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Josephson-vortex states at higher magnetic fields in $Bi_2Sr_2CaCu_2O_{8+y}$

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Abstract

Josephson-vortex (JV) states in $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi-2212) have been studied by measuring the flow resistance of JVs and I–V characteristics with a current along the c-axis and a magnetic field parallel to the superconducting layers. In the flow resistance, periodic oscillations have been found as a function of the parallel field. As this phenomenon is related to the formation of a triangular lattice of JVs as the ground state, the 3D-ordered state of JVs can be determined in the magnetic phase diagram. With increasing the doping level of Bi-2212, the 3D-ordered phase is shifted towards a higher magnetic field and a higher temperature, which is well explained by the theoretical analyses. Above the 3D-ordered phase, JV state has been studied with I–V characteristic measurements, in which the voltage shows a distinct change in the exponent of the power-law dependence to the current between two phases. This suggests that the 3D-ordered phase changes to the disordered phase along the c-axis.

Keywords: Josephson-vortex; Magnetic phase; Vortex state; Bi-2212

1. Introduction

High T_c superconductors (HTSCs) generally consist of iterative stacks of the Cu–O superconducting layers and the non-superconducting ones. This structure causes a weak Josephson coupling between the superconducting layers through the non-superconducting ones in strongly anisotropic superconductors such as $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi-2212). This Josephson coupling is called as intrinsic Josephson junctions (IJJs) [1]. The 2D nature of the layered structures in HTSCs shows characteristic features in vortex matter physics. In the perpendicular magnetic fields to the layers, HTSCs show distinguished features of pancake vortices [2]. In the parallel fields to the layers, magnetic field penetrates into the materials as Josephson vortices (JVs) in superconducting state. Theoretical studies on JVs have been made extensively in the past decade [3–8]. However, experimentally, it has been studied mainly only on $YBa_2Cu_3O_{7-\delta}$ (YBCO); the melting transition of the JV system [9,10], the oscillatory melting temperature, and the vortex–smectic phase [11], for example. Few experimental results have been reported on the magnetic phase diagram of the JV system in strongly anisotropic HTSCs. Fuhrer et al. [12] have suggested from the results of the c-axis resistivity measurements that the melting transition is interpreted as a K–T (Kosterliz–Thouless) depairing of inter-layer vortex/anti-vortex pairs. Mirkovic et al. [13] have suggested from the results of the in-plane resistance measurements in the Corbino geometry that the first-order melting transition of pancake vortices changes to a second order vortex–crystal–vortex–smectic phase transition nearly parallel to the layers.

Recently, we have found a new method to study the magnetic phase diagram of JV system in Bi-2212 by using the periodic oscillations in flow resistance of JVs [14]. The magnetic phase, where the periodic oscillations can be observed, is assigned as the 3D-ordered state of JVs, which was confirmed by the 'beat' effect in the flow

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resistance [15]. Therefore, we can determine the 3D-ordered phase of JVs [16–18]. However, there was an ambiguity in determining the upper boundary of the ordered phase at higher magnetic fields and in discussing the JV states above the upper boundary. In this paper, to confirm the upper boundary of the 3D-ordered phase, we have studied the doping effect to the periodic oscillations and the JV state at higher magnetic fields by measuring the I–V characteristics.

2. Experiments

Single crystals of Bi-2212 were grown with a travelling solvent floating zone method [19]. Preparation of the samples is described in elsewhere [15]. Three samples for the measurements were prepared by annealing at suitable temperatures in oxygen atmosphere with slightly over-doped sample A ($T_c = 85.8$ K) with a size of $w = 20.8$, $l = 23.0$, $t = 0.9$ μm, moderately over-doped sample B ($T_c = 82.8$ K) with 11.2, 12.4 and 0.5 μm, and heavily over-doped sample C ($T_c = 78.0$ K) with 14.0, 15.4 and 1.2 μm, respectively, where w is the length perpendicular to the magnetic field, l the length parallel to the field and t the thickness. Temperature dependence of the c-axis resistivity on these samples without magnetic field is shown in Fig. 1. A sharp superconducting transition can be seen in three samples. Temperature dependence of the resistivity in the normal state shows good coincidence to the doping levels as shown in Fig. 2 in Ref. [20], and the absolute values of the resistivity are nearly the same order.

Flow resistivity of the IJJ structure (schematically drawn in the inset of Fig. 1) was measured with a four-probe contact configuration in the applied field H. Details of the JV flow measurements are also described in Ref. [12]. The maximum magnetic field applied is 70 kOe in the flow resistivity measurements.

