Supercond. Sci. Technol. **15** (2002) 1658–1662 PII: S0953-2048(02)38803-1

A search for the coherently radiating fluxon state in stacks of long intrinsic Josephson junctions

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Received 26 June 2002
Published 14 November 2002
Online at stacks.iop.org/SUST/15/1658

Abstract
We studied the motion of fluxons in a stack of intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals in a long junction limit. Driven by the tunnelling bias, current Josephson fluxons excite plasma oscillations and move in resonance with the plasma propagation modes. We examined two types of samples in this study; mesa structure (UD1) and a stack of junctions sandwiched between normal-metallic electrodes (DSC1). In a high magnetic field, the hysteresis in the *I–V* characteristics of both-types of samples vanished. The resulting single *I–V* curve exhibited a cusp structure at characteristic bias voltages which were believed to be boundaries of different moving fluxon configurations. We studied the sample-geometry dependence of the cusp characteristics by comparing the results from the two types of samples.

1. Introduction

Collective plasma oscillations and fluxon dynamics in vertically stacked long Josephson junctions have recently been studied extensively [1–11]. The effort has been motivated mainly by the high possibility that the systems in the flux-flow mode can be applied to high-frequency devices such as THz local oscillators and mixers. When the thickness of the superconducting layers is smaller than the London penetration depth, plasma oscillations become phase-locked by the strong inter-layer coupling, which is known to be brought about by either inductive [1–4, 6] or charging [9, 10] effect. Stacked intrinsic Josephson junctions with atomic-scale superconducting layers, as in highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), provide natural superlattices of the strong mutual coupling. The propagation of plasma oscillations in such vertical Josephson junctions is described by coupled sine-Gordon differential equations with solutions of different modes corresponding to the number of intrinsic junctions in a stack. The dispersion relation of the propagating plasma oscillations is a mixture of transverse and longitudinal modes, where the in-phase transverse mode represents the fastest propagation.

Fluxons in a stack of intrinsic junctions, when driven by a tunnelling bias current along its length direction, excite plasma oscillations inside the junctions. If the driving velocity of the fluxons matches a propagation mode velocity of plasma excitation, a resonance takes place and the fluxon dynamics itself becomes phase-locked along the vertical direction. Once the plasma oscillations by the phase-locked fluxon flow are in-phase over the whole stacked junctions, the resultant electromagnetic radiation can be coherent with strong output power and a narrow linewidth. Investigation of the interplay between plasma-excitation modes and the fluxon dynamics is thus an important issue. In this study we investigated characteristic properties of field-generated fluxons revealed in their current–voltage (*I–V*) curves which may result from the fluxon–plasma interplay. Special attention has been paid to searching the cusp-like characteristics in *I–V* curves, which may represent the in-phase coherent radiation state as suggested by numerical simulations [9, 10].

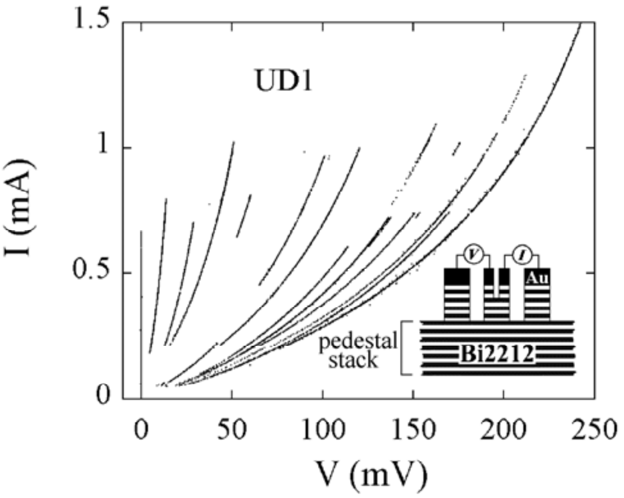

Figure 1. Zero-field I–V curves taken at $T = 4.2$ K of the mesa UD1 which contains 12 intrinsic junctions. Inset: a four-terminal measurement configuration for the central mesa of the lateral dimensions of $10 \times 45\ \mu m^2$.

