Electron Mobility, Conductivity, and Superconductivity near the Metal-Insulator Transition

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The disorder parameter $k_F l$ for amorphous InO_x is measured by a novel application of the surface electric field effect and is varied by thermal annealing. The normal-state conductivity and superconducting T_c both vary as $(k_F l)^{-2}$ and critical disorder occurs at $k_F l \approx 3^{1/2}$, as a result of Anderson localization in this low-carrier-density material.

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Proximity to the metal-insulator (M-I) transition is thought to be part of the cause for depressed superconducting transition temperatures in many classes of bulk disordered materials.[1,2] Anderson, Muttalib, and Ramakrishnan[2] recently proposed an explanation in terms of disorder-enhanced Coulomb repulsion near the M-I transition. However, unphysically large conductivity scales were needed to fit experimental data on the high-T_c metals. The present work examines amorphous indium oxide, a-InO_x, which when annealed transforms from an insulator ($T \to 0$) to a dirty superconductor with a T_c close to that of In. Quantitatively, disorder is represented by the parameter $k_F l$, the product of the Fermi wave vector and the elastic-scattering mean free path. It is determined in the present work by a novel application of the surface electric field effect to a disordered metal and is systematically varied for a given sample by thermal annealing. The results give strong evidence that both the normal-state conductivity $\sigma(T=0)$ and T_c are gradually depressed to zero at a critical disorder parameter $k_F l \approx 3^{1/2}$, as a result of the dominant influence of Anderson localization.[3,4]

Amorphous InO_x is ideally suited for the study of superconductivity near the M-I transition because low $k_F l$ values are obtained as a consequence of a low free-electron density, typically 10^{20} to 10^{21} cm^{-3}, depending on O content, and an amorphous structure ($l \gtrsim 5$ Å). As discussed below, the low electron density also leads to small Coulomb-interaction corrections to the theoretical critical value of $k_F l$. The samples are 600-Å-thick films, deposited on 0.6-cm-square glass substrates by reactive ion-beam sputtering of indium in the presence of oxygen.[5] These are essentially bulk specimens[6] and are to be contrasted with polycrystalline In_2O_3 produced by other techniques, which is not superconducting.[7] Furnance annealing in N_2 for several minutes at 100 to 160 °C causes $k_F l$ to increase, and may transform the asymptotic low-temperature state from an insulator to a superconducting metal.

For the two films reported here, the In concentrations are 45% for sample A and 44% for sample B, as determined by Rutherford backscattering analysis. (Stoichiometric In_2O_3 contains 40% In.) As-prepared room-temperature conductivities are 54 and 225 Ω^{-1} cm^{-1}, respectively. There is also a 0.7% Ar component picked up from the sputtering gas. Previous transmission-electron-microscopy analysis showed that similarly prepared films are amorphous.[5,8] Sample B may have small inclusions of crystalline indium oxide. No microcrystallinity was observed in similarly heat-treated specimens,[8] even though l, calculated from free-electron formulas, is as large as 40 Å in annealed samples.

Mobilities in a-InO_x were determined from the surface electric field effect.[9] A capacitor structure was fabricated by placing a 13-μm Mylar dielectric in contact with the film and overlaying a second electrode shaped to expose van der Pauw contacts at the corners of the film. A field effect is observed when a static voltage V is applied between the capacitor plates. The change in the film sheet conductance G, typically 0.1% or less, is proportional to V. The mobility μ_c is obtained by associating the modulation in G with the surface charge areal density CV/A according to $\delta G = \Lambda \delta\sigma = (CV/A)\mu_c$. The capacitance C was measured independently. The method also gives the electron density, calculated as $\sigma/e\mu_c$. The static charge penetrates the screening distance Λ, which is about 2 Å, if we assume a free-electron gas.

