Laser processed channels of easy vortex motion in $YBa_2Cu_3O_{7-\delta}$ films

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Vortex dynamics in laser-patterned channels for easy motion in $YBa_2Cu_3O_{7-\delta}$ thin-film bridges has been investigated by electric transport and magneto-optical measurements. It has been found that the laser-writing technique, relying on selective deoxygenation of the illuminated areas of $YBa_2Cu_3O_{7-\delta}$ films, enables manufacturing of channels with the decreased field of the first penetration and pinning strength. Current-induced vortices confined in such channels move coherently within a limited temperature and bias ranges. Coherence in vortex motion was confirmed by the direct observation of self-resonant, Josephson-like current steps on the bridge current-voltage characteristics. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2128481]

Dissipation in current biased high-temperature superconducting bridges at zero magnetic field is due to the motion of Abrikosov vortices created by the self-field of the current. Vortices and antivortices nucleate at the opposite edges of the bridge, move toward the bridge center, and annihilate. Current-driven vortices wander between pinning sites along spontaneous channels of easy vortex motion.[1] In bridges with the width smaller than the effective penetration depth of the magnetic field λ_d, strong interactions between moving vortices may result in their coherent motion. On the other hand, in wide bridges, vortices nucleate and penetrate simultaneously at different positions along the bridge edges and nonhomogeneities and intrinsic pinning become important, leading to differences of vortex velocities along different channels. As a result, the coherence in vortex motion breaks down and large bridges behave like ordinary superconducting films. To ensure coherent vortex motion over a wide range of experimental conditions, one may fabricate artificial channels of easy vortex motion by selectively modifying pinning strength.[1–4] This can be achieved through modulation of the sample thickness, introduction of spatially ordered radiation defects, modulation of the film composition, or patterning of multilayer structures. Coherent vortex motion in bridges wider than λ_d can be also achieved by imposing artificial periodic pining structures.[5,6]

One of the hallmarks of the coherent vortex motion is the appearance of Josephson-like effects manifesting themselves as sharp kinks or steps on the current-voltage (I-V) characteristics of microwave-irradiated bridges.[5–8] The steps appear at voltages at which the inverse of the vortex time of flight across the bridge coincides with one of the harmonics of the incident microwave frequency. For strongly coherent motion, Josephson-like current steps appear even in the absence of external radiation. The, so-called, self-resonant steps appear at voltages for which the inverse of the time of flight matches the frequency of vortex nucleation.[6]

In this letter, we report on artificial channels of easy vortex motion, created in $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films by means of a laser-writing (LW) technique.[9] The LW process is fully reversible and nondestructive from the structural point of view, but it significantly alters superconducting and transport properties of YBCO films. We demonstrate the effectiveness of laser-patterned channels for vortex motion by means of magneto-optical (MO) imaging and transport measurements.

In our experiments, we employed 0.3-μm-thick epitaxial YBCO films grown using a conventional metalorganic chemical vapor deposition technique on single crystalline $LaAlO_3$ substrates.[10] The x-ray diffraction pole figures and θ-2θ scans (not shown) demonstrated that in our films there was a strong, inplane texture with the c axis perpendicular to the substrate. The as-deposited films exhibited zero resistivity at T_{c0}=91.4 K, a superconducting transition width ΔT_c =0.4 K, and the critical current density J_c of 1.5 MA/cm^2 at 77 K.[10]

The LW process was performed using green light from a continuous wave Ar-ion laser, plus a focusing microscope objective and a computer-controlled X-Y translational sample holder held in a nitrogen gas chamber. The laser beam, focused into a spot of $\sim$5 μm diameter, heated the illuminated part of the film to approximately 500 °C and activated the deoxygenation process. The actual LW was performed in two

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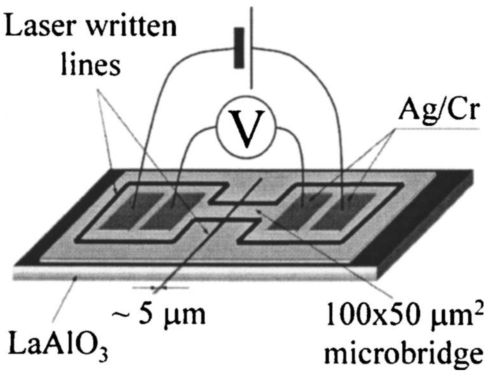

FIG. 1. Schematics of a superconducting device consisting of a laser inhibited YBCO bridge with a single 5-μm-wide, LW channel oriented perpendicular to the direction of the bridge axis.

