Periodic Oscillations of Josephson-Vortex Flow Resistance in $Bi_2Sr_2CaCu_2O_{8+y}$

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To study the Josephson-vortex system, we have measured the vortex-flow resistance as a function of magnetic field parallel to the *ab* plane in $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals. Novel periodic oscillations of the vortex-flow resistance have been observed in a wide range of temperatures and magnetic fields. The period of the oscillations corresponds to the field needed to add "one" vortex quantum per "two" intrinsic Josephson junctions. The flow velocity is related to a matching effect between the lattice spacing of Josephson vortices along the layers and the width of the sample. These results suggest that Josephson vortices form a triangular lattice in the ground state where the oscillations occur.

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High-T_c cuprate superconductors have provided an interesting field in the vortex matter physics, due to their pronounced layered structures, as well as to the presence of large thermal fluctuations. Novel phenomena, such as first-order vortex lattice melting [1] and disorder-induced phase transition [2], have been experimentally confirmed for fields perpendicular to the layers ($B \perp ab$). On the other hand, the Josephson-vortex matter, which is realized for fields parallel to the layers ($B \parallel ab$), has recently attracted much attention because of fundamental interest and also for prospective applications [3].

The periodic pinning potential caused by the layered crystal structure, so-called intrinsic pinning [4], influences the thermodynamics of the Josephson-vortex system. In this situation, several theoretical studies have been done on the existence of a smectic phase [5], an oscillatory behavior of the melting transition temperature $T_m(B)$ [5], and a tricritical point on the melting transition line [6]. In the vortex-solid state, field-induced structural transitions between several phases have been expected from the anisotropic London theory [7] and the lowest Landau level approximation of the Lawrence-Doniach model [8].

Recently, the oscillations of $T_m(B)$ have been found in a 60-K phase of $YBa_2Cu_3O_{7-\delta}$ (YBCO) [9], which has higher anisotropy than the optimally doped YBCO. They have also suggested the existence of a smectic phase. In the more anisotropic material $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO), Mirkovic *et al.* have recently studied the vortex lattice melting transition in a wide range of angles and fields using in-plane resistance measurements in the Corbino geometry [10]. They have suggested that the first-order melting transition of pancake vortices changes to a second order vortex-crystal–vortex-smectic phase transition for fields nearly parallel to the *ab* planes.

Although both measurements in YBCO and BSCCO systems have provided an insight into the solid-liquid or solid-smectic phase transitions, the nature of the Josephson-vortex system in the solid phase itself is still unclear. From standard transport measurements, it is difficult to investigate the solid state, because resistivity goes to zero due to the pinning effects from quenched disorder. In small samples, such as mesa structures of about 100 μm in length, a collective Josephson-vortex flow appears in the *c*-axis resistance even at low temperatures [11]. This flow resistance can be used to probe the vortex-solid phase.

In this Letter, we present a study on the vortex-flow resistance of Josephson vortices using BSCCO single crystals. We have found novel periodic oscillations of the flow resistance of Josephson vortices as a function of the in-plane magnetic field. The period of the oscillations suggests that Josephson vortices form a compressed triangular lattice along the *c* axis. Furthermore, the existence of other phases is suggested for fields below threshold values of about 7 to 9 kOe.

High quality single crystals of BSCCO were grown by traveling-solvent floating-zone technique [12]. A platelet of single crystal was carefully cut into narrow strips. After forming a four-contacts configuration using silver paste, the center of the strips was milled by focused ion beam (FIB) as shown in Fig. 1. The same process to fabricate similar structures has been used for BSCCO whiskers [13]. This type of sample is called intrinsic Josephson junctions since BSCCO crystals form Josephson junctions naturally in their crystal structures [14]. The inset of Fig. 1 shows a schematic illustration of the sample. The dimensions [width $(w) \times$ length $(l) \times$ thickness (t)] of the measured samples *A*, *B*, and *C* are $7.3 \times 12.9 \times 1.3$, $18.0 \times 16.5 \times 1.6$, and $31.0 \times 17.5 \times 2.0$ μm^3, respectively [15]. The superconducting transition temperature T_c is 86 K in all samples.

