We present results of the disorder-induced metal-insulator transition (MIT) in three-dimensional amorphous indium-oxide films. The amorphous version studied here differs from the one reported by Shahar and Ovadyahu [Phys. Rev. B 46, 10917 (1992)] in that it has a much lower carrier concentration. As a measure of the static disorder we use the dimensionless parameter \( k_F \ell \). Thermal annealing is employed as the experimental handle to tune the disorder. On the metallic side of the transition, the low temperature transport exhibits weak-localization and electron-electron correlation effects characteristic of disordered electronic systems. These include a fractional power-law conductivity versus temperature behavior anticipated to occur at the critical regime of the transition. The MIT occurs at \( k_F \ell \approx 0.3 \) for both versions of the amorphous material. However, in contrast with the results obtained on the electron-rich version of this system, no sign of superconductivity is seen down to \( T \approx 0.3 \) K even for the most metallic sample used in the current study. This demonstrates that using \( k_F \ell \) as a disorder parameter for the superconductor-insulator transition (SIT) is an ill defined procedure. A microstructural study of the films, employing high resolution chemical analysis, gives evidence for spatial fluctuations of the stoichiometry. This brings to light that, while the films are amorphous and show excellent uniformity in transport measurements of macroscopic samples, they contain compositional fluctuations that extend over mesoscopic scales. These, in turn, reflect prominent variations of carrier concentrations thus introducing an unusual type of disorder. It is argued that this compositional disorder may be the reason for the apparent violation of the Ioffe-Regel criterion in the two versions of the amorphous indium oxide. However, more dramatic effects due to this disorder are expected when superconductivity sets in, which are in fact consistent with the prominent transport anomalies observed in the electron-rich version of indium oxide. The relevance of compositional disorder (or other agents that are effective in spatially modulating the BCS potential) to other systems near their SIT is discussed.

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I. INTRODUCTION

The metal-insulator and the superconductor-insulator transitions (MIT and SIT respectively) are two major representatives of quantum phase transitions that have been extensively studied over the last decades. Disorder driven MIT could be affected by a number of means; doping, pressure, stress, etc. A unique method to drive the system from the insulating to the metallic (or superconducting) state is feasible in some metallic glasses prepared from the gaseous phase. Amorphous films quench-condensed onto substrates by vacuum deposition usually contain microvoids and have a lower mass density than the respective equilibrium material and thus, on average, smaller interatomic overlaps. Thermal treatment at precrystallization temperatures may then be used to reduce the free volume created by the microvoids. In this method one controls the interatomic overlap in a similar vein as in employing hydrostatic pressure on a solid. The main difference is that thermal annealing inevitably causes an irreversible volume change.

Thermal annealing has been employed to change the resistivity of amorphous indium-oxide films while monitoring their optical properties. Typically, 3–5 orders of magnitude in room temperature resistivity could be obtained accompanying a \( \approx 3\% \) reduction in sample thickness (measured by x-ray interferometry), which is a much larger volume change than is commonly achievable by hydrostatic pressure. Using this technique, the SIT in three-dimensional indium-oxide films was mapped by measuring the low temperature conductivity as a function of disorder. The amorphous indium oxide had an electron density of \( \approx 10^{21} \) cm\(^{-3} \) and the samples static disorder was characterized by \( k_F \ell \) (defined in Sec. II). In this version of indium oxide, superconductivity survived in samples with \( k_F \ell \gtrsim 0.24 \), and, somewhat paradoxically (but reconcilable by an inhomogeneous scenario discussed in this paper), insulating behavior sets in at smaller disorder, for \( k_F \ell \lesssim 0.3 \). The observation that both limits are below the Ioffe-Regel criterion motivated us to conduct the present study employing the same technique of tuning disorder and using the same material but with a much smaller carrier concentration. The idea was to see whether the problem is related to the existence of superconducting or to electron-electron \((e-e)\) correlations effects; in either case one expects the results to depend on carrier concentration.

