VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Lina STEPONAVIČIENĖ

INVESTIGATION AND CONTROL OF MOTION OF MAGNETIC VORTICES IN THE THIN SUPERCONDUCTING $YBa_2Cu_3O_{7-x}$ FILMS

SUMMARY OF DOCTORAL DISSERTATION

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Lina STEPONAVIČIENĖ

MAGNETINIŲ SŪKURIŲ JUDĖJIMO $YBa_2Cu_3O_{7-X}$ SUPERLAIDŽIŲ SLUOKSNIŲ KANALAIS TYRIMAS IR VALDYMAS

DAKTARO DISERTACIJOS SANTRAUKA

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Introduction

Topicality of the problem. Experimental research deduced that occurrence of mixed phase is related to magnetic flux penetration into a superconductor in a form of Abrikosov magnetic vortices, the motion of which in superconductor reduces characteristics in superconducting low and high power electronic devices. In superconducting electronic devices the motion of vortices causes electronic noise and when the motion is highly intensive it causes irreversible thermal damage (i.e. the device's burnout). Thus, research of mixed-state occurrence in the superconducting material, the main characteristics of the mixed-state and state's development with increase in temperature and bias current are very important from point of view of fundamental research and practical applications trying to forecast casual occurrence and development of undesirable phenomena.

In this work analyzed and explored technology of superconducting films with regions of weak superconductivity with controllable properties produced by means of a laser writing technique. The purpose of current work is to explain the origin, nature and mechanism of the pinning force of Abrikosov magnetic vortices. Our results demonstrating a way how to control flux motion, method how to assess the character of this motion and methods how to evaluate amount of dissipated energy due to vortex motion can be used for development of novel superconducting devices for accurate measurements of magnetic field strength or strength of electric current with accuracy limited by the single quantum of magnetic flux.

The object of the research. 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 devices which contain regions of weak superconductivity manufactured by means of laser writing technique at temperatures lower than its critical temperature.

Aim of the work. To investigate and to explain electric and magnetic properties of the mixed-state $YBa_2Cu_3O_{7-x}$ devices laser-patterned out of $YBa_2Cu_3O_{7-x}$ films grown by means of metalo-organic-vapour-deposition (MOCVD) technique and which contain regions of weak superconductivity manufactured by means of laser-writing technique.

Tasks of the work

1. To manufacture $YBa_2Cu_3O_{7-x}$ superconducting devices with regions of weak superconductivity out of $YBa_2Cu_3O_{7-x}$ superconducting films

grown by a MOCVD technique and to investigate size and shape of these regions versus laser beam's power.

2. To investigate electric and magnetic properties of $YBa_2Cu_3O_{7-x}$ superconducting devices with regions of weak superconductivity and to explain conditions of mixed-state appearance and development in the superconducting device by means of regularities of these properties variation.
3. To investigate the character of motion of Abrikosov magnetic vortices along regions of weak superconductivity of $YBa_2Cu_3O_{7-x}$ devices versus the device's temperature and strength of biasing current dependences.

Methodology of research. A method of laser-writing of regions of weak superconductivity in the $YBa_2Cu_3O_{7-x}$ material has been adopted for prepared $YBa_2Cu_3O_{7-x}$ superconducting thin films prepared by MOCVD technique. We used a scanning tunneling microscopy and four-, three- and two-probe measurement methods to determine electric properties of $YBa_2Cu_3O_{7-x}$ superconducting thin films modified by laser. Qualitative results of magnetic flux penetration into superconductor measurements were obtained using the magnetooptical measurements technique. A level of oxygen partial depletion has been measured from spectra X-ray microanalysis technique.

Scientific novelty

1. A technique for laser-writing of regions of weak superconductivity has been adopted for MOCVD $YBa_2Cu_3O_{7-x}$ superconducting thin films. It is experimentally demonstrated that oxygen partially decomposed regions in a 0.3μm-thick $YBa_2Cu_3O_{7-x}$ superconducting film can be produced by means of a computer-controlled scanning of a high-power laser beam focused down to 5 μm in diameter. The level of deoxygenation in the film depends on laser power.
2. It was determines that due to nonuniform diffusion of oxygen along crystalline structure of the $YBa_2Cu_3O_{7-x}$ superconductor, the optically induced heating affects oxygen nonuniform distribution in the region of weak superconductivity of the superconducting film and the oxygen remnant content in the laser activated areas depends on initial oxygen content which was in the film before starting laser-writing procedures.
3. Due to strong pinning force of oxygen additional vacancies acting as structural extended defects in the superconducting film, the Abrikosov magnetic vortices in the $YBa_2Cu_3O_{7-x}$ films can move coherently along

laser-written regions of weak superconductivity. The strength of the pinning force in oxygen partially decomposed material can be controlled by means of film's temperature and biasing conditions. The efficiency of this control can be estimated from the shape of film's stepped-like current-voltage dependence measured at temperatures below critical temperature of the superconducting material.

Practical value. Results of research can be applied for the development of novel superconducting devices measuring with accuracy of magnetic flux quantum $\Phi_o = 2.067833758(46)\times10^{-15}$ Wb the strength of magnetic field or/and bias current.

