Observation of a Well Defined Transition from Weak to Strong Localization in Two Dimensions

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We have measured the low temperature $T \leq 20$ K magnetoconductance (MC) of ultrathin films that have strong spin-orbit interactions and conductances G spanning the weakly $G \gg G_{00} = e^2/2\pi^2\hbar$ and strongly localized $G \ll G_{00}$ regimes. For $G \gg G_{00}$, the MC is negative in agreement with weak localization theory, and for $G \ll G_{00}$, it is positive in accord with theories of electron hopping transport. The MC changes sign when $G \approx G_{00}$, independent of material and temperature. The data suggest that a well defined conductance separates the weak and strong localization regimes in two dimensions.

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One of the predictions of the scaling theory of localization is that no true metallic state exists in two dimensions (2D). This is because all electronic states in a disordered potential, no matter how weak the disorder, are localized in infinite 2D systems [1,2]. When the disorder is strong and consequently the length over which the conduction electron states are localized ξ is short, the effects of the localization are easy to observe. For instance, the conductance G exhibits an exponential temperature dependence because electron transport occurs via thermally activated hopping between the localized states [3]. On the other hand, in weakly disordered systems, ξ can be quite long, exceeding either the distance that an electron travels between events in which it is inelastically scattered to another state ℓ_{in} or the actual size of the sample L_s. Here, the conductance decreases only logarithmically with decreasing temperature [2,4,5]. To distinguish these regimes, the electrons in systems for which $\xi < \ell_{\text{in}}$ are "strongly localized" and those for which $\ell_{\text{in}} < \xi$ are "weakly localized." Thus, while no metal to insulator transition exists in 2D, the electronic states do evolve from a strongly localized to a more extended weakly localized form with decreasing disorder or, equivalently, increasing G [1,2]. Measurements of the temperature dependence of the conductance of 2D electron systems suggest that this evolution is gradual [6,7]. We present magnetoconductance (MC) measurements to show that, in fact, there is a well defined $G, \simeq e^2/2\pi^2\hbar \equiv G_{00}$, separating these two regimes.

A great deal of work has demonstrated that the magnetoconductance of disordered 2D systems, when the magnetic field is applied perpendicular to their planes, is dominated by quantum mechanical interference effects [5,8,9]. These effects and, therefore, the MC depend sensitively on whether the electronic states involved in transport are extended [5] or localized [8–14]. In systems with strong spin-orbit (SO) interactions, the difference between the MC in the weakly and strongly localized regimes is particularly clear. With this in mind, we performed systematic measurements of the low temperature $T \leq 20$ K MC of samples that have conductances spanning the weak and strong localization regimes. In the weak localization regime where $G \gg G_{00}$ we find that the MC, defined as $\Delta G/G(0) = [G(H) - G(0)]/G(0)$, of ultrathin Cu/Ge, Ag/Ge, and Au/Ge films is negative indicating that there is strong SO scattering in these films [5]. In the strong localization regime where $G \ll G_{00}$ it is positive. It changes sign at a well defined conductance $G \simeq G_{00}$ independent of material and temperature. This behavior suggests that there is a low temperature minimum metallic conductance in 2D and it has a universal value.

The Cu/Ge, Ag/Ge, and Au/Ge films used for these studies were thermally evaporated onto fire-polished glass substrates that were kept below 10 K. In all cases, approximately 6 Å of pure Ge was evaporated and the noble metals were deposited atop this layer. The Ge underlayer was necessary for producing ultrathin films with homogeneous properties down to $\sim$1 nm [6,7]. These metals were chosen because the SO interactions between the conduction electrons and the metal ions are known to be strong [5]. Through successive evaporations of the noble metal we are able to produce a series of samples with sheet conductances that cover the strongly to weakly localized regimes. Four terminal low frequency ac and dc transport measurements were done *in situ* at low temperatures $T \leq 20$ K. A superconducting solenoid surrounded the evaporator and produced a magnetic field up to 8 T perpendicular to the film.

