Resistance Anomaly and Excess Voltage near Superconducting Interfaces

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We present resistance and current-voltage characteristics of an aluminum film with two regions of different superconducting transition temperatures. The voltage and hence resistance increase above normal state values near the transition. The excess voltage disappears with increasing bias current, accompanied by negative differential resistances. This behavior is associated with the charge imbalance that accompanies normal-superconducting interfaces and phase slip centers.

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The decrease of the resistance from the normal state value is a routine manifestation of the onset of superconductivity. Yet a number of recent publications [1–11] report an anomalous increase in the resistance above the normal state value (R_N) in the vicinity of the superconducting transition. This ubiquitous anomaly demands further exploration. Although Kwong *et al.* [1] attributed the resistance anomaly to differences between the nonequilibrium quasiparticle and pair electrochemical potentials (μ_n and μ_s, respectively), the current-voltage (I-V) characteristics and the length scale of the nonequilibrium region were not explored. We report work near T_C where the nonequilibrium length weakly diverges. Together with the spatial variation of T_C of our aluminum film, this allows us to place voltage probes within the charge imbalance region. We deduce that the nonequilibrium charge imbalance near normal-superconducting (N-S) interfaces and phase slip centers (PSCs) are ultimately responsible for the observed behavior.

We also observe for the first time excess voltage and other features in the I-V characteristics at dc bias currents above the critical current (I_C) [12]. This is likely the result of long quasiparticle relaxation times and interactions between adjacent PSCs [13] whose location and motion is weakly affected by the voltage probes. Throughout the Letter a normal metal (N) refers to a superconductor at temperatures above its transition temperature (T_C).

Our aluminum film and voltage probes are lithographically patterned in a continuous layer (Fig. 1). The voltage probes, 1 μm wide, are at various distances from the interface between the two regions. The T_C of the hashed region on the left and of the N probes is decreased by a few percent through exposure to a CF_4 reactive ion etch [14]. For this sample, $T_{C1} = 1.407$ K and $T_{C2} = 1.452$ K where these refer to the T_C's of the etched and unetched film far away from the interface. The thickness and width of the film are 250 Å and 20 μm, respectively. Both regions have nearly identical normal state properties [14]. The resistivity, diffusion constant, elastic mean free path are ~2 $\mu\Omega$ cm, ~40 cm^2/sec, and ~100 Å, respectively. The residual resistance ratio is ~2.2, and the coherence length $\xi(T)$ is ~1 μm for the results reported here.

Tunnel junctions are commonly used to decouple the probes from the film. Because of difficulties in integrating tunnel junctions and our etch process, we used narrow voltage probes. Such contacts have been used in the past [2,15,16]. S probes will measure μ_s and N probes measure μ_n, although the presence of these probes does locally shift T_C via the proximity effect. Four terminal measurements are carried out in the earth's magnetic field using a lock-in amplifier to measure R vs T at zero dc bias current. The differential resistance (dV/dI vs I) is measured at a fixed temperature with an increasing dc bias current on which a 0.2 μA ac current is superposed. I-V characteristics are obtained by integrating dV/dI. (dc techniques yield similar results with lower signal-to-noise ratio.)

Figures 2(a) and 2(b) show R vs T data of several sections near the etched-unetched interface. The anomaly is manifested only with S (unetched) probes (a) and is observed even if the probes do not span the interface, provided they are located within ~±15 μm from it.

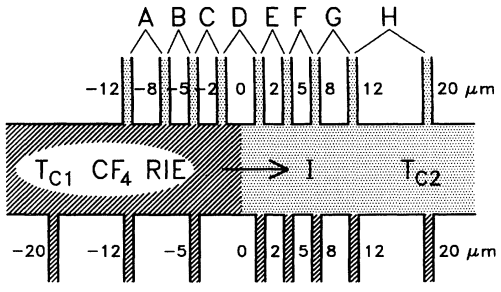

FIG. 1. The aluminum film structure with multiple voltage probes at various distances from the etched-unetched interface. Hashed areas represent regions where the T_C is decreased. Dotted areas were not exposed to the etch. The interface is designated as the origin; negative positions represent the etched region and the positive positions the unetched region. Each voltage probe is marked with the distance (in μm) of its inner edge from the interface. A, B, ..., H refer to sections between the probes.