Defended propositions

1. The superconducting $YBa_2Cu_3O_{7-x}$ devices containing regions of weak superconductivity can be laser-patterned/-written at room temperature into a nitrogen gas ambient out of $YBa_2Cu_3O_{7-x}$ superconducting films grown by means of MOCVD technique. The critical parameters (i.e. I_c, T_c, H_{c1}) as well as residual oxygen content at surface and bulk of the laser modified region depends on incident optical power and initial content of oxygen x in the material before illumination.
2. The first magnetic flux in a form of Abrikosov magnetic vortices penetrates regions of weak superconductivity of a dc-biased $YBa_2Cu_3O_{7-x}$ superconducting device and creates mixed–state material. Vortex density increases with bias current I increase and at $I > I_c$, the vortex motion along regions of weak superconductivity determines a level of electric energy dissipation which can be estimated from the shape of the nonlinear current-voltage dependences of our superconducting devices at temperatures $T < T_c$.
3. The coherent motion of Abrikosov vortices along regions of weak superconductivity is responsible for "step-like" current-voltage characteristics of $YBa_2Cu_3O_{7-x}$ superconducting devices at temperatures $T < T_c$ and bias currents $I > I_c$. Additional oxygen vacancies in the laser-modified superconducting material affect decrease of pining force of strong pinning centres in modified regions and create favourable conditions for coherent vortex motion. The amplitude of voltage "steps" in the current-voltage dependence depends on the condensation energy of single vortex-antivortex pair, the "step" number shows the number of the vortex-antivortex pairs moving along a region of weak superconductivity. However, the

voltage amplitude of the “steps” does not depend on strength of biasing current and velocity of moving vortices.

The scope of the scientific work. The scientific work consists of introduction, 3 chapters, conclusions, list of references, and list of author‘s publications related with current dissertation. The total scope of the dissertation is 85 pages, 36 pictures, 21 numbered equations, and 85 references cited in the current dissertation.

1. The superconductivity phenomenon in type-II superconductors

This chapter describes a review of the superconductivity phenomenon and analyses properties, phases and critical parameters of type-II superconductor $YBa_2Cu_3O_{7-x}$. It also presents the properties and features of Abrikosov magnetic vortices and of their motion as well as the origin and mechanism of pinning force in the type-II superconductor.

2. Methods of production and testing of the $YBa_2Cu_3O_{7-x}$ superconducting thin films

A superconducting 0.3 μm thick, 100 μm long, and 50 μm wide devices were laser-patterned from $YBa_2Cu_3O_{7-x}$ epitaxial films, which were grown by means of metaloorganic chemical vapor deposition (MOCVD) onto crystalline $LaAlO_3$ substrates.

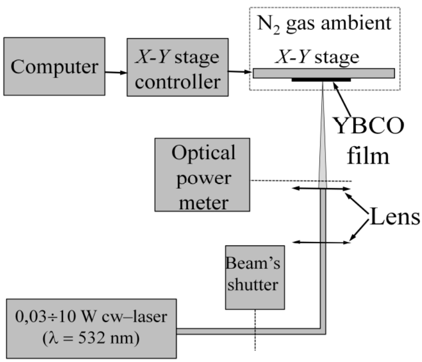

Fig. 1. A schematics of the computer-controlled setup for laser-patterning of $YBa_2Cu_3O_{7-x}$ superconducting devices and laser-writing regions of weak superconductivity in it

The films were laser-patterned at room temperature using a green-color, Ar-ion, cw-laser focused by optical lenses (Fig. 1) into a light spot's diameter of approximately 5 μm. Ready for patterning $YBa_2Cu_3O_{7-x}$ films were attached perpendicularly to the laser beam's direction on a computer-controlled *X–Y* translational stage and mounted into a nitrogen gas ambient. Resistivity *vs.* temperature and *I–V* curves of the $YBa_2Cu_3O_{7-x}$ devices were measured in a 2-, 3- and 4-probe arrangement at dc-bias. The tested $YBa_2Cu_3O_{7-x}$ sample was thermally anchored to a Cu holder inside a He gas cooling cryostat (Fig. 2).

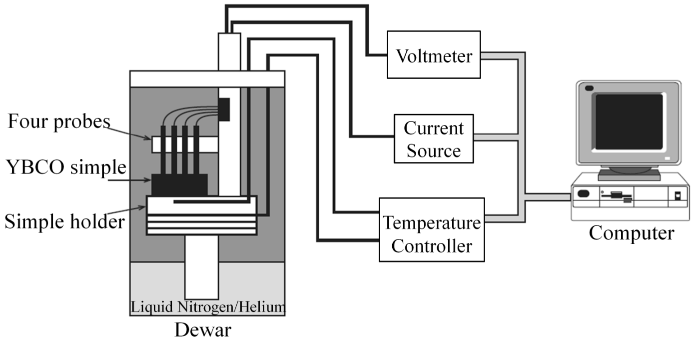

Fig. 2. A schematic of the computer-controlled setup for electrical measurements of resistivity *versus* temperature and current-voltage dependences of $YBa_2Cu_3O_{7-x}$ superconducting devices

Voltage between internal electric contacts was measured by a nanovoltmeter (KEITHLEY 2182A). Sample temperature was measured by a device of temperature control (CRYO.CON 32B). External electric contacts were connected to the source of direct current (KEITHLEY 6221 DC). Computers used a program created in LabVIEW software environment to process received signals.

