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Thermal Fluctuations in YBCO Thin Film on MgO Substrate

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The c-axis orientation $YBa_2Cu_3O_\delta$ thin film was prepared directly on MgO substrate by the pulse laser deposition. The thickness of the film was 170 nm. The superconducting critical temperature was $T_{c50\%} = 89$ K and the width of superconducting transition was $\Delta T = 1.6$ K. Temperature dependence of the critical current of the film was obtained from the temperature dependences of the imaginary part of the AC susceptibility using the Bean model. The critical current density was $J_c = 1.2 \times 10^7$ A/cm^2 at 77 K in the self field. The critical exponents were calculated for several values of the DC applied magnetic field using the temperature dependences of magnetoresistivity. The thermal fluctuations in vicinity of the critical temperature were analysed.

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1. Introduction

The high temperature superconductors (HTS) possess special features in comparison to the classical ones. HTS are extreme second type with the large penetration depth λ of the order of 10^3–10^4 Å [1] and very small coherence length ξ of the order of 10 Å. That makes the Ginzburg–Landau parameter $\kappa = \lambda/\xi$ of the order of 10^2 or more. Other important superconducting parameters are also extremely anisotropic (e.g. the ratio of c- to ab-direction of penetration depths $\gamma = \lambda_c/\lambda_{ab}$ is of the order of 10–10^2 for YBCO and of the order of 10^4 for BiSCO), as well as the critical currents, the irreversibility fields and others, because of the anisotropic layered structure of weakly coupled CuO_2 superconducting planes. As a consequence, the huge thermal fluctuations around the critical temperature of the superconducting transitions in HTS are observed. Within this critical region the competition between the critical fluctuations at lower temperatures and the Gaussian (stochastic) fluctuations at the temperatures above the critical temperatures exists and depends on the applied magnetic field as well as the applied pressure [2–4]. Because of the huge anisotropy the superconductors exhibit generally the three-dimensional (3D) to the two-dimensional (2D) transition in the critical region for polycrystalline, single crystal as well as for thin film samples [5–8]. There is also observed the crossover from 2D to 1D in Hg-Tl 1223 polycrystalline superconductor [9].

In this paper the critical currents and the thermal fluctuations of the $YBa_2Cu_3O_\delta$ thin film prepared on MgO substrate close to the zero resistance critical temperature were studied and the relevant critical exponents were obtained.

2. Experimental

The sample was prepared by the pulsed laser deposition (PLD) on single crystal (100) one side polished MgO substrate. Our PLD setup (Neocera) was running on excimer laser (Coherent COMPexPro 110F) with a wavelength of 248 nm. Pulse energy was 200 mJ and repetition rate was 10 Hz. During deposition substrate temperature and O_2 partial pressure were set to 750 °C and 100 mTorr, respectively. Deposition lasted 50 min. After deposition O_2 partial pressure was set to 300 Torr and sample was cooled to 400 °C with ramp 3 °C/min and then annealed in this temperature for 30 min. The target used during film preparation was made from powder obtained by standard solid-state reaction technique, pressed at a pressure of 0.7 GPa and sintered at 940 °C for 72 h. The distance between target and substrate was 9 cm. The film thickness was determined using XRF spectrometer and it was 170 nm. X-ray diffraction on the film on MgO substrate showed excellent c-axis orientation and no secondary phases were detected in the XRD spectra.

The AC susceptibility was measured by a mutual inductance bridge working at frequency 188 Hz. The Stanford SR 830 lock-in nanovoltmeter was a source of AC current for the transmitting coil which is producing AC magnetic field and also the same lock-in nanovoltmeter

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was used to measure signal from the mutual inductance bridge. The temperature dependences of resistance were carried out using the standard four-point AC method with Stanford SR 830 lock-in nanovoltmeter. The AC susceptibility as well as the resistance measurements were done with the c-axis perpendicular to the applied magnetic field configuration. The electrical contacts were made by sputtering silver using DC magnetron. To avoid short-circuit between sputtered contacts we put on the sample surface mask that ensures 1 mm gap between the contacts. Next the wires were glued to the sputtered contacts by Leitsilber 200 silver paint and then heated up to 300 °C. In both types of experiments the temperature was monitored and controlled by Lake Shore temperature controller employing a chromel-gold-0.07% Fe thermocouple with an accuracy of 0.05 K.