In this work we map the MIT in three dimensional amorphous indium-oxide films with a carrier concentration that is 2–3 orders of magnitude lower than the material used in Ref. 7. No sign of superconductivity is found down to \( T \approx 0.3 \) K, and normal transport properties are observed for both the insulating and metallic regimes. However, the critical disorder, separating the metallic from the insulating regime, still appears to be given by \( k_F \ell \approx 0.3 \) as in the electron-rich phase. By comparison, the MIT in the previously studied crystalline version of indium oxide occurs at \( k_F \ell \approx 0.75 \), which led us to examine the structural differences between the two phases that might account for the different \( k_F \ell \) at the transition.

We present data on the microstructure of both the electron-rich and the low carrier-concentration versions of
amorphous indium oxide using high resolution microscopy and energy-dispersive local probe. Chemical analysis reveals that the indium-oxygen ratio fluctuates across the sample on mesoscopic scales. Combining this information with Rutherford backscattering and Hall effect measurements suggests that large spatial fluctuations of carrier concentration exist in these amorphous samples. The specifics of this inhomogeneity is argued to be a natural cause for a variety of transport anomalies in these as well as in other systems where superconductivity plays a role at experimentally accessible temperatures.

II. SAMPLES PREPARATION AND MEASUREMENTS TECHNIQUES

The In$_2$O films used here were e-gun evaporated on room-temperature microscope slides using 99.999% pure In$_2$O$_3$ sputtering target pieces. Deposition was carried out at the ambience of $(2–5) \times 10^{-4}$ Torr oxygen pressure maintained by leaking 99.9% pure O$_2$ through a needle valve into the vacuum chamber (base pressure $\approx 10^{-6}$ Torr). Rates of deposition used for the samples reported here were typically 0.18–0.8 Å/s. For this range of rate-to-oxygen pressure, the In$_2$O samples had carrier concentration $n$ in the range $(5–13) \times 10^{18}$ cm$^{-3}$ measured by Hall effect at room temperature. Electron-rich In$_2$O samples used in the study (with carrier concentration in the $10^{21}$ cm$^{-3}$ range) were produced with the conditions described earlier. The films’ thickness in this study was 900–1500 Å, which makes them effectively three dimensional (3D) down to the lowest temperature in our experiments ($\approx 0.3$ K) for most of the samples used in this work.

The as-deposited samples had extremely high resistivity $\rho$ of the order of $10^3$–$10^6$ Ωcm. These were barely measurable even at room temperature. To carry out the low temperature studies, the samples $\rho$ had to be reduced by several orders of magnitude. This was achieved by thermal annealing. A comprehensive description of the annealing process and the ensuing changes in the material microstructure are described elsewhere.$^{6,9}$ For completeness, we give here the basic protocol that was used in this study. Following deposition and initial conductance measurement, that in many cases required the use of electrometer (Keithley 617), the sample was attached to a hot stage at a constant temperature $T_a$, initially 5–10 degrees above room temperature. The resistance $R$ of the sample was observed to slowly decrease over time. $T_a$ was raised by a few degrees whenever $\Delta \rho/\rho$ over 24 hours was less than 1$\%$ (and the value of the resistance was still higher than desired). To obtain a sample with $\rho$ that was useful for the measurements reported here usually took 20–38 thermal cycles. The annealing temperature $T_a$ was limited to $\approx 370$ K to minimize the risk of crystallization. The amorphicity of the samples during the annealing process was monitored by checking the diffraction pattern of a controlled specimen prepared on a carbon-coated copper grid. The control specimen was deposited simultaneously with the sample used for the transport measurement, but its thickness was limited to 200–300 Å to facilitate high resolution microscopy. Electron-diffraction micrograph of the as-deposited material is shown in Fig. 1(a) along with a micrograph taken for the same grid after a prolonged period of thermal annealing resulting in resistance change of more than three orders of magnitude.

Note the characteristic broad rings of the amorphous phase, and in particular the absence of any diffraction ring of either crystalline indium oxide or metallic indium.

Conductance and Hall effect measurements were carried out on samples that were patterned in a six-probe configuration using stainless-steel masks during deposition. We used a standard Hall-bar geometry with the active channel being a strip either 0.6 mm or 1 mm wide, and 10 mm long. The two pairs of voltage probes (that doubled as Hall probes), were spaced 3 mm from one another along the strip. This arrangement allowed us to assess the large scale uniformity of the samples, both in terms of the longitudinal conductance and the Hall effect. Excellent uniformity was found on these scales; resistivities of samples separated by 1 mm along the strip were identical to within $\pm 2\%$ for all the samples used in the study. It should be noted however that microstructural studies performed in the course of the study revealed prominent inhomogeneities on mesoscopic scales ($10^{-2}$–$10^{-3}$ Å). The effects of these medium-scale irregularities on electronic transport are discussed in the next section.

