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ANOMALOUS REVERSIBLE TORQUE IN LAYERED SUPERCONDUCTING $Bi_2Sr_2CaCu_2O_x$ SINGLE CRYSTAL

Z. Drzazga, W. Borgieł

Institute of Physics, Silesian University, Uniwersytecka 4, 40-007 Katowice, Poland

R. Szymczak and H. Szymczak

Institute of Physics, Polish Academy of Sciences
Al. Lotników 32/46, 02-668 Warszawa, Poland

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Magnetic anisotropy of layered superconducting $Bi_2Sr_2CaCu_2O_x$ single crystal was investigated by the torque method in the reversible regime. The torque was analyzed in the model taking into account 2D layered structure. Considered model gives the better fit to the data when the magnetic field is applied near (a, b) plane. Obtained results establish to 6×10^3 value of the superconducting effective mass anisotropy coefficient ε.

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1. Introduction

The discovery of the high-T_c oxide superconductors has provoked extensive studies on the superconducting and magnetic properties of them. It was generally recognized that superconducting materials are anisotropic. The anisotropy plays an important role in the properties of the high-T_c materials. The bismuth family $Bi_2Sr_2CaCu_2O_x$ is thought to be one of the most anisotropic. The parameter ε which characterizes anisotropy is defined by the square root of the ratio of $m_{\|}$ and $m_{\perp}$ which are the Ginzburg–Landau superconducting effective masses [1] for the pair motion along the c direction and in the (a, b) plane respectively. Various experimental methods including resistance, magnetization and torque measurements are used to determine the intrinsic anisotropy of the high-T_c superconductors. The magnetic torque experiments have proved to be an extremely powerful technique to obtain the square root of the effective mass ratio according to the Kogan [2] model. The values obtained from these measurements for ε were $\varepsilon \approx 8$ for $YBa_2Cu_3O_x$ [3, 4], $\varepsilon \approx$ 55–400 for $Bi_2Sr_2CaCu_2O_x$ [5–7] and $\varepsilon \approx 94$ for $Tl_2Ba_2CaCu_2O_x$ [8]

respectively. Rather big discrepancies among the reported in literature results for parameter ε especially for Bi compounds suggest that Kogan's formula [2] based on the anisotropic Landau model is not applicable to the highly layered anisotropic superconducting materials.

The aim of this paper is the interpretation of the torque data for the $Bi_2Sr_2CaCu_2O_x$ in the reversible regime and the extraction of the effective mass ratio $m_\perp/m_\parallel$ and information about the critical field H_{c2} from model calculations which contains quasi-2D behaviour of layered superconductors [11, 12]. The paper is organized as follows. Section 2 contains the information about experimental details and Sec. 3 describes the model which has been applied. The description of the obtained results from modeling calculation is given in Sec. 4. The discussion ends the paper.

2. Experimental

For this work we have measured single crystals of $Bi_2Sr_2CaCu_2O_x$ which were obtained by float zone melting technique [13]. Samples had form of platelets with c-axis perpendicular to the surface. The dimensions of the largest sample were $5.4\times2.6\times0.9$ mm^3. The real structure of the investigated samples was checked by the Laue and rotation crystal patterns. The distribution of the orientation of the c-axis was found to be ±0.15 deg. The distribution of (a,b) plane was ±2.0 deg.

Crystals used in our experiments were irradiated by fast neutrons with fluence of 1.5×10^{17} neutrons/cm^2 which in effect enhanced pinning potential and critical current [14]. The superconducting transition of samples was measured resistively to yield $T_c(\rho=0)=86.6$ K [15].

The anisotropy measurements of the $Bi_2Sr_2CaCu_2O_x$ were carried out with the torsion magnetometer in the magnetic field up to 1.76 T. The magnetic field was rotated with velocity of 0.1 rpm in the plane containing the c-axis. The torque was measured as a function of the angle ϑ_H between the c-axis and the field direction. A narrow region ($\vartheta_H\approx90$ deg) around the (a,b) plane was precisely investigated. The sample was cooled down through the critical temperature in a very low (0.002 T) magnetic field to the measurements temperature. Then the magnetic field was switched on the measuring value along the c-direction and torque was measured during rotation of the applied field.