The laser power, ranging from 2.3–2.8 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. In this way, the $YBa_2Cu_3O_{7-x}$ film was laser-patterned into a set of six microbridges with large contact areas: five with channels and one left without channel as a reference (pristine) bridge. The X-ray diffraction pole figures and θ–2θ scans demonstrated that the superconducting films had in-plane texture with the crystalline c-axis oriented perpendicularly to the substrate. Fig. 3 shows $YBa_2Cu_3O_{7-x}$ thin film with laser-patterned (brighter) insulating lines.

The low illumination power, ranging from 0.3–0.6 W from our Ar-laser and a slower velocity of 50 μm/s of the X–Y stage were used for laser writing of 5 μm wide channel for easy vortex motion, keeping the film in a nitrogen gas. In the laser writing 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.

Four silver electrodes (Fig. 3 inset (a)) were thermally deposited in low vacuum for each superconducting device by means of 0.1 μm thick silver layer evaporation through special mask.

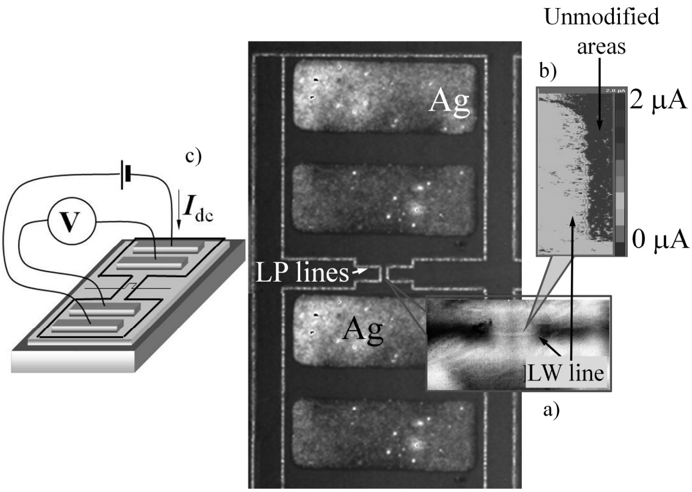

Fig. 3. A view of $YBa_2Cu_3O_{7-x}$ thin film with laser-patterned (brighter) insulating lines. Bright areas correspond to higher transparency of the light when sample is illuminated from the bottom side. Inset a) magnetooptical image of the penetration of the 280 G magnetic field into the superconducting device containing laser-written line. Inset b) a photograph obtained at room temperature (T = 300 K) by means of the scanning tunneling microscope. Inset c) represents a schematic of a single superconducting device with region of weak superconductivity and electric scheme for measurements of device's electric properties

After the silver deposition, the devices were additionally annealed at temperature 300 ^{o}C in oxygen ambient for 1 hour. The chosen temperature for annealing was too low for oxygen redistribution in the superconducting sample, but high enough for silver diffusion into the superconducting thin film. Direct measurements of contact resistance of $Ag/YBa_2Cu_3O_{7-x}$ interfaces showed their resistivity as negligible in results of measurements of electric properties of $YBa_2Cu_3O_{7-x}$ devices.

The scanning tunneling microscopy (Fig. 3 inset (b)) analysis confirmed that channel's material was of lower electric conductivity and of lower critical magnetic field H_{c1}. The magnetoptical image (Fig. 3 inset (c)) confirms that first magnetic flux penetrates the area of weak superconductivity and the remaining area of the device or contact pads is practically free of flux penetration. This let us to conclude that LW procedure resulted in partially deoxygenation of $YBa_2Cu_3O_{7-x}$ material with considerably decreased parameter H_{c1}. It means that oxygen content in the LW-region of the $YBa_2Cu_3O_{7-x}$ film can be controlled during the LW procedure by varying the incident light power from the cw-laser.

3. Abrikosov magnetic vortices in weak superconductivity areas in superconductor $YBa_2Cu_3O_{7-x}$ device

Both the pristine-bridge (1 curve in to Fig. 4(a)) and the laser-written bridge (Fig. 4(a) 2 curve) have a metallic like resistivity *versus* temperature dependence and onset temperature the superconducting state at $T_c = 91.2$ K.

The temperature of onset of the superconducting state was not influenced by our laser writing procedures, as it reflected the properties of the banks of the bridge untreated by laser-writing procedures. The laser-written bridge exhibited a low-temperature resistive tail. The increased room temperature resistivity was associated with channel incorporation into laser writing bridge structure.

The nonlinear *I–V* curves of the laser writing bridge exhibit voltage steps (curve 2 in to Fig. 4(b)) in the temperature range between $0.94T_c$ and $0.975T_c$. 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 $YBa_2Cu_3O_{7-x}$ 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 (1 curvein to Fig. 4(b)). It had no steps on the *I–V* curve in whole range of tested temperatures. The step-like *I–V* dependences, observed in LW-bridges, appear in a limited range of temperatures and biasing currents, was attributed to energy dissipation caused by the coherent motion of Abrikosov vortices in the LW-channel of the superconducting microbridge.