Most of the conductance versus temperature $\sigma(T)$ measurements were done in the $1.3 \leq T \leq 15$ K range by a four terminal dc technique using Keithley K220 current source while monitoring the voltage with Keithley K2000. For lower temperatures measurements (down to $\approx 280$ mK), we used a four terminal ac technique with the lock-in PAR124A. In all cases care was taken to maintain linear-response conditions by keeping the voltage across the sample low enough. This was verified by measuring the current-voltage characteristics at the lowest temperature of the experiment.

As in previous studies,$^{6,8}$ we use in this work $k_F\ell = (3\pi^2)^{2/3} \frac{h\omega}{e^2\varepsilon_{\text{meas}}}$ as a dimensionless measure of the material disorder. This is based on free-electron expressions using the measured room-temperature conductivity $\sigma_{\text{RT}}$ and the carrier concentration $n$, obtained from Hall-effect measurements, as
III. RESULTS AND DISCUSSION

One of the main goals of the research was to identify the critical $k_F\ell$ at which the metal-to-insulator transition occurs in the low-$\eta$ version of In$_x$O. This was accomplished by measuring $\sigma(T)$ over a certain range of temperatures, then extrapolating the data to $\sigma_0 \equiv \sigma(T \to 0)$ to determine whether the system is insulating ($\sigma_0 < 0$) or metallic ($\sigma_0 > 0$). Four different deposition batches were used in this phase of the research. In each of these, thermal annealing was used, in effect, generating samples with different $k_F\ell$ from the same physical specimen. A specific series of $\sigma(T)$ for samples labeled by their $k_F\ell$ values is shown in Fig. 2. Note that the $\sigma(T)$ plots for samples with $k_F\ell \gtrsim 0.4$ are nearly parallel to each other, a feature commonly found in many systems on the metallic side of the metal-insulator transition. The usual practice adopted in these cases is to extract the value of $\sigma_0$ by fitting the measured $\sigma(T)$ for a given sample to

$$\sigma(T) = \sigma_0 + A \cdot T^\frac{1}{2},$$

that presumably describes transport corrections to the conductivity due to either weak-localization or $e$-$e$ interactions effects. Equation (1) offers a reasonably good fit to the data of samples having $k_F\ell \gtrsim 0.4$ (Fig. 2).

However, the temperature dependence of the conductance for samples that are in the immediate vicinity of the transition suggests that another $\sigma(T)$ law might be relevant, and that should perhaps be taken into account in extrapolating $\sigma(T)$ to zero temperature. So, before discussing the $\sigma_0$ versus $k_F\ell$ results we digress now to examine the data, shown in Fig. 3, for samples in the critical regime of the transition.

The figure illustrates how the form of $\sigma(T)$ changes when the system goes from metallic to insulating behavior [Fig. 3(a)]. The outstanding case is the middle curve that belongs to a sample that is just insulating; it fits well a power-law dependence $\sigma(T) \propto T^\frac{1}{4}$ over a wide range of temperatures as illustrated in Fig. 3(c). A temperature dependence of this form is consistent with the interaction effect proposed by Larkin and Khmel’nitskii (LK). These authors observed that at the transition the contribution of Coulomb interactions to the conduceance may be expressed by

$$\sigma(T) \sim \frac{e^2 k_F}{\hbar} \left( \frac{T}{T_F} \right)^\frac{1}{4},$$

where $\eta$ is the exponent that describes the spatial dependence of the Coulomb potential $e\phi(r) \propto r^{-\eta}$ (with $1 < \eta < 3$). Note that this implies the lack of metallic screening at this range of disorder, heralding the approach of the dielectric phase.

An alternative to the LK mechanism, offered by Imry, has been invoked to account for a $\Delta \sigma(T) \propto T^\frac{1}{3}$ component observed in three-dimensional In$_2$O$_{3-x}$ samples near the transition. The Imry mechanism takes account of the scale dependent diffusion that is a property of the critical regime. To obtain the $1/3$ exponent, it also assumes a linear-with-temperature electron inelastic rate $\tau_{in}^{-1}$. A scattering rate $\tau_{in}^{-1} \propto T$ is consistent with the results of our magneto-conductance measurements in the range $4 \text{ K} < T < 77 \text{ K}$ discussed later (Fig. 9).