The sensitivity of torque magnetometer was 10^{-9} N m. In the temperatures above 70 K the torque curve showed a characteristic maximum when magnetic field passed through the (a,b) plane. Irreversible effects quickly disappeared with increasing temperature and magnetic field. No hysteresis was found within our experiments accuracy in magnetic field above 0.5 T and $T>75.5$ K. However the shape of peak and its position was found to be a slight function of temperature and magnetic field similarly to the results of paper [9]. Interpretation of the torque data within Kogan's formula [2] is open to discussion. Steinmayer et al. suggested in [10] that the reliable values of anisotropy from Kogan's formula is only obtained for field above 2 T because of influence of the lock-in peak for HTC superconductors. Figure 1 presents the torque measured for single crystal Bi_2Sr_2CaCuO in magnetic field 0.5 T and temperature 78 K. We try to test these experimental results with model presented further below.

3. Model

Measurements of the reversible torque in $Bi_2Sr_2CaCu_2O_x$ show a structure (see Fig. 1). The torque T as a function of angle ϑ_H (the angle between applied field $\boldsymbol{H}$ and c-axis) shows sharp maximum near 90° and some cavity lightly below. The traditionally used phenomenology of Kogan's [2] seems to describe the behaviour of the torque in $YBa_2Cu_3O_x$ [3, 4] well but not in higher anisotropic superconductors as Bi- and Tl-based compounds [6–8]. The above discrepancies are probably connected with 2D character of those superconducting materials.

Recently Feinberg and Villard [8] proposed the model which is able to take into account a layered structure of superconductors. The details were formulated in [8, 9]. Below we present formulas which were used. We have assumed that model from [8] describes well the behaviour of the torque in the vicinity of the critical angle ϑ_c. For smaller angles ($\vartheta < \vartheta_c$) the simple phenomenological description taken from [2] should coincide well with that given in [9]. In the interpretation of the experimental results we join together both models described in [2] and [9].

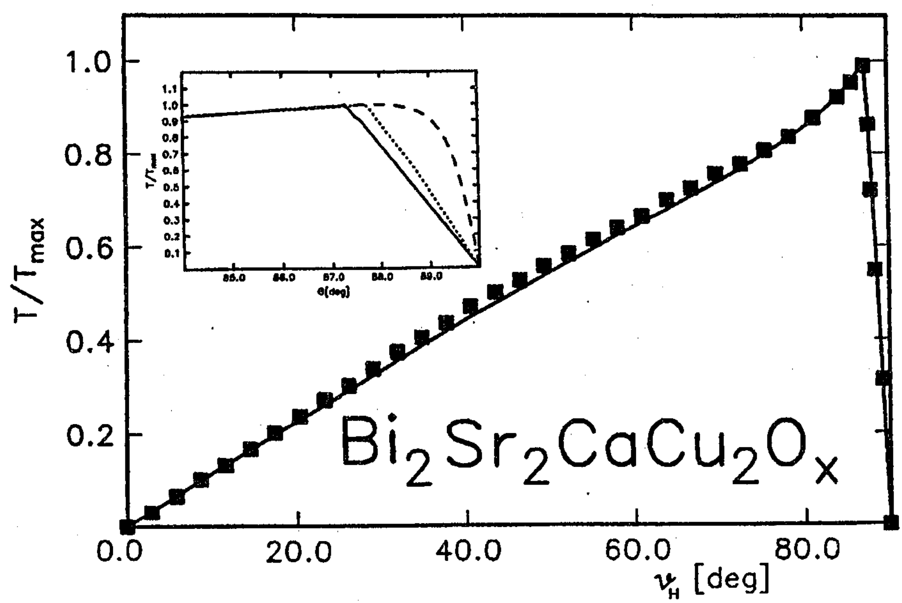

Fig. 1. The experimental data (filled squares) for relative torque T/T_{max} of the $Bi_2Sr_2CaCu_2O_x$ superconductor as a function of angle ϑ_H obtained in magnetic field $H = 0.5$ T and temperature $T = 78$ K. The continuous line presents results of the model calculations with $\varepsilon = 78$, $H_{c2} = 100$ T. The insert shows structure of the relative torque versus ϑ_H in the vicinity of critical angle ϑ_c for Kogan's formula (broken), experiment (dotted) and current model (continuous) line respectively.