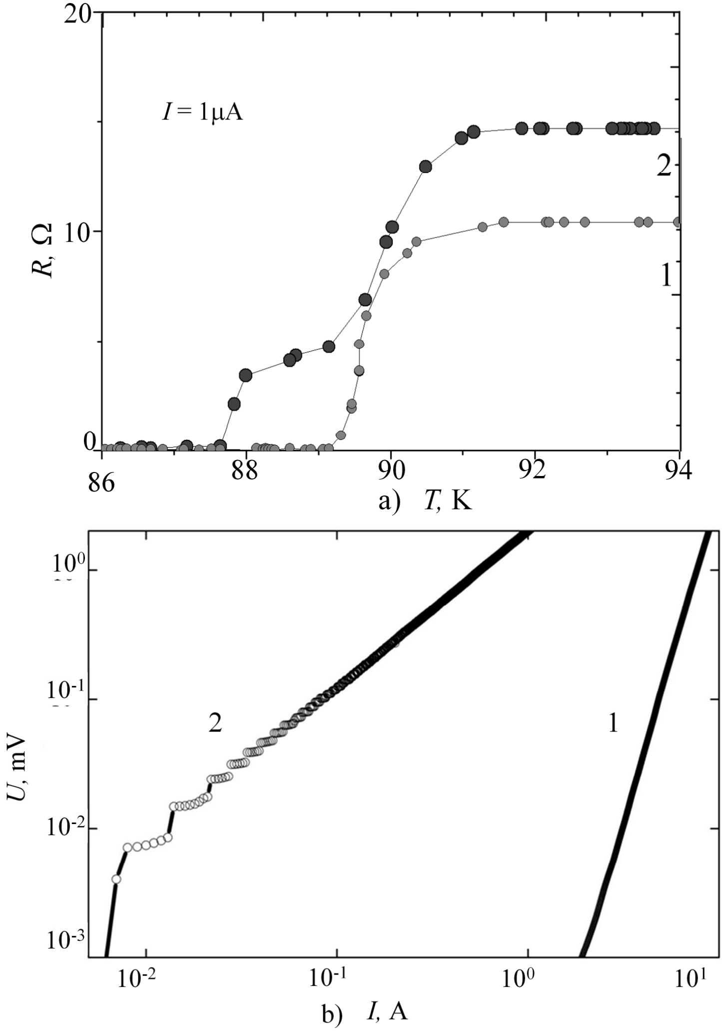

Fig. 4. Electrical resistance dependence on temperature when the flowing electrical current is 1 μA (a) and the voltage – current dependences at *T*=88.2 K in the logarithmic scale (b) of the devices of superconductive $YBa_2Cu_3O_{7-x}$ layer without (1) and with (2) area of weak superconductivity

Appearance of the voltage steps on the laser writing bridge *I–V* curve can be attributed to the coherent vortex motion. The steps appear at bias currents higher than the critical current of the $YBa_2Cu_3O_{7-x}$ 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. 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 laser writing bridge. The number of vortex-antivortex pairs in the channel of the laser writing 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. 6. 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 laser writing channel should be inversely proportional to the temperature dependence of the condensation energy of a flux line per unit length given as $N \sim E(T)^{-1}$. Here $E(T) = \Phi_0^2/(4\pi\mu_0\lambda_{ab}^2(T))$, μ_0 is the permeability of free space, and $\lambda_{ab}(T) = \lambda_{ab}(0)/(\sqrt{1-T/T_c})$ is the temperature dependent magnetic field penetration depth along $a - b$ plane of a $YBa_2Cu_3O_{7-x}$ superconductor $\lambda_{ab}(0) = 130$ nm, and A – free parameter which increased from 3×10^{-12} to 2×10^{-10} for the biasing currents ranging from 0.04 mA to 0.7 mA.

Fig. 6 (dashed lines) demonstrates the fitting results of $N(T)$ dependences to the experimental data. In our calculations, we used one fitting parameter A. 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. 6 and one is more consistent with superconductivity onset temperature $T_c = 91.2$ K of the laser writing non-treated $YBa_2Cu_3O_{7-x}$ material. This result confirms our assumption that oxygen depletion from the laser writing 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 $YBa_2Cu_3O_{7-x}$ film's surface and temperature T is related with the superconducting properties of the material located in the film's bottom.

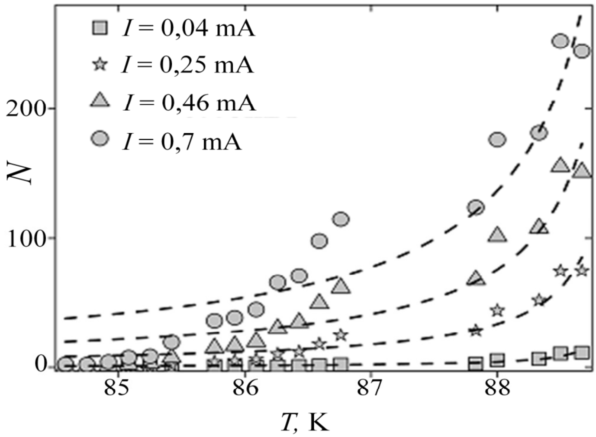

Fig. 6. The pairs of Abrikosov magnetic vortices/antivortices N dependence on temperature T (characters). The dotted line indicates the inverse condensation energy dependence on temperature, when the flowing electrical current I = 0.04; 0.25; 0.46; 0.7 mA

Calculated curves fit better the region of higher temperatures of the $N(T)$ curves (Fig. 6). 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 $J_c(T)$ dependencies shown in Fig. 7 have been determined using a 10 μV voltage criterion. Under this criterion, the supercurrent in both the pristine (2 curve in Fig. 7) and channelled bridge (1 curve in Fig. 7) samples appears at the temperature just below T_c.

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 laser writing 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, while the $J_c(T)$ of the single channel bridge shows that despite increasing the concentration of oxygen vacancies, the laser writing deoxygenation process decreases the overall pinning strength.

