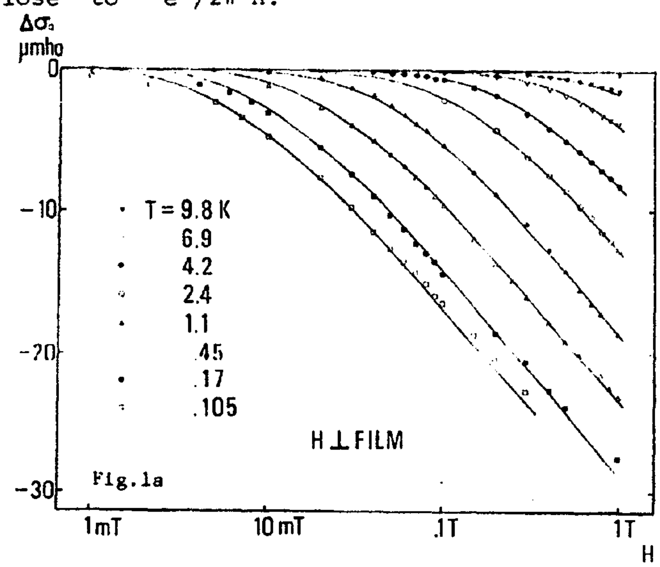
Department of Physics, Faculty of Science,

University of Tokyo

Recently we studied electronic conduction in high resistive thin metal films[1,2] and found that both the localization[3,4] and the interaction[5,6] effects contribute to the temperature and magnetic field dependence of the conductivity. It was also found that spin-orbit interaction and spin-flip scattering[7] are important in the loclaization mechanism[8,9], which is the main origin of the magnetic field dependence. A number of similar experiments reported up to the present could be interpreted on the same line. However the temperature dependence of the conductivity due to the localization effect has not been clearly observed especially for the films with strong spin-orbit interaction. It is theoretically predicted that the conductivity of these films increases with decreasing temperature as lnT. This effect can be called the anti-localization. In this paper we will show experimental evidences of the anti-localization in Bi thin films.

The films are deposited in a vacuum of 10^{-6} Torr onto glass substrates at room temperature with the thickness of 80 - 120 A. The conductivity of the film ranges from 0.5 to 2 mmho at 4.2 K. All the samples thus prepared show similar temperature and magnetic field dependence, and we will show here the results for a typical Bi film with the thickness of 90 A.

Figure 1a and 1b show the magnetic field dependence of the sheet conducticity $(\Delta\sigma_\square(H) = \sigma_\square(H) - \sigma_\square(0))$ of the Bi film at various temperatures. The field is perpendicular (a) and parallel (b) to the film. In both directions of the magnetic field at low temperatures, lnH dependence is observed though there is an anisotropy with respect to the direction of the field. The coefficient of the lnH term in parallel field is about twice as large as that in perpendicular field, and is very close to $-e^2/2\pi^2\hbar$.



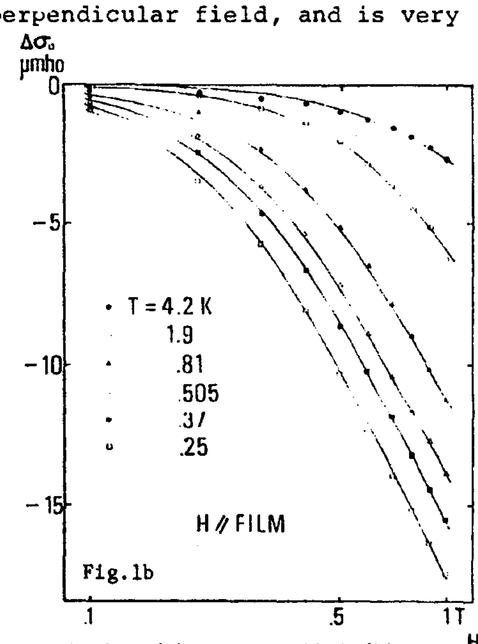


Fig.1 Sheet conductivity of a Bi film vs. magnetic field perpendicular (a) and parallel (b) to the film at various temperatures. Here $\Delta\sigma_\square = \sigma_\square(H) - \sigma_\square(0)$, and $\sigma_\square(0)$'s are given in Fig.2. Solid lines are theoretical curves calculated from eq.1 (a) and eq.2 (b) with parameters given in the text.

Figure 2a and 2b show the temperature dependence of the conductivity of the same sample in various magnetic fields; the field is perpendicular (a) and parallel (b) to the film. Logarithmic temperature depndence of the conductivity is observed below 1.5 K in zero magnetic field. When the field is applied, the lnT dependence with a larger coefficient appears at low temperatures in both directions of the field. The temperature region of this lnT dependence grows as the field is increased, the value of the coefficient being almost constant.

