Observation of Ultrahigh Critical Current Densities in High-T_c Superconducting Bridge Constrictions

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Narrow bridge structures were precisely fabricated (using novel ion-beam-milling techniques) on pulsed-laser-deposited $YBa_2Cu_3O_7$ films. The bridges have a length scale down to $L \simeq 500$ Å. Supercurrents were observed to flow across the bridge structures with critical current densities up to $J_c \simeq 1.3 \times 10^9$ A/cm^2, the highest critical current densities yet reported. The current-density magnitudes are consistent with the Onsager-Feynman vortex-ring-creation mechanism (for producing voltages across narrow constrictions) in the length scale region of $\xi \ll L \leq \Lambda$, with ξ the coherence length and Λ the London penetration depth. The highest J_c is in good agreement with the critical depairing mechanism.

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The study of critical current densities in restricted geometries for high-T_c superconductors is both of technical importance (for the fabrication of superconducting devices) and of intrinsic physical interest (for the understanding of superconducting transport through the material). A particularly interesting geometry consists of a narrow "superconducting bridge" of width L connecting two "bulk superconductors." The natural length scales of the bulk superconductor are the London penetration depth Λ and the coherence length ξ (roughly the size of an electron pair or equivalently the size of the core of a superconducting vortex). High-T_c superconductors, e.g., the $YBa_2Cu_3O_7$ (YBCO) films of interest in this work, are partly characterized[1] by the large values of $\kappa = \Lambda/\xi$.

Recently, Tahara *et al.*[2] reported critical-current-density studies for superconducting bridges, fabricated from YBCO films, having widths in the range $L > \Lambda$, and found that the critical current density J_c increased as L is decreased. Their highest value was $J_c \simeq 2.4 \times 10^7$ A/cm^2, and they theoretically predicted that an order of magnitude higher in J_c could be achieved if L were brought down significantly below Λ. In this paper, we experimentally confirm this theoretical prediction. Other experimental groups discussing the problems of achieving high critical current densities include Oh *et al.*,[3] Mannhart *et al.*,[4] Roas, Schultz, and Endres,[5] and Chaudhari, Dimos, and Mannhart[6] for YBCO and Gavaler *et al.*[7] for NbN films.

We report ultrahigh critical current densities, with values up to $J_c \simeq 1.3 \times 10^9$ A/cm^2, for YBCO microbridge constrictions studied in the regime $\xi \ll L \leq \Lambda$. The large critical current densities are consistent with the Onsager-Feynman vortex-ring-nucleation model as a limiting factor for superconducting flow and the highest critical current density is also consistent with the critical depairing mechanism.

High-quality YBCO thin films were prepared by using pulsed-laser-deposition techniques with a film thickness of $\simeq 5000$ Å. All of the films used for microbridge fabrication were deposited on MgO(100) substrates at 750 °C, and then quenched *in situ*. X-ray-diffraction measurements indicated the samples were c-axis oriented. Pole-figure analysis of the (0,1,2) peak indicated some misorientation in the a-b plane peaked strongly at 90° and to a much lesser extent at 45°. The thin films studied had room-temperature resistivity of 300 $\mu\Omega$, and showed sharp superconducting transitions ($\Delta T_c \sim 0.5$ K) at $T_c \simeq 90$ K. Inductive measurements of the critical current densities at 77 K in the unpatterned films were typically in the range $(2\text{–}4) \times 10^6$ A/cm^2.