A mesa formed on the surface of a single crystal has, in general, a large pedestal part underneath. Since the Josephson fluxons inside a mesa are supposed to be coupled strongly to the ones in the pedestal part the fluxon motion in the mesa may be significantly influenced by the pedestal part. Thus, in this study we also investigated the fluxon motion in a system where the pedestal part was eliminated. In the I–V characteristics of such a system we observed features which deviated from the typical ones usually found in mesa structure.

2. Experiment

We prepared a mesa structure on the planar surface of underdoped Bi-2212 single crystals (see the inset of figure 1). We also prepared one sample (DSC1), employing the double-side cleavage technique [13] with an as-grown Bi-2212 single crystal. In the latter type a stack contained a few tens of intrinsic Josephson junctions sandwiched between top and bottom Au electrodes (see the inset of figure 4), without the pedestal part. In this paper we report the typical results from a mesa-structure sample (UD1) and the results from the sample DSC1. The doping level of the sample UD1 was lowered to reduce the Josephson plasma frequency by weakening the interlayer coupling for other experimental purposes (the result is not reported in this paper). The underdoped crystals were prepared by vacuum annealing as-grown crystals made by the travelling-solvent-floating-zone method. A few-thousand-Å-thick Au film was first deposited on the surface of a freshly cleaved single crystal. A mesa structure was then fabricated by a combination of photolithographic patterning and ion-beam etching. The details of the procedure can be found in [12]. The measurement configuration of the mesa UD1 is shown in the inset of figure 1. The lateral dimension of each smaller mesa in the central mesa was $10 \times 13\ \mu m^2$. The total thickness of the central mesa was usually less than 200 Å, containing a little more than ten intrinsic junctions.

For the fabrication of the sample DSC1 we followed the general procedure of the double-side cleavage technique, the details of which can be found in [13]. The sandwiched stack drawn schematically in the inset of figure 4 was 190 μm long, 2 μm wide, and 30 nm thick. However, by mistake in the sample fabrication process, the upper 50 nm thickness of the Bi-2212 stack was not fully removed. The thickness of the top and bottom Au electrodes were 120 nm and 40 nm, respectively. Although the sample DSC1 did not result in an ideally rectangular shape the main part of the huge pedestal stack in the mesa-structure sample like UD1 was successfully eliminated. In the geometry we also made the sample width comparable to the Josephson penetration depth. Apparently the boundary conditions of this shape should better mimic those of systems adopted in numerical simulations [1–4, 6, 9, 10].

Measurements for the sample UD1 were done in a standard four-terminal configuration shown schematically in the inset of figure 1. I–V characteristics were taken in various external magnetic fields applied in parallel with the plane direction. I–V characteristics for the sample DSC1 were taken in a two-terminal configuration using an analog storage microscope while sample cooling and the magnetic field application were achieved using a system Model MPMS by Quantum Design. Special care was taken to align a field to the superconducting layers, following the method in [14]. The field-alignment resolution for the sample UD1 was 0.01°, while that for the sample DSC1 was 0.05°.

3. Results and discussion

The c-axis I–V data of the mesa UD1 taken at 4.2 K (figure 1) show a superconducting branch and the usual multiple quasiparticle branches. Irregularities seen in the I–V data are supposed to be due to the defects introduced during the process of reducing the doping level of the crystal. The mesa is seen to contain 12 intrinsic junctions, which is in agreement with the number of junctions estimated from the etching time. The smallest critical current 0.67 mA in the supercurrent branch corresponds to the junction critical current density of 150 A cm^{-2} and the Josephson plasma frequency of 39 GHz which is much lower than the value 150–200 GHz of as-grown single crystals.

Figure 2 shows I–V curves obtained for dc external magnetic fields applied in parallel with the junction planes. It illustrates the gradual suppression of the critical current for each branch for fields from 0.1 T up to 0.77 T. The critical current, persisted up to the highest field used in figure 2, was found to disappear only around $H_c = 1$ T (data are not shown). It indicates the existence of weak pinning of the Josephson fluxons. Once the fluxons are depinned in a higher bias current an appreciable flux-flow resistance is seen to appear for a field above 0.1 T. One also notices in figure 2 that depinned fluxons exhibit the sub-branch splitting, which takes place as the coupled fluxons move in resonance with different plasma-oscillation modes. The maximum number of different modes available are the same as the number of Josephson junctions in the mesa. In an external magnetic field similar sub-branch splitting was observed previously in a mesa system of Bi2212 single crystals [7], but with sub-branches far less than the number of junctions contained in the mesa.

