Fiske steps in intrinsic $Bi_2Sr_2CaCu_2O_{8+x}$ stacked Josephson junctions

V. M. Krasnov
Department of Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden and Institute of Solid State Physics, 142432 Chernogolovka, Russia

N. Mros
Department of Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden

A. Yurgens
Department of Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden and P. L. Kapitza Institute, Kosygina 2, 117334 Moscow, Russia

D. Winkler
Department of Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden

(Received 15 December 1998)

Current-voltage characteristics in the *c*-axis direction were studied experimentally for small-area $Bi_2Sr_2CaCu_2O_{8+x}$ mesas containing only a few intrinsic stacked Josephson junctions. Fiske steps in such junctions were observed. This is direct evidence for the existence of the ac Josephson effect in intrinsic high-T_c Josephson junctions. From observation of a periodic modulation of Fiske step amplitude as a function of magnetic field we obtain that the spacing between intrinsic Josephson junctions, 15.5 Å , is equal to that given by the crystalline structure of $Bi_2Sr_2CaCu_2O_{8+x}$. [S0163-1829(99)04813-4]

The intrinsic Josephson effect,[1] observed in high-T_c superconductors (HTSC's), is attributed to Josephson coupling between atomic-scale superconducting layers. Therefore, highly anisotropic HTSC compounds can be considered as stacks of intrinsic Josephson junctions. Such natural stacked Josephson junctions (SJJ's) could be promising objects for applications in cryoelectronics.

Basically, the existence of the intrinsic Josephson effect in HTSC's is supported experimentally.[1,2] However, the behavior of intrinsic SJJ's is far from being totally understood. Recently, evidence for the existence of Josephson plasma waves in HTSC's was provided from microwave absorption-reflection experiments.[3–5] On the other hand, the main fingerprints of the ac Josephson effect such as Shapiro and Fiske steps in current-voltage characteristics (IVC's) have not yet been observed in HTSC intrinsic SJJ's (see, e.g., Refs. 6 and 7), although they were observed for low-T_c superconducting (LTSC) SJJ's.[8,9]

Fiske steps in IVC's of Josephson junctions are caused by an interaction (geometric resonance) of the ac Josephson effect with electromagnetic cavity modes in a transmission line formed by the junction.[10–12] This results in the formation of standing-wave patterns in the junction.[13] We should note that the cavity modes are different from the Josephson plasma modes and have a different dispersion relation. Due to the ac Josephson effect, a current inside the junction is oscillating at a Josephson frequency,

$$\omega_J = \frac{2e}{\hbar} V,$$

where V is the dc voltage across the junction. Fiske steps appear when the Josephson frequency approaches the resonant frequencies of cavity modes. Geometric resonances manifest themselves in the IVC's as a series of steps with a constant voltage separation when the magnetic field is applied parallel to the junction plane.

In the current paper, we study experimentally the *c*-axis transport properties of small-area $Bi_2Sr_2CaCu_2O_{8+x}$ mesa structures containing only a few intrinsic SJJ's. A well-defined Fiske step structure was observed. This is direct evidence for the ac Josephson effect in intrinsic HTSC SJJ's. The dependence of the steps on the junction size and in-plane magnetic field was studied. Clear periodic modulation of the step amplitude as a function of magnetic field was observed. From this we estimate the spacing between intrinsic Josephson junctions to be 15.5 Å , in excellent agreement with that given by the crystalline structure. This confirms that it is indeed the layered structure of $Bi_2Sr_2CaCu_2O_{8+x}$ which causes the appearance of atomic-scale intrinsic Josephson junctions.

We phenomenologically describe HTSC's as a stack of intrinsic Josephson junctions with the following parameters: d and λ_S, the thickness and London penetration depth of superconducting layers; t, the thickness of the tunnel barrier between the layers; $s=t+d$, the space periodicity of the stack; and L, the length of the stack. We assume that $\lambda_S \gg s$.

