Effects of Zeeman splitting on weak antilocalization

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The magnetoresistance of Au-doped indium oxide metallic films exhibits an isotropic component. This is interpreted as evidence for the destruction of weak antilocalization due to the interplay between the Zeeman effect and spin-orbit scattering.

Quantum-mechanical contributions to the low-temperature electron transport in the diffusive regime have been extensively studied during the past decade. Within the single-particle picture, the most significant quantum-mechanical correction arises from the interference between time-reversed paths, called backscattering. The sign of the correction is either positive or negative, depending on the relative strength of the spin-orbit (SO) scattering.[1] Application of a magnetic field affects this quantum interference causing magnetoresistance (MR). This is commonly attributed to the Aharonov-Bohm (AB) effect. But, the AB effect is not the only way a magnetic field can influence backscattering: In 1981, Maekawa and Fukuyama[2] suggested that when SO scattering is present, the Zeeman splitting due to an applied field may play a similar role. The symmetry of the time-reversed paths is broken by the Zeeman splitting if their spin states are not identical everywhere. This mechanism, which requires finite SO scattering, yields MR which is always positive. An essential difference between these sources of MR is that the first is flux driven, whereas the latter depends only on the magnetic-field strength. Applying a magnetic field in parallel to a thin enough film will differentiate between the two mechanisms since, in such a case, the flux through time-reversed paths will be small, even though the field is not. In this Brief Report we report on the results of a systematic experiment which give clear evidence for the existence of the Maekawa-Fukuyama MR mechanism.

Samples used in this study were thin films of In_2O_{3-x} prepared in the following manner: Pure (99.997%) In_2O_3 was evaporated from an electron-gun source onto two glass slides simultaneously. This was followed by evaporation of 2 Å mass equivalent of Au from a Knudsen source onto one of the slides in order to introduce SO scattering.[3] The films were then removed from the vacuum system and crystallized as described elsewhere.[4] Magnetoresistance measurements of the samples were done with a standard four-probe technique. Magnetic fields of up to 0.7 T were applied using a split-coil electromagnet. The cryostat used can be rotated in the magnetic field, enabling the measurement of perpendicular and parallel MR at the same cool-down.

Figure 1 depicts the conductance as a function of temperature, $G(T)$, of the doped and undoped samples. Both curves conform to a $\ln(T)$ law as expected of weakly localized, two-dimensional systems.[1]

Figure 2 shows the perpendicular and parallel MR of the undoped sample. It is observed that in the entire range of fields and temperatures studied and for *both* field orientations, the MR is purely negative. These MR data can be explained by weak-localization theories (without the need to include electron-electron interactions, spin-flip, or spin-orbit terms in the analysis in agreement with previous[5] studies of undoped In_2O_{3-x} metallic samples).

The data in Fig. 2 were fitted to

$$\frac{\Delta R}{R}=\frac{e^2R_\square}{2\pi^2\hbar}\left[\psi\left(\frac{L_H^2}{L_0^2}+\frac{1}{2}\right)-\psi\left(\frac{L_H^2}{L_\phi^2}+\frac{1}{2}\right)-\ln\left(\frac{L_0^2}{L_\phi^2}\right)\right] \tag{1a}$$

for perpendicular fields and

$$\frac{\Delta R}{R}=-\frac{e^2R_\square}{2\pi^2\hbar}\left[\ln\left(1+\frac{L_\phi^2d^2}{12L_H^4}\right)\right] \tag{1b}$$

for parallel fields, where $R_\square$ is the film sheet resistance, d is its thickness, L_0, L_ϕ, and L_H are the elastic, inelastic, and magnetic lengths, respectively. The resulting fitting parameters (Fig. 2) are clearly plausible.