Assuming that creation of additional flux lines in the channel area of our device gives additional voltage steps on the I–V curve, the number of vortex–antivortex pairs N in the channel can be estimated from ratio $N = U/U_h$, where U is the experimentally measured voltage on the I–V dependence and U_h is the averaged voltage of the single step, calculated using the same I–V dependence.

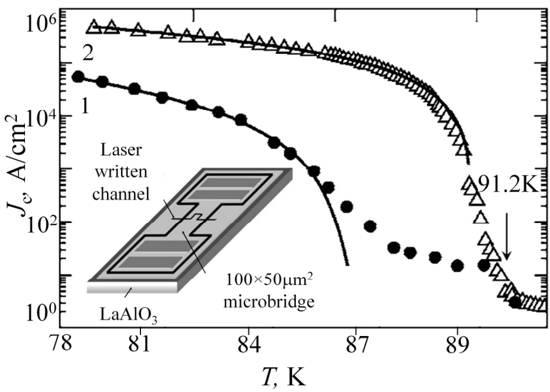

Fig. 7. The critical electric current density dependence on temperature in the logarithmic scale of the superconductive $YBa_2Cu_3O_{7-x}$ layers: the first curve corresponds to the structure with a channel (inset), the second curve corresponds to the structure without a channel

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 (curve 1 in to Fig. 8).

Increasing temperature, the I_{40} decreases exhibiting two linear slopes, both crossing at temperature $T_c = 86.8$ K, which was prior to our work determined as the zero-resistance critical temperature of the channel material: $T_c = 86.7$ K. 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 $YBa_2Cu_3O_{7-x}$ microbridge with the laser writing channel is determined by two different physical processes. Figure 8 demonstrates our results of I_{40} calculations using $E(T)$ dependence the dotted line (curve 2 in to Fig. 8). The linear slop of $I_{40}(T)$ at higher temperatures has similar trend as I_{40} calculated using the $E(T)$ dependence. The latter indicates that at higher temperatures, ranging from $0.95T_c$ to $0.975T_c$, the $N(T)$ behavior can be explained by the temperature-dependent change in vortex condensation energy in our $YBa_2Cu_3O_{7-x}$ microbridge. 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.

Most probably the two different slopes in $I_{40}(T)$ dependence are caused by the pinning force versus temperature dependence in the channel area.

Our tested $YBa_2Cu_3O_{7-x}$ films are characterized by screw dislocations 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, the residual electric resistance of grow defects in our superconducting films decreases.

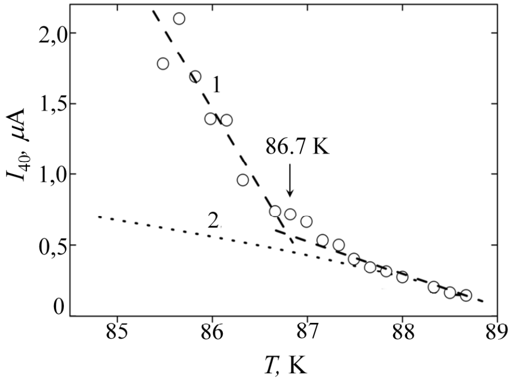

Fig. 8. The current I_{40}, whose self-magnetic field creates 40 pairs of magnetic vortices/antivortices pairs versus temperature: (1) extracted from experimental I–V dependences, (2) estimated using vortex condensation energy versus temperature

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., $0.95T_c$ – $0.975T_c$, 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 $YBa_2Cu_3O_{7-x}$ microbridge.

The voltage steps in I–V dependences were attributed to energy dissipation caused by the coherent motion of Abrikosov magnetic vortices in the laser writing channel of the superconducting device. The voltage amplitude of a given step at a fixed temperature consists of two parts, denoted in Fig. 9 as U_h and U_{h1}, respectively.

The voltage U_h (Fig. 9) is associated with energy dissipation in the superconductor, due to the appearance of additional vortex-antivortex pair in the laser writing channel. Magnetic vortices, as miniature magnets all together oriented same direction, strongly interact with each other. In the case of the coherent motion, the laser writing channel is full of vortices, which are arranged into a triangle magnetic lattice. Thus, an additional vortex-antivortex pair can be introduced into the laser writing channel's area only if vortices are more tightly squeezed, making some additional space for the new flux line. Moving coherently, Abrikosov vortices are spaced at a distance $d = \sqrt{2\Phi_0 /(\sqrt{3}B)}$, which is inversely proportional to the current-self produced magnetic field inductance B. If appear additional vortex-antivortex pairs in our laser writing channel, this process induces additional voltage steps with the amplitude U_{st}.

The energy dissipation due change in vortex velocity v can be determined as a subtraction $U_{h1} = U_{st} - U_h$.

