Periodic oscillations of Josephson-vortex flow resistance in oxygen-deficient $YBa_2Cu_3O_x$

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We measured the Josephson vortex flow resistance as a function of magnetic field applied parallel to the *ab* planes using annealed $YBa_2Cu_3O_x$ intrinsic Josephson junctions having high anisotropy ($\sim$40) by oxygen content reduction. Periodic oscillations were observed in magnetic fields above 45–58 kOe, corresponding to dense-dilute boundary for Josephson vortex lattice. The observed period of oscillations, which agrees well with the increase of one fluxon per two junctions ($H_p = \Phi_0/2Ls$), may correspond to formation of a triangular lattice of Josephson vortices as has been reported by Ooi *et al.* for highly anisotropic ($\geqslant$200) Bi-2212 intrinsic Josephson junctions.

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INTRODUCTION

The crystalline structure of high-T_c superconductors can be considered as a stack of Josephson coupled superconducting CuO_2 layers oriented perpendicularly to the *c* axis. These junctions are called intrinsic Josephson junctions (IJJs).[1,2] When a magnetic field is applied parallel to the *ab* planes of the single crystal, Josephson vortices (JVs) carrying one flux quantum and whose cores are located in the nonsuperconducting layers, may form lattice structures.[3] When a bias current is applied along the *c* axis, the JVs flow along the *ab* direction because of the so-called Lorentz force and a flux-flow voltage, which is proportional to the flow velocity, appears.

The aim of this paper is to observe the JVs flow in $YBa_2Cu_3O_x$ (Y-123)[4] IJJs, especially the periodic oscillations of the JVs flow resistance by the edge effect through which one could analyze the JVs lattice structure. So far as resistance oscillations in Y-123 IJJs, Ling *et al.* found oscillations in the dynamical resistance of Y-123 IJJs at the temperature near the midpoint of superconducting transition for *mm*-sized samples at the magnetic field 0–300 Oe.[5] At relatively high temperature (80.54 K), they observed peaks at $H \sim 3\Phi_0/Ls = \Phi_0/L(s/3)$ for the series of samples with length 0.65–1.9 mm and explained the period by the junction thickness corresponding to the distance of CuO_2-Y-CuO_2 layers (0.34 nm$\approx s/3$). Here Φ_0, L, and s express flux quantum, junction length perpendicular to the magnetic field and the period of junction array (=*c* axis lattice constant of Y-123), respectively. The next peak was observed at $\sim 8\Phi_0/Ls$. The origin of these peaks remains an open question. At slightly low temperature (79.80–79.50 K), they observed periodic oscillations in the dynamical resistance with period ranging from 11 to 16 Oe which was close to $\Delta H \sim \Phi_0/L(2s) = 13.5$ Oe for the Y-123 IJJs with $L = 0.65$ mm and offered several speculations for the doubling of s. The origin of the doubled period of junction array $2s$ has been depicted as the formation of the triangular lattice of the JVs by Ooi *et al.*,[6] because the *c* axis constant is doubled. They also found that the oscillation starts at above the certain magnetic field ($\sim$7 kOe). Since the oscillations found by Ling *et al.* starts from zero field with the period of 11 Oe (and then change to 16 Oe), there remains a question whether the origins of the oscillations in the two cases (Refs. 5 and 6) are identical or not.

Fabricating the artificial stacked array junctions, Krasnov *et al.* observed clear oscillations in the dynamical resistance of Nb-Cu (20/15 nm) superlattice at the temperature near the superconducting transition (7.5 K) for 20 μm-ϕ sample at the magnetic field from 1.86 to 2.75 kOe with the period one fluxon per junction (Φ_0/Ls).[7] The period was explained by the periodic Fraunhofer dependence of Josephson critical current $[I_c(H)]$ in junction array in the three-dimensional (3D) regime where coherence length perpendicular to the layers is larger than the period of the array ($s = 35$ nm).

It should be noted that the findings in $Bi_2Sr_2CaCu_2O_x$ (Bi-2212; Ref. 8) IJJs by Ooi *et al.* are for the flow resistance $R_{FF} = V_{FF}/I_{bias}$ at substantially low temperature compared to T_c [from 4.2 K to (T_c-5) K] with precise periodicities and with high oscillation intensities.[6] Machida has studied the mechanism of these oscillations theoretically and elucidated the matching between the flowing triangular JVs lattice and the junction edges for the cause of the oscillations.[9] Koshelev has sketched out the distortion of the triangular JVs lattice at the edges and has pointed out that the origin of the oscillation derives from the inverse relation of the flow resistance to the $I_c(H)$ in junction array.

