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On the dynamics of vortices in BSCCO(2223)/Ag tape

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Abstract

Magnetic relaxation measurements in BSSCO(2223)/Ag rolled tape were performed at different temperatures and magnetic fields applied along the *c*-axis. The crossover in vortex dynamics has been found on the temperature dependence of the activation energy U_0. It is argued that the crossover T^* might be associated with the melting of the 2D vortex lattice.

Keywords: Activation energy; Lattice vortex melting

1. Introduction

The dynamics of the flux in high temperature superconductors (HTS) was widely investigated both experimentally and theoretically. While in rather well defined structures, like $RBa_2Cu_3O_{7-\delta}$ single crystals, the situation has been already quite well mapped, in Bi(2223)/Ag tapes, the experimental findings are still rather contradictory. For example, Mittag et al. [1] found the temperature dependence of the activation energy in this compound to be nearly monotonous, with increase followed by very slow decay (almost saturation) at higher temperature. Similar results were obtained in Ref. [2], for magnetic field oriented both parallel and perpendicular to the sample surface. Quite different shape of the temperature dependence was obtained by Kopelevich et al. [3]. These authors found a very pronounced peak at around 20 K, followed by a sharp drop. The first attempt how to explain the non-monotonous temperature dependence of activation energy was that of Hagen and Griessen [4] who assumed a distribution of pinning potentials and elaborated an inversion scheme for evaluation of this distribution from experimental relaxation data. According to this approach, the activation energy should increase with temperature. Another approach, based on the work of Beasley et al. [5], was used by Xu et al. [6], for interpretation of relaxation measurements in the *c*-axis oriented powder specimen YBCO. They also observed the activation energy increasing with temperature.

In this paper we discuss the temperature dependence of the activation energy observed in BSSCO(2223)/Ag tape.

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2. Experimental

The BSCCO(2223)/Ag tape was prepared by standard PIT technique followed by rolling and thermal treatment as described in Ref. [7]. The sample had the rectangular shape $5 \times 2.8 \times 0.032$ mm^3. For determination of the activation energy we used the dynamic relaxatione method [8,9]. Magnetic hysteresis loops (MHLs) were measured by means of vibrating sample magnetometer (VSM) Model 155 with magnetic field up to ± 2 T, in the temperature interval 4.5–70 K. Magnetic field was always applied along the normal to the sample surface ($B \| c$). Before each measurement the sample was cooled at zero external field (ZFC). Then the hysteresis curves were recorded at various constant magnetic field sweep rates ranging from 0.9 to 90 mT/s. From these MHLs the normalized dynamic relaxation rate $Q = \mathrm{d}\ \ln m / \mathrm{d}\ \ln(\mathrm{d}B/\mathrm{d}t)$ was determined.

The temperature dependence of the normalized dynamic relaxation rate $Q = \mathrm{d}\ \ln m / \mathrm{d}\ \ln(\mathrm{d}B/\mathrm{d}t)$ at different B is shown in Fig. 1.

The temperature dependence of activation energy U_0 might be extracted from the following equation [9]:

$$Q = \frac{kT}{\left(U_0 + \mu kT \ln\left(\frac{\nu_0 B}{2a\,\mathrm{d}B/\mathrm{d}t}\right)\right)}, \quad (1)$$

where ν_0 is the attempt velocity of vortices, $2a$ is sample thickness, μ is the exponent within the collective creep theory [10], μ determines the different current limits. For $\mu = 1/7$ the large current limit is

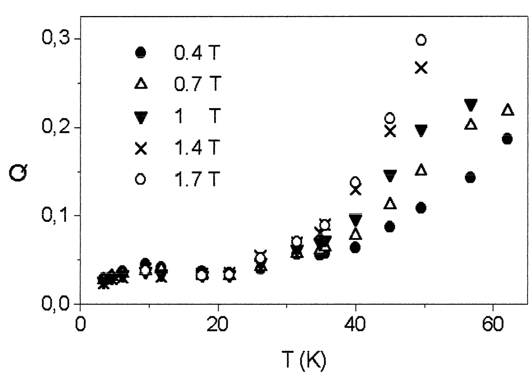

Fig. 1. The normalized relaxation rate Q derived at $B = 0.4$–1.7 T from the set of MHLs measured with various sweep rates.

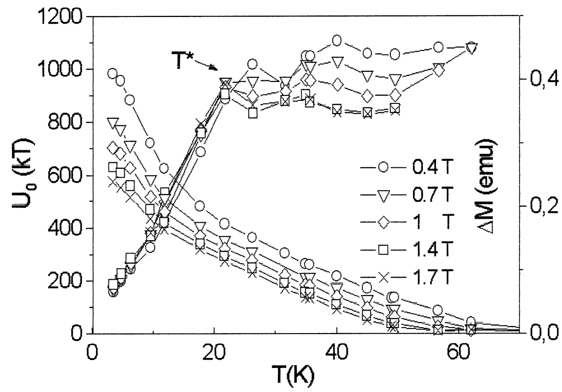

Fig. 2. Temperature dependence of the activation energy calculated from Eq. (1) with $\nu_0 = 10$ m/s, $a = 10^{-4}$ m, $\mathrm{d}B/\mathrm{d}t = 10^{-2}$ T/s, $\mu = -1$ and the irreversible magnetization ΔM.

considered, for 3/2 there is intermediate currents regime and 7/9 is small currents at high fields and temperatures and $\mu = -1$ is the case of the Anderson model [11].