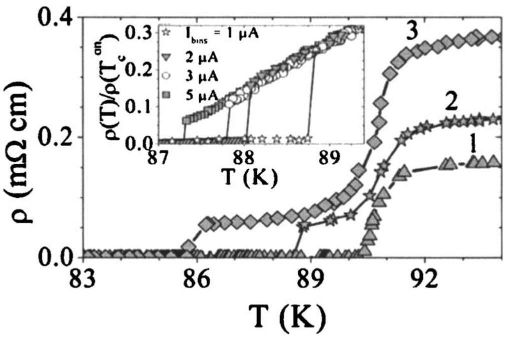

FIG. 3. Resistivity vs temperature dependences of a 50-μm-wide and 100-μm-long YBCO bridge with a single 5-μm-wide LW channel (2 - stars) and with two LW channels separated by 10 μm (3 - diamonds), measured with a dc current of 1 μA. Curve (1 - triangles) was recorded for a channel-free reference device. The inset shows evolution of the resistive tail with changing dc current for a single-channel device.

different modes. In the first, so-called optical inhibition mode,[11] the laser was operated at high power (typically 2.3–2.8 W) and the sample was translated at low velocity of 5 μm/s. Under the above conditions, we could obtain a total destruction of superconductivity along the LW path. This mode of operation was used to define the overall topology of our 50-μm-wide and 100-μm-long YBCO bridges embedded between large contact pads, as is shown in Fig. 1. In the second mode, the laser output power was much lower (0.3–0.6 W) and spot velocity was typically much higher ($\sim$50 μm/s), resulting in a controlled partial deoxidization of the film.[9] This latter LW mode was used to write across our YBCO bridges channels of easy vortex motion by locally depressing (but not destroying) the superconductivity (see Fig. 1).

The quality of pristine YBCO films and the effectiveness of the LW procedure were tested by magneto-optical (MO) imaging.[12] For this purpose, a ferrimagnetic garnet film with in-plane anisotropy was placed directly on top of the tested sample. The garnet was observed using a polarized-light microscope with nearly crossed polarizers. In such an arrangement, the intensity of the reflected light was proportional to the local magnetic induction perpendicular to the garnet, allowing direct observation of flux penetration into the YBCO film.

Figure 2(a) shows a MO micrograph image of the remnant field in a square contact pad, obtained after cooling the sample in the magnetic field of 600 G and turning off the field at 60 K. Bright areas correspond to high intensity of the local magnetic field. A defect-free film should exhibit a symmetric pyramid-like pattern of the remnant field with no additional bright areas, as we observe in Fig. 2(a). The above MO test allowed us to screen our YBCO films and only samples with no apparent defects were used in the final LW processing of channels.

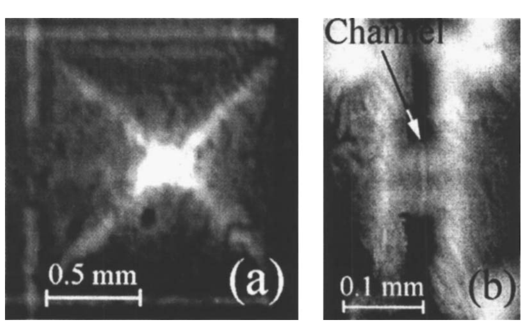

FIG. 2. (a) MO image of the remnant magnetic field in a square contact pad of the bridge structure obtained after cooling the sample in 600 G and turning off the magnetic field at $T=60$ K. (b) MO image of the penetration of 280 G magnetic field into the bridge area containing one LW channel. Bright areas in (a) and (b) correspond to higher intensity of a local magnetic field.

Figure 2(b) shows a MO image of the YBCO bridge containing one LW channel in the 280 G external magnetic field. We note that the field penetrates along the edges of the bridge and across the LW channel, leaving the remaining volume of the constriction practically flux free. Our MO observations revealed that the field of the first flux entry into the channel area is considerably smaller than the first penetration field into the bulk of the sample. This confirmed that LW procedure resulted in creation of channels with considerably decreased critical current and critical field.

Figure 3 shows the superconducting transitions for bridges with one (curve 2) and two (curve 3) channels, as well as of the unwritten, reference sample (curve 1). All structures were fabricated in the same YBCO film. As expected, formation of LW channels in our bridges resulted in the increase of the sample normal-state resistivity. Room-temperature resistivity of the bridge with a single LW channel was $1.48\rho_r$, while that of the bridge with two channels was $2.27\rho_r$, where $\rho_r=0.48$ mΩ cm is the resistivity of the pristine (reference) bridge. In addition, bridges containing channels show two-step superconducting transitions with pronounced, current-dependent low-temperature resistive tails. The temperature at which the resistivity tail drops to zero, T_{c0}, decreases with increasing bias current, as is shown in the inset in Fig. 3. At the same time, the temperature of the superconductivity onset $T_c^{on}=91.2$ K is not affected by the LW procedures, since it reflects the superconductivity onset in the banks of the bridge. The deoxygenation process in thin films, as opposed to single crystals, does not degrade as much the critical temperature as it depresses the critical magnetic field and enhances the penetration depth.[1,13] The decrease of the critical field decreases the vortex penetration field and the strength of intrinsic pinning, allowing for easier penetration and motion of self-field vortices in the channel area. The latter claim is corroborated by the measured temperature dependence of the critical current.

