Proceedings of the 14th International Symposium Ultrafast Phenomena in Semiconductors, Vilnius 2010

Investigation of Vortex Density in Laser-Written Π-Shaped Channel of YBCO Bridge by Means of *I–V* Dependences

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A current-self-induced magnetic field H_j, such that $H_{c1} < H_j < H_{c2}$ at $T < T_c$, penetrates a thin-film, type-II superconductor forming the Abrikosov magnetic vortex–antivortex pairs in the film's areas of weakest superconductivity. Our atomic force microscopy and scanning tunneling microscopy images confirm that in 50 μm wide, 100 μm long and 0.3 μm thick $YBa_2Cu_3O_{7-x}$ superconducting devices magnetic flux penetrates first into a 5 μm wide, Π-shaped and partially deoxygenated ($x \approx 0.2$) channel for easy vortex motion. When the Lorentz force overcomes pinning force in the channel, the flux starts to move and its drift dissipates energy inducing dc voltage. This work reports on the density of coherently moving vortices along the channel vs. temperature in range from $0.93T_c$ to $0.97T_c$. Our simulations show that the vortex density vs. temperature dependence extracted from *I–V* measurements of our devices follows the temperature dependence of magnetic field penetration depth and the coherence length of the superconductor.

PACS: 74.78.−w, 74.25.Sv, 74.25.F−, 74.25.Wx

1. Introduction

The critical current I_c of the superconductor is defined to be the current that destroys the superconductivity of the material. The I_c imposed by the current-self-induced critical magnetic field H_{c1} is called current of depairing of the Cooper pairs in the superconductor and can be expressed as: $I_d(T) \sim \Phi_0 A/[3\sqrt{3}\mu_0\lambda^2(T)\xi(T)]$. Here $\Phi_0 = h/2e$ is the flux quantum, A is the superconductor's geometry related parameter, μ_0 is the permeability of the vacuum, $\lambda(T)$ is the temperature dependent magnetic field penetration depth into superconductor, and $\xi(T)$ is the superconducting coherence length of the superconductor [1]. Experimentally measured I_c of the superconducting film cannot be associated with the depairing current. The reason is that the current-self produced magnetic field penetrates into type-II superconductor in a form of magnetic vortex–antivortex pairs, each carrying Φ_0 [2], creating a so-called mixed state of the material. The vortex, wich diameter is of order of 2ξ, expresses itself a circular current flowing around the normal core and producing a magnetic field of the same direction as that of the current-self-produced magnetic field [1, 2].

The electric current applied to the superconducting film creates the Lorentz force, which pushes flux lines perpendicularly to the current's direction from film's edges towards its center. Flux lines start to move when the Lorentz force exceeds strength of the pinning force in the film (i.e. at $I = I_c$). Flux drift dissipates energy and induces a voltage drop.

If vortices are tightly squeezed and strongly interacting with each other, the vortex motion expresses itself as a Josephson-like effect exhibiting voltage steps on the current–voltage (*I–V*) characteristics. The steps appear at voltages for which inverse of the time of flight of flux line matches the frequency of its nucleation [3].

We report our measurement results of the vortex density motion vs. temperature in current-biased $YBa_2Cu_3O_{7-x}$ (YBCO) microbridges, containing the laser-written (LW) channels. Being partly deoxygenated ($x \approx 0.2$), the channel exhibits lower H_{c1}, as compared with laser untreated areas of the microbridge [4]. Thus, the current-self-produced first magnetic field penetrates

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only the area of channel and forces flux lines to move along it.

