Transport properties of high-angle grain boundary weak links in $YBa_2Cu_3O_7$ thin films

D. K. Lathrop, B. H. Moeckly, S. E. Russek, and R. A. Buhrman
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853-2501

(Received 11 September 1990; accepted for publication 3 December 1990)

By patterning ~ 1-μm-wide microbridges in laser ablated $YBa_2Cu_3O_7$ films containing high-angle tilt boundaries, weak links have been isolated with critical currents low enough to avoid self-screening effects. The current-voltage characteristics of these high-angle tilt-boundary weak links are well described by the resistively shunted junction model, if noise rounding is included. The response of the supercurrent to magnetic field and temperature indicates that the weak links are spatially nonuniform, consisting of relatively small areas of high critical current density, J_c, separated by areas with very low or zero J_c. The response to rf power suggests that the current-phase relation is nonsinusoidal.

Since the initial fabrication of high quality thin films of $YBa_2Cu_3O_7$, many efforts have been made to fabricate Josephson tunnel junctions or weak links in these films. Various factors have made this task difficult, including the short coherence length of $YBa_2Cu_3O_7$, the superconductor's reactivity with many materials, and the anisotropy of the normal and superconducting properties. However, it is well known that grain boundaries in this material have superconducting weak link properties which can be at least approximately described by the Josephson equations, and that these properties are dependent on the orientation of the two grains.[1,2] By studying naturally occurring grain boundaries in polycrystalline thin films, insight into the nature of the Josephson-like properties of high-temperature superconductor weak links can be obtained. In this letter we present a brief initial report of the results of a study of the current voltage (*I-V*) characteristics, including the effect of temperature and magnetic field and the response to incident microwave radiation (7–10 GHz) of isolated high-angle tilt boundary weak links formed in comparatively high quality $YBa_2Cu_3O_7$ thin films.

The weak links described in this letter are 0.6–3-μm-wide microbridges patterned onto $\sim$250-nm-thick polycrystalline $YBa_2Cu_3O_7$ thin films. These films were produced by laser ablation on mechanically or chemically polished MgO substrates using by now standard conditions.[3] The films are oriented with the *c*-axis perpendicular to the plane of the substrate, and x-ray pole figures indicate that about 80% of the grains have their *a* and *b* axes oriented parallel to the MgO principal axes, while the rest of the grains are rotated 45°, or in some instances $\sim$27°, to this. This results in the presence of a large number of high-angle tilt boundaries, which have been shown to have weaker superconducting properties than low-angle tilt boundaries.[1,2] Transmission electron microscopy studies[4] on these films reveal that the size of an area that is rotated by 45° is typically greater than 1 μm^2. Thus by patterning narrow microbridges in these films, a single one of these grain boundaries can be isolated and studied.

Direct transport measurements on such microbridges show that the low-temperature (4.2 K) critical current density (J_C) of the tilt boundaries typically varies by about a factor of 10 across a 1 cm^2 film. Depending upon the details of the film growth process we find that the mean tilt boundary J_C can vary from $\sim 5\times10^4$ to $\sim 5\times10^6$ A/cm^2 while maintaining a bulk film critical transition temperature, T_C, above 85 K. In order to examine the intrinsic Josephson-like properties of the weak link it is necessary to have the weak link width $w \leqslant \lambda_J$, the Josephson penetration depth. For the microbridge linewidth employed here, this requires that $J_C \leqslant 10^5$ A/cm^2 and it is such tilt boundary weak links that will be discussed here. Tilt boundary weak links with $J_C > 10^5$ A/cm^2 exhibit characteristics of one-dimensional flux flow (i.e., an "excess current"[5] in the *I-V* characteristic) and flux creep, depending on the magnitude of J_C and will be described in detail elsewhere.

As demonstrated by Fig. 1, the *I-V* characteristics of weak links with $J_C \leqslant 10^5$ A/cm^2 can be fit rather well by the resistively shunted junction (RSJ) model. Close inspection, generally does show deviations from the simply RSJ prediction. Such departure are similar to those seen in high quality low-temperature superconductor microbridges[6] and are generally attributed to ac supercurrent resonance effects, apparently due to a cavity established by the overall electrode structure, rather than an excessively high dielectric constant in the junction as suggested by Mannhart *et al.*[7] When the weak link's critical current is $\leqslant 100$ μA and/or the temperature approaches T_C, the effect of thermal noise is evident and is very well modeled by the standard noise theory,[8,9] as is shown in inset (b) of Fig. 1.

