# Resistance Anomaly near the Superconducting Transition Temperature in Short Aluminum Wires

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(Received 4 January 1991)

We report a systematic experimental study of the superconducting resistive transition in one-dimensional Al wires of length 0.6 to 110 $\mu$m. Shorter wires show a peak in resistance as a function of temperature near $T_c$, with a value *above* the normal-state resistance. Near the peak, the resistance *decreases* sharply in a magnetic field of only a few Oe. In the same regime, the current-voltage characteristic resembles that of a superconductor-insulator-normal tunnel junction. These new results may be a manifestation of coherent effects in small superconducting samples.

PACS numbers: 74.40.+k, 74.75.+t

Over the years, one-dimensional (1D) superconducting wires have been studied extensively to observe a wide range of interesting physical phenomena.[1-6] One dimensionality requires that the cross-sectional dimensions of the wire be small compared to the superconducting coherence length $\xi(T)$ and the penetration depth $\lambda(T)$. The present understanding of the behavior of the resistance of a superconducting wire as a function of temperature, $R(T)$, may be divided into three different regimes. At temperatures above the mean-field $T_c$, there is a region of excess conductivity due to superconducting fluctuations.[1,2] In samples with disorder, this region may be further complicated by other quantum corrections[2] such as weak localization and electron-electron interaction. Just below $T_c$, there is an exponential tail in resistance due to the occurrence of thermally activated phase slips.[3] In the third regime, below (but not too close to) $T_c$, there is an apparent contribution[5] due to macroscopic quantum tunneling. The theoretical models[6,7] used to interpret all these effects have generally assumed a very long wire compared to $\xi(T)$. The question addressed by the work presented here is how these well-tested results are modified when the lengths of the wires are comparable to $\xi(T)$. Issues of this kind have been addressed[8] in the context of quantum coherence in *normal* (nonsuperconducting) metals manifested as weak localization or conductance fluctuations. There, the electron phase relaxation length $L_\phi$ sets the length scale.

For this work, samples were patterned on silicon substrates by electron-beam lithography using a single-layer resist. Aluminum films were deposited by electron-beam evaporation at room temperature followed by lift-off processing. We have studied more than thirty samples of different widths, resistivities, and geometries that include loops. The data presented in this article were all measured on wires 200 nm wide, $\simeq$42 nm thick. We shall return to discuss other samples later. Wires were patterned in the standard four-terminal measurement configuration on the same chip (Fig. 1, inset). The length of wires between the measurement probes ranged from 0.6 to $\simeq$110 $\mu$m and they shared no common lengths. The resistance was measured using a PAR 5301 lock-in amplifier at a frequency of 111 Hz. Because of the low sample resistances ($<15\ \Omega$) and the required low bias currents, the signal-to-noise ratio for dc measurements was not adequate. Each measurement lead had a 1-k$\Omega$ resistor in series in addition to its own electrical resistance to provide protection from accidental electrical discharge and also to reduce rf interference at the sample. The sheet resistance of the film defining the wires was $R_\square=0.33\ \Omega$ at 4.2 K with a resistivity ratio of 2.7. Based on previous literature[2,6] and the critical-field measurements of codeposited samples, we estimate the zero-temperature coherence length $\xi(0)\simeq170$ nm and the zero-temperature penetration depth $\lambda_{\rm eff}(0)\simeq80$ nm. The width of the wires is less than $\xi(T)$ and $\lambda_{\rm eff}(T)$ in the entire temperature regime reported here,[9] and the wires are therefore one dimensional.