The characteristic feature of SJJ's consisting of N junctions is that the dispersion relation of electromagnetic waves is split into N branches[14] with characteristic velocities[15,16]

$$c_n = c_0 \left[1 - \cos\left(\frac{\pi n}{N+1} \right) \right]^{-1/2}, \quad n = 1,2,\ldots,N, \qquad (1)$$

where $c_0 = c\sqrt{td/2\lambda_S^2 \varepsilon_c}$ is the Swihart velocity of the single junction, c is the velocity of light in vacuum, and ε_c is the dielectric constant of the tunnel barrier. The lowest velocity c_N characterizes the motion of a triangular fluxon lattice, which is energetically the most favorable fluxon mode in the static case at high magnetic fields. For $N \gg 1$, the lowest velocity may be written as

$$c_N \simeq \frac{c}{2}\sqrt{\frac{ts}{\lambda_{ab}^2 \varepsilon_c}}, \tag{2}$$

where $\lambda_{ab} = \lambda_S \sqrt{s/d}$ is the effective London penetration depth of the stack.[17] Taking reasonable parameters for $Bi_2Sr_2CaCu_2O_{8+x}$, $s = 15.5$ Å, $t \simeq 12$ Å, $\lambda_{ab} \simeq 1700$Å, $\varepsilon_c \simeq 25$, and $N = 5$, we estimate $c_N/c \simeq 0.83 \times 10^{-3}$. Note that the velocity in Eq. (2) is similar to that obtained in Ref. 18, but takes into account the nonzero thickness of S layers. However, c_N cannot be identified as a limiting velocity for fluxon propagation. In SJJ's, certain fluxon modes can propagate with velocity $u > c_N$.[14] Recently, it was shown that the motion of a single fluxon at $u > c_N$ accompanied by emission of electromagnetic waves is possible.[19,20]

The time-averaged voltage across the junction generated by fluxon motion is proportional to the velocity and number of fluxons in the junction and therefore is proportional to the applied magnetic field, for large enough H. Thus the ratio V/H for fluxon motion with velocity u can be estimated as

$$V/H = Nsu. \tag{3}$$

We note that this ratio is independent of the junction length.

Geometric resonances occur when an integer number of half the wavelength fits into the junction length. This gives the positions of Fiske step voltages in SJJ's:

$$V_{FS} = \sum_{n=1}^{N} m_n \frac{\Phi_0 c_n}{2L}, \tag{4}$$

where Φ_0 is the flux quantum and m_n is an arbitrary integer. In Eq. (4) we did not disregard phase unlocked states; i.e., we allowed any of the SJJ's to be in any of the geometric resonances. On the other hand, phase locking plays an important role for strongly coupled SJJ's. In Ref. 15 two-dimensional geometric resonances were considered representing various phase-locked states. We can expect that the most prominent Fiske steps will occur at

$$V_m = mN \frac{\Phi_0 c_N}{2L}, \tag{5}$$

when all the SJJ's are synchronized at the lowest cavity mode branch. For a $Bi_2Sr_2CaCu_2O_{8+x}$ mesa with $L = 20$ μm and $N = 5$, this gives a voltage spacing between such Fiske steps of $\Delta V_N = 65$ μV.

The amplitude of Fiske steps in current is oscillating with H with periodicity[12,15]

$$\Delta H = \frac{\Phi_0}{Ls}, \tag{6}$$

i.e., with the same periodicity as the critical current. Moreover, the field dependence of the amplitudes of even and odd Fiske steps are out of phase with each other. That is, Fiske step maxima of even steps occur at fields giving minima in