A procedure was developed to routinely and reliably fabricate superconducting microbridges. First, the films were patterned by standard photolithography. The YBCO thin films were precoated with photoresist, soft baked at 95 °C for 15 min, and then exposed to UV radiation. After treating with 319 developer, the films were then hard baked at 105 °C for 15 min and etched in ethylenediamine tetra-acetic acid solution. Tolerances from 20 to 50 μm were routinely obtained. Second, accurate ion-beam milling was accomplished using a computer-controlled system. The well focused gallium-ion beam was used to mill unwanted areas of the YBCO

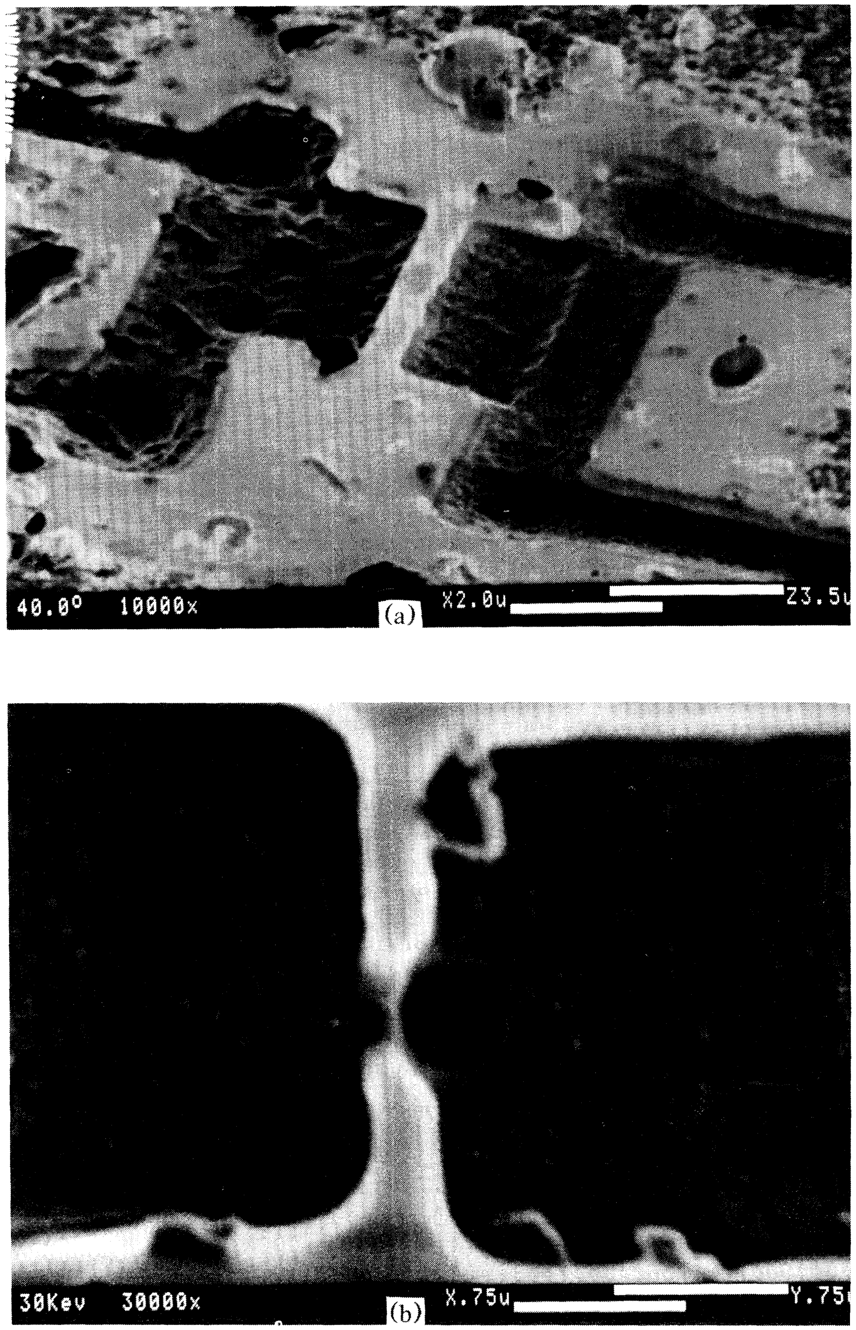

FIG. 1. Geometrical view of two YBCO microbridges. $L = 4000$ Å for bridge (a) and $L = 500$ Å for bridge (b). The bright area is YBCO film and the black is substrate.