The $G(T)$ of Cu/Ge, Ag/Ge, and Au/Ge from three experimental runs are plotted on a log-log scale in Fig. 1(a). Results from additional runs are similar. By rescaling the temperature axis for each film all of the data can be made to fall on a single smooth trajectory shown as the solid line [7]. Similar scaling has been observed in other systems, and its origin has been attributed to a marginal metal to insulator transition in two dimensions [7]. It is remarkable that a single scaling trajectory works for three different materials, but we will not pursue the implications of this scaling any further. The primary purpose of displaying the data in the scaled form is to demonstrate that the evolution of $G(T)$ from the strongly to weakly localized regimes is smooth and gradual.

The conductance as a function of temperature at the extremes, $G \gg G_{00}$ and $G \ll G_{00}$, can be understood in terms of established theories. Theoretically, in the weakly

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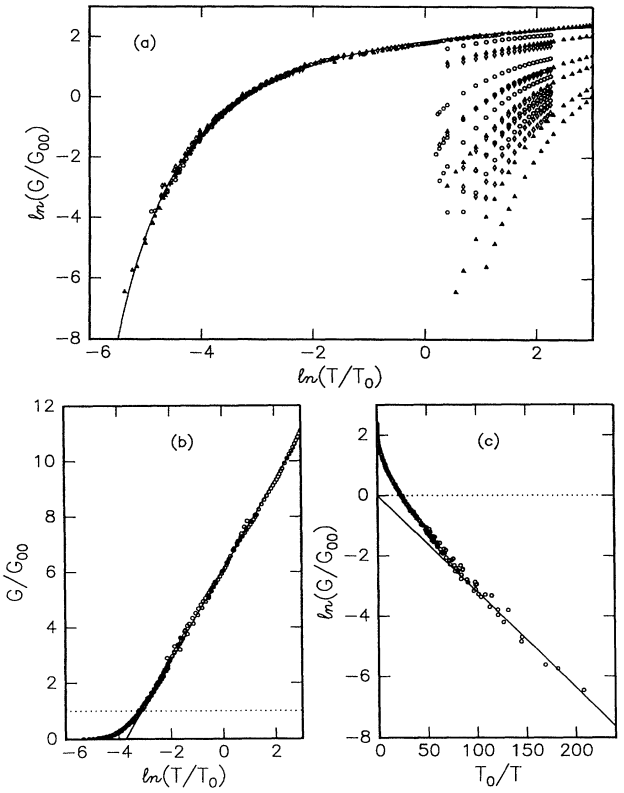

FIG. 1. (a) Sheet conductance in units of $G_{00} = e^2/2\pi^2\hbar$ versus temperature with $T_0 = 1$ K on logarithmic scales for Cu/Ge (circles), Ag/Ge (triangles), and Au/Ge (diamonds) films with thicknesses in the range $0.3 < t < 2$ nm. The solid curve and points on it were obtained by adjusting T_0 for each film described in Ref. [7]. (b) Semilogarithmic plot of G/G_{00} vs T^{-1} for the rescaled data. The line is a fit to the low G limit. (c) G/G_{00} vs $\ln(T)$ for the rescaled data. The line is a fit to the high G limit.

localized regime where $\xi > \ell_{in}$ and correspondingly $G \gg G_{00}$,

$$G(T) - G(T_e) = AG_{00}\ln(T/T_e), \quad (1)$$

where T_e is an arbitrary temperature and $A \sim 1$. This behavior stems from disorder enhanced e^--e^- interaction and quantum interference effects in 2D [2,4–6]. Far below G_{00}, the conductance is expected to have an exponential dependence on temperature,

$$G \propto \exp[-(T_0/T)^{\nu}], \quad (2)$$

that is, characteristic of systems where electron hopping between localized states dominates the conduction [3]. For Mott variable range hopping, $\nu = 1/3$ [12,14]. For variable range hopping with a soft gap in the density of states near the Fermi energy, $\nu = 1/2$ [11,12,14] and with a hard gap in the density of states $\nu = 1$ [15]. We compare the scaled data with these theories in Figs. 1(b) and 1(c). In the extremes, $G \gg G_{00}$ and $G \ll G_{00}$, $G(T)$ follows Eq. (1) with $A \simeq 1.4$ and approaches Eq. (2) with $\nu = 1$, respectively. For a range of conductances between these extremes, $G(T)$ is neither logarithmic nor exponential.

