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TUNNELING MEASUREMENTS OF FLUCTUATION EFFECTS NEAR THE SUPERCONDUCTOR TO INSULATOR TRANSITION

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Abstract—We present measurements of the temperature dependence of the tunneling density of states near the Fermi energy, $G_0(T)$, and resistive transitions, $R(T)$, of ultrathin PbBi films. Both $R(T)$ and $G_0(T)$ broaden substantially near the superconductor to insulator transition (SIT). The broadening in $R(T)$ is not affected by the proximity of a ground plane suggesting that long range Coulomb interactions are not important to the SIT. The results suggest that the transport properties of films near the SIT are influenced by fluctuations in both the phase and the amplitude of the order parameter. We discuss the data in terms of recent theories of the superconducting transition in low superfluid density systems. © 1998 Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

Because the superfluid density is low in films near the two-dimensional superconductor to insulator transition (SIT) and high temperature superconductors, thermal and quantum fluctuations are believed to exert a strong influence on their superconducting transitions and properties [1–3]. Very recently, for example, it was proposed that thermal and quantum phase fluctuations in the superconductor order parameter reduce the resistively measured mean field transition temperature, T_{mf}, well below the temperature at which Cooper pairs form in these systems [1]. Electron tunneling done in tandem with transport measurements offer the opportunity to explore this conjecture and add general insight into the relative importance of fluctuations in the order parameter phase and amplitude. Tunneling experiments can reveal fluctuations in the energy gap, Δ, or amplitude and transport experiments sense fluctuations in the phase.

In this paper, we compare the resistive transitions, $R(T)$, and the temperature dependence of the tunneling density of states near the Fermi energy, $G_0(T)$, of homogeneous $Pb_{0.9}Bi_{0.1}$ films with different superfluid densities. Far from the SIT, $R(T)$ is sharp and $G_0(T)$ exhibits a discontinuity in its slope at the same temperature, consistent with a BCS superconductor with a large superfluid density. Closer to the SIT, these features and the overall temperature dependencies become broader both above and below the estimated mean field transition temperature, T_{mf} [4]. Furthermore, we note that the resistive transitions are not influenced by the presence of a nearby ground plane. These results indicate that amplitude and phase fluctuations persist together below T_{mf} and long-range Coulomb interaction effects play a minor role in their origin. We discuss these results in terms of recent theories of low superfluid density superconductors [1, 3].

2. EXPERIMENTAL DETAILS

We used $Pb_{0.9}Bi_{0.1}$ films that were thermally evaporated onto a 6-Å Ge underlayer that had been previously deposited onto a fire-polished glass substrate. The substrate was maintained at $T \approx 8$ K for these depositions. Experiments indicate that these films are homogeneous [5]. The films were in thermal contact with the mixing chamber of a dilution refrigerator or a pumped ^{4}He pot in a cryostat. The layout of the samples is shown in Fig. 1. There are two areas of the film that are equivalent in size, one with an Al strip and its natural oxide layer underneath, A, and the other, B, without. The Al strip, which was deposited directly on the substrate at room temperature, and its natural oxide served as the normal counterelectrode and barrier for the tunnel junction. The oxide tunnel barrier was estimated to be 30-Å thick and the tunnel junction resistance exceeded the film sheet resistance by more than a factor of 100. The Al strip had a resistivity of about 20 $\mu\Omega$-cm, a thickness of approximately 10 nm and a width of 0.8 mm or 1/4 of the film area in region A. We performed four terminal transport measurements of the resistance of the film in the regions A and B and four terminal measurements of the tunnel junction conductance.

