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Magnetoresistance oscillations in granular Sn wires near the superconductor-insulator transition

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We report on a series of magnetoresistance measurements of *in situ* grown granular Sn wires with widths from 1100–2000 Å. The magnetoresistance is measured within the superconducting resistive transition of wires with different normal state resistances and the results are compared to two-dimensional (2D) granular Sn films. Both the wires and the 2D films exhibit two distinct magnetic-field regimes: a low-field weak positive magnetoresistance regime and a high-field strong positive magnetoresistance regime. In addition, the wires exhibit strong reproducible magnetoresistance oscillations within the low-field regime near the superconductor-insulator transition, which are not observed in the 2D films. We attribute these magnetoresistance oscillations to the effects of screening currents circulating around phase coherent loops of weakly linked superconducting grains. The observed magnetoresistance at different field strengths in the wires and films allows for a clear and coherent interpretation of the mechanisms causing the magnetoresistance behavior, and the magnetic-field tuned superconductor-insulator transition. [S0163-1829(98)00646-8]

The effect of dimensionality on electron localization and superconductivity has been a subject of study for decades. In particular, there have been numerous experiments performed investigating the two-dimensional (2D) superconductor-insulator transition (SIT) in ultrathin metal films. Depending on the morphology of the film the SIT is understood to be driven by two distinct microscopic mechanisms.[1–10] In the case of a *uniform* film the morphology is homogeneous on an atomic scale and the SIT is driven by the suppression of the amplitude of the order parameter. In the case of a *granular* morphology, where the film consists of grains tens to hundreds of Å in size, the individual grains in the film are large enough to support a bulk superconducting order parameter while they may be only weakly coupled or even uncoupled to each other. As R_N increases phase fluctuations between the grains are enhanced. This results in the destruction of the long-range superconducting phase coherence across the film, which drives the SIT.

Experiments on uniform and granular superconducting films, as well as on ordered Josephson junction arrays, have shown that the application of a magnetic field can be used to tune these systems through the SIT.[9–14] Recently studies of the SIT have been extended from the 2D to the 1D limit.[15–19] While the SIT in uniform wires was found to be qualitatively similar to the 2D case, the superconducting resistive transitions showed systematic excess broadening as the cross-sectional area of the wire was reduced.[16] The magnetoresistance of these uniform wires was particularly surprising. Below the mean field T_c, but in the regime dominated by resistive fluctuations, small magnetic fields were found to actually enhance the superconductivity, giving rise to a substantial negative magnetoresistance.[19] In granular wires a study of the SIT revealed an unusual effect in the normal state of the wire that was found to preempt the SIT: a discontinuous transition between the strongly localized (insulating) and weakly localized state (''metallic'') was observed.[17] This effect, however, did not appear to significantly alter the superconducting behavior of the system, which was qualitatively similar to that observed in 2D granular films.

Our initial motivation for studying the granular wires in a magnetic field was to investigate its influence on the unusual discontinuous localization transition observed in the normal state. The magnetic field was found to have no apparent effect on this transition. We, therefore, proceeded to study the magnetoresistance in the superconducting transition region for a series of granular Sn wires. This paper reports on these experiments. Our results have shown some marked differences from the magnetoresistance observed in 2D granular films.[9,13] We have found that the wire resistance, within the superconducting resistive transition, exhibits strong reproducible oscillations as a function of magnetic field perpendicular to the plane of the sample. These oscillations occur in a low-field regime where the expected positive magnetoresistance is relatively weak. At higher fields, where there is a strong positive magnetoresistance, the oscillations disappear as the film is driven normal. We believe that the oscillations are due to screening currents induced by magnetic flux threading phase coherent loops of grains. Similar behavior has been observed in regular Josephson junction arrays.[20] In comparing the results of our magnetoresistance measurements on wires to those of 2D films we are able to conclude that the enhancement of phase fluctuations, caused by increasing magnetic field, occurs in a different manner at different field strengths, and that the magnetic-field tuned SIT in the granular systems ultimately occurs through destruction of the superconductivity within the grains.[13]

