Electronic Transport in Underdoped YBCO Nanowires: Possible Observation of Stripe Domains

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Abstract

We have fabricated and measured the transport properties of a series of $YBa_2Cu_3O_{7-\delta}$ nanowires ranging from $100-200nm$ in width. In all samples we observe hysteretic steps in the current-voltage characteristics below the superconducting transition temperature T_c and switching fluctuations in the resistance as the temperature is varied well above T_c. The data may be evidence for the formation of a domain structure such as charge stripes.

Key words: Cuprates ; pseudogap ; stripes ; nanowires

1. Introduction

Although the boundaries and behavior of the pseudogap regime in underdoped high-T_c cuprates have been widely explored, the electronic structure and microscopic origin of this phase remains elusive. One attractive class of theories invokes symmetry-breaking order parameters [1–3], opening up the possibility of domain effects which might be directly observable in mesoscopic samples.

To probe the electronic structure in this regime, we have developed a technique involving electron-beam lithography and low temperature argon ion milling that allows us to fabricate nanowires with superconducting properties that are not significantly degraded from the starting cuprate film. We report here on samples with widths down to $100nm$ patterned from underdoped $YBa_2Cu_3O_{7-\delta}$ films grown by pulsed laser deposition on $LaAlO_3$ substrates, with $T_c \approx 70-80K$. Characteristic lengths are the Ginzburg-Landau coherence length $\xi \approx 2nm$, the London penetration depth $\lambda \approx 200nm$, and the stripe correlation length ζ, estimated from neutron data [4,5] to be at least $35nm$. Thus, our samples are mescoscopic, with $w \approx 3\zeta$, $w < \lambda$, and $w \approx 50\xi$, where w is the width of the nanowire.

The current-voltage characteristics (IV's) are measured with a standard four-probe technique on segments with lengths ranging from $700nm$ to $1800nm$.

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2. Results and Discussion

Figure 1 shows representative IV's of a nanowire at a series of temperatures. As the current is increased, we find the onset of a finite phase diffusion voltage at a critical current I_p, followed by a step-like switch at a higher current I_c. Additional steps occur at higher current values. These steps are more prominent at low temperatures and exhibit hysteresis.

An important question is whether the step structure is localized or extends across the entire length of the sample. To test this, we compare simultaneous measurements of the voltage across roughly half of a wire to that across the entire length. As displayed in Figure 2, some voltage steps are correlated and scale with the length, suggesting long-range spatial correlations. Other steps are confined to one of the segments, suggesting the formation of discrete resistive domains.

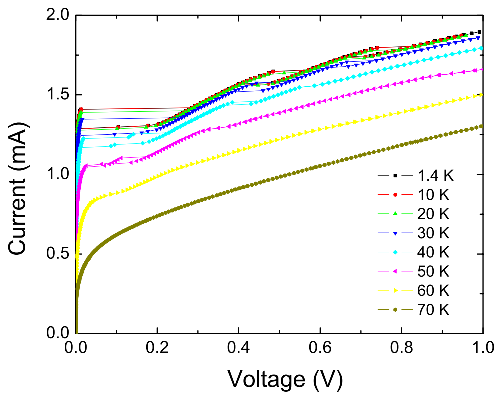

Fig. 1. Current-voltage characteristics at different temperatures for a 200nm wide nanowire with $T_c = 75K$.

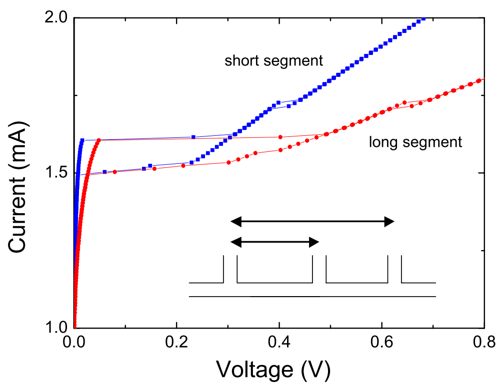

Fig. 2. Comparison of IV's of two overlapping segments.

Above T_c we observe jumps of both signs in R(T) confined to the temperature range associated with the pseudogap state for this doping level. These jumps occur as the temperature is varied, as in Figure 3, and also have been observed as a function of time at fixed temperature. In simultaneous measurements on overlapping segments, most of the jumps are found to be correlated and scale with the segment resistance, consistent with long-range, in-plane correlations. However, we also observe correlated changes in R that are not proportional to the total resistance, which could arise from domains smaller than the sample size. In a few cases, we have also seen anti-correlated (opposite sign) jumps, which would require complex dynamics such as a domain wall moving between segments.

Possible explanations for the step structure in the IV and R(T) data are limited. Explanations based on Josephson junctions between grains, vortex flow, and phase slip centers can likely be ruled out. The critical current densities at the switching currents are too high for junctions, the samples are too wide for phase slip centers, and the dissipation above I_c is too large to be explained via flux flow. Further, none of these models can easily account for the extended spatial correlations.

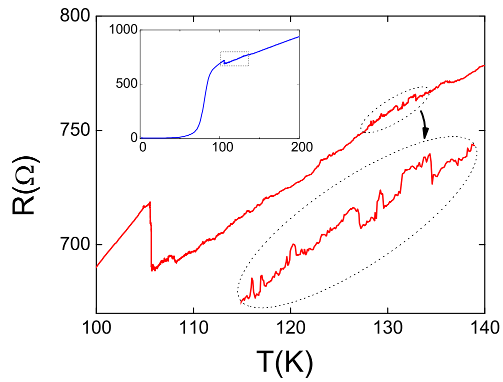

Fig. 3. Resistance vs. temperature for a 200nm wide, 700nm long nanowire at a bias current of 100μA; the inset shows the resistive transition and identifies the region of fluctuations.

These results instead suggest the nucleation of a mesoscopic domain structure. Domains can generate switches in the IV curves and R(T) via reorientations, and de-pinning. One attractive scenario is the formation of ordered charge stripes predicted for highly-correlated electronic systems [1]. These are expected to feature large in-plane anisotropy in the resistivity in the pseudogap regime and, as noted, may exhibit long correlation lengths. In such a model, the switching behavior may arise from the alignment of stripe domains along or orthogonal to the nanowire. Thus, the mesoscopic sizes involved here may not only allow the observation of individual domain rearrangements, but also affect the dynamics of the domains due to geometrical constraint or pinning.

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