From the theories of the localization [8,9,10,11] the expressions for the temperature and magnetic field dependence of the conductivity are given as

$$\sigma_\square(H_\perp, T) = \frac{-e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{1}{a\tau_0}\right) - \psi\left(\frac{1}{2}+\frac{4}{a\tau_{so}}\right) - \frac{1}{2\sqrt{1-\gamma}}\left\{\psi\left(\frac{1}{2}+\frac{2}{a\tau_{so}}\left(1+\sqrt{1-\gamma}\right)\right) - \psi\left(\frac{1}{2}+\frac{1}{a\tau_\varepsilon}+\frac{2}{a\tau_{so}}\left(1-\sqrt{1-\gamma}\right)\right)\right\}\right] + \text{const.} \quad (1)$$

in perpendicular field, and

$$\sigma_\square(H_\parallel, T) = \frac{e^2}{4\pi^2\hbar}\left[2\ln\left(1+\frac{t^2 a\tau_{so}}{48\ell_H^2}\right) + \frac{1}{\sqrt{1-\gamma}}\ln\left(1+\sqrt{1-\gamma}+\frac{t^2 a\tau_{so}}{24\ell_H^2}\right) - \frac{1}{\sqrt{1-\gamma}}\ln\left(1-\sqrt{1-\gamma}+\frac{\tau_{so}}{2\tau_\varepsilon}+\frac{t^2 a\tau_{so}}{24\ell_H^2}\right)\right] + \text{const.} \quad (2)$$

in parallel field. Here τ_0 is elastic scattering time, τ_{so} spin-orbit scattering time, τ_ε inelastic scattering time, $\psi(x)$ the di-gamma function, $a = 4D/\ell_H^2$, $\ell_H^2 = c\hbar/eH$, D the diffusion constant, $\gamma = (g\mu_B H\tau_{so}/2\hbar)^2$, t the film thickness, and g the carrier g-factor. In these expressions we assume that τ_{so} is isotropic and much shorter than τ_ε. In the theories the conductivity depends on temperature through τ_ε, which is known to be proportional to T^{-P} where P is 1, 2, 3 or 4 depending on the nature of the film and temperature region [3,12].

Solid lines in Fig.1 are the theoretical curves of $\Delta\sigma_\square(H)$ calculated from eqs. 1 and 2 respectively, where we use parameters as follows; $D = 10 cm^2/sec$, $\tau_0 = 1.6 \times 10^{-13}$ sec, $\tau_{so} = 4 \times 10^{-13}$ sec and τ_ε's are determined to be consistent with the experiment as shown in Fig.3. We set t = 180

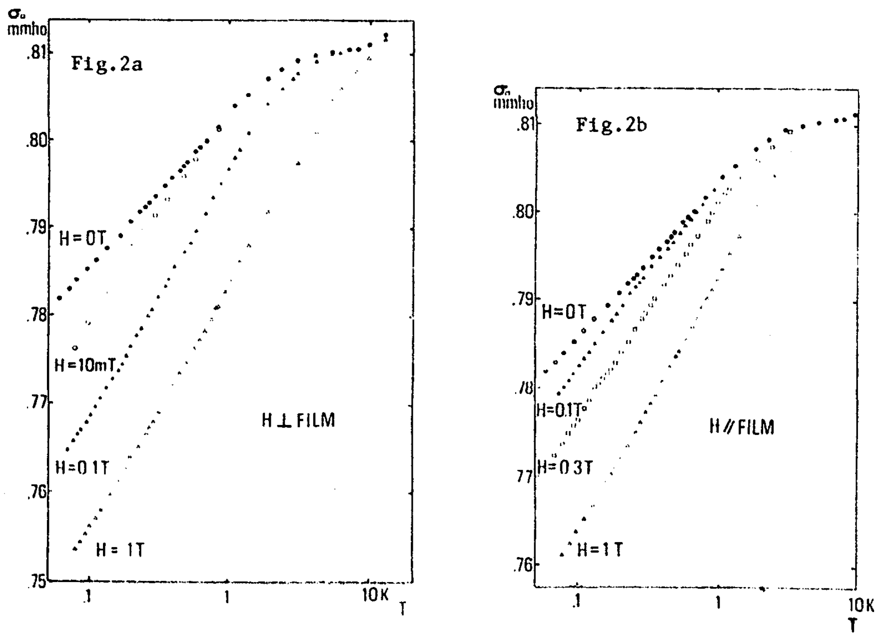


Fig.2 Sheet conductivity of the Bi film vs. temperature in various magnetic field perpendicular (a) and parallel (b) to the film.