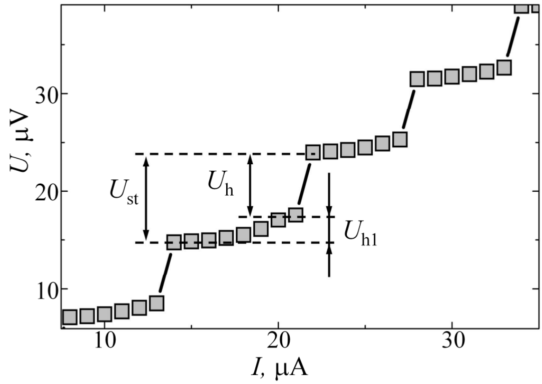

Fig. 9. The structure of electrical voltage step in voltage – current dependences. U_{st} – whole voltage of one one elektrical voltage step, U_h and U_{h1} represent electric voltage amplitude associated with appearance of additional vortex pair and with increase in velocity of magnetic vortices, moving along channel

The energy dissipation due change in vortex velocity v can be determined as a subtraction $U_{h1} = U_{st} - U_h$. The velocity of vortices $\eta v \sim F_L - F_p$ should increase with increasing the Lorentz force $F_L \sim I\Phi o \sim ma$. Here m is the "effective mass" of the Abrikosov vortex, a is the acceleration of vortex, I is the strength of bias current, and $\eta = f(B,T)$ is the viscosity coefficient of the superconducting medium, which is, in turn, a function of the current self produced magnetic inductance B and temperature of the superconducting device. The dissipative coherent vortex motion develops electric voltage in the superconductor (along the direction of bias current): $U_{h1} \sim N\Phi_0 v = Bv \sim ma$. For this reason, the U_{h1} increases with increasing the bias current within a single voltage step on the *I–V* dependence and in this way adds some small input to overall value of U_{st}, especially clear visible at low bias currents. For example, $I \leq 10 \cdot I_c$ in the case of *I–V* measured for single laser writing channel device at $T = 0.959 \cdot T_c$. However, at higher bias currents (i.e. $10I_c < I < 19I_c$), the input from U_{h1} decreases below resolution limit of our measurement setup. Assuming that at mentioned temperature Abrikosov magnetic vortices in the biased device, provided with a single laser writing channel appears in area of extremely low pinning, then any weak electric current, which self produced magnetic field can create only a single pair of Abrikosov vortices, will appear to be the superconducting critical current for the superconductor and this current is able to turn-on a coherent vortex motion along a partly-deoxygenated laser writing channel of the superconducting device.

General conclusions

1. The current self produced the first magnetic field in a form of Abrikosov magnetic vortices penetrates regions of weak superconductivity produced by a cw-laser writing technique in the dc-biased $YBa_2Cu_3O_{7-x}$ thin film devices. The density of magnetic vortices can be controlled by means of device's temperature and the biasing current.
2. Oxygen additional vacancies created by means of laser writing technique in the regions of weak superconductivity of $YBa_2Cu_3O_{7-x}$ superconducting devices, act as extended structural defects at temperatures below critical temperature of the superconductor T_c. The pinning force of oxygen vacancies in the superconductor can counteract with the extremely strong pinning force produced by other structural defects such as grain boundaries, screw dislocations etc. and affect a decrease of overall pining force in the region of weak superconductivity of the device. The overall pining force in the devices with regions of weak superconductivity can be controlled by means of variation of device's temperature.
3. The coherent motion of Abrikosov magnetic vortices in the regions of weak superconductivity starts when the time of nucleation of vortex-antivortex pairs coincides with the sum of vortex-antivortex transit to the annihilation line of the region of weak superconductivity and time of annihilation of moving pairs. The voltage amplitude of voltage "steps" in nonlinear current-voltage dependences of the $YBa_2Cu_3O_{7-x}$ superconducting devices at temperatures below critical temperature of the superconducting material mainly depends on energy of

condensation of vortex-antivortex pair in the superconductor and very little depends on variation of velocity of their motion along the region of weak superconductivity of the device.

List of published works on the topic of the dissertation

In the reviewed scientific periodical publications

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Steponavičienė, L.; Šulcas, J.; Jukna, A.; Jung, G.; Plaušinaitienė, V.; Abrutis, A.; Maneikis, A.; Gong, M.; Sobolewski, R. 2011. Investigation of vortex density in laser-written Π-Shaped channel of YBCO bridge by means of *I-V* dependences. *Acta Physica Polonica A*, 119(2): 180–182. ISSN 0587-4246 (ISI Web of Science).

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In the other editions

Steponavičienė, L.; Jukna, A. 2011. Magnetinių sūkurių koherentinio judėjimo $YBa_2Cu_3O_{7-x}$ superlaidžiuosiuose plonuosiuose sluoksniuose, su lazeriu įrašytu Π-formos sūkurių kanalu, tyrimai, sluoksniais tekant srovei $I \sim I$c: *Mokslas – Lietuvos ateitis*, 3(6): 105–110. ISSN 2029-2341 print / ISSN 2029-2252 online.

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MAGNETINIŲ SŪKURIŲ JUDĖJIMO $YBa_2Cu_3O_{7-x}$ SUPERLAIDŽIŲ SLUOKSNIŲ KANALAIS TYRIMAS IR VALDYMAS

Mokslo problemos aktualumas. Eksperimentiniais tyrimais nustatyta, jog mišriosios fazės atsiradimas, susijęs su magnetinio srauto prasiskverbimu į superlaidininką Abrikosovo magnetiniais sūkuriais, kurių judėjimas superlaidininku blogina tiek didelės, tiek ir mažos galios superlaidžiųjų elektroninių prietaisų charakteristikas. Superlaidžiosios elektronikos prietaisuose, sūkurių judėjimas sąlygoja elektroninio triukšmo atsiradimą, o kai judėjimas ypač intensyvus – jis tampa negrįžtamų pokyčių (t. y. prietaiso „sudegimo“) priežastimi. Tad medžiagos mišriosios fazės atsiradimo, jos savybių ir vystymosi tyrimai labai svarbūs tiek fundamentine, tiek ir praktinių taikymų prasme, siekiant prognozuoti atsitiktinį nepageidaujamų reiškinių atsiradimą ir jų vystymąsi.

