Observation of Conductance Fluctuations in Large In_2O_{3-x} Films

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We have measured the magnetoconductance in the hopping regime of two thin films of crystalline In_2O_{3-x}. The films are 18 nm thick and have large (macroscopic) areas 2×2 and 1×0.3 mm^2. We observe a large positive magnetoconductance and reproducible conductance fluctuations. The conductance fluctuations are easy to observe below 100 mK and their amplitude is consistent with simple ensemble averaging of phase-coherent regions. When the field is rotated into the plane of the film, the field scale for the conductance fluctuations increases by a factor of 2 suggesting that they are partly due to orbital effects.

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The phenomenon of conductance fluctuations (CF) discovered by Umbach *et al.*[1] has attracted considerable attention.[2] These fluctuations can be observed in very small metallic structures if the phase-coherence length of the diffusing electron L_ϕ is comparable to the sample length L. One feature of the CF that is now well understood theoretically is that their rms amplitude ΔG is "universal," independent of the specific nature of the material being studied. For a thin film of length L and width W at sufficiently low temperatures such that $L_\phi \gtrsim L$ and W, the conductance is found to fluctuate by $\sim e^2/h$ as the magnetic field H is changed. When H is perpendicular to the sample plane, the CF have a characteristic field[3] $H_c \sim (h/e)/L_\phi^2$.

The average conductance $\langle G\rangle$ of metallic systems is much larger than e^2/h and typically $\Delta G/\langle G\rangle \sim 0.001$–$0.05$. If L and W are greater than L_ϕ, the CF decrease in size and simple considerations give[4,5]

$$\Delta G = \alpha[(W/L)^{1/2}(L/L_\phi)^{-1}]e^2/h\,, \tag{1}$$

where α is a constant ~ 1. The term in brackets decreases with increasing temperature and accounts for ensemble averaging. Further reduction in ΔG can be caused by energy averaging as has been described elsewhere.[3] For these reasons CF are usually a small correction to the average conductance of metallic systems.

Conductance fluctuations in small (mesoscopic) systems exhibiting hopping conductivity have been reported by several groups.[6-8] Most systems studied are gated semiconducting devices and $\Delta G/\langle G\rangle$ can be larger than 1. One interesting issue in this field is whether the observed CF in a magnetic field are due to quantum interference[9] (QI) or are the result of the change in the energy of the electrons due to the Zeeman effect.[6] In Si MOSFETs (metal-oxide-semiconductor field-effect transistors), the CF are predominantly due to Zeeman effects.[6,10] In this Letter, we report measurements in the hopping regime of the magnetoconductance (MC) of macroscopically large In_2O_{3-x} samples. We observe a very large positive MC and reproducible CF.[11,12] At low temperatures, the relative size of the CF $\Delta G/\langle G\rangle$ can be as large as 0.1 even though L and W are 2–3 orders of magnitude larger than the relevant L_ϕ. A simple analysis shows that the observed CF are consistent with the assumption that QI effects are dominant.

The samples studied were thin films ($d \simeq 18$ nm) of polycrystalline In_2O_{3-x} prepared by evaporating pure In_2O_3 onto glass substrates and heat treated as described elsewhere.[13] Ohmic contacts were obtained using gold wire thermally bonded to pressed In contacts. The two samples studied most extensively are shown in Fig. 1. We note that the evaporations for these two samples were not done at the same time. Sample 1 (S1) has four In contacts and the effective area for two-wire measurements is not well defined. Initially, the two extra contacts were used to check for a possible contact resistance (not observed). For measurements between contacts 1 and 2 we assume $W_1\times L_1 \simeq 2\times2$ mm. This gives an $R_\square$ consistent with the $R_\square$ of sample 2 (S2) which has similar microscopic parameters as will be discussed later. S2 has only two contacts and its geometry is more clearly defined with $W_2\times L_2 \simeq 1.0\times0.3$ mm. For low-voltage ($\sim\mu$V) measurements on high-resistance samples we used a two-wire ac technique incorporating a phase-sensitive lock-in detector to detect the output from a current-sensitive preamp. Measurements were taken between 0.01 and 1 K for magnetic fields 0–8 T perpendic-

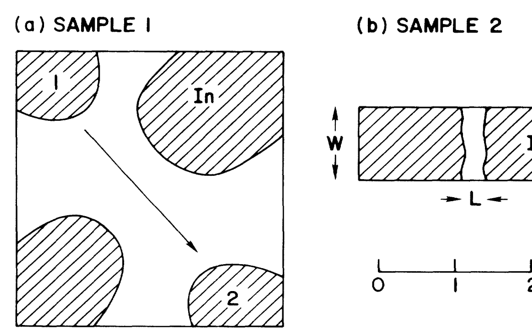

FIG. 1. Schematic drawing of (a) sample 1 and (b) sample 2. The In contacts are above a thin film of In_2O_{3-x}.