The conductance component associated with the Imry and the Larkin-Khmel’nitskii mechanism is proportional to $k_F^{\frac{1}{2}}$ and $\frac{e^2}{\hbar}$, respectively. Here $L_{in} = \sqrt{D \tau_{in}}$ is the inelastic diffusion length ($D$ is the diffusion constant that in the critical regime is scale dependent), and $L_T = k_F^{\frac{1}{2}}(\frac{T}{T_F})^\frac{1}{4}$ is the LK interaction length. The prefactors associated with $\Delta \sigma$ of these
mechanisms are not presently known so we cannot determine their relative contribution. However, for either mechanism, the $T^1$ term should be observed once $L \ll \xi_c$, where $\xi_c$ is the correlation length\(^{12}\) and $L$ is the relevant scale for the measurement at hand. Therefore, over some temperature range, $\sigma(T)$ of metallic samples that are sufficiently close to the transition may be describable by

$$\sigma(T) \sim \sigma_0 + A \cdot T^1,$$  

(3)

where $\sigma_0 \propto \frac{e^2}{\hbar c} > 0$ and $A$ is the sum of the contributions of the Imry and LK mechanisms.

As may be expected from the similarity between the two functions, the $\sigma(T)$ of the (metallic) samples can be fitted to either Eq. (1) or (3) almost equally well except near the transition where Eq. (3) is a better fit. For the sample with $k_F\ell = 0.42$ [top curve in Fig. 3(a)], the best fit to Eq. (3) yields a chi-square test value of $\chi^2 \simeq 0.013$ as compared with $\chi^2 \simeq 0.08$ for the best fit to Eq. (1). In general, fitting $\sigma(T)$ to Eq. (1) typically gave a higher value for the zero-temperature conductivity [the $k_F\ell = 0.42$ sample data gave $\sigma_0 \approx 6.3 \Omega^{-1} \text{cm}^{-1}$ versus $\sigma_0 \approx 4.1 \Omega^{-1} \text{cm}^{-1}$ using Eqs. (1) and (3), respectively, a $\approx 50\%$ difference]. The difference in $\sigma_0$ between the two fitting possibilities however is less important for larger $k_F\ell$, as can be seen in Fig. 4(a). For comparison, Fig. 4(a) also includes the results of $\sigma_0$ versus $k_F\ell$ for In$\text{O}_x$, the crystalline version of 3D indium oxide.

It is noteworthy that metallic samples with $\sigma_0 \ll \sigma_{\text{min}} = \frac{e^2}{\hbar c} k_F$ are obtained in both systems ($k_F$, calculated by the free-electron expression, is $\approx 8 \times 10^6 \text{cm}^{-1}$ and $\approx 12 \times 10^6 \text{cm}^{-1}$ for the In$_n$O and In$_3\text{O}_{3-x}$, respectively). Quantum and $e$-$e$ interaction effects are therefore quite prominent in the low temperature transport properties of these samples.

Data delineating the critical $k_F\ell$ for the transition in the high-$n$ version of In$_n$O are shown in Fig. 4(b). This is based on the dependence of the activation energy $T_0$ on $k_F\ell$ for samples that are on the insulating side of the transition (but close to it).\(^{13}\) These samples exhibit a peculiar $\sigma(T)$ law that empirically has been fitted to simple activation: $\sigma(T) \propto \exp(-T_0/T)$. The critical $k_F\ell$ may be determined in this case by extrapolating $T_0(k_F\ell)$ to zero.\(^{14}\)