2. Sample and experimental background

For laser-patterning of devices we used 0.3 mm thick epitaxial YBCO films grown by a conventional metal-organic chemical vapor deposition (MOCVD) technique [5] on $LaAlO_3$ substrates. The films were characterized by the superconducting transition's onset $T_c^{on} = 91.2$ K, a width of the transition $\Delta T_c = 0.4$ K, and critical current density $J_c(77 \text{ K}) = 1.5$ MA/cm^2. A green light from an Ar laser, was focused by a microscope into a light spot diameter of 5 μm and was used for laser-patterning of 50 μm wide and 100 μm long YBCO devices (see Fig. 1). Heated areas of the film surrounded by nitrogen gas were fully deoxygenated converting them into an insulator. Details are given in Ref. [4]. The LW procedure of Π-shaped channel was performed by a 5 μm wide light spot, which heated the film up to ≈ 500 °C and formed only partly deoxygenated areas ($x \approx 0.2$) [4]. Our atomic force microscopy (AFM) and scanning tunneling microscopy (STM) (see Fig. 1) analysis confirmed that channel's material was of lower electric conductivity and of lower critical magnetic field H_{c1} [4, 6]. Thus, at temperature $T = 88.2$ K $< T_c$ and biasing current $I \geq 10\mu$A $\approx I_c$ (curve 2, Fig. 1), magnetic vortices are tightly squeezed in the channel and move coherently. This result confirms that voltage steps are related only with the presence of the channel in our device [there were no voltage steps on the I–V curve of the reference device (curve 1)], indicating an entrance of additional vortex–antivortex pairs into a channel. The "voltage height" of the step U_{st} at a given temperature does not depend on biasing conditions, e.g. at $T = 87.5$ K the averaged $U_{st} \approx 7.8$ μV remains constant when biasing current increases as much as 4 times [6]. This work investigates the dependence of the density of the Abrikosov magnetic vortices moving along the LW channel of the superconducting YBCO device vs. its temperature and biasing conditions.

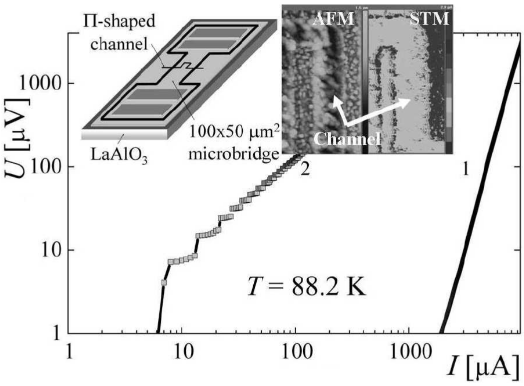

Fig. 1. Current–voltage dependence of a laser-patterned $YBa_2Cu_3O_{7-x}$ superconducting device containing a 5 μm wide, laser-partly deoxygenated ($x \approx 0.2$), Π-shaped channel for easy vortex motion (2) and channel free (reference) device (1) at $T = 88.2$ K. Insets: (left) the device's geometry and (right) the AFM and STM images (at $T = 300$ K) of the Π-shaped channel.

3. Results and discussion

Assuming that creation of additional flux lines in the channel area of our device gives additional voltage steps on the I–V curve [6], the number of vortex–antivortex pairs N in the channel can be estimated from ratio of the current dissipation in vicinity of the n-th and n-th $+ m$ step. At a given biasing current and temperature of the superconductor, $N = U/U_{st}$, where U is the experimentally measured voltage on the I–V dependence at a given temperature (Fig. 1) and U_{st} is the averaged voltage of the single step, calculated using the same I–V dependence. Using the above mentioned method, we calculated the current I_{40} at which the self-magnetic field can create 40 vortex–antivortex pairs in the channel vs. temperature dependence (Fig. 2, curve 1). Increasing temperature, the I_{40} decreases exhibiting two linear slopes, both crossing at temperature $T \approx 86.8$ K, which was prior to our work determined as the zero-resistance critical temperature of the channel material: $T_{c0} = 86.7$ K [4, 6]. Presence of two slopes in the $I_{40}(T)$ dependence indicates that the vortex number in the channel vs. temperature dependence $N(T)$ in our YBCO microbridge with the LW channel is determined by two different physical processes.

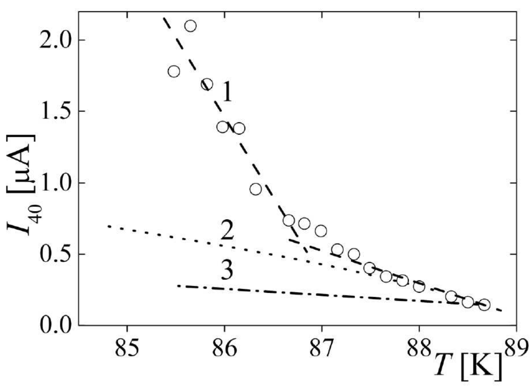

Fig. 2. The current I_{40}, whose self-magnetic field creates 40 pairs of magnetic vortices–antivortices in the YBCO device's Π-shaped channel for easy vortex motion, vs. device's temperature extracted from experimental I–V dependences (1), estimated using vortex condensation energy vs. temperature $\varepsilon(T)$ (2) and estimated using a relationship $\Phi_0 = B(T)S(T)$ (3) dependences, respectively.