First, we present the most striking result of our experiment: the behavior of $R(T)$ in zero magnetic field[10] for samples $A$–$E$, shown in Fig. 1. We have normalized the resistances to the value at 1.4 K to highlight the

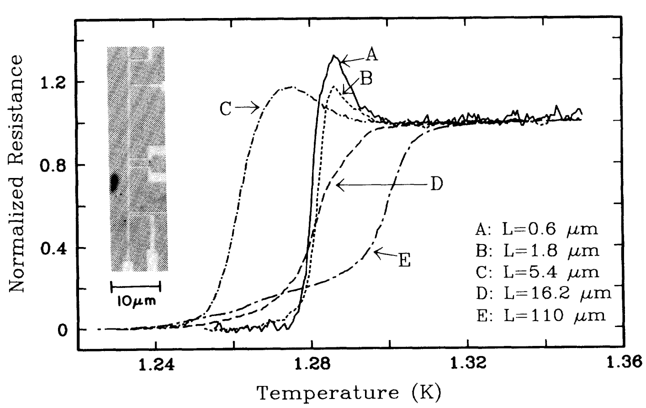


FIG. 1. Normalized resistance as a function of temperature for the five samples $A$–$E$ showing the resistance anomaly. Longer wires display a smaller and broader peak. Inset: The sample configuration for the three shortest wires.

differences in the same figure. The measuring current was 50 nA (rms) for all samples except $A$, for which it was 100 nA to obtain a better signal-to-noise ratio. Samples $A$, $B$, and $C$ show unexpected peaks in resistance *above* the normal-state value with decreasing temperature very near the superconducting transition. The longer wires, $D$ and $E$, do not show such obvious peaks but appear to have some remnant anomalous structure along the resistive transition. In general, the peaks appear to decrease in magnitude and the transition becomes broader as the wires become longer.

Current theoretical models[6,7] for a long superconducting wire do not predict an increase in resistance with decreasing temperature. According to the thermally activated phase-slip model, the existence of an exponential tail in the resistive transition of a long wire is due to random phase slips [each occurring on a length scale of $\simeq \xi(T)$] along the length of the wire, $L$. The observed resistance due to this mechanism should increase linearly with $L$. The normalized resistance (in Fig. 1) should then, be independent of $L$, as long as the activation energy for a phase-slip process is independent of the length. If one may ignore the anomalous peaks, there is evidence that the activation energy increases as the length of the wire becomes comparable to or less than $\xi(T)$.

Figure 2 shows the differential resistance ($dV/dI$) of sample $A$ measured at different temperatures near the transition. The measurement is done by superposing a 20-nA rms ac current on top of a slowly ramped dc current. In the normal state [Fig. 2(a)], $dV/dI$ is constant, as expected, implying a linear $I$-$V$ characteristic. At a temperature close to the occurrence of the peak along the resistive transition [Fig. 2(b)], the $I$-$V$ behavior is nonlinear. The surprising aspect of the nonlinearity is that $dV/dI$ (for low bias) is *larger* than the normal-state resistance. For high enough bias currents, $dV/dI$ does indeed reach the normal-state value. This shows that even though we are measuring a simple superconducting wire, the $I$-$V$ behavior shows a similarity to that of a superconductor–insulator–normal-metal tunnel junction a little below $T_c$ of the superconductor.[6] Near the midpoint of the resistive transition [Fig. 2(c)], the behavior agrees with what we would expect of 1D wires, i.e., a *minimum* in $dV/dI$ close to zero bias. At lower temperatures [Fig. 2(d)], we can see the critical current develop. It is clear that the nonlinear behavior in Fig. 2(b) is linked to the superconductivity.

Figure 3 shows the effects of an applied magnetic field $H$ on the resistive transition of samples $A$–$E$. An essential part of the anomaly we report here is that an appli-