Comparing the data for the three different versions of the material there are two issues that require elucidation: the difference between the various phases in terms of exhibiting superconductivity at the experimentally accessible range, and the difference in the value of $k_F\ell$ at which the metal-insulator transition occurs. Note that electron-rich In$_n$O samples with $k_F\ell \gtrsim 0.3$ exhibit superconductivity for $T \lesssim 3 \text{ K}$ [Fig. 4(b)] while the low-$n$ In$_n$O version shows no sign of superconductivity down to $\approx 0.3 \text{ K}$ even for samples with $k_F\ell$ as high as 0.68 (Fig. 5). It seems plausible that the difference between the high-$n$ In$_n$O and the low-$n$ version is the large disparity in their carrier concentration. Likewise, the low carrier concentration of In$_3\text{O}_{3-x}$ ($n \approx 5 \times 10^{19} \text{ cm}^{-3}$) is presumably the main reason for the absence of superconductivity in this system.\(^{15}\) A difference of 2–3 orders of magnitude in carrier concentration is large enough to push down the superconducting transition temperature $T_c$ well below the experimental range; a mere factor of 3 in the BCS potential suffices to shift $T_c$ from 3–4 K to less than 10 mK.

**FIG. 4.** (Color online) (a) The extrapolated values for the zero-temperature conductance as function of the disorder parameter $k_F\ell$. Data shown for the In$_n$O samples are based on extrapolation using Eq. (1) (full diamonds) and Eq. (3) (empty diamonds) respectively. The data for the crystalline version (circles) are for comparison (taken from Ref. 8). (b) The activation energy $T_0$ of electron-rich In$_n$O samples as function of $k_F\ell$ from which the critical disorder is estimated by extrapolation along the dashed line (see text for details). The dotted line depicts the qualitative dependence of $T_c$ on $k_F\ell$ (based on Ref. 7).

**FIG. 5.** (Color online) Conductivity as a function of temperature plots for two In$_n$O films. (a) Electron-rich sample that shows a transition to a superconducting state below $T \approx 1.5 \text{ K}$ (sample thickness $= 1300 \text{ Å}$). (b) $\sigma(T)$ for In$_n$O sample with a much lower carrier concentration (but less disorder) exhibiting normal transport properties down to $0.3 \text{ K}$ (sample thickness $= 1000 \text{ Å}$). The dashed line is a fit to $\sigma(T) = \sigma_0 + A \cdot T^{0.3}$. The small value of the exponent in this case may suggest that the film is not far from crossing over to a 2D behavior at the lower temperatures (which may result in a logarithmic dependence).
The important corollary that follows from this observation is this: \( k_F \ell \) is not a good parameter to characterize disorder when superconductivity is concerned. Reducing \( k_F \) (by e.g., decreasing the carrier concentration), weakens the BCS potential, and the superconducting transition temperature will decrease more than by reducing \( \ell \) to achieve the same \( k_F \ell \). Increasing the static disorder will reduce \( \ell \), but this is not necessarily detrimental to superconductivity. It may actually enhance it.\(^{16}\) Even in the case that superconductivity is suppressed by disorder it is a weaker effect than the exponential decrease associated with reducing the BCS potential; the latter can easily push the transition temperature to well below experimental reach creating the false appearance of a superconductor to metal transition. \( k_F \ell \) may still be a descriptive measure of disorder when care is taken to keep \( k_F \) constant in the process of varying the disorder as was done in Ref. 7.

Despite the huge difference in their carrier concentration (more than two orders of magnitude), the MIT in the two In\(_2\)O versions occurs at essentially the same \( k_F \ell \) (see Fig. 4).

Our conjecture, that the apparent violation of the Ioffe-Regel criterion in the electron-rich In\(_2\)O is due to correlations, is not supported. The low value of \( k_F \ell \) at the transition is therefore more likely related to some properties of the amorphous phase that differ from the crystalline version of the material where the critical \( k_F \ell \) is close to unity.

The crystalline and amorphous phases of indium oxide differ in several aspects (in addition to symmetry). While the crystalline version, in agreement with theoretical considerations,\(^{17}\) behaves as a nearly free electron system,\(^{18}\) optical absorption due to interband transition of In\(_2\)O samples is inconsistent with a parabolic conduction band.\(^{6}\) Values of \( k_F \ell \) estimated for this material by using free-electron formulas may therefore be questionable. Another possibility is that transport in the system is more inhomogeneous than might be judged by the space-filling, physically uniform structure reported for this material.\(^{7,19,20}\) Note that when the sample resistivity is not uniform, \( k_F \ell \) based on macroscopic measurements of conductance and carrier concentration may not be telling of the relevant disorder and the calculated value of \( k_F \ell \) may differ from that associated with the “average” disorder. This could be a real problem when the inhomogeneity in the system is so gross as to cause current to flow preferentially through only part of the structure.

