Investigation of Density and Velocity of Abrikosov Vortices in $YBa_2Cu_3O_{7-x}$ Superconducting Thin Films with a Laser-Written Channel for Easy Vortex Motion

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Received 19 November 2010; accepted 22 April 2011

The 0.3-μm-thick, 50-μm-wide and 100-μm-long $YBa_2Cu_3O_{7-x}$ superconducting bridges with a laser-written, single, Π-shaped channel have been investigated by means of electronic transport measurements at temperatures below the onset of the bridge's superconducting transition temperature. Our results demonstrate that the coherent vortex motion confined in the Π-shaped channel can be used for determination of both the density and velocity of Abrikosov magnetic vortices in the channel. The coherent motion of Abrikosov vortices expresses itself as Josephson-like voltage steps, observed on the current-voltage characteristics of our microbridges, measured at zero external magnetic field, in a limited range of temperatures and bias currents. The steps' amplitude corresponds to the entrance of an additional vortex-antivortex pair into the channel's area and change in the vortex velocity. This amplitude also affects the increase of the Lorentz force for energy dissipative drift of the magnetic flux in the channel, but it does not increase, however, with the increase of the biasing current. We present and discuss the results of experimentally measured and calculated energy dissipation, which originated from variations in the vortex density and velocity when the vortices are moving along the channel of the superconducting bridge.

Keywords: II-type superconductor, thin film, critical temperature, critical current, easy vortex motion, energy dissipation, channel for easy vortex motion, Lorentz force, pinning force.

INTRODUCTION

If, at temperatures lower than the superconductor's critical temperature T_c, the applied magnetic field H_J generated by the applied dc bias current is larger than the first critical magnetic field of a superconductor H_{c1} it penetrates a superconducting film in a form of quantized magnetic flux lines (magnetic vortices), each embracing a single flux quantum $\Phi_o = \frac{h}{2e} = 2.07 \times 10^{-15}$ Wb [1]. Due to the Meissner-Ochsenfeld's effect (i.e., effect of absolute diamagnetism) [2] the current-self-produced $H_J > H_{c1}$ penetrates edges of the superconducting film in a form of Abrikosov vortices at one edge and antivortices at the another one. Simultaneously, the applied electric current creates Lorentz force F_L, which forces magnetic flux lines to move from film's edges towards its center [3]. In the ideal case of a type-II superconductor, the energy dissipation happens at any biasing condition, because F_L in the superconductor acts on all magnetic flux lines, as on a "solid lattice" of magnetic vortices, forcing them to move all together [4].

However, in real type-II superconductors, the pinning force F_P resists the flux drift tending to stop flux lines at pinning centers. The most effective pinning centers are large-size defects, point defects [5], grain boundaries [6], screw dislocations [7], etc., and tend to pin individual flux lines or resist the motion of the whole "lattice" of magnetic vortices in the film. However, in the case of $F_L \geq F_P$, the Lorentz force randomly nucleates vortex-antivortex pairs at opposite edges of the film, pushing them perpendicularly to the current direction towards film's center. A nucleation, motion and annihilation of Abrikosov vortices expresses itself as energy dissipation in a superconductor at temperatures $T < T_c$ and zero external magnetic field. The flux drift in type-II superconducting devices can be used for generation of high power and jitter-free ultrafast electrical transients [8]. However, in most cases it negatively affects operation of low- and high-power and ultra-low electronic noise superconducting devices restricting their performance, initiating large electronic noise amplitude, or, even, affecting irreversible damaging of the actual device [9].

Motion of Abrikosov vortices in superconducting devices is called 'coherent,' when they are tightly squeezed and strongly interact between each other [10], or, when they interact with a spatially periodic pinning landscape [11]. The Josephson-like effect–appearance of voltage steps on the current–voltage (I–V) – is a hallmark of the coherent vortex motion. The steps appear 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 [12].

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This work reports our results of experimental measurements and analysis of energy dissipation due to the coherent vortex motion in a Π-shaped channel of a $YBa_2Cu_3O_{7-x}$ superconducting device. The level of energy dissipation has been evaluated by means of the *I–V* characteristics of laser-patterned $YBa_2Cu_3O_{7-x}$ superconducting devices containing a laser-written Π-shaped channel of easy vortex motion. The voltage steps, observed on the *I–V* curve of our superconducting microbridge, appear due to the current induced coherent vortex motion in the channel's segments, which are oriented perpendicularly to the current's direction. The step's shape and its voltage amplitude, as well as the step's number on the *I–V* curve have been used as indicators of the vortex density and their velocity of motion along the superconducting channel.