Šiame darbe pritaikyta superlaidžių darinių, turinčių kontroliuojamų charakteristikų silpnojo superlaidumo sritis, lazeriu formavimo technologija. Tyrimais siekiama paaiškinti Abrikosovo magnetinių sūkurių prieraišos jėgos kilmę, pobūdį ir mechanizmą.

Tyrimų objektas. Antrosios rūšies superlaidininko $YBa_2Cu_3O_{7-x}$ mišrioji fazė plonuose sluoksniuose, kuriuose lazerio spinduliuote suformuoti superlaidieji dariniai, turintys silpnojo superlaidumo sritis.

Darbo tikslas ir uždaviniai. Darbo tikslas – pritaikius silpnojo superlaidumo sričių formavimo plonuosiuose $YBa_2Cu_3O_{7-x}$ sluoksniuose technologiją, paaiškinti mišriosios fazės superlaidžiųjų darinių, su silpnojo superlaidumo sritimis, elektrines ir magnetines savybes, dariniais tekant elektros srovei, kurios stipris $I > I_c$, kai darinių temperatūra $T < T_c$.
Tikslui pasiekti iškelti trys uždaviniai:

1. MOCVD būdu užaugintuose superlaidininko $YBa_2Cu_3O_{7-x}$ sluoksniuose lazeriu suformuoti darinius, turinčius silpnojo superlaidumo sritis, ir ištirti tų sričių dydžio ir formos priklausomybę nuo lazerio spinduliuotės galios.

2. Iš elektrinių ir magnetinių savybių kitimo dėsningumų paaiškinti mišriosios fazės atsiradimo $YBa_2Cu_3O_{7-x}$ superlaidžiuosiuose dariniuose, su silpnojo superlaidumo sritimis, sąlygas ir vystymosi ypatumus.
3. Ištirti Abrikosovo magnetinių sūkurių judėjimo pobūdžio $YBa_2Cu_3O_{7-x}$ dariniuose, turinčiuose silpnojo superlaidumo sritis, priklausomybę nuo darinio temperatūros ir juo tekančios elektros srovės stiprio.

Tyrimų metodika. Darbe taikomos $YBa_2Cu_3O_{7-x}$ superlaidžiųjų darinių, su silpnojo superlaidumo sritimis, formavimo lazeriu, keturių, trijų bei dviejų įvadų medžiagos elektrinių savybių tyrimų ir skenuojančio tunelinio mikroskopo tyrimų metodikos. Magnetinio srauto prasiskverbimo į superlaidininką kokybiniai tyrimų rezultatai gauti magnetooptinių tyrimų įranga. Cheminių elementų kiekybinė analizė atlikta skenuojančiu elektroniniu mikroskopu, su jame integruotu Rentgeno spindulių energijos dispersijos spektroskopu.

Mokslinis naujumas

1. Pritaikyta $YBa_2Cu_3O_{7-x}$ darinių, turinčių silpnojo superlaidumo sritis, formavimo lazeriu technologija.
2. Nustatyta, jog Abrikosovo magnetinių sūkurių prieraišos jėga priklauso nuo lazerio spinduliuotės galios, naudotos silpnojo superlaidumo srities formavimui ir sąlygojančios deguonies vakansijų kiekio ir tankio pokytį superlaidininke.
3. Nustatyta, jog siaurame temperatūrų intervale $T < T_c$, superlaidžiuoju dariniu tekant srovei $I > I_c$, Abrikosovo magnetiniai sūkuriai ir antisūkuriai juda koherentiniu judėjimu, kuris atsiranda silpnojo superlaidumo srityje esant ypatingai silpnai sūkurių prieraišos jėgai. Sūkuriams ir antisūkuriams judant koherentiškai, darinių voltamperinėse charakteristikose stebimi elektrinės įtampos „laipteliai“, kuriuos sąlygoja sūkurių ir antisūkurių porų atsiradimas.

Praktinė vertė. Gauti tyrimų rezultatai gali būti panaudoti kuriant magnetinio lauko ir/ar elektros srovės stiprio etaloninių matavimų prietaisus, kurių jautris ribojamas magnetinio srauto kvanto $\Phi_o = 2{,}067833758(46)\times10^{-15}$ Wb dydžiu.

Ginamieji teiginiai

1. MOCVD būdu užaugintuose $YBa_2Cu_3O_{7-x}$ superlaidžiuose sluoksniuose lazerio spinduliu kambario temperatūroje inertinių dujų

aplinkoje galima suformuoti darinius, turinčius silpnojo superlaidumo sritis. Tokių sričių kritiniai superlaidininko parametrai (t. y. I_c, T_c, H_{c1}) priklauso nuo lazerio spinduliuotės galios ir lazerio šviesą sugėrusios superlaidininko medžiagos pradinio deguonies kiekio.

