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Stabilization of the in-phase fluxon state by geometrical confinement in small $Bi_2Sr_2CaCu_2O_{8+x}$ mesa structures

S. O. Katterwe and V. M. Krasnov*

Department of Physics, AlbaNova University Center, Stockholm University, SE-10691 Stockholm, Sweden

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The in-phase (rectangular) fluxon lattice is required for achieving coherent THz emission from stacked Josephson junctions. Unfortunately, it is usually unstable due to mutual repulsion of fluxons in neighbor junctions, which favors the out-of-phase (triangular) lattice. Here we experimentally study magnetic field modulation of the critical current in small Bi-2212 mesa structures with different sizes. Clear Fraunhofer-like modulation is observed when the field is aligned parallel to CuO planes. For long mesas the periodicity of modulation is equal to half the flux quantum per intrinsic Josephson junction, corresponding to the triangular fluxon lattice. However, the periodicity is changed to one flux quantum, characteristic for the rectangular fluxon lattice, both by decreasing the length of the mesas and by increasing magnetic field. Thus, we demonstrate that the stationary in-phase fluxon state can be effectively stabilized by geometrical confinement in small Bi-2212 mesa structures.

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Josephson flux-flow oscillators can provide a remarkable linewidth ~ 1 Hz in the sub-THz frequency range[1] but with a small power $\lesssim \mu$W. The emission power can be increased by phase locking of several coupled oscillators.[2,3] The strongest coupling is achieved between atomic scale intrinsic Josephson junctions (IJJs), naturally formed in single crystals of high-temperature superconductor $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212).[4] Furthermore, a large energy gap in Bi-2212 facilitates operation in the important THz frequency range. Therefore, stacked IJJs are intensively studied as possible candidates for tunable, high-power THz oscillators.[3,5–10]

To achieve power amplification, Josephson vortices (fluxons)[11] should form the rectangular (in-phase) lattice in the stack. Unfortunately, it is usually unstable due to mutual repulsion of fluxons, which favors formation of the triangular (out-of-phase) lattice. Motion of the triangular lattice leads to out-of-phase oscillation in neighbor junctions, which results in destructive interference and negligible emission. Thus, the major challenge for achieving coherent THz emission from stacked IJJ is to promote the in-phase fluxon state.

Fluxon distribution in a stack is governed by three forces: the in-plane fluxon repulsion, the fluxon-edge interaction, which promote the rectangular fluxon lattice, and the interlayer fluxon repulsion, which promotes the triangular lattice. Therefore, the in-phase state can be stabilized by reducing the interlayer force in comparison to the in-plane forces. This can be achieved by decreasing the interlayer coupling,[12] decreasing the junction length L,[6,7,12] or increasing the fluxon density.[6,7] The symmetry of the fluxon lattice can be understood from the analysis of the magnetic field modulation of the critical current $I_c(H)$ (Ref. 7): the rectangular lattice leads to conventional Fraunhofer modulation with periodicity of one flux quantum Φ_0 per junction, while the triangular leads to the $\Phi_0/2$ periodicity because the lattice parameter in the c axis direction is doubled.

Here we study size and magnetic field dependence of $I_c(H)$ in small Bi-2212 mesa structures. We observe a clear Fraunhofer-like modulation of $I_c(H)$ and demonstrate that it changes from the $\Phi_0/2$ characteristic for the triangular lattice to the Φ_0 characteristic for the rectangular lattice, both with increasing the field and decreasing the junction size. Observed results are in good agreement with numerical simulations and prove experimentally that the in-phase fluxon state is effectively stabilized by geometrical confinement in small IJJs.

Previous studies of IJJs did not reveal clear periodic modulation of $I_c(H)$.[4,12–16] The same is true even for low-T_c stacks.[4,15,17] This was explained by existence of multiple metastable fluxon modes in long strongly coupled stacked junctions.[12,15] So far, $\Phi_0/2$ and Φ_0 modulations were observed only in the dynamic flux-flow state both for low-T_c stacks[18] and IJJs.[19–21] However, it is not necessarily associated with $I_c(H)$ modulation.[13,15,18] Furthermore, its interpretation may be ambiguous because even the rectangular lattice can lead to $\Phi_0/2$ modulation of the flux-flow resistance.[22] Therefore, it is necessary to analyze the *static* critical current, not the least because this is the most important fingerprint of the dc-intrinsic Josephson effect.