film. Ion-beam milling produced several superconducting microbridges from $L \simeq 500$ to 4000 Å with accuracy better than 10%. The milling was done in several stages, between which measurements were made to assure that (at each stage of milling) the bridge retained its superconducting integrity. Shown in Fig. 1(a) is an $L \simeq 4000$ Å microbridge, and shown in Fig. 1(b) is an $L \simeq 500$ Å microbridge. In total three microbridge junctions were fabricated with the following cross sections: (a) $L = 4000$ Å, $t = 5000$ Å; (b) $L = 500$ Å, $t = 5000$ Å; (c) $L = 500$ Å, $t = 2000$ Å, where t is the film thickness.

Standard four-point probe dc measurements were performed on these microbridges. To obtain high-quality leads

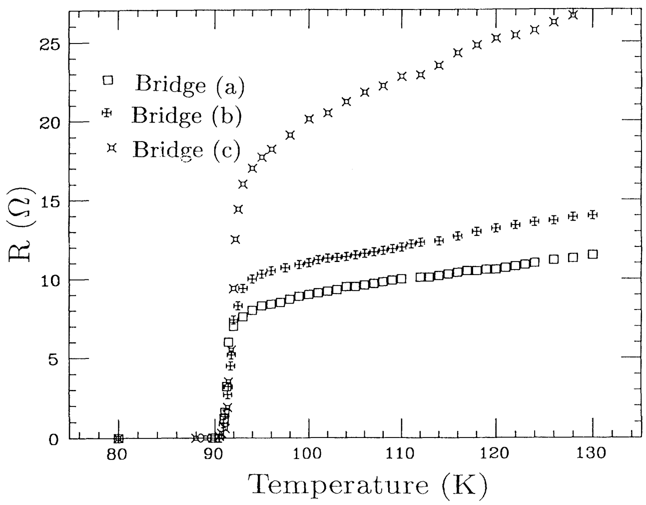

FIG. 2. Temperature dependence of the resistance of the three microbridges.

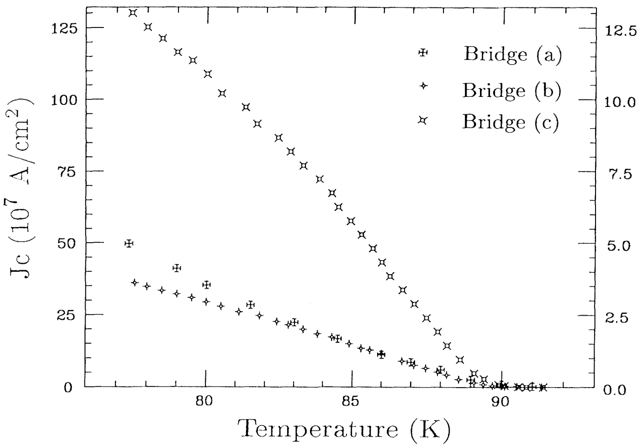

FIG. 3. Critical current densities as a function of T for the three microbridges. The reader is referred to the scale on the right-hand side of the figure for microbridge (a).

onto the films, the films were first cleaned with methanol, and then a layer of silver bar was evaporated onto the contact area. Indium soldering was employed to connect silver wires to the silver bar. A Keithly programmable current source was used. An HP multimeter was employed for voltage measurements, with a resolution of ~ 0.1 mV. (The critical current for the $L \simeq 500$ Å microbridge corresponds to a resistivity $< 3\times 10^{-14}$ Ω cm.) The current-voltage characteristic in the smallest microbridge was measured with the bridge immersed in liquid nitrogen at $T = 77$ K to prevent heating.

Figure 2 shows the temperature-dependent resistance of microbridge junctions (a), (b), and (c), indicating the transition to the superconducting state. In Fig. 3 critical current densities J_c as a function of T are plotted for the three microbridge junctions. Finally, in Fig. 4 a typical voltage-current characteristic at 77 K is shown. The other junctions exhibit the same behavior. The critical current densities measured on (a), (b), and (c) microbridges at 77 K were 5×10^7, 3.6×10^8, and 1.3×10^9 A/cm^2, respectively. In arriving at the current density, we divided the total current by the geometrical cross-sectional area of the microbridge (Lt) with no assumptions made about the distribution of the current.