Below, we present measurements of G_0, which is proportional to the number of states within $\pm 1.75\, k_B T$ of the Fermi energy, E_F. Explicitly [6],

$$G_0 \propto \int_{-\infty}^{\infty} N_N(E) N_S(E) \frac{\partial f}{\partial E} dE$$

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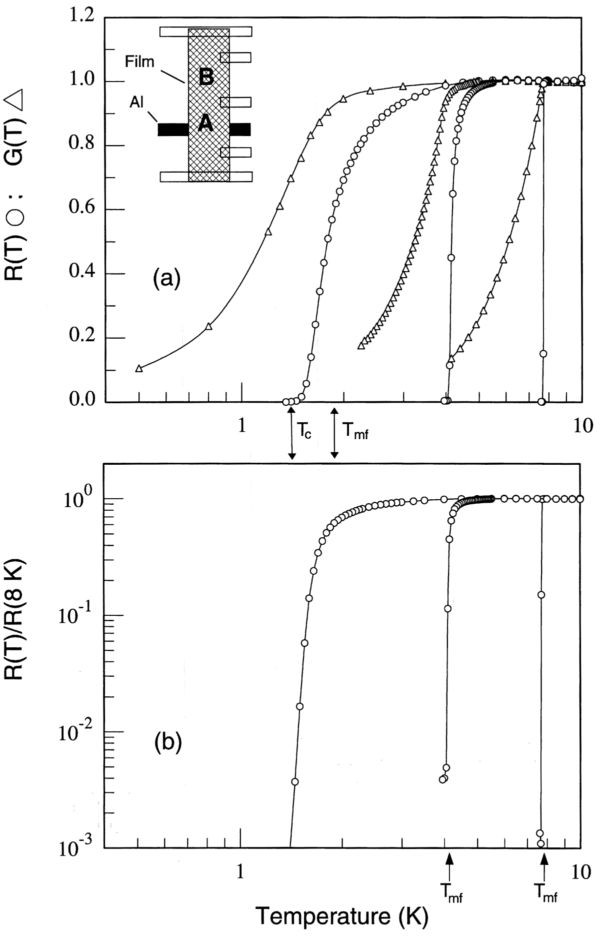

Fig. 1. (A) Resistance (○) and tunnel junction conductance at zero bias (△) normalized to their values at 8 K for three PbBi films with R(8 K) and T_{mf} from left to right of 4400 Ω and 1.8 K, 714 Ω and 4.2 K, and 3.8 Ω and 7.7 K. Inset: sample layout. (B) Same resistance data as in (A) plotted on a logarithmic scale.

where E is the quasiparticle energy measured relative to E_F and f is the Fermi function. $N_N(E)$ is the normal state density of states and $N_S(E)$ is the superconducting density of states which is given by $|E|/\sqrt{E^2 - \Delta^2}$ for a BCS superconductor. Δ is the energy gap. Disorder effects reduce $N_N(E)$ as well as Δ. When the film does not superconduct, the temperature-dependent G_0 has a weak, nearly logarithmic form. The logarithmic form comes from the Coulomb anomaly in the normal state [7]. Here, we present data normalized to remove this Coulomb anomaly from G_0.

3. RESULTS

In Fig. 1, we compare the temperature dependence of the junction conductance G_0 with the resistive transition, *R(T)*, of three different films. The thickest film, with $T_{mf} = 7.6$ K, exhibits a very sharp drop in *R(T)* and G_0 at T_{mf} as expected for a BCS like superconductor. In fact, because PbBi is a strongly coupled superconductor, G_0 drops more abruptly below T_{mf}, than it would for a weakly coupled BCS superconductor. The abrupt drops become rounded in the thinner films. The rounding begins at T_{mf} (taken as the *R(T)* midpoint). As we pointed out previously, the effective width of *R(T)* becomes comparable with T_{mf}. Despite the rounding, it is still possible to observe that T_{mf} coincides closely with the temperature at which G_0 changes most rapidly.

Interestingly, the broadening persists below T_{mf} as well. G_0 dropped to 50% at a temperature, $T/T_{mf} = 0.8$ in the highest T_{mf} film and 0.67 in the lowest T_{mf} film. The enhanced broadening in *R(T)* below T_{mf} is brought out in Fig. 1b, where the data are plotted on a logarithmic scale. T_c, the temperature at which the resistance is nearly zero is 0.8 T_{mf} in the lowest T_{mf} film. In the figure, T_c is chosen to be the temperature at which $R/R_N < 10^{-3}$.