Mesa structures, containing few IJJs, were fabricated on Bi-2212 single crystals with $T_c = 82$ K. Some mesas were focused ion beam trimmed to reduce the size. Details of mesa fabrication can be found in Ref. 23. Table I summarizes properties of studied mesas. Samples were mounted on a rotatable sample holder with the rotation step $\sim 0.02°$. All measurements were performed at $T = 1.6$ K.

In Bi-2212 mesas the top IJJ is always deteriorated and has much smaller I_c than the rest "bulk" IJJs.[24] With increasing current, I, it switches into the quasiparticle (QP) branch $V_1(I)$, while "bulk" IJJs remain in the stationary state up to much larger current. Since we are interested in the collective behavior associated with the symmetry of the fluxon lattice, we have to study the "bulk" $I_c(H)$. To do so, we first carefully measured $V_1(I)$ at $H = 0$ and then automatically subtracted it from I-V characteristics (IVCs) of our mesas.

Figure 1 shows IVCs of the mesa 4b with subtracted $V_1(I)$ of the surface IJJ for different magnetic fields. It is seen that subtraction works very well, with the accuracy better than 10 μV at all fields. At low fields, IVCs switch from the

TABLE I. Summary of studied mesas on the same Bi-2212 single crystal. L and W are the length and width of mesas in directions perpendicular and parallel to H, respectively; I_{c0} is the average critical current for IJJs in the mesa at $H=0$; $\lambda_J=\sqrt{(\Phi_0 csLW)/(16\pi^2 I_{c0}\lambda_{ab}^2)}$ is the calculated Josephson penetration depth (Ref. 11), where $s=1.5$ nm is the interlayer spacing in Bi-2212 and $\lambda_{ab}\simeq 200$ nm is the effective London penetration depth across CuO planes; $H_0=\Phi_0/Ls$ is the field at which flux per junction is $\Phi=\Phi_0$; and H_0^{exp} is the measured periodicity of $I_c(H)$ modulation at large H.

Mesa	L (μm)	W (μm)	I_{c0} (μA)	λ_J (μm)	H_0 (T)	H_0^{exp} (T)
4*a*	5.1	1.4	75.0	0.68	0.27	0.26
4*b*	2.7	1.4	39.5	0.69	0.51	0.55
6*b*	2.0	1.7	39.8	0.65	0.69	0.662

superconducting to the QP branches at $I>I_c$, as indicated by arrows in Fig. 1(a). At higher field, a flux-flow branch with distinct Fiske steps[13,20] develops at $I>I_c$, as seen from Fig. 1(b). In the presence of Fiske steps, switching from the superconducting to the flux-flow state remains abrupt, as can be seen from the IVC at $H=0.87$ T. However, even without Fiske steps, transition from the superconducting to the flux-flow branch is sharp, which allows unambiguous determination of I_c, as indicated by solid arrows in Fig. 1(b). Strong modulation of $I_c(H)$ is evident from Fig. 1.

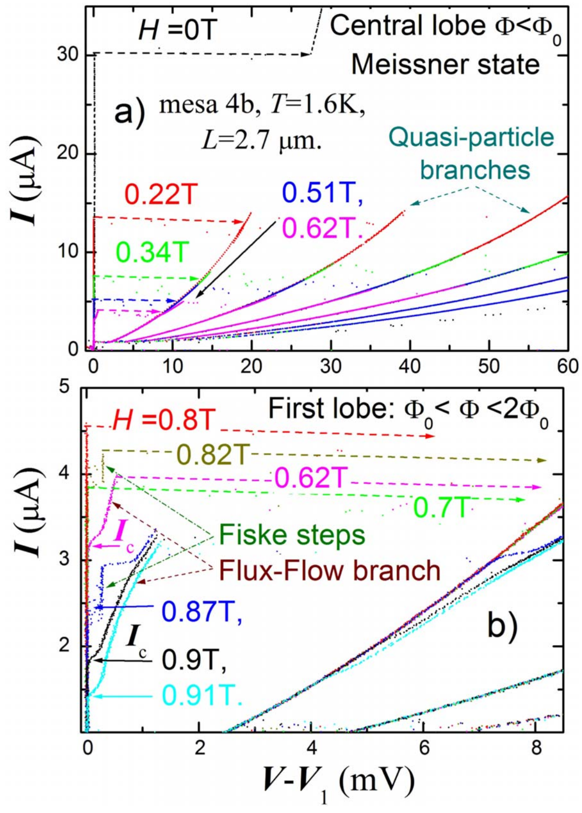

FIG. 1. (Color online) *I*-*V* characteristics of the mesa 4*b* with the subtracted quasiparticle branch of the surface junction at different magnetic fields: (a) within the central Meissner lobe of $I_c(\Phi)$ and (b) for $1<\Phi/\Phi_0<2$. Flux-flow and Fiske steps are seen.