To understand the large magnitude of critical current density we examined several theoretical models, each of which had some partial success. (i) The flux-creep model gives a reasonable temperature dependence for J_c as the critical temperature is approached, but the electric-field dependence of current density was not in very good agreement with the notion of a pinning thermal-activation energy. (ii) In order for a flux-pinning thermal-activation energy to explain the observed current-voltage characteristics, the activation energy itself would have to depend on the square of the current density. Presently, this is beyond the scope of proposed flux-pinning models. (iii) It is difficult to separate out the contributions to the critical current due to edge-barrier effects as opposed to bulk effects. (iv) The critical "depairing" current [given by $J_c(\text{depairing}) = c\phi_0/16\pi^2\Lambda^2\xi$, where ϕ_0 is the flux quantum] gives $J_c \sim 1.3\times 10^9$ A/cm^2 for $\Lambda \sim 1000$ Å and $\xi \sim 10$ Å in good agreement with our highest-critical-current sample. However, this leaves unexplained the somewhat lower values also observed in the thicker samples. (v) We considered the Onsager-Feynman[8] mechanism for critical velocities. In this model the critical velocity of the superconducting pair flow (in the regime $\xi \ll L_{\text{eff}} < \Lambda$) is due to the creation of vortex rings as given in the Onsager-Feynman theory by

$$v_c \simeq (4\hbar/ML_{\text{eff}})\ln(L_{\text{eff}}/\xi)\,, \tag{1}$$

where $M = 2m$ is the mass and $q = 2e$ is the charge of an

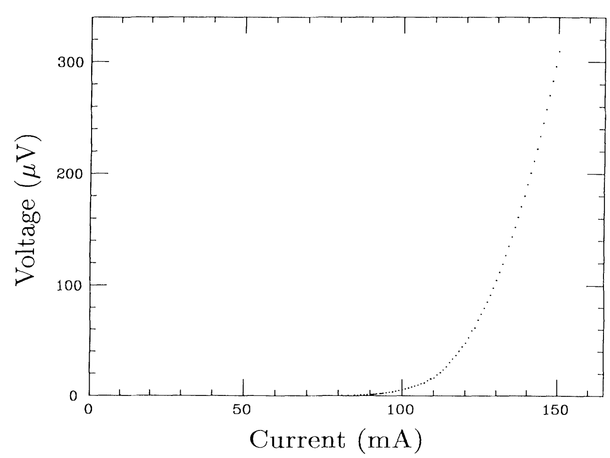

FIG. 4. Voltage-current characteristics of the bridge in Fig. 1(b) at 77 K.

electron pair. The critical current density is

$$J_c = q n_s v_c \,, \tag{2}$$

where the density of superconducting pairs is given by n_s. The London penetration depth Λ is determined as

$$(c/\Lambda)^2 = 4\pi n_s q^2/M \,, \tag{3}$$

so that Eqs. (1)-(3) yield

$$J_c \simeq (1/\pi)(\hbar c^2/q\Lambda^2 L_{\text{eff}})\ln(L_{\text{eff}}/\xi) \,, \tag{4}$$

where L_{eff} is the effective length scale of the microbridge cross section. This theory gives $J_c \sim 10^8$ A/cm^2 for $L_{\text{eff}} \geq 500$ Å and $J_c \sim 10^9$ A/cm^2 for $L_{\text{eff}} \leq 500$ Å. This is in reasonably good agreement with our results. The effective length scale is reduced whenever the microbridge cross-sectional area is made smaller.

In summary, we have shown that (by careful fabrication of superconducting microbridges) it is possible to obtain (in YBCO) critical current densities $\sim 10^9$ A/cm^2. The limitations on the critical current densities are not at present fully understood, but appear to be due to vortex-ring creation.