MATERIALS AND METHODOLOGY

The testing $YBa_2Cu_3O_{7-x}$ microbridges

A superconducting 0.3-μm-thick, 100-μm-long, and 50-μm-wide devices were laser-patterned from $YBa_2Cu_3O_{7-x}$ (YBCO) epitaxial films, which were grown by means of metaloorganic chemical vapor deposition (MOCVD) onto crystalline $LaAlO_3$ substrates. Details of the MOCVD method and technology of thin YBCO films are given in Ref. [13].

The films were laser patterned (LP) using a green-color, continuous-wave Ar-ion laser [14], focused by an optical microscope into a light spot's diameter of 5 μm.

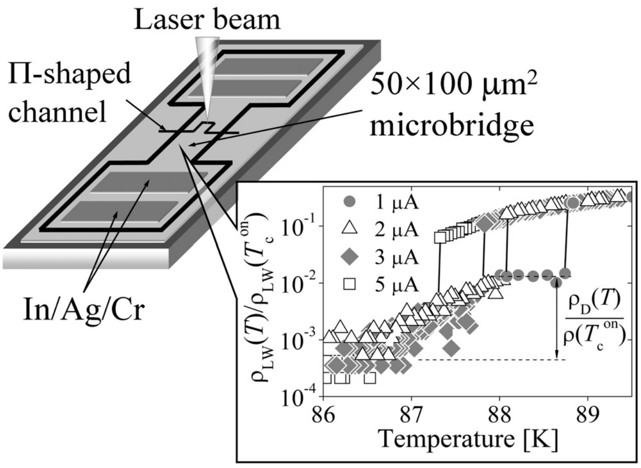

Fig. 1. A laser-patterned 50-μm-wide and 100-μm-long $YBa_2Cu_3O_{7-x}$ microbridge with a laser-written Π-shaped channel for easy vortex motion. Inset: the reduced resistivity $\rho_{LW}(T)/\rho_{LW}(T_c^{on})$ *vs.* temperature dependence of the microbridge measured at bias current of I = 1, 2, 3, and 5 μA. The reduced resistivity $\rho_D(T)/\rho(T_c^{on})$ depends on the resistivity of resistive clusters ρ_D in the superconducting film manufactured by means of MOCVD technique

Ready for patterning YBCO films were attached perpendicularly to the laser beam's direction on a computer-controlled *X-Y* translation stage and placed in a nitrogen gas atmosphere.

The laser power of 2.3 W ÷ 2.8 W and the stage's scanning speed of 5 μm/s ensure full deoxygenation (i. e., $x > 0.6$ in $YBa_2Cu_3O_{7-x}$) of the laser illuminated areas of the superconducting film, converting them into an insulator [15]. In this way, the YBCO film was LP into a set of six microbridges with large contact areas: five with channels (Fig. 1) and one left without channel as a reference (pristine) bridge.

The X-ray diffraction pole figures and θ–2θ scans (not shown here) demonstrated that the superconducting films had in-plane texture with the crystalline *c*-axis oriented perpendicularly to the substrate.

The low illumination power, ranging from 0.3 W-to-0.6 W from our Ar-laser and a slower velocity of 50 μm/s of the *X–Y* stage were used for laser-writing (LW) [14] of a Π-shaped, 5-μm-wide channel for easy vortex motion (Fig. 1), keeping the film in a nitrogen gas. In the LW regime, the film's illuminated areas were only partly (i. e., at $x \sim 0.2$) deoxygenated, exhibiting I_c, T_c and H_{c1}, comparatively lower than that of the laser untreated film's areas [16].

The electric and magnetic properties of the microbridges

The resistivity *vs.* temperature and the *I–V* characteristics of the YBCO microbridges at zero external magnetic field were measured in a 4-probe arrangement at dc biasing. The tested microbridges were thermally anchored to a Cu holder inside a temperature-controlled liquid-nitrogen cryostat, operating at a temperature range from 70 K to 300 K. To achieve temperatures below 78 K, a vacuum pumping of liquid nitrogen has been applied.

