Evidence for Current-Driven Phase Slips in $YBa_2Cu_3O_{7-\delta}$ Microstrips

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Abstract. We report distinctly nonlinear current-voltage characteristics in thin-film microstrips of high-T_c superconducting $YBa_2Cu_3O_{7-\delta}$, fabricated by a novel chemical-free technique. Both current-biased and voltage-biased measurements were made between 4.2K and T_c≈91K. Discontinuities were seen for the former and *S*-shaped non-linearities for the latter, in striking agreement with the 1D phase-slip phenomenology established for low-T_c nanowires. For our quasi-2D high-T_c microstrips, our observations indicate the formation of current-driven phase slip lines well below T_c.

Keywords: Phase Slips, High-T_c, Superconductivity, Cuprates
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The ability of a superconductor to transport current with no resistance is one of its more important physical properties. Many proposed superconductive devices are designed around this fundamental property. However, the transition into the resistive state can vary vastly, depending on a superconductor's physical dimensions and chemical composition, as well as temperature and magnetic field. In reduced dimensions, a superconductor can become resistive through the occurence of phase slips [1–4]. For the current-driven phase slip process, the superconducting order parameter (OP) fluctuates between a finite value and zero, within a region spanning two coherence lengths 2ξ. As the OP fluctuates, its phase ϕ slips by 2π, while the superfluid momentum $p=\nabla\phi$ decreases by $2\pi/L$, where L is the length of the sample. While producing local dissipation, this decrease in momentum allows the superconducting condensate to remain below its critical velocity, thus preserving its long-range phase coherence.

It is well known that current-driven phase slips are manifested as distinct non-linearities in the current-voltage (*I*-*V*) characteristics [1]. Such nonlinear *I*-*V* characteristics have been well studied in conventional low-T_c superconductors, most recently in quasi-1D nanowires of Pb and Sn [5, 6]. For the high-T_c superconductors, several transport studies have been reported on chemically- or physically-etched cuprate thin films, ranging from 100nm to 20μm in width [7–13]. In these studies, highly non-linear *I*-*V* characteristics were seen below T_c, and attributed to either collective flux flow, vortex instability, phase slip regions or mesoscopic domains. All of these measurements were made under *current*-biasing. Here we present both *current*- and *voltage*-biased *I*-*V* measurements made on epitaxial $YBa_2Cu_3O_{7-\delta}$ (YBCO) microstrips, which were fabricated by a chemical-free method to ensure optimal doping.

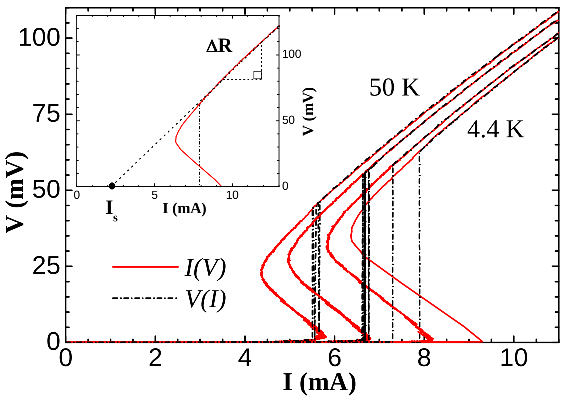

FIGURE 1. Current-voltage characteristics of an optimally-doped YBCO microstrip 1μm wide and 80μm long. Main panel shows data taken at 4.4, 30.0, 42.5 and 50.0 K, under both *current*-biasing (dashed) and *voltage*-biasing (solid). Inset shows the intersection (I_s) of the dV/dI (=ΔR) incline with the current axis.

Our chemical-free technique for fabricating YBCO microstrips is based on selective epitaxial growth [14]. Different regions of a YBCO film were physically and electrically isolated by amorphous $SrTiO_3$(STO) barriers patterned by electron-beam lithography. Atomic force microscopy (AFM) images of the YBCO deposited on top of the STO barriers indicated their amorphousness, while resistance versus temperature measurements confirmed their insulating behavior. *I*-*V* measurements were made in both voltage-biased $I(V)$ and current-biased $V(I)$ modes. The current and voltage signals were pulsed, with widths of 200μs and duty cycles of 5%, in order to minimize Joule heating.

