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Current-Voltage Dependences of $YBa_2Cu_3O_{7-\delta}$ Superconducting Thin Films with Laser-Written Channel of Easy Vortex Motion

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$YBa_2Cu_3O_{7-\delta}$ superconducting bridges containing laser-performed single, Π-shaped channel have been investigated at temperatures below the material's critical temperature T_c by means of electronic transport measurements. It has been shown that the coherent vortex motion confined in a channel's Π-shaped horizontal-part of the superconducting bridge might be affected by the thermal unbinding of vortex-antivortex pairs (Kosterlitz-Thouless-Berezinskii phase transition). The coherent vortex motion was observed as the Josephson-like voltage "steps" in the nonlinear current-voltage dependences in a limited range of temperatures, bias currents, and the external magnetic fields. The amplitude of the voltage steps did not depend on the above listed experimental conditions. However, the number of vortex-antivortex pairs, their mutual interaction and ordering depended on the bias current, temperature, and the amplitude of the external magnetic field. Our experimental data, as well as relevant calculations are presented and discussed.

Keywords: superconductor, critical temperature, critical current, vortex motion, laser writing of channels, artificial channels, pinning force, Kosterlitz-Thouless-Berezinskii phase transition.

1. INTRODUCTION

A magnetic field of a dc bias current penetrates a superconducting microbridge in a form of Abrikosov magnetic vortices and antivortices at temperatures below the critical temperature T_c of the superconductor. These vortices and antivortices, each embracing the flux quantum $\Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}$ Wb, randomly nucleate at opposite edges of a microbridge, move towards bridge's center, and annihilate there. Condensation and nucleation of Abrikosov vortices and velocity of flux motion, which is resisted by viscous drag and by lattice inhomogeneities that pin this flux, are responsible for current dissipation and onset of an energy dissipative state (resistive state) in the superconducting film at zero external magnetic field and temperatures below T_c. The onset of the energy dissipative state, caused by flux motion, restricts the performance of superconducting devices [1] and initiates larger amplitude of electronic-noise [2] or even affects a burning of devices [3].

The motion of Abrikosov magnetic vortices is called "coherent" when they are tightly squeezed and strongly interact between each other [4], or when they interact with a spatially-periodic pinning landscape [5]. Josephson-like effect-appearance of voltage steps on the current-voltage ($I–V$) dependences of microwave irradiated bridges [6] – is the hallmark of the coherent vortex motion. The steps appear with presence of microwaves 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 radiation and even with absence of microwaves, when the inverse of the time-of-flight of vortices across the half-width of the bridge matches the frequency of the vortex nucleation at the bridge's edges [5].

In thin films of the superconducting cuprates, it is believed that there is a population of pairs of vortices-antivortices even at zero applied current or zero external magnetic field. In the presence of a current, the pairs are unbind. The flux lines experience a Lorentz force, which moves vortices and antivortices towards opposite edges of the superconducting microbridge and therefore the microbridge responses voltage to an applied current. According to the Kosterlitz-Thouless-Berezinskii (KTB) theory, the Abrikosov magnetic vortices and antivortices should condensate into bound pairs at low temperatures at which the attractive potential between the vortex and antivortex in the pair is logarithmic [7]. In presence of bound pairs, there is no big change in sample's resistivity versus temperature ($\rho(T)$) dependence, but instead there would be a stronger response observed in the $I–V$ dependence, since increasing current can unbind weakly bound vortex-antivortex pairs [8].

It is worth noting that a presence of KTB transition in two-dimensional (2-D) cuprate superconductors is still questionable. Some works report on no evidence for vortex unbinding even in unit-cell-thick films of YBCO [9]. Some other works confirm a presence of the 2-D vortex fluctuations [10] and claim that unbinding of vortex-antivortex pairs results not only change in $I–V$ dependences of the cuprate superconductors but also

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affects the shape of the resistive transition from their superconducting state to the normal state [11].

This work reports our results of the *I–V* dependences studies of $YBa_2Cu_3O_{7-\delta}$ (YBCO) superconducting thin films with laser performed, Π-shaped channel of easy vortex motion. The Josephson-like voltage steps, observed on the *I–V* characteristics of the superconducting microbridges, confirm the coherent vortex motion in the channel parts oriented perpendicularly to the current biasing our samples. It has also been demonstrated that the voltage steps can be used as indicators of the superconducting properties versus temperature, biasing current, and the external magnetic field applied to the channeled superconducting bridge.