While the resistance of the strips was smaller than 1 Ω before the milling process, the resistance of samples *A*, *B*, and *C* increased after fabrication to 1400, 560, and 315 Ω at room temperature, respectively. Therefore, the measured resistance is almost equal to the *c*-axis resistance of the junctions, and the contribution of in-plane resistivity can therefore be neglected. In the small mesa crystals of BSCCO, the flow of Josephson vortices, which is not

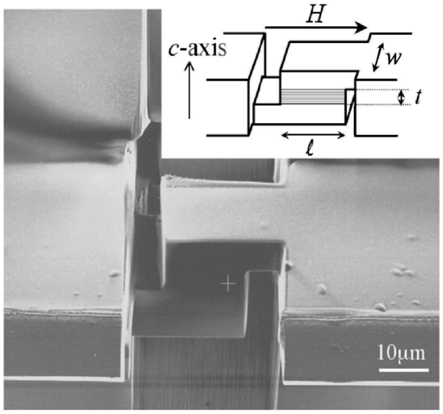

FIG. 1. An FIB image of a typical sample. Schematic drawing of the junction (hatched part) is shown in the inset. The magnetic field is applied along the l direction. A definition of the junction dimensions is also indicated.

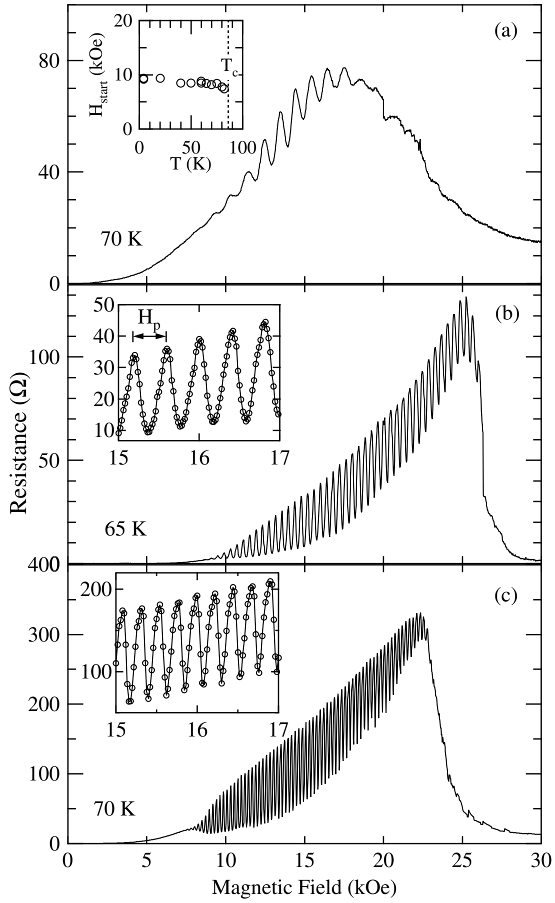

FIG. 2. Flow resistance of Josephson vortices as a function of magnetic field of samples A (a), B (b), and C (c) with an applied current of 1, 1, and 10 μA, respectively. The inset of (a) shows the temperature dependence of H_{start} for sample B. The enlarged figures of the flow-resistance oscillations of samples B and C are shown in the insets of (b) and (c), respectively.

strongly affected by pancake vortices, has been realized in the so-called lock-in state [11,16,17]. It was possible to orient the ab planes parallel to the magnetic field with an accuracy of 0.005° by adjusting the flux-flow resistance to its maximum value.

When the field is applied parallel to the ab planes in the superconducting state, the constant current along the c axis drives Josephson vortices to a direction perpendicular to both current and field. This motion of vortices causes the flow resistance. Up to the present, it has been reported that the flow resistance increases smoothly with increasing field because only the number of vortices increases [16,17]. However, we have discovered novel oscillations as a function of field as shown in Fig. 2. When the magnetic field is increased, a finite flow resistance appears at ~2–6 kOe depending on the sample and current density. This field may be related to pinning effects of Josephson vortices due to the surface boundary of the junctions. The oscillations start from a constant field $H_{\mathrm{start}} \sim$ 7–9 kOe in all samples. The period H_{p} of the oscillations is quite constant in a wide range of magnetic fields.

As the magnetic field is increased, the average flow resistance of the oscillations increases and drops suddenly above a field H_{stop}. This field decreases with increasing the absolute value of the angle (θ) between the magnetic field and the ab plane. This may be due to a breakdown of the lock-in state because the pancake vortices penetrate into the layers and prevent the flow of Josephson vortices when the c-axis component of the magnetic field exceeds the c-axis lower critical field H_{c1}. H_{stop} is nearly proportional to $1/\sin\theta$ with a coefficient of the order of H_{c1}. The maximum of H_{stop} reached 70 kOe in the best alignment setup. On the other hand, H_{start} and H_{p} almost did not change even if the field is intentionally shifted from the optimal position.

The temperature dependence of the flow resistance has also been measured from 4.2 K to T_{c}. The periodic oscillations can be observed in all temperatures below ($T_{\mathrm{c}} - 5$) K. H_{p} is independent of temperature. These facts show that the oscillations are related only to the field component parallel to the ab plane, namely, the dynamics of the Josephson vortices. H_{start} is almost constant as a function of temperature, but slightly decreases near T_c as shown in the inset of Fig. 2(a).

