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Current Distribution in Y–Ba–Cu–O Superconducting Microbridges Containing Π-Shaped Channel for Easy Vortex Motion

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A mixed state in dc-biased thin films of II-type superconductors realizes the Abrikosov magnetic vortices/antivortices, which are the result of the current-self magnetic field penetration into the film at temperatures lower than its critical temperature T_c. A nucleation of vortices/antivortices at the superconducting film's edges, their motion perpendicular to the direction of biasing current, and the annihilation in the film's center originates from a current dissipation in the superconductor and expresses itself in experiments as a dc voltage. This work reports on the results of simulation of current density in a 50 μm wide, 100 μm long, and 0.3 μm thick $YBa_2Cu_3O_{7-x}$ microbridges containing Π-shaped 5 μm wide single channel of easy vortex motion fabricated by means of laser-writing technique. Analyzing a two-dimensional-net of resistors and assuming that, due to the Meissner–Ochsenfeld effect, the magnetic flux penetration into superconducting film is nonlinear, we demonstrate that presence of a Π-shaped channel causes a non-homogeneous distribution of current in the microbridge.

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1. Introduction

Current dissipation in the mixed state of type-II superconductors is a measure of density of the Abrikosov magnetic vortices/antivortices and velocity of their motion under influence of the current-self produced Lorentz force given by $\boldsymbol{F}_L = \boldsymbol{J} \times \boldsymbol{B}/c$ [1]. Here $\boldsymbol{J}$ is the density of biasing current, $\boldsymbol{B}$ is the current-self produced magnetic inductance, and c is the speed of light. As the vortex motion determines the critical current density J_c of the superconducting film, research of superconductors emphasizes importance to control vortex motion using various techniques. In general, vortex velocity depends on the ratio between F_L, which pushes vortices to move, and the pinning force $F_p = J_c B/c$, which immobilizes them at pinning centers. The biasing current density predetermines the strength of F_L. The force F_p depends on the homogeneity of the superconducting thin film's composition [2], structure [3], and geometry (e.g., thickness and/or width) [4]. Thus, F_p can be modified using various methods: an introduction of columnar defects into the superconducting film [3], local variations in film's thickness or in chemical composition [2, 4], introduction of periodic magnetic barriers [5], etc. Recently, authors in Ref. [6] demonstrated that control of vortex motion in $YBa_2Cu_3O_{7-x}$ (YBCO) superconducting microbridges realizes through artificial channels for easy vortex motion manufactured by the means of a laser writing technique.

Light's interaction with the YBCO film, which is surrounded by nitrogen gas, causes its partial deoxygenation ($x \approx 0.2$) [7]. The channel, oriented perpendicularly to the biasing current [6, 7], exhibits weaker superconductivity (i.e., the lower T_c and J_c) in respect of the laser untreated film's areas [7]. Due to the Meissner–Ochsenfeld effect (i.e., state of an absolute diamagnetism), the current-self-produced magnetic field penetrates at the superconducting channel's edges in a form of the Abrikosov magnetic vortices (in one edge of the channel) and in a form of magnetic antivortices in another one. When the Lorentz force exceeds the pinning force (i.e. $J = J_c$), the vortices/antivortices start to move towards the film's center where they annihilate. Flux drift dissipates energy

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and induces a voltage drop. If the flux lines are tightly squeezed and strongly interact with each other, its drift expresses itself as a Josephson-like effect [8], i.e., voltage steps on the current–voltage (I–V) characteristics of superconducting microbridges in the range of temperatures from $0.95T_c^{on}$ to $0.97T_c^{on}$, where T_c^{on} is the critical temperature of the laser untreated superconductor) [5, 6, 9]. In the presence of microwave (MW) irradiated microbridges, the steps on I–V dependences 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 MW frequency [8]. For MW non-radiated microbridges, these steps appear at voltages for which the inverse of the time of flight of flux line matches the frequency of its nucleation [5].

This paper reports on the modeling results of current distribution in current-biased YBCO superconducting films containing 5 μm wide Π-shaped channels in which the Abrikosov vortices move coherently in absence of MWs. The I–V dependences of these microbridges demonstrate voltage steps in the narrow range of temperatures $T < T_c^{on}$ with almost the same voltage amplitude of the steps for comparatively large range of biasing current [9]. We use a two-dimensional (2D) net of resistors to imitate the electrical properties of the mixed-state of the channel area, as well as electric properties of laser untreated areas of the superconducting YBCO microbridge.

2. Samples and model of simulation

A current distribution at temperatures $T < T_c^{on}$ in the 0.3 μm thick, 50 μm wide, and 100 μm long epitaxial YBCO superconducting microbridge, which contains a 5 μm wide Π-shaped channel for easy vortex motion [9], was simulated by means of the 2D net of resistors schematically shown in Fig. 1. All resistors with a nominal value of 1 Ω (open symbols) imitate the laser untreated areas of the YBCO microbridge in the superconducting state, while the 100 kΩ resistors (closed symbols) represent the channel's area (i.e., the same superconductor, but in the mixed state). We have investigated two different cases of channel: the linear channel and the Π-shaped channel, with $h = 30$ μm and $w = 10$ μm (Fig. 1). Each of the resistors used in this model represents a 2×2 μm^2 area of the microbridge. To have a better understanding of the current distribution, the biasing current through the 100 kΩ resistors is kept the same in both cases of channel's geometry.