The configurations of the JVs lattice in stacked Josephson junctions have been discussed theoretically[10–13] and the magnetic field necessary for filling uniformly all the layers of the IJJs with JVs has been deduced as

$$H_{\text{d-d}} = \alpha(\Phi_0/s\lambda_j), \quad (1)$$

where $\lambda_j = \gamma s$ expresses the size of the nonlinear JV core along the layer (the frequently-called "the Josephson penetration depth λ_j of IJJs"), γ is the anisotropy factor, and α is $1/2\pi$, $1.4/2\pi$, $(1/12)^{1/2}$, or $(3/4)^{1/2}$, respectively, depending on the theoretical approaches for Refs. 10–13. Experimentally, if JVs uniformly fill all the layers in the IJJs, each Josephson junction in the IJJs would show similar behavior as a function of the magnetic field. Then, the oscillation in JVs flow resistance appears because of the interference of JVs lattice with the edges; $H_{\text{d-d}}$ is a good measure of the starting field of the oscillations in JVs flow resistance H_s. In Ref. 6, Ooi *et al.* have suggested that the H_s relates to the $H_{\text{d-d}}$ obtained in Ref. 11. Such fields are in inverse proportion to the anisotropy factor γ from Eq. (1).[10–13] The inverse relation has been proved by the decreased H_s with increasing γ observed in the Bi-based high-T_c superconductors.[14,15]

Note that at substantially low temperature compared to T_c, the oscillations in flux-flow resistance have been observed mostly in the Bi-based high-T_c superconductors. Such oscillations should be generally observable in high-T_c superconductors at low temperature. Because Y-123 has a high Josephson plasma frequency with a range beyond THz, which is significantly higher than that of Bi-2212 ($\sim$0.1 THz),[16] the Y-123 IJJs are much more attractive candidates for the actual THz device applications. However, the intrinsic Josephson effect observed in Y-123 was indecisive due to its low anisotropy which causes strong interlayer coupling.[17] In order to observe periodic oscillations of the JVs flow resistance at $T \ll T_c$, JVs are required to fill all layers in the IJJs, namely to form the lattice. Because such fields are in inverse proportion to γ, the fully oxidized Y-123 ($\gamma > 7$) requires extremely high magnetic fields, above 300 kOe, according to Eq. (1). To observe $H_{\text{d-d}}$ in Y-123, it is obviously necessary to increase the anisotropy of Y-123. Recently, we fabricated the Y-123 IJJs using high quality single-crystal whiskers and observed clear multibranch structures which are closely comparable to that for Bi-2212 (Refs. 18 and 19) since we notice that the anisotropy γ can be controllably increased with decreasing the oxygen content in the Y-123. In this paper, we report on the observation of the periodic oscillations of the JVs flow resistance in Y-123 IJJs with precise periodicities and with substantial oscillation intensities by annealing the sample in vacuum to increase anisotropy. In addition, the starting field H_s will be discussed in the relation with γ.

EXPERIMENTAL

Y-123 single crystal whiskers were grown by the Te-doping method.[19,20] The whiskers used for the measurements had flat *ab*-plane surfaces about 25 μm in width and 2 mm in length. The thickness along the *c* axis was about 5 μm. Four electrodes were placed on the Y-123 whisker using silver paste for transport measurements. We fabricated micron-scale *in-line-shaped* IJJs using a three-dimensional focused (Ga-) ion beam (FIB) etching method,[21] eliminating the non-uniformity, which is a typical problem in the surface junction of mesa-type IJJs. We estimated the size of the IJJs from a scanning ion microscope (SIM) image. The lengths of the IJJs perpendicular to the magnetic field (L) were 1.0, 1.9, and 4.3 μm for IJJs-1, −2, and −3, respectively. The depths along the field direction within the *ab* planes were about 5 μm for the three IJJs. The relatively long scales along the field direction were chosen so as to enhance the edge effect.

TABLE I. The parameters of Y-123 IJJs samples used for the flux-flow resistance oscillations measurements.

