Magnetic Torque in the Vortex State of $Bi_2Sr_2CaCu_2O_{8+\delta}$ Single Crystal below 30 K

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Abstract

The magnetic torque originating from the intrinsic pinning parallel to the CuO_2 plane and the flux pinning perpendicular to the CuO_2 plane has been measured as a function of the angle θ between the CuO_2 plane and the applied magnetic field. The average length of path for fluxoids running parallel to the CuO_2 plane (Josephson vortex) was calculated from the measurements as a function of θ ($0^\circ \leq \theta \leq 90^\circ$)at 4.4 K, 6.2 K and 12 K. The amount of flux pinned perpendicular to the CuO_2 plane showed saturation at about 0.5 T. The depinning of the flux pinned perpendicular to the CuO_2 plane at 4.4 K was studied as a function of the temperature and the applied magnetic field parallel to the CuO_2 plane.

Key words: $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal; Magnetic torque; Intrinsic pinning ; Flux pinning ;

The vortex state in strongly anisotropic superconductor has been investigated with respect to magnetic field, orientation of magnetic field to crystal axis and temperature [1-5]. The vortices penetrate a crystal stepwise by creating vortex segments parallel (Josephson vortices) and perpendicular to the layers. We have measured the magnetic torque caused by the vortex structure in the strongly anisotropic Bi2212 single crystal under applied magnetic field B_a tilted to c-axis.

The schematic set-up is shown in Fig. 1. A Bi2212 crystal (3 mm length L, 1 mm wide W, 0.038 mm thickness D) was glued to a Si host reed in the direction as the CuO_2 plane was parallel to the Si surface. The reed was clamped at one end between copper flats, which were mounted on a rotatable holder. The θ denotes the angle between B_a and CuO_2 plane. This arrangement is used for a vibrating reed technique [6]. The resonance frequency f and the amplitude u were measured as a function of magnetic field. Below about 20 K, the reed was bent by magnetic torque and touched to an electrode above the magnetic field B_s. This was detected by the abrupt increase of f and also the decrease of u.

Fig. 2 shows the θ dependence of B_s at 4.4 K, 6.2 K and 12 K. At 4.4 K and $0^\circ \leq \theta \leq 60^\circ$, the data are well fitted to

$$B_s^2 = \gamma(\sin\theta \cdot \cos\theta)^{-1} \qquad \gamma : constant. \qquad (1)$$

In the consideration of experimental results expressed by Eq. (1), the average length of path for fluxoids running parallel to CuO_2 plane L_Φ is calculated by the following analysis. The torque caused by a fluxoid ΔT and the number of fluxoid N through a crystal at $B_a > \mu_0 H_{c1}$ are

$$\Delta T = (B_a \Phi_0 L_\Phi \sin\theta)/\mu_0 \qquad (2)$$

$$N = B_a W (D\cos\theta + L\sin\theta)/\Phi_0, \qquad (3)$$

where Φ_0 is a fluxoid, μ_0 is magnetic permeability of vacuum. If we take the total torque T_s which corresponds to the torque for the reed to touch the detect electrode (see Fig. 1), the relation between T_s and B_s is written as follows,

$$T_s = B_s^2 \frac{L_\Phi W}{\mu_0} \sin\theta \cdot \cos\theta (D + L\tan\theta), \qquad (4)$$

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where T_s can be calculated from the values of the elastic coefficient of Si plate , the distance between a Si plate and a detect electrode and the sizes of Si plate. In comparison Eq. (1) with Eq. (4), it is said that L_Φ has the following θ dependence,

$$L_\Phi = LD(D + L\tan\theta)^{-1}. \quad (5)$$

In Fig. 3, the relation between L_Φ and θ represented by Eq. (5) is shown by solid curve and the points plotted by symbols show the values calculated from the data of Fig. 2 using Eq. (4). In the above discussion, we have neglected the torque T' which is caused by fluxiods perpendicular to CuO_2 plane because the thickness of sample is two orders smaller than the sample length. When L_Φ is smaller than the sample thickness, the effect of T' has to be taken into consideration. The direction of T' is opposite to T. In Fig. 3, the data points deviate from the curve at large θ, which indicates that the torque T' works effectively at these regions. On the other hand, the deviation of data points at 12 K for small θ is considered to show that the torque T becomes small at high temperature.

In the next measurements, after the zero-field cooling, the magnetic field was applied up to 0.3 T (or 0.5 T, 1 T, 2 T , 3 T) at θ=90°, then B_s' was measured after rotating the holder to θ=0°. In this condition, the Si plate was forced to bend to the direction of drive electrode by the magnetic torque caused by the flux pinned perpendicular to CuO_2 plane. Fig. 4 shows the temperature dependence of B_s'. When the field applied at θ=90° was larger than 0.5 T, the values of B_s' were almost the same at 4.4 K. This means that the amount of pinned flux saturates at about 0.5 T in this crystal. The temperature dependences of B_s' indicate that the depinning of the flux pinned perpendicular to CuO_2 plane was more promoted by the larger magnetic field applied parallel to the CuO_2 plane.

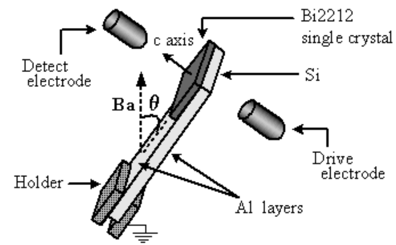

Fig. 1. Sample set-up.

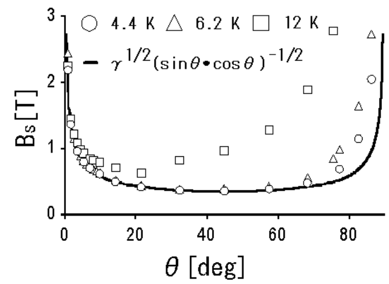

Fig. 2. The angle θ dependence of B_s at 4.4 K, 6.2 K and 12 K. Solid curve is represented by Eq. (1).

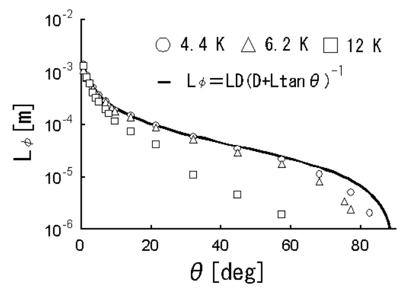

Fig. 3. The θ dependence of L_Φ at 4.4 K, 6.2 K and 12 K. Solid curve is represented by Eq. (5).

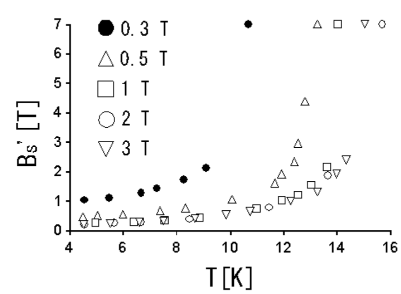

Fig. 4. Temperature dependence of B_s'. The values of magnetic field indicate those applied at θ=90°.

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