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Magnetic phase diagram of Josephson vortices in $Bi_2Sr_2CaCu_2O_{2+y}$

K HIRATA
Superconducting Materials Center, National Institute for Materials Science, 1-2-1 Sengen, Tsukuba 305-0047, Japan
E-mail: HIRATA.kazuto@nims.go.jp

Abstract. We show experimental results on magnetic phases of Josephson vortices (JVs) in $Bi_2Sr_2CaCu_2O_{2+y}$, obtained from the JV flow-resistance measurements. Periodic oscillations in the flow-resistance enable us to assign the phase of the long-range 3D ordered state, which was confirmed by the beating effect. We have made preliminary experiments on the doping effect to the JV magnetic phase. The doping effect is reflected not only in the lower boundary of 3D ordered phase, but also in the upper boundary. Above the upper boundary, the flow-resistance shows different behaviours, which may be related to the strength of the interlayer coupling of the JVs along the *c*-axis, and to the creation/annihilation of pancake vortex/anti-vortex pairs, thermally and magnetically.

Keywords. Vortex flow-resistance; Josephson vortex; magnetic phase.

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1. Introduction

When a magnetic field is applied parallel to the Cu–O superconducting layers of high T_c superconductors (HTSCs), it penetrates as Josephson vortices (JVs) in the superconducting state of the materials. This is caused by the layered crystal structure of HTSCs, consisting of the Cu–O superconducting layers and the non-superconducting ones alternatively. These iterative stacks result in a weak Josephson coupling between the Cu–O layers, which are called as intrinsic Josephson junctions (IJJs) [1]. Theoretical studies on the JVs have extensively been made (soon after the discovery of HTSC); thermally-activated disordered vortex state [2], Kosterlitz–Thouless (K–T) transition in the smectic vortex state [3], new vortex phases [4,5] and a change of a tricritical point in the dimension of the melting transition [6], and the K–T type phase and the melting of 2D quasi-lattice [7]. However, JV system has not been studied well experimentally in strongly anisotropic HTSC's such as $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi-2212). Only in $YBa_2Cu_3O_{7-\delta}$, were found many characteristics of JV system such as the melting transition [8–10], the oscillatory melting temperature [11], and the vortex smectic phase [9]. Few experimental results have been reported on the magnetic phase diagram in Bi-2212. It has been suggested by Fuhrer *et al* [12] that the melting transition is obtained by the *c*-axis resistivity measurements on Bi-2212 with different current densities in the parallel magnetic fields. The transition is interpreted as a K–T transition involving depairing of the inter-layer vortex/anti-vortex pairs.

However, there is no experimental evidence on the melting transition of JVs from measurements of thermodynamical physical parameters of strongly anisotropic HTSCs. Most of the difficulties in the experiments to study the JV system are due to very small value of the change in the physical parameters at the phase boundary. Shear modulus of JVs between the layers is very low, for example, and hence, a change in free energy is too small at the boundary as observed by the experiments [7]. Recently we have found a new method to study the magnetic phase diagram of JV system by using the periodic oscillations in flow-resistance of JVs [13]. The period H_{p} of the oscillations is defined as $H_{\mathrm{p}} = \phi_0/2ws$, where ϕ_0 is the flux quantum of 2.07×10^{-7} G cm^2, and s the thickness of one IJJ in Bi-2212 of about 15 nm. This is a strong evidence of the formation of JV lattice. From this phenomenon, we can deduce the configurations of JVs. This phenomenon is caused by the intrinsic boundary effect of the sample on the JV flow, related to the configurations of JVs [14,15]. The period of the oscillations depends on the size of the junction and the magnetic field. This is scaled with the Josephson length λ_{J} [14]. When the size is comparable to λ_{J}, or in high magnetic fields, the oscillations exhibit period of the well-known Fraunhofer type. The period becomes double, namely, $2H_{\mathrm{p}}$. This has been confirmed by the experiments too [16].

In this paper, the magnetic phase, in which the periodic oscillations are observed, has been confirmed to be a 3D-ordered vortex state by the 'beating' effect [17]. We show the doping effect in the magnetic phases of JVs in the over-doped region of Bi-2212 from preliminary experimental results.

