"Weak" localization and electron scattering in silver thin films

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Measurements of the anomalous dependence of the resistance of silver thin films on the magnetic field and the temperature reveal the temperature dependence of the scale time for inelastic electron scattering. The spin relaxation times are also found.

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The particular ways in which electron localization in disordered systems manifests itself depend on the effects of the various relaxation mechanisms for the electron energy

and spin, so that an experimental study of "weak" localization can yield important information about electron scattering processes (see, for example, Ref. 1 and the papers cited there).

In two-dimensional disordered films [with a thickness d no greater than the diffusion length $L_\varphi = (D\tau_\varphi)^{1/2}$ corresponding to the relaxation time τ_φ of the phase of the electron wave function] the localization component of the resistance in a magnetic field directed perpendicular to the plane of the film ($H_\perp$) is suppressed at $H \gtrsim \Phi_0/4\pi L_\varphi^2$, where Φ_0 is the quantum of magnetic flux. This effect gives rise to a negative magnetoresistance. The phase relaxation of the wave function is determined by inelastic scattering over the time τ_ϵ and by scattering accompanied by spin flip at paramagnetic impurities with a characteristic time τ_s, i.e., $\tau_\varphi^{-1} = \tau_\epsilon^{-1} + \tau_s^{-1}$. The strong spin-orbit interaction during elastic scattering by impurities ($\tau_{so} \ll \tau_\varphi$, where τ_{so} is the scale time for the spin relaxation caused by the spin-orbit interaction) changes the nature of the $R(H)$ dependence and gives rise to a positive magnetoresistance at fields $H \lesssim \Phi_0/4\pi L_\varphi^{*2}$, where $L_\varphi^* = (D\tau_\varphi^*)^{1/2}$ and $\tau_\varphi^{*-1} = \tau_\varphi^{-1} + 2\tau_{so}^{-1}$. A theoretical expression for the $R(H_\perp)$ dependence has been derived for the case of a spin-orbit interaction[1]:

$$\frac{R(0) - R(H)}{R(0)} = \frac{e^2 R_\square}{2\pi^2 \hbar} \left\{ \frac{3}{2} f\left(\frac{4\pi L_\varphi^{*2}}{\Phi_0} H\right) - \frac{1}{2} f\left(\frac{4\pi L_\varphi^2}{\Phi_0} H\right) \right\}, \quad (1)$$

where $R_\square$ is the surface resistivity of the film, $f(x) = \ln x + \psi(1/2 + 1/x)$, and $\psi(y)$ is the logarithmic derivative of the Γ function. In simple metallic systems (having a single type of charge carrier and no multivalley effects), the $R(H)$ dependence is thus determined by the relationships among the times τ_ϵ, τ_s, and τ_{so}.

In the present experiments we studied silver films with a thickness $d = 20$–120 Å and a surface resistivity $R_\square = 3$–200 Ω, synthesized by rf sputtering of pure silver (99.99%) in argon on room-temperature glass substrates. The procedure for determining the properties of the samples has been described elsewhere[2] (for the case of copper films). The measurements were carried out with a direct current (at a field $E \lesssim 0.1$ V/cm). The voltage across the sample was measured by a digital voltmeter with a sensitivity of 10^{-7} V. To improve the accuracy of the measurements, a photolithographic technique was used to fabricate from the films narrow strips (10 μm wide) up to 20 cm long in the form of a meander line. The magnetoresistance was measured over the temperature range 1.4–40 K with the help of a superconducting solenoid having a maximum field ~60 kOe.