2. Elektros srovei, tekančiai $YBa_2Cu_3O_{7-x}$ dariniais, stiprėjant, jos kuriamas magnetinis srautas pirmiausiai prasiskverbia į dariniuose esančias silpnojo superlaidumo sritis Abrikosovo magnetiniais sūkuriais, sukuriant mišriąją medžiagos fazę. Esant temperatūrai $T < T_c$, papildomų sūkurio ir antisūkurio porų atsiradimas ir judėjimas sąlygoja energijos nuostolių didėjimą ir lemia darinių netiesinių voltamperinių charakteristikų formą.
3. $YBa_2Cu_3O_{7-x}$ darinių „laiptuotų“ voltamperinių charakteristikų atsiradimą lemia koherentinio Abrikosovo magnetinių sūkurių ir antisūkurių judėjimas silpnojo superlaidumo sritimi, kurioje, dėl lazerio spinduliu sukurtų papildomų deguonies vakansijų, sūkurių prieraišos jėga ypatingai maža. Elektros įtampos „laiptelių“ aukštis priklauso nuo sūkurio ir antisūkurio poros kondensacijos energijos, o „laiptelių“ skaičius – nuo silpnojo superlaidumo sritimi judančių sūkurių porų skaičiaus, tačiau, didėjant elektros srovės, tekančios superlaidininku, stipriui, „laiptelių“ forma silpnai priklauso nuo sūkurių judėjimo greičio.

Darbo apimtis

Disertaciją sudaro įvadas, 3 skyriai, išvados, cituotos literatūros sąrašas, publikacijų disertacijos tema sąrašas.

Bendra disertacijos apimtis – 85 puslapiai, 36 iliustracijos, 21 numeruotų formulių. Rašant disertaciją buvo panaudoti 85 literatūros šaltiniai.

Įvadiniame skyriuje nagrinėjamas problemos aktualumas, formuluojamas darbo tikslas bei uždaviniai, aprašomas mokslinis naujumas, pristatomi autoriaus pranešimai ir publikacijos, disertacijos struktūra.

Pirmas disertacijos skyrius skirtas literatūros analizei. Jame nagrinėjamas superlaidumo reiškinys, superlaidžios medžiagos, jų kritiniai parametrai, fazės, Abrikosovo magnetiniai sūkuriai ir antisūkuriai bei koherentinis jų judėjimas, prieraišos mechanizmai.

Antrajame skyriume aprašomos tyrimo metodikos ir metodai. Superlaidžiųjų darinių formavimui naudojama lazerio technologija.

Trečiame disertacijos skyriuje aprašoma pritaikyta $YBa_2Cu_3O_{7-x}$ sluoksnių ir darinių gamybos technologija. Pateikiami $YBa_2Cu_3O_{7-x}$ superlaidžių darinių, suformuotų lazerio spinduliuotės poveikiu medžiagai, eksperimentiniai tyrimai. Pasiūlytas būdas kaip suskaičiuoti Abrikosovo magnetinius sūkurius ir antisūkurius, aprašomas jų judėjimas bei preiraišos mechanizmai $YBa_2Cu_3O_{7-x}$ dariniuose, turinčiuose silpnojo superlaidumo sritimis.

Bendrosios išvados

1. Silpnojo superlaidumo srityse, suformuotose nuolatinės veikos 532 nm bangos ilgio Ar jonų nuolatinės veikos lazerio spinduliuote, superlaidžiuose $YBa_2Cu_3O_{7-x}$ dariniuose Abrikosovo magnetinių sūkurių tankis priklauso nuo darinio temperatūros ir juo tekančios elektros srovės stiprio.
2. Lazerio spinduliuote formuojant $YBa_2Cu_3O_{7-x}$ darinių silpnojo superlaidumo sritis, dariniuose sukuriamos deguonies vakansijos. Deguonies vakansijos superlaidininke žemoje temperatūroje T = 86,7 K tampa išplėstiniais struktūriniais defektais. Šių defektų kuriama Abrikosovo magnetinių sūkurių prieraišos jėga, žemesnėje nei 86,7 K temperatūroje, gali konkuruoti su kitų defektų (tokių kaip tarpgrūdinės sritys, sraigtinės dislokacijos) kuriama ypač stipria prieraišos jėga. Keičiant superlaidžiojo darinio su silpnojo superlaidumo sritimis temperatūrą galima valdyti Abrikosovo magnetinių sūkurių prieraišos jėgą bei jų judėjimą.
3. Silpnojo superlaidumo sritimis Abrikosovo magnetiniai sūkuriai gali judėti koherentiškai. Toks judėjimas atsiranda tuomet, kai sūkurio ir antisūkurio užgimimo darinio kraštuose laikas sutampa su suma sūkurio ir antisūkurio lėkio iki anihiliacijos linijos laiko ir anihiliacijos laiko. Elektros srovės stipriui didėjant, sūkurio judėjimo greičio kitimo indėlį į elektrinės įtampos laiptelio superlaidžiojo darinio voltamperinėje charakteristikoje formą lemia sūkurių magnetinės gardelės inertiškumo didėjimas didėjant sūkurių skaičiui.

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INVESTIGATION AND CONTROL OF MOTION OF MAGNETIC VORTICES IN THE THIN SUPERCONDUCTING $YBa_2Cu_3O_{7-x}$ FILMS

Summary of Doctoral Dissertation
Physical Sciences, Physics (02P),
Condensed Matter: Elektronic Structure; Elektrical, Magnetic and Optical Properties; Superconductors; Magnetic Resonance, Relaxtion; Spectroscopy (P260)

Lina STEPONAVIČIENĖ
MAGNETINIŲ SŪKURIŲ JUDĖJIMO $YBA_2CU_3O_{7-X}$ SUPERLAIDŽIŲ SLUOKSNIŲ KANALAIS TYRIMAS IR VALDYMAS

Daktaro disertacijos santrauka
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