The wires are grown by thermally evaporating material through a lithographically fabricated metallic shadow mask on top of an insulating substrate, as described previously.[16] The substrate with mask is mounted in a cryogenic evaporator where it is positioned at the center of a 5-T superconducting magnet such that the magnetic field is always perpendicular to the wire. All depositions and measurements are carried out under UHV conditions *in situ*. Preevaporated Au pads make contact to the wire and four terminal measurements are made along different sections of the wire. Standard ac lock-in resistance measurements and dc current-voltage (I-V) measurements are used to determine the wire resis-

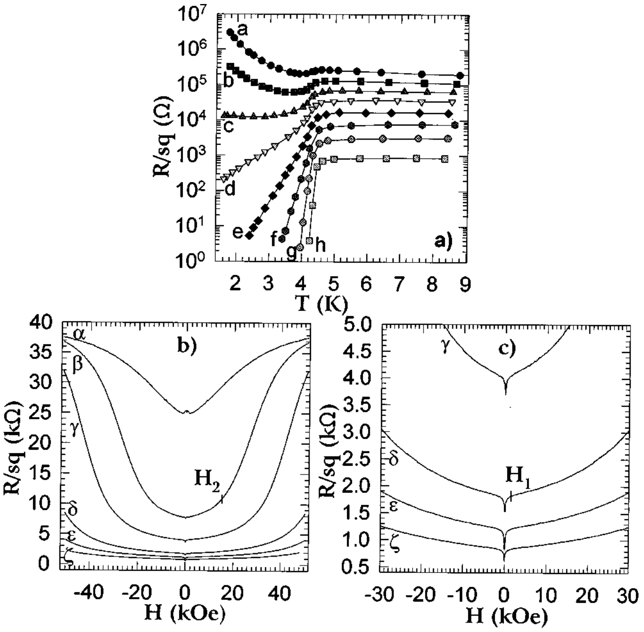

FIG. 1. (a) SIT for a granular Sn film. (b) Magnetoresistance for curve *d*; curves α–ζ, $T=4.36$, 3.97, 3.6, 2.95, 2.5, and 2.01 K. (d) Resistance scale in (b) expanded; curves γ–ζ, $T=3.6$, 2.95, 2.5, and 2.01 K.

tance. Since the I-V curves show nonlinearity at very low currents, particularly in the superconducting resistive transitions, the wire resistance is determined by measuring either the dc zero bias resistance or by using an ac measuring current of at most 10 nA. We have measured the magnetoresistance of a series of Sn wires, with widths of 1100–2000 Å and lengths of 1–4 μm.

Figure 1(a) shows the evolution of $R(T)$ for a series of 2D granular Sn films spanning the SIT. The magnetoresistance at different temperatures along curve *d* is shown in Figs. 1(b) and 1(c). The magnetoresistance for curves e–h exhibit similar qualitative features. The magnetoresistance shows three distinct regimes at low temperatures, which are gradually smeared out as the bulk T_c is approached from the lower temperatures. Close to zero field, $0<H\lesssim H_1\approx 1$ kOe, there is a sharp increase in resistance with field [see Fig. 1(c)].[9] At higher fields, $H_1\lesssim H\lesssim H_2$, the resistance shows a very weak field dependence. For still higher fields, $H\gtrsim H_2$, the resistance rises rapidly and will reach the normal state resistance at the critical field H_c of the Sn grains.