The flux-driven nature of the MR can be easily demonstrated in this particular case: We have found that when

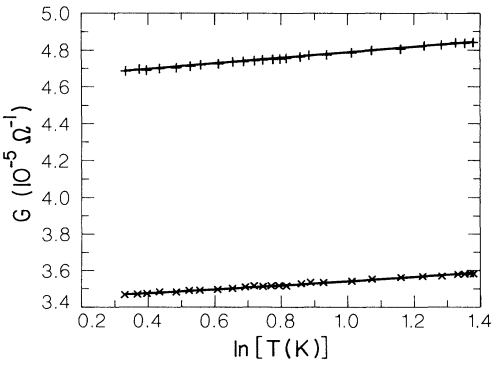

FIG. 1. Conductance vs temperature for two 80-Å-thick samples. One sample is doped with an additional 2 Å mass equivalent of gold (+). The other is undoped (×).

the MR curves are plotted against the flux through time-reversed paths, HL_ϕ^2 for perpendicular fields and $HL_\phi d$ for parallel fields, the two sets of data nearly coincide.

In contrast, this simple behavior is not followed by the sample with SO scattering. The MR of the Au-doped sample are plotted in Figs. 3(a) (perpendicular field) and 3(b) (parallel field). These data exhibit qualitatively different behavior. Not only is the temperature dependence radically different, but, interestingly, the perpendicular and parallel MR have *opposite* signs for weak enough fields. Obviously, no flux rescaling can cause the two graphs to overlap. We now show that this seemingly dramatic finding actually follows from the Maekawa-Fukuyama mechanism.

Including the Maekawa-Fukuyama term in the MR expressions results in

$$\frac{\Delta R}{R}=\frac{e^2R_\Box}{2\pi^2\hbar}\left\{\psi\left[\frac{\tau_H}{\tau_0}+\frac{1}{2}\right]-\psi\left[\frac{\tau_H}{\tau_1}+\frac{1}{2}\right]-\frac{1}{2\sqrt{1-\gamma}}\left[\psi\left[\frac{\tau_H}{\tau_+}+\frac{1}{2}\right]-\psi\left[\frac{\tau_H}{\tau_-}+\frac{1}{2}\right]\right]-\ln\left[\frac{\tau_0}{\tau_1}\right]\right\} \tag{2a}$$

for perpendicular fields and

$$\frac{\Delta R}{R}=-\frac{e^2R_\Box}{2\pi^2\hbar}\left\{\ln\left[\frac{\tau_0}{\tau_1}+\frac{D\tau_0d^2}{3L_H^4}\right]+\frac{1}{2\sqrt{1-\gamma}}\left[\ln\left[\frac{\tau_0}{\tau_+}+\frac{D\tau_0d^2}{3L_H^4}\right]-\ln\left[\frac{\tau_0}{\tau_-}+\frac{D\tau_0d^2}{3L_H^4}\right]\right]-\ln\left[\frac{\tau_0}{\tau_1}\right]\right\} \tag{2b}$$

for the parallel orientation. Here,

$$\tau_1^{-1}=\tau_\phi^{-1}+4\tau_{\rm SO}^{-1},$$

$$\tau_\pm^{-1}=\tau_\phi^{-1}+2\tau_{\rm SO}^{-1}(1\pm\sqrt{1-\gamma}),$$

$$\gamma=\left[\frac{g\mu H}{2\hbar}\tau_{\rm SO}\right]^2,$$

$$\tau_n=\frac{L_n^2}{4D},\quad n=\phi,{\rm SO},H,0\ .$$

Results of theoretical best fits using Eqs. (2a) and (2b) are depicted in Figs. 3(a) and 3(b). Also, the effect of the Zeeman term is illustrated in Fig. 3(b) by plotting the expected MR without its inclusion. Evidently, the Zeeman-splitting term is crucial for reproducing the posi-