Sample	IJJs-1	IJJs-2	IJJs-3
L (μm)	1.0	1.9	4.3
D (μm)	4.9	4.95	5.1
t (μm)	0.4	0.2	0.3
T_c (K)	37	22.5	35
γ (estimated)	37	46	39
H_p calculated (kOe)	8.8	4.7	2.1
H_p observed (kOe)	8.6	5.5	2.0
$H_{\text{d-d}}$ calculated (kOe)	65	52	63
$H_{\text{d-d}}$ observed (kOe)	56	45	60

The total thickness t of the IJJs was about 0.2–0.4 μm along the *c* axis, corresponding to approximately 170–340 junctions in the stack. Table I summarizes the parameters of the Y-123 IJJs examined in this paper. Figure 1(a) shows a SIM image of the IJJs-2 fabricated into the in-line shape. After the FIB etching, the IJJs were annealed at 400 °C in vacuum for 1–2 h for oxygen reduction in order to increase their anisotropies.

The transport properties of IJJs were measured by "the physical property measurement system" (Quantum Design, PPMS) equipped with 70 kOe split pair magnets and a rotational sample stage. Prior to the measurements, the *ab* plane of the IJJs was precisely adjusted to the magnetic field by the

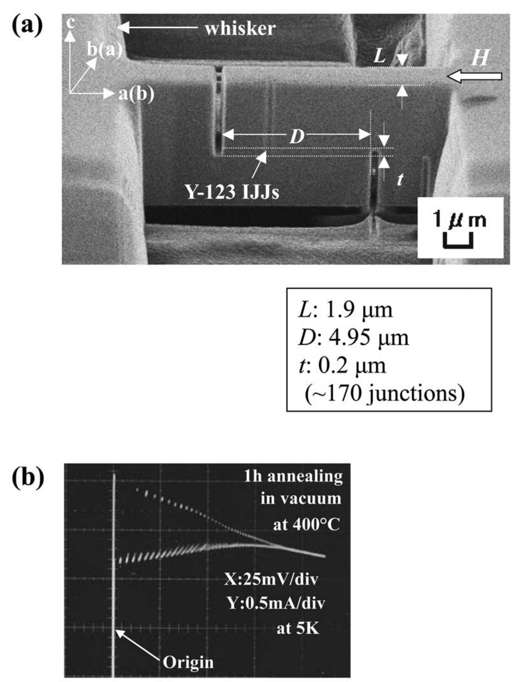

FIG. 1. (a). Scanning ion microscope (SIM) image of the in-line shaped Y-123 intrinsic Josephson junctions. The cross-sectional area and thickness of junctions are about 9.4 μm^2 and 0.2 μm, respectively. (b). Typical current-voltage (I-V) characteristics of the Y-123 intrinsic Josephson junctions under the zero field at 5 K (See Ref. 19).

angular dependence of the flow resistance (*lock-in* curve) under the constant magnetic field at a temperature just below T_c. When the field direction is close to the *ab* plane, the vortices become a *lock-in* state,[22,23] which is expected to be free from pancake vortex which goes across the superconducting CuO_2 planes. The flux-flow voltages were measured by the standard four-probe method with a dc current under the increasing magnetic field H parallel to the *ab* planes ($H \| ab$ plane). We define the flow resistance as this voltage divided by the dc bias current for the measurement.

RESULTS AND DISCUSSIONS

Figure 1(b) shows the typical current-voltage (I-V) characteristics of the Y-123 IJJs under the zero field at 5 K.[19] The I-V characteristics show clear multiple branches with large hysteresis typical for IJJs, suggesting that our *in-line shaped* Y-123 IJJs made of single crystal whiskers are homogeneous and of good quality.

Three oxygen reduced whiskers, fabricated in bridge shape, were prepared with different oxygen contents for estimating the anisotropy of the whisker whose T_cs range 40–90 K. Although this method is introduced in Refs. 24 and 25 we describe it in brief for clarity. We measured the angular dependence of the resistivity ρ at various magnetic fields H in a flux liquid state. We evaluated a reduced field by the effective mass model

$$H_{red} = H(\sin^2 \theta + \gamma^{-2} \cos^2 \theta)^{1/2}, \quad (2)$$

where θ is the angle between the *ab* plane and the magnetic field.[26] We plotted the ρ-H_{red} relation, and estimated the anisotropic factor γ, which gives the best scaling for the ρ-H_{red} relations. Figure 2(a) shows three data points, from which the critical temperature (T_c) dependence of anisotropy (γ) (γ-T_c relation) can be fitted by a straight line. Empirically, the anisotropy increases with decreasing the oxygen content in the Y-123.