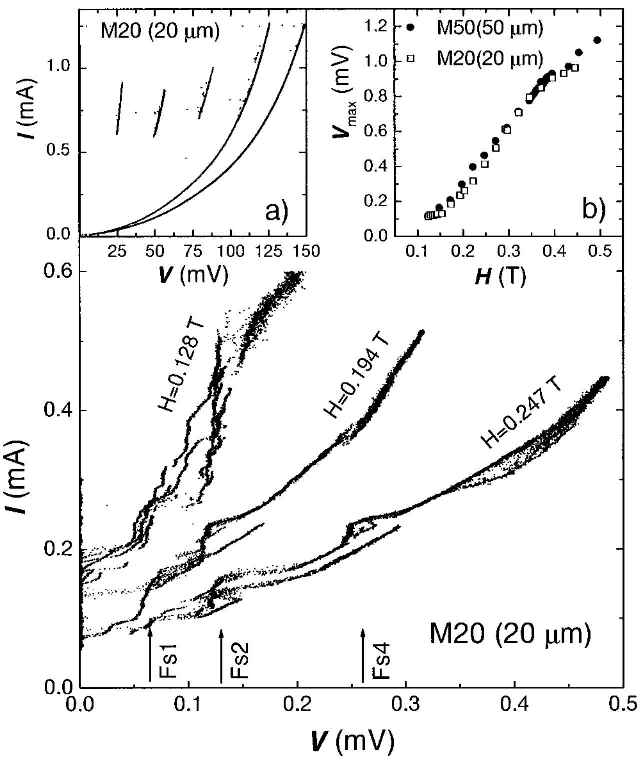

FIG. 1. Flux-flow branches of the IVC's for $M20$ at three different $H \| ab$. Fiske steps are seen. Arrows indicate the expected positions of the phase-locked geometrical resonances, Fs1,2,4 for the lowest cavity mode branch. (a) The quasiparticle branches in the IVC's. (b) The dependence of the maximum flux-flow voltage on the magnetic field for mesas $M50$ and $M20$.

odd steps and vice versa. We note that the periodicity ΔH in Eq. (6) depends only on the junction length and the crystalline structure. For a $Bi_2Sr_2CaCu_2O_{8+x}$ mesa with $L = 20$ μm, $\Delta H = 0.0667$ T.

For studying the intrinsic Josephson effect, mesa structures were fabricated on surfaces of $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals.[2] Mesas with different dimensions 50×10 μ m^2($M50$) and 20×10 μm^2($M20$) were fabricated simultaneously for each single crystal. The procedure makes it possible to fabricate mesas containing only a few intrinsic SJJ's. Several contacts on the top of the mesas allow for four probe measurements. The inset (a) in Fig. 1 shows the c-axis IVC's for mesa $M20$ at $T = 4.2$ K. It is seen that the intrinsic Josephson junctions have tunnel-type IVC's with well-defined superconducting and quasiparticle branches. The mesa studied consists of five SJJ's. Similar gap features were observed for mesa $M50$.

When a magnetic field H was applied perpendicular to the longest junction side and along the ab plane, a low-resistance branch developed in the IVC's. Figure 1 shows such branches for three different magnetic fields. It is seen that the voltage increases with H. Inset (b) in Fig. 1 shows the dependence of the voltage of the low-resistance branch versus the magnetic field for both mesas $M50$ and $M20$. The current in inset (b) is equal to the maximum bias current at which the voltage jumps to the quasiparticle branch at the highest applied magnetic field. From inset (b) it is seen that the voltage of the low-resistance branch increases approximately linearly with H and is independent of the length of the mesa. There-