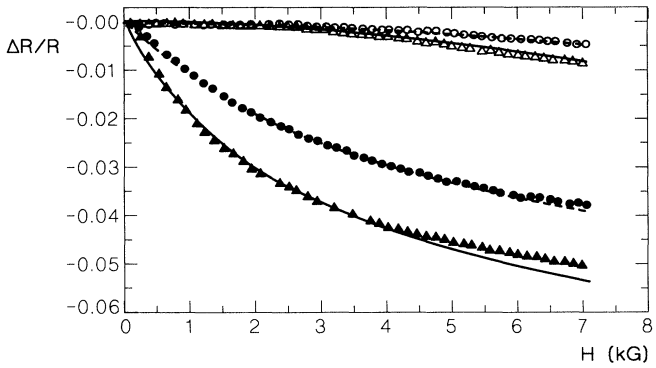

FIG. 2. MR for the undoped sample. ●, perpendicular orientation, $T=4.1$ K; ○, parallel orientation, $T=4.1$ K; ▲, perpendicular orientation, $T=1.4$ K; △, parallel orientation, $T=1.4$ K. The solid line is a theoretical fit for $T=1.4$ K based on Eq. (1) with $L_\phi=2900$ Å. The dashed line is for $T=4.1$ K ($L_\phi=2050$ Å). The actual film thickness ($d=80$ Å) and the measured elastic length ($L_0=20$ Å) were used in the calculations.

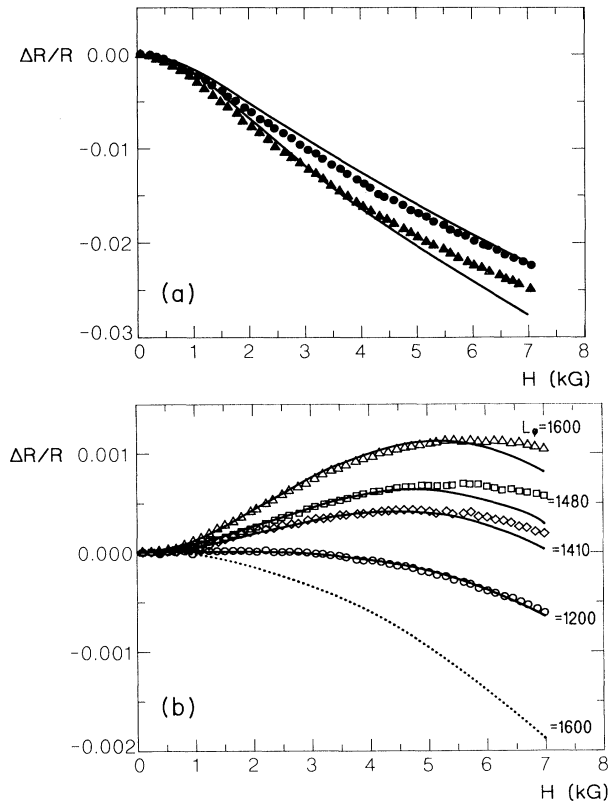

FIG. 3. (a) Perpendicular MR for the Au-doped sample. ●, $T=4.1$ K; ▲, $T=1.4$ K. The lines are best fits calculated using Eq. (2a) with $L_{\rm SO}=3600$ Å, $L_0=20$ Å. $L_\phi=1200$ and 1600 Å for 4.1 and 1.4 K, respectively. The data at intermediate temperature and their best fits were omitted for clarity. (b) Parallel MR for the sample in (a). △, $T=1.4$ K; □, $T=1.7$ K; ◇, $T=2.17$ K; ○, $T=4.2$ K. The solid lines are best fits calculated using Eq. (2b) with $L_{\rm SO}=3600$ Å, $L_0=20$ Å, $d=80$ Å, and $D=2.2$ cm^2/sec. The dotted line is the best fit for 1.4 K using the same parameters as above but neglecting the Zeeman-splitting term.

tive parallel MR [see Fig. 3(b)] but it has a small effect on the perpendicular MR. L_ϕ in this sample is about 60% smaller than the respective value of the "control" (undoped) sample. We attribute this difference to the increased disorder in the Au-doped sample. The diffusion constant, estimated[6] from the measured charge density N and the sheet resistance $R_\square$, is smaller by 60% in the doped material. It is also conceivable that some of the Au impurities act as inelastic-scattering sources (through, e.g., local phonon modes). We note that in the fitting routine, D was taken as a parameter for the parallel MR data (the MR shape is extremely sensitive to the precise value of D). The best-fit value [Fig. 3(b)] was found to be a factor of 2 bigger than the calculated one. On the other hand, d was fixed to the *same* value as in the undoped sample and a constant value of L_{SO} was used for the entire temperature range and for both field orientations. Thus, the fitting is highly nontrivial and should be regarded as being quite reasonable and suggestive. The fits of the Au-doped sample are not as good as those obtained for the undoped sample. Such a problem has been encountered in previous studies[2,7] and it may reflect a dependence of either L_ϕ or L_{SO} on the magnetic-field strength.[8]