2. EXPERIMENTAL

2.1. Laser patterning of the superconducting devices

Our 0.3-μm-thick, epitaxial YBCO films have been grown on $LaAlO_3$ substrates by a metaloorganic chemical vapor deposition (MOCVD) technique. The X-ray diffraction pole figures and θ–2θ scans (not shown) demonstrated that the films had in-plane texture with the *c*-axis oriented perpendicular to the substrate. The as-deposited films exhibited zero resistivity at $T_{c0} = 91.4$ K, a superconducting transition width of $\Delta T_c = 0.4$ K, and critical current density $J_c(78\text{ K}) = 1.5 \times 10^6$ A/cm^2.

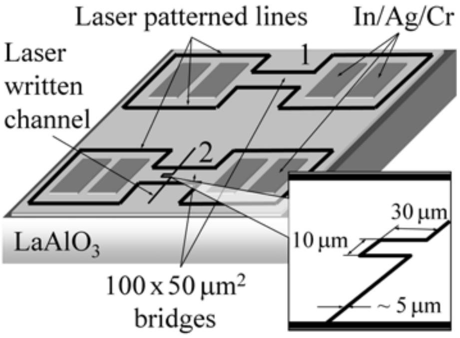

Fig. 1. 100-μm-long, 50-μm-wide, and 0.3-μm-thick YBCO bridges laser patterned from a single YBCO film which was deposited onto $LaAlO_3$ substrate: 1 – the pristine bridge and 2 – the bridge with LW channel for easy vortex motion

The films were patterned [12 – 13] using a green-color beam of a continuous wave Ar-ion laser. For laser patterning (LP) procedures, the film was attached to a computer-controlled *X-Y* translation stage and placed in a nitrogen gas atmosphere. The laser power of 2.3 W – 2.8 W resulted in full deoxygenation of the illuminated areas of superconductor, when the YBCO film was moved perpendicularly to the laser beam direction with a velocity of 5 μm/s. The width of the LP line was limited by the size of our laser beam spot focused using a microscope down to ~ 5 μm in diameter. In this way, our samples were patterned into a set of six, 50-μm-wide × 100-μm-long, bridges with large contact areas (sample 1 in Fig. 1).

Lower power of 0.3 W – 0.6 W of the laser radiation and scanning velocity of 50 μm/s, was used for laser writing (LW) procedure of a Π-shaped, 5-μm-wide channel for easy vortex motion (see sample 2 in Fig. 1).

2.2. Measurement setup

Resistivity vs. temperature and *I–V* curves were measured in a 4-probe arrangement at dc bias current. The tested YBCO sample was thermally anchored to a Cu holder inside a He-gas-cooling cryostat.

The *I–V* dependences versus temperature were collected without and with a presence of an external magnetic field. The magnetic field was produced by the Helmholtz coils which were separated at a distance equal to the radii of the coil, and placed symmetrically along the common axis going also through the centre of the tested sample and oriented perpendicularly to the surface of the YBCO film. The amplitude of the external magnetic field could be varied was controlled by a dc current source in range of $\mu_0 H = 0\text{ mT} \div 7\text{ mT}$.

3. RESULTS AND DISCUSSION

3.1. Magnetooptical measurements

The quality of the pristine sample and the LW effectiveness were tested by magneto-optical measurements. The results of measurements demonstrated that the magnetic field of the first flux entry into the channel area was considerably smaller then the first penetration field into the bulk of the sample [14]. The LW channel exhibited considerably decreased critical magnetic field when compared with the critical magnetic field measured in the LW-non-modified YBCO film areas. A depression of the critical magnetic field in the deoxygenated channel resulted in a decrease of the overall pinning strength what facilitated easy motion of Abrikosov magnetic vortices in the LW–channel [15].

3.2. Resistivity measurements

Both our pristine-bridge (dashed line in Fig. 2) and the LW-bridge (symbols) have a metallic like resistivity versus temperature dependence with same residual resistivity ratio $\rho(300\text{ K})/\rho(100\text{ K}) = 2.74$ and superconductivity onset temperature $T_c^{on} = 91.2$ K (Fig. 2). The superconductivity onset temperature, was not influenced by our LW procedures, as it reflected the properties of the banks of the bridge untreated by LW. However the room-temperature resistivity of the LW-bridge $\rho_{LW}(300\text{ K}) = 717.5$ μΩ cm, appeared to be almost 1.5 times higher than that one of the pristine-bridge.

