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Interfacial resistive anomaly at a normal-superconducting boundary

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We have observed an anomalous peak ($\sim$5% of the normal-state resistance) in the resistive transition of a thin-film aluminum system consisting of regions of different, but comparable, transition temperatures. The peak occurs at slightly above the transition temperature of the lower T_c section. The magnitude decreases with the distance of the voltage probes from the normal-superconducting (N-S) interface with a characteristic length scale of a few μm and is sensitive to a magnetic field. This anomaly appears to be consistent with a nearly constant superconducting potential near a N-S interface.

Several experiments have attempted to investigate the spatial dependence of the potentials in a superconducting film in the vicinity of a phase-slip center.[1,2] Recently, results have emerged on the anomalously long length-scale proximity effect in modulated T_c structures.[3] These results prompted us to investigate the behavior of the resistive transition near a single normal-superconducting interface.[4] There has also been an interest in the properties of one-dimensional (1D) superconductors[5] which has prompted a similar investigation on 1D structures elsewhere.[6]

In this paper, we report measurements of the resistance across a 2D film whose T_c has been modified using a reactive-ion etch. The etching process suppresses T_c by up to 3% without adversely affecting other transport properties.[3,7] The resistance was measured using several probes placed symmetrically about the interfaces [see inset of Fig. 1(a)]. For temperatures near the T_c of the etched film, the resistance sampled by unetched probes closest to the interface shows a remarkable anomaly: the film's resistance is higher than its normal-state value. This increase in resistance falls off with distance of the probes from the interface. Finally, it is enhanced by small perpendicular magnetic fields (<2 G) but is quenched at higher fields (>10 G). This peak is absent when the leads are etched. The presence of this anomaly is evidence for a nearly constant superconducting potential near a N-S interface. No similar anomaly associated with N-S interfaces has been reported in the literature.

Our samples are lithographically patterned aluminum films with a thickness of 250 Å, a width of 10 μm, and a total length of 2 mm. The voltage leads are located symmetrically about a 50-μm-long section which has been etched. In the sample described in this paper, the relative T_c's of the two regions are different by $\sim$45 mK. Our films are relatively clean, with a residual resistance ratio of 3.23 and diffusion constant of 70 cm^2/s. The 2-μm-wide voltage leads were placed at 0, 4, 9, 16, and 50 μm from each of the two N-S interfaces and are designated as A–E, respectively. A schematic representation of such a film is shown in the inset of Fig. 1. Other samples investigated have pairs of voltage leads located within the etched regions, and these leads show no anomaly.

Thin films of aluminum are chosen for this study because of the relatively long coherence length in this material. For aluminum in the dirty limit close to T_c, the coherence length $\xi(T)$ is $\sim$1 μm.[3,8] This permits the use of photolithography to define voltage probes with a spacing comparable to the coherence length. The presence of a region with a lower T_c allows us to investigate the spatial dependence of the potentials without resorting to a phase-slip center induced by a large current density. The etching process also allows us to define precisely the location of the interface so as to ensure its proper alignment with respect to the voltage probes. The sharpness of the interface has been confirmed by scans performed with an Auger electron microprobe having a spatial resolution of $\sim$1 μm.[9]

The voltage leads and the film were deposited simultaneously as a continuous film. The leads outside the etched region were masked by the photoresist and thus remained unetched. Consequently, these voltage leads are expected to exhibit a superconducting transition similar in temperature and width to that of the unetched portion of the film under study. Unless otherwise noted, for the work described in this paper, we have used an ac resistance bridge applying a fixed current of 0.3 μA at 17 Hz. During the measurement with a particular pair of voltage leads, the temperature is typically stepped in intervals of 1.0 mK. Each data point is averaged over a minimum of 30 readings.

The resistive transitions as measured across voltage pairs A–E are shown in Figs. 1(a) and 1(b). In Fig. 1(a), we show the measured resistance across pairs of symmetrically placed leads. The resistance of the outermost pair, E, decreases rapidly by about a third of its value and then decreases gradually by another one third before the etched region undergoes its superconducting transition. This behavior is consistent with the resistive transition of two materials with similar T_c's in series with each other.[10] The resistance of the innermost pairs of voltage leads (pairs A and B) exhibits the anomalous behavior. In Fig. 1(a), the resistance of pair A is constant with decreasing temperature until $\sim$1.34 K, where it increases by about 5% and then rejoins the other curves. Furthermore, the resistance across pair B displays a similar (though smaller) anomaly of about 3% of the normal resistance. The absolute magnitude of the resistance increase observed with pair A is

