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# New lock-in phenomena in intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+y}$ with hole-array

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ABSTRACT

Dynamical behaviour of Josephson and pancake vortices (JVs and PVs) in intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi-2212) single crystal with a nano-size hole-array has been studied to measure the flow-resistance of the vortices. In the magnetic field perpendicular to the superconducting layers, flow resistance of PVs measured with the *in-plane* current shows a matching behaviour as usually observed at the matching fields. After the measurements, the sample was fabricated into the *in-line* shaped structure for the *c*-axis current measurements to obtain the JV flow-resistance. Instead of the usually-observed lock-in phenomenon of JVs in Bi-2212, several peaks are observed with changing the angle from the *in-plane* magnetic field to show the enhancement of the flow-resistance at some typical angles. When PVs are introduced into the sample with changing the angle, are trapped into holes, and are interacted with JVs, it is clearly seen that the well-aligned PVs cause the enhancement of the JV flow-resistance.



## 1. Introduction

Dynamical motion of Josephson vortices (JVs) in the Josephson junctions enables us to invent some new devices for high-speed signal-processing, mass communications, and storages. Superconducting devices have been developed with their high-speed performance and less energy consumption. Recent developments of cryo-cooler technology enable us to use them for cooling without any difficulty. Among the superconducting devices, JVs act as a promising signal transformer, because of their high-speed propagation close to the light velocity and the low energy consumption. Single JV in the single Josephson junction (JJ), consisted of $Nb/AlO_2/Nb$, was observed as a soliton in the Josephson transporting line [1]. Annihilation of two solitons moving in opposite directions was confirmed to collide with a breathing mode.

High $T_c$ superconductors (HTSCs) have a layered structure, stacking of superconducting layers and non-superconducting ones, which causes a strong anisotropy in superconductivity and also in vortex physics. Furthermore, this structure causes a weak coupling between the superconducting layers, and hence becomes multiply-stacked intrinsic Josephson junctions (IJJs) [2]. JVs in IJJs of HTSCs can move very fast also. It may be suitable for high-speed and new functional devices, when appropriate nano-structured electrodes or some kinds of gates are fabricated to each superconducting layer for controlling the dynamical motion of JVs and the superconducting phases.

New functional devices of controlling the vortex motion have been proposed and confirmed experimentally, which appear as a remarkable functional such as flux quanta diode, vortex lens, vortex pumping and ratchet effect [3–7]. However, they are consisted of spatially-asymmetric potential wells, dots, and anti-dots in low $T_c$ superconductors with a time-symmetric input current. Most of the devices are operated for the motion of vortices in one direction as in an irreversible characteristic. For the reversible function, Ustinov et al. [8] have proved the ratchet effect with applying a bi-harmonic microwave to single JJ. However, these devices are fabricated by using photo- and electron-beam lithography, and it takes long time and needs complicated fabrication processes.

Using HTSCs materials of IJJs, dynamical motion of JVs can be applied to generate a coherent THz emission [9]. However, up to now, only the weak emission could be obtained [10], and it is very hard to control the dynamical motion of JVs coherently. We have observed periodic oscillations in the flow resistance of JVs against the parallel magnetic field to the superconducting layers [11], which is a kind of coherent motion of JVs. In this paper, we report on the dynamical motion of JVs for the purpose to control them, in which we have introduced pancake vortices (PVs), playing a role for pinning of JVs and a transport media with the arrangement of PVs to the array of anti-dots holes.

## 2. Experimental

High quality single crystals of $Bi_2Sr_2CaCu_2O_{8+y}$ were grown with a travelling solvent floating zone method [12]. Sample preparation is described elsewhere [13]. The superconducting transition

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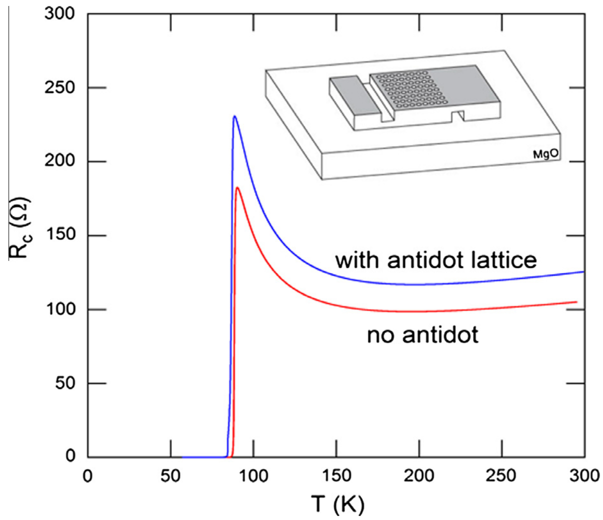


**Fig. 1.** Temperature dependence of the *c*-axis resistance with and without anti-dots lattice. Inset shows a schematic drawing of Bi-2212 sample with anti-dots hole array.