3. Discussion

During the evaluation of experimental data we found a linear dependence of magnetization M of $\ln(\mathrm{d}B/\mathrm{d}t)$ overall temperature and field region. Půst [12] has shown that such a dependence is predicted for Anderson model [11] and we, thus, put μ in Eq. (1) is equal to -1. It is worthwhile to mention that above $T \approx 20$ K the slight deviation from the linear behavior in $M \sim \ln(\mathrm{d}B/\mathrm{d}t)$ is observed. $U_0(T)$ is shown in Fig. 2, together with temperature dependence of the irreversible magnetization defined as $\Delta M = (M_+ - M_-)/2$, where M_+ and M_- are the magnetization on the descending and ascending field branch of the hysteresis curve, respectively. While the irreversible magnetization decreases somewhat smoothly with increasing temperature, the activation energy undergoes a dramatic development. U_0 increases with temperature as $U_0 \sim T$ up to T^* and above T^* the activation energy U_0 is almost saturated. While for magnetic fields ranging from 0.7 to 1.7 T the change in the character of the $U_0(T)$ dependence is observed lying at the same temperature, $T^* \approx 22$ K, at fields below $B = 0.7$ T this crossover shifts to slightly higher temperatures ($T^* = 26$ K at $B = 0.4$ T).

The crossover in the $U_0(T)$ dependence implies substantial changes in the vortex dynamics. The very similar picture in $Q(T)$ dependence was also observed by Kopelevich et al. [3] in a highly textured Bi(2223) compound produced by cold pressing. They observed, however, peak at $T^* \approx 20$ K in the $U_0(T)$ dependence (see figure 3 in Ref. [3]) and ascribed it to the interplay between quenched and thermal disorder. The difference in the shape of $U_0(T)$ in our and Kopelevich et al. [3] case is due to different way of estimation of U_0. They estimated the temperature dependence of activation energy U_0 as $U_0 \sim T/Q$ neglecting the second term in denominator of Eq. (1).

Comparing our measurements to those of Kopelevich et al. [3], we can conclude the following: the drastic change in the behavior of $U_0(T)$ is observed in both samples at the same temperature T^*, a slight shift to higher temperatures was observed in our sample at low fields, below $B = 0.5$ T.

According to Blatter et al. [13] the melting temperature of 2D vortex lattice T_m^{2D} can be expressed as: $T_m^{2D} \cong (T_{BKT} 4\sqrt{3}\pi)(1/1 - T_{BKT}/T_{c0})$ where T_{c0} is the mean-field transition temperature, T_{BKT} is the Berezinskii–Kosterlitz–Thouless transition temperature, above that the characteristic correlation length diverges. For the strongly layered Bi-based compounds it was found $T_m^{2D} \approx 25$ K. The theoretical melting temperature T_m^{2D} is field independent, whereas the melting temperature for 3D-vortex regime is expected to vary as $B^{-1/2}$ [13].

The crossover observed at ≈ 20 K both in our sample and that in Ref. [3] might be therefore associated with melting of the 2D vortex lattice. For 0.4 T, this crossover shifts to higher temperature. This implies that the vortex system at fields below $B = 0.4$ T might be still in the 3D-vortex regime, where T_m^{3D} is field dependent. Since lattice of 2D vortices is much more susceptible to random disorder (pinning) and thermal fluctuations than a 3D vortex lattice, it is reasonable to expect that T_m^{2D} will be lower than T_m^{3D}, for any field value. Such a behavior is also seen in our experiment.

The crossover field B_{3D-2D} between the 3D and 2D regimes was in Ref. [14] calculated as $B_{3D-2D} \approx \Phi_0/\gamma^2 d^2$, where Φ_0 is flux quantum, γ is anisotropy parameter, and d is distance between CuO_2 planes. In Ref. [14], this field was estimated for Bi-based materials to be $B_{3D-2D} = 0.64$ T, while Blatter et al. [13] found much lower value, $B_{3D-2D} = 0.36$ T. Such a difference might be due to absence of exact data on the anisotropy parameter in the BSSCO(2223) tapes. The field of 0.5 T, below that the crossover in $U_0(T)$ starts to move to higher temperatures, is just between the above two estimates and can be assigned to the 3D–2D transition.

It is worth mentioning that the irreversible magnetization ΔM (see Fig. 2) drops below $T^* \approx 22$ K rather steeply, while at higher temperatures the decrease is much more gradual.

We found the following arguments supporting the conclusion that the crossover on $U_0(T)$ for Bi(2223)/Ag tape is due to vortex lattice melting.

- The theory [13] predicts the change in vortex dynamics on $U_0(T)$ at $T_m^{2D} = 25$ K, close to our experimental value.
- According to the theory, T_m^{2D} is field-independent, which is the case of our sample at fields above ≈ 0.5 T.
- Position of the crossover is the same for our sample as for that of Kopelevich et al. [3].
- Position of the crossover starts to shift at fields below ≈ 0.5 T, the field that is in accord with theoretical predictions for 3D–2D transition. Below this limit the crossover position becomes field-dependent as predicted for the 3D vortex lattice melting.

In summary, the temperature dependence of activation energy $U_0(T)$ for Bi(2223)/Ag tape was found to exhibit well pronounced change of vortex dynamics. It was attributed to melting of the vortex lattice (2D at fields above 0.5 T, and 3D at lower fields).

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