Figure 1 shows, for several temperatures, the dependence of the resistance on the strength of a magnetic field oriented perpendicular to the plane of the film for a sample with $d \cong 60$ Å and $R_\square$ (4.2 K) = 17.86 Ω. The electron mean free path in this sample was $l \cong 50$ Å. The solid curves in Fig. 1 are theoretical, plotted from Eq. (1); as adjustable parameters for fitting the theoretical curves to the experimental data, we used the times τ_φ and τ_φ^* shown in Fig. 2. The good agreement between the experimental data in fields $H > \pi ckT/2eD$ and the theory ignoring the electron-electron interaction is evidence that the interaction constant in silver is small at a small total momentum $g(T)$. As the temperature is lowered, there is a transition from the single-paramater curves $R(H_\perp)$ ($\tau_\varphi = \tau_\varphi^*$) obtained at $T > 10$ K to two-parameter curves ($\tau_\varphi \neq \tau_\varphi^*$) at $T \lesssim 10$ K. This behavior results from a transition from the case $\tau_\varphi \ll \tau_{so}$ to $\tau_\varphi \gg \tau_{so}$. The temperature dependence of

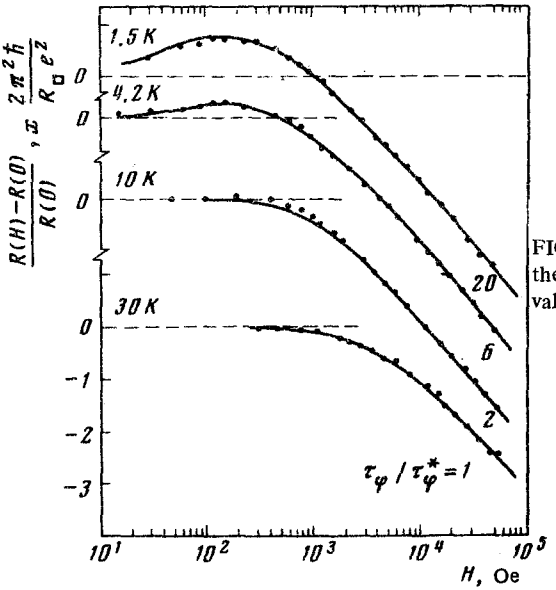

FIG. 1. The $R(H_\perp)$ dependence. Solid curves–theoretical, calculated from Eq. (1) with the values of τ_φ and τ_φ^* shown in Fig. 2.

τ_φ indicates that the primary mechanism for the relaxation of the electron wave function at $T \gtrsim 5$ K is inelastic scattering. This inelastic scattering of the electrons is apparently a scattering by two-dimensional phonons (for films of thickness $d \cong 60$ Å, the condition under which thermal phonons may be regarded as two-dimensional, $T \lesssim 2\pi\hbar v_{ac}/kd$, where v_{ac} is the sound velocity, is satisfied at $T \lesssim 30$ K). The experimental value found for the index p in the dependence $\tau_\varphi \sim T^{-p}$ is approximately equal to the value expected for this case, $p = 2$ (Fig. 2). In the temperature range studied, electron–electron scattering

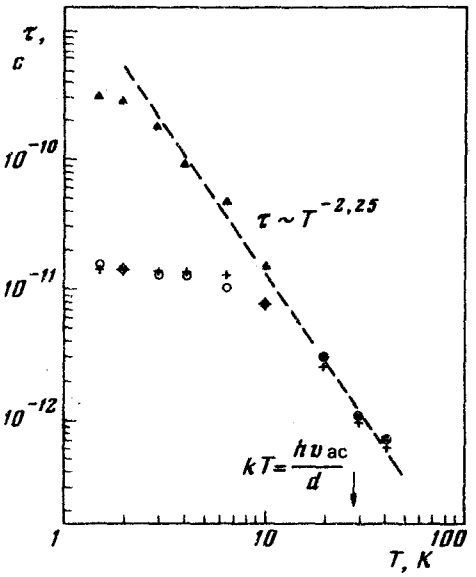

FIG. 2. $\tau_\varphi(T)$ and $\tau_\varphi^*(T)$. ▲, ○–Experimental values of τ_φ and τ_φ^*, respectively; +–values of τ_φ^* calculated from τ_φ and $\tau_{so} = 3 \times 10^{-11}$ s.

does not have any important effect on τ_φ; in the two-dimensional case $[d \ll (\hbar D/kT)^{1/2}]$, it leads to a dependence[3] $\tau_e^{ee} \sim T^{-1}$. The absolute values of τ_φ varied only slightly from film to film, lying in the range $(5\text{-}20) \times 10^{-11}$ s at $T = 4.2$ K. The slowing of the increase in $\tau_\varphi(T)$ at $T \lesssim 2\text{-}5$ K observed for several samples apparently results from a limitation imposed on τ_φ by the temperature-independent scale time for electron scattering with spin flip. For all the samples studied, the values of τ_s exceed $\sim 2 \times 10^{-10}$ s. [For the sample whose $\tau_\varphi(T)$ dependence is shown in Fig. 2, this time is $\tau_s \cong 3 \times 10^{-10}$ s.]