It is difficult to obtain homogeneous oxygen-deficient samples with T_cs lower than 40 K by annealing the bridge-shaped samples. Thus, in order to obtain IJJs with $T_c < 40$ K, the in-line shaped IJJs of Y-123 are annealed in vacuum. Figure 2(b) shows resistivity-temperature (ρ-T) characteristics of the IJJs-2 with a dc current of 10 μA. Zero resistance is obtained at 22.5 K, and the anisotropy of the sample is estimated as $\gamma \sim 46$ [solid square in Fig. 2(a)] from linear extrapolation of the obtained γ-T_c relation. In the similar manner, the anisotropies of IJJs-1 and IJJs-3 are expected as $\gamma \sim 37$ and $\gamma \sim 39$, respectively.

It should be noted, Rapp *et al.* reported that $\gamma = 83$ for the polycrystalline thin film with $T_c = 42$ K (Ref. 17) which is factor 2-3 larger than ours. It should be emphasized that our estimation for γ has been done using single crystals at the superconducting state.

Figure 3 shows the JVs flow resistance of the IJJs as a function of the magnetic field (R-H curve) with dc currents of (a) 140–180 μA, (b) 6–15 μA, and (c) 30–100 μA for IJJs-1, IJJs-2, and IJJs-3, respectively at 5 K. In the field higher than 56 kOe, 45 kOe, and 60 kOe for IJJs-1, IJJs-2, and IJJs-3, respectively, the flow resistance shows periodic oscillations with period $H_p \sim \Phi_0 / 2Ls$. The observed onset fields of the periodic oscillations in JVs flow resistance shows good agreement with the dilute-dense boundary predicted by Koshelev in Eq. (1) with $\alpha = 1/2\pi$,[10] which are $H_{\text{d-d}} = \Phi_0 / 2\pi\gamma s^2 = 65$ kOe, 52 kOe, and 63 kOe, for IJJs-1, IJJs-2, and IJJs-3, respectively.

In the R-H curve for IJJs-2 shown in Fig. 3(b), the maxima of oscillations increase with increasing the magnetic field. The periodic oscillations are unclear in the dc bias current lower than 5 μA, mainly due to the noise level of our measurement system. On the other hand, the oscillation in flux-flow resistance disappears above 14 μA. This current level is 4.5% of the critical current (310 μA) at the zero