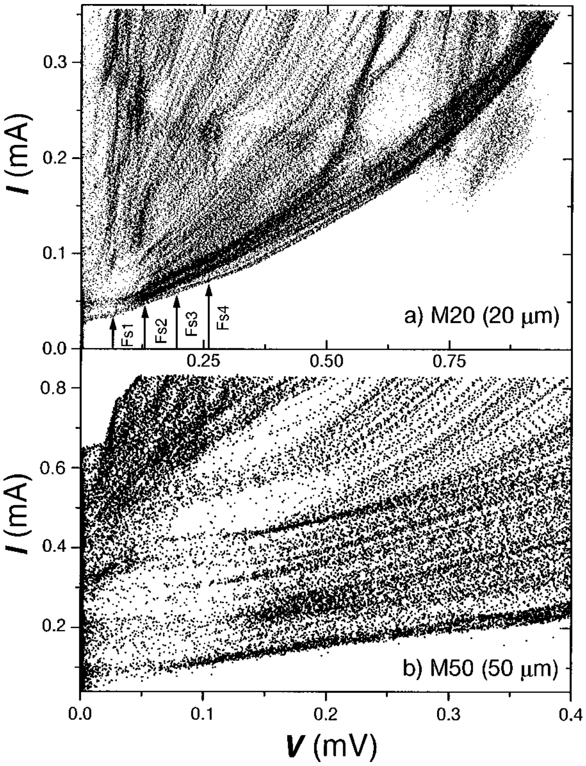

FIG. 2. Flux-flow branches in IVC's recorded during continuously sweeping the magnetic field for (a) $M20$ and (b) $M50$. The development of the flux-flow branch and the Fiske step structure is seen. Arrows in (a) show the expected positions of the four first phase-locked geometrical resonances, Fs1–4, for the lowest cavity mode branch. The voltage scale in (b) was made 2.5 times smaller than in (a) to show that the voltage is inversely proportional to the length of the mesas.

fore, we identify the low-resistance branch with the Josephson flux-flow branch; see Eq. (3).

In Fig. 2 the IVC's of (a) 20-μm and (b) 50-μm mesas are shown for a continuous sweep of the magnetic field. The development of the flux-flow branch with H is clearly seen. The maximum flux-flow voltage divided by H increases slightly (but nonmonotonously) with H. From Eq. (3) we obtain for the maximum fluxon velocity $u_{max}/c \simeq 0.94–1.18\times10^{-3}$, in agreement with previously reported values.[6,21,22] The value u_{max}/c is somewhat larger than the estimated value $c_N/c \simeq 0.83\times10^{-3}$. We note that the flux-flow branch consists of multiple closely spaced but distinct subbranches, with the number of subbranches larger than the number of intrinsic SJJ's in the mesa. Some of the subbranches can be seen in Fig. 1. Sweeping IVC's back and forth with the same applied field we observed a hysteretic switching between subbranches. Previously similar behavior was observed for LTSC (Ref. 23) and HTSC (Ref. 24) SJJ's. Observation of flux-flow subbranches may be further evidence for the existence of multiple quasiequilibrium Josephson fluxon modes in intrinsic SJJ's (Refs. 19 and 25) in the dynamic state, with each subbranch corresponding to the motion of a particular fluxon mode. Previously, experimental evidence for the existence of such modes in the static case was observed both for HTSC (Refs. 25 and 26) and LTSC (Ref. 23) SJJ's.

The most striking feature of Figs. 1 and 2 is the existence

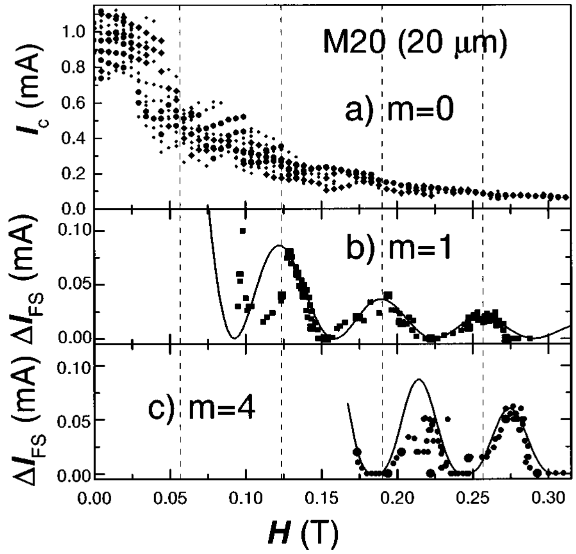

FIG. 3. The magnetic field dependence of (a) the critical current $(m=0)$ and the current amplitudes of (b) the first and (c) the fourth-order phase-locked Fiske steps for $M20$ at $T=4.2$ K. Clear periodic modulations of the Fiske step amplitudes are seen. The grid spacing is equal to the periodicity expected for intrinsic Josephson junctions.