In the following we describe how some structural attributes of the amorphous indium oxides give rise to inhomogeneities in these systems (and possibly in other multicomponent systems like alloys and metal oxides). These may lead to a host of low temperature transport anomalies when superconductivity is involved in addition to an underestimated \( k_F \ell \).

The stoichiometric compound In\(_2\)O\(_3\) is an ionic insulator with a large (\( \approx 3.6 \) eV) band gap. It is a well characterized material, and has a cubic structure with 48 oxygen atoms and 32 indium atoms in a unit cell. The naturally occurring material however is oxygen deficient, and films of crystalline indium oxide usually contain 5–10% oxygen vacancies.\(^{21}\) This gives rise to carrier concentration \( n \approx 6 \times 10^{19} \text{ cm}^{-3} \), and a factor of \( \pm 2 \) around this value may be affected by changing the stoichiometry using, e.g., UV treatment.\(^{22}\) The limited range of achievable \( n \) is due to constraints imposed by crystal chemistry.

Amorphous indium-oxide, being relatively free of these constraints, may be prepared with a much wider atomic ratio of oxygen indium. This makes it possible to make stable (more accurately, metastable with a long lifetime at room temperatures and below) films with optical gaps between 2.5 eV and 1.1 eV and carrier concentration of \( \approx 5 \times 10^{18} \ldots 10^{22} \text{ cm}^{-3} \), respectively.\(^{6}\) The correlation between stoichiometry and carrier concentration of amorphous indium oxide is shown in Fig. 6.

The freedom from crystal chemistry constraints is perhaps also the reason for the emergence of compositional-disorder in these amorphous oxides. This kind of spatial disorder has far reaching consequences, especially when superconductivity is involved. Spatial disorder means that the material parameters vary in space; disordered systems are inhomogeneous by definition.

The nature of the inhomogeneity however, depends on the type of disorder. Quenched disorder of the ionic potential is common in most disordered electronic systems. Large spatial fluctuations of carrier concentration on the other hand are unlikely to occur in systems with monoatomic metallic systems, but they are quite prominent in all versions of the amorphous indium oxides. Figure 7 is a micrograph taken by a scanning mode of a transmission electron microscope. The contrast mechanism in the micrograph is due to absorption; changing the angle between the sample plane and the electron beam axis does not turn a black region into white (as it often would in a crystalline sample where the main contrast mechanism is Bragg scattering). There are no holes in the film and thickness variations are relatively small; AFM line scans show 5–20 Å surface roughness for 200 Å films deposited on glass substrates (the smaller value obtained for the low-\( n \) version of the material). Chemical analysis, using energy dispersive x-ray spectroscopy and electron energy-loss spectroscopy (EELS) revealed that regions with higher
transmission (white patches in the figure) are richer in oxygen, poorer in indium content, and vice versa for the black regions. Variations in the O-In ratio between these regions could be as high as 15–40% for a sampling area of 50 Å². The uncertainty in these measurements is mainly due to the background signal from the carbon support that includes a certain amount of oxygen. This source of error may be mitigated by making self-supporting films, but a systematic study of thickness dependence will be necessary to get a more accurate estimate of stoichiometry. Note, however, that a mere 10% variation in O-In ratio is equivalent to an order of magnitude difference in the local carrier concentration (cf., Fig. 6), which is tantamount to a factor of two in the thermodynamic density of states.

The spatial range of these compositional fluctuations can be assessed by Fourier transforming line scans of the intensity, averaged over the entire micrograph area (only a part of which is shown in Fig. 7). Results of such analyses, done for the two In₂O₃ samples of Fig. 7, are shown in Fig. 8. The flattening out of the spectrum at the small spatial scales is partly due to the smoothing effect of oxygen diffusion and partly due to the STEM resolution. Note that the low-n In₂O₃ is somewhat more uniform than the high-n version. However, in both cases the spectrum is skewed in a similar way and the compositional fluctuations persist over scales extending up to 300–800 Å.

