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I–V curves of Y–Ba–Cu–O microbridges in the flux flow regime

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Abstract

We report on measurements of I–V curves in microbridges of thin Y–Ba–Cu–O films of different thickness, in the presence of external magnetic fields up to 6 T. A discontinuity is observed at a critical voltage, V^*, in the flux flow regime, reflecting an electronic instability, as predicted by Larkin and Ovchinnikov (LO), and in agreement with results reported by Doettinger et al. [Phys. Rev. Let. 73 (1994) 1691]. The critical voltage, V^*, and the flux flow resistance, R_0, in the limit $V \rightarrow 0$, are calculated by fitting the data to the LO model. We find that the vortex critical velocity, v^*, at the instability, derived from V^*, decreases with magnetic field and film thickness. These results, not predicted by the LO theory, reflect the dependence of the (spatially averaged) quasiparticle energy relaxation rate on magnetic field and film thickness.

Keywords: I–V curve; Y–Ba–Cu–O; Electronic instability

Larkin and Ovchinnikov (LO) predicted a discontinuity in the voltage–current characteristic (V–I) of superconductors at a critical voltage V^*, where an abrupt switching of the sample into a state of higher electric resistivity occurs and negative differential resistivity sets in [1]. The nonlinear resistance just below V^* is expected to be $R = R_0(1 + (V/V^*)^2)$. The abrupt switching at V^* is a result of electronic instability at a critical vortex velocity, v^*, in the flux flow regime, due to the shift of the quasiparticle distribution in the vortex cores to higher energies.

The prediction for a discontinuation in the V–I curves was confirmed experimentally in low-T_c [2–4] and in high-T_c superconductors [2], and a reasonable agreement with the LO theory was found. In this manuscript we present V–I curves for YBCO microbridges of different thicknesses and report on a new observation namely, that the critical vortex velocity v^* depends strongly on R_0 or, equivalently, on the film thickness.

Experiments were preformed on epitaxial YBCO films of 110–140 nm thickness, grown on (1 0 0) $SrTiO_3$ wafers by laser ablation deposition, with c-axis orientation normal to the substrate. The 1×1 cm^2 film was patterned into 10 equally spaced bridges of 12×120 μm^2 by deep UV photolithography and Ar ion milling at 77 K, as shown in Fig. 1, all in the same (1 1 0) node direction of the anisotropic pair wavefunction of the YBCO film. Finally, gold contacts were prepared by lift off, and the wafer was annealed in 0.8 atm. oxygen, first at 700 °C for 0.3 h for the

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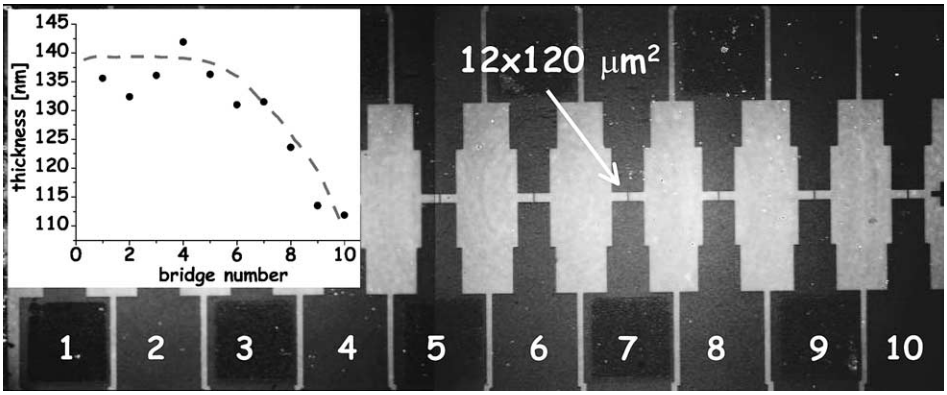

Fig. 1. Optical image of 10 YBCO microbridges with dimensions of 12×120 μm^2. The inset presents thickness dependence of all bridges. The dashed line is a guide to the eye.

gold contacts, and then at 450 °C for 1 h for the oxygen doping level of the YBCO film. This yielded overdoped films with T_c of 86 (±0.5) K. The inset of Fig. 1, shows the thickness in nanometer of each microbridge as measured by an atomic force microscope (AFM). Each thickness value is an average over 16 such measurements taken along the length of the bridge. The transport measurements were done on all 10 microbridges in the same cooling run. Four points I–V measurements were performed by sweeping the voltage to 5 V at temperatures in the flux flow regime, in the presence of different external magnetic fields from 2 to 6 T, applied parallel to the c-axis. The experiments are carried out not far below T_c, at 60–70 K, where the LO theory is valid. Various sweep rates of the voltage have been tested to assure that heating effects are negligible.

A typical V–I curve, measured at 70 K in the presence of 4 T magnetic field, is shown in Fig. 2. A voltage jump of ~20 V occurs at ~110 mV. In order to obtain V^* and R_0 we plot V/I vs. V^2, and fit the data points close to the instability to $V/I = R_0 + V^2(R_0/V^{*2})$, see the inset to Fig. 2. From the slope and the intercept of this line we extract R_0 and V^*. The critical velocity of vortices at the instability, v^*, can be calculated from $E^* = V^*/L = -(v^* \times B)$, where B is the magnetic-flux density and L is the sample length between the voltage contacts. According to the LO model, the critical velocity v^* is proportional to the square root of the energy relaxation rate [1].

