Fractional matching of vortices in Bi$_2$Sr$_2$CaCu$_2$O$_8+y$ with triangular array of antidots

S. Ooi, T. Mochiku, K. Hirata
National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan
E-mail: OOI.Shuuichi@nims.go.jp

Abstract. To explore the fractional matching effect in vortex states of high-$T_c$ superconductors with lattice of artificially-introduced pinning centers, we have measured the in-plane vortex-flow resistance and the critical current as a function of magnetic field in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ single-crystal films having a triangular array of antidots. At the temperature very close to $T_c$ ($T < T_c$), fine dip structures in vortex-flow resistance and peaks in the critical current were observed in fractions 1/4, 1/3, 1/2, 2/3, 3/4, and 6/7 of the first matching field $H_1$. While most of fractional numbers are understood from a simple geometrical consideration on the arrangements of triangular lattices of vortices on the underlying array of antidots, the matching effect in 1/2 of $H_1$ implies a presence of interstitial vortices in comparison with simulations [Reichhardt C and Grønbech-Jensen N, 2001 Phys.Rev. B 63 054510].

1. Introduction
Influence of regular arrays of pinning centers on the vortex arrangements and its dynamics have extensively studied using micro- or nano-fabrication techniques, which have been rapidly progressing recently, toward the understanding of vortex physics and artificial controls of the vortex behavior for applications like a vortex rectifier [1, 2]. Artificial holes (antidots) or magnetic dots fabricated using electron beam lithography or focused ion beam (FIB) techniques have been applied as pinning centers in various conventional superconductors like Nb, Pb, and Al [3, 4, 5]. Commensurability between Abrikosov vortex lattice and the underlying array of pinning potentials has been investigated mainly, and observed as matching effects in measurements of magneto-resistance, critical current and magnetization, when the applied magnetic flux density coincides with the density of pinning centers, that is first matching field $H_1 = \Phi_0/a_0^2$ for square lattice, here $\Phi_0$ is magnetic flux quantum and $a_0$ is lattice spacing of pinning lattice. Although dips or peaks by the matching effects normally appear in integral multiples of $H_1$ in the vortex-flow resistance or the critical current as a function of field, respectively, they have been sometimes observed in fields of $f : H_1$ ($f :$ fractional number). For examples, peaks of magnetization at $f=1/2, 1/4, 1/5, 1/8$, and $1/16$ have been reported in Pb/Ge multilayers with a square lattice of submicron holes[6, 7]. The 1/2 and 3/2 fractional matching effects have been found in Nb films with square array of antidots[8] and rectangular array of magnetic dots [9]. The reason why the fractional matching effect has not been always observed depending on samples may be related to the sample quality, because long-range vortex-vortex interactions without disturbance by the residual pinnings are needed to keep a lattice structure with longer lattice spacing than $a_0$. 

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While thin films of conventional superconductors have been used in these researches, as it is easy to obtain their high quality films, studies on artificial pinning array in high-$T_c$ superconductors were limited in YBa$_2$Cu$_3$O$_{7-\delta}$ thin films made by magnetron sputtering technique [10, 11]. Since in high-$T_c$ superconductors, large thermal fluctuation causes new vortex phases, i.e., the vortex liquid, it is interesting to compare the matching effect in high-$T_c$ superconductors with that in the conventional ones. Especially, high quality samples of Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212) is useful to explore the sensitive fractional matching effect.

In the present study, we have used Bi2212 single-crystal films, which are prepared by a repeat of peeling to keep the quality of single crystals, because a sample with less amount of disorders is better to study the influence of artificially introduced pinning centers. We have already observed the matching effect in vortex-flow resistance in the samples with triangular and square antidots arrays [12, 13] and even with tiny surface structures [14]. Following these studies, here we report the experimental results on the fractional matching effect found by the detailed measurements near $T_c$.

