Size-dependent transformation from triangular to rectangular fluxon lattice in Bi-2212 mesa structures

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Abstract. We present a systematic study of the field and size dependencies of the static fluxon lattice configuration in Bi-2212 intrinsic Josephson junctions and investigate conditions needed for the formation of a rectangular fluxon lattice required for a high power flux-flow oscillator. We fabricate junctions of different sizes from Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ and Bi$_{1.75}$Pb$_{0.25}$Sr$_2$CaCu$_2$O$_{8+x}$ single crystals using the mesa technique and study the Fraunhofer-like modulation of the critical current with magnetic field. The modulation can be divided into three regions depending on the formed fluxon lattice. At low field, no periodic modulation and no ordered fluxon lattice is found. At intermediate fields, modulation with half-flux quantum periodicity due to a triangular lattice is seen. At high fields, the rectangular lattice gives integer flux quantum periodicity. We present these fields in dependence on the sample size and conclude that the transitions between the regions depend only on $\lambda_J(J_c)$ and occur at about 0.4 and 1.3 fluxons per $\lambda_J$, respectively. These numbers are universal for the measured samples and are consistent with performed numerical simulations.

1. Introduction

Stacked Intrinsic Josephson Junctions (IJJ), naturally formed in Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi-2212) high-temperature superconductors, are intensely studied candidates for tunable, high-power THz oscillators due to their large energy gap and possibility of power amplification from coupled junctions [1, 2]. However, coherent power amplification in flux-flow oscillators requires a rectangular Josephson fluxon lattice. The triangular lattice, which is favored by interplane repulsion of fluxons, results in an out-of-phase oscillation between neighboring junctions which causes destructive interference. The fluxon lattice has previously been studied from periodic oscillations in the flux-flow resistance [3, 4] and Fraunhofer modulation [5], and it was shown that the in-phase state can be stabilized by high fields and geometrical confinement in small mesas. Here we present a systematic study of the field and size dependencies of the static fluxon lattice configuration in Bi-2212 mesa structures.

A Fraunhofer modulation of the critical current $I_c$ as a function of magnetic field is one of the fingerprints of the dc-Josephson effect. In the case of IJJ made of Bi-2212, the observed modulation differs from the ordinary Fraunhofer modulation in two ways: First, the atomic separation between junctions by $s = 1.5$ nm results in a short Josephson penetration depth

$$\lambda_J = \sqrt{\frac{\Phi_0 s}{4\pi\mu_0 J_c \lambda_{ab}^2}}.$$ 

Here, $\lambda_{ab} \approx 200$ nm is the London penetration depth. For typical $c$-axis critical current densities of $J_c \approx 10^3$ A cm$^{-2}$ for Bi-2212 and $10^4$ A cm$^{-2}$ for Bi(Pb)-2212 [6], the Josephson penetration depth

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becomes 0.7μm and 0.2μm, respectively. Therefore, the junctions are completely shielded at small fields. At slightly higher fields, individual, weakly interacting fluxons enter the junctions. The ordinary Fraunhofer modulation requires a uniform penetration of magnetic field into the junctions. At low fields, therefore, only a decrease in critical current due to motion of disordered fluxons is observed. Second, the fluxons distribute into a two-dimensional lattice rather than a one-dimensional chain due to additional interlayer repulsion from fluxons in neighboring junctions. At low fields, the interlayer repulsion energetically favors the formation of the triangular lattice, which is stable under high currents for all integer and half-integer flux values. For higher fields, the rectangular lattice can be formed due to a higher interlayer repulsion and interaction with the boundaries. This lattice withstands a higher current at Φ = (k + 1/2)Φ0, where k is an integer, similar to the ordinary Fraunhofer modulation. The rectangular lattice leads to a modulation with an integer flux quantum periodicity as in the single junction case. The triangular fluxon lattice instead has an effectively doubled lattice constant causing a half integer modulation that corresponds to “adding one flux quantum per two junctions” [7], and sub-dominant maxima appear.

2. Experimental

Intrinsic Josephson Junctions of different sizes down to 1.5 times the Josephson penetration depth λJ were fabricated on top of freshly cleaved single crystals of Bi-2212 and Bi1.75Pb0.25Sr2CaCu2O8+x [Bi(Pb)-2212] using the mesa technique, Ar ion milling and Focused Ion Beam trimming. Details of the sample fabrication can be found in Ref. [8].

All measurements were performed in a cryogen-free cryostat at a base temperature of 1.8 K and magnetic fields up to 17 T. One of the main experimental challenges was the precise alignment of the superconducting copper-oxide planes parallel to the field in order to prevent Abrikosov vortices from entering. This was achieved using a rotational sample holder with a resolution better than 0.02° and searching for the maximum of the quasiparticle resistance, indicating the absence of Abrikosov vortices. Reproducibility of the modulation patterns during field sweeps up and down proves that no Abrikosov vortices are being trapped. Due to a partial passivation of the top junction, an additional voltage from a non-linear contact resistance arises. This was carefully extracted from the current-voltage characteristics (IVC), fitted, and subtracted.