For comparison, standard Hall-effect measurements were made in a fixed 1.3-kOe magnetic field with use of the van der Pauw contacts. Charging mobilities were found to be invariably larger than the Hall mobilities, $\mu_H = c|R_H|\sigma$, obtained from Hall coefficients. Room-temperature results $\mu_H \approx 1$ cm^2 V^{-1} s^{-1} and $\mu_c \approx 10$ cm^2 V^{-1} s^{-1} are obtained for as-deposited samples. Annealing at temperature stages up to about 160 °C increases μ_H by

as much as a factor of 10. The increase is μ_c is less, so that in annealed samples μ_c is about a factor of about 2 larger than μ_H. Temperature dependences of μ_c and μ_H are qualitatively similar. The interpretation of the experiment rests on the assumption that the larger μ_c is a correct measure of the bulk mobility. In a degenerate electron gas, the electron states are in effect spread out over the bulk of the specimen. Surface anomalies such as localized surface states, which could trap part of the surface charge, and surface scattering do not appear to be significant as these mechanisms ought to reduce the apparent mobility. The Hall effect can lead to anomalous results for the electron density because of the sensitivity to arrangements of microscopic diffusion paths in inhomogeneous metals.[10] An extreme case, for example, is the Hall mobility in granular Al/Al_2O_3, which appears to be affected by percolation.[11]

The disorder parameter is obtained from the free-electron model of the Boltzmann conductivity, $\sigma_B = e^2 k_F^2 l/3\pi^2\hbar$. Room-temperature measurements are good estimates of σ_B and hence were used to compute $k_F l$ according to

$$k_F l = (3\pi^2\hbar\sigma_B/e^2)(e\mu_c/3\pi^2\sigma_B)^{1/3}. \quad (1)$$

That σ is not constant near 300 K indicates some uncertainty in the result for σ_B.

Results for sample A are shown in Fig. 1, which gives the temperature dependence of μ_c for various stages of anneal indicated by the $k_F l$ values. The sample was initially on the insulator side of the M-I transition and illustrates the mobility gap, $\mu_c \to 0$ as $T \to 0$ for $k_F l \lesssim 1$. Similar behavior is seen in the Hall carrier density plotted in the inset. The room-temperature Hall coefficient remains constant through the M-I transition, while carrier freezeout is observed only in the insulator phase at low temperatures. The field effect gives a smaller carrier density, varying from (2 to 3)$\times 10^{20}$ cm^{-3} in the metallic region. This first observation of a constant R_H on the metallic side of the M-I transition of an amorphous metal confirms the scaling theory result obtained by Shapiro and Abrahams.[12] The data do not show the large change predicted by interaction theory,[13] given by $\delta R_H/R_H = -2\delta\sigma/\sigma$. Sample A became superconducting for $k_F l > 1$ with a maximum T_c of 2.9 K.

Sample B was initially metallic and superconducting. A larger number of annealing stages were studied for this sample in order to examine in some detail the $k_F l$ dependence of the normal-state conductivity and superconductivity in the metallic region. The temperature dependence of the conductivity is plotted in Fig. 2 on a $T^{1/4}$ temperature scale, since this functional form best describes $\sigma(T)$ and gives the normal-state conductivity $\sigma(0)$ by the dashed-line extrapolations. We note that the temperature-dependent part of $\sigma(T)$ is independent of disorder over a wide temperature range. For much of the data, $\sigma(T) - \sigma(0)$ is smaller than $\sigma(0)$, and so the data lie outside the critical region