This magnetoresistance behavior can be qualitatively understood in the following manner. For $0\lesssim H\lesssim H_1$ the strong magnetoresistance is a result of increasing phase fluctuations between the grains. Due to fluxoid quantization, as a magnetic field is applied, screening currents flow around phase coherent loops of interconnected grains to screen out the excess field. As screening currents are driven through constrictions between grains their susceptibility to phase fluctuations increases causing dissipation and a corresponding increase in the film resistance. The screening currents grow until they are flowing at a maximum value around the smallest possible phase coherent loops in the granular network. This length scale is given by $H_1\sim 1000$ Å. A further increase in field causes the screening currents to oscillate with H as integer number of flux quantum pass through loops in the film.[21] Since the film is macroscopic, and there is a wide distribution of loop sizes, the oscillating screening currents will average out to an almost constant film resistance. This is the origin of the weak positive magnetoresistance in the field regime, $H_1\lesssim H\lesssim H_2$. Above H_2 the field becomes strong enough to induce pair breaking effects, which reduce the amplitude of the superconducting order parameter and the T_c of the grains. Finally, at $H=H_c$, the amplitude of the order parameter and the T_c of the grains will go to zero and the superconductivity of the film will be completely destroyed. This suggests that the magnetic field tuned SIT, which occurs at high fields, is driven by the reduction in the amplitude of the order parameter within the grains, which in turn causes an increase in phase fluctuations between grains. In contrast, the enhancement of phase fluctuations observed at lower fields, $H<H_2$, due to screening currents, does not substantially increase the film resistance, and is not strong enough to drive the SIT.

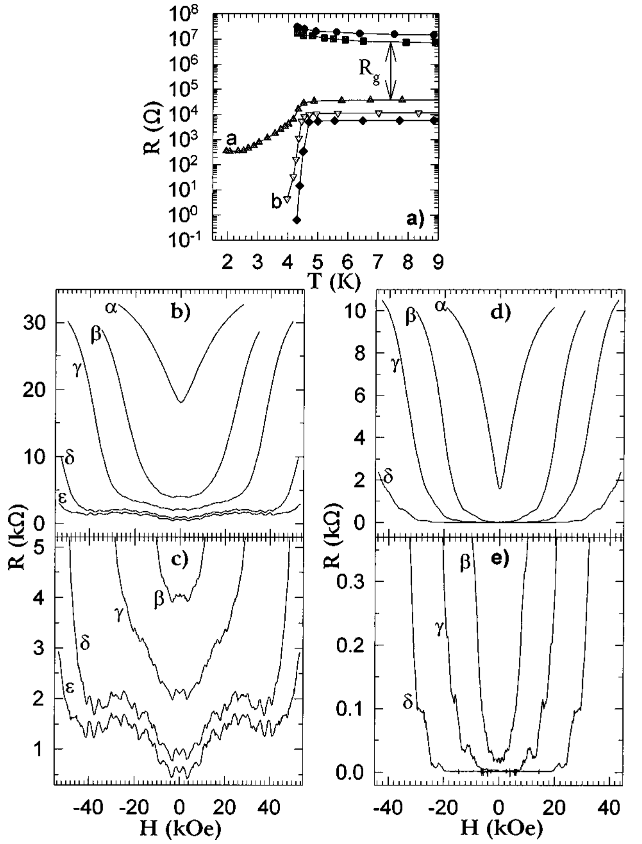

FIG. 2. (a) The SIT for a 2000-Å-wide granular Sn wire. (b) Magnetoresistance for curve *a*; curves α–ϵ, $T=4.36$, 3.97, 3.6, 2.95, and 2.5 K. (c) Resistance scale in (b) expanded. (d) Magnetoresistance for curve *b*; curves α–δ, $T=4.36$, 3.97, 3.6, and 2.95 K. (e) Resistance scale in (d) expanded.

Extending the study of the magnetoresistance to granular wires is impeded by the unusual discontinuous localization transition that we observed in the normal state of these systems,[17] as shown in Figs. 2(a) and 3(a) for a 2000- and 1100-Å wide Sn wire, respectively. This discontinuity in the normal-state resistance R_N, called the resistance gap R_g, affects the superconducting properties by eliminating the superconducting resistive transitions for which no corresponding R_N exists. Since the magnitude of R_g is dependent on the wire width, there is a limitation as to how small the wire can be, while still having an appreciably broad superconducting resistive transition with significant phase fluctuations. Thus, the smallest wire measured was 1100 Å wide.