A, the double value of the deposited thickness, to make the results in the parallel field consistent with those in perpendicular field. This factor of 2 is almost common both in Bi films and in noble metal films[2]. We also assume here that g-factor of the film is isotropic and equal to 2 because of the polycrystal structure of the film.* If we take a large value of the g-factor as that of bulk single crystal Bi, the amplitudes of the theoretical curves and the coefficient of the lnH term are reduced.

The experimental data in both directions of the field can be well reproduced with the above parameters as shown in the figures.

From these analyses the exponent P of the temperature dependence of τ_ε is determined to be 1 below 1.5K and the change of P to 2 is observed in high temperatures as seen in Fig.3. This change of P was theoretically predicted in dirty two-dimensional metals[12,13].

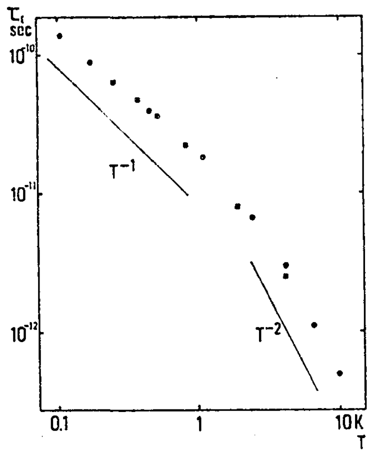


Fig.3 Temperature dependence of inelastic scattering time (τ_ε) deduced from the data shown in Fig.1a (●) and 1b (■).

The Coulomb interaction between electrons can also cause the change in $\Delta\sigma_{\parallel}(H)$. However, judging from the successful fitting only by the localization theories, we conclude that interaction effect contribute little to $\Delta\sigma_{\parallel}(H)$.

The lnT term of the conductivity due to both the localization and the interaction between electrons is summarized[14] as $(e^2/2\pi^2\hbar)(-P/2+1-3F/4)\ln T$ in zero magnetic field and $(e^2/2\pi^2\hbar)(1-F/4)\ln T$ in the field higher than $4\pi k_B T/g\mu_B$ and $\hbar c/4eD\tau_\varepsilon$, here $\tau_{so} \ll \tau_\varepsilon$ and τ_ε is assumed to be proportional to T^{-P}.

From the data shown in Fig.2, the coefficient of the lnT term in H = 1T is almost equal to $e^2/2\pi^2\hbar$ and that in zero magnetic field is $0.6\times(e^2/2\pi^2\hbar)$. These values agree well with the above equations if we take $P \simeq 1$ and $F \simeq 0$. This value of P is consistent with the data in Fig.3.

The deviation from the lnT dependence above 1.5 K in zero magnetic field is related to the change of the temperature dependence of τ_ε, and is consistent with the localization theories in which the lnT dependence of the conductivity does not appear unless τ_ε is proportional to T^{-P}. Furthermore it is expected in the theories that when P = 2 and F = 0 the temperature dependence of the conductivity vanishes in zero magnetic field. On the other hand the lnT term, arising only from the Coulomb interaction, continues in H = 1T. This trend is actually observed above 4 K as seen in Fig.2.

From all these results we conclude that the anti-localization effect due to the strong spin-orbit interaction does exist in the Bi films. The other lnT term with

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* Kochowski and Oplitski[15] studied the electric conduction of Bi films prepared by a similar method. They found that the major carrier is hole, and that the carrier number is about $2 \times 10^{19}/cm^3$ below 100 K though this value is much larger than that in bulk Bi. Judging from the measurement of the Hall effect of our films, their conclusion can also be adopted for our films, and this may reduce the value of g-factor from the bulk one to 2.

the opposite sign arising from the Coulomb interaction coexists with this, and consequently the observed sign of the lnT term is positive. When the additional conductivity due to the localization mechanism depends weakly on temperature because of a small amount of magnetic impurity[7,16] or by some other reasons, it is hard to observe the anti-localization effect. This is the reason why we did not observe the effect in noble metal films[2] while the positive magnetoresistance due to the localization effect appears in them.

Very recently we have observed superconductivity in Bi films which are prepared by the same method with the thickness of more than 120 A. The transition temperature is estimated to be below 100 mK. The superconductivity can affect the localization and the interaction effects, and therefore for these films we should take all the effects into account. However, for the film discussed above, any sign of superconductivity is not observed down to 80 mK, and we have analyzed the results ignoring the superconductivity. The influence of the superconductivity is small when the transition temperature is much lower than the temperature region where the conductivity of the film is studied.

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