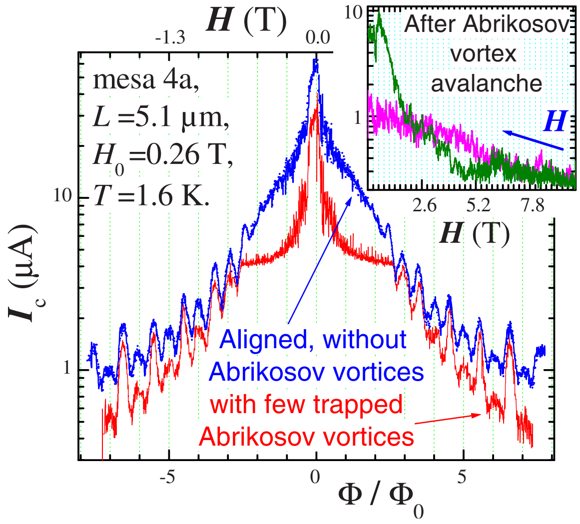

FIG. 2. (Color online) Experimental $I_c(\Phi)$ for the long mesa: without Abrikosov vortices (blue line, four field sweeps) and with few immobile Abrikosov vortices (lower red line, two field sweeps). Three field regions can be distinguished: (i) $\Phi<2\Phi_0$: metastable region with strong fluctuations and without modulation; (ii) $2\Phi_0<\Phi<5\Phi_0$: $\Phi_0/2$ modulation with even integer and half-integer maxima; and (iii) $\Phi>5\Phi_0$: transition to Φ_0 modulation with a predominance of half-integer maxima. Inset shows $I_c(\Phi)$ for two sweeps down from 10 T.

Field alignment was crucial for observation of $I_c(H)$ modulation. Misalignment with respect to CuO planes led to avalanche entrance of Abrikosov vortices with increasing field. After that, $I_c(H)$ patterns become heavily distorted, irreversible, and completely lack periodic modulation, as shown in the inset of Fig. 2.

At low H alignment is complicated by field lock-in along CuO planes.[21] To avoid lock-in hysteresis, we looked at a high-field $H=15$ T magnetoresistance at bias close to the sum-gap voltage.[24] The magnetoresistance is negligible for precise in-plane field alignment but has a substantial negative value for the c axis field component.[25] Importantly, it has no angular hysteresis, which facilitates accurate alignment of mesas. Even after perfect alignment, presence of trapped Abrikosov vortices affected the I_c, as shown by the lower red line in Fig. 2. Yet, immobile vortices do not distort the qualitative shape of $I_c(H)$. To get rid of trapped vortices, samples were heated above T_c after alignment. Misalignment is less critical for small mesas. For mesas $\lesssim 1$ μm we were able to sweep the field up to 10 T without trapping vortices.

Figures 2 and 3 represent main experimental results of our work: magnetic field modulation of the "bulk" I_c for Bi-2212 mesas of different sizes. Vertical grid lines in all figures correspond to integer flux quanta per IJJ. All shown patterns are perfectly reversible, indicating that alignment was fine and Abrikosov vortices did not enter into the mesas up to the largest field.

Figure 2 shows the I_c vs flux per junction, $\Phi=HLs$ (in a semilog scale) for the long mesa 4*a*, with $L=5.1$ μm and $L/\lambda_J\simeq 7.5$, where λ_J is the Josephson penetration depth (see Table I). At low field, I_c rapidly decreases with H and at $H\gtrsim 0.5$ T, the oscillatory behavior appears. The period of