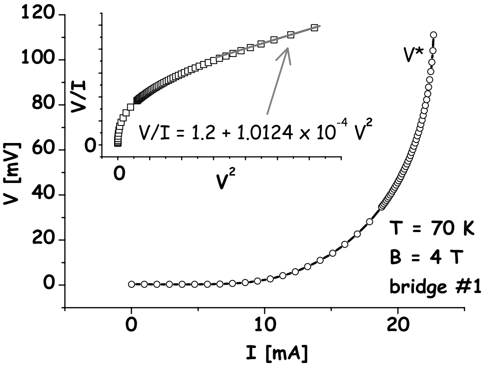

Fig. 2. Typical V–I curve of a microbridge at 70 K and external magnetic field of 4 T. V^* denotes the voltage at the electronic instability. Inset: plot of V/I vs. V^2 for a demonstration of the fitting procedure.

Figs. 3 and 4 show R_0 and v^*, respectively, for each of the bridges. The different symbols relate to different external magnetic fields. Apparently, both parameters increase as the film thickness decreases. The dependence of R_0 on film thickness is plotted in the inset to Fig. 3.

Fig. 4 and its inset show clearly that v^* decreases with increasing magnetic field. Similar magnetic field dependence was observed by Doettinger et al. [2,5]. They showed that v^* displays a crossover from magnetic field independent behavior at high fields to a $v^* \sim B^{-0.5}$ behavior at low fields. The reason for this behavior at low magnetic fields is that $v^*\tau$, where τ is the energy relaxation time, must reach at least the intervortex

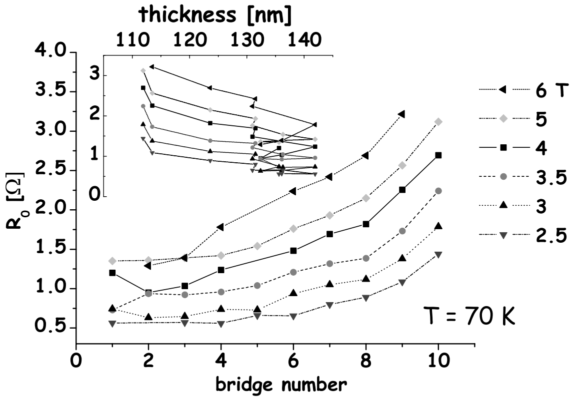

Fig. 3. R_0 for all bridges at 70 K in various external magnetic fields. Inset: R_0 as a function of thickness.

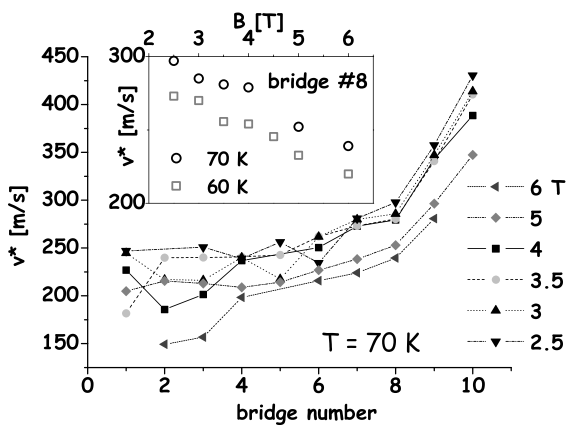

Fig. 4. v^* for all bridges at 70 K in various external magnetic fields. Inset: v^* as a function of magnetic field for bridge number 8, at 60 and 70 K.

distance in order to ensure spatial homogeneity of the nonequilibrium quasiparticle distribution [5]. In the temperature regime of our measurements (60–70 K), as demonstrated in the inset to Fig. 4, the crossover field is not yet reached at 6 T.

Apparently, for all magnetic fields, both R_0 and v^* vary monotonically as the film thickness is decreasing from bridge #1 (~140 nm) to #10 (~110 nm). In Fig. 5 we plot v^{*2} vs. R_0 for the same applied magnetic fields. We find that v^* increases with R_0. This result, though not predicted directly by the LO theory, is reasonable since the nonequilibrium effects are always limited by the quasiparticle energy relaxation rate which is expected to increase with increasing R_0.

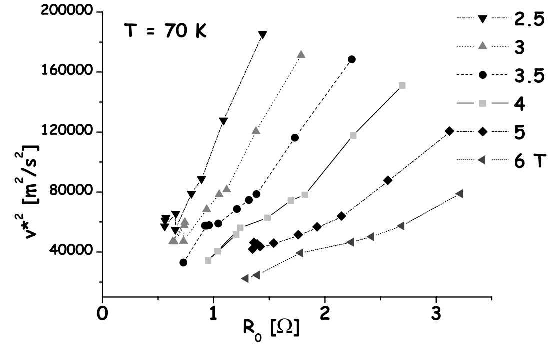

Fig. 5. v^{*2} as a function of R_0 at 70 K in various external magnetic fields.

In summary, we presented V–I curves for YBCO microbridges along the (1 1 0) direction from which we derived the parameters describing the vortex instability in the flux flow regime. Both v^* and R_0 strongly depend on film thickness, increasing with decreasing film thickness. A relation between v^* and R_0 was observed experimentally and interpreted by the mutual dependence of v^* and R_0 on the energy relaxation rate.

The instability parameters are directly related to the energy relaxation rate, which, in turn, is connected to the energy gap of the superconductor. Therefore, measurements of the electronic instability in the flux flow regime may serve as a powerful tool for investigations the order parameter and its symmetry. In particular, since the order parameter in YBCO is characterized by a d-wave symmetry, we expect slower motion of vortices along the nodes. The observed strong dependence of instability parameters on experimental conditions requires special care in extracting the energy gap. A search for effects of the symmetry of the order parameter on the vortex motion in YBCO is being conducted. We will report on these experiments elsewhere.

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