Crossover from Two to One Dimension in *In Situ* Grown Wires of Pb

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Using a novel fabrication technique, we have studied the metal-insulator transition in *in situ* grown wires of Pb with cross-sectional areas as small as 10^{-13} cm^3. We find that as we cross over into the 1D regime, fluctuations dominate the superconducting transition. Although existing fluctuation models work well at the larger cross-sectional areas, there is systematic deviation as the wires become smaller. We speculate that this may be due to 1D Coulomb correlation effects.

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Superconductor-insulator transitions in thin metal films in the two-dimensional limit have been extensively studied in the past few years [1-5]. By appropriate substrate preparation, it is possible to grow uniform amorphous films as thin as 5 Å (1 to 2 monolayers). In such films, it has been seen that the superconducting transition temperature is well defined and depressed compared to the thick film limit and is dependent upon the film thickness (or sheet resistance) [1,2]. It has been argued that the T_c depression arises from Coulomb correlation effects that occur because of strong disorder and reduced dimensionality [6,7]. In earlier studies and also in the data presented here, the superconducting transition widths remain sharp in these uniform films, even at the depressed transition temperature and can be described quantitatively by our existing understanding of fluctuation effects. This is unlike the case of granular films where the onset of the resistive transition is usually close to the bulk T_c value, but where the transitions are extremely broad in temperature and "T_c" is not well defined [4,5].

Efforts have been made to extend these studies to the one-dimensional limit [8-10]. Aside from the obvious technical difficulties the main obstacle is that, unlike the 2D case, it has heretofore not been possible to change the cross-sectional area of the wire continuously *in situ* and thus avoid sample to sample variations. The most systematic of these studies was by Graybeal *et al.* [8] in which wires of various widths were fabricated on a single film of amorphous Mo-Ge.

In this Letter, we describe our results of the crossover from 2D films to 1D wires. Our results show that existing fluctuation models become inadequate as the samples' cross-sectional areas become smaller and we cross over into the 1D regime: Below the mean-field transition, we find large excess resistance which varies systematically with cross-sectional areas. We have fabricated wires with cross-sectional area as small as 1.5×10^{-13} cm^2 and have developed techniques to continuously vary this area *in situ* [11]. We fabricate metallic stencils (Fig. 1) consisting of structures having overhangs on a GaAs substrate. The structure thus consists of a substrate on which a shadow mask has been fabricated. We can routinely fabricate stencils with openings as narrow as 150 Å. The lines are smooth with edge roughness of about 30 Å. Leads are then attached to the appropriate positions to ensure a four-terminal measurement and the substrate is mounted in a low-temperature evaporator previously described [12]. With the temperature of the substrate held at 5 K, films of uniform thickness of Pb were grown by first evaporating a monolayer of Ge followed immediately by Pb. Continuity typically occurred at 5 Å of Pb and for thicknesses over 10 Å the conductance scaled linearly with thickness, implying uniformity. Wire resistance was monitored during deposition and the sensitivity of the measurement was better than 1 part in 10^4 of the normal state resistance of the wire. The resistance was determined by measuring current-voltage characteristics. Since the *I-V* curves of these wires became nonlinear at higher current densities, measuring currents were kept well below 10^{-9} A to ensure the measurements were in the Ohmic region.

Extensive efforts were made to shield the sample from external noise. All measurements were performed in an rf shielded room and all leads were isolated using both room temperature and cryogenic filters. We have performed measurements on over 25 wires and we report here measurements on seven samples ranging in width from 150 Å to a 2D case of 6 μm width. A variety of thicknesses for each wire were studied and in all cases, the length of the wires was 6 μm.