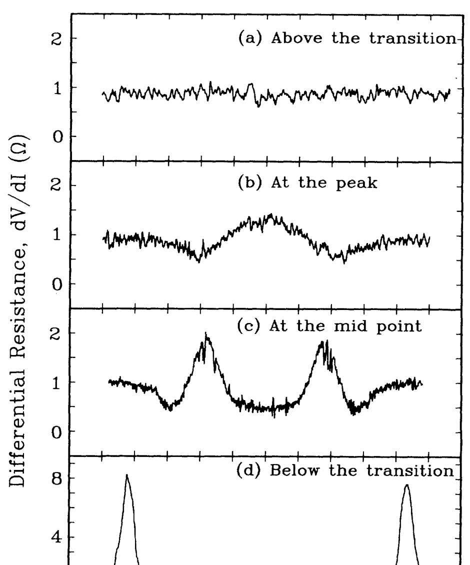


FIG. 2. Differential resistance as a function of the bias current for sample $A$ at four different temperatures in zero magnetic field. (a) Above the transition, (b) at the resistance peak, (c) at the midpoint of the transition, and (d) below the transition. (b) more closely resembles the $dV/dI$ of a superconductor–insulator–normal-metal tunnel junction than that of a wire.

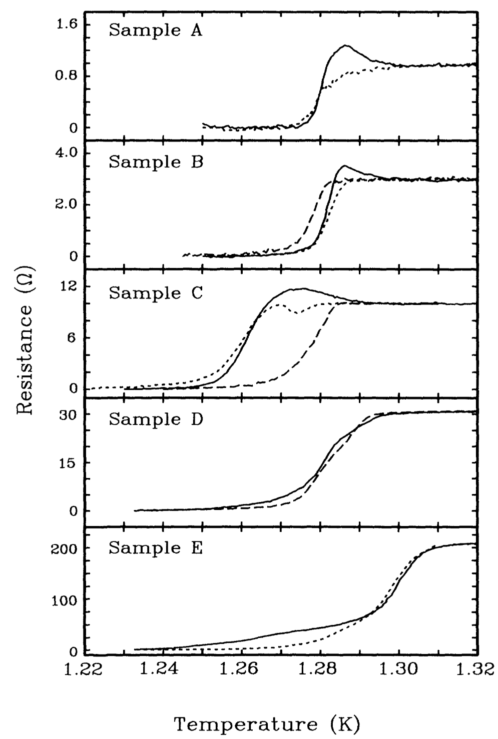


FIG. 3. Resistance as a function of temperature for samples $A$–$E$ in various applied magnetic fields. The bias current was 50 nA (rms). The solid lines correspond to $H=0$, dotted lines to $H=8$ Oe, and dashed lines $H=15$ Oe.

cation of a small magnetic field causes a *reduction* in the resistance. Figure 3 shows that just $H \gtrsim 8$ Oe removes the resistance peak for the shorter samples *A* and *B*. The longer sample *C* has some remnant anomalous behavior in a field of 8 Oe with the peak location shifted to a lower temperature and a decrease in the peak value of the resistance. At $H = 15$ Oe, there is no longer a trace of the anomaly in sample *C*. Sample *D*, which did not show as obvious a peak as the shorter wires, does have the anomalous response to the applied magnetic field for a field of 15 Oe. The longest wire, sample *E*, has the anomaly pushed down to a lower temperature, while the width of the resistance peak is considerably broadened. A field of 8 Oe produces the expected suppression of $T_c$ at the upper part of the resistance curve, whereas at the lower end it produces the anomalous response. In general, $R(T)$ curves with a magnetic field of $\simeq 15$ Oe have the expected exponential dependence on temperature as predicted by the theoretical models[6,7] for a long wire.

The magnetic-field dependence shown in Fig. 3 can be viewed in a different way if we plot the magnetoresistance at a fixed temperature near the peak along the resistive transition. Figure 4 shows such a measurement for sample A. In this situation, the usual behavior[2] should give rise to a monotonic increase in resistance with increasing magnetic field. Here, on the contrary, the resistance falls to almost 20% of the normal-state value with an application of a few oersteds and then rises. The sharpness of the decrease is quite surprising. The precise shape of the magnetoresistance curve is sensitive to the temperature at which the measurement is made, as suggested by Fig. 3.