2. Experimental

Single crystals of Bi-2212 were grown with a travelling solvent floating zone method [18]. The preparation of the samples is described elsewhere [13]. Two samples for the measurements were prepared by annealing with slightly over-doped sample A (T_{c} = 85.8 K) with a size of w = 20.8 μm, ℓ = 23.0 μm and t = 0.9 μm, and moderately over-doped sample B (T_{c} = 82.8 K) with 11.2 μm, 12.4 μm and 0.5 μm, respectively, where w is the length of the sample perpendicular to the magnetic field and t the thickness of IJJ. Temperature dependence of the *c*-axis resistivity on these samples without magnetic field is shown in figure 1. A sharp superconducting transition can be seen in both samples with the transition width less than 1 K in the inset of figure 1.

Flow resistance of the fabricated IJJ (schematically drawn in the inset of figure 2) was measured with a four-probe contact configuration in the applied field H with AC (13 Hz) and DC current. Details of the JV flow measurements are also described in ref. [13]. Figure 2 shows typical curves of the flow-resistance of samples A and B with applied current of 1 μA at 70 K in the low magnetic fields in intervals of 100 Oe and 20 Oe, respectively. The flow-resistance begins to oscillate with the period H_{p} for fields above 4 kOe and 8 kOe, respectively. Flow-resistance is normally

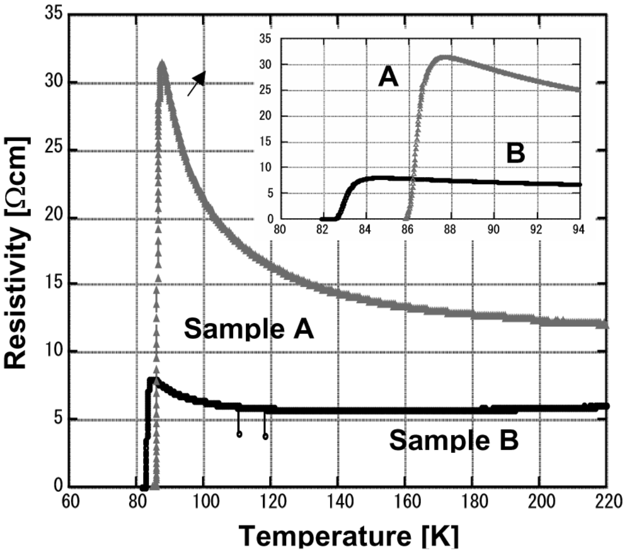

Figure 1. Temperature dependence of resistivity for samples A and B. The inset shows the resistivity in the vicinity of superconducting transition, which shows a sharp superconducting transition at $T_\mathrm{c} = 85.8$ K and 82.8 K with less than 1 K temperature width in both samples.

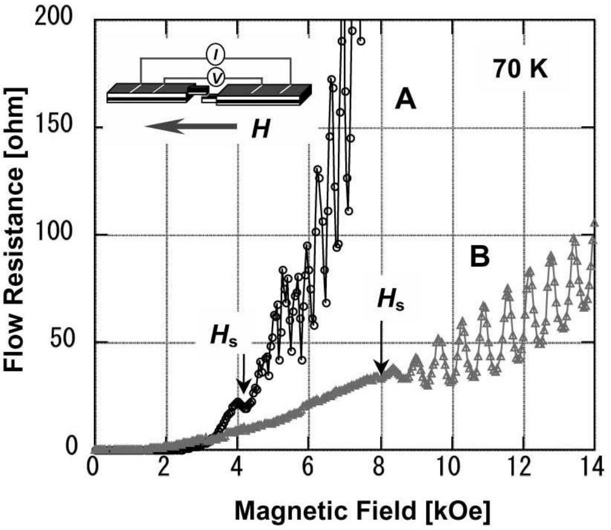

Figure 2. Josephson-vortex flow resistance of samples A and B as a function of the parallel field at 70 K. H_s denotes the starting magnetic field of the periodic oscillations, which corresponds to the lower boundary of the 3D-ordered JV phase.

proportional to the applied current and the total number of JV in the area ($w \times t$) perpendicular to the magnetic field. As the current is the same in both samples and the area of sample A is four times larger than that of sample B, the resistance of sample A becomes four times larger than that of sample B, as shown in figure 2.