The $J_c(T)$ dependencies shown in Fig. 4 have been determined using a 10 μV voltage criterion. Under this criterion, the supercurrent in both the pristine and channeled-

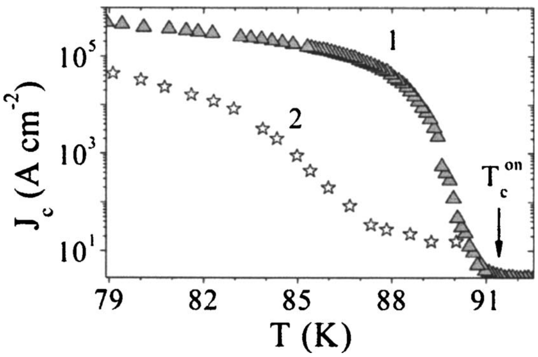

FIG. 4. Temperature dependence of the critical current density for a reference bridge (1 - triangles) and a bridge containing a single LW channel (2 - stars).

bridge samples appears at the temperature just below T_c^{on}. However, in the pristine bridge $J_c(T)$ increases faster and at 77 K is almost an order of magnitude larger than in the bridge with one LW channel. The shape of the $J_c(T)$ dependence is also affected. The $J_c(T)$ dependence, observed for the reference bridge, follows the behavior expected for a strong intrinsic pinning mechanism,[1] while the $J_c(T)$ of the single-channel bridge shows that despite increasing the concentration of oxygen vacancies, the LW deoxygenation process decreases the overall pinning strength.

Confinement of the dissipative vortex motion to our LW channel with reduced pinning and increased magnetic field penetration depth creates favorable conditions for coherent motion of vortices. Indeed, our experiments reveal a pronounced step structure in *I*-*V* curves of bridges with LW channels. We attribute these step structures to the self-resonant Josephson-like effect.[6] Figure 5 shows the *V*-*I* characteristics with step-like structures, measured for a single-channel bridge at two different temperatures close to T_c. The inset in Fig. 5 indicates the current onsets (arrows) of the coherent vortex motion. Strong interaction between moving vortices is a necessary condition for maintaining coherence in their motion. Therefore, a minimum number of vortices in the channel is required to fulfill this condition. Vortex density in the current-induced dissipative state is proportional to the current flow resulting in the steps appearing only above some minimum current I_{min}. Since the penetration depth λ_d increases with increasing temperature, the minimum number of vortices required for establishing the coherent-flow condition, and consequently the I_{min}, decreases with increasing temperature (see arrows in Fig. 5). It is well known that it is difficult to maintain coherent motion of vortices moving at high velocities.[5] Thus, the increase of the bias current leads to a gradual decrease of the amplitude of self-resonant steps and eventual disappearance of the step structure.

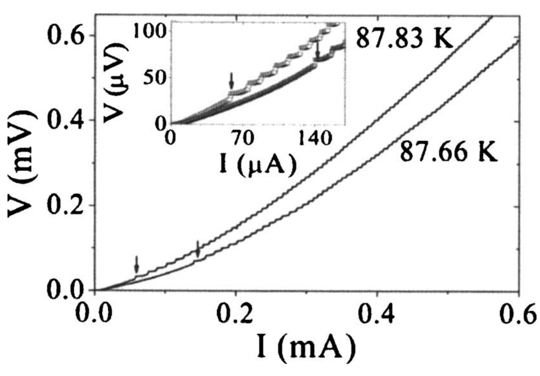

FIG. 5. *V*-*I* curves of a single-channel bridge at T=87.66 and 87.83 K in zero applied field. The arrows mark an onset of the Josephson-like step structures. Inset: low voltage part of the *I*-*V* curves on the expanded scale.

In conclusion, we have successfully fabricated artificial channels for vortex motion by means of the LW technique. Pinning in LW channels is strongly reduced, enabling coherent motion of vortices in a restricted temperature and bias range. The favorable conditions for coherent motion allow for the appearance of self-resonant quasi-Josephson steps even in the absence of periodic pinning in the channel.

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