Figure 2(b)–(e) show the magnetoresistance at different temperatures along curves a and b in Fig. 2(a). The overall qualitative shape of curves α–ϵ in Fig. 2(b) closely resembles that of Fig. 1(b) for the 2D granular film. The wire exhibits a low-field regime with a weak positive magnetoresistance and a high-field regime with a strong positive magnetoresistance, although the strong magnetoresistance near zero field is now absent. In Fig. 2(c) the resistance is plotted on an expanded scale and significant differences from the 2D case now become apparent. There are strong oscillations in the magnetoresistance throughout the low-field regime, $0 \lesssim H \lesssim H_2$, which disappear in the high-field regime. The shape of the resistance oscillations is similar to those observed in the Little-Parks experiment,[22] except that here we see a superposition of oscillations of different frequencies. The oscillations are reproducible and do not depend on either the field orientation or the direction of the field sweep. As the temperature is lowered, the oscillations occur out to higher fields and become more pronounced, while the positions and the frequencies of the oscillations remain constant. The dominant oscillation in Fig. 2(b) has a well-defined period of, $\Delta H \simeq 3300$ Oe, which corresponds to a phase coherent loop size of $A^{1/2} \simeq 780$ Å. The highest frequency oscillation has an oscillation period of $\Delta H \simeq 560$ Oe. The associated length scale, $A^{1/2} \simeq 1900$ Å, is very close to the width of the wire. There is also a much slower oscillatory structure observable in curves δ and ϵ with $\Delta H \approx 50$ kOe, yielding $A^{1/2} \simeq 200$ Å, approximately the size of the Sn grains. Figures 2(d) and 2(e) show the magnetoresistance for curve b in Fig. 2(a) where the wire has a lower R_N and a sharper superconducting transition. The resistance oscillations are now mostly suppressed due to the stronger coupling between grains.

Figure 3 shows the magnetoresistance behavior at different temperatures for a 1100-Å-wide wire, where the superconducting transitions are now all relatively sharp. The magnetoresistance exhibits a single long period magnetoresistance oscillation, while the higher-frequency oscillations, seen for the broad transition of the 2000-Å-wide wire, have largely disappeared. At the lowest temperatures the wire resistance is measured to be zero and shows no magnetoresistance until close to H_2. Although curve b of Fig. 2(a) and curve α of Fig. 3(a) have very similar superconducting transition widths the amplitude of the magnetoresistance oscillation is significantly larger for the 1100-Å-wide wire. What is perhaps most striking about the magnetoresistance of the 1100-Å wire is an apparent ''negative resistance'' at certain fields, clearly observed in the lowest-temperature curves. We have seen evidence of this behavior in a 1400-Å-wide wire as well, though it is less pronounced. It has not been observed in the 2000-Å-wide wire. It appears that the smaller the wire and the voltage probes the more likely a ''negative resistance'' is observable and the larger its magnitude. The ''negative resistance'' occurs at fields close to H_2, within the low-field regime, and is repeatable with the direction of field sweep and the field orientation. We speculate that this apparent ''negative resistance'' is an artifact caused by the screening currents in the narrow voltage probes distorting the current path. More careful experiments in this regime are needed to pinpoint the mechanism.