3. Results and discussion

In figure 2, the flow-resistance is shown for two samples at 70 K as a function of magnetic field. The periodic oscillations begin at the magnetic field $H_{\rm s}$ of 4.21 kOe and 8.03 kOe for samples A and B, respectively. Above $H_{\rm s}$, the oscillations are observed continuously with the period of $H_{\rm p}$. In this magnetic field range, JVs form a triangular lattice [13–15]. Figure 3 shows the experimental evidence of the 3D-ordered state of JVs, in which a ‘beating’ effect can be observed [17] as shown in figure 3b. It can be explained as the effect caused by the difference between the effective width $w_{\max}$ and $w_{\min}$. When the *in-plane* angle θ of the magnetic field to the edge of the sample is changed as shown in figure 3a, the period of beating $H_{\rm beat}$ is expressed as $H_{\rm beat} = \phi_0/(w_{\max} - w_{\min})s$, $w_{\max} - w_{\min} = 2\ell \sin\theta$. This relationship holds/fits well qualitatively to the experimental results. If the JVs are not in a well-ordered line-like state even along the perpendicular direction to the superconducting layers, the beating effect cannot occur, because the period of each oscillation is determined by the effective width defined between the front and rear side edges of the sample. It is strongly suggested that the JVs must penetrate the lines from the front side to the rear of the sample forming a 3D-ordered state.

The field $H_{\rm s}$ is a full-filling state of JVs to the IJJs and determines the lower boundary of the 3D-ordered state of JV triangular-lattice phase. According to ref. [14], $H_{\rm s}$ is expressed as $H_{\rm s} = \phi_0/(2\pi\gamma^2 s)$, where γ is the anisotropy parameter of Bi-2212. Then, we can deduce the anisotropy parameter as 350 and 180 for samples A and B, respectively. Doping effect appears significantly in the lower boundary of the 3D-ordered state of the JV triangular lattice. Details of the anisotropy dependence on $H_{\rm s}$ are discussed in ref. [19].

With respect to an upper boundary $H_{\rm u}$ of the 3D-ordered JV lattice phase, we have reported on sample A [20], which is shown in figure 4. A characteristic feature of the sample is a broad peak in the flow-resistance which decreases to a finite value above 30 K. The finite value implies that the decrease in flow-resistance is not caused by the misalignment of the sample with respect to the parallel field, because the flow resistance drops to zero abruptly when there is a misalignment as shown in figure 2 of ref. [13]. Incorporation of the pancake vortices with the *out of plane* component of the applied magnetic field causes a reduction of the JV flow-resistance completely. Then, in this case, it is considered that there must be some resistance to overcome the JV flow, which is discussed later.

In figure 5a, the flow-resistance of sample B with smaller anisotropy is shown as a function of the magnetic field at higher temperatures. The periodic oscillations can be observed close to 80 K and the starting field of the oscillations is almost independent of the temperature as shown in figure 5b. The maximum magnetic field of the periodic oscillations, which equals the upper boundary $H_{\rm u}$ of the 3D-ordered phase, suddenly decreases starting from about 76 K as shown in figure 5c. This characteristic is nearly the same as in sample A, taking into account the

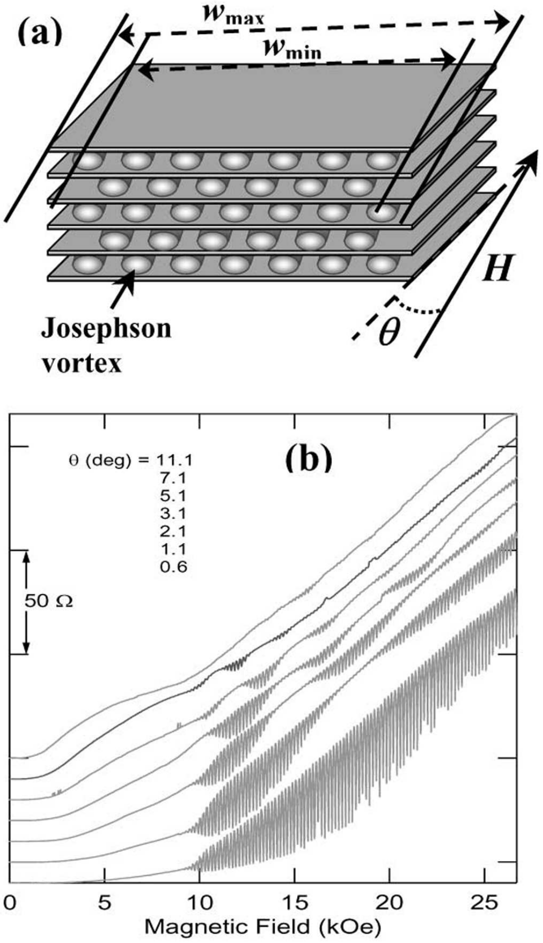

Figure 3. (**a**) Schematic drawing of the Josephson vortices in IJJs when the parallel magnetic field is applied with the *in-plane* angle θ. The effective widths $w_{\max}$ and $w_{\min}$ of the sample to the magnetic field are shown. (**b**) With changing angle θ, the flow resistance shows the beating effect in the amplitude of oscillations.

