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ScienceDirect
Physica C 463–465 (2007) 276–280
PHYSICA C
www.elsevier.com/locate/physc

Josephson vortices in annular-type intrinsic Josephson junctions

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Accepted 7 February 2007
Available online 2 June 2007

Abstract

In the rectangular-, or, square-shaped intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_{8+y}$, we found the periodic oscillations in Josephson vortex (JV) flow-resistance against the parallel magnetic fields with the *c*-axis current. We have tried to study the JV flow-resistance in the annular-type IJJs, and have found the oscillations with fundamental and superimposed periods determined by the effective widths of the junction perpendicular direction to the field and the current, which suggest that JVs are a three-dimensionally ordered state of JVs even in a non-continuous media, and well correlated each other along the junction.

PACS: 74.60.Ge; 74.25.Dw; 74.25.Fy; 74.72.Hs

Keywords: $Bi_2Sr_2CaCu_2O_{8+y}$; Flux flow-resistance; Josephson vortex; Vortex state

1. Introduction

In the annular (Lyngby)-type single Josephson junction (JJ) made of conventional metal superconductors, single Josephson vortex (JV) flow by the current perpendicular to the junction shows a quantum tunnelling at low temperatures through a potential made of the magnetic field [1]. In the multiple intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi-2212) with a rectangular or square shape, macroscopic quantum tunnelling has recently been observed in the *c*-axis current at low temperatures [2], and it happens at higher temperatures and higher rates than in the conventional metal superconductors [3], which will provide a new application of IJJs for a quantum computer.

On the flow-resistance of JVs in the IJJs of Bi-2212, we found the periodic oscillations as a function of the magnetic field parallel to the superconducting layers with the current along the *c*-axis [4]. The collective motion of JVs is restricted by the boundary conditions, and reveals as the large amplitude of periodic oscillations [4,11]. The periodic oscillations can be deduced with the numerical calculations using sine-Gordon equation for a single Josephson junction [5], but the amplitude of the oscillations in the calculations is too small to compare with the experiments. The periodic oscillations in the current-driven mode can be observed only in the small current limit, and can be assigned as the three-dimensionally long-range-ordered (3DLO) state of JVs in the ground state [6]. The effect of the boundary conditions also has been confirmed in the "beating" effect [7], which is caused by the misalignment of the "in-plane" magnetic field to the edge of the sample. From the flow-resistance and the *I*–*V* characteristics measurements crossing the upper boundary of the 3DLO state, we suggest that the JVs are in ordered state in "in-plane", but have less ordering along the *c*-axis [8]. This JV state is considered to correspond to the two-dimensionally quasi long-range-ordered state [6]. Therefore, the JV flow measurements provide us as a useful probe to investigate the JV state and the magnetic phase diagram of strongly anisotropic superconductors such as Bi-2212, which cannot be obtained with the other methods because of the small enthalpy change at the phase boundary in the JV system [6].

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0921-4534/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.physc.2007.02.049

Furthermore, the new type of device using the annular-type IJJs has been proposed [9], which may generate a microwave to combine and annihilate the vortex–anti-vortex pairs composed of JVs with a strong current applied along the *c*-axis at the potential barrier/well for JVs in the static field. In the small current region, the flow-resistance shows a well-ordered characteristic of JVs in both side of the ring, which appears as the periodic oscillations. We also have tried to observe such a phenomenon of the new device in measuring *I*–*V* characteristics with a large current in static magnetic fields. So, this measurement technique is effective to study the JV state and has been applied to the annular-type IJJs made of Bi-2212.

2. Experimental

For the fabrication of the junctions, we have used high quality single crystals of Bi-2212, which were grown by travelling-solvent floating-zone method [10]. A cleaved platelet of single crystals was cut into narrow bars in a width of about 40 μm and a length of about 2 mm, using a dicing machine. After forming a four-contacts configuration with a silver paste, center of the bar was milled by a focused ion beam with Ga-ions perpendicular- and parallel-direction to the *ab* plane. A schematic drawing of the sample and an SEM picture of the junction part of the fabricated junction are shown in the inset (a) and (b) of Fig. 1, respectively. The superconducting transition temperature is 87.8 K with slightly over-doping in carrier concentration. IJJs consist of 6 μm in the inner diameter r_{in}, 12 μm in the outer diameter r_{out} and about 1 μm in thickness *d*, estimated from the inset (b) of Fig. 1. Schematic drawing of the set-up for the measurements is shown also in the inset