At low temperatures, the MC of ultrathin films with $G \gg G_{00}$ is dominated by weak localization effects [5]. These effects appear when the phase coherence time of the conduction electron states, which is usually determined by the inelastic scattering time, exceeds the time between electron-impurity elastic scattering events. In this regime, the partial waves generated by elastic impurity scattering events in between inelastic scattering events can interfere. This quantum interference reduces (increases) backscattering of the electrons from impurities and thereby, increases (decreases) the conductance from its Drude value in systems with (without) strong SO interactions. Applying a magnetic field perpendicular to a film reduces the electron phase coherence time, which destroys these interference effects and restores the conductance to its Drude value. In systems with strong SO interactions, therefore, the low field MC due to quantum interference is negative [5]. It becomes more negative with decreasing temperature as the inelastic scattering time increases.

In Fig. 2, we show typical data ΔG for a series of Ag/Ge films at $T = 3$ K. For $G > G_{00}$, at the lowest fields the MC is negative indicating that the SO scattering rate exceeds the inelastic scattering rate at this temperature. The data for films with $1/G = R < 2$ kΩ are well fitted by the theory of weak localization using reasonable parameters for the elastic, inelastic, and SO scattering rates [5]. The fits are shown as the dashed lines. Fits to data obtained at different temperatures yielded an inelastic diffusion length that increased with decreasing temperature as $\ell_{in} \propto 1/\sqrt{T}$ in agreement with other experiments [5]. Data from higher sheet resistance films could not be fit by weak localization theory. This is not surprising, however, as it only

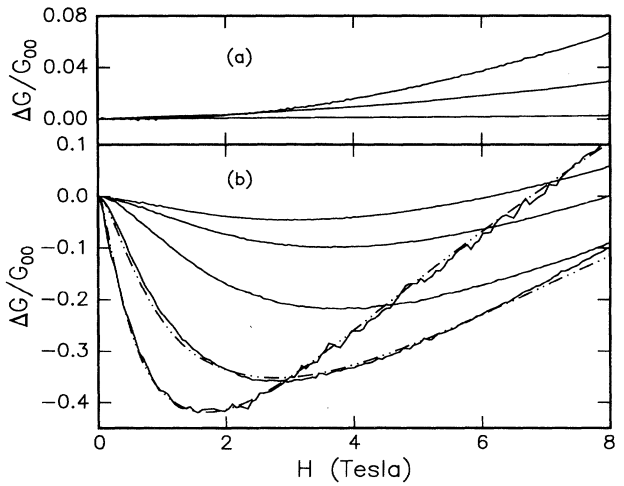

FIG. 2. ΔG in units of G_{00} as a function of magnetic field at $T = 3$ K for Ag/Ge films with conductances less than G_{00}. The sheet resistances at zero field are from top down: (a) 87, 283, 4000, (b) 13.8, 8.5, 3.9, 1.3, 0.57 kΩ. The dash-dotted lines are fits by weak localization theory [5].

applies to the weak disorder limit. Nevertheless, the field and temperature dependence of ΔG for films with $G > G_{00}$ qualitatively resembles the form expected for quantum interference effects in the presence of SO interactions and, hence, stems from the same physical effects. ΔG for films $G < G_{00}$ do not exhibit these field and temperature dependences. In particular, ΔG at low fields becomes more positive with decreasing temperature rather than more negative as expected (see discussion above). Models of the MC in strongly localized systems can account for this temperature dependence.

The orbital contribution to the MC in strongly localized 2D systems also emanates from quantum interference effects [12–14]. These effects were first described by Nguyen, Spivak, and Shklovskii, who pointed out that a given electron hop between localized states involves virtual transitions to nearby localized states [8,9]. Thus, a hop may occur via different trajectories which contain different sets of intermediate states. The most important trajectories are dominated by *forward* scattering by the intervening impurities because of the exponential spatial decay of the localized states. An applied magnetic field can change the probability of a hop by altering the relative phases of these trajectories. In particular, hops that have low probability because of destructive interference between trajectories become more probable in field. Theories that take the percolative nature of the transport into account indicate that the low probability hops primarily determine a sample's conductance and, therefore, applying a magnetic field increases a film's conductance [8]. Quantitatively, theories based on this picture predict that $\Delta G/G(0) \propto H^2$ at low fields and increases in size with decreasing temperature. For Mott variable range hopping, $\Delta G/G(0) \propto T^{-1}$ [12]. The predicted field dependence agrees with experiment, but there is some discrepancy between the measured and predicted temperature dependence [12].