2. Experiments
High-quality single crystals of Bi2212 were grown by the traveling-solvent floating-zone technique [15]. Since Bi2212 single crystals are easily cleaved along the $ab$-plane, thin single-crystal films with submicron thickness are available through the cleaving by adhesive tapes. First, the bulk crystals were fixed on MgO substrates by a polyimide. After thinning the crystals sufficiently, thin Au layer (20 nm) was deposited on the surface as electrodes. Patterns of the films for four-terminals resistance measurements were made using a photolithographic and an Ar-ion milling processes. Triangular array of holes was fabricated by the FIB milling using Micron JFIB-2100 in the central part of films between the voltage electrodes. The dose amount of 3nC/cm$^2$ of the beam used to make the holes corresponds to the milled thickness of 1 $\mu$m in our experimental condition. It is enough to perforate Bi2212 films (100 to 300 nm). The superconducting transition temperature $T_{c0}$ of the sample determined from zero resistance with a current of 10$\mu$A is 89.0 K.

3. Results and discussions
From just below $T_{c0}$, a dip structure in the magnetic field dependence of the vortex-flow resistance is observed in the first matching field $H_1 \simeq B_1 = 2\Phi_0/\sqrt{3}a_0^2 \simeq 23.9$ G for the triangular array of holes.
antidots with $a_0=1\mu m$. As the temperature is decreased, the flow resistance gradually becomes small, and fine structures appear at 87.8 K in the first period of the matching effect (0 < $H < H_1$) as shown in Fig. 2. Interestingly, the dip fields of the fine structures in the $R_{\text{flow}}$-$H$ curve are found to be $H_1$ multiplied by fractional numbers. The assigned fractional numbers for the dips are $1/4$, $1/3$, $1/2$, $2/3$, $3/4$, and $6/7$. These dip structures are observable in so narrow range of temperature as to mostly disappear at 87.6K.

The same features are also revealed in the critical current measurements. $I_c$ measured using a voltage criterion of $0.2\mu V$ at 87.7K is plotted as a function of field in Fig. 3. Although an expected peak in $6/7H_1$ is not clear at this temperature, other peaks corresponding to the dips in the flow resistance are identified.

These dips or peaks in both measurements are related to the fractional matching effect of vortices. The matching conditions between the vortices and the lattice of holes for $H < H_1$ was obtained from a geometrical consideration in the case of square pinning array [7]. In the triangular lattice of holes, fractional matching conditions of vortices are found in the similar manner that the larger triangular lattices of vortices with the period $a_{k,l}$ exactly fit onto the triangular lattice of holes with the period $a_0$. From this constraint, we can expect the fractional matching effect in

$$H = H_{k,l} \simeq B_{k,l} = \frac{2\phi_0}{\sqrt{3}a_{k,l}^2} = \frac{B_1}{(k + f(l))^2 + 3/4l^2},$$

here $f(l) = 0$ or 1/2 for even or odd $l$, respectively. The fractional matching fields normalized by $H_1$, calculated from some $k$ and $l$, are $H_{1,1} = 1/3$, $H_{2,0} = 1/4$, $H_{2,1} = 1/7$, $H_{3,0} = 1/9$, and so on. The matching at 1/3 and 1/4 are consistent with our observation. If we focus on the unoccupied holes instead of the vortices, the matching at 2/3, 3/4 and 6/7 above $H > 1/2$, are comprehensible since the empty holes can form the triangular lattices with $a_{1,1}$, $a_{2,0}$ and $a_{2,1}$ at those fields, respectively. It seems that the fractional matching effect is nearly symmetric with
respect to $H = 1/2$. Only the matching at 1/2 is special, because it does not have index of $k$ and $l$.

The fractional matching effect of vortex system with arrays of pinning potentials has been studied in 2D case by simulations of Reichhardt et al.[16]. According to their results, a peak of the critical current was observed at 1/2 as well as other expected matching peaks in the weak pinning case. At 1/2, interstitial vortices, which is not trapped on holes, had an important role to form a lattice structure[16]. Because the half of vortices is interstitial vortex in their result, the matching effect at 1/2 may become faint due to a loss of the pinning force.

In conclusion, to study the commensurability between vortices and underlying antidots lattice, we have measured the vortex-flow resistance and the critical current as a function of field in Bi2212 single-crystal films with the triangular lattice of artificial antidots. The fractional matching effect of vortex has first been observed in high-$T_c$ materials to our knowledge. While the measured matching fields fall into several series of 1/3, 1/4, and 1/7, the matching effect at 1/2 is not explained from the simple geometrical consideration, where there may exist the interstitial vortices.

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