Through an independent determination of τ_φ and τ_φ^* we can determine τ_{so} in these films. Figure 2 shows, along with the experimental values of τ_φ^*, values calculated for τ_φ^* from the experimental values of τ_φ and from the temperature-independent value $\tau_{so} = 3 \times 10^{-11}$ s. For the pure films, τ_{so} is essentially independent of the thickness, lying in the range $(2\text{-}5) \times 10^{-11}$ s. Contamination of the films by impurities having a large atomic number Z (when films were deposited in an apparatus which had been used immediately beforehand for the deposition of lead) led to a decrease in τ_{so} by about an order of magnitude, with no change in τ_φ. This fact, combined with the nonmonotonic Z dependence observed for τ_{so} in various metals [in pure Mg ($Z = 12$), $\tau_{so} = 1.7 \times 10^{-10}$ s (Ref. 4); in Cu ($Z = 29$); $\tau_{so} \cong 3 \times 10^{-12}$ s (Ref. 2); in Ag ($Z = 47$); $\tau_{so} \cong (2 - 5) \times 10^{-11}$ s], shows that the spin-orbit interaction is determined primarily by impurities in the copper and silver films studied by us.

The index p in the expression $\tau_\varphi \sim T^{-p}$ can be determined independently by comparing the coefficients (A) of the logarithmic component of the resistance of the disordered thin films $[R(T_1) - R(T_2)]/R(T_1) = A(e^2 R_\square / 2\pi^2 \hbar) \ln(T_2/T_1)$, in the cases $H = 0$ and $H \gg \Phi_0/4\pi L_\varphi^2$. This logarithmic component results from the joint manifestation of localization and the electron-electron interaction. In an analysis of the theoretical function[2,5]

$$\frac{R(T_1) - R(T_2)}{R(T_1)} = \frac{e^2 R_\square}{2\pi^2 \hbar} \left\{ (1 - F) \ln \frac{T_2}{T_1} + \frac{3}{2} \ln \frac{\tau_\varphi^*(T_1)}{\tau_\varphi^*(T_2)} - \frac{1}{2} \ln \frac{\tau_\varphi(T_1)}{\tau_\varphi(T_2)} \right\} \tag{2}$$

it should be noted that for most of the films which have been studied the logarithmic region in the $R(T)$ dependence is observed in a temperature range in which the spin-orbit interaction is strong ($\tau_{so} \ll \tau_\varphi$) and τ_φ^* is only a weak function of T; the second term in this expression makes essentially no contribution to A. At $H = 0$ we expect $A = 1 - F - p/2$, while at $H > \Phi_0/4\pi L_\varphi^2$ the temperature dependence of the localization component of the resistance should be suppressed, and A should increase to $1 - F$. For films in which $\tau_\varphi(T)$ does not retard the increase at low temperatures, we do in fact observe a change in A, from $A \cong 0$ at $H = 0$ to $A \approx 1.1 \pm 0.1$ at $H > \Phi_0/4\pi L_\varphi^2$. These results correspond to the value $p \cong 2$ and are in agreement with the value found for p from the $R(H_\perp)$ dependence. We might note that the value $A \sim 1$ at $H > \Phi_0/4\pi L_\varphi^2$ indicates that the screening parameter F in these films is small. For the sample whose $\tau_\varphi(T)$ dependence is shown in Fig. 2, a logarithmic dependence $R(T)$ is observed at $T \lesssim 6$ K. Because of the decrease in p in this temperature range, caused by the onset of spin-flip scattering, the increase in A with increasing H is less pronounced: from $A \cong 0.7$ at $H = 0$ to $A \cong 1.2$ at $H > \Phi_0/4\pi L_\varphi^2$.

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