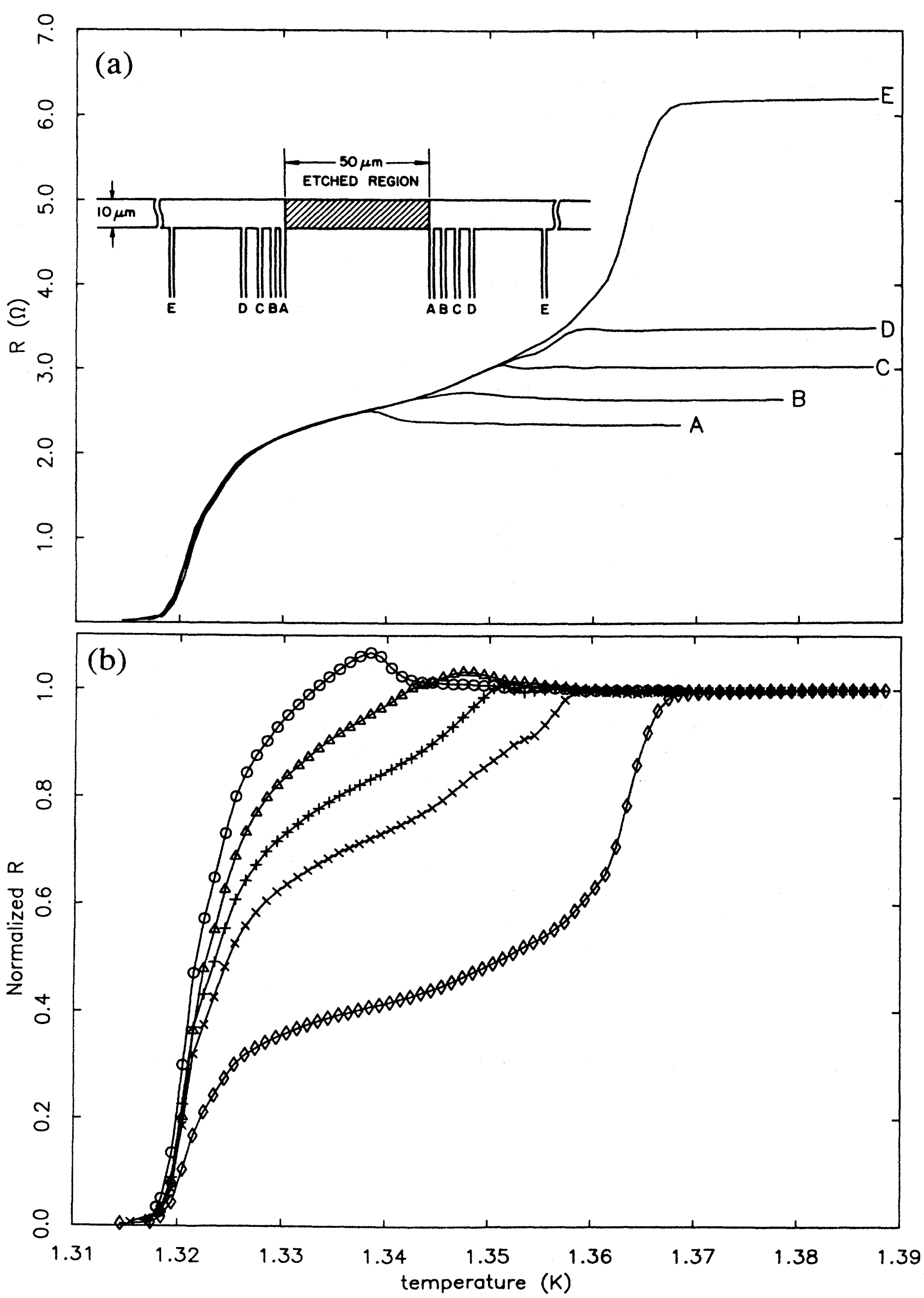

FIG. 1. (a) Resistive transitions measured using voltage probes A–E (see inset) are shown as solid lines. The resistive anomaly is resolved by voltage leads A and B. (b) Plot of the normalized resistances shown in (a), for pairs A (○), B (△), C (+), D (×), and E (◇). The anomaly can be clearly observed at voltage leads A and B, and is absent for the outer leads. The magnitude of the anomaly decreases in both absolute and relative size with increasing distance from the N-S interface. In the inset of (a), a schematic diagram of the sample is shown. The central 50-μm section of the film is etched, depressing its T_c by $\sim$45 mK. Voltage lead pairs are located symmetrically about the etched-unetched interfaces and (in this case) are unetched. Pairs A, B, C, D, and E are positioned so that their inner edges are 0, 4, 9, 16, and 50 μm from the interface.

larger than that with pair B. We note that the temperature of the resistance maximum in pair B is shifted slightly upward from that of pair A.