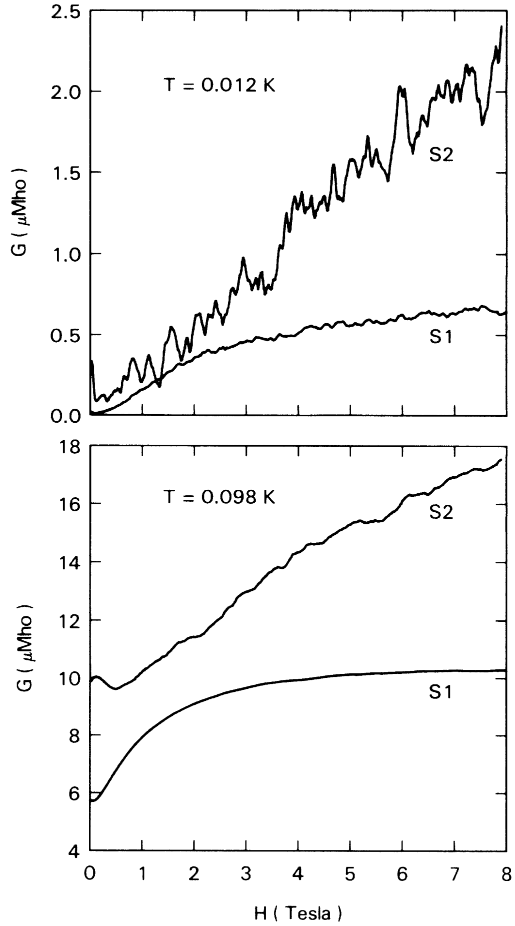

FIG. 2. Magnetoconductance data for S1 and S2 at $T=0.012$ and 0.098 K.

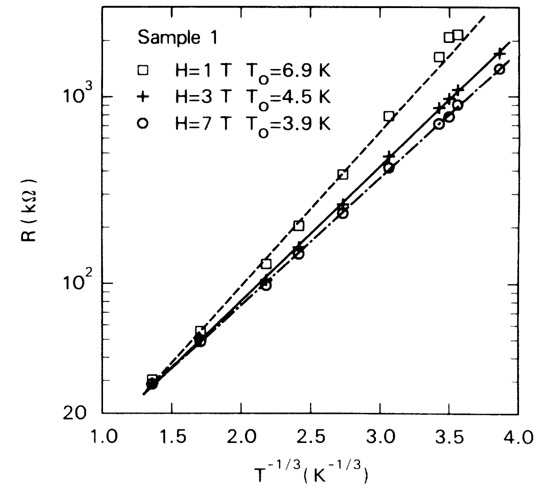

FIG. 3. $R(T)$ measurements for S1 at three magnetic fields. The lines are fits by Eq. (2).

ular to the plane of the sample.

Measurements of conductance as a function of the applied magnetic field are shown in Fig. 2 for S1 and S2. There are two main features observed: an overall positive MC and (reproducible) fluctuations. If we rotate S2 so that H is in the plane of the sample, the field scale for both features increases by a factor of ~ 2. This seems to imply that orbital (QI) effects are involved although it does not necessarily follow that the same physical mechanism is responsible for both features. In fact, the two phenomena have different characteristic fields associated with them, a difference that becomes more pronounced at lower temperatures. The characteristic field of the background MC is fairly independent of temperature below 1 K while the characteristic field for the "riding" fluctuations has a pronounced temperature dependence as detailed below.