In a small magnetic field, the critical current of a *uniform* rectangular weak link with minimal screening of the applied field will oscillate in a manner similar to a Fraunhofer diffraction pattern, with a period H_0 given by

$$H_0 = \Phi_0 w(d + 2\lambda_L). \tag{1}$$

Here Φ_0 is the flux quantum ($h/2e$), w is the width of the junction, d is the thickness of the normal (or insulating) region, and λ_L is the London penetration depth. This should be valid as long as the width w is less than the Josephson penetration depth λ_J. Assuming a low-temperature value of $\lambda_L = 1500$ Å, $w = 1$ μm, and $d \ll \lambda_L$ we obtain an expected oscillation period of 6.2 G for a typical $YBa_2Cu_3O_7$ weak link. A weak link whose J_C is

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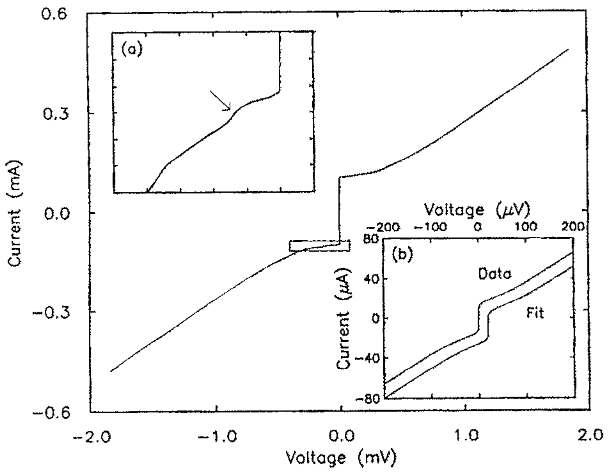

FIG. 1. I-V curve for typical high-angle grain boundary microbridge at 4.2 K. Inset (a) is an expanded view of the same data, the arrow points to a small deviation from ideal RSJ behavior probably due to supercurrent self-resonant effects. Inset (b) shows data for the same device taken at 60 K and a fit to the RSJ model with noise rounding. The curves are offset for clarity, but when overlaid the fit is essentially exact.

nonuniform will still exhibit a critical current whose magnitude oscillates with magnetic field, but the successive maxima will not follow a $\sin(x)/x$ behavior, and the minima may not reach zero.[10]

In Fig. 2(a) the behavior of typical weak link in small magnetic field is presented and is useful for illustrating four points. First, the maxima do not follow a $\sin(x)/x$ behavior, and in fact the fourth maxima is 80% the height of the central peak. Since self-shielding effects should not be effective for this low J_C weak link this suggests that the grain boundary consists of relatively small areas of strong contact separated by areas of little or no coupling, as the possible simulation in Fig. 2(b) shows. Second, the minima do not reach zero, which simply means that the weak link is asymmetric about its center. Third, the critical current experiences abrupt jumps, which we believe is the effect of flux jumping into or out of adjacent grains. And finally, the periodicity is ~ 10 G, which is consistent with the expected periodicity for this size microbridge (1.2 μm wide), indicating that λ_L in the vicinity of the tilt boundary is fairly close to the expected bulk value.

Figure 3 shows the critical current of a weak link as a function of temperature. Near T_C the behavior of I_C can generally be fit reasonably well by the functional form

$$I_C \propto (1 - T/T_C)^N, \tag{2}$$

where $N \geqslant 1.5$. Typically we find that the sharper the resistive transition of the microbridge, and the closer the extrapolated T_C of the weak link is to the zero resistance point of the resistive transition, the closer N is to 1.5. We take this to strongly suggest that measurements of $N \sim 2$ simply represent a nonuniformity in T_C along the tilt boundary, similar to the nonuniformity in J_C evident from the magnetic field behavior, and does not indicate the presence of a normal layer at the tilt boundary. This latter hypothesis is of course also incompatible with the mea-