Finally, the *R(T)* in regions A and B were *identical* for each of the three films indicating that the Al strip exerted a negligible influence on the transport.

4. DISCUSSION

The excess broadening in *R(T)* and $G_0(T)$ indicate that fluctuation effects strongly influence the superconducting transition [4, 8]. In the following, we discuss three different models of the nature of those fluctuations.

Emery and Kivelson [1] recently proposed that both thermal and quantum phase fluctuations in low superfluid density superconductors drive their resistively measured transition temperature below the temperature at which the energy gap first forms. This effect results from the competition between the energy gain of establishing phase order between different regions of the film and the energy cost of the Coulomb interactions created by the local superfluid density fluctuations that phase ordering requires [9]. Generally speaking, the lower the superfluid density, the poorer the screening and the larger the cost of establishing phase coherence [1]. The separation of T_{mf} from T_c shown in Fig. 1 and the substantial decrease in the G_0 above T_c, indicating that a gap has started to form, qualitatively agree with this picture. On the other hand, this theory predicts that bringing a metal plane close to a film with low superfluid density enhances T_c by reducing the Coulomb interaction effects. The identical nature of the *R(T)* in regions A and B of the film disagrees with this prediction. In general, the absence of the ‘screening’ effect in a film so close to the SIT calls into question the general idea that disorder-enhanced Coulomb interactions drive the SIT [10, 11]. Earlier screening experiments on films further from the SIT have led to similar results [12–14]. Our experiment implies that the interactions responsible for the SIT must occur on length-scales shorter than $\sim$3 nm.

Alternatively, the data, especially the broadening of $G_0(T)$ below T_{mf}, suggest that both amplitude and phase fluctuations are important to the transitions. Above T_{mf}, the role of amplitude fluctuations is very familiar. They give rise to the Aslamasov–Larkin para-conductance fluctuations in *R(T)* and an associated decrease in the density of quasi-particle states near the Fermi energy [9]. Below T_{mf}, amplitude fluctuations, while present, usually do not influence the dissipative processes. Rather, phase fluctuations, created by the motion of thermally activated free vortices, are responsible. This picture breaks down if phase and amplitude fluctuations become strongly linked as they might in homogeneous films near the SIT. In these, the superfluid density is low because the spacing between energy levels in a coherence volume sized region becomes comparable with Δ. Under these circumstances the average number of cooper pairs in a coherence volume, N_{coh} is of order 1 [4]. Phase and amplitude fluctuations become linked because the energy gained in coupling the phases of different regions depends on Δ, or N_{coh}. In contrast, the superfluid density in granular films becomes low because the coupling between grains weakens. In most granular films, N_{coh} remains large and the density of states maintains a nearly BCS form, even on the insulating side of the transition [15].

A third scenario attributes the behavior directly to quantum fluctuations in the amplitude of the order parameter. Belitz and Kirkpatrick recently developed a theory of the superconductor to normal metal quantum phase transition. They show that quantum fluctuations in the critical temperature and consequently, energy gap grow upon approaching this quantum phase transition. These spatial fluctuations are strongest in two dimensions. The growth in the broadening of G_0 shown in Fig. 1 agrees semi-quantitatively with this theory [3]. In addition, the earlier observed smeared appearance of the tunneling DOS as a function of voltage at low temperatures also agrees with a model of spatial fluctuations in the energy gap [4].

5. SUMMARY

We have presented tunneling data that show evidence for strong fluctuations in the amplitude of the superconducting order parameter near the SIT. A simple argument and a recent theory suggest that these amplitude fluctuations are at least partially responsible for the broadening of the resistive transitions near the SIT in homogeneous films. In addition, we described a transport experiment employing a ground plane that seems to rule out the long-range Coulomb interaction as the source of these fluctuations.

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