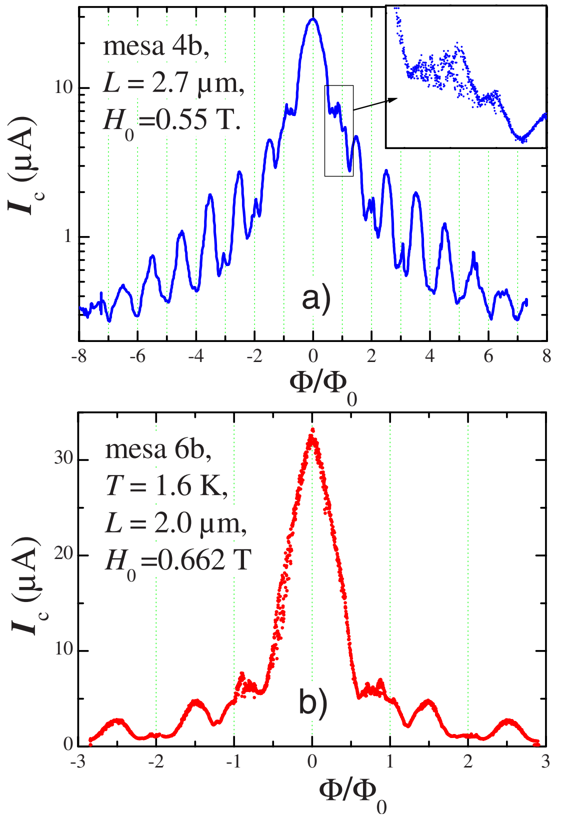

FIG. 3. (Color online) Experimental $I_c(\Phi)$ for (a) moderately long (in a semilogarithmic scale) and (b) shortest mesas. It is seen that integer maxima are rapidly decreasing with increasing field and decreasing L. At $\Phi/\Phi_0 > L/\lambda_j$ only half-integer maxima are seen, indicating transition to the rectangular fluxon lattice. Inset in (a) shows metastable sub-branches at $\Phi/\Phi_0 \sim 1$, measured by repeated field sweeps.

modulation is initially $\Phi_0/2$ rather than Φ_0, with maxima both at integer and half-integer Φ_0. However, with increasing field the amplitude of integer maxima rapidly decreases and at high fields maxima at half-integer Φ/Φ_0 become dominant.

Figure 3(a) shows $I_c(\Phi)$ (in a semilog scale) for the moderately long mesa 4*b* with $L=2.7$ μm and $L/\lambda_J \simeq 3.9$. Here the maxima at integer Φ/Φ_0 are strongly suppressed even at low fields. At $\Phi > 3\Phi_0$, integer maxima completely disappear and the $I_c(\Phi)$ switches to the conventional Fraunhofer modulation with the one flux-quantum periodicity and maxima at half-integer Φ/Φ_0.

Finally, $I_c(\Phi)$ for the shortest mesa (6*b*) is shown in Fig. 3(b). The length of the mesa is $L=2.0$ μm and $L/\lambda_J = 3.1$. Here the integer maxima are suppressed almost completely already for $\Phi = 2\Phi_0$.

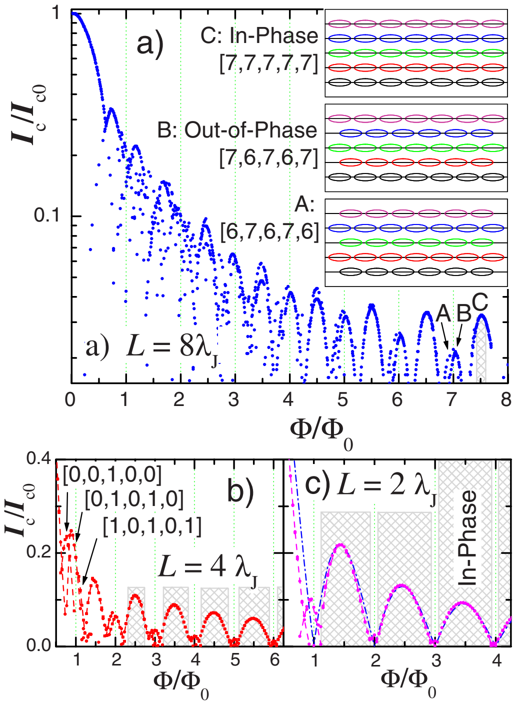

FIG. 4. (Color online) Simulated $I_c(\Phi)$ for stack of 5 IJJs with (a) $L=8\lambda_J$ (in a semilog scale), (b) $L=4\lambda_J$, and (c) $L=2\lambda_J$. Transition from $\Phi_0/2$ to Φ_0 periodicity occurs with increasing Φ and decreasing L and reflects transition from triangular to rectangular fluxon lattice, as shown by snapshots in panel (a). Shaded areas indicate regions of stability of the rectangular lattice. For the shortest stack it becomes dominating and $I_c(\Phi)$ is close to the Fraunhofer pattern (the blue dashed-dotted line).