Figure 2 shows resistive transition curves at various thicknesses for three widths. To compare samples, we have chosen to plot the data in the form of $R_\square$ vs T. Presenting the data in this manner compares wires of identical thicknesses and enables us to identify deviations due to differences in wire widths. We see that as the wire widths become narrower, the resistive transition becomes consistently wider. Since for all widths, the onset of continuity occurred at about the same thickness ($\sim$5 Å) and the conductance scaled linearly with thickness, we are

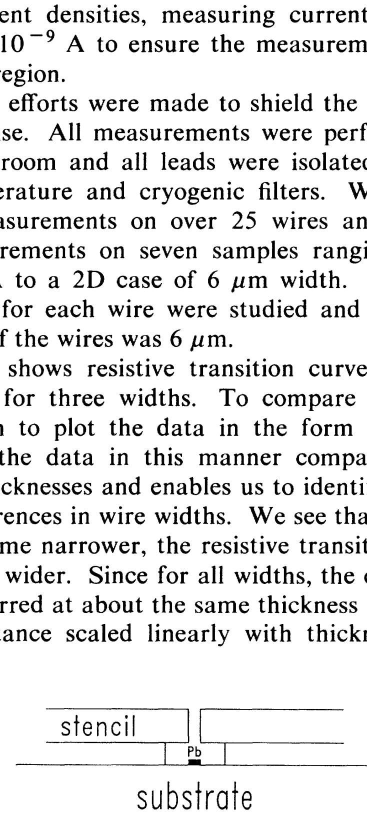

FIG. 1. Cross-sectional view of stencil structure. The Pb films are evaporated through the shadow mask structure fabricated on the substrate.

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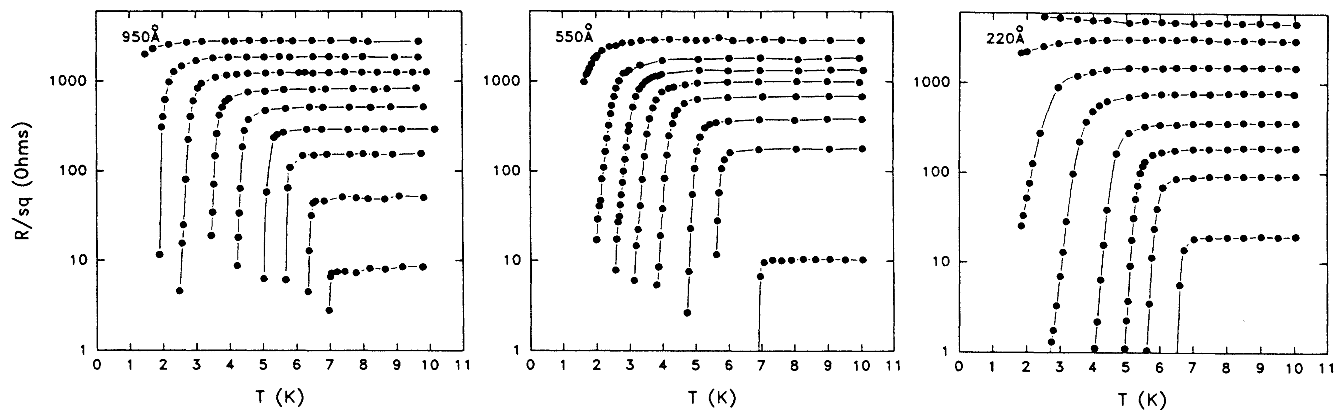

FIG. 2. Resistive transitions for three wires of different widths at various thicknesses. Note the transitions become broader with decreasing wire size. The lines are a guide to the eye.

confident that the transition widths are intrinsic and not caused by spurious effects such as inhomogeneities. In fact for the smaller wires (e.g., 220 Å, shown in Fig. 2) we suspect that the smaller wires will not go completely superconducting. If we extrapolate our data in the 220 Å wire in Fig. 2 to $T=0$, then for thicknesses that are just on the superconducting side of the transition, we will obtain a finite value of R. While this extrapolation does not prove the suspicion, it is suggestive and lower-temperature studies are necessary. We are beginning to explore this lower-temperature regime in a dilution refrigerator equipped with an *in situ* evaporator in order to study this destruction of superconductivity due to fluctuation effects in one dimension.

We characterize these fluctuations by plotting the resistive transition widths of various wires in Figs. 3(a) and 3(b). Here the transition width is arbitrarily defined as the temperature interval between 20% and 80% of the normal state resistance. In the 2D regime, the transition width is determined solely by fluctuation effects and hence $R_\square$ (film thickness). Films of identical $R_\square$ should have the same transition width. In Fig. 3(a), we have plotted the transition width versus $R_\square$ for various wires. We see that as the widths become smaller, there is a systematic increase in transition widths for the same $R_\square$ (thickness). Obviously, the transition widths depend not only on thickness, but also on wire width.