Our preliminary results of electric measurements of a reference microbridge showed a metallic like resistivity versus temperature dependence with a residual resistivity ratio $\rho(300\ K)/\rho(100\ K) = 2.74$. The T_c onset of the superconducting state in our reference microbridge was at $T_c^{on} = 91.2$ K, with the T_c width of $\Delta T_c = 0.4$ K. The critical current density J_c was measured by means of nanosecond-pulsed electric current [9] and for the reference microbridge at $T = 78$ K it was found to be $J_c(78\ K) = 1.5 \times 10^6$ A/cm^2. The current-induced Joule heating in the microbridge contacts was negligible and did not affect the superconducting properties of the microbridge in the whole range of tested temperatures.

The quality of the LP and LW procedures in our superconducting films were verified by magneto-optical (MO) measurements. The qualitative analysis of MO images of remnant magnetic field and images of the penetration of magnetic field into the microbridge [17] demonstrated that the magnetic field of the first flux entry into the channel's area and H_{c1} was considerably smaller then the first penetration field into the laser untreated bulk samples and their H_{c1}. A depression of the critical magnetic field in a deoxygenated channel resulted in a decrease of the overall pinning strength what facilitated easy vortex motion in the LW-channel [16, 17].

At low temperatures, the LW-bridge exhibited a current dependent resistive tail (Fig. 1), which determined the temperature of the zero-resistivity T_{c0} of the device. The resistive tail appeared due to the motion of Abrikosov vortices in the channel. Due to this reason, T_{c0} of the LW-bridge decreased from 88.6 K down to 87.3 K, when the bias current was increased from 1 μA to 5 μA (Fig. 1).

There was also a residual resistivity ρ_D remaining even below T_{c0}. The ρ_D depended on temperature, but it did not depend on the bias current (Fig. 1), and dropped below the resolution limit of our measurement setup at $T \leq 86.7$ K [16].

RESULTS AND DISCUSSIONS

Analysis of *I–V* curves

The nonlinear *I–V* curves of the LW-bridge exhibit voltage steps (curve 2 in Fig. 2) in the temperature range between $0.94T_c^{on}$ and $0.975T_c^{on}$. The steps appear at the bias current $I \geq I_c$ and in the case of $T = 88.2$ K can be clearly identified up to $I \sim 20I_c$. The critical current I_c of the YBCO sample was determined from the *I–V* curve by means of a 10-μV-voltage criterion. The criterion may be fulfilled either by a voltage drop because of the current flow across resistive clusters or by a dissipative vortex motion in the channel.

For larger currents, i. e. $I > 20I_c$, at $T = 88.2$ K, the voltage amplitude of the step falls below trustworthy resolution limit of our experimental setup. For comparison, we have measured the *I–V* characteristics of the reference microbridge (curve 1 in Fig. 1). It had no steps on the *I–V* curve in whole range of tested temperatures.

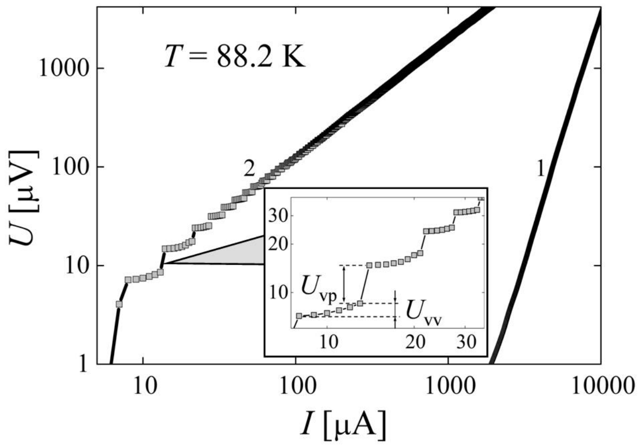

Fig. 2. Typical current-voltage (*I–V*) characteristics of a 0.3-μm-thick, 50-μm-wide and 100-μm-long $YBa_2Cu_3O_{7-x}$ microbridge with a Π-shaped channel for easy vortex motion (2) and a channel-free (reference) device (1) at $T = 88.2$ K ($0.967T_c$) and the zero external magnetic field. Inset demonstrates a low bias current part of the second *I–V* dependence on an expanded scale

The step-like change in voltage was attributed to energy dissipation caused by the coherent motion of Abrikosov vortices in the LW-channel of the superconducting microbridge [16 – 18]. The voltage amplitude of a given step at a fixed temperature consists of two parts, denoted (see inset of Fig. 2) as U_{vp} and U_{vv}, respectively. Both voltages are discussed below in a detail.