Naturally, any isotropic, positive MR mechanism might serve to explain our data. For instance, the MR due to electron-electron interactions[9] is positive and isotropic and therefore might be a possible alternative explanation. We have estimated the contribution of the MR due to interaction and found it to be at least an order of magnitude smaller than the observed effect. More importantly, by reference to the "control" sample (where no positive MR is observed), one has to conclude that the mechanism involved is related to the Au doping. To assume that the electron-electron MR is enhanced by Au-doping seems highly artificial.

There are several reasons why the Zeeman-splitting term is more prominent in our experiment than in previous studies.[10] As pointed out by Bergmann,[3] the relative importance of the Zeeman term involves the parameter h/mD which is close to unity in the present work (m in In_2O_{3-x} is[11] $0.3m_0$ and D is ≈ 1 cm^2/sec). In addition, rather stringent conditions must be fulfilled in order to observe purely negative MR for perpendicular fields and positive MR for parallel fields: Small AB flux is required for parallel fields which means that $L_\phi d \ll L_H^2$. At the same time, L_{SO} must be sufficiently larger than L_ϕ (in order to have only negative perpendicular MR) but small enough so that the Zeeman-splitting term will not be negligible. If these conditions are not met the influence of the Zeeman-splitting term will be less dramatic. To test this line of reasoning, we have prepared another sample with somewhat larger thickness and an increased Au content. Figure 4 shows the perpendicular and parallel MR of a 120-Å-thick In_2O_{3-x} sample doped with 3 Å Au. Positive MR is now observed at low fields for both field orientations so the case for an isotropic component in MR is not as apparent.

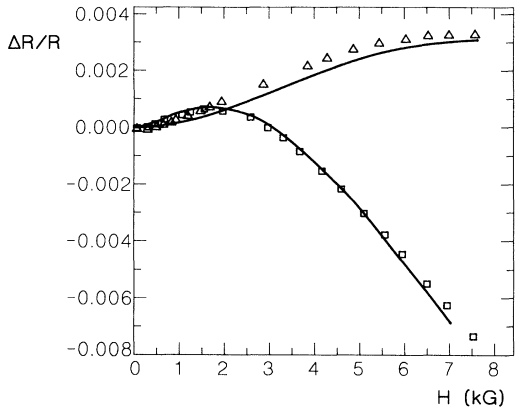

FIG. 4. Perpendicular and parallel MR for a 120-Å-thick sample doped with 3 Å mass equivalent of gold at 1.4 K with $R_\square = 4.5$ kΩ. The lines are best fits calculated using Eq. (2) with $L_\phi = 890$ Å, $L_{SO} = 1700$ Å, and $D = 0.8$ cm^2/sec.

In summary, we have presented clear and systematic evidence for the relevance of the Zeeman-splitting term in controlling weak-antilocalization effects. Our results establish the conditions under which such effects are most prominent, which should be valuable for studies of systems with restricted geometries.

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[6] The diffusion constant is given by $D = \frac{1}{4}(V_F^2\tau_0)/3 = (3\pi^2/12)(h/e^2)(RdN^{1/3})^{-1}h/m \approx (3k\Omega/R)(Nd^3)^{-1/3}h/m$ (N is the electron density obtained from room-temperature Hall measurement). Using this relation we get $D \approx 1.6$ cm^2/sec for the undoped sample ($R \approx 2$ kΩ, $N \approx 9\times 10^{19}$ cm^{-3}) and $D \approx 0.9$ cm^2/sec for the Au-doped one ($R \approx 2.8$ kΩ, $N \approx 1.8\times 10^{20}$ cm^{-3}).

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[10]See, e.g., S. Kobayashi and F. Komori, Prog. Theor. Phys. **84**, 224 (1985), and references therein.

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