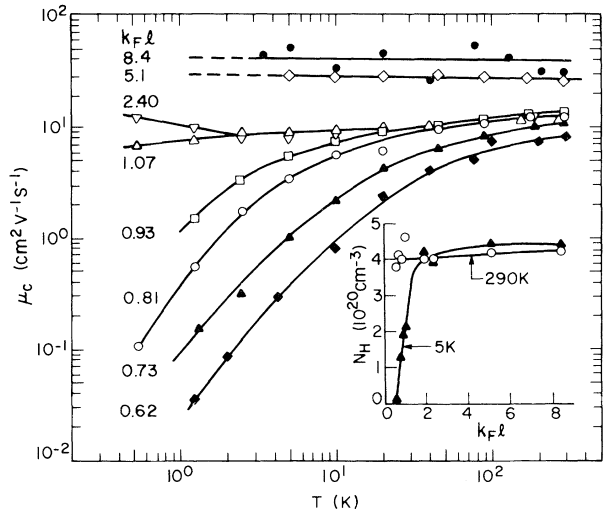

FIG. 1. Temperature dependence of the field-effect mobility in sample A for various stages of anneal denoted by the $k_F l$ values. Inset: $k_F l$ dependence of the Hall carrier density at temperatures of 290 and 5 K.

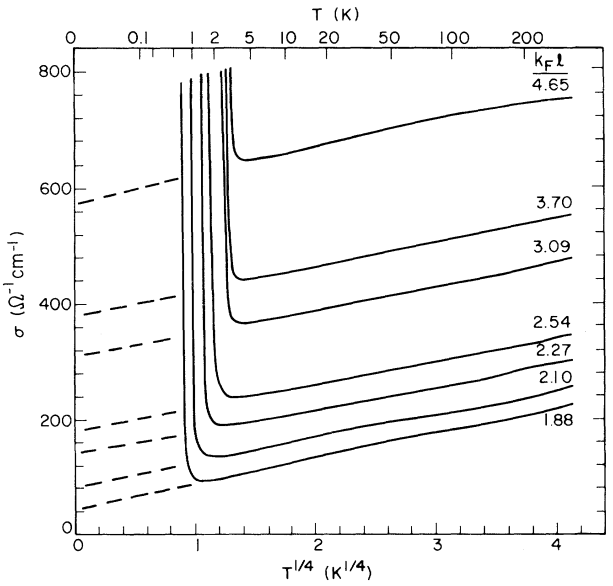

FIG. 2. Temperature dependence of the electrical conductivity of sample B at various stages of anneal with $k_F l$ values given. Extrapolated dashed lines give $\sigma(0)$.

of the M-I transition. The superconducting transition temperature T_c is taken at the temperature where $\sigma(T)$ increases by a factor of 2 over the extrapolated normal-state dependence. The transitions are rounded by superconducting fluctuations near T_c. Nonuniversal power-law dependences of $\sigma(T)$ near the M-I transition have been observed. For sample A the dependence near the critical region is closer to $T^{1/3}$, while in samples with less oxygen component a $T^{1/2}$ dependence is found. Both localization and interaction theories predict that the conductivity increases with temperature, as observed.[14,15] At present, theories which include the electron-phonon interaction and strong disorder are incomplete.[16-18]

Linear dependences of $\sigma(0)/\sigma_B$ and T_c on $(k_F l)^{-2}$ are found, as shown in Fig. 3. Localization theory with interaction corrections gives the following expression for the reduced conductivity[3,4,19]:

$$\sigma(0)/\sigma_B = 1 - 3(k_F l)^{-2}[1 + 3^{1/2}\gamma(F)]. \quad (2)$$

The Hartree Coulomb interaction term $F \approx 0.9$ leads to a small interaction correction $\gamma(F) = 0.02$, according to the most recent theory.[20] The line through the $\sigma(0)/\sigma_B$ data in Fig. 3 is Eq. (2) computed with $\gamma(F) = 0$, showing the agreement given by a purely localization effect. Although the critical value of $k_F l = \sqrt{3}$ so obtained could be special to the small interaction correction in this sample, we attach significance to our observation that $\sigma(0)$ scales with σ_B as predicted by theory.[19] The three metallic-region points for sample A indicate a critical $k_F l$ for that sample which is about 7% larger. Figure 3 shows that T_c is degraded with the same dependence as $\sigma(0)$. Hence, a localization mechanism for the destruction of superconductivity is the likely explanation.