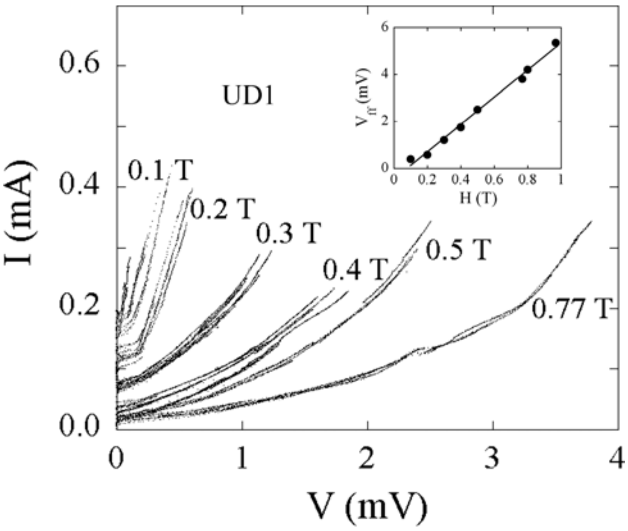

Figure 2. The evolution of the supercurrent branch of the mesa UD1 in low dc magnetic fields between 0.1 T and 0.77 T. The inset shows a linear magnetic-field dependence of the flux-flow voltage V_{ff}.

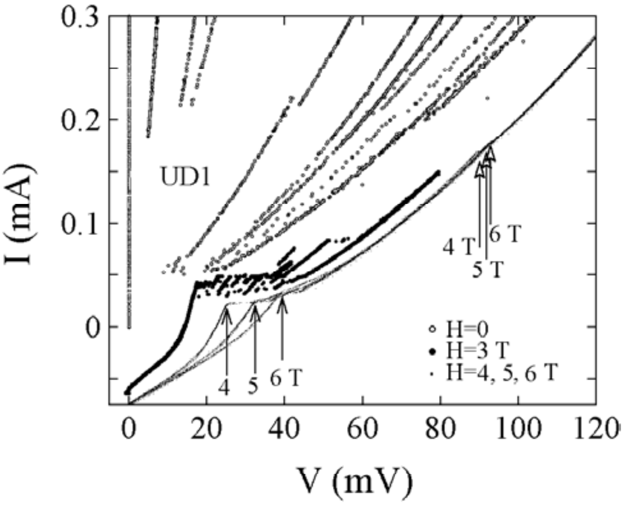

Figure 3. *I–V* characteristics of the mesa UD1 in dc magnetic fields of $H = 0$, 3, 4, 5 and 6 T. The curve for 3 T (the ones for 4, 5 and 6 T) is shifted downward by 0.065 mA (by 0.075 mA) for the clarity of illustration.

The flux-flow resistance of fluxons generated by low-intensity external magnetic fields mainly cause the suppression of critical current. The critical current of UD1 vanishes completely above the characteristic field $H_c \simeq 1$ T and a resistance in the *I–V* characteristics starts appearing. Even for a magnetic field smaller than H_c, however, the 'supercurrent' branch becomes resistive at high bias currents. If we define the flux-flow voltage, V_{ff}, as the maximum voltage attained by the 'supercurrent' branch for a given magnetic field intensity, V_{ff} is almost linearly proportional to H as shown in the inset of figure 2, except for the small field offset due to a finite pinning of fluxon lines.