These details are more easily observed in the plots [see Fig. 1(b)] of the resistance normalized to its values at 1.39 K. Here, it is clear that only the innermost pairs of leads (pairs A and B) exhibit the anomalous behavior. Studies with *etched* (normal) probes, usually located within the etched region, do not exhibit this anomaly. Likewise, no anomaly is present for samples whose etched and unetched regions have T_c difference less than $\sim$30 mK. The last situation would result in the absence of any well-defined N-S interface in the presence of a previously observed long-range proximity effect.[10] We thus assert that the resistive anomaly is observable over a characteristic length scale of a few μm and is clearly associated with the superconducting potential in the presence of N-S interfaces.

We have examined the effect of weak magnetic fields on the resistive anomaly. Figure 2 plots the resistance of the film as measured by pairs A and B for $H=0$, 2, 6, and 10 G. In both cases, the application of a 2-G field suppresses the T_c in accordance with the elastic mean free path (estimated to be 160 Å) while *enhancing* the magnitude of the resistive anomaly. In stronger fields, the T_c is depressed further while the anomaly is quenched for $H > 10$ G. We have also investigated the dependence of the peak magnitude on excitation current. For smaller current densities, we found no significant change in the magnitude. This suggests that the anomaly does not originate from a fixed potential drop across the interface. The temperature corresponding to the peak appears to shift slightly, suggesting that the N-S interface may move as the driving current changes.

The significance of a number of mechanisms can be readily excluded. First, the importance of Andreev scattering[11] can be ruled out since it cannot produce an increase in the resistance at the interface above that of the normal state. Fluctuations in the phase of the order parameter[12] may produce an excess voltage close to T_c. However, again, such fluctuations cannot generate a resistance above the normal-state value. Besides Andreev scattering, quasiparticles incident upon a N-S interface at small angles may undergo specular reflection. For S-N-S layered structures whose N region is a semimetal or semiconductor, this effect may manifest itself, at $T < T_{cS}$, as a rise in the resistance above the normal state.[13] However, the magnitude of this effect is of order $(k_B T/E_F)^2$, where E_F is the Fermi energy of the N region. For aluminum close to T_c, $(k_B T/E_F)^2 < 10^{-10}$. Thus this mechanism should be unimportant as well. Nevertheless, these processes probably contribute to the observed anomaly and may have a role in the detailed description of the system.

Although this anomaly may seem unexpected, its presence could be consistent with the existing theoretical description of the potentials near a N-S interface. In Fig. 3, we have sketched schematically the spatial variation of the pair and quasiparticle potentials for $T_{cN} < T < T_{cS}$. (Here, T_{cS} and T_{cN} refer to the transition temperatures of the unetched and etched sections.) In this temperature range, a N-S interface is present. Quasiparticles are injected from the N region into the S region, where the quasiparticle potential approaches the superconducting pair potential on a length scale λ_Q. This quasiparticle potential was measured in the Dolan and Jackel experiment,[1] and its behavior is not in question here. Within the S region, the chemical potential of the Cooper pairs must be constant.[14] This dictates a discontinuity of the superconducting potential at the N-S interface, as shown in Fig. 3. Since the potential of the film in the normal state changes linearly with position, there exists a region near the N-S interface in which the superconducting potential exceeds IR_N. Thus for superconducting electrodes placed sufficiently near the interface at $T < T_{cS}$, the potential exceeds the normal-state value. We believe this is the origin of the observed anomaly in our system. Note that the distance over which this anomaly manifests itself is related to the resistivity of the material (which controls the

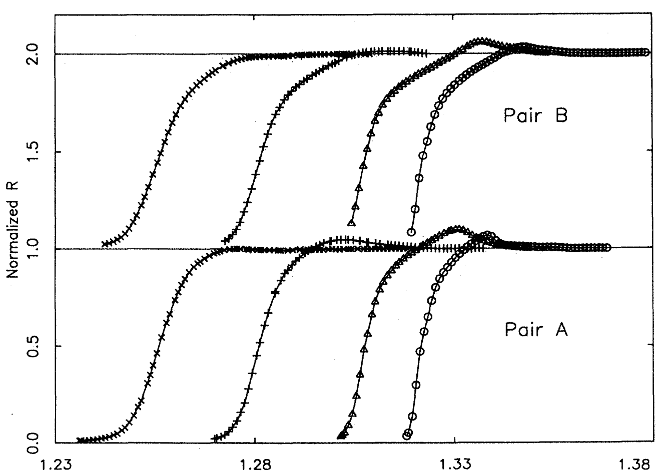

FIG. 2. Effect of a magnetic field on the resistive anomaly, with $H=0$ G (○), 2 G (△), 6 G (+), and 10 G (×). In both the lower (pair A) and upper traces (pair B), we observe that the resistive transition is shifted to lower temperatures monotonically with increasing field. However, the magnitude of the resistive anomaly increases, at first, with magnetic field (2 G), then decreases, and is completely quenched in a field of 10 G. Note that data for pair B are shifted by one in the ordinate for clarity.