In the 1D regime, the transition widths should depend on the cross-sectional area of the wire. The appropriate parameter should then be R and not $R_\square$. In Fig. 3(b), we have plotted the transition width versus R for the various wires widths. We see that the fluctuations depend on cross-sectional area in a systematic way. This plot gives us confidence that insofar as the length scale for the superconducting fluctuations is concerned, we are in the 1D limit for $R > 10$ kΩ. This length scale is on the order of ξ, the dirty limit Ginzburg-Landau (GL) coherence length. Using a free-electron model, we estimate an elastic mean free path $l \approx 5$ Å for our films. This results in a dirty limit ($T=0$) coherence length of roughly 60 Å. Taking into account the temperature dependence of the coherence length, we estimate that we should cross over from two to one dimension in the vicinity of 500 Å. Indeed, while Fig. 3(b) shows the expected dependence

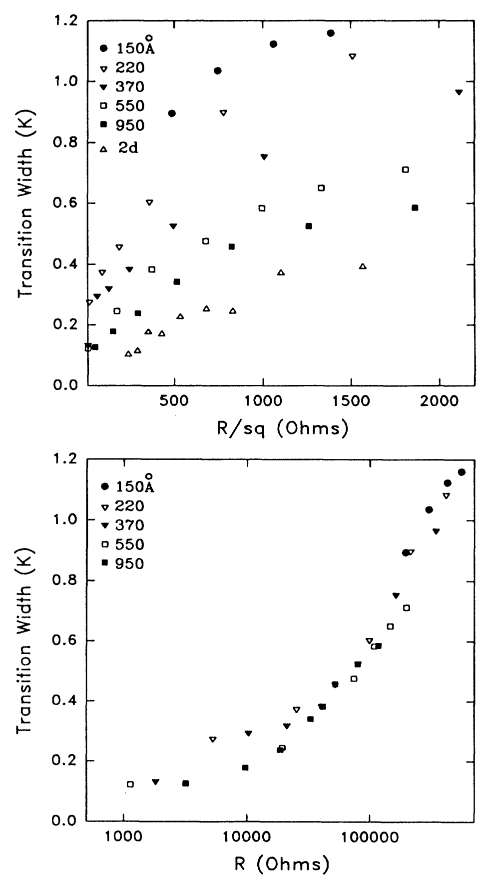

FIG. 3. Transition widths vs $R_\square$ and R. The transition widths scale with cross-sectional area of the wire, implying that we are in the 1D limit.

with R for the narrow wires, the wide (6 μm) film does not fit on this curve.

For the moment, we are unable to make any strong statements about changes in T_c with linewidth for a given $R_\square$ (thickness). It is well known that in 2D, there is a strong variation of T_c with $R_\square$. From these and earlier studies we know that there is some variation from sample to sample in T_c for a given $R_\square$ [13]. A possible explanation for this effect may be variations in charge screening caused by thickness variations in the Ge underlayer. With this uncertainty, we cannot identify any substantial depression of T_c with wire width down to about 220 Å. However, there is a strong indication of T_c depression in the 150 Å sample. This can be seen in Fig. 4 where we have plotted $R_\square$ vs T. We have chosen for each wire width the data set where $R_\square$ is close to the reported superconductor-insulator transition for Pb in 2D (roughly 10^4 Ω). Clearly the narrowest wire is on the insulating side of this transition while in the 2D limit, it is close to the superconducting-insulator transition. We note that the electron thermal diffusion length $l_t = (hD/kT)^{1/2}$, where D, the electron diffusivity, is roughly 400 Å at 4 K. It is not unexpected that a dimensional crossover in the normal state occurs for widths in this regime. In hindsight, this result is also not surprising if we look back at the 2D case. There, significant deviations from the bulk T_c occur at thicknesses less than 150 Å. We would expect further suppression of the T_c as the widths become smaller than 150 Å. We are currently exploring this regime.