The calculation of equilibrium properties of flux lines in presence of core anisotropy were performed in [8]. The flux lattice Gibbs energy for ϑ_H close to the critical ϑ_c in notation taken from [9] has the following form:

$$G = \frac{B^2}{8\pi} + \frac{H'^* B}{4\pi} - \frac{H\,B}{4\pi}\sin\vartheta_H - \frac{h^* B}{\pi} n_K L_K e^{-(1/n_K) L_K}, \tag{1}$$

$$\cos\vartheta_c = (1/\pi)\left[2\alpha_1 \frac{H^*}{H}\left(1+\varepsilon^2\frac{H^*}{H}\right)\right]^{1/2}, \tag{2}$$

where $H = |\boldsymbol{H}|$ — external applied field, $B = |\boldsymbol{B}|$ — induction inside the sample, ϑ_H — angle between $\boldsymbol{H}$ and c-axis, $h^* = \phi_0\varepsilon^{-1/3}\alpha_1/4\pi\lambda^2$, ϕ_0 — quantum flux, $\varepsilon = (m_\perp/m_\parallel)^{1/2}$, $m_\perp, m_\parallel$ — effective electron mass in direction perpendicular and parallel to the planes in the sample. The quantity λ is the averaged penetration length defined $\lambda = (\lambda_\parallel^2\lambda_\perp)^{1/3}$,

$$H^* = \phi_0\varepsilon^{-1/3}/4\pi\lambda^2[\ln\sqrt{H_{c2}/B} + \alpha], \tag{3}$$

$$H'^* = \phi_0\varepsilon^{-1/3}/4\pi\lambda^2[\ln\sqrt{H_{c2}/B} + \alpha - \alpha_1], \tag{4}$$

$$\alpha = \alpha_0 - \alpha_1\sin^2(\pi z/d), \qquad \alpha_1 < \alpha_0, \tag{5}$$

α describes sinusoidal modulation of the core energy along the z direction perpendicular to the planes. The n_K, density of solitons (kinks) is given by the formula [9]

$$n_K = 1/[L_K|\ln(q_1/q_c - 1)|], \tag{6}$$

where

$$L_K = (d/\pi)\sqrt{K_1/2V} \quad \text{is the kink length,} \tag{7}$$

$$q_c = (4/\pi)\sqrt{V/2K_1}, \tag{8}$$

$$q_1 = HB\cos\vartheta_H/4\pi K_1. \tag{9}$$

The so-called lock-in transition occurs at $q_1 = q_c$ when n_K goes to zero and the flux lattice becomes exactly parallel to the layers. From minimization of the G the following equations of state and expression for the reversible torque are obtained:

$$B = H\sin\vartheta_H - H'^* - \frac{2h^* B}{B + \varepsilon^2 H^*} n_K L_K, \tag{10}$$

$$T = V_0\frac{H^2}{4\pi}\left[\sin\vartheta_H\cos\vartheta_H - \pi\sin^2\vartheta_H\left(\frac{2h^*}{H\sin\vartheta_H + \varepsilon^2 H^*}\right)^{1/2} n_K L_K\right] \tag{11}$$

(V_0 — the volume of the sample). In order to describe the torque T for angles from the interval $[0, \vartheta_c - \Delta]$ (Δ describes the vicinity of the ϑ_c) we have applied the formula justified in [9] of the form

$$T = V\frac{\phi_0 H}{64\pi^2\lambda^2}\frac{(\varepsilon^2-1)}{\varepsilon^{2/3}}\frac{\sin 2\vartheta_H}{(\sin^2\vartheta_H + \varepsilon^2\cos^2\vartheta_H)^{1/2}} \times \ln\left[\frac{\varepsilon\eta H_{c2}}{H(\sin^2\vartheta_H + \varepsilon^2\cos^2\vartheta_H)^{1/2}}\right], \tag{12}$$

notation is the same and η is the simple scaling dimensionless parameter taken here to be equal to 1.