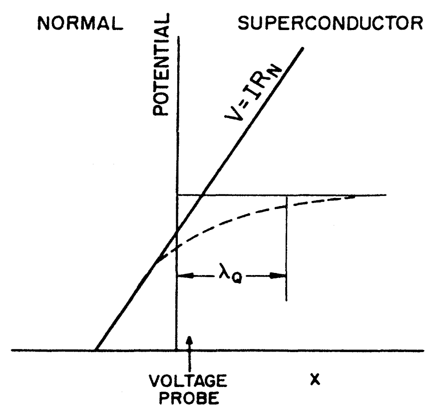

FIG. 3. Spatial dependence of the pair (horizontal line) and quasiparticle potentials (dashed line) in the vicinity of one of the two N-S interfaces. In the standard picture, the pair potential is constant in the S region. The quasiparticle potential decays over a characteristic length λ_Q in this region. The potential in the normal state increases linearly with position. As the probes are placed symmetrically about the etched region in our experiments, the potentials are antisymmetric with respect to the midpoint of the etched region, with the two N-S interfaces contributing equally to the overall magnitude of the anomaly. Note that the anomaly is largest for superconducting probes placed closest to the interface and diminishes with increasing probe separation.

slope of the normal-state-potential line) together with the spatial extent of the nonequilibrium region (which is set by the relaxation of the charge imbalance). If the film is highly resistive, or if this nonequilibrium region is small, both the length scale over which the anomaly can be observed and its magnitude would be much smaller.

Two factors contribute to our ability to resolve this effect. First, our ability to locate the electrodes precisely permits us to place them within the short length scale over which this effect is present. Second, aluminum thin films may be particularly favorable because of their long coherence and charge-imbalance lengths. Furthermore, clean films can be readily prepared so as to maximize the effect depicted in the figure. It is unclear whether the nearly superconducting nature of the "N" material plays a role in our ability to resolve this anomaly.

We now consider the observed dependence of the anomaly on magnetic field. Two factors can contribute to the quenching of the anomaly. First, due to the higher diffusion constant of the S region (typically 20% above that of the N region), its T_c is suppressed more in the presence of a small magnetic field.[14] Close to T_c, this will enhance the extent of the proximity effect and cause the actual N-S interface to shift away from the probes. Second, even in small magnetic fields, the width of the transition increases. In stronger magnetic fields, the superconducting transitions become broad and the N-S interface is obscured. However, this picture does not explain the increase of the anomaly for $H=2$ G, since λ_Q is expected to decrease with small fields.

Similar anomalies have been observed recently in short 1D aluminum wires by Santhanam *et al.*[6] They speculate that the origin of these effects is intimately connected with the 1D nature of the conductors as well as the interactions of these conductors with the leads. Tidecks[15] also observed resistance anomalies in 1D conductors, which he attributed to the presence of collective modes. Our samples are not in this regime. Thus it is unclear how the interpretation of these data relates to this work. A similar anomaly was also found in Cu-Zr alloys doped with magnetic impurities.[16] The role of the magnetic impurities appears to be important and is probably unrelated to our results with aluminum.

In conclusion, we have observed a resistive anomaly at a N-S interface in 2D aluminum thin films with regions of similar T_c's. The anomaly falls off with distance from the N-S interface. It is quenched by the application of a field >10 G. The spatial dependence of the anomaly is qualitatively consistent with a constant superconducting pair potential in the S region. Various mechanisms may contribute to the overall voltage drop close to T_c and are likely important for a detailed description of the system. For example, they could be responsible for the enhancement of the anomaly in a 2-G field, which is not otherwise understood in terms of Fig. 3.

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[7] We have found that the reactive-ion etching process induces surface damage on the aluminum film without removal of material. Using Auger microprobe analysis together with depth profiling, we found that the etch modifies the native oxide located on the top 50 Å of the film. In particular, oxygen is removed while fluorine is incorporated in this surface layer. These observations are reproducible from batch to batch, providing that all process parameters (notably the plasma power density and the substrate temperature) are held fixed. The depletion of oxygen from the aluminum film is consistent with the supression of its T_c by the etch.

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[10] The length scale over which the proximity effect extends (from the unetched region into the etched region of the film) diverges with decreasing ΔT_c, where ΔT_c is the T_c difference between the two regions (see Ref. 3). For the sample of Fig. 1, a ΔT_c of 45 mK in the relatively clean film gives rise to two distinct transitions, as seen across probes E. On the other hand, among the samples measured in this study, we find that a single homogeneous transition prevails for ΔT_c less than ~ 30 mK. Thus, the properties of the samples used in the present study are consistent with the long-range proximity effect reported in Ref. 3.

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