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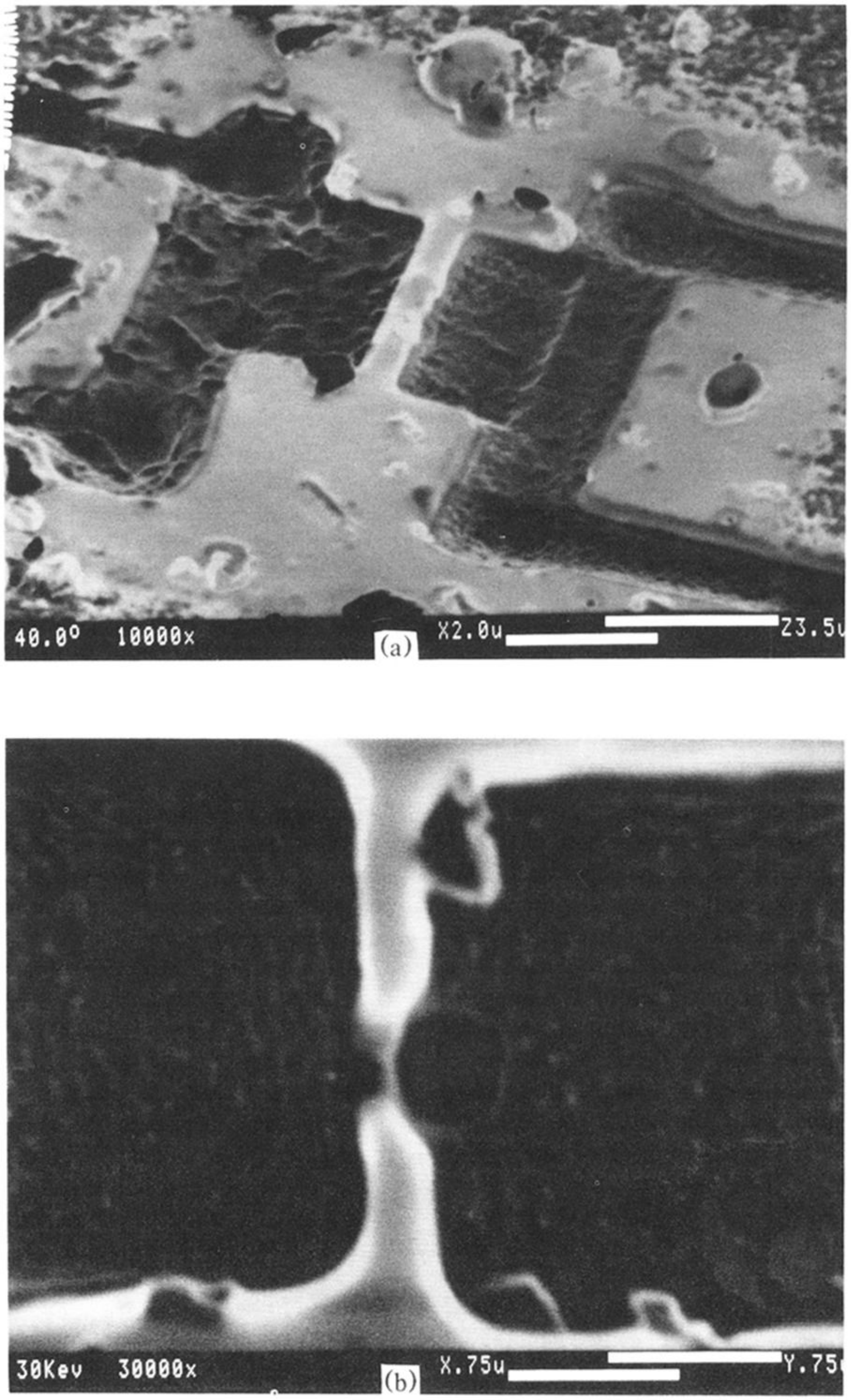

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