We believe that the observed MC results from the delocalizing effect of the magnetic field as first suggested by Lee and Fisher.[14] Figure 3 shows typical $R(T)$ data for S1 at three magnetic fields. Above 1 T, these data are consistent with the usual[15] Mott formula for variable-range hopping (VRH) in a two-dimensional system:

$$R(T)=R_0\exp(T_0/T)^{1/3}. \tag{2}$$

T_0 is given by $k_BT_0=\beta/N(0)\xi^2d$, where[15] $\beta\simeq 3$, k_B is Boltzmann's constant, ξ is the localization length, d is the film thickness, and $N(0)\simeq 2\times 10^{32}$ $\mathrm{erg}^{-1}\mathrm{cm}^{-3}$ is the density of states at the Fermi level. Both samples can show deviations at very low temperatures from the expected $T^{-1/3}$ behavior. We find, however, that the data are less well described by either $T^{-1/2}$ or $T^{-1/4}$ laws. Below 1 T our data show a temperature dependence that is faster than $T^{-1/3}$. This may imply that electron-electron interactions are becoming more important.[16] Following Roy *et al.*,[17] we interpret the observed decrease of T_0 with H as an increase of ξ as anticipated by theory.[14,18,19] The effect on ξ is not large, but the exponential amplification embodied in Eq. (2) translates into a rather large (2 orders of magnitude) positive MC at 10 mK.

The observed large MC is an interesting result; but, the main subject of this Letter is the observation of CF in a macroscopic system. Let us then focus on the CF. To simplify our analysis, we shall only consider the CF between 3 and 8 T and use an "average" ξ obtained from the temperature dependence of the average R between 3 and 8 T. The main reason for restricting our analysis to this field range is that this is a range where our data obey Eq. (2) and therefore ξ can be unambiguously calculated. We find $\xi=38$ nm for S1 and $\xi=35$ nm for S2. Using an average ξ does not change any of the following conclusions.

The temperature dependence of the half-width of the autocorrelation function H_c for S2 is shown in Fig. 4 and the rms amplitude ΔG for S1 and S2 is shown in Fig. 5. The $H_c(T)$ for S1 (not shown) are approximately the same as for S2. The observed H_c exhibit a power-law

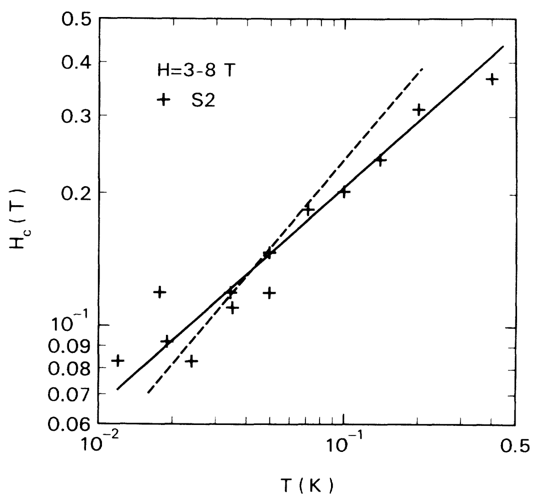

FIG. 4. Magnetic-field scale of the conductance fluctuations for S2. The lines are predicted values assuming that the CF are due to orbital (solid line) or Zeeman (dashed line) effects.

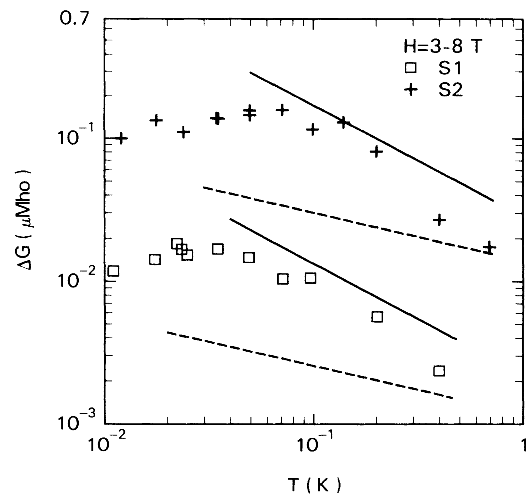

FIG. 5. rms amplitude of the conductance fluctuations. The lines are obtained from Eq. (1) with $L_\phi = r$ (dashed lines) and $L_\phi = L_c$ (solid lines).

temperature dependence suggesting $H_c(T) \sim T^{1/2}$. The ΔG for these samples (Fig. 5) show a similar (to each other) temperature dependence with both samples exhibiting a weak maximum. We also note that the ΔG of the two samples have a quite different magnitude.