Voltage U_{vp} in the *I–V* curve

The voltage U_{vp} does not increase with the increase of the bias current in the tested range of currents. For example, at $T = 88.2$ K the average step height is $U_{st} \sim 7.6$ μV and is almost constant up to $n = 100$, while, simultaneously, the bias current increased as much as 6 times, i. e., from 0.1 mA up to 0.6 mA. The voltage U_{vp} is associated with energy dissipation in the superconductor, due to the appearance of additional recombination vortex-antivortex pairs in the LW-channel [18]. Moving coherently, magnetic vortices strongly interact with each other. Therefore, in the case of the coherent motion, the LW-channel is full of vortices, which are arranged into a triangle magnetic lattice [19]. Thus, an additional vortex-antivortex pair can be introduced into the LW-channel only if vortices are more tightly squeezed, making some free space for the additional flux. Moving coherently, Abrikosov vortices are spaced at a distance inversely proportional to the current-self-produced *B* [19]:

$$d = \sqrt{2\Phi_0 / (\sqrt{3}B)} \ . \qquad (1)$$

If appearance of additional vortex-antivortex pairs in our LW-channel induces additional voltage steps with the amplitude U_{st} greater than the number of vortex-antivortex pairs *N* in the channel of the LW-bridge can be estimated from the ratio of dissipation (dynamic resistance) in the vicinity of the n^{th} and $n^{th} + m$ step.

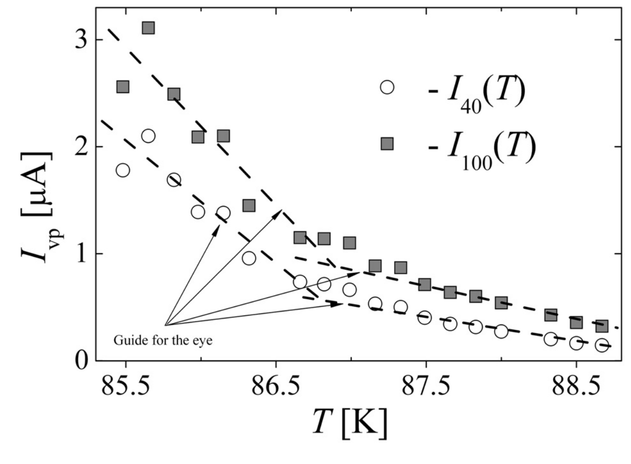

Fig. 3. Current, which self-magnetic field creates 40 and 100 vortex-antivortex pairs of in a 0.3-μm-thick, 50-μm-wide and 100-μm-long $YBa_2Cu_3O_{7-x}$ microbridge containing a Π-shaped channel for easy vortex motion versus device's temperature at zero external magnetic field

At a given bias current and $T = 88.2$ K (see Fig. 2), the number of vortex-antivortex pairs is given by

$$N = U/U_{st} \ , \qquad (2)$$

where *U* is the experimentally measured voltage derived from the *I–V* curve (Fig. 2) and U_{st} is an average voltage of a single pulse, calculated from the *I–V* curve. Using this method, we calculated the currents I_{40} and I_{100}, which self-magnetic-field created 40 and 100 vortex-antivortex pairs in the LW-channel, *vs.* temperature (Fig. 3). Increasing temperature, both I_{40} and I_{100} decrease, but both exhibit similar linear-slopes, crossing at the temperature

$T \sim 86.8$ K. This temperature appears to be close to the original temperature $T^* = 87.7$ K [16], which was determined from the zero-resistivity ρ_D critical temperature of the LW-channel (Fig. 1).

A presence of two different slopes in the $I_{40}(T)$ and $I_{100}(T)$ dependences indicates that number of moving vortices along the LW-channel *vs.* temperature dependence $N(T)$ in the LW-channel can be predetermined by two different pinning processes. At temperatures $T_c^{on} > T > 86.8$ K, the energy dissipation in the LW-channel can be affected by vortex pinning on resistive clusters originated from growth defects in the YBCO film manufactured by means of MOCVD technique. Using our experimentally measured resistive transition data (Fig. 1), one can verify that the voltage drop across the residual resistivity can contribute less than 5 % to the 10-μV-criterion at temperatures below T_{c0}. Thus, the main contribution to resistivity comes from the dissipative motion of Abrikosov magnetic vortices. However, resistive clusters can contribute the pinning force in the LW-channel. Oxygen depletion causes a decrease of density of the Cooper pairs in the LW channel [15], which, in turn, reduces the efficiency of strong pinning centers, associated with the growth defects of the YBCO film.