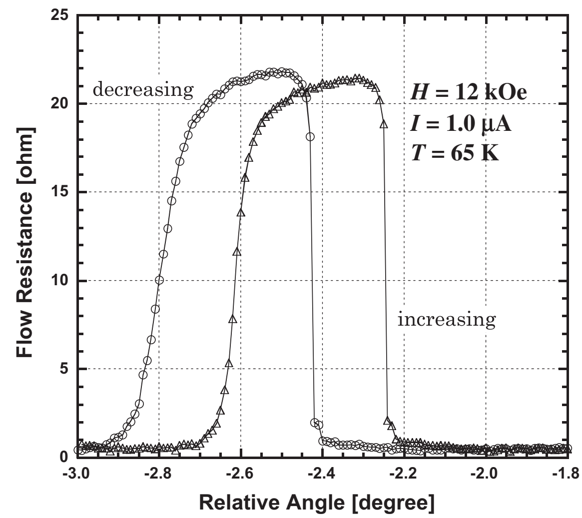


**Fig. 2.** Typical lock-in phenomena in the flow-resistance measurements of JVs against angle at 65 K with a dc current of 1.0 μA and a magnetic field at 12 kOe.

temperature $T_c$ of the sample in the *in-line* shape was 88.5 K, and, after fabricating the anti-dots array using a focused ion beam (FIB; Hitachi FB-2100), $T_c$ decreased to 86.5 K, which was determined by the zero-resistance criterion and was drawn in Fig. 1. Damage by the FIB and the reduction of oxygen doping in vacuum or FIB ion-beam may cause slight deterioration of $T_c$.

A schematic drawing of the junction part in the Bi-2212 sample is shown in the inset of Fig. 1. The size of the junction is 22.1 μm in width, 14.5 μm in length, and 0.3 μm in thickness. The size of the hole and of the lattice spacing in the square lattice is about 0.2 μm and 1.0 μm, respectively. The flow resistance of the fabricated IJJs was measured with a four-probe contact configuration with a constant dc current source (Keithley 2400) and a dc nanovoltmeter (Keithley 2182A) in an applied field $H$ along the length. The relative angle between the sample plane (superconducting plane) and the magnetic field is controlled with an accuracy of 0.001°. The details of the JV flow resistance measurements are described also in Ref. [11].

## 3. Results and discussion

Fig. 2 shows a typical example of angular dependence of the JV-flow resistance in Bi-2212 single crystal sample without anti-dots hole-array, changing the relative angle between the magnetic field and the superconducting planes, and with dc current of 1 μA at 65 K and magnetic field of 1.2 T [14]. The flow resistance shows a plateau, and the perpendicular threshold field component is almost constant which is close to the first critical magnetic field $H^c_{c1}$. JV flow is considered to happen in the magnetic field region, in which the perpendicular component $H^c$ is less than the $H^c_{c1}$ [15].

However, in the sample with anti-dots hole-array, the resistance shows sharp peaks in the perpendicular magnetic field component $H^c$ less than the $H^c_{c1}$. Fig. 3a and b shows the JV flow-resistance in the magnetic field from 1 to 10 kOe with a dc constant current of 1 μA at 70 K with increasing and decreasing the angle, respectively. The peaks have a hysteresis about 0.2°. The magnetic field region, in which the peaks are observed, becomes narrower with increasing magnetic field, as in the case of the flow-resistance obtained without the hole-array [15]. There observed five main peaks in each field. Besides them, sub-peaks can be seen between the main peaks. Typically, at 3 kOe, they are clearly observed. To analyze these peaks, we re-plotted the resistance to the *c*-axis component $H^c$ of the applied magnetic field $H$, as shown in Fig. 4.

To re-plotting the flow-resistance of Fig. 3, we have to determine the absolute angle $\theta$ between the magnetic field $H$ and superconducting layers as the centre peak angle $\theta_0 = 0$. In Fig. 4a and b, the resistance is plotted against the *c*-axis component $H^c = H\sin\theta$. The main and sub-peaks are well aligned in each applied magnetic field at the fixed field of about every 20 Oe interval. So, it is clearly seen that the peaks occur depending on the *c*-axis component $H^c$ and, furthermore, at the typical magnetic field discussed below. Here, when we consider about the vortex matching field to the hole-array; $\phi_0/a_0^2 = 2.07 \times 10^{-7}/(1 \times 10^{-4})^2 = 20.7$ Oe with $\phi_0$ of the flux quantum and $a_0$ of the lattice spacing of hole-array [13], the magnetic field component is well coincided to the interval. The sub-peaks also are located at the half-matching fields. It is strongly suggested that the flow-resistance of JVs is closely related to the arrangement of PVs. These peaks are observed at lower magnetic fields less than 6 kOe. At higher magnetic fields, the sub-peaks are smeared out, and only the main peaks can be seen clearly.

Interaction between PVs and JVs are discussed by Koshelev et al. [16]. Chain vortex state of PVs is a typical example of the interaction, being located near and on the JVs. Dynamically, in the presence of PVs, mobility of JVs suffers a damping, and is strongly suppressed. Moving JV lattice forces oscillating zigzag deformation of PV stacks, which causes damping. Then, what will happen when the PVs are well aligned? In the integer- or half-integer-matching field of $H^c$, PVs are well aligned perpendicular to the JVs motion in this experimental setup. PVs are stacked well straight along the hole direction. This PV alignment becomes a well-aligned periodic well to the JV movement. This situation is quite different from the zigzag configuration of PVs in the magnetic field without the matching, and the damping will be reduced. Therefore, at the integer- or half-integer-matching field of $H^c$, the mobility might be enhanced compared to those in the other magnetic field. We can observe the enhancement of resistance as the peaks in the magnetic field range approximately from −40 to 40 Oe at 70 K, which is well coincided to the value of $H^c = 41$ Oe, which is calculated from the plateau width $w$ in Fig. 2 as $H^c = 12$ [kOe]$\sin(w/2)$ ($w = 0.39°$). This indicates that the peaks are a kind of the plateau of the lock-in phenomena without the anti-dots array, but the JVs are flowing in the periodic media produced by the hole-array lattice.

To confirm a mechanism of the JV resistance enhancement with anti-dots array, we have to make further experiments in different temperature and another sample with changing the direction of