Numerical simulations following the coupled sine-Gordon formalism were performed to determine the lattice state at currents just below to the critical current. The average of the normalized displacement of fluxons in neighboring junctions was calculated for different values of Φ and L. Details of the simulation method can be found in the supplementary material of Ref. [5].
3. Results and discussion

An IVC of a stack of 56 IJJ at zero field is shown in Fig. 1(a). The critical current was extracted automatically from the maximum current within a small window around \( V = 0 \) as shown in figure 1(b) for different applied fields. Its dependence on magnetic field is shown in Fig. 2. The field is expressed as flux per junction, \( \Phi = B s L \), where \( L \) is the mesa size perpendicular to the magnetic field. The observed behavior differs qualitatively from a simple Fraunhofer pattern in the expected way: At low fields, \( B < 2.5 \, \text{T} \), no modulation is observed, but only a continuous decrease of the critical current. Then, at slightly higher fields, the modulation starts, but obeys extra sub-dominant maxima at fields corresponding to integer numbers of flux quanta in each junction which leads to a half flux quantum periodicity. Finally, at fields higher than of 9.6 \, \text{T}, the sub-dominant maxima disappear and the ordinary \( \Phi_0 \) periodicity arises.

The onset of the modulation as well as the transition in periodicity, i.e., the disappearance of additional peaks, was determined for different samples on different crystals, and plotted versus the normalized junction length \( L/\lambda_J \) in Fig. 3. This figure represents the phase diagram of the fluxon lattice in stacked IJJs. As indicated by the red dash-dotted line, the modulation starts at about 0.4 fluxons per \( \lambda_J \), corresponding to 0.8 and 2.5 \, \text{T} for Bi-2212 and Bi(Pb)-2212, respectively. This is about double the value of the critical field \( B_{\text{tr}} = \Phi_0/2\pi\lambda_J s \) where fluxons start to fill all layers homogeneously with one fluxon per \( 2\pi\lambda_J \) \[9\]. The triangular-to-rectangular transition occurs at about \( 1.3\Phi_0/\lambda_J \) for the investigated samples, which corresponds to 2.7 and 8.3 \, \text{T}, respectively, for Bi and Bi(Pb). According to Ref. [9], the rectangular lattice remains stable up to the critical current for \( B > B_{\text{tr}}/2 \cdot L/\lambda_J \), where \( L \approx 0.484 \). This is plotted as a green dotted curve in Fig. 3. The difference between the linear approximation and the theoretical parabola has little practical significance, since it may be impossible to align large junctions perfectly, while small junctions are in the in-phase state almost as soon as modulations start.

The background color of Fig. 3 represents the results of our numerical simulations. A number close to zero results from a rectangular lattice (red), while a triangular lattice gives a value of 0.5 (green). Intermediate states with an oblique lattice are blue, while missing fluxons or an oblique lattice with a lattice constant of more than two junctions result in numbers greater than 0.5 and are colored yellow. In the white low-field region, not all junctions are filled with fluxons. The simulations are consistent with both theory and our experimental data: At low fields, single fluxons enter the junctions and start to form a lattice, which becomes more and more regular until the critical current starts to oscillate with half-integer periodicity. At this size-independent field, the lattice is triangular, but with increasing field the lattice becomes distorted into an oblique lattice near half-integer flux values of \( \Phi = (k + 1/2)\Phi_0 \). At even higher fields the lattice finally becomes rectangular and stabilizes. The triangular lattice at \( \Phi = k\Phi_0 \), however, never completely disappears \[9\].
Figure 3. Fluxon phase diagram for stacked Josephson junctions: Starting point of $I_c(B)$ modulation (filled symbols) and transition from half-integer to integer $\Phi_0$ modulation (open symbols) occur at about 0.4 fluxons per $\lambda_J$ (red dash-dotted line) and 1.3 fluxons per $\lambda_J$ (blue dashed line), respectively. The critical field $B_{cr}$ indicating the onset of a homogeneous filling of the layers (solid black line) and the field $B_{l1}$ where a stable rectangular lattice up to the critical current appears (green dotted line) are taken from Ref. [9] and shown for comparison. The background colors illustrate the average of the normalized displacement of fluxons in neighboring junctions obtained from numerical simulations of the lattice configuration at currents close to the critical current.

4. Summary and conclusion
We experimentally investigated the fluxon phase diagram of stacked IJJ by studying the Fraunhofer modulation of the critical current in well-aligned small Bi-2212 mesa structures. In particular, we find that the in-phase fluxon state required for the realization of a coherent THz flux-flow oscillator is achieved if $\Phi \geq 1.3\Phi_0 L/\lambda_J$ and $\Phi \neq k\Phi_0$. For Bi-2212 and Bi(Pb)-2212, this corresponds to about 3 and 9 T, respectively.

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