Due to proximity effect [20] at lower temperatures (i. e. $T < 86.8$ K), the resistivity of resistive clusters appears to be below resolution limit of our measurement setup. In range of mentioned temperatures the extended point-defects, produced by oxygen vacancies, predetermine the pinning force in the LW-channel. Because of weakened pinning of strong pining centres (i. e. growth defects) in the LW channel area, vortices start to move along the channel at bias currents that are order of magnitude lower than this one measured in the laser untreated reference bridge (Fig. 2).

Voltage U_{vv} in the *I–V* curve

The voltage U_{vv} has been estimated from experimental *I–V* dependences (see inset of Fig. 2) of YBCO microbridge containing LW-channel for easy vortex motion. In general case:

$$U_{vv} = U_{st} - U_{vp}\,, \tag{3}$$

here U_{vv} is an indicator of energy dissipation related with change in velocity v of Abrikosov magnetic vortices moving along the LW-channel. The velocity of vortices should increase with increasing the Lorentz force:

$$\eta v = F_L - F_p\,, \tag{4}$$

here $F_L \sim I\Phi_0$ – is the Lorentz force causing vortex motion in the LW-channel, I – is the strength of the bias current, and $\eta(B, T)$ – is the viscosity coefficient of the superconducting medium. Then, the dissipative coherent motion of Abrikosov magnetic vortices develops electric voltage in the superconductor (in the direction of bias current) [21]:

$$U_{vv} \sim N\Phi_0 v = Bv\,. \tag{5}$$

For this reason, the U_{vv} increases with increasing the bias current within a single current step on the *I–V* dependence and in his way adds some small input to overall value of the voltage step U_{st} at low bias currents $I \le 10I_c$. (Fig. 2). However, at higher bias currents (i. e. $10I_c < I < 19I_c$), the input from U_{vv} decreases below resolution limit of our measurement setup. Temperature dependent $U_{vv}(I)$ and $U_{vv}(I/I_c)$ curves, measured at temperatures $T = 87.2$, 87.7, 88.0, 88.3, and 88.5 K for the YBCO superconducting microbridge, which contains Π-shaped channel for easy vortex motion, are shown by a log-log plot and semi-log plots in Fig. 4. It clear from this figure that $U_{vv}(I)$ dependence is a function of ambient temperature. The U_{vv} versus reduced current I/I_c dependence at lower temperatures shows faster decrease, if compare it with that one measured at higher temperatures. E. g. in the case if the reduced current increases for one order of magnitude, the $U_{vv}(87.2\text{ K})$ at temperature $T = 87.2$ K decreases for 30 times, but the $U_{vv}(88\text{ K})$, measured at temperature $T = 88$ K, decreases for as much as 110 times.

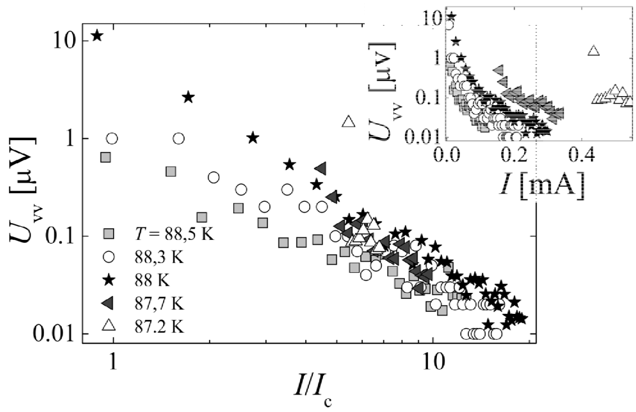

Fig. 4. A log-log plot of voltage U_{vv} caused by energy dissipation due to vortex velocity variations versus reduced current at various temperatures of a 0.3-μm-thick, 50-μm-wide and 100-μm-long $YBa_2Cu_3O_{7-x}$ microbridge, which contains a Π-shaped channel for easy vortex motion. Data extracted from experimentally measured the *I–V* curve. Inset represents a semilog plot of U_{vv} versus biasing current I of the same dependences

The $U_{vv}(I/I_c)$ dependence in the regime of coherent vortex motion can be explained by non-homogeneous vortex density in the Π-shaped LW-channel of the YBCO microbridge. The Π-shape of the channel affects non-homogeneous distribution of bias current in the microbridge [21]. Nonuniform density of current affects non-homogeneous distribution of the current-self produced magnetic field inductance or non-homogeneous distribution of vortex-antivortex pairs in the LW-channel.