The LW-bridge exhibited a low-temperature resistive tail. As it is demonstrated in inset in Fig. 2, the resistive tail is current-dependent. For that particular reason the zero-resistivity temperature T_{c0} of the LW-bridge decreases from 88.6 K down to 87.3 K, when current increases from 1 μA to 5 μA.

There is also a residual resistivity tail remaining even below temperature T_{c0}. The resistivity of this tail ρ_D depends on temperature, but does not depend on bias current. Inset in Fig. 2 demonstrates that the relative resistivity $\rho_D(T)/\rho(T_c^{on})$ dropped below the resolution limit of our measurement setup at temperatures $T \leq 86.7$ K.

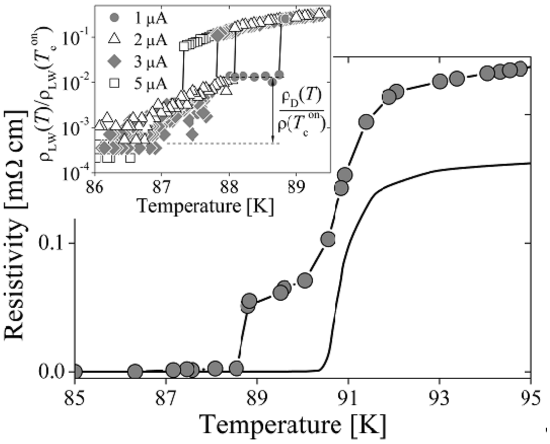

Fig. 2. The resistivity versus temperature dependence of a LW-bridge containing a 5-μm-wide channel for easy vortex motion (symbols) and same dependence for pristine sample at 1 μA dc bias. The inset: semilog plots of the normalized resistivity for the LW-bridge at 1, 2, 3, and 5 μA bias currents

The increased room temperature resistivity was associated with channel incorporation into LW-bridge structure. Then, assuming that the room temperature resistivity of Π-shaped channel was $\rho_{ch} \sim 2.3$ mΩ cm, from experimental data in [16], we could estimate the oxygen depletion degree in the LW channel area as $\delta \sim 0.2$. This result is consistent also with characteristic critical temperature of the LW- material as $T_{c0} \sim 86$ K [16].

3.3. Current-voltage dependences

The nonlinear *I-V* curves of the LW-bridge exhibit clear steps (Fig. 3) in the temperature range between T_{c0} and T_c^{on}. Appearance of the voltage steps on the LW-bridge *I-V* curve can be attributed to the coherent vortex motion and quasi-Josephson effects [5]. The steps appear at bias currents higher than the critical current of the YBCO sample I_c, which was determined using a 10-μV-voltage criterion. The "voltage height" of any of step at a given temperature does not increase with the bias current increase. For example, at $T = 87.5$ K the averaged step's height of ~7.8 μV appears to be constant up to $n = 123$ (setup resolution), while the bias current increases from 0.2 mA up to 0.6 mA. The later indicates that the Lorentz force does not change in the parts of the Π-shaped channel oriented perpendicularly to the biasing current direction. The current is mainly located in the sidewalks or focused in the samples center, when biasing current flows (see Fig. 1) from the left to the right and from the right to the left, respectively, out-running the parts of the LW-channel oriented perpendicularly to the biasing current direction.

If this is the case, then the subsequent steps observed on the *I-V* characteristics should be associated with the entrance of additional vortex-antivortex pairs into the channel of the LW-bridge. The number of vortex-antivortex pairs in the channel of the LW-bridge was estimated from the ratio of dissipation (dynamic resistance) in the vicinity of the n^{th} and $n^{th}+m$ step. Results of this estimation at bias current $I = 0.04$, 0.25, 0.46, and 0.7 mA are plotted in Fig. 4. Assuming that the density of vortex pairs increases with temperature and the bias current increase, the temperature dependence of number of vortex pairs in the LW cannel should be inversely proportional to the temperature dependence of the condensation energy of a flux line per unit length given as [17]:

$$N \sim \frac{1}{\varepsilon(T)} = A\frac{4\pi\mu_0\lambda_{a-b}^2(T)}{\Phi_0^2}, \qquad (1)$$

here μ_0 is the permeability of free space, and

$$\lambda_{a-b}(T) = \lambda_{a-b}(0)\,(1 - T/T^*)^{-1/2} \qquad (2)$$

is the temperature dependent magnetic field penetration depth along $a-b$ plane of a YBCO superconductor at $T \sim T_c^{on}$, with $\lambda_{a-b}(0) \sim 130$ nm [18], and A – free parameter.