3. Results and discussion

The dispersion (χ') and absorption (χ'') parts of AC susceptibility as a function of the temperature were measured for the several applied magnetic fields. The selected curves of these measurements are shown in Fig. 1. From onset of superconducting transition of dispersive part of AC susceptibility the intra-grain critical temperature was determined. The value of this temperature is 87.6 K. From the absorption part of AC magnetic susceptibility the critical current densities were calculated. They were obtained from the position of absorption peaks adapting Bean's critical state model and its extensions. At the temperature corresponding to the peak position the AC magnetic field amplitude H_{AC} penetrates into center of the sample and the current induced by the magnetic field flows uniformly throughout the entire sample and it is equal to the critical current density. From the Bean model [10] the following equation for critical current density can be drawn:

$$J_c = \frac{2H_{\text{AC}}}{b}, \tag{1}$$

where H_{AC} is the value of the applied AC magnetic field and b is the sample dimension perpendicular to the AC magnetic field. The thickness of the sample $b = 170$ nm was taken to calculate the critical current densities.

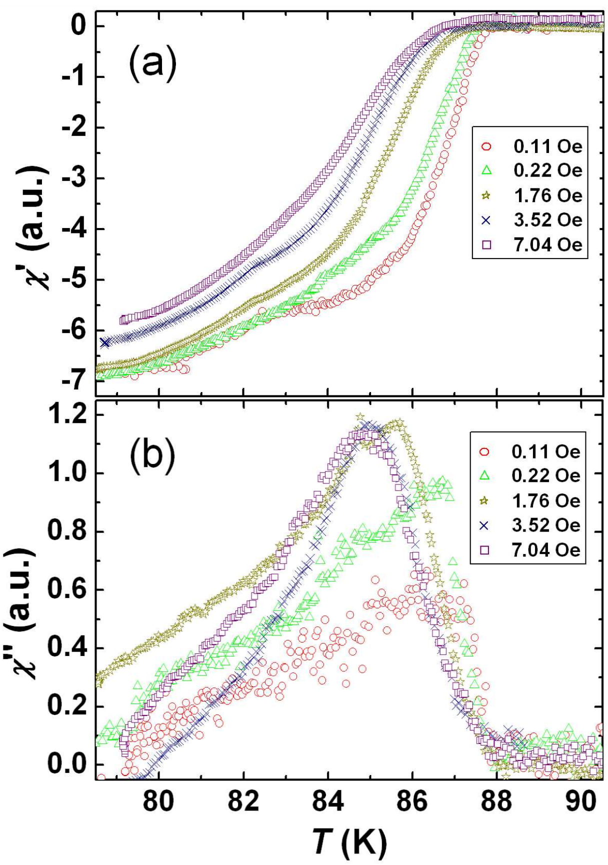

Fig. 1. Dispersion (a) and absorption (b) parts of the AC susceptibility of YBCO thin film on a MgO substrate as a function of temperature for several values of the applied magnetic field.

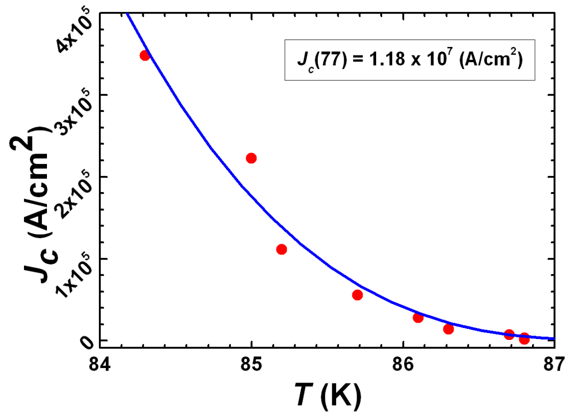

Fig. 2. Critical current J_c versus temperature obtained from the AC susceptibility using the Bean model (closed circles) of YBCO thin film on a MgO substrate. The solid line is the fit to Eq. (2).

