Vortex States in Strongly Anisotropic HTSC in Parallel Magnetic Field

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Abstract. High $T_c$ superconductors (HTSCs) for the application of magnets and cables are usually used in a magnetic field parallel to the superconducting layers, using the intrinsic pinning of vortices in the layered structures. However, vortex states in the parallel field have not been well understood in strongly anisotropic superconductors. We have studied the vortex states by measuring the flow resistivity of Josephson vortices (JVs). From the measurements, we can determine the 3D-ordered phase of JVs, which means that JVs are well ordered and are considered not to influence the dissipation of the superconducting state. However, by the $R$-$T$ measurements, we have found the excitation of pancake vortex/anti-vortex pairs to reduce the flow resistance. This limits the application of HTSC materials in the parallel magnetic fields.

1. Introduction
High $T_c$ superconductors (HTSCs) generally consist of the iterative stacks of the Cu-O superconducting layers and the non-superconducting ones. This structure causes the Josephson coupling between the superconducting layers in strongly anisotropic superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (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 applied to the layers, HTSCs show distinguished features of pancake vortices (PVs) [2]. In the parallel field applied to the layers, the magnetic field penetrates into the materials as Josephson vortices (JVs) in the superconducting state. Theoretical studies on JVs have been made extensively in the past decade [3-7]. However, in the experiments, it has been studied mainly only on YBa$_2$Cu$_3$O$_{6.8}$ (YBCO); the melting transition of the JV system [8-10], the oscillatory melting temperature, and the vortex smectic phase [11], for example. Few experimental results have been reported on the JV system in strongly anisotropic HTSCs.

Recently, we have found a new method to study the magnetic phase diagram of the JV system in Bi-2212 by using the periodic oscillations in flow resistance of JVs [12]. The magnetic phase, where the periodic oscillations can be observed, is assigned as the 3D-ordered state of JVs, which was confirmed by the “beating” effect in the flow resistance [13]. Then, we can determine the 3D-ordered
phase of JVs [14-16]. In this paper, we have studied to confirm the 3D-ordered phase and JV state for the applications by measuring the flow resistance of JVs.

2. Experiments

Single crystals of Bi-2212 were grown with a travelling solvent floating zone method [17]. Preparation of the samples is described elsewhere [12]. Sample for the measurements was in a slightly over-doped state ($T_c=85.8$K) and was fabricated using a focused ion beam with a size of $w=20.8$, $l=23.0$, and $t=0.9$ μm, where $w$ is the length perpendicular to the magnetic field, $l$ the length parallel to the field and $t$ the thickness. Flow resistivity of the IJJ structure (schematically drawn in the inset of Fig.2 (a)) 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.

3. Results and Discussion

Figure 2 (b) shows typical data of the flow resistivity under the parallel magnetic fields in Bi-2212. The resistivity increases monotonously with increasing magnetic field at the beginning, oscillates suddenly with a constant period at the magnetic field $H_s$ as shown in Fig.2(c). The oscillations stop at $H_u$, shown as an arrow in Fig.2 (b), which is confirmed not to be caused by the misalignment of the sample to the magnetic field. The magnetic field $H_u$ corresponds to the upper boundary of the 3D-ordered phase of JVs. From $H_s$ and $H_u$, it corresponds to the magnetic field range where the triangular

Figure 1. Schematic drawing of Josephson vortices among the superconducting layers in HTSCs.

Figure 2. (a); Schematic drawing of the sample and the electrodes. (b) and (c); Typical data of flow resistivity of the sample measured with a dc current of 1 μm and at 40K. $H_s$ shows the magnetic field to start the periodic oscillations, and $H_u$ the upper magnetic field of the oscillations.
lattice of JVs is formed [14-16]. Then, we can determine the 3D-ordered phase.

We also made $R$-$T$ measurements with a field cooling and warming-up process, which is shown in Fig.3. With increasing temperature after applying a magnetic field at 5K, the resistance decreases suddenly at the magnetic field $H_d$. This happens only in zero-field cooling and warming-up process. With a field-cooling process, there is no flow resistance at lower temperatures. This is not caused by the misalignment of the sample to the magnetic field, because we could observe the periodic oscillations during increasing the magnetic field at 5K. This sudden drop is explained by the thermal excitation of the PV/anti-PV pairs, which are well known to exist even in a Bragg lattice of PVs in the perpendicular field [2]. In the field cooling process, there are many PV/anti-PV pairs excited at high temperatures, and, when it is cooled down, these pairs are frozen. Then, it causes no flow resistance at lower temperatures. In the zero-field cooling, there are few PV/anti-PV pairs at low temperature. With increasing temperature, these pairs are excited thermally and act as the pinning centers for JVs at lower temperatures, as the pinning centers of PVs are strong enough at low temperatures. With increasing temperature, the pinning effect to the PVs becomes weaker, and the flow of the JVs recovers again, which can be seen at higher temperatures in the zero-field cooling process in Fig.3.

The magnetic phase diagram of JV’s is shown in Fig.4, obtained from the $R$-$H$ and $R$-$T$ measurements. From the $R$-$H$ measurements, we could define the phase boundary $H_s$ and $H_u$. Between them, JV state is in the 3D-ordering. Above the boundary $H_m$ there is a disordered state in Bi-2212 intrinsically. This state has a disorder along the $c$-axis and a 2D quasi-long range ordering in-plane [7,18]. Then, these JV states cause any dissipation in superconducting state besides the contribution of the quasi-particles. However, the boundary $H_d$, obtained from the $R$-$T$ measurements, has a serious problem in the applications of strongly anisotropic HTSC materials. This boundary exists between 20-
30K in higher magnetic field than 15kOe and decreases with increasing temperature as shown in Fig.4. Above the boundary, it is considered that there exist many PVs (anti-PVs), thermally or magnetically excited, even in the 3D-ordered state of JV system. The thermally-excited PV pairs were predicted for JV system in 2D superconductors by many theorists just after the discovery of HTSC [3]. The present measurements were made in the low current limit less than 0.01 of the critical current density in Bi-2212. In the applications of HTSC materials, much larger current is applied close to the critical current density. Then, when these PV pairs exist even in the parallel fields, these pairs are easily moved by the Lorentz force and cause large dissipation, if there are no strong pinning centers for PVs. This causes a serious problem for the applications of HTSCs in magnetic fields.

The boundary $H_u$ limits the applications of HTSCs in temperature and magnetic field. For the superconducting magnets, 70kOe is the limit for a real use at 20K, for example. However, the measurements were made in a good quality single crystal of Bi-2212 with less pinning centers for PVs. The effect of pinning centers for PVs and JVs on the current density and the anisotropy of the materials is not investigated in these experiments. Further experiments will be necessary to understand the mechanism of JV pinning in the parallel fields.

4. Conclusion
We have studied the JV states by measuring the flow resistivity. From the $R$-$H$ measurements, we can determine the 3D-ordered phase of JVs, which means that JVs are well ordered and are considered not to influence to the dissipation of the superconducting state. However, by the $R$-$T$ measurements, we have found a sudden drop in the flow resistance in the zero-field cooling&warming-up process. The sudden drop is explained by the thermal and magnetic excitation of PV/anti-PV pairs, which is an intrinsic property of Bi-2212. The boundary of the excitation exists between 20-30K above 15kOe and above 30K at lower magnetic fields. This boundary limits the application of HTSC materials in magnetic fields.

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