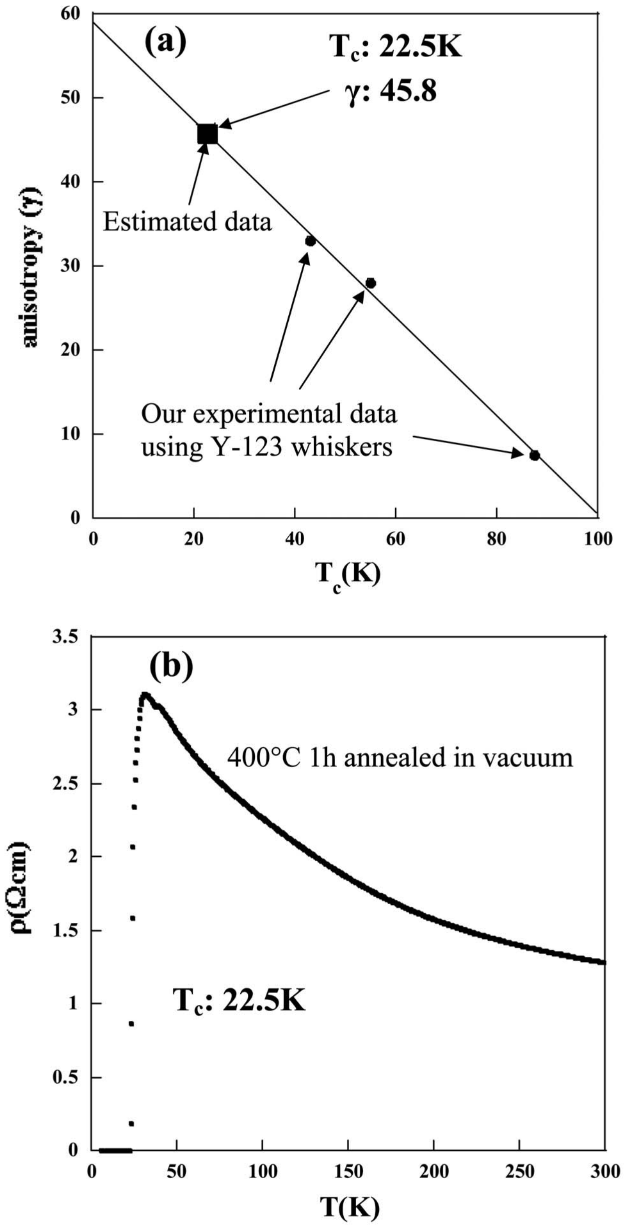

FIG. 2. (a). Critical temperature (T_c) dependence of anisotropy (γ) for Y-123 single crystal whiskers. (b). Resistivity-temperature (ρ-T) characteristics of the annealed Y-123 intrinsic Josephson junctions. The Y-123 intrinsic Josephson junctions were annealed at 400 °C for 1 h in vacuum.

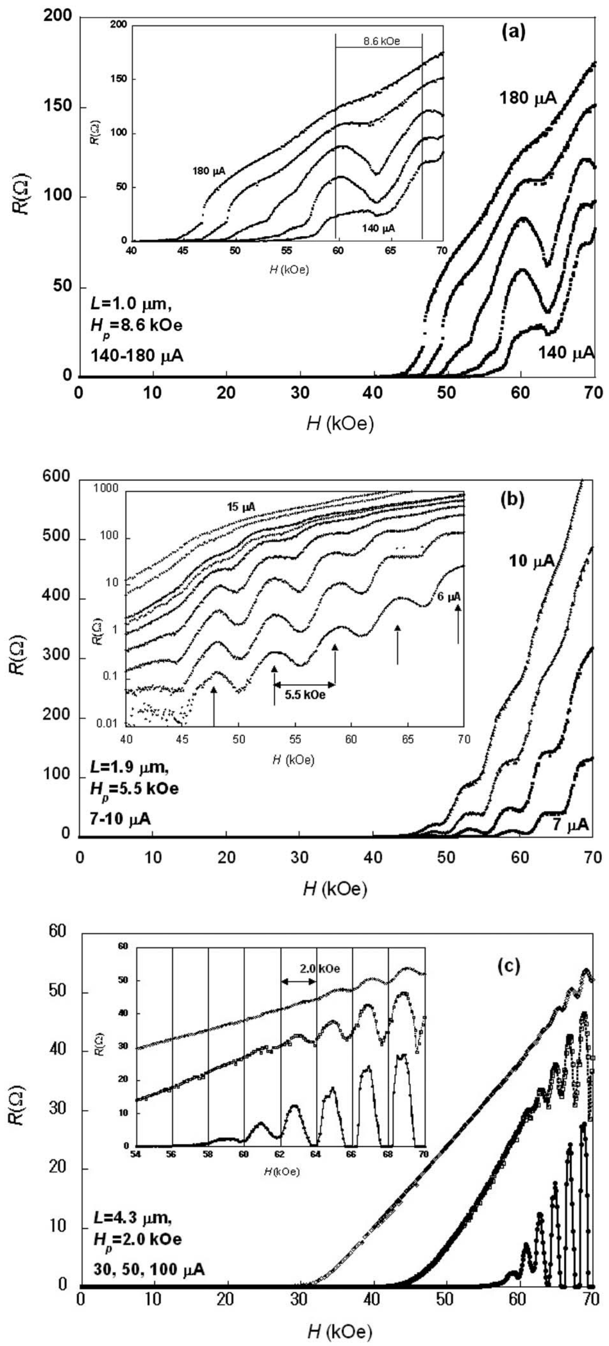

FIG. 3. Josephson vortices (JVs) flow resistance as a function of the magnetic field parallel to the *ab* planes at 5 K. Shown in the inset is the close-up of the flow resistance oscillations. (a) IJJs-1 with $L=1.0$ μm, (b) IJJs-2 with $L=1.9$ μm, and IJJs-3 with $L=4.3$ μm.

field. The clear periodic oscillations appear in the current level between 6 and 12 μA.