For $H \sim 1$ T, the branch-splitting in each quasiparticle branch also starts vanishing, merging into a single quasiparticle curve. For further higher magnetic fields the hysteresis in different quasiparticle curves gradually disappears and all the branches finally merge into a single curve for fields beyond

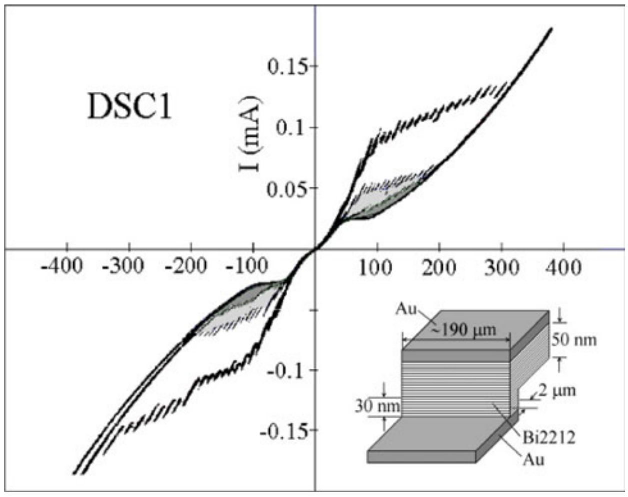

Figure 4. Variation of *I–V* characteristics of the sample DSC1, for external magnetic fields of $H = 0.5$, 1.0 and 2.0 T, fabricated by removing the main part of the pedestal stack.

3–4 T (figure 3). One notices in the figure that prior to the complete disappearance of the hysteresis the characteristic currents, where switching to near-by quasiparticle branches take place, keep decreasing with fields but become insensitive to the field beyond 4 T. Thus, beyond 4 T, a cusp-like structure forms for the characteristic current value as denoted by thin-head arrows in figure 3. The cusp position moves to higher voltages for higher magnetic fields without any further decrease in its current values. This is the generic feature observed in four different mesa samples studied so far. The sample DSC1 without the main pedestal stack, however, shows different features as will be explained below. In magnetic fields beyond 4 T another cusp-like structure is observable in each *I–V* curve as denoted by void-head arrows in figure 3. With increasing applied magnetic field, the voltage value of the high-voltage cusp also increases almost linearly to the field value but with a much slower rate than the low-voltage cusp.

Numerical studies with coupled sine-Gordon equations [9, 10] have shown that structural transitions of the moving Josephson-fluxon patterns take place with a gradual variation of the applied dc magnetic field or the tunnelling bias current. According to the analysis the voltage range below the position of the low-voltage cusp may correspond to the the random distribution and the irregular motion of Josephson fluxons. It is also predicted that the low-voltage cusp almost represents the lowest-velocity mode of plasma propagation. On the other hand, the voltage range beyond the high-voltage cusp may represent the state where all the fluxons in the stacks of junctions move in phase and the coherent radiation is feasible. A mixture of different modes with higher disorder in the fluxon distribution may exist in the region between the two cusps.

In figures 4 and 5 we plot the field dependence of *I–V* characteristics of the sample DSC1, measured in a two-terminal configuration. Fields were applied in parallel with the stacked superconducting layers perpendicular to the length direction. The contact resistance, ∼150 Ω, was not subtracted in the plot. The data were taken by an analog oscilloscope with the sample at the liquid-helium temperature and were recorded on polaroid films. The data were then digitized using

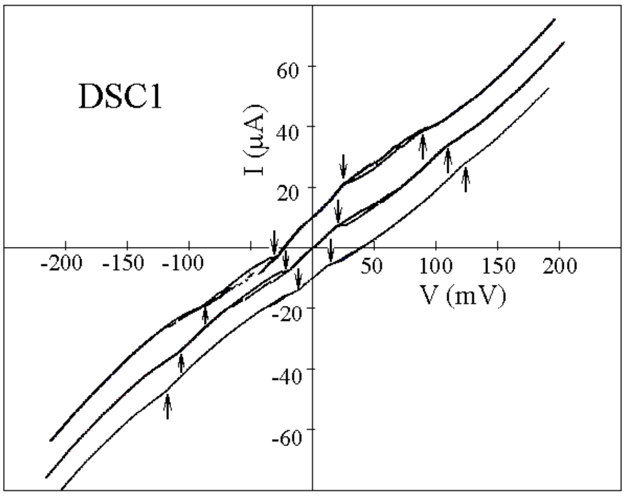

Figure 5. Variation of *I*–*V* characteristics of the sample DSC1, for external magnetic fields of $H = 3.0$, 4.0 and 5.0 T, which clearly show the low- and high-voltage cusps. For clarity, the 3.0 T curve (5.0 T curve) was shifted upward (downward) by 10 μA.

a scanner. The overall shape of the stack was 190 μm long and 80 nm thick. The data in figures 4 and 5 are supposed to be from the 190-μm-long and 30-nm-thick portion of the stack, since the upper 50 nm thickness of the stack was not fully removed.