of well-defined steps of nearly constant voltage. The voltages of the steps are independent of the magnetic field; however, their amplitude in current does change with H. From Figs. 1 and 2(a) it can be seen that steps with the largest amplitudes form a step structure with the voltage separation $\Delta V=65 \pm 5$ μV, which is in the range of the estimated value of the voltage spacing $\Delta V_N=65$ μV for the lowest phase-locked Fiske steps, Eq. (5), for our 20-μm mesa. The expected positions for the first four such resonances are shown by arrows in Figs. 1 and 2(a). The important consequence of the geometric resonance is that the voltage at the resonance should be inversely proportional to the junction length; see Eqs. (4) and (5). To check this we made a comparison with mesa $M50$, which is 2.5 times longer than $M20$. In Fig. 2(b), the first step at $V\simeq26$ μV is clearly seen for $M50$. It has 2.5 times smaller voltage than that for $M20$. To show this more clearly, we have plotted Fig. 2(b) with the voltage scale 2.5 times smaller than that in Fig. 2(a), so that Fiske steps should occur at the same position on the horizontal axes in both Figs. 2(a) and 2(b). A step sequence with voltage spacing about 26 μV was also seen for the longer mesa. However, the steps were not as sharp, which can be explained by a decrease of the resonance quality factor[12] with increasing L. Besides the main resonances, corresponding to the lowest phase-locked Fiske steps, other steps with a smaller amplitude and a smaller voltage separation are also visible in Fig. 1. Those steps might be due to other geometric resonances, described by Eq. (4).

From Fig. 2(a) it can be seen that the steps are stratified along the current axis. Such stratification is due to the oscillatory behavior of the step amplitude with magnetic field. Figure 3 shows the magnetic field dependence of current amplitudes for Fiske steps of different orders for the 20-μm mesa: (a) the critical current I_c, $m=0$, $V=0$ μV; (b) $m=1$, $V\simeq65$ μV; and (c) $m=4, V\simeq260$ μV. In Fig. 3(a), circles and diamonds correspond to increasing and decreasing the magnetic field, respectively. The critical current was measured in the following manner: for each magnetic field several thousand switching events from zero voltage to the resistive state were measured and the probability distribution histogram $P(I_c)$ was drawn. Large and small symbols represent main and secondary peaks of $P(I_c)$. For more details see Refs. 25 and 26. From Fig. 3(a) it is seen that the $I_c(H)$ pattern is very complicated. It consists of multiple branches and does not exhibit clear periodicity. Such behavior is attributed to existence of multiple quasiequilibrium Josephson fluxon modes in long strongly coupled SJJ's.[19,25] A drop in I_c at $H \simeq 0.05$ T represents the lower critical field $H_{c1}^{||}$ of the mesa. Note that this value is about two orders of magnitude larger than $H_{c1}^{||}$ of bulk HTSC single crystals.[27] This is due to the ineffectiveness of screening in our mesa consisting of only a few intrinsic SJJ's with extremely thin layers,[19] which are almost transparent for $H||ab$.

In Figs. 3(b) and 3(c) small and large symbols represent single-run measurements and the results of averaging over several hundred successive current sweeps, respectively. The solid lines are quasiperiodic Fraunhofer-type functions which are guides for the eye. From Figs. 3(b) and 3(c) a clear periodic modulation of the step amplitudes is seen. The observed periodicity is in excellent agreement with $\Delta H = 0.0667$ T, Eq. (6), expected for the modulation of the Fiske step amplitude for the intrinsic SJJ's in this mesa, which is also used as a grid spacing in Fig. 3. To our knowledge, such a clear periodic behavior, which can be unambiguously attributed to intrinsic Josephson junctions, is observed for the first time. Note that a modulation with the same characteristic field interval can also be seen for particular $I_c(H)$ branches in Fig. 3(a). From Figs. 3(b) and 3(c) it is also seen that oscillations of the amplitude of an odd step, $m=1$, are out of phase with those of an even step, $m=4$, as it should be for Fiske steps both in single and stacked Josephson junctions.[12,15]

