Scale dependent superconductor-insulator transition

D. Kowal and Z. Ovadyahu

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

Abstract

We study the disorder driven superconductor to insulator transition in amorphous films of high carrier-concentration indium-oxide. Using thin films with various sizes and aspect ratios we show that the 'critical' sheet-resistance $R_{\square}$ depends systematically on sample geometry; superconductivity disappears when $R_{\square}$ exceeds $\approx 6$ k$\Omega$ in large samples. On the other hand, wide and sufficiently short samples of the same batch exhibit superconductivity (judged by conductivity versus temperature) up to $R_{\square}$ which is considerably larger. These results support the inhomogeneous scenario for the superconductor-insulator transition.

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INTRODUCTION

Sufficiently strong spatial disorder may precipitate an insulating phase in an otherwise metallic system. When the ground state of the metal under study is a superconductor, the disorder-driven transition is called the superconductor to insulator transition (SIT). The SIT has been studied over many decades, especially in thin films where tuning the disorder is readily achieved by varying the film thickness [1, 2, 3, 4, 5, 6, 7, 8]. Many common features of the SIT in such 2D (two-dimensional) systems were found in different superconducting materials. On the other hand some details of the resistive transition such as re-entrant behavior, prompted researchers to focus on systems that are structurally ‘homogeneous’ presumably with the hope of being able to characterize the “clean” physics of the SIT. It was however found out that even purely amorphous materials, that structurally show no irregularities on scales of $\approx 10$ A, often exhibit features that are suggestive of (transport) inhomogeneities [3].

In this note we give further evidence for the inhomogeneous nature of transport near the SIT of amorphous indium-oxide ($In_xO$) films. Using samples with lateral sizes of 1 mm to 0.45 $\mu$m, and aspect ratios in the range 1 to $\approx 10^3$ we show that the conductivity at liquid helium temperatures is strongly scale dependent. The results are interpreted as evidence for long-range potential-fluctuations, and it is suggested that their presence be taken into account in trying to explain details of the SIT.

EXPERIMENTAL

Sample preparation and measurements techniques

The present study was done on thin films of amorphous indium oxide $In_xO$. These were prepared in a vacuum chamber capable of achieving a base pressure of better than $3 \cdot 10^{-7}$ mbar and equipped with electron-beam and Knudsen evaporation sources. Oxygen, cleaned by cold trap, could be bled into the chamber at controlled rates though a needle valve. Standard glass slides were used as substrates. These were chemically cleaned before being placed in the chamber. A setup for plasma cleaning of the substrates was used prior to deposition using pure oxygen. After plasma cleaning for a few minutes in an atmosphere of $2 \cdot 10^{-7}$ mbar, the chamber was pumped down to better than $5 \cdot 10^{-6}$ mbar. Films were prepared by e-beam evaporation of 99.999% pure pressed In$_2$O$_3$ pieces manufactured by Cerac as described in detail elsewhere [10].

A quartz crystal thickness monitor (calibrated against a Tolanski interferometer) was used to determine deposition rates and film thickness. The $In_xO$ films used in this study were deposited at a rate of 1 A/s to a nominal thickness of 200-250 Å. These conditions yield the relatively high carrier concentration $n \gtrsim 5 \cdot 10^{21}$ cm$^{-3}$ ($In_xO$ samples with $n$ smaller than $\approx 10^{20}$ cm$^{-3}$ are not superconducting down to 1 K). The as-prepared films were studied by high resolution transmission electron microscopy and exhibited microstructure and diffraction patterns that are typical for amorphous structures (c.f., figure 1).