In trying to understand the increased width of the observed transitions, we have fitted the resistive transitions to fluctuation models both above and below T_c (assuming

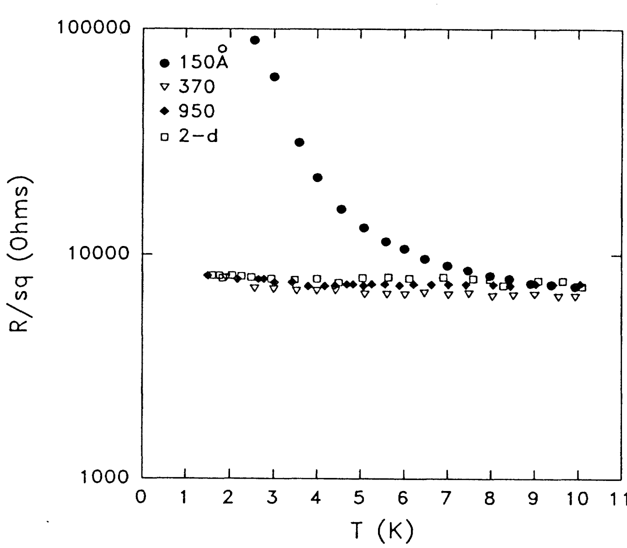

FIG. 4. Resistive transitions for four samples of different widths. All samples are about the same thickness ($R_\square$). The 150 Å sample clearly indicates insulating behavior due to lateral confinement of the normal electrons.

that T_c lies somewhere in the middle of the transition region) [14]. Above T_c, we have used the Aslamasov-Larkin (AL) model which has T_c as the only free parameter [15]. The AL model predicts excess conductance above T_c of the form

$$\Delta G = e^2/16\hbar \frac{\xi(0)}{L}(1-T_c/T)^{3/2} \text{ for 1D}.$$

Here L is the sample length and $\xi(0)$ is the ($T=0$) dirty limit Ginzburg-Landau coherence length: $\xi(0) = 0.855 \times \sqrt{\xi_0 l}$, where l is the elastic mean free path and ξ_0 is the clean limit coherence length. We have also assumed a simple scaling for ξ_0 such that with decreasing T_c, the clean limit coherence length increases in a BCS manner:

$$\frac{\xi_0(T_c)}{\xi_0(T_c=7.2\text{ K})} = \frac{\Delta(T_c=7.2\text{ K})}{\Delta(T_c)} = \frac{7.2\text{ K}}{T_c}.$$

The last step in this assumption is justified since previous tunneling measurements on 2D Pb films have shown that $2\Delta/kT_c$ remains constant as T_c is depressed [2].

Below T_c, we have used the Langer-Ambegaokar-McCumber-Halperin (LAMH) [16,17] model for 1D superconductors. This model predicts thermally activated resistive tails below T_c of the form

$$R = \frac{\pi\hbar^2\Omega}{2e^2kT} e^{-\Delta F/kT}.$$

Here ΔF is an activation energy for a phase slip to occur and Ω is a phase-slip attempt frequency:

$$\Delta F = \frac{8\sqrt{2}}{3}\left(\frac{h_c^2(T)}{8\pi}\right)V,$$

$$\Omega = (L/\xi\tau)\sqrt{\Delta F/KT},$$

where $\tau = \pi\hbar/8k(T_c - T)$, $h_c^2/8\pi$ is the condensation energy per volume, and V is the volume of the fluctuating region. Again for consistency, we have assumed that as T_c decreases, the condensation energy scales from its bulk value in a BCS manner:

$$\frac{h_c^2(T_c=7.2\text{ K})}{h_c^2(T_c)} = \frac{\Delta^2(T_c=7.2\text{ K})}{\Delta^2(T_c)} = \left(\frac{7.2\text{ K}}{T_c}\right)^2.$$

We note that the LAMH model is applicable for the clean limit. Our modification consists of using the dirty limit coherence length. We also note that both models break down near T_c. In performing these fits, we have only adjusted T_c to obtain the best fit in the AL regime and then used this same T_c in the LAMH expression for below T_c. For all practical purposes, this procedure resulted in a T_c value close to the temperature at the resistive midpoint $R/2$.