We now show that these features of $H_c(T)$ and $\Delta G(T)$ can be accounted for by assuming they arise from orbital effects analogous to the CF observed in metallic systems. According to Nguyen, Spivak, and Shklovskii,[9] the characteristic field for the fluctuations in the hopping regime is given by $H_c = \gamma(h/e)/r^{3/2}\xi^{1/2}$, where r is the hopping length and γ is a constant of order 1. For 2D VRH, this implies $H_c \sim T^{1/2}\xi^{-1}$ which is consistent with the observed temperature dependence. It also accounts for the near equality of H_c for the two samples since their ξ's differ by only 10%. If we adjust $\gamma = 0.42$, the theory produces the solid line shown in Fig. 4. In this model, the CF are the result of QI within a single hop. An alternative model is that the CF are the result of Zeeman effects. In this case, we can estimate H_c by assuming $\mu_B H_c$ is equal to the Mott energy in 2D: $\mu_B H_c = (1/4\beta)k_B T(T_0/T)^{1/3} \sim T^{2/3}\xi^{-2/3}$, where μ_B is the Bohr magneton. This produces the dashed line shown in Fig. 4. Clearly the fit is better assuming QI.[20] Another test of this issue is what happens when we rotate the magnetic field. If H is in the plane of S2 and perpendicular to the current, the measured H_c are larger by a factor of ~ 2. If the CF are due to Zeeman effects, we expect no change in H_c. Alternatively, if the H_c are due to QI, we expect H_c to increase by a factor[21] $\sim(\pi/4)(r\xi)^{1/2}/d \simeq 3$. We conclude that the observed CF are at least partly due to QI effects.

As an interesting exercise we can use Eq. (1) to estimate the size of the observed CF. In the hopping regime it has been proposed[9,22] that the relevant phase-coherence length is the hopping length. If $a=1$ and we choose $L_\phi = r = \xi(T_0/T)^{1/3}$, we obtain the dashed lines shown in Fig. 5. Alternatively, if we choose $L_\phi = L_c = r(r/\xi)^\nu$, where $\nu = \frac{4}{3}$ in 2D, we obtain the solid lines. L_c is the correlation radius proposed by Shklovskii and Efros[16] and is the average distance between "key resistances" in the sample. Figure 5 shows that we obtain a reasonable estimate of the measured values using either $L_\phi = r$ or L_c. However, we note that for samples more insulating ($T_0 > 16$ K) than those described here ($T_0 \sim 5$ K), Eq. (1) no longer gives a reasonable estimate.[23] Finally, since the microscopic parameters of these two samples are very similar, we expect $\Delta G_2/\Delta G_1 \simeq (W_2/W_1)^{1/2}(L_1/L_2)^{3/2}$. Putting in the numbers we get $\Delta G_2/\Delta G_1 = 12$ which compares favorably with the observed value of ~ 10. Of course, this agreement is better than should be expected given our lack of precise knowledge of L_1 and W_1.

Below 100 mK, $\Delta G(T)$ seems to have a weak maximum which is a qualitatively different behavior than that seen in diffusive systems. In the latter case $\Delta G(T)$ is a monotonically decreasing function of the temperature as implied by Eq. (1). We believe that this is a real feature of the data and is not an artifact of the measurement. For example, we do not suspect significant "self-heating" given the observation that both $R(T)$ and $H_c(T)$ continue to change in a monotonic fashion even at the lowest temperatures. Therefore, the weak maximum may simply imply that the size of the fluctuations within a phase-coherent region δg is less than the "universal" value e^2/h. Indeed, this is the expected result. Once the g of the phase-coherent region is less than e^2/h, δg is no longer universal and is believed to be proportional to g itself.[24]

In summary, we have observed prominent magnetoconductance fluctuations in the hopping regime of macroscopically large In_2O_{3-x} samples. The CF are easy to observe in our large samples at low temperatures primarily because the average G is small. For T_0 not too large, the amplitude of the CF can be estimated using a simple extension of the "universal conductance theory" as embodied in Eq. (1). Our observations support the physical picture that the CF are due to quantum interference as implied by the temperature dependence and anisotropy of H_c. In particular, we find that the relevant phase-coherent area is consistent with the "cigar-shape" geometry[9] characteristic of QI in hopping systems.

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[20]In 2D a measurement of $H_c(T)$ can be used to distinguish between QI and Zeeman since they have different temperature dependences. This is not the case in 1D where the two effects have the same ($T^{1/2}$) temperature dependence.

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