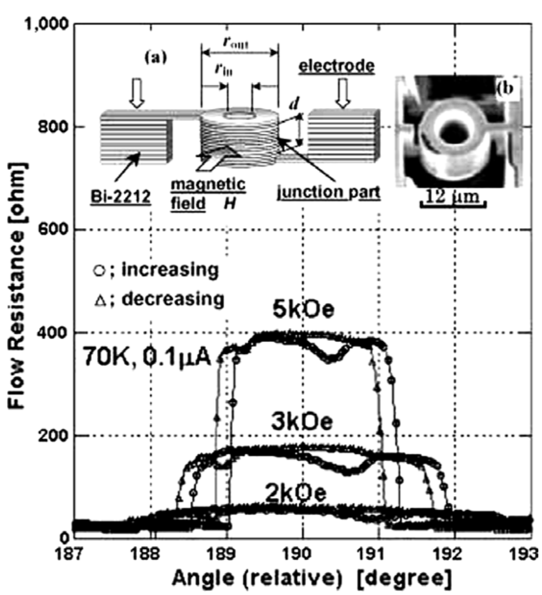

Fig. 1. Angular dependence of the flow-resistance at 70 K. Inset (a) schematic drawing of the junctions and inset, (b) secondary electron image of annular-type junction with the focused ion beam system, used in the experiment.

(a). The alignment of the field parallel to the superconducting layers has been achieved by measuring the angular dependence of the flow-resistance, and by setting the angle to its maximum value with an accuracy of 0.005°. The angle-dependence of the flow-resistance is shown in Fig. 1 with magnetic fields at 2, 3, and 5 kOe. In the annular-type junctions, it shows the plateau around the exact alignment, which becomes larger in height and sharper in width with increasing magnetic field. Additionally, a dip structure can be seen, which was not observed in the rectangular shape junctions. The dip structure appears just before locking out of the JVs from IJJs with rotating the sample in both directions. The flow-resistance shows hysteresis in angle-scanning directions. The rough alignment of the sample to the field is made to set the angle to the half value in both directions, and the fine alignment to measure the flow-resistance and to find the angle, at which the periodic oscillations continue as much as possible with increasing the field.

In the flow-resistance measurements, a constant current of dc or ac (13.6 Hz) is applied with three to four orders smaller than the critical current of the junctions. The resistance comes mainly from the junction part along the *c*-axis, because the *in-plane* resistance is three orders of magnitude smaller than that along the *c*-axis. With the current applied perpendicular to the superconducting layers, JVs move along the layers by the Lorentz force, which causes a flow voltage between the electrodes measured with Keithley 2182 nano-voltmeter and LR-700 ac resistance bridge for dc and ac current, respectively. It is generally considered that the magnitude of flow-resistance is proportional to the number of JVs and the magnitude of the currents. Therefore, with a constant current, we can anticipate that the flow-resistance shows a linear dependence to the magnetic fields. However, as shown in Ref. [4], the flow-resistance shows distinguished features in such strongly anisotropic HTSC's as Bi-2212, which happens even in the annular-type junctions.

3. Results and discussion

3.1. JV flow-resistance in the annular-type junctions

Fig. 2 shows the flow-resistance of the annular-type junctions shown in the insets of Fig. 1 as a function of magnetic field at 4.3 K and 60 K with the ac current of 0.1 μA. Increasing magnetic field, the flow-resistance increases monotonically. However, the resistance suddenly oscillates above about 6 kOe as seen clearly in the inset of Fig. 2. The magnetic field H_s at the beginning of the oscillations is inversely proportional to the anisotropic parameter γ as $H_s = \phi_0/2\pi\gamma s^2$ ($\gamma = \lambda_c/\lambda_{ab}$; λ is the penetration depth, ϕ_0 the flux quantum of 2.07×10^{-7} gauss cm^2, *s* the distance between the superconducting layers 1.5 nm) [11,12]. From $H_s = 6$ kOe, the value of γ is estimated as about 240, which ranges in the slightly over-doping. The oscillations continue to the magnetic fields larger than 70 kOe at 4.3 K.