The magnetic flux moves along channel's parts, what are oriented perpendicularly to the bias current. Thus, vortex-antivortex pairs in the LW-channel's parts, what appear to be oriented parallel to the bias current direction, can't move, because vortices and antivortices located in these parts of the channel can not annihilate with theirs antipodes. Thus, at low biasing conditions ($I \sim I_c$), the squeezing of magnetic lattice of Abrikosov vortices in different parts of the LW-channel might be different, depending on local direction of the biasing current. Moreover, a nonuniform current density (i. e. current-self produced nonuniform magnetic field) in the LW-channel containing microbridge [21] affects nonuniform distribution of density of Abrikosov vortices in the channel as well as nonuniform velocity of their motion along different parts of this LW-channel.

The increase of the bias current-self-produced magnetic field affects vortex density increase in the LW-channel as well as the stronger interaction between them. At $I \geq 10I_c$, when Abrikosov vortices appear to be even more tightly squeezed in the LW-channel area, a difference in local vortex densities and velocity of their motion diminishes. The F_L accelerates whole magnetic lattice as a solid and change in vortex velocity depends mainly on ratio between F_L and F_p in the LW-channel area. This ratio predetermines the resistive clusters in the LW-channel at higher temperatures, i. e. at $T > 86.8$ K. When temperature decreases, the resistance of grain boundaries gradually decreases due to increase of the proximity effect in the LW-channel. Thus, at temperatures $T < 86.8$ K the pinning force of resistive clusters and grain boundaries diminish and the extended-point defects of oxygen vacancies predetermine the pinning force in the LW-channel. Most probably, this temperature dependent change of pinning mechanism in the LW-channel is responsible for the change of the slope of the $U_{vv}(I/I_c)$ *vs.* temperature dependence.

CONCLUSIONS

At temperatures below the material's superconductor onset temperature, we have observed a quasi-Josephson-effect produced by Abrikosov vortices coherently moving along the Π-shaped artificially deoxygenated channel, incorporated into a 0.3-μm-thick, 50-μm-wide and 100-μm-long $YBa_2Cu_3O_{7-x}$ superconducting microbridge. It has been demonstrated, that the coherent vortex motion confined in the channel can be used for determination of the density and velocity of Abrikosov vortices in the channel. Coherent motion of the magnetic flux expresses itself as Josephson-like voltage steps, observed on the on the *I–V* curve of our microbridges measured at zero external magnetic field in a limited range of temperatures and bias currents. There are several factors, which predetermine shape of the single voltage step on the current-voltage dependence of our device. They are: the entrance of additional vortex-antivortex pairs, due to the penetration of the bias current-self produced magnetic field into the channel area, and the change in the velocity of Abrikosov vortices, due to a non-homogeneous distribution of electric current in the device (i. e. non-homogeneous distribution of the bias current self produced magnetic field), which is affected by the presence of a Π-shaped channel in the superconducting device. Motion of the magnetic flux in the vortex channel of our superconducting device at temperatures $T > 86.8$ K has been determined by the resistive clusters in the LW-channels of MOCVD prepared device, but at lower temperatures (i. e. at $T < 86.8$ K), the velocity of the magnetic flux in the channel appears to be limited by the extended-point defects of oxygen vacancies. Based on our results we also conclude that the pinning mechanism of Abrikosov vortices depends on temperature. This phenomenon can predetermine the temperature dependent energy dissipation originated from change in velocity of magnetic flux moving along Π-shaped channels of our devices *versus* bias current dependence.

Acknowledgments

Work in Rochester was supported by the NSF Grant No. ECS-0609140, with an additional support provided by the BBN grant and the NYSTAR grant to the University of Rochester CEIS Center.

One of authors (Arturas Jukna) wants to acknowledge financial support of the Fulbright Alumni Fund from the Ministry of Education and Science of the Republic of Lithuania.

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Presented at the National Conference "Materials Engineering'2010"
(*Kaunas, Lithuania, November 19, 2010*)