It is interesting that these oscillations are observed only at sufficiently small currents. I-V characteristics of sample B are shown in Fig. 3. In the fields where the resistance is minimum, the nonlinearity of I-V curves becomes large and a kink structure is observed around 50 μA. The periodic appearance of this structure as a function of fields corresponds to the oscillations of the flow resistance. At larger currents > 200 μA the oscillatory behavior disappears completely.

H_{p} depends on the dimensions of the junctions. To extract H_{p}, the power spectrum densities for the three

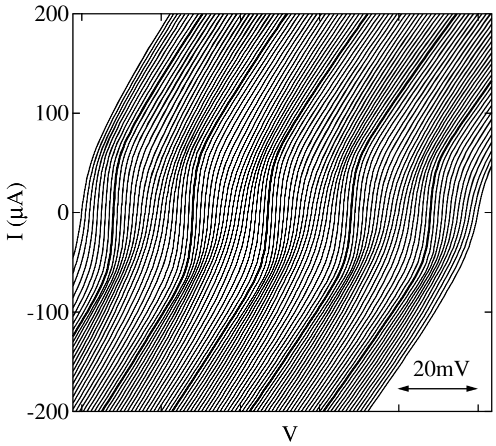

FIG. 3. I-V characteristics of sample B at various fields from 14 k to 16 kOe for every 20 Oe at 65 K. Each curve is shifted by a 1 mV step. Bold lines show I-V curves where the resistance is minimum.

samples, which are obtained from the data of Fig. 2 by fast Fourier transform, are shown in Fig. 4. The sharp fundamental peaks indicate that H_p is uniform over a wide range of fields. The small peaks, corresponding to second harmonic waves, are observed because the oscillations are slightly distorted from the sinusoidal. The positions of the peaks are plotted as a function of the width (w) of samples in the inset of Fig. 4. It is clear that $1/H_p$ is proportional to the width (w) of the samples.

In the following, an interpretation of the results is presented. Supposing that Josephson vortices uniformly penetrate into each junction, the increment of the field (H_0) needed to add one vortex per layer is then ϕ_0/ws, where ϕ_0 ($\simeq 2.07 \times 10^{-7}$ G cm^2) is the flux quantum and

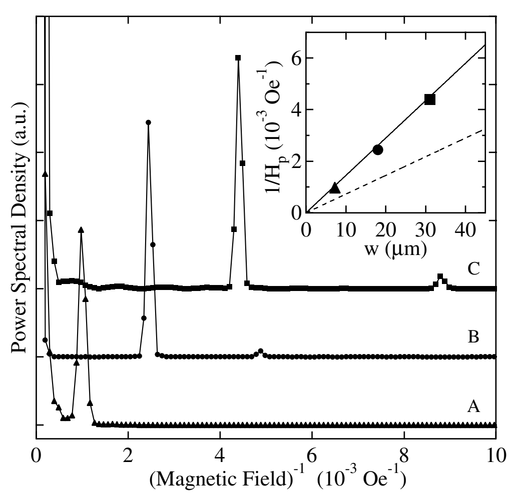

FIG. 4. Power spectral densities of the oscillations for samples A, B, and C. The vertical axes are shifted properly. In the inset, solid markers show the inverse of H_p, which is estimated from the positions of the peaks in the spectra, as a function of the sample width (w). The broken and solid lines represent $1/H_0(w)$ and its double, respectively.

s ($= 15$ Å) the junction thickness, namely, the distance between the superconducting CuO_2 layers. $1/H_0(w)$ is shown as a broken line in the inset of Fig. 4. Interestingly, the experimental values of $1/H_p$ are close to twice of $1/H_0(w)$, which means that H_p corresponds to adding "one" flux quantum per "two" layers. We can check whether the resistance takes a maximum or a minimum when the field is nH_p (n: integer). Experimentally, we have confirmed that the oscillations have minima at nH_p.