Given the surprising nature of the results we have described, we have attempted to the best of our ability to rule out spurious measurement artifacts. The measurements were carried out in two different cryostats, a

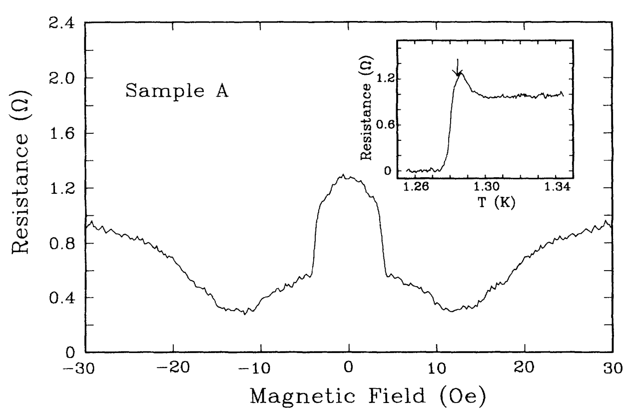


FIG. 4. Resistance as a function of magnetic field for sample *A*. Inset: The temperature at which the magnetoresistance trace was taken along the resistive transition. Conventional behavior would have resulted in a monotonically increasing resistance with increasing magnetic field.

pumped $^4$He system with a Mumetal shield and a $^3$He system. Many of the measurements were repeated on different days (some with thermal cycling to room temperature) and no substantial difference in the measured properties was observed. Results were also verified using a SR-510 lock-in amplifier in specific instances. The measurement results were checked to be independent of frequency from 11 Hz to 1.11 kHz. To eliminate possible contamination of the aluminum as the origin of the observed phenomena, we have deposited films in different evaporators and with different aluminum source materials. The general features remain the same.

Now we briefly mention the results on other samples we have studied in this connection. (i) For two different samples of the same geometrical structure and similar material properties, the *magnitude* of the anomaly is not necessarily the same although the qualitative features are quite similar. (ii) It appears that cleaner samples [i.e., those with larger $\xi(T)$] display the resistance anomaly more prominently. (iii) Samples designed to contain loops whose overall dimensions between the measurement probes are not large ($\lesssim 50$ $\mu$m) also show evidence for the anomalous behavior both in $R(T)$ and in their response to a small magnetic field. The effects due to the multiply connected geometry, such as Little-Parks[11] oscillations, can be seen superposed on the anomalous background. (iv) We have attempted to study these effects in another material system. One set of samples was prepared using 0.5-$\mu$m-wide indium wires that contained a 2.5-$\mu$m-long wire and square loops of 2.5 $\mu$m on a side. These did not show any sign of the anomaly. This may not be at all surprising, however, since $\xi(0)$ in indium is much shorter than in Al. In addition, $T_c$ of indium is nearly 3 times larger than that of Al; so if the absolute temperature is of any relevance to the effect (in addition to the relative temperature $T/T_c$), then indium may turn out to be a poor candidate for its observation.

We note that the anomaly has not been seen in previous experiments[1-5] which involved longer narrower 1D wires. In fact, it is most clearly evident in samples with a total resistance of only a few ohms, typically less than 15 Ω. If such a low resistance is indeed required to observe the anomaly, then the narrower wires must also be correspondingly shorter. While wider wires show less anomalous behavior, this may be linked to the criterion for one-dimensionality not being satisfied.

There have been some previous experimental results that have some similarity to the behavior we are reporting. Lindqvist, Nordström, and Rapp[12] reported a small resistance peak anomaly in Cu-Zr alloys with dilute magnetic impurities. The presence of magnetic impurities was the key to their observations. This is not likely to be the case in our experiments, as common magnetic impurities do not have moments in Al.[2] Lindqvist, Nordström, and Rapp did not show any relationship between the size of their samples and the observed behavior. Also, the characteristic magnetic field required to affect the resistance peaks in their samples was at least 3 orders of magnitude larger than in our samples, where it is just a few oersteds. Other observations of an increase in resistance in superconducting thin films[13] with homogeneous disorder ($R_{\square} \simeq h/4e^2 \simeq 6.45$ kΩ) were due to electron localization prior to the establishment of long-range superconductivity. Our samples ($R_{\square} \simeq 0.5$ Ω) are *not* in this regime. Weak-localization effects have been studied quite thoroughly in previous experiments[2] on Al films and wires and no observation similar to ours has been reported. We note that a recent observation of negative magnetoresistance in small samples designed to have superconducting-normal interfaces[14] is explained simply in terms of a nonequilibrium charge-imbalance model.[14,15] Such a model is insufficient to explain our results.