4. Results and conclusions

The torque curve (Fig. 1) was fitted by the effective mass model [2] and model modified by the lock-in of flux for fields close to the layer direction (described in Sec. 2). The main fitting parameters obtained within modeling were $\varepsilon = 78$ and $H_{c2} = 100$ T. The obtained values seem to be reasonable and coincide with reported in [6]. Analogical value of the square root of the effective mass ratio ε was derived from measuring the longitudinal and transverse components of the equilibrium magnetization of crystals oriented at arbitrary angles with respect to the applied direction [16]. The value of ε equal to 78 obtained for $Bi_2Sr_2CaCu_2O_x$is markedly higher than for $YBa_2Cu_3O_x$ ($\varepsilon \approx 8$) which indicates existence of giant internal anisotropy. It means that superconducting effective mass anisotropy ratio $m_\perp/m_\parallel$ is greater than 6000.

The torque fit curve according to Kogan's formula markedly deviates near $\vartheta_H \approx 90$ deg (see insert in Fig. 1, the broken line). Taking into account the trapping of vortex cores between layers leads to an improvement of the fit to the experimental data (see insert in Fig. 1, continuous and dotted lines). For calculations which give the best fit to the measured torque (Fig. 1) the following values of the decisive parameters were obtained: $\alpha_0 = 0.5$, $\alpha_1 = 0.4$, $\lambda = 350$ nm with $\varepsilon = 78$ and $H_{c2} = 100$ T (ε, H_{c2} are reasonable and coincide with reported in [6, 16]).

In order to investigate the torque behaviour in layered quasi-2D superconductors we have performed several calculations of the torque using different values of $\varepsilon = (m_\perp/m_\parallel)^{1/2}$, λ, α_1, H and H_{c2}. Additionally, we have calculated critical value ϑ_c as a function of ε, λ, H and H_{c2}. Formulas and definitions we have applied were explained in Sec. 2. The obtained results are presented in Figs. [2–4]. In all calculations for the modulation quantity $\alpha(z)$ the average over the layers which is simply equal to $\alpha(z) = \alpha_0 - \alpha_1/2$ [8] has been taken. The parameter Δ was always constant and established to be 5 deg. The detailed behaviour of the torque in the vicinity of ϑ_c as a function of several parameters is presented in Fig. 1 and Fig. 2. It is known that field H_{c2} has a marked influence on the curvature of the torque curve. Nevertheless, ε has decisive influence on the position and shape of the peak (see insert of the Fig. 2). The angular halfwidth is thought to be a direct measure anisotropy. The calculated critical angle ϑ_c (Fig. 3 and Fig. 4) is also a function of the values of λ and α_1 when the trapping of vortex cores between layers is admissible. Parameters λ and α_1 describe directly layered structure. In every figure the special case which corresponds to the best fit to presented in Fig. 1 is marked by filled square. The other needed model parameters were the same as reported above when Fig. 1 was discussed.

We have shown that the value of ε has decisive influence on value ϑ_c which was predicted earlier also by Kogan's model [2]. However, ϑ_c depends additionally on sinusoidal modulation of core flux energy (α_1) and average penetration length (λ). Generally, when ε increases starting from 1 to values less than 10, ϑ_c increases and reaches maximum value. When ε belongs to the interval 10–100 we have observed decreasing of ϑ_c which depends on values of λ (Fig. 3) and α_1 (Fig. 4). The descent of ϑ_c versus ε is markedly greater for low values of λ. For