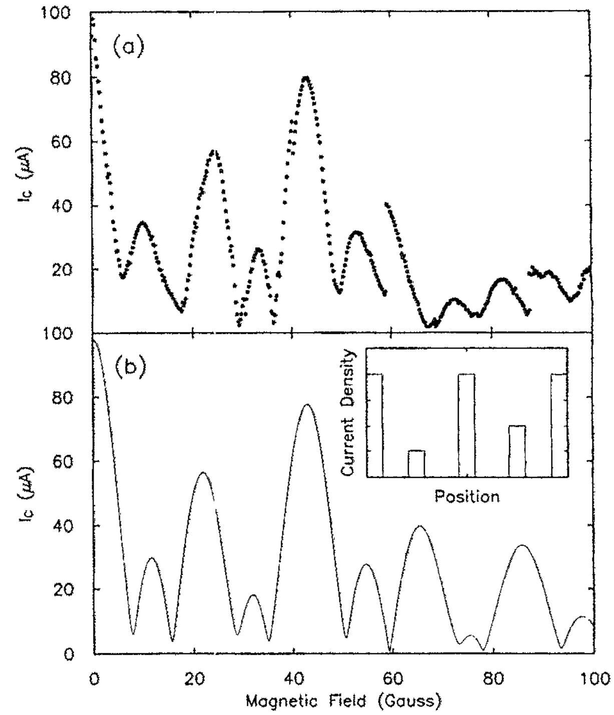

FIG. 2. (a) Critical current vs magnetic field for a typical device exhibiting oscillatory behavior, but the peak heights are uneven and the minima do not quite reach zero. (b) Theoretical behavior of an asymmetric, nonuniform junction showing many of the same features as the real device. The inset is the local critical current vs position used for this simulation.

sured conductance of the weak link ($G \sim 1$–10×10^8 S/cm^2) being much less than that of a normal conductor, given that electron microscopy studies of these tilt boundaries show only a 3–4-nm-wide disordered transition region.[11]

The current voltage characteristics were examined

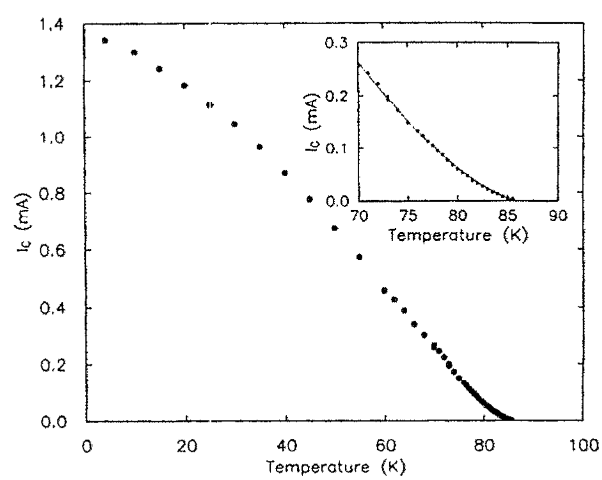

FIG. 3. Critical current vs temperature for a relatively strong high-angle grain boundary weak link. Inset is an expanded view near T_C with a fit to $(1 - T/T_C) - ^{1.5}$.

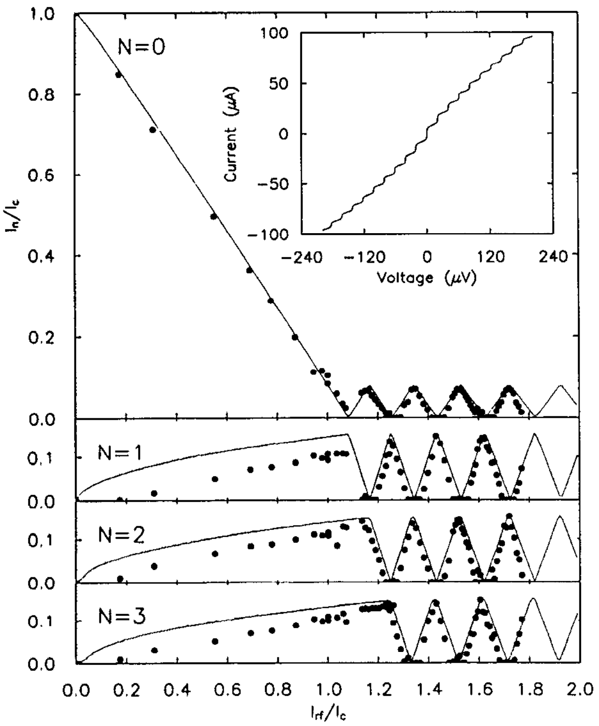

FIG. 4. Step size vs microwave current for the $N = 0$, 1, 2, and 3 steps. The solid line is from a numerical solution of the RSJ equations with a parallel microwave current source. The inset is the *I-V* curve for this microbridge with 7 GHz microwaves applied, showing the constant voltage steps at 14 μV intervals.

with microwaves of frequency 7–10 GHz applied. The inset in Fig. 4 shows a typical *I-V* curve with microwaves applied, displaying the expected constant voltage steps at integral multiples of $hv/2e$.