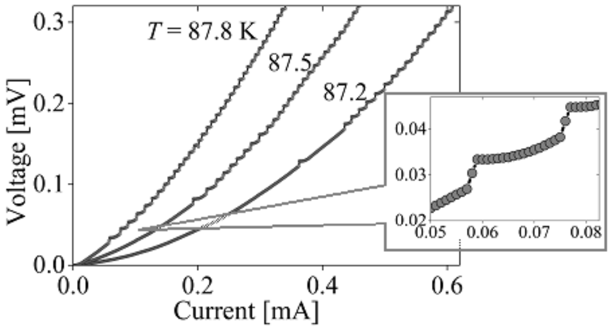

Fig. 3. Voltage *vs.* bias current dependences at $T = 87.2$, 87.5, and 87.8 K of the LW-bridge at the zero external magnetic field. The inset shows the quasi-Josephson step attributed to entrance of additional vortex – antivortex pair into the channel area at temperature $T = 87.8$ K

Fig. 4 (dashed lines) demonstrates the fitting results of $N(T)$ dependences to the experimental data. In our calculations, we used one fitting parameter A (see eq. 1), which increased from 3×10^{-12} to 2×10^{-10} for the biasing currents ranging from 0.04 mA to 0.7 mA. Our fitting gave the onset temperature of the superconducting state in the superconducting sample as $T^* = 89.3$ K. This temperature has been identified as the same in range of ±0.6 K for all $N(T)$ curves shown in Fig. 4 and one is more consistent with superconductivity onset temperature $T_c^{on} = 91.2$ K of the LW non-treated YBCO material. This result confirms our assumption that oxygen depletion from the LW film is not homogeneous. The activation energy of atomic oxygen diffusion perpendicularly to the Cu-O planes is an order of magnitude higher than that one of the direction parallel to the Cu-O plane. Therefore, the most pronounced oxygen depletion is expected to occur at the YBCO film's surface and temperature T^* is related with the superconducting properties of the material located in the film's bottom.

Calculated curves fit better the region of higher temperatures of the $N(T)$ curves (Fig. 4). Much worse fitting results have been obtained in the temperature range between 84.5 K and 86.8 K at higher bias currents of 0.46 mA and 0.7 mA.

The number of moving vortices at the zero external magnetic field depends on the current-self produced magnetic field: $N = B/\Phi_0$, therefore, a decrease in number of vortices that was observed by us experimentally (Fig. 4) might be associated with a KTH transition in the LW-channel of the YBCO film at $T_{KTB} \sim 86.1$ K [15]. If this is the case, the unbinded vortex-antivortex pairs can affect a decrease of the number of current-self magnetic field produced Abrikosov vortices. Current unbinded vortex-antivortex pairs when current-self produced Lorentz force for unbind pairs exceeds pinning force and vortices start to move towards edges of the superconducting bridge. The appearance of bound pairs affects a squeezing of the magnetic lattice of the current-self magnetic-field produced Abrikosov vortices. A presence of unbinded pairs speeds up vortex annihilation before vortices reach their annihilation line in the center of the bridge.

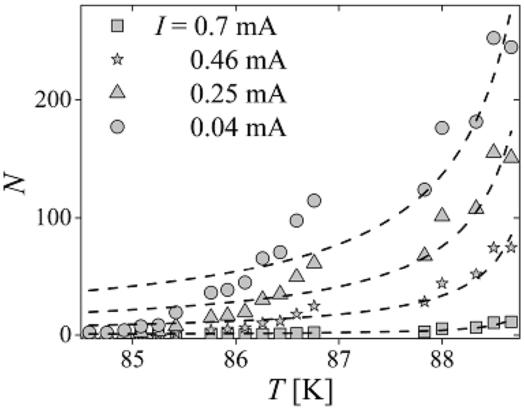

Fig. 4. Number N of vortex-antivortex pairs versus temperature estimated from the I–V dependences of the LW-bridge at various bias currents and zero external magnetic field. Dashed lines represent best fit of experimental data to inverse of condensation energy of a flux line vs. temperature

In the case of coherent vortex motion (strongly squeezed magnetic lattice) in the LW-bridge, the KTB transition can decrease vortex density, what is consistent with our fitting results obtained at lower temperatures (Fig. 4). However, change squeezing of magnetic lattice of vortices should turn-off temporarily the coherent vortex motion in the LW-channel. When the Lorentz force is strong enough to unbind all vortex-antivortex pairs, the coherent motion in the channel should recover. This property is clearly seen in the I–V dependence, measured at $T = 87.2$ K, where the voltage steps in the LW-channel temporarily disappear in a range of the bias currents between 0.37 mA and 0.44 mA and then again appear at currents $I > 0.44$ mA.