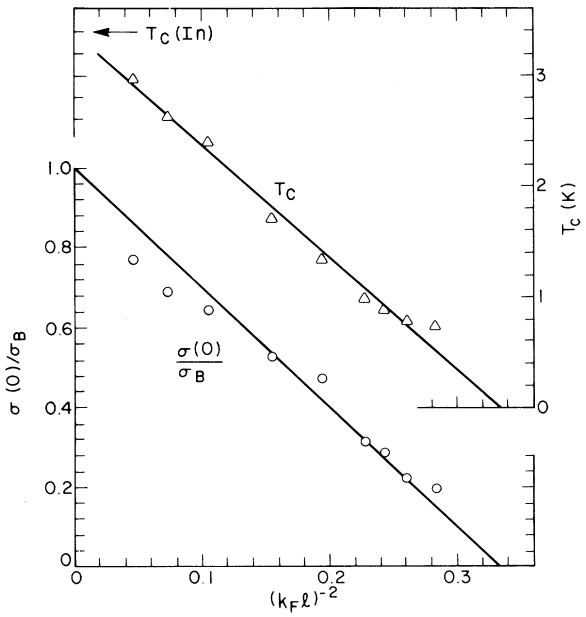

FIG. 3. Superconducting transition temperature and zero-temperature extrapolated conductivity normalized to the Boltzmann conductivity vs parameter $(k_F l)^{-2}$ for sample B. Arrow marks T_c for pure In. Lower line is theoretical, Eq. (2) with $\gamma(F) = 0$.

A second-order $(k_F l)^{-2}$ correction to T_c, given by the upper line in Fig. 3, is consistent with early predictions[21,22] of no effect on T_c to first order in $(k_F l)^{-1}$. Note that in the limit $(k_F l)^{-2} \to 0$, T_c approaches that of pure In, 3.4 K. Since a-InO_x has a lower electron density than In, and hence a larger Coulomb pseudopotential μ^*, the same T_c implies a larger electron-phonon attraction λ as well. From the McMillan formula for T_c with the assumption of the Debye temperature of In, we find $\mu^* = 0.28$ and $\lambda = 1.3$ for a-InO_x, compared to respective values of 0.12 and 0.83 for pure In. The theory of Ref. 2 predicts that T_c is rapidly depressed to zero in the metalic region $k_F l \sim 2.2$, in disagreement with the observed gradual dependence. For the data nearest the M-I transition, the localization-theory scaling length, $\xi_s \approx g_c/\sigma(0) \approx 60$ Å, is comparable to the superconducting coherence length, $(\xi_0 l)^{1/2} = 200$ Å. Here, $g_c = e^2/\pi^2\hbar$ and ξ_0 is the BCS length. The theory of Ref. 2 treated only the effect of disorder on Coulomb repulsion and did not include the effect on the density of states. The latter has thus far been treated theoretically only for two-dimensional superconductors.[16]

Amorphous InO_x thus has several important properties for studying Anderson localization effects in superconductors. As a result of a large field-effect modulation of the conductance, $k_F l$ values are easily obtained. Interaction effects nearly cancel in this material of low free-electron density, leading to a critical disorder point determined primarily by the localization term. Hence, the superconducting T_c and electrical conductivity extrapolate to zero at critical disorder $k_F l \approx \sqrt{3}$. We find that the mobility remains finite at low temperatures in the metallic region, where the samples are superconducting. As the metal-insulator transition is approached, the Hall coefficient remains constant as predicted by localization scaling. We did not use the Hall coefficient, which would have given a factor of about 2 smaller values of $k_F l$.

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$$\gamma(F) = 0.915\{\tfrac{1}{3} + 4F^{-1}[1 + \tfrac{3}{4}F - (1+\tfrac{1}{2}F)^{3/2}]\}$$

is derived in Ref. 15, as corrected by P. A. Lee (private communication), replacing an earlier result (cf. Ref. 17) $\gamma(F) = 0.915(\tfrac{1}{3} - F/4)$.

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