In summary, Fiske steps in $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic stacked Josephson junctions were observed. This is direct evidence for the existence of the ac Josephson effect in intrinsic HTSC Josephson junctions. Our conclusion is supported by (i) observation of the step structure in the *c*-axis IVC's consisting of steps with nearly constant voltage and with the spacing between steps corresponding to the phase-locked geometric resonance at the lowest cavity mode branch, Eq. (5); (ii) by the inverse proportionality of the step voltage to the length of the stack; and (iii) the current amplitudes of the steps being periodic in applied magnetic field in the *ab* plane with the periodicity defined by the crystalline structure and the length of the mesa, Eq. (6). This confirms that it is indeed the layered structure of $Bi_2Sr_2CaCu_2O_{8+x}$ which causes the appearance of atomic-scale intrinsic Josephson junctions. (iv) We observe that oscillations of current amplitudes of odd and even steps are out of phase as a function of *H*. From the observed value of Fiske step voltages we obtain the lowest Swihart velocity $c_{(N=5)} \simeq 2.51 \times 10^7$ (cm/s) for our mesas containing $N=5$ intrinsic SJJ's. For bulk $Bi_2Sr_2CaCu_2O_{8+x}$ material with $N \gg 1$ we estimate, from Eqs. (1) and (2), $c_{(N\to\infty)} \simeq 2.42\times 10^7$ (cm/s). Finally, we note that geometric resonances may be also visible in rf reflection-absorption experiments as a series of peaks at frequency intervals $\Delta\nu = c_n/2L$, since Josephson plasma resonances can couple to geometric resonances.[28]

The work was supported by Swedish Superconductivity Consortium and in part by the Russian Foundation for Basic Research under Grant No. 96-02-19319.

[1] R. Kleiner *et al.*, Phys. Rev. Lett. **68**, 2394 (1992); Phys. Rev. B **49**, 1327 (1994).
[2] A. Yurgens *et al.*, Phys. Rev. B **53**, R8887 (1996).
[3] S. Uchida and K. Tamasaki, Physica C **293**, 1 (1997).
[4] K. Kadowaki *et al.*, Phys. Rev. B **56**, 5617 (1997).
[5] O. K. C. Tsui *et al.*, Phys. Rev. Lett. **73**, 724 (1994).
[6] Yu. I. Latyshev *et al.*, Physica C **293**, 174 (1997).
[7] A. Irie and G. Oya, Physica C **293**, 249 (1997).
[8] V. M. Krasnov *et al.*, Phys. Rev. B **49**, 12 969 (1994).
[9] A. Ustinov *et al.*, Phys. Rev. B **48**, 10 614 (1993).
[10] M. D. Fiske, Rev. Mod. Phys. **36**, 221 (1964).
[11] I. M. Dmitrenko *et al.*, JETP Lett. **2**, 17 (1965).
[12] I. O. Kulik, JETP Lett. **2**, 84 (1965).
[13] S. G. Lachenmann *et al.*, Phys. Rev. B **48**, 3295 (1993).
[14] S. Sakai, P. Bodin, and N. F. Pedersen, J. Appl. Phys. **73**, 2411 (1993).
[15] R. Kleiner, Phys. Rev. B **50**, 6919 (1994).
[16] S. Sakai *et al.*, Phys. Rev. B **50**, 12 905 (1994).
[17] J. Clem and M. Coffey, Phys. Rev. B **42**, 6209 (1990).
[18] L. N. Bulaevskii *et al.*, Phys. Rev. B **53**, 14 601 (1996).
[19] V. M. Krasnov and D. Winkler, Phys. Rev. B **56**, 9106 (1997).
[20] G. Hechtfisher *et al.*, Phys. Rev. Lett. **79**, 1365 (1997).
[21] G. Hechtfisher *et al.*, Phys. Rev. B **55**, 14 638 (1997).
[22] J. Ung Lee, *et al.*, Appl. Phys. Lett. **67**, 1471 (1995); Physica C **277**, 7 (1997).
[23] V. M. Krasnov *et al.*, Phys. Rev. B **54**, 15 448 (1996).
[24] J. Ung Lee *et al.*, Appl. Phys. Lett. **71**, 1412 (1997).
[25] V. M. Krasnov *et al.*, Physica C **304**, 172 (1998).
[26] N. Mros *et al.*, Phys. Rev. B **57**, R8135 (1998).
[27] V. M. Krasnov *et al.*, Physica C **174**, 440 (1991); N. Nakamura *et al.*, Phys. Rev. Lett. **71**, 915 (1993).
[28] N. F. Pedersen *et al.*, Phys. Rev. B **6**, 4151 (1972).