Figure 1 plots representative *I*-*V* data taken on a 1μm

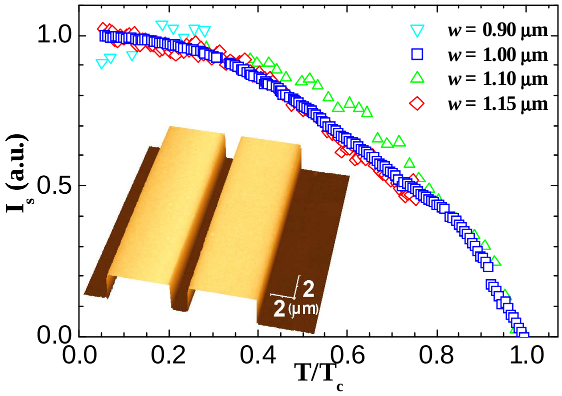

FIGURE 2. Intersection point (I_s) of the linear dV/dI incline with the current axis, plotted in arbitrary units versus reduced temperature T/T_c. I_s can be interpreted as the time-averaged value of the supercurrent through the phase slip region [1]. Main panel shows data for YBCO microstrips of various widths. Inset shows a perspective AFM image of a typical YBCO microstrip, with the light regions being the amorphous barriers and middle dark region being the epitaxial channel.

wide 80μm long microstrip at various temperatures. Each $V(I)$ shows an abrupt voltage jump at a critical level of current, while each $I(V)$ shows an s-shaped non-linearity which coincides with the voltage jump. This observation bears striking resemblance to the *I*-*V* measured on superconducting Pb and Sn nanowires, whose widths w are smaller than their coherence lengths ξ [5]. In these 1D geometries, the s-shaped non-linearities have been clearly identified as manifestations of phase slip centers using a time-dependant Ginzburg-Landau formalism [15]. In our YBCO microstrips, where $w > \xi$, the appearance of similar *I*-*V* non-linearities can be attributed to the formation of phase slip lines, which are 2D analogues of phase slip centers [16, 17].

According to the phase slip model of Skocpol, Beasley and Tinkham (SBT) [1], non-equilibrium quasiparticles due to the OP fluctuations should diffuse over a distance Λ_Q on either side of a phase slip region before recombining into the condensate, giving rise to an increment of resistance (ΔR) along the sample [1]. The linear dV/dI incline from above the voltage jump can be related to Λ_Q through the relation $2\Lambda_Q/L = \Delta R/R$, where L is the sample length and R is the normal-state sample resistance. From our data on YBCO, the quasiparticle relaxation length Λ_Q was determined to be 20.1μm at 4.2K. This experimental value varies little between samples, and shows a weak temperature dependence except near T_c where it expectedly diverges.

Furthermore, the OP fluctuations should cause the supercurrent to oscillate within the phase slip region [1]. Following the SBT treatment, the time-averaged value of the supercurrent (I_s) can be determined from the intersection of the $V(I)$ incline with the current axis (see inset of Fig.1). Figure 2 shows temperature dependance of the I_s extracted from our *I*-*V* data for YBCO microstrips of various widths. Plotted in arbitrary units, the different I_s curves appear to have a similar temperature dependence. This independence of I_s on sample width attests to the universality of the phase slip process governing the transport in our YBCO microstrips.

In summary, our measurement of the *I*-*V* characteristics in optimally-doped YBCO microstrips have provided clear evidence for current-driven phase slips well below T_c. Our results imply that the formation of phase slip lines (PSL), which are 2D analogues of phase slip centres (PSC), determines the transition of our YBCO microstrips into the resistive state. Further studies are needed to elucidate the analogy between PSC and PSL, particularly whether their formations are based on similar physical mechanisms.

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