Samples for measuring large scale material properties and Hall-effect measurements were defined by placing an appropriate aluminum mask over the substrate during the deposition. To study the scale dependence, we compared the properties of batches of simultaneously prepared samples of common width and different lengths down to less than a micron. These were prepared by a lift-off technique: Strips of amorphous indium-oxide, 0.5 mm wide and few millimeters long were made using a mechanical mask. Thin fibers were then pulled from a drop of 7031-GE varnish and placed across the strip. The
thickens the fibers could be controlled in the range of $\approx 50 \mu m$ down to less than 0.2 $\mu m$ by proper dilution of the varnish in a 1:1 solution of ethanol and toluene (varnish thinner), and by the speed at which the fibers were pulled. The slides were then returned to the vacuum chamber and a $\approx 300$ Å layer of gold was deposited over the $In_xO$. Finally the slides were immersed in varnish thinner to dissolve the fibers and wash away the gold that was on them. This left a series of gaps in the gold layer which defined indium oxide samples all "cut" from the same thin film, having a common width but different lengths. Longer samples could be made by using commercial copper wire instead of the varnish fibers. Electrical connections were made by soldering wires to small pieces of indium metal pressed onto the gold contacts. Before depositing the gold and after completing sample preparation the fibers/gaps were viewed through an optical microscope at x400 magnification to see the range of sample lengths obtained and their geometrical quality. Figure 2 shows a SEM micrograph of a 0.9 $\mu m$ long amorphous sample. The borders were checked to be smooth and equidistant over the entire width of the sample (500 $\mu m$) to within $\approx 10\%$.

RESULTS AND DISCUSSION

As prepared films of $In_xO$ are usually insulating and exhibit negative temperature coefficient of resistivity from room temperatures down, and some form of variable range hopping may be observed at the 10-100 K range [10]. Samples that are near the SIT in the insulating side tend to show simple activation at liquid helium temperatures. Namely, $R_{c}(T)$ is seen to follow $R_{c}(T) \propto \exp(-\frac{T}{T_0})$ with typical activation energy $T_0$ of order 3-15 K depending on disorder. This is true in 3D [11] as well as in the 2D regime [3, 4, 5, 6, 7, 8] and is still one of the important unsolved issues of transport near the SIT [12]. Figure 3 illustrates this behavior for a large-area film measured at several stages of annealing (disorder). Note that as the sheet-resistance $R_c$ at $T \approx 4$ K is reduced by annealing, so does the activation energy, and for $R_c \approx 6$ kΩ the temperature dependence becomes rather weak. In fact, as shown in the inset, samples with this value of $R_c$ are superconducting below $\approx 0.3$ K. A 'critical' $R_c$ may be thus identified at the value of $R_c \approx 6$ kΩ for the SIT in this system. A similar value for $R_c$ has been reported by other researchers.

A somewhat different situation is encountered in the small-area samples. This is illustrated in figures 4a and 4b that show $R_c(T)$ data for a single batch of samples at two stages of annealing and for samples with different length $L$. Note that $T_0$ has a marked dependence on $L$ (and/or the aspect ratio) and this leads to a significant variation of $R_c$ as the temperature is lowered (figure 4a). Upon further annealing (causing a decrease in the average disorder), this disparity makes for a sharper division of the $R_c(T)$ data; The two longest samples in the batch are still activated with $T_0$ somewhat reduced relative to the previous stage. However, the two shortest samples of the same batch now show a clear tendency to become superconducting at low temperatures (figure 4b). This is a striking result as the samples are all made from the same batch and in fact show very similar resistances at higher temperature. Moreover, associating, as previously done, $R_c$ with the value of the sheet resistance that separates these two groups we now get a value that is at least twice larger than that of the large-area samples of the same material. It is emphasized that the length-controlling fibers were placed on the common $In_xO$ strip in close proximity to one another and at no particular order (i.e., no hierar-
FIG. 3: Resistance versus temperature for a large area (500x500 µm²) InₓO film at various stages of the annealing process (labeled with their activation energies or by "S" when superconducting in range). Inset shows a similar film measured to lower temperatures revealing its superconductivity.

These dependencies of the transport properties on sample scale and aspect ratio is suggestive of a percolation phenomena in an inhomogeneous media. As argued before [3] the inhomogeneity is a natural consequence of disorder, and inasmuch as superconductivity is concerned, the effect of disorder may be highly accentuated.