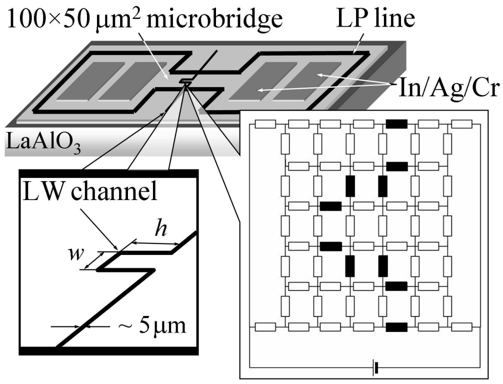

Fig. 1. Laser patterned $YBa_2Cu_3O_{7-x}$ microbridge with a 5 μm wide Π-shaped laser-written channel for easy vortex motion [5, 6, 9] and a schematic view of dc-biased two-dimensional net of resistors of nominal values 1 Ω (open symbols) and 100 kΩ (closed symbols) imitating electric properties of this microbridge with Π-shaped channel. In real scheme, each of the resistors replaces 2×2 μm^2 area of the microbridge.

3. Results and discussion

Figure 2 represents our simulation results of current distribution in our 2D net of resistors imitating the superconducting YBCO microbridge with a line-shaped channel for easy vortex motion. The current peaks appear due to the presence of corner-resistors (see electric scheme in Fig. 1) imitating the state of an absolute diamagnetism in the laser untreated parts of the microbridge biased at current $I \ll I_c$. At biasing conditions used in simulations, the I_c of the channel material is expected to be of several orders in magnitude lower than I_c of the laser untreated material at the same temperature $T < T_c^{on}$ [7]. Thus, in our case, the critical state is established only near edges of the microbridge (Fig. 2). This is in good agreement with the well-known behavior of the current-biased superconducting microbridge. In the case when flux has penetrated laser untreated areas and a critical state with $I = I_c$ has been established near its edges, the current flows over entire width of the microbridge in order to shield the flux-free central region of the microbridge.

Four additional current's peaks of lower amplitude appear due to the presence of the linear channel. It is worth

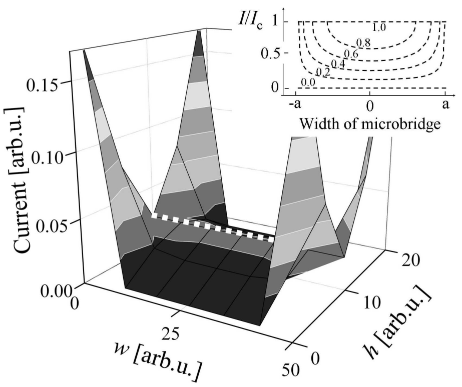

Fig. 2. Simulation results of current density in a 2D net of electric resistors (Fig. 1) imitating the $YBa_2Cu_3O_{7-x}$ microbridge with a linear channel. The white dashed line represents the channel's location. Inset: a qualitative view of the reduced current I/I_c distribution in our superconducting stripe at temperatures $T < T_c$ (data are taken from [10, 11]).

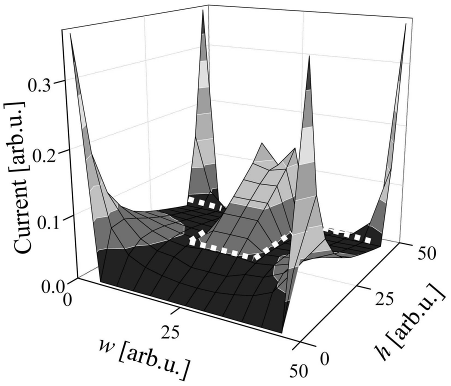

Fig. 3. Simulation results of electric current distribution in the 2D net of electric resistors, imitating the superconducting microbridge with Π-shaped 30 μm high and 10 μm wide channel. The white dashed line represents the channel's location.

mentioning that in all cases of our simulations the current flowing through the 100 kΩ resistors is the same, independent of these resistors' specific location in the 2D net.

In the case of Π-shaped channel with $h = 30$ μm and $w = 10$ μm (Fig. 3), the current distribution in the 2D net of resistors shows additional peaks in the mid section of the sample. Thus, the presence of the Π-shaped channel affects non-homogeneous current distribution not only on the edges of the microbridge, but also in its central, i.e., in the flux-free region. Our simulations show that 30 μm high and 10 μm wide channel can cause a significant increase (as much as 10 times) of the current density in local areas of the superconducting microbridge (Fig. 3). A local increase in J affects a non-homogeneous distribution of current-self produced magnetic field in the channel area and nonuniform density of the Abrikosov magnetic vortices in different segments of the Π-shaped channel. Assuming that $F_{\mathrm{L}} \sim B$, the drift velocity of the flux lines moving along different segments of the Π-shaped channel can also be nonuniform and direction of their motion perpendicular to the current direction depends on the homogeneity of channel's deoxygenation of the superconducting device.

4. Conclusions

We report on the results of simulation of current distribution in the superconducting microbridge with linear and Π-shaped channel for easy vortex motion by means of the 2D net of resistors. Our simulation demonstrates that a local J in the $YBa_2Cu_3O_{7-x}$ microbridge with channel for easy vortex motion depends on two factors. The first factor is the Meissner–Ochsenfeld effect of laser--untreated parts of the microbridge. Being absolutely diamagnetic, the laser-untreated areas resist the magnetic flux penetration, and, therefore, the field penetrates at the edges of the microbridge. The second factor is the very presence of the channel for easy vortex motion and its geometry. Varying the channel's geometry one can drive a local J into the central (flux-free) region of the microbridge for as much as 10 times. Both above mentioned factors are responsible for not only the nonuniform density of the Abrikosov vortices in the channel, but also for the nonuniform velocity of their motion along it.

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