The above experimental results can be explained by assuming that: (1) the lattice structure of the Josephson-vortex system is triangular, and (2) at both the right and left sides of the junction, a surface barrier, i.e., Bean-Livingston barrier [18], acts on the vortices. For example, in a field of $n(H_0/2) \approx nH_p$, Josephson vortices are distributed as schematically shown in Fig. 5(a). This ordered state matches exactly the width of the junctions. When the vortex lattice flows from left to right, vortices at the right side exit through the surface potential and enter from the left side simultaneously. The total potential felt by the lattice from both sides becomes maximum. In this situation, the average velocity and hence the resistance of the vortex flow is minimum. In a short time scale, the velocity of the vortex lattice oscillates with time whenever vortices go over the boundaries. As the field is increased, additional vortices are forced to enter into the ordered lattice. The Josephson-vortex lattice can then move more easily since the total potential decreases due to the mismatching between the width of the junctions and the lattice spacing of the vortices. Hence, the flow resistance becomes larger than that in the above matching case. When the field exceeds $(n + 1/2)(H_0/2)$, the lattice starts to return to the matching state. At $(n + 1)(H_0/2)$, the matching between the Josephson-vortex lattice and the size of the junction is recovered as shown in Fig. 5(b), where the Josephson vortices enter in alternate layers in comparison with Fig. 5(a). Hence, it is plausible that the oscillation period of the flow resistance is half of H_0. When the Lorentz force from the applied current becomes large enough comparing with the effect of the surface potential, it is expected that the oscillations smear out, which explains qualitatively the I-V characteristics.

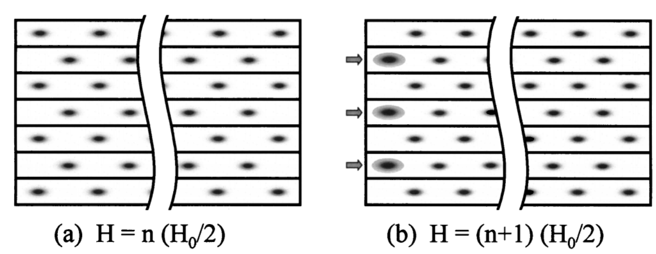

FIG. 5. Schematic pictures of the configuration of Josephson-vortex lattice when the magnetic fields are equal to (a) $n(H_0/2)$ and (b) $(n + 1)(H_0/2)$, where n is an integer.

There are several theoretical studies with respect to the equilibrium phase diagram of the Josephson-vortex system in anisotropic layered superconductors [5–8]. Ivlev *et al.* [7] have derived from the London theory the structure of Josephson-vortex lattice in high fields as a compressed hexagon of triangular lattice. Their analysis, however, is not adequate in the case of strong magnetic fields of the order of $\phi_0/\gamma s^2$, where γ is the anisotropy ratio [19]. In BSCCO, it is not clear whether this theory can be applied at the field where the oscillations occur, since this field is estimated to be 46 kOe with $\gamma \sim 200$ [20]. On the other hand, an extensive Monte Carlo simulation based on a 3D anisotropic frustrated XY model has shown that the ground state of the system is a triangular lattice in which Josephson vortices are distributed in every layer for anisotropy parameters $\gamma \geq 8$ when the filling factor is $1/32$ [6]. In BSCCO, it is expected that a compressed triangular lattice is the highest field phase even below the tricritical point value ($\sim$ 13 kOe with $\gamma \sim 200$) by rescaling [6]. Recently, Ikeda has studied extensively the ground states of Josephson-vortex solid in almost the whole range of fields [8]. According to his results, a triangular lattice appears above $1.4\phi_0/2\pi\gamma s^2$. This value is $\sim$10 kOe with $\gamma \sim 200$. Hence, the expected lower boundary fields of the triangular lattice are very close to H_{start}. The fact that the temperature dependence of H_{start} is very weak is consistent with this theoretical analysis. These facts suggest that H_{start} is the lower boundary field of the triangular lattice phase.

For magnetic fields lower than H_{start}, the oscillations cannot be observed in spite of the existence of a finite flow resistance. At lower magnetic fields, it is difficult to form a triangular lattice because the distance between the vortices is large. Ivlev *et al.* have predicted that a triangular array becomes unstable with respect to the formation of several new types of vortex lattices at low fields [7]. Furthermore, below the lower boundary fields of the triangular lattice, the existence of various structures of the Josephson-vortex lattice, defined as integer, rotated, and floating solids have been indicated precisely by Ikeda [8]. In this situation, the periodic oscillations might not be expected because of successive structural transitions of the Josephson-vortex lattice as a function of field.

In summary, we have measured the flow resistance of Josephson vortices in BSCCO single crystals. Novel oscillations of the Josephson-vortex flow resistance as a function of field have been observed. The period of the oscillations depends only on the width of the junctions. The fact that the period is $H_0/2$, which is the field needed to add *one* Josephson vortex per *two* layers, suggests that the lattice structure of the Josephson vortices is triangular. The oscillations originate from a matching between the triangular lattice and the width of the junction perpendicular to the field direction. At present, our measurements do not access the boundary between the lattice and liquid phases of the Josephson-vortex system. Further measurements based on this phenomenon would make it possible to investigate the phase diagram of the Josephson-vortex system including the liquid state.

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