The argument is based essentially on the phenomenon of universal conductance fluctuation: Superconductivity usually vanishes when the average conductance of the 2D system is comparable with $e^2/h$. At this degree of disorder the conductance of the underlying diffusive metal fluctuates considerably on scales of order $L_\phi$, the phase-coherent length. In fact, the local conductivities $g(L_\phi)$ are naturally distributed over a $\pm e^2/h$ range, which means that at the transition to strong localization the distribution-width of the local conductances is of order unity. Therefore as the average critical disorder is attained, there are perforce some regions of the sample where the local disorder is smaller than critical and these regions may be locally superconducting. It is easy to see that from the point of view of conductivity the system may appear ‘granular’ with small superconducting regions embedded in an insulating matrix (and a complementary situation on the ‘weakly localized’ side of the transition). This may happen even in a structurally featureless amorphous structure as are the samples in the present case (as mentioned above, c.f., figure 1). Such a scenario is generic and should be pertinent for all materials where sub-critical disorder does not appreciably decrease $T_C$. These then include all systems that obey the Anderson Theorem as well as metals that show ‘enhancement’ phenomena.

If one allows for just short-range disorder, these arguments cannot however account for the spatial scale over which the results in figures 4a and 4b are still size dependent. Gaussian disorder could conceivably lead to an inhomogeneous situation on scale of order $L_\phi$, the hopping problem on the insulating side of the transition). Neither of these lengths is larger than 1 µm at liquid helium temperatures whereas significant size dependence is observed in our experiments up to $L$ that is at least one order of magnitude larger.

The relevant scale for the actual ‘granularity’ may of course be larger than the size of the individual superconducting island; several such islands may be Josephson-coupled to form a larger cluster. But this still leaves unanswered the scale dependence of the activation energy observed in figure 4a to extend over tens of microns. It would therefore seem necessary to consider the existence of long-range potential-fluctuations in these samples, which is not an uncommon phenomenon in amorphous materials [13]. In fact, long-range fluctuations in the disorder may be expected to be present when the dis-

FIG. 4: (a) Resistance versus temperature for a single batch of InₓO film with a common width of 500 µm and length as shown. Each sub-sample is labeled with its activation energy $T_0$ (see text). (b) Same batch of samples as in (a) after further thermal annealing.
FIG. 5: The electric field $F_c$ that reduces the resistance by 1% (relative to the linear response value) as function of the sample length $L$. The dashed line is merely a guide to the eye.

order is large as must be the case here (strong disorder is actually required when a high carrier-concentration system is to be rendered Anderson localized). This is due to the cost of creating a potential gradient which would favor large potentials drops on the longer spatial scales. Naturally then, long range potential fluctuations should be a consideration especially when the sample is prepared or is later exposed to room (or higher) temperatures.

The presence of long-range potential-fluctuations in these films is also reflected in the current-voltage ($I-V$) characteristics of the studied samples. In their normal state all our samples showed deviations from Ohmic behavior above a characteristic voltage $V_C$. These deviations were always such that $\partial R / \partial V < 0$, which is presumably related to the fact that the temperature coefficient of the resistance is negative at helium temperatures. As a rule, the critical field $F_C = V_C / L$ at which non-linearity became important was noticeably larger at small $L$. This trend is illustrated in figure 5 for all the relevant samples used in our study. Despite the scatter in the data, it is clear that long samples are "softer" than short ones as may be expected from long-range fluctuations; samples with larger $L$ are associated with with larger local fields hence they are more susceptible to non-linearity at any macroscopic field. Note that $F_C$ at which measurable deviations from Ohm’s law are observed is scale-dependent over the same range of $L$ where the data in figure 4a and 4b exhibit scale-dependence.

In summary, we have presented experimental evidence for the inhomogeneous nature of transport in an amorphous system near the SIT. The results seem to suggest the relevance of long-range potential-fluctuations which may result from thickness and/or composition variations to which characterization methods such as diffraction, STM, TEM, as well as other form of microscopy may not be as sensitive as charge transport. These issues clearly deserve further experimental and theoretical elucidation.

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