Our data agree with this general picture when $G \ll G_{00}$. We show an example of this in Fig. 3 for a Cu/Ge film which had $\nu \simeq 1$. At low fields, the MC grows as the square of the magnetic field and assumes a weaker dependence at high fields. The region over which the quadratic dependence holds decreases in size with increasing sheet resistance. The slopes of fits to the H^2 dependence grow with decreasing temperature as $T^{-\beta}$ with $\beta \simeq 2$ for this film and ranging from 1 to 2 for all of the Cu/Ge, Ag/Ge, and Au/Ge films.

From the above, we conclude that the MC of all our films with $G \ll G_{00}$ is dominated by quantum interference effects. More importantly, from these data and additional measurements [16] we conclude that even with strong SO interactions, the MC is positive in strongly localized systems, unlike weakly localized systems. This is in agreement with the theory of Meir *et al.* [10]. This behavior points to the fundamentally different nature of the interference effects operating in weakly and strongly localized regimes.

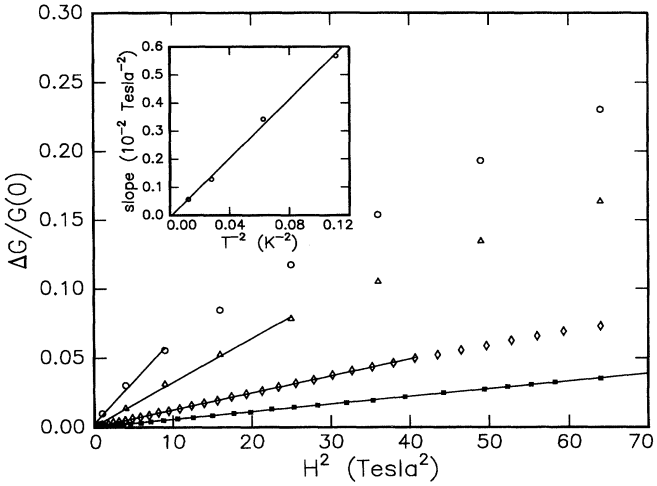

FIG. 3. The magnetoconductance of a single film with $G < G_{00}$ at different temperatures: $T = 3$ K and $R(0) = 1.06$ MΩ (circles); $T = 4$ K and $R(0) = 438$ kΩ (triangles); $T = 6$ K and $R(0) = 160$ kΩ (diamonds); $T = 9$ K and $R(0) = 89.2$ kΩ (solid squares). The solid lines are linear fits and the inset shows the slope of the fits as a function of $1/T^2$.

Because the MC must change sign between these two regimes, it is possible to determine the conductance above which extended states dominate and below which localized states dominate the MC [11]. We determine the corresponding sheet resistance $R^{\pm}$ for a given temperature by plotting the MC at 1 T as a function of sheet resistance. Data from three different experiments, two with Cu/Ge and one with Ag/Ge, at different temperatures are shown in Fig. 4(a). The smooth evolution of the data allows $R^{\pm}$ to be measured to ≃10% in all cases. That is, $R^{\pm}$ is well defined. Moreover, $R^{\pm}$ does not depend on the field at which it is measured provided it does not exceed the field at which the MC exhibits a minimum in the weakly localized regime. We demonstrate this in Fig. 4(b) by plotting the MC at three different fields.

