Crossing vortex-lattices state probed by c-axis resistance in $Bi_2Sr_2CaCu_2O_{8+y}$

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Abstract

To investigate the properties of crossing lattices of pancake and Josephson vortices, we have measured the c-axis resistance $R_c(H)$ as a function of field in $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) intrinsic Josephson junctions. When the sample is rotated in an applied field, Josephson-vortex flow resistance appears in the so-called lock-in state. Additionally, many equal steps of the resistance are observed in the range of fields where the crossing lattices are expected. The relationship between this phenomenon and crossing lattices is discussed.

Key words: vortex lattice; $Bi_2Sr_2CaCu_2O_{8+y}$; intrinsic Josephson junction; crossing lattices

1. Introduction

Recently, in the highly anisotropic superconductor $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO), a new vortex structure, namely a crossing lattices of pancake and Josephson vortices, has attracted much attention. This model has been successful in explaining the angular dependence of the melting transition field H_m, and the vortex chains embedded in triangular vortex lattices [1]. Experimentally, the crossing lattices state has been recently observed using a scanning micro-Hall probe in fields of less than 100 Oe [2]. In higher fields, however, there are several unresolved phenomena. Mirkovic *et al.* have shown that the angular dependence of H_m has stepwise behaviors in high fields [3]. In the crossing lattices phase, a sign of structural transitions has been found in 2-3 kOe ab-plane field component from local magnetization measurements [4]. It is necessary to study details of the crossing lattices state to understand these phenomena.

In order to obtain additional information about tilted vortex phases, we have measured the c-axis resistance $R_c(H)$ as a function of field using intrinsic Josephson junctions of BSCCO. Previously, we have shown that the first-order melting transition can be observed from these measurements [5]. Since a finite vortex-flow resistance appears even in the solid phase with large currents, it is possible to study the properties of vortex states in tilted fields including the crossing lattices.

2. Experiments

High quality single crystals of BSCCO were grown by traveling-solvent floating-zone technique. A platelet of single crystals was carefully cut into narrow strips with a length of about 50 μm. After forming a four-contacts configuration using silver paste, the center of the strips was milled by focused ion beam to make two channels on both top and bottom surfaces. A schematic drawing is shown in the inset of Fig. 1. Because of the large anisotropy of BSCCO, the measured resistance is mainly due to the c-axis resistance [5]. The superconducting transition temperature T_c is 86 K in all samples.

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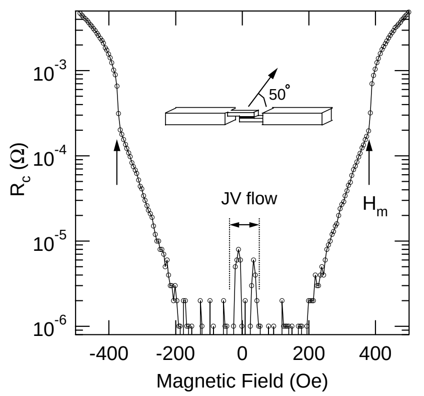

Fig. 1. The field dependence of c-axis resistance at 70 K in a sample with an ab-plane area of $100 \times 27\mu m^2$. The field is tilted 50° from ab-plane. The applied current is 3 mA. The inset shows a schematic drawing of the sample. The central part corresponds to the intrinsic Josephson junction.

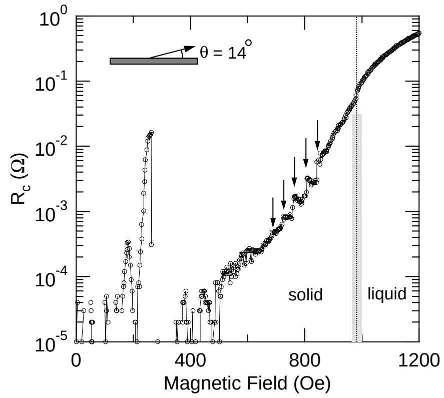

Fig. 2. The field dependence of c-axis resistance at 70 K in a sample with an area of $10.2 \times 13.6\mu m^2$. The field is applied at 14° from ab-plane and perpendicular to the short length of the sample. The applied current is 100 μA corresponding to 72 A/cm^2. The vertical line at about 1000 Oe indicates the boundary between the vortex solid and liquid states. Arrows show the position of the anomalous steps.

3. Results and Discussion

Figure 1 shows $R_c(H)$ for a field tilted 50° from the ab-plane. A sharp drop in resistance is observed around 400 Oe due to the vortex-lattice melting transition. Since the applied current density 110 A/cm^2 is large, a finite vortex-flow resistance is observed even below H_m. As the field decreases, this flow resistance becomes small. In lower fields, however, the flow resistance increases again and peaks are observed around zero field. The angular dependence of the peak field approximately scales with the c-axis field component. Therefore, it can be represented by $H_0/\sin\theta$, where θ is the angle between the field direction and the ab-plane, and H_0 is 25 Oe obtained from fitting the data. Since H_0 is close to the c-axis lower critical field, these peaks suggest the existence of a flow of Josephson vortices in the lock-in state undisturbed by pancake vortices.

In a smaller sample, an anomalous staircase behavior of the flow resistance was observed in the vortex solid phase as shown in Fig. 2. This is seen in tilted fields from $\theta = 10°$ to $26°$. Also, it is found from the angular dependence of $R_c(H)$ that the intervals of the step fields ($\Delta H_{\rm step}$) scale with the c-axis component of fields and $\Delta H_{step}\sin\theta$ is about 9.5 Oe. Therefore, ΔH_{step} is mainly related to pancake vortices.

In tilted fields below $H_m(\theta)$, the existence of crossing lattices of pancake and Josephson vortices has been suggested [1]. From both ab- and c-axis components of the field, in which the steps appear, we can estimate the numbers of Josephson and pancake vortices in the sample. In an applied field of 800 Oe and $\theta = 14°$, the number of pancake vortices is ~ 1300 per layer. Meanwhile, the distribution of Josephson vortices is estimated to be 0.57 per junction. Supposing that the crossing lattices are formed, the number of pancake vortices located on the top and along a single Josephson vortex is ~ 42. The increment in magnetic field needed to add one pancake vortex on the top of a Josephson vortex is about 9.4 Oe. This value is close to $\Delta H_{\rm step}$. A matching effect between the vortex-lattice spacing and the sample size has been observed in the case of the Josephson-vortex system [6]. Hence, this staircase behavior may be related to a matching effect between the number of pancake vortices on a Josephson vortex and the width of the sample. A sample-size dependence is needed to confirm this assumption.

In summary, we have measured the c-axis resistance of intrinsic Josephson junctions of BSCCO in tilted fields to study the behaviors of Josephson and pancake vortices and their mixtures, including the crossing lattices phase. We have observed a staircase behavior in $R_c(H)$. The properties of the steps may be explained by a matching effect between the number of pancake vortices on a Josephson vortex and the sample width.

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