The $N(T)$ dependence is inversely proportional to the temperature dependence of the vortex condensation energy of a flux line per unit length of the superconductor: $\varepsilon(T) = \Phi_0^2/4\pi\mu_0\lambda_{a-b}^2(T)$, where $\lambda_{a-b}(T) = \lambda_{a-b}(0)(1 - T/T_c)^{-1/2}$ is the temperature dependent depth of the magnetic field penetration into the a–b crystalline plane of the YBCO with $\lambda_{a-b}(0) = 130$ nm at temperature $T \to 0$ [7]. Figure 2 demonstrates our results of I_{40} calculations using $\varepsilon(T)$ dependence (see the dotted line 2). The linear slop of $I_{40}(T)$ at higher temperatures has similar trend as I_{40} calculated using the $\varepsilon(T)$ dependence. The latter indicates that at higher temperatures, ranging from $0.95T_c^{on}$ to $0.975T_c^{on}$, the $N(T)$ behavior can be explained by the temperature-dependent change in vortex condensation energy in our YBCO microbridge [8]. However, at lower temperatures ($0.94T_c \leq T \leq 0.95T_c$), $I_{40}(T)$ dependence appears to be different and the simulation result does not fit the experimental curve.

Temperature-dependent spacing of 40 vortex–antivortex pairs in the channel area affecting $N(T)$ dependence can be estimated using a simple relationship $\Phi_0 = BS\cos\alpha = 2.07 \times 10^{-15}$ Wb, where B is the magnetic field induction perceived by a single magnetic flux, S is the superconductor's area seized by the single flux, and $\alpha = 90°$ is the angle between B and normal of S. Assuming $B \sim I$ (here I is assumed to be equal in all segments of the Π-shaped channel), $S(T) \sim \xi(T) = \xi_{a-b}(0)(1 - T/T_c)^{-1/2}$ with $\xi_{a-b}(0) = 2.1$ nm [9] and taking into consideration the fact that coherently moving magnetic vortices are arranged into a magnetic lattice and spaced at a distance $d = \sqrt{2\Phi_0/\sqrt{3}B}$, we calculate the same $I_{40}(T)$ dependence and plot it in Fig. 2 as the dash-dotted line 3. These results let us to conclude that experimental $I_{40}(T)$ dependence in the range of temperatures $0.94T_c \leq T \leq 0.95T_c$ cannot be explained by temperature-dependent spacing of vortices in the channel area.

Most probably the two different slopes in $I_{40}(T)$ dependence are caused by the pinning force vs. temperature dependence in the channel area. Our tested YBCO films are characterized by spiral-like dislocations [10] exhibiting strong pinning force for moving vortices in the channel area. Due to the proximity effect at low temperatures, i.e., at $T < 86.7$ K [4], the residual electric resistance of grow defects in our superconducting films decreases. This causes a decrease in pinning efficiency, and an increase in number N of coherently moving magnetic flux lines in the channel. Thus, in the range of higher temperatures, i.e., $0.95T_c^{on}$–$0.975T_c^{on}$, the $I_{40}(T)$ dependence is characterized by the temperature dependent pinning of the grow defects and at temperatures $0.94T_c \leq T \leq 0.95T_c$ the temperature-dependent overall pinning caused by extended defects of oxygen vacancies in the superconducting channel of the YBCO microbridge.

In conclusion, a density of the Abrikosov magnetic vortices vs. temperature and biasing conditions were investigated in $YBa_2Cu_3O_{7-x}$ microbridges with a Π-shaped channel for easy vortex motion. Our results confirm that the first magnetic flux of the current-self-produced magnetic field penetrates the channel, initiating coherent vortex motion. The current, which creates some fixed number (e.g., 40) of vortex–antivortex pairs in the channel, decreases with the temperature increase, exhibiting two linear slopes. A presence of these slopes is related with a step-like change in the temperature-dependent pinning properties in the microbridge at $T \leq 86.8$ K.

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