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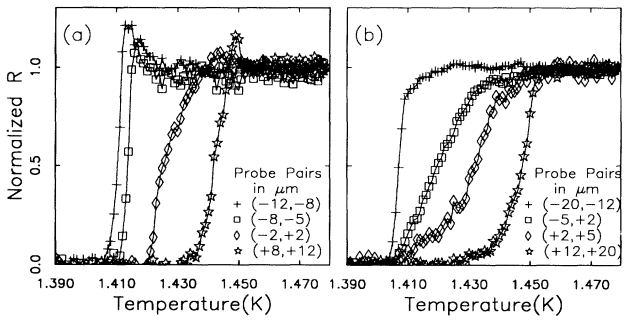

FIG. 2. Resistive transitions at zero bias current. (a) With S (unetched) probes the resistance anomaly is observed. Note that the voltage probes need not span the etched-unetched interface in order to observe the anomaly. (b) With N (etched) probes, no resistance anomaly is observed.

Figures 3(a) and 3(b) show the unusual dV/dI and I-V characteristics at several temperatures just below T_{C1}. When I_C is exceeded, a voltage develops rapidly and increases to above IR_N, consistent with the zero current bias results of Fig. 2(a). As the current is increased further, this excess voltage is given up in increments (see, for example, data at $T = 1.370$ K), and the voltage eventually approaches the usual normal state Ohmic behavior at high currents. As T_C is approached, the features are broadened but still present. The incremental decrease in the excess voltage, which manifests itself as a series of negative peaks in dV/dI, is the nonlocal phenomenon that will be discussed later in this Letter.

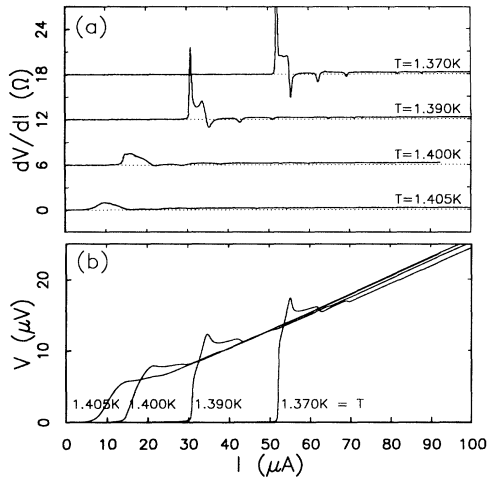

FIG. 3. (a) Behavior of dV/dI vs I at several temperatures. Each trace is shifted for comparison. (b) I-V characteristics obtained by integrating the graphs in (a). The voltage probes are superconducting and located at -12 and -8 μm from the etched-unetched interface. (Both the etched and unetched probes are superconducting since the measurements are performed at temperatures below T_{C1}).

When a current flows into a superconductor from a normal region, the quasiparticle distribution is driven away from thermal equilibrium, and this produces a charge imbalance region near the interface. A similar phenomenon occurs around a PSC, which is nucleated at some location where I_C is locally depressed. The quasiparticles and pairs have different electrochemical potentials within the nonequilibrium region, which extends a distance λ_{Q^*} near the N-S interface or around the PSC [17,18]. The difference between the potentials has been directly measured near N-S interfaces [15], and around PSCs [12,19]. In aluminum, λ_{Q^*} is long and the resistivity is low. In our film, the estimated λ_{Q^*} is $\sim 10-20$ μm at $T = 1.390$ K with an inelastic scattering time of $\sim 10-40$ ns. The enhancement of λ_{Q^*} due to the proximity to T_C, together with the gradual spatial inhomogeneity induced around the etched-unetched interface, makes our aluminum film particularly favorable for measurements of nonequilibrium behavior.