We interpret $R^{\pm}$ as the boundary between the weakly and strongly localized regimes. Recent numerical calculations of Meir *et al.* support this conjecture [10]. These workers showed that at $T = 0$ the MC is negative in 2D electron systems with SO interactions for which $\xi > L_s$ and positive for $\xi < L_s$ where L_s is the system size. At finite temperatures, it has been argued that ℓ_{in} rather than L_s becomes the relevant physical length scale [2,6,11] for quantum coherence effects. Thus, Meir *et al.*'s criterion for where the MC changes sign coincides with where the transition from strong to weak localization occurs, i.e., $\xi \simeq \ell_{\text{in}}$. Furthermore, the data in Fig. 4(a) show that $R^{\pm}$ changes very little with temperature $1 \leq T \leq 6$ K and is independent of whether the films are Cu/Ge or Ag/Ge. Additional data on Au/Ge and at higher temperature $T = 9$ K are also consistent with this result. That is, $R^{\pm}$ assumes a constant value of 75 kΩ ± 10%. A constant $R^{\pm}$

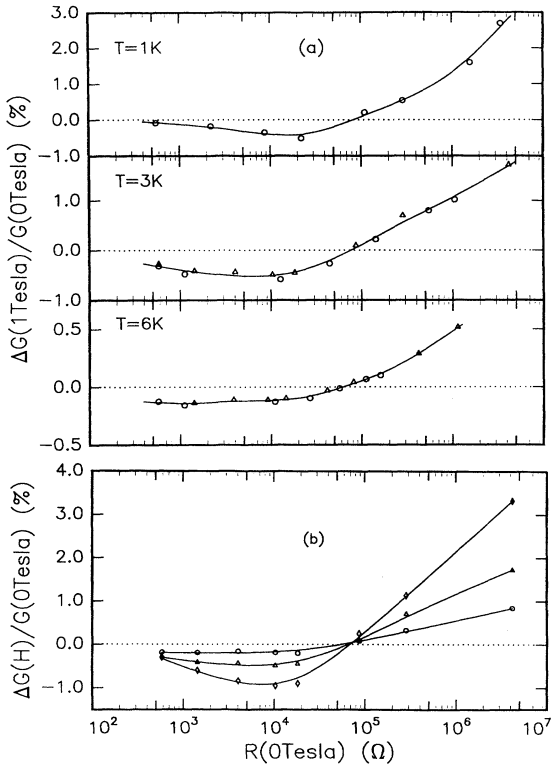

FIG. 4. (a) The magnetoconductance at 1 T as a function of sheet resistance for Cu/Ge (circles) and Ag/Ge (triangles) films. (b) The magnetoconductance as function of sheet resistance for a series of Ag/Ge films which are shown in Fig. 2 at 0.5 T (circles), 1 T (triangles), and 2 T (diamonds). The lines are guides to the eye.

cannot be understood from a simple extrapolation of weak disorder theory which would predict that ℓ_{in} and ξ would depend on temperature, film thickness, material, etc. For example, our fits showed that $\ell_{\text{in}} \sim 1/\sqrt{T}$ in the weak disorder limit.

We do not know why G_{min} assumes a value close to $e^2/2\pi^2\hbar$. It may be related to the fact that this value sets the scale for weak localization and electron-electron interaction effects in disordered systems. It is interesting to note that the insulator to quantum Hall state transition ($\nu = 2$) that has been observed in 2D electron gases also occurs near this conductance. In those systems the magnetic length, rather than ℓ_{in} and L_s, is compared to ξ to determine whether the transport exhibits strongly localized or quantum Hall state behavior [17].

Finally, Shapir and Ovadyahu observed a change in the sign of the MC of Au doped polycrystalline InO_x films that they attributed to weak localization effects with SO interactions [11]. Contrary to our findings, however, $R^{\pm}$ depended on temperature and fell within a sheet resistance range where Mott variable range hopping dominated transport [11]. The explanation of these differences probably lies in the fact that those films were polycrystalline. Intercrystallite transport could dominate the resistance of those films to give a hopping dependence to $G(T)$ and intracrystallite transport could dominate the MC to give a weakly localized dependence to the MC.

In summary, we have shown that the MC in ultrathin films changes sign at a sheet conductance $1/R^{\pm} \simeq G_{00}$, independent of temperature and for different materials. We have argued that this sheet conductance separates the weakly and strongly localized regimes in two-dimensional systems. It serves, therefore, as a minimum metallic conductance. Further work on other systems over a wider temperature range is needed to determine whether its value is universal.

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