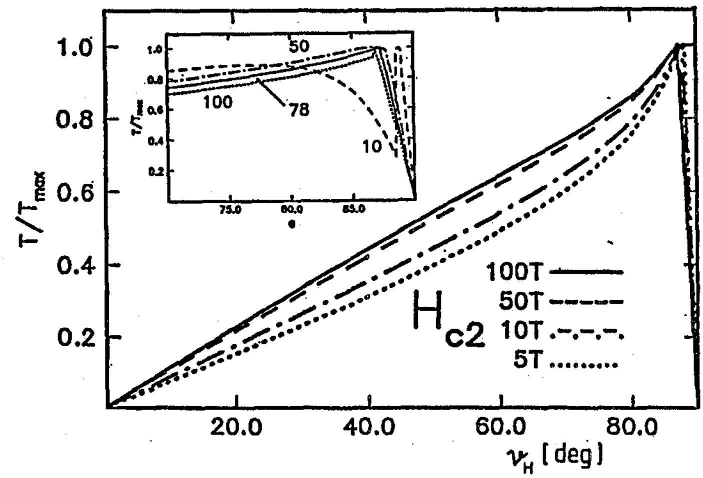

Fig. 2. The relative torque $T/T_{\max}$ as a function of angle ϑ_H for established $\varepsilon = 78$ and for different values of H_{c2}. For details of the model and values of the other parameters see the text. The insert shows structure of the relative torque versus ϑ_H in the vicinity of critical angle ϑ_c for several ε which are marked in the picture.

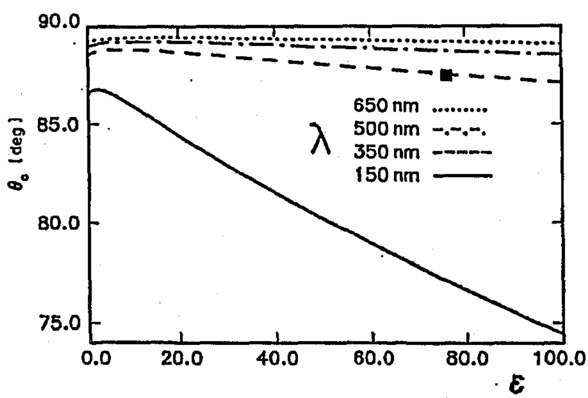

Fig. 3. The critical angle ϑ_c as a function of ε for different values of parameter λ. The filled square corresponds to the value for the best fit to the experimental data. For details of the model and values of the other parameters see the text.

λ greater than 500 nm practically saturation of ϑ_c was observed. The increase in α_1 causes the lowering of critical angle ϑ_c (Fig. 4). It is noteworthy that taking into account the trapping of the vortex cores between layers shifts the maximum of the torque towards higher angles ϑ_H especially for $\varepsilon > 5$.

Summarizing, we conclude that it was possible to apply the model proposed by Feinberg and Villard in [11, 12] in order to get satisfactory agreement with experimental (Fig. 1) data obtained under the field closed to the (a, b) plane and determine the superconducting effective mass anisotropy from torque measurements.

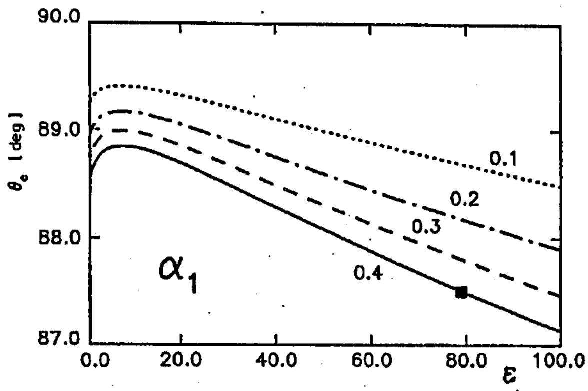

Fig. 4. The critical angle ϑ_c as a function of ε for different values of modulation parameter α_1 equal to 0.4, 0.3, 0.2, 0.1 respectively. The filled square corresponds to the value for the best fit to the experimental data. For details of the model and values of the other parameters see the text.

As reasons for rather big discrepancies of the model parameters (ε, H_{c2}) reported in various papers [5–7, 16], except imperfections of the investigated samples, it may be that flux-pinning under the field near the (a, b) plane is not neglected completely in real crystals of HTC-superconductors. The performed calculations and comparison with experimental data prove that the layer discreteness can modify much torque behaviour observed in the strong anisotropic bismuth family superconductors.

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