If a pair of S probes is located around the N-S interface [1] and spaced a distance a apart where $a < \lambda_{Q^*}$, then the measured voltage must exceed the normal state value since μ_s is constant and set by λ_{Q^*} on the S side of the N-S interface [20]. In contrast, μ_n is a smoothly varying function and does not exceed the normal state value. Thus, a pair of N probes would always register a voltage (resistance) less than the normal state value.

Figure 4 shows the spatial variation of I_C, obtained at two temperatures. The film has a constant I_C on either side far from the etched-unetched interface. As expected, the etched side has a lower I_C corresponding to its lower T_C. The T_C of the film also shows a similar spatial dependence. Hence, as the temperature is swept from $T < T_{C1}$ to $T > T_{C2}$ at zero bias current, the N-S interface traverses the film from left to the right of the etched-unetched interface, through sections A to H. Thus, the resistance anomaly is observed not only with S probes located around the etched-unetched interface but also with other pairs of S probes [Fig. 2(a)].

We now concentrate on the explanation of the anomaly in the I-V characteristics, which is successfully modeled

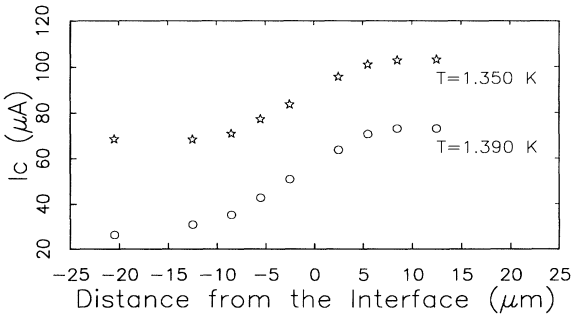

FIG. 4. Spatial variation of I_C near the etched-unetched interface. Each curve corresponds to a different temperature, and both temperatures are below T_{C1}.

by the charge imbalance processes around PSCs. As seen in Fig. 4, at low current bias, the entire film is superconducting. With increasing bias current PSCs are sequentially introduced into the film from left to right (consistent with the spatial variation of I_C). Because I_C is locally enhanced near the voltage probes (the film carries current whereas the probes do not), PSCs will preferentially be nucleated between the probes (forming a "cell"). Once a PSC is located in a cell, the S probes will register a voltage higher than the normal state value IR_N providing the probe spacing a is much less than λ_{Q^*}. This follows since the voltage drop around an isolated PSC, $\Delta\mu_s$, is $I_n\rho(2\lambda_{Q^*})$, where I_n is the averaged normal current at the center of the PSC and ρ is the normal resistance per unit length. The higher voltage is a consequence of $\Delta\mu_s$ being set by λ_{Q^*} and not a. With higher currents a second PSC enters into the adjacent cell. By symmetry, the nonequilibrium regions between the adjacent PSCs must each be confined to a distance of $\sim a/2$ from each PSC. Thus, the onset of the second PSC leads to reduction of the voltage and a negative dV/dI across the first cell.

With this model of anomaly in mind, we focus attention on the I-V characteristics of section A in Fig. 3. Initially, a PSC is located to the left of probe A reflecting the lower I_C of that section. When the current exceeds I_C of section A, PSC_A is introduced between the pair of probes A, and a voltage that exceeds the normal state develops. With a further increase in current, PSC_B is introduced in cell B, and the spatial extent of the nonequilibrium region around PSC_A is curtailed. Thus, the excess voltage is abruptly given up, resulting in a negative dV/dI peak. (In this model, the voltage ought to revert to the normal state value once PSC_B is introduced since the nonequilibrium region would be confined to the cell length a. The disagreement in the data from this expected behavior will be discussed later in the Letter.) With lower temperature, the excess voltage shifts to higher bias currents and the features become sharper. This is in accord with the smaller spatial variations of I_C, which produce a more rapid introduction of PSCs between the voltage probes and consequent sharper features for a given change in current.