difference in T_c. A significant difference between sample B and sample A is the sudden drop of the flow-resistance at higher magnetic fields and an abrupt recovery of it as clearly seen in figure 5c. It happens almost independent of temperature and does not reproduce at the same magnetic field. This characteristic also cannot be explained only by the misalignment of the sample. The phase boundaries of H_u and H_s are shown in figure 6 for sample B. Upper critical field H_{c2} was obtained from the measurements of temperature dependence of the c-axis resistance near the superconducting transition.

One of the possible explanations for the above experimental results on two different anisotropic samples might be a phase transition from the 3D-ordered triangular

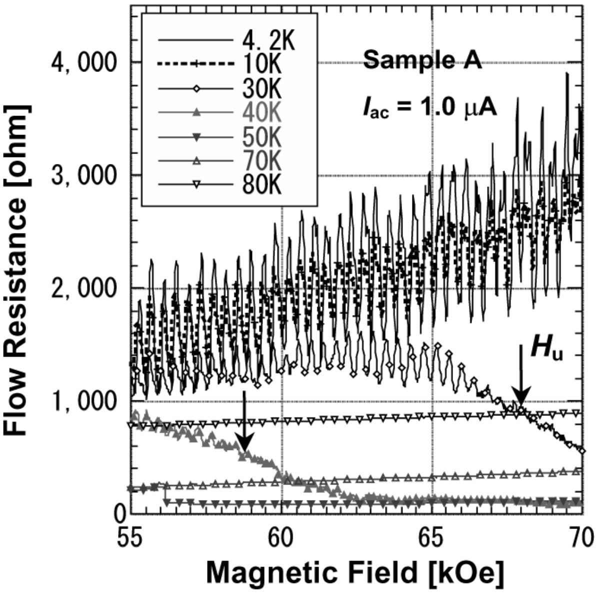

Figure 4. Josephson-vortex flow resistance measured on sample A as a function of magnetic field at various temperatures and higher magnetic fields. H_u denotes the magnetic field of the end of the periodic oscillations, which corresponds to the upper boundary of the 3D-ordered JV phase.

lattice phase to another phase. The vortex state in the other phase showing the reduction of the flow-resistance without the periodic oscillations is not in a disordered state in the *in-plane*, which may enhance the flow velocity because of the lack of the total vortex-line potential (edge barrier) at the edge of the sample. This may be caused by the presence of pancake vortex/anti-vortex pairs across the Cu–O superconducting layers, which are excited magnetically and thermally, with increasing magnetic field and temperature. In strongly anisotropic HTSC materials, it has been discussed that thermal fluctuation is a typical feature even when the field is perpendicular to the layers. The thermal fluctuation causes pancake vortex/anti-vortex pairs, which has been confirmed in the JV system also by the Monte-Carlo simulations [7]. It is noted that in sample B the flow-resistance recovers to almost the extrapolated value of the flow-resistance at lower magnetic fields after the sudden decrease as shown in figure 5a. This means that, if the sudden decrease of resistance is caused by the generation of pancake vortex/anti-vortex pairs, JV system has the same configuration as in the 3D-ordered state without the periodic oscillations. Absence of periodic oscillations means that there is no long-range ordering along the *c*-axis, but there forms a 2D ordered state in the *in-plane*. This may suggest a 2D quasi-long-range crystalline ordering of JV system proposed by Hu and Tachiki [7]. To understand the JV system better, we have to develop the JV flow-resistance experiments by changing the doping level further, and to confirm the reproducibility.