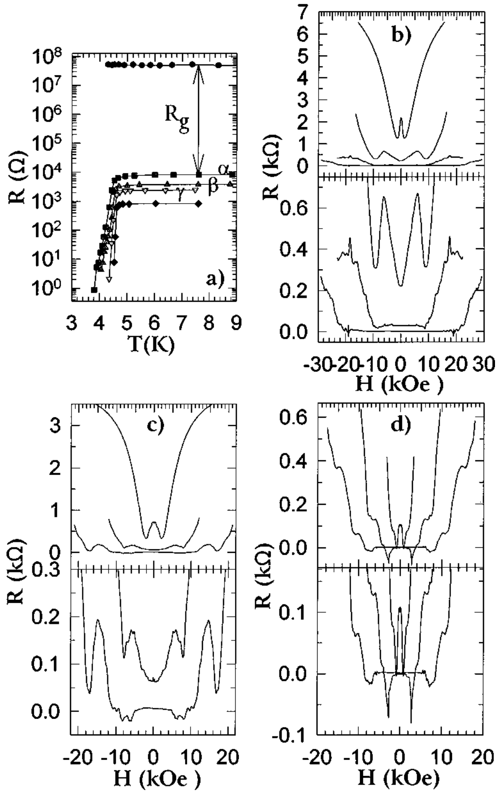

FIG. 3. (a) SIT for a 1100-Å-wide wire. (b) Magnetoresistance for curve α at $T = 4.36$, 4.04, 3.6, and 2.95 K. (c) Magnetoresistance for curve β at $T = 4.36$, 4.04, and 3.6 K. (d) Magnetoresistance for curve γ at $T = 4.36$, 4.04, and 3.6 K. (b)–(d) Bottom plots show an expanded resistance scale.

The magnetoresistance behavior observed in the granular wires is consistent with and supports our understanding of the magnetoresistance for 2D films. The differences can be understood as a consequence of the wire width. In the low-field regime, $H < H_2$, the magnetoresistance is dominated by screening currents between superconducting grains that enhance phase fluctuations. In the high-field regime, $H > H_2$, the magnetoresistance is dominated by the destruction of the amplitude of the order parameter within the grains, which also enhances the phase fluctuations, although in a different manner. The finite wire width limits the possible phase coherent loop areas that can exist along the length of the wire. The screening currents therefore only oscillate within a restricted frequency range in H. The oscillation frequencies are also no longer quasicontinuous but have a discrete set of values. This has several consequences for the magnetoresistance. The sharp increase in resistance seen near zero field in the 2D case, which depends on a quasicontinuous set of loop sizes, is no longer expected to occur in the wires. Furthermore, because of the limited number of loops in the wire the resistance oscillations from different loops no longer average out to the flat weak magnetoresistance observed in the 2D films, instead a superposition of the discrete frequencies is observable. In a sense this represents a *fingerprint* for a particular wire and is reproducible for any given section of a wire. The approximate range of loop sizes in a wire should fall within the range, $(grain\ diameter)\lesssim A^{1/2}\lesssim(wire\ width)$. This corresponds to a range of oscillation periods for a 2000-Å-wide Sn wire of $0.5\lesssim\Delta H\lesssim 50$ kOe, which is consistent with our observations. The oscillations persist up to the crossover field H_2, after which they quickly disappear as the resistance rapidly rises to the normal state R_N. This rapid rise in resistance, also seen in the 2D films, is a consequence of pair breaking within the grains as indicated by the disappearance of the oscillations.

In summary, we have measured the magnetoresistance along the resistive transitions of granular Sn wires and films on the superconducting side of the SIT. In 2D films, we have identified three field regimes in which the magnetoresistance shows markedly different behavior. These behaviors are all dictated by the strength of the phase fluctuations between the superconducting grains, which we have shown are driven by different mechanisms at different field intensities. In the wires the discreteness of the local structure of the grains becomes important. These finite-size effects have allowed us to see oscillations in the wire resistance as a function of field strength, which we associate with screening currents flowing around phase coherent loops of grains. This has led to a clearer microscopic understanding of the effect of a magnetic field on the superconducting coherence in this inhomogeneous granular system. However, the superconducting properties of the 2D films and the wires studied here do not show significant qualitative differences, and we emphasize that the behavior of the wires results from a lack of self-averaging, not a dimensional crossover from two dimensions to one. We believe that our results confirm that the magnetic-field tuned SIT in granular films or wires is ultimately driven by the suppression of the amplitude of the order parameter within the grains at high magnetic fields.

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