The role of PSCs successfully models the data in Figs. 5(a) and 5(b), which show dV/dI's and I-V characteristics of sections A–H. In trace A, a positive dV/dI peak and excess voltage is observed as PSC_A is introduced between the first pair at -12 and -8 μm. A negative dV/dI peak is observed when PSC_B is introduced between the second pair B. At this same bias current, a positive dV/dI peak and excess voltage is observed in trace B with the introduction of PSC_B. This sequential behavior is repeated [traces A–F in (a)] until the bias current approaches the spatially constant I_C value in the region far from the etched-unetched interface. Above this current, all the charge is carried by the quasiparticles. Thus,

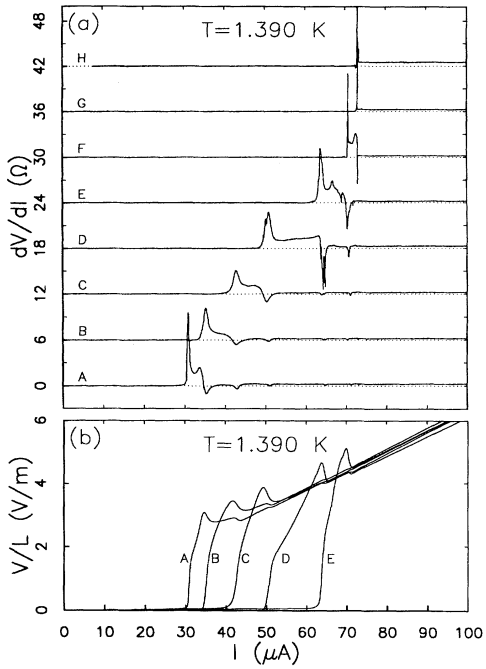

FIG. 5. (a) The dV/dI's are measured across sections A–H using pairs of adjacent S probes at $T = 1.390$ K. Each trace is shifted for comparison. Trace A corresponds to the voltage across section A, trace B across section B, and so on. (b) I-V characteristics are obtained from integrating graphs in (a).

neither an excess voltage nor a negative dV/dI peak is observed [trace G and H in (a)].

We have argued that the excess voltage is a manifestation of the introduction of PSCs. This should produce a single negative dV/dI peak when the next PSC is nucleated to the right of the sampled region, accompanied by the disappearance of all the excess voltage. However, in Fig. 5(b), the excess voltage persists even after a new PSC is nucleated in the neighboring cell. Also, a series of subsequent smaller dV/dI features is also observed in Fig. 5(a). [They are also seen in Fig. 3(a).] Comparing traces A–H, it is apparent that these peaks occur when new PSCs are introduced even as far as 16 μm away from the sampled region.

These new nonlocal phenomena can be attributed to the interaction between adjacent PSCs. Since two PSCs within λ_{Q^*} of one another repel, it is likely that when a new PSC is added, it will be located in the right half of its cell since there are no more PSCs to the right. With the addition of this PSC, existing PSCs become more closely packed and are progressively centered within their cells. This leads to a successive and discrete diminution of the excess voltage as the nonequilibrium region around each PSC becomes more confined to its cell. These features associated with the interaction between PSCs are absent in a second experiment on a film with only one pair of S probes. The excess voltage is smoothly extinguished over

a similar range of bias currents, without the subsequent features in dV/dI.

We have provided an explanation of the excess voltage and the nonlocal phenomenon in terms of the nucleation and interaction of PSCs. The interactions between PSCs together with the measurement of the excess voltage with probes placed within the charge imbalance region has not been observed previously. The length of the charge imbalance region is accentuated because of the smooth and shallow gradient in I_C together with long characteristic length scales in our film. In principle, aluminum thin films with modified T_C should be an ideal system to probe within the nonequilibrium region around phase slip centers. We have also developed an alternative description of the different nonequilibrium potentials μ_s and μ_n that exist near interfaces and will include this description in a longer paper.

In conclusion, we observe a resistance increase and excess voltage above normal state values near T_C, together with a nonlocal effect, in an inhomogeneous aluminum film. These observations are explained by the nonequilibrium near *N-S* interfaces and around PSCs where differences between μ_n and μ_s extend over the charge imbalance length. We also observe a new nonlocal phenomenon, which is most likely due to interactions between PSCs. It is reasonable to expect much of the same physics to be present in other inhomogeneous superconducting systems.

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