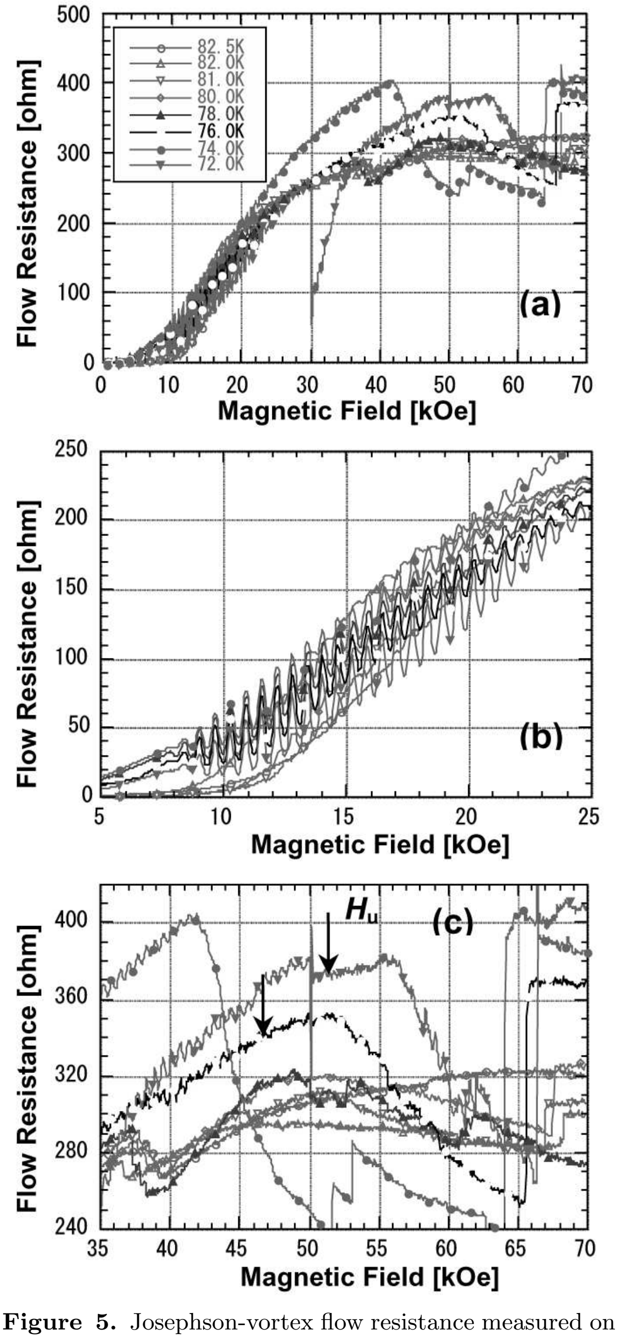

Figure 5. Josephson-vortex flow resistance measured on sample B as a function of magnetic field at higher temperatures close to (**a**), enlarged part of that at lower magnetic fields (**b**), and enlarged part of that at higher magnetic fields (**c**).

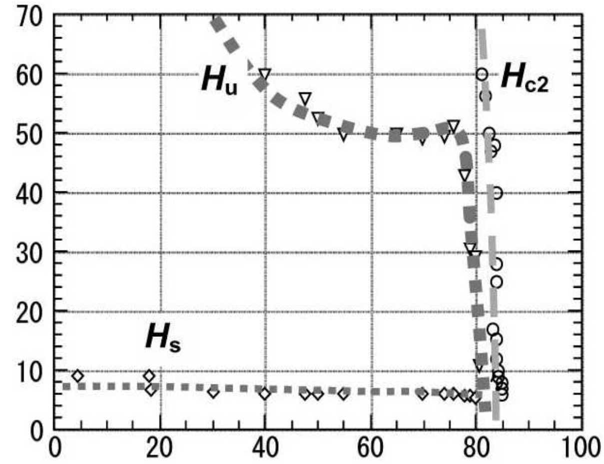

Figure 6. Magnetic phase diagram of Josephson vortex system in Bi-2212 (sample B), obtained from the measurements of Josephson-vortex flow resistance. The dotted and broken lines are drawn to see the boundaries clearly.

4. Summary

In conclusion, we have measured JV flow-resistance on the IJJs of Bi-2212 single crystals with slight and moderate doping samples, and have studied the magnetic phase diagram of JV system, making use of the observed periodic oscillations. Lower and upper phase boundaries of the 3D-ordered JV lattice phase have been obtained. The lower phase boundary is a beginning of the formation of JV lattice, with full-filling of the JVs to the layers. The upper phase boundary is a phase transition from JV lattice state to the 2D quasi-ordered state, accompanied by pancake vortex/anti-vortex pairs across the superconducting layers.

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