Figure 4 shows the variation of the *I*–*V* characteristics for dc magnetic fields of 0.5 T (the curve surrounding the largest area), 1.0 T (the curve surrounding the outer boundary of the lightly and darkly shaded areas as a whole), and 2.0 T (the curve surrounding the darkly shaded area only). The total number of quasiparticle branches was 19–20. The overall feature of the *I*–*V* characteristics in these relatively low magnetic fields is very similar to the ones obtained from the mesa samples including UD1, except for the larger return current. The smaller hysteresis with the larger return current is not well understood because the junction capacitance for the samples DSC1 and UD1 with similar junction areas is supposed to be close to each other. In this sample also the critical currents suppress rapidly until the external field H increases up to 2 T. The lower-voltage cusp already starts appearing for $H = 2$ T near 50 mV.

In figure 5 we show the follow-up trend of *I*–*V* characteristics for fields 3.0, 4.0 and 5.0 T. For the sake of clear illustration the 3.0 T curve (5.0 T curve) was shifted upward (downward) by 10 μA. For $H = 3.0$ T the hysteresis disappears and *I*–*V* characteristics collapse again almost into a single curve. In the 3.0 T curve, in addition to the clear appearance of the low-voltage cusp (denoted by the downward arrow), the high-voltage cusp (denoted by the upward arrow) also appears, very similar to the behaviour observed in the mesa samples. The detailed behaviour of the low-voltage cusp, however, is quite different from that of the mesa samples. With increasing H, instead of an increase of the voltage with saturated minimum current as in UD1, both the current and voltage values of the low-voltage cusp keep decreasing. But the voltage values of the high-voltage cusp increases in a faster rate with increasing H.

It is not clear whether the difference in the *I*–*V* characteristics of the two different-types of samples was a result of the difference in the sample geometry. Since the sample DSC1 itself was not in an ideal shape we cannot claim for certain that features observed from DSC1 was more intrinsic to the stacked junctions than those from UD1. To our knowledge no analytical explanation is available to date about the development of the clear low-voltage cusp structure in high magnetic fields. The nature of the region below the low-cusp voltage should be also further clarified. It is necessary to examine, in a more direct way, whether the high-voltage cusp is indeed the boundary of the region of highly coherent fluxon configuration.

4. Conclusion

In summary, we investigated *I*–*V* characteristics caused by field-generated Josephson fluxons. We used samples of mesa structure fabricated on the surface of Bi-2212 single crystals. In this study we also investigated any possible influence of the huge pedestal part underneath the mesa structure on the fluxon-flow characteristics of the mesa itself. To that end, we fabricated a sample (DSC1) with a stack of a few tens of intrinsic junctions sandwiched by two thick Au electrodes by removing the main part of the pedestal. We observed a cusp-like structure in the *I*–*V* characteristics of both types of samples. The low-voltage cusp may reveal the collective fluxon motion corresponding to the slowest plasma-propagation mode. The high-voltage cusp may be located at the boundary of the most coherent in-phase motion of the fluxons along the vertical direction. A variation of the field dependence of the low-voltage cusp in DSC1 from the typical field dependence of mesa samples including UD1 may have been caused by the elimination of the pedestal part, which should be further confirmed using a more direct means such as detection of Shapiro steps by the fluxon-excited plasma oscillations.

Acknowledgments

The underdoped single crystals were provided by M Oda, N Momono, and M Ido in Hokkaido University. This work was supported by National Research Laboratory Project administered by KISTEP and Microwave Application Research Center administered by ADD.

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