The amplitude of the steps was measured, by fitting them to the RSJ model with noise rounding in the small capacitance limit.[8,9] The fits were performed on the *I-V* curves in the vicinity of each step, with the step height, current offset, and voltage offset as parameters and the resistance fixed at the measured value in the absence of microwaves. Although the measurements were performed at 4.2 K, the effective noise temperature at which the best fit was obtained in the absence of microwaves was somewhat higher than this, 8–10 K, due to noise from outside the cryostat.

As the microwave power at the weak link is increased, and the critical current decreases, the apparent noise temperature which yields the best fit increases. This continues until the first zero of the critical current, at which point the noise temperature is 40–50 K. Increases in the microwave power beyond this, with the constant voltage steps oscillating as expected, does not increase the apparent noise temperature further. This elevated noise temperature is most likely an artifact of the measurement and analysis, probably due to the assumption in the analysis of a sinusoidal current-phase relation. Numerical simulations without noise and with a distinctly nonsinusoidal current-phase relation generally show small subharmonic steps at positions close to the major steps. The presence of thermal noise in the real case will completely wash out these subharmonic steps but their presence will cause the normal steps to appear more rounded.

Figure 4 shows the size of the first three steps as a function of microwave power (expressed as a microwave current). The values of I_N are from fits with an effective noise temperature of 40 K above the first zero of I_0, and the best fit noise temperature below this. The theoretical curves were obtained by using a fourth-order Runge–Kutta algorithm to solve the RSJ differential equation with a parallel microwave current source added. For the weak link shown, the fit is quite good throughout the range of I_{rf} examined.

Taken together, these measurements begin to give a picture of the nature of these high-angle grain boundary weak links. The magnetic field behavior indicates that these Josephson-like links are nonuniform and often asymmetric, consisting of a few areas (perhaps 3 to 5) of good superconducting contact with widths about 5–10% the full width of the microbridge. Thus the *local* J_c in the regions of good contact can be two to six times the value averaged for the boundary. These good regions might be nonuniform in both J_C and T_C, making measurements of the exact behavior of I_C with temperature difficult. If we consider the tilt boundary as a normal metal and use the observed 3–4 nm as the thickness of the weak region, the range of resistivities of our devices is 3–100 mΩ cm. This suggests that the weak region is at best a poor conductor, with a resistivity still more than an order of magnitudes above the resistivity of the bulk superconductor. Finally the less than ideal ac Josephson effect behavior, which in the context of the RSJ model shows up as an increasing apparent noise temperature with rf power, suggests that the tilt boundary is not an ideal Josephson junction.

This research was supported by the Office of Naval Research (N00014-89-J-1692) and by the Defense Advanced Research Project Agency (N00014-88-K-0374). Additional support was received from the National Science Foundation through the use of the facilities of the National Nanofabrication Facility and the Cornell Materials Science Center.

[1] S. E. Russek, D. K. Lathrop, B. H. Moeckly, R. A. Buhrman, D. H. Shin, and J. Silcox, Appl. Phys. Lett. **57**, 155 (1990).
[2] J. Mannhart, P. Chaudhari, D. Dimos, C. C. Tsuei, and T. R. McGuire, Phys. Rev. Lett. **61**, 2476 (1988); D. Dimos, P. Chaudhari, J. Mannhart, and F. K. LeGoues, Phys. Rev. Lett. **61**, 219 (1988).
[3] B. H. Moeckly, S. E. Russek, D. K. Lathrop, R. A. Buhrman, J. Li, and J. W. Mayer, Appl. Phys. Lett. **57**, 1687 (1990).
[4] M. G. Norton (private communication).
[5] J. R. Waldram, A. B. Pippard, and J. Clarke, Philos. Trans. Roy. Soc. London A **268**, 265 (1970).
[6] A. Barone and G. Paterno, *Physics and Applications of the Josephson Effect* (Wiley, New York, 1982), Chap. 9, p. 191.
[7] J. Mannhart, R. Gross, K. Hipler, R. P. Huebener, C. C. Tsuei, D. Dimos, and P. Chaudhari, Science **245**, 839 (1989).
[8] V. Ambegaokar and B. J. Halperin, Phys. Rev. Lett. **22**, 1364 (1969).
[9] P. A. Lee, J. Appl. Phys. **42**, 325 (1971).
[10] A. Barone and G. Paterno, *Physics and Applications of the Josephson Effect* (Wiley, New York, 1982), Chap. 4.
[11] D. H. Shin, J. Silcox, S. E. Russek, D. K. Lathrop, B. Moeckly, and R. A. Buhrman, Appl. Phys. Lett. **57**, 508 (1990).