These scales are comparable or even larger than the length scales that may be relevant for transport: \( L_{in}, L_T, \ell_c \) (and \( \xi, \) the superconducting coherence length). Pertinent information on these transport parameters may be obtained by analyzing magneto-conductance (MC) data. We have measured ten In₂O₃ metallic samples at 4 K, and for comparison, also at 77 K. At small fields the MC for all metallic samples was positive and that remained so down to 2 K (tested on one of these samples). Spin orbit scattering in In₂O₃ is therefore rather limited in strength. A negative MC component however does appear at high fields as seen in the data described in Fig. 9.

Figure 9 compares the MC of our most metallic In₂O₃ sample with a In₂O₃₋ₓ sample of comparable resistivity. The latter system has been extensively studied and exhibits \( L_{in} \) of 1000–1300 Å at \( \approx 4 \) K for samples with \( k_F \ell \) of order 2–5. The field at which the MC crosses over from \( H^2 \) to a weaker dependence is \( \approx 25 \) times larger for the In₂O₃ sample. This suggests a considerably smaller \( L_{in} \) than that of In₂O₃₋ₓ at the same temperature. We have analyzed the low field MC for the amorphous sample using Kawabata’s expression:

\[
\frac{\Delta \sigma}{\sigma} = \frac{\tau_{el} m}{12 \tau_{H^2}} \approx \frac{\tau_{el}}{12 \tau_{H^2}}
\]

in conjunction with the Drude expression for the conductivity \( \sigma = \frac{n e^2}{m} \tau_{el} \) using \( m* \approx 0.28 \).

![FIG. 7. STEM (scanning transmission electron microscopy) picture of In₂O₃ films. These are typical for the low-n version with carrier concentration \( n = 5 \times 10^{18} \) cm⁻³ (a), and the electron-rich version with \( n = 3 \times 10^{19} \) cm⁻³ (b). The films are 300 Å thick (rather than the 1000–1400 Å thick films used for transport) to achieve a good spatial resolution, and they were thermally annealed to make them characteristic of samples near their respective MIT (a) and SIT (b) transition.](image)

![FIG. 8. (Color online) Fourier transforms of the STEM micrographs taken from the same samples shown in Fig. 7 and plotted as a function of the spatial scale. These were averaged over individual line scans taken across each micrograph. The dashed lines are merely guides to the eye.](image)

![FIG. 9. (Color online) Magneto-conductance for a metallic In₂O₃ film \( (k_F \ell = 0.68) \) shown for 77 K and 4.1 K. These are compared with the magneto-conductance for a crystalline indium-oxide sample \( (k_F \ell = 2.3) \) taken at 4.11 K. Dashed lines depict the \( \Delta \sigma / \sigma \propto H^2 \) law expected for small fields. Arrows mark the fields where \( \Delta \sigma / \sigma \) deviates from the parabolic law. The ratio \( \Delta \sigma / \sigma \propto T_{H^2} \langle 77 \rangle \) measured for ten In₂O₃ samples in the parabolic part of the MC was 78 ± 4. Using Kawabata’s expression (Ref. 24) \( \Delta \sigma / \sigma \propto T_{H^2}^{1/2} \), this is consistent with \( \tau_{el} \propto T^{-1} \) in this range of temperatures. Note the negative MC of the In₂O₃ sample (at 4.1 K) for \( H > 6.5 \) T.](image)
(mass of the free electron). This yield the parameters: \( \tau_d \approx 6 \times 10^{-15} \text{ s} \), \( \ell \approx 12 \text{ Å} \) (using \( V_F \approx 2 \times 10^7 \text{ cm/s} \), \( L_m \) (at 4.1 K) = 450 ± 20 Å, \( D \approx 2 \text{ cm}^2/\text{s} \). The interaction length is then 70 Å and 140 Å depending on whether \( L_T = k_F^{-1}(T) \ell \) or \( \sqrt{\frac{eD}{h^2}} \), respectively. At temperatures relevant for our experiments these length scales are not large enough to average out the compositional inhomogeneities observed in these materials.