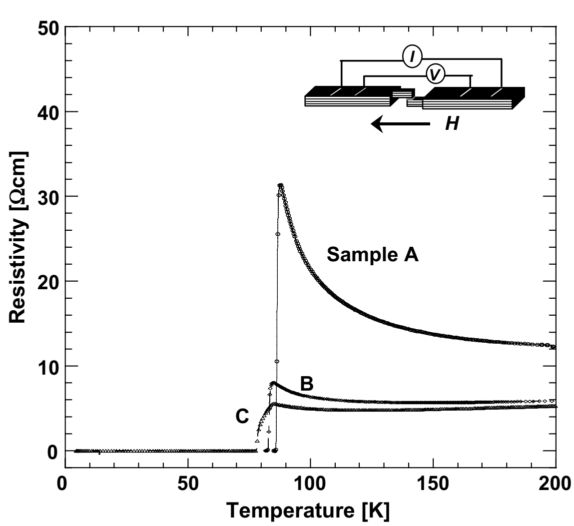

Fig. 1. Temperature dependence of resistivity in samples A, B and C. Inset shows a schematic drawing of the IJJ structure and measurement set-up.

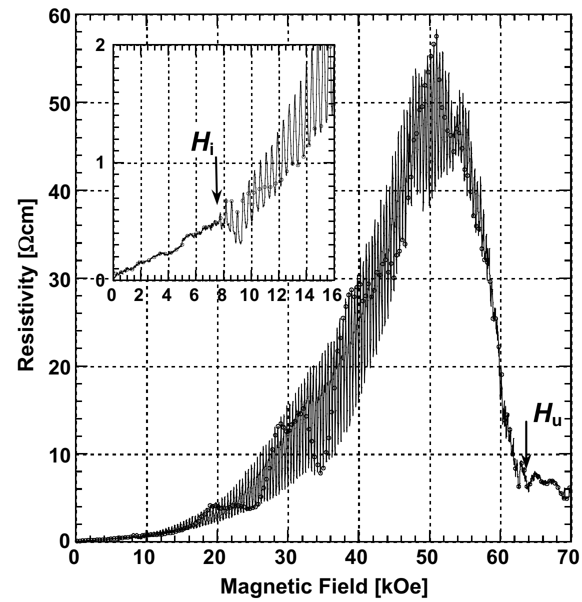

Fig. 2. Typical data of flow resistivity of sample A measured with a dc current of 1 μm and at 40 K. H_i shows the starting magnetic field of the periodic oscillations, and H_u the upper magnetic field.

3. Results and discussion

Typical data of the flow resistivity in sample A are shown in Fig. 2 with the applied dc-current of 1 μA at 40 K. The resistivity increases proportionally to the magnetic field at the beginning, and suddenly begins to oscillate from the magnetic field H_i. After going up to the maximum, the oscillations stop at the magnetic field H_u with a finite resistivity. These characteristic magnetic fields are indicated by arrows in the figure.

The value of H_i in sample A, B, and C is 4.7, 7.8, and 9.3 kOe, and the anisotropy parameter $\gamma(=\lambda_c/\lambda_{ab}$; λ_c and λ_{ab} are the penetration depth in Bi-2212) is estimated as 436, 263, and 220, respectively, according to the formula $H_i = (1.40\phi_0)/(2\pi\gamma s^2)$ [21], where ϕ_0 is the flux quantum of 2.07×10^{-7} Gauss·cm^2, s the distance between the superconducting layers in IJJs of about 1.5 nm in Bi-2212. This is the lower boundary of the 3D-ordered phase.

In Fig. 3, temperature dependence of the lower boundary H_i is shown for three samples. H_i is almost independent of temperature, and slightly increases at lower temperatures, which may be related to the temperature dependence of the anisotropic parameter, namely, penetration depth of JV in Bi-2212. H_i decreases with increasing a doping level of carriers to the samples, namely, with decreasing anisotropic parameter γ. The doping dependence of H_i and the normal resistance are discussed elsewhere in detail [22].

At the highest temperature of the boundary, H_i may correspond to the magnetic field of the critical point $H_c = \phi_0/(2 \cdot 3^{1/2}\gamma s^2)$ [7]. In the magnetic phase below H_i, several ordered phases have been proposed without complete full-filling of JVs to the IJJs [21,23]. However, we could not observe systematically any oscillations, a large change