Fig. 5 demonstrates the I–V dependences of the LW-bridge measured at $T = 88$ K in presence of the external magnetic field $\mu_0 H_{\mathrm{ext}} \leq 6.7$ mT. The stepped I–V dependence showed slight decrease of the bridge's resistivity when the external magnetic field was increased up to $\mu_0 H_{\mathrm{ext}} \leq 1.3$ mT. However, when the magnetic field exceeded 1.3 mT, the resistivity of the LW-bridge suddenly jumped for the factor of almost two as compared to the starting value and again monotonically decreased when the external magnetic field increased in range of $1.3\ \mathrm{T} < \mu_0 H_{\mathrm{ext}} \leq 6.7$ T.

The application of the external magnetic field affects amplitude of current–self produced magnetic field. As for vortex motion in the LW-channel, the external magnetic field shifts the vortex annihilation line from the sample's center towards one of its edges. Then, vortex and antivortex each are exerted by Lorentz force of different strength and, therefore, both are moving with different velocities towards their new annihilation line. When the external magnetic field exceeds the current-self-produced magnetic field in the LW-channel, the annihilation line of vortices appears to be located out of the 50-μm-wide YBCO bridge. This might cause abrupt change in resistivity of the LW-sample. According to our estimations [19] of the current-self produced magnetic field, a value $\mu_0 H_{\mathrm{ext}} = 1.3$ mT (see Fig. 5) is consistent with that one of current-self produced magnetic field in the LW-sample.

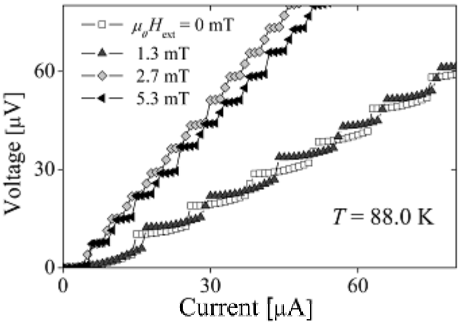

Fig. 5. Voltage *vs.* bias current dependences at temperature $T = 88$ K of the LW-bridge at various external magnetic fields $B_{\mathrm{ext}} \leq 5.3$ mT

The thermally activated flux motion in high-T_c superconducting cuprates depends on change in energy of flux activation. It has been experimentally shown that the activation energy W depends on the external magnetic field as $W = f(\mathrm{H}^{-1/2})$ [20]. Following [20], an increase for 2 times of the external magnetic field in the oxygen deficient ($\delta \sim 0.2$) LW-sample should result from a decrease for 2 times of vortex pinning energy. Obviously, this property can be easy verified at comparatively low currents (low heating effect) in superconducting samples with higher values of pinning force. However, in the LW-sample even in the case of weak currents (see Fig. 5), the pinning force is expected as negligibly small and changes in force's amplitude most probably would be difficult to distinguish in the I-V dependences.

Finally, if the KTB transition is present here, then unbinding of vortex-antivortex pairs should effect motion of vortices in the LW-channel and modify the I-V dependences of the LW-bridge. This effect might also be related to small changes of the I-V dependences measured in the presence of the external magnetic field.

The research of magnetic-field impact on vortex motion in the LW-channel of YBCO thin film microbridges is still in progress. The main purpose of these experiments is to prove a presence/absence of the KTB transition in the LW superconducting YBCO material and to demonstrate possibilities for control easy motion of Abrikosov magnetic vortices in the artificial channels by the external magnetic field.

CONCLUSIONS

We have observed a quasi-Josephson effect produced by coherently moving vortices in the horizontal parts of the Π-shaped artificial channel incorporated into the YBCO superconducting bridge. The channel was produced by laser writing (LW) technique, which led to partial oxygen removal from laser-activated area of the YBCO bridge. The stepped-like *I–V* dependences, observed in LW-bridges, appear in a limited range of temperatures and biasing currents, showing that Abrikosov magnetic vortices moving coherently in the LW-channel of the YBCO film. The change in temperature, biasing current and the external magnetic field can modify the stepped-like *I–V* dependences of the LW-bridge demonstrating possibilities of control of vortex motion depending on mentioned above external parameters.

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