We now speculate on possible sources for this anomaly. Using nonlinear Ginzburg-Landau equations, Fink and Grünfeld[16] have calculated the variation of the superconducting order parameter below $T_c$ in a wire carrying a current in the presence of sidebranches. They find that the magnitude of the order parameter is higher at the nodes than in the middle of the wire. This implies that for a current-carrying short wire the superconductivity can occur at the nodes at a higher temperature than in the middle of the wire. We may then treat a short wire near $T_c$ as a coherent region comprising normal ($N$) and superconducting ($S$) metals. $N$-$S$ interfaces are known to give rise to quasiparticle charge imbalance induced by the bias current.[14,15,17] Near $T_c$, the voltage probes are within the characteristic length $\lambda_Q^*$, associated with the quasiparticle charge imbalance. Depending on whether the voltage probes are superconducting or not, the measured voltage can be quite different[17,18] and thus may play a role in the observed resistance behavior. However, it is still difficult to understand the resistance peak and the related current-voltage curves. In the presence of a magnetic field $\lambda_Q^*$ is modified;[14,15] another length scale of relevance is the magnetic pair-breaking length $l_s = \sqrt{3}h/2\pi eHW$. For a wire of width $W = 200$ nm at $H = 10$ Oe, $l_s = 5.7$ $\mu$m and is comparable to the lengths of our intermediate wires. This may play a role in determining the sensitivity of our samples to weak magnetic fields.

Blonder, Tinkham, and Klapwijk,[19] in their discussion of normal-superconducting microconstrictions, invoke the presence of a barrier of strength $Z$ at the $N$-$S$ interface. Larger values of $Z$ yield more tunnel-junction-like behavior. As mentioned previously, it is not unlikely that we have an $N$-$S$ interface for each node in our samples. To explain our data within this model, the effective $Z$ must be sufficiently large to result in a tunnel-junction-like behavior. $Z$ must also be quite sensitive to temperature and applied magnetic field. Sample size and its dimensionality must play an important role in such a behavior.

We thank C. P. Umbach for assistance in the sample preparation. We acknowledge useful discussions with M. Büttiker and W. J. Skocpol.

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[9]Note that for temperatures close to $T_c$, $\xi(T) = \xi(0)/(1 - T/T_c)^{1/2}$ and $\lambda_{\text{eff}}(T) = \lambda_{\text{eff}}(0)/(1 - T/T_c)^{1/2}$.

[10]Because of the trapped flux in the Nb-Ti magnet used, there was a shift of $\simeq 6$ Oe in the ambient field that had to be canceled to obtain the true "zero" field. The basic results have been confirmed in a different Dewar with Mumetal shield in samples with higher $T_c$.

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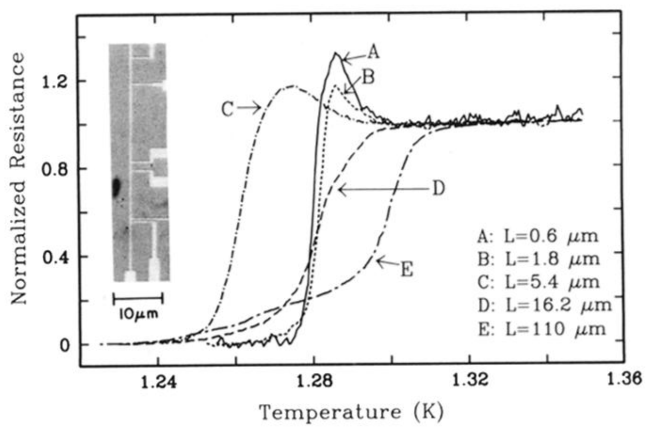


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