The critical currents as a function of temperature were calculated using Eq. (1). They are shown in Fig. 2. Their temperature dependences were fitted using the Ginzburg–Landau approach expressed by the following formula [11]:

$$J_c = J_{c0}\left(1 - \frac{T}{T_{c0}}\right)^n, \tag{2}$$

where T_{c0} is the temperature in which the whole sample stayed superconducting. T_{c0} depends on the applied magnetic field. J_{c0} is the critical current extrapolated to 0 K. The results of the fit to temperature dependences of the critical current densities using Eq. (2) were shown in Fig. 2. The fitted parameters were as follows: $J_{c0} = 7 \times 10^9$ A/cm^2 and $n = 3.0$. The zero resistance critical temperature $T_{c0} = 87.6$ K was taken from experiment. Taking advantage of the fitting parameters the critical current at 77 K was calculated. It was $J_c = 1.2 \times 10^7$ A/cm^2.

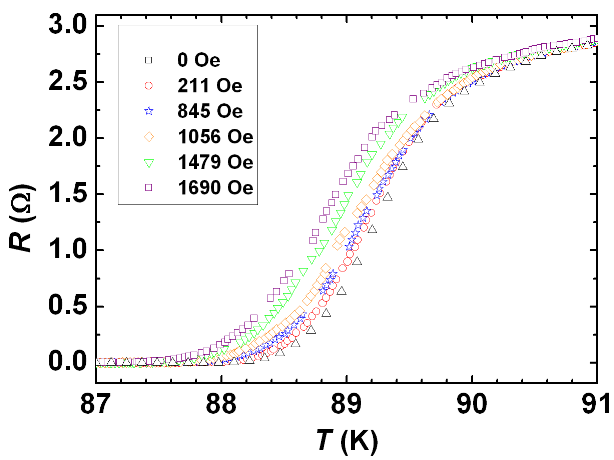

Fig. 3. Resistance versus temperature of YBCO thin film on a MgO substrate within the range of superconducting transition for several values of the applied magnetic field.

The selected curves of the temperature dependences of resistance for the several applied magnetic fields are shown in Fig. 3. The basic parameters obtained from $R(T)$ dependence for the zero applied magnetic field are as follows: the zero resistance temperature $T_{c0} = 87.8$ K was obtained with the 1 μV/cm electrical field criterion, $T_{c50\%} = 89.1$ K and $T_{c\_onset} = 91.4$ K.

The thermal fluctuations were studied on the basis of the temperature dependences of the resistance using the following formula:

$$\Delta\sigma = K\varepsilon^{-\lambda}, \tag{3}$$

where $\varepsilon = (T - T_c)/T_c$, λ is a critical exponent and K is a constant. The temperature dependence of excess conductivity is defined within the Ginzburg–Landau mean field approximation as:

$$\Delta\sigma(T) = \frac{1}{R(T)} - \frac{1}{R_R(T)}, \tag{4}$$

where $R(T)$ is the measured resistivity and $R_R(T)$ is the resistivity obtained by the linear extrapolation of the resistivity data from about 130 K down to the onset temperature. The determination of $\Delta\sigma$ involved the determination of R_R for temperatures near T_c by extrapolating of the high temperature behaviour as follows:

$$R_R(T) = R_0 + \left(\frac{\mathrm{d}R}{\mathrm{d}T}\right) T, \tag{5}$$

where R_0 and $\mathrm{d}R/\mathrm{d}T$ are constants. The way to determine the critical exponents was described in the paper [12]. To obtain values of critical exponents λ, Eq. (3) was transformed into the following formula:

$$\log \Delta\sigma = -\lambda \log \varepsilon + \mathrm{const}, \tag{6}$$

where the searched value of critical exponent λ is equal to negative value of the slope of the fitted line to the linear parts of the dependence from Eq. (6). The relation (6) is shown in Fig. 4. In the critical region, in which the critical fluctuations are observed, the full dynamical scaling theory [13] predicts that the excess conductivity in Eq. (3) diverges at the critical temperature with the critical exponent given by the relation

$$\lambda = \nu\,(2 + z - d + \eta)\,, \tag{7}$$

where ν is the critical exponent for the coherence length, z is the dynamical exponent, d is the dimensionality of fluctuations spectrum and η is exponent for the order parameter of the correlation function. The thermodynamic properties of superconductors in the critical region are the same as for 3D-XY model. Then, according to the papers [2, 14] one should substitute $\nu = 2/3$, $z = 3/2$ and $\eta = 0$.

