# Josephson Vortex Flow in $Bi_2Sr_2CaCu_2O_{8+y}$

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**Abstract**

In order to study the magnetic phase diagram of Josephson vortices, we have measured their flow resistance as a function of parallel magnetic field in $Bi_2Sr_2CaCu_2O_{8+y}$. Periodic oscillations are observed from about 6 kOe to larger than 70 kOe, which suggests the formation of Josephson vortex lattice as the ground state. However, depending on the applied current, we have found that Josephson vortex lattice in higher fields is not only triangular but also rectangular due to dynamical effects of Josephson vortex flow.

*Key words:* Josephson vortices; vortex lattice; $Bi_2Sr_2CaCu_2O_{8+y}$; flow resistance

High $T_c$ superconductors (HTS's) have provided interesting fields in condensed matter physics. For instance, in the vortex matter physics, the anisotropy of HTS has prompted the understanding of the vortex states in superconductors in general. When a magnetic field is applied perpendicular to the Cu-O planes, first-order melting transition has been confirmed experimentally and proved theoretically. Most of the significant behaviors in the vortex states is caused by large thermal fluctuations and anisotropy caused by the layered crystal structure. In parallel magnetic fields, interesting characteristics have been proposed in highly anisotropic superconductors: existence of a smectic phase [1], an oscillatory behavior of the melting transition $T_m(B)$ [1], and a tri-critical point on the melting transition line [2]. In the underdoped $YBa_2Cu_3O_{7-y}$, the oscillatory behavior of the melting transition $T_m(B)$ of Josephson vortices has been observed [3]. However, there are few experimental evidences on Josephson vortex state in highly anisotropic superconductors such as $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO).

For the fabrication of the intrinsic Josephson junctions, we have used single crystals of BSCCO, which were grown by traveling-solvent floating-zone technique. A cleaved platelet of single crystals was carefully cut into narrow bars with a width of about 50 $\mu$m and a length of about 2 mm. After forming a four-contacts configuration using silver paste, the center of the strips was milled by focused ion beam. A schematic drawing of the sample is shown in the inset of Fig. 1. The superconducting transition temperature $T_c$ is 86 K in all samples. The alignment of the field parallel to the Cu-O planes has been achieved by measuring the angular dependence of the flow resistance, and setting it to its maximum value with an accuracy 0.005°.

Recently, we have observed periodic oscillations in the flow resistance of Josephson vortices in intrinsic Josephson junctions with the $c$-axis current [4], as shown in Fig.1. The periodic oscillations have been observed in a wide range of temperatures and fields. We found that the period $H_p$, shown in the inset of Fig.1, is only related to the width $w$ of the junction in the perpendicular direction to the parallel magnetic field, and is expressed as $H_p = H_0/2$, $H_0 = \phi_0/ws$, where $\phi_0$ is the flux quantum and $s(= 15$ Å) the distance between the Cu-O layers, *i.e.* the thickness of one intrinsic Josephson junction. This means that the period $H_p$ corresponds to the increment/decrement of the field, *i.e.* adding/removing "one" flux quantum to/from every "two" junctions. This characteristic behavior can be explained by assuming the formation of a triangular lattice of Josephson vortices and the

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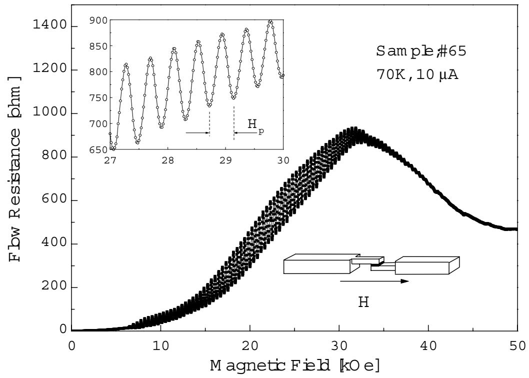


Fig. 1. Magnetic field dependence of the $c$-axis flow resistance with a current of $10\mu$A at 70 K in the sample with junction area of $17.6 \times 14.0\mu$m$^2$. The inset shows an enlargement of the main figure. A schematic drawing of the sample is also shown. The dark part in the center indicates the intrinsic Josephson junction.

existence of potential barriers against Josephson vortex flow located at the boundary of the junctions. It is also suggested that below 6 kOe Josephson vortices are in a different phase. Therefore, we conclude that the measurement of the flow resistance is a very useful probe to investigate the magnetic phase diagram of Josephson vortices, even in the solid phase.