Although it may have no direct bearing on the main issues of this work, it is important to point out that the MC of the In\(_x\)O samples differs from the MC in the crystalline version by more than the magnitude of \( L_m \). The negative MC component of the metallic sample in Fig. 9, that is just observable above \( \approx 6.5 \text{ T} \), becomes quite noticeable at lower temperatures (but down to 1.4 K it is only seen above \( \approx 3 \text{ T} \)). The MC in diffuse In\(_2\)O\(_{3-x}\) samples is purely positive, throughout the entire range up to fields of 12 T and down in temperature from 77 K to \( \approx 40 \text{ mK} \). There is also a difference between In\(_x\)O and the crystalline In\(_2\)O\(_{3-x}\) version in terms of the MC for insulating samples; the MC in insulating In\(_2\)O\(_{3-x}\) starts positive and becomes negative at high fields,\(^{25}\) while just the opposite is observed in our insulating In\(_x\)O sample (with \( k_F \ell = 0.23 \)) for temperatures below 3 K.

Results of MC measurements on In\(_x\)O films were reported by Lee \textit{et al.}\(^{26}\) Their results differed from ours; they observed positive MC only above 8–10 K while the low field MC became negative at lower temperatures. It should be noted however that the In\(_x\)O films of Lee \textit{et al.} were presumably the electron-rich version (and exhibited superconductivity for \( T < 1 \text{ K} \) when the resistance was low enough). More work is needed to identify the origin of the mechanism that is responsible for the negative MC at both the metallic and insulating regime of the different versions of In\(_x\)O.

Fluctuations in carrier concentrations on the spatial scales observed in the amorphous indium oxides constitute an important type of disorder. Screening is more effective in our experiments these length scales are not large enough to average out the compositional inhomogeneities observed in these materials.

Although it may have no direct bearing on the main issues of this work, it is important to point out that the MC of the In\(_x\)O samples differs from the MC in the crystalline version by more than the magnitude of \( L_m \). The negative MC component of the metallic sample in Fig. 9, that is just observable above \( \approx 6.5 \text{ T} \), becomes quite noticeable at lower temperatures (but down to 1.4 K it is only seen above \( \approx 3 \text{ T} \)). The MC in diffuse In\(_2\)O\(_{3-x}\) samples is purely positive, throughout the entire range up to fields of 12 T and down in temperature from 77 K to \( \approx 40 \text{ mK} \). There is also a difference between In\(_x\)O and the crystalline In\(_2\)O\(_{3-x}\) version in terms of the MC for insulating samples; the MC in insulating In\(_2\)O\(_{3-x}\) starts positive and becomes negative at high fields,\(^{25}\) while just the opposite is observed in our insulating In\(_x\)O sample (with \( k_F \ell = 0.23 \)) for temperatures below 3 K.

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maximum of samples increased monotonously with disorder reaching a dimensional system. The activation energy of the insulating scenario, it appears that the modulation depth of local superconducting properties caused by potential fluctuations is much less conspicuous than that of fluctuations in carrier density. In conducting properties caused by potential fluctuations is much more powerful agent for local modulation of $T_c$, which can be of either sign. Spatial fluctuation in the BCS potential, on the other hand, is a mild effect on $n$. However, the range of disorder where this mechanism is relevant is limited to the vicinity of the transition; for sufficiently strong disorder the localization length $\xi$ will be everywhere smaller than $\xi_L$ and there will be no superconducting islands in the system. In this case the transport mechanism will revert to normal VRH as seen in the experiment. At smaller disorder, on the other hand, many of the superconducting islands may be Josephson-coupled to form large superconducting clusters. Effective Josephson coupling through insulating $\text{In}_2\text{O}$ layers has been observed experimentally. Global superconductivity may result in the system with the associated percolative features discussed in Ref. 20. In this picture $\sigma(T)$ is a nontrivial result of hopping conductivity modulated by the compounded effect of the temperature-dependent appearance of superconducting islands and the evolution with temperature of their local pair potential. In view of the transport features described above this seems to be a prime avenue to look for a solution to this problem.

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13. Samples with $k_F \ell \gtrsim 0.25$ in this electron-rich version of In$_x$O$_{2-x}$ are superconducting at liquid-helium temperatures, and therefore the critical $k_F \ell$ cannot be determined by the low-temperature method used for the nonsuperconducting In$_2$O$_3$ and the low-$n$ version of In$_x$O.
15. Crystalline indium-oxide films were measured down to $\approx 12$ mK showing no sign of superconductivity; F. P. Milliken and Z. Ovadyahu (unpublished).