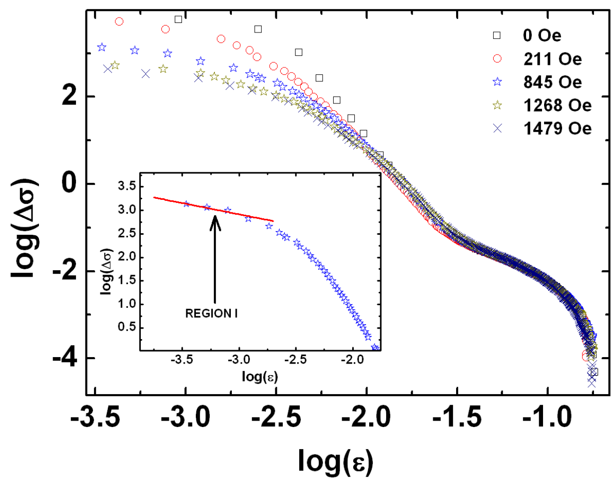

Fig. 4. The $\log(\Delta\sigma)$ versus $\log(\varepsilon)$ dependence for several values of applied magnetic field. Inset: an example of linear fitting within the region used in analysis of critical exponents.

In the temperature interval further from the critical temperature the critical exponents are dominated by Gaussian fluctuations. The mean field Ginzburg–Landau theory predicts that $\nu = 1/3$, $z = 2$ and $\eta = 0$. Thus, as in the paper [15], the Gaussian fluctuations can be described by

$$\lambda = 2 - \frac{d}{2}, \tag{8}$$

where d is the dimensionality of fluctuations spectrum.

The critical exponents as a function of the applied magnetic field for region I which starts at T_{c0} and ends at 88 K were calculated using Eq. (6). These results are shown in Fig. 5. The critical exponent is equal to $\lambda = 0.53$ at $H = 0$ Oe. Further on the critical exponents decrease with increase of the applied magnetic field up to $\lambda = 0.35$ at $H = 1690$ Oe. The critical exponents decrease linearly in the range of the applied magnetic field used in the experiment. Taking advantage of Eq. (7) the dimensionalities of the fluctuating system were calculated and they are $d = 2.7$ and $d = 3.0$, respectively. It means that 3D fluctuating system is observed in the vicinity of the zero resistance critical temperature.

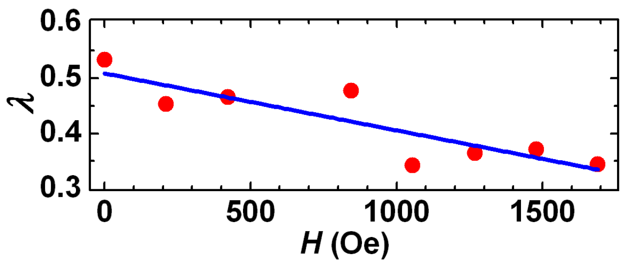

Fig. 5. Critical exponent obtained from the linear fit of $\log(\Delta\sigma)$ versus $\log(\varepsilon)$ dependence as a function of the applied magnetic field.

4. Conclusions

The results of the paper may be summarized as follows:

1. The critical currents of the single phase and *c*-axis oriented YBCO thin film on MgO substrate were calculated from the a.c. susceptibility measurements using the Bean model. The temperature dependence of the critical current was found and was fitted using the Ginzburg–Landau approach expressed by Eq. (2).

2. The big value of the critical current $J_c = 1.2 \times 10^7$ A/cm^2 as well as the large fitted exponent $n = 3.0$ confirm the very strong pinning of this specimen.

3. Close to the zero resistance critical temperature the critical exponents as a function of the applied magnetic field show linear decrease with the increasing field.

4. Dimensionalities of the fluctuating system were calculated using Eq. (7) and they are $d = 2.7$ and $d = 3.0$ for $H = 0$ Oe and for $H = 1690$ Oe, respectively. It means that in the thin film the 3D fluctuating system is observed.

Acknowledgments

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