The observed periods of flow resistance oscillations H_p are approximately 8.6, 5.5, and 2.0 kOe, for IJJs-1, IJJs-2, and IJJs-3, respectively. According to the equation $H_p=\Phi_0/2Ls$, and the measured L from each SIM image, the calculated periods are 8.8, 4.7, and 2.1 kOe, respectively. The observed periods show good agreement with $H_p=\Phi_0/2Ls$, that is, one fluxon per two junctions. The formation of the triangular JVs lattice could be the origin of this period as has been proposed by Ooi *et al.* for the Bi-2212 IJJs.[6,27]

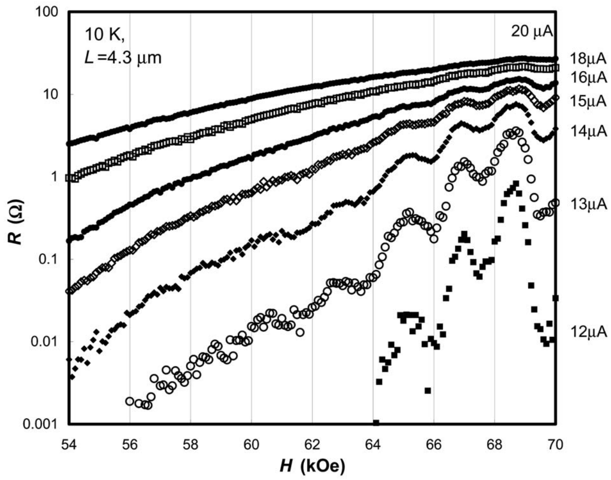

FIG. 4. Josephson vortices (JVs) flow resistance as a function of the magnetic field parallel to the *ab* planes at 10 K for IJJs-3 with $L=4.3$ μm.

The flow resistance oscillations are hardly observed at 10 K. Only from the IJJs-3, we succeeded to observe oscillations as shown in Fig. 4 at the low current levels. Although the oscillation intensity is small, the phase and the period of oscillations are identical to those observed at 5 K shown in Fig. 3(c).

Recently, Ustinov and Pedersen have proposed that both half and one fluxon period oscillations can be explained by the Fiske steps of a single Josephson junction.[28] As has been shown in the uniform multibranch structure in our IJJs, it is not likely that only one junction contributes the flow voltage. Nevertheless, it is necessary to check whether the Fiske step from the weakest single layer in the IJJs could be an alternative origin of the JVs flow resistance oscillations or not. We estimate the Fiske step voltage of a single-layer junction. The Fiske step voltage is expressed as

$$V_f=(\Phi_0/2L)c_s, \tag{3}$$

where c_s is the Swihart velocity $[c_s=c_o(d\sqrt{\varepsilon_r d})^{1/2}]$, c_o is the velocity of light in vacuum, ε_r (=10 for Y-123) is the dielectric constant, $d\sim d_I+2\lambda_L$, λ_L (=140 nm for Y-123) is the London penetration depth, and d_I (=0.84 nm for Y-123) is the thickness of nonsuperconducting layer.[29–31] This Fiske-step voltage is estimated as $V_f\sim 2.8$ mV for IJJ-2 having $L=1.9$ μm. It suggests that the JVs flow voltage in our IJJs-2 during the flux-flow resistance measurement (shown in Fig. 3) are a few order lower than that of Fiske step voltage in a single-layer junction, therefore the periodic oscillations observed in this experiment is not due to the Fiske steps.

CONCLUSIONS

We have successfully observed the periodic oscillations of vortex flow resistance in oxygen deficient Y-123 intrinsic Josephson junctions which have anisotropic factors ~40.

The period of flux-flow oscillations showed good agreement with $\Phi_0/2Ls$, indicating that "one" Josephson vortex is added per "two" intrinsic Josephson junctions for each oscillation period. However, such periodic oscillation only appears above the magnetic fields of 45–58 kOe, which might correspond to the boundary between dilute and dense Josephson vortex lattices. Obviously, this threshold field is higher than those observed in high anisotropic Bi-2212 intrinsic Josephson junctions because of the one order low anisotropies for the oxygen-reduced Y-123 IJJs studied here.

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