In the LAMH model, one factor that is not known with precision is the volume V of the fluctuating region. It should be approximately $kw\xi t$ where ξ is the coherence length and w and t are the widths and thicknesses of the wires, respectively. k is a constant of order unity and is mostly determined by a geometric factor to account for

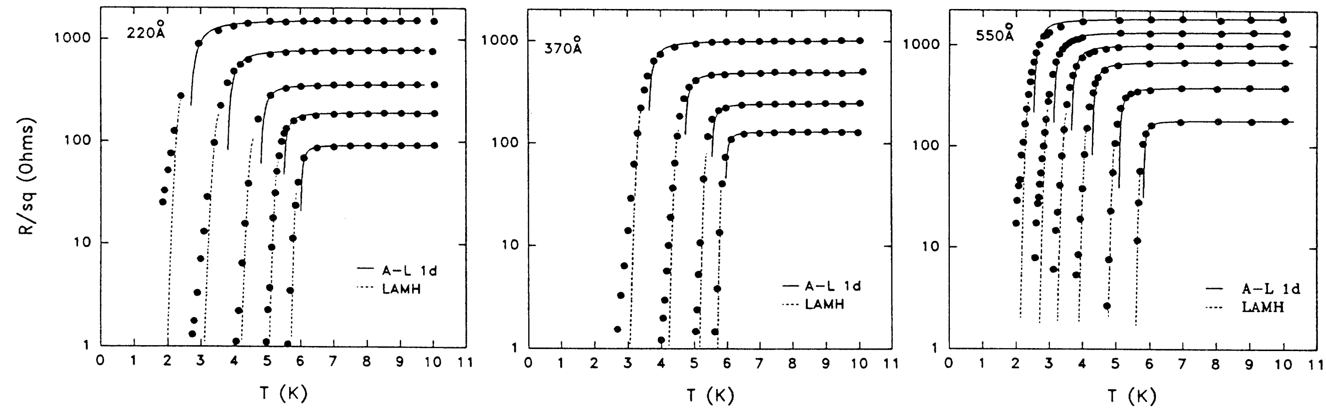

FIG. 5. Resistive transitions for three wires of different widths and the resulting fluctuation fits. The LAMH fits systematically deviate with decreasing thickness and wire width. Both the AL and the LAMH model are not valid near T_c.

the exact length scale on which the GL order parameter decays. A numerical integration of the decay length yields $k=2.9$. From our determined value of T_c from the AL fits, we obtain $k=3$ for all the LAMH fits. These two values are in good agreement.

In Fig. 5 we have plotted the results of our fit for both the one-dimensional AL model above T_c and the LAMH model below T_c. We see that the LAMH comparison to the wider wires at the higher T_c's (corresponding to larger cross-sectional areas) is good. However, as the wires become narrower and the transition temperature is suppressed (corresponding to smaller cross-sectional areas), there is deviation from the LAMH calculation. This deviation grows with decreasing size until whatever mechanism is causing this enhanced resistance dominates the $R(T)$ curves. This enhanced resistance is temperature dependent and so is not due to extraneous noise effects. Since we are in a regime where 1D Coulomb correlation effects are not negligible, it is possible that these correlations modify the LAMH model. One-dimensional Coulomb correlations will result in charge density fluctuations along the wire. In these regions, the GL order parameter (and the energy gap) would be suppressed, resulting in enhanced phase slipping in these temporally varying regions of fluctuating charge density. Such an effect would lead to excess resistance tails since these regions would have a smaller condensation energy. We emphasize that this effect is not due to granularity but is caused by charge density fluctuations due to imperfect electron screening caused by disorder and the one-dimensional nature of the wire. We also point out that it is unlikely that this deviation is caused by modulation of the wire widths due to edge roughness. If this were the case, then such modulation would exist at all wire thicknesses as more Pb was deposited. Then we would expect the LAMH model to have the same deviation at all wire thicknesses. Our data show that the deviation grows with decreasing thickness, making it unlikely to be caused by edge roughness.

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