For better understanding of experimental data, in Fig. 4 we show numerically simulated $I_c(\Phi)$ for $N=5$ stacked IJJs of different lengths: (a) $L=8\lambda_J$ (in the semilog scale), (b) $L=4\lambda_J$, and (c) $L=2\lambda_J$. Simulations were made within the coupled sine-Gordon formalism[3] with parameters typical for Bi-2212 IJJs (for details see the supplementary material[26]). It is seen that the overall behavior of $I_c(\Phi, L)$ is very similar to experimental data: for the long stack in Fig. 4(a) three field regions can be distinguished, similar to that in Fig. 2:

(i) at low field $\Phi \lesssim 2\Phi_0$ there are strong fluctuations of I_c due to chaotic switching between multiple metastable fluxon modes[12,15] and no clear modulation of $I_c(\Phi)$;

(ii) at intermediate fields $2\Phi_0 < \Phi < 6\Phi_0$ modulation with periodicity of $\Phi_0/2$ appears. The fluxon lattice is not yet formed in this field range, and modulation is due to switching between certain quasiperiodic modes.[26]

(iii) At high fields, approximately given by

$$\Phi/\Phi_0 \gtrsim L/\lambda_J, \qquad (1)$$

the in-plane separation between fluxons becomes $\lesssim \lambda_J$ so that nonlinear cores of fluxons[11] overlap, leading to enhancement of the in-plane fluxon repulsion and formation of the regular fluxon lattice. Simultaneously, maxima at integer Φ/Φ_0 become weaker than at half-integer Φ/Φ_0 so that periodicity of modulation becomes Φ_0.

In shorter stacks, metastable region (i) becomes smaller. In Figs. 3(a) and 4(b) it is seen only at $\Phi \sim \Phi_0$. In the inset of Fig. 3(a) we show this metastable region, measured by repeated field sweeps. Certain sub-branches can be distinguished, indicating a reduced number of metastable modes[15] in comparison to the long junction case (Fig. 2). In Fig. 4(b) we marked the most probable modes, which cause distinct sub-branches in $I_c(\Phi)$. Metastable states eventually disappear for $L < \lambda_J$.

Even region (ii) disappears in shorter stacks; here integer maxima are always smaller than half-integer. They are further suppressed with increasing H and decreasing L, as seen from Figs. 3 and 4. For shorter stacks the Φ_0 periodicity is established at smaller Φ/Φ_0, in agreement with Eq. (1). For $L<\lambda_J$, only maxima at half-integer Φ/Φ_0 are left, and $I_c(\Phi)$ becomes close to conventional Fraunhofer pattern [also shown in Fig. 4(c)].

The observed transition from $\Phi_0/2$ to Φ_0 periodicity of $I_c(\Phi)$ is a consequence of transition from the triangular to the rectangular fluxon lattice.[6,7] This is illustrated by snapshots in Fig. 4(a), which show fluxon distributions at both sides of the subdominant maximum at $\Phi/\Phi_0 \simeq 7$ and the dominant maximum at $\Phi/\Phi_0 \simeq 7.5$. It is seen that the rectangular (in-phase) lattice occurs at the dominant half-integer maximum. For the stack with $L=2\lambda_J$ the in-phase state is stable practically in the whole field range, marked by the shaded area in Fig. 4.[26]

The observed good agreement between experimental data and simulations confirms our estimation of $\lambda_J \simeq 0.7$ μm, see Table I, and shows that the coupled sine-Gordon equation[3] provides a quantitative description of IJJs. Therefore, the predicted coherent THz emission[4–6] should also be feasible. From the analysis above, we arrive at the following recommendations for such the device: (i) $H>\Phi_0/\lambda_J s \simeq 2$ T is required [see Eq. (1)]. (ii) Accurate alignment at such fields is critical. (iii) Small mesas $L\sim 4\lambda_J \simeq 3$ μm would be needed: for longer mesas the in-phase mode is not stable enough, while for smaller stacks the flux-flow state is less stable. (iv) The number of IJJs should be small $N\sim 10$. More junctions may be difficult to phase lock due to appearance of out-of-phase dislocations between in-phase-locked blocks[6] and can also be prone to self-heating.[24] (v) Emission power from small mesas is small. Therefore, achieving large total power $\gtrsim 1$ μW would require phase locking of arrays of stacks.[2]

In summary, we observed clear Fraunhofer-like modulation of $I_c(H)$ in small Bi-2212 mesas. The periodicity of modulation changes from $\Phi_0/2$ to Φ_0, indicating transition from the triangular to the rectangular fluxon lattice, both with increasing H and decreasing mesa size. Our results provide clear evidence for the dc-intrinsic Josephson effect. They can also be important for realization of the coherent THz flux-flow oscillator because they demonstrate that the required in-phase fluxon state can be effectively stabilized by geometrical confinement in small Bi-2212 mesas.

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*vladimir.krasnov@fysik.su.se

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[26] See EPAPS Document No. E-PRBMDO-80-R06926 for the variety of fluxon states that can be explicitly seen forming the simulation program provided in the supplementary. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html