As shown in Fig 1, with increasing magnetic field, the average flow resistance increases monotonically accompanied with the periodic oscillations, and has a maximum around 32 kOe, and then decreases gradually. For large deviations of the field from the Cu-O planes, the $c$-axis component of the field may exceed the lower critical field. In this case, pinning effect from the pancake vortices affects the Josephson vortex flow, and the resistance suddenly drops close to zero in a finite magnetic field. However, from the figure, it is clear that a finite flow resistance remains beyond the maximum. In Fig. 2, the flow resistance at 10 K is shown, measured with $c$-axis currents of 1 and 10 $\mu$A. For 1 $\mu$A, the flow resistance increases monotonously, and periodic oscillations with $H_p = H_0/2$ continues to fields larger than 70 kOe. Therefore, misalignment of the fields is very little from the Cu-O planes, and, in the lower current limit, Josephson vortices form triangular lattice in the ground state. In the higher current of 10 $\mu$A, the flow resistance is much enhanced. It is noted from the inset (a) of Fig. 2 that above 40 kOe, the period changes to twice of that in lower magnetic fields. The period $H_p$ becomes equal to $H_0$. This suggests that, in every period, "one" flux quantum is added to every "one" intrinsic junction simultaneously; *i.e.* in-phase coherent motion of Josephson vortices. Such a dynamical effect has been theoretically discussed by Machida [5] and Koshelev [6]. With increasing current, the phase difference between the layers changes from $\pi$ to 0. This

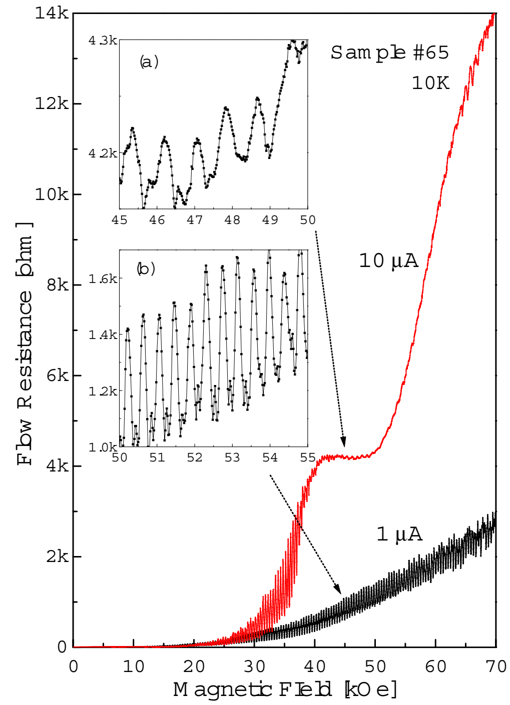


Fig. 2. Field dependence of the flow resistance at 10 K with $c$-axis currents of 1 and 10 $\mu$A. The insets (a) and (b) show enlargement of the main figure 10 and 1 $\mu$A respectively in order to make the oscillations visible. It is easily seen that the period in (a) is double of that in (b).

corresponds to a structural change of the Josephson vortex lattice from triangular to rectangular, and an enhancement of the flow resistance.

In summary, we have measured the flow resistance of Josephson vortices in BSCCO intrinsic Josephson junctions to study their magnetic phase diagram. We have observed novel periodic oscillations in the flow resistance, which exist in a wide range of temperatures and magnetic fields. In the lower current limit, the period of the oscillations indicates the formation of a triangular lattice of Josephson vortices, suggesting that the latter is the ground state. In higher currents, the period changes to twice to that for lower currents. This is considered as a consequence of the dynamical effect of Josephson vortices.

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