Vol 13 No 4, April 2004
1009-1963/2004/13(04)/0529-03

Chinese Physics

© 2004 Chin. Phys. Soc.
and IOP Publishing Ltd

Fiske steps in surface intrinsic Josephson junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals*

Zhu Xiao-Bo(朱晓波)†, Wei Yan-Feng(魏延锋), Zhao Shi-Ping(赵士平),
Chen Geng-Hua(陈赓华), and Yang Qian-Sheng(杨乾声)

Key Laboratory of Extreme Conditions Physics, Institute of Physics and Center for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100080, *China*

(Received 27 October 2003)

Current–voltage characteristics of the surface intrinsic Josephson junctions under a magnetic field parallel to CuO_2 planes have been studied experimentally. Fiske steps in such a junction have been observed. The Swihart velocity for the junction is found to be 7.2×10^5m/s, which corresponds to the velocity mode of a single junction.

Keywords: Fiske steps, intrinsic Josephson junctions
PACC: 7450, 7340, 7340G

Highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) cuprate superconductor can behave as stacks of intrinsic Josephson junctions (IJJs). Due to the stack arrangement of such IJJs, the properties of BSCCO can be qualitatively different in many ways from those of a single Josephson junction. For example, the velocities of electromagnetic modes in N-stacked IJJs are split into N branches.[1,2] Krasnov *et al*[3] have observed Fiske steps experimentally when all the stacked IJJs are synchronized at the lowest cavity mode branch. The surface IJJs, namely the junctions with the first superconducting CuO_2 double-layer plus the metal contact film as one electrode and the second CuO_2 double-layer as the other, are a special case in the stacked IJJs, since they are located on the top of stacked IJJs and the superconductivity in the first CuO_2 double-layer is weakened.[4,5] In this short note, we report the first observation of Fiske steps in the current–voltage characteristics (IVCs) of such surface IJJs. Our results show that the surface IJJs are more like a single Josephson junction. These results will be helpful to understand the properties of stacked IJJs.

Our BSCCO single crystals were grown by the travelling solvent floating zone method. The crystals were nearly optimally doped (bulk $T_c \sim 91$K). Small pieces of these crystals with a typical size of 0.6mm×0.6mm×0.05mm were glued onto Si substrates. After in situ cleaved at liquid nitrogen temperature, a 50-nm-thick Au film was immediately deposited on the cleaved surface by evaporation. Mesas with dimensions of 5μm×5μm were fabricated using standard photolithography and Ar-ion milling.

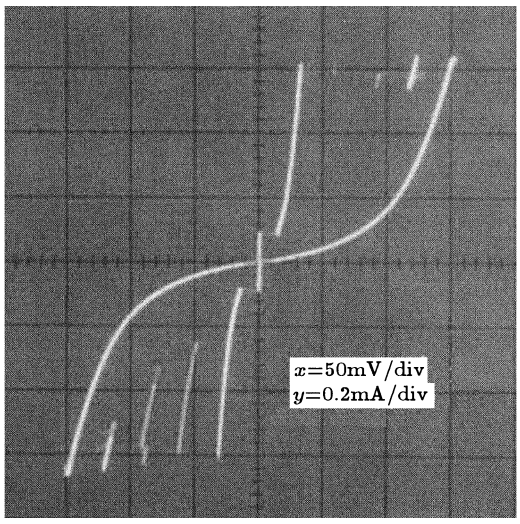


Fig.1. Current–voltage characteristic of an IJJ at 4.2K without external magnetic field. The mesa contains five junctions and the critical current I_c' of the surface IJJ is only one-sixth that of the inner IJJs.

Figure 1 shows the typical IVC of our IJJs at 4.2K without external magnetic field. The junction number

*Project supported by the National Center for R & D on Superconductivity and the Ministry of Science and Technology of China (Grant No NKBRSF-G19990646).
†E-mail: xbzhu@aphy.iphy.ac.cn

N in the mesa is determined to be 5 from the number of the observed quasiparticle branches. The critical current I_c' of the surface IJJ is only one-sixth of that of the inner IJJs, because superconductivity in the first CuO_2 double layer is weakened due to the possible surface degradation and its contact with the metal film.[4,5]

We have successfully observed resonant-like current steps in the first branch of IVC under magnetic fields. Figure 2 shows the field dependence of the IVCs at 4.2K. When the magnetic field B is increased from zero, I_c' decreases and a clear resonant step (Fiske step) first appears at about 150μV (Fig.2(b)). For B=0.36T another resonant step appears at about 300μV (Fig.2(c)), and for B=0.54T, I_c' decreases to about 40μA and the Fiske steps vanish. We did not observe any other resistive branches which are regarded as the flux-flow branches caused by the Josephson vortex-flow in the IJJs as discussed in Refs.[3], [6] and [7]. This indicates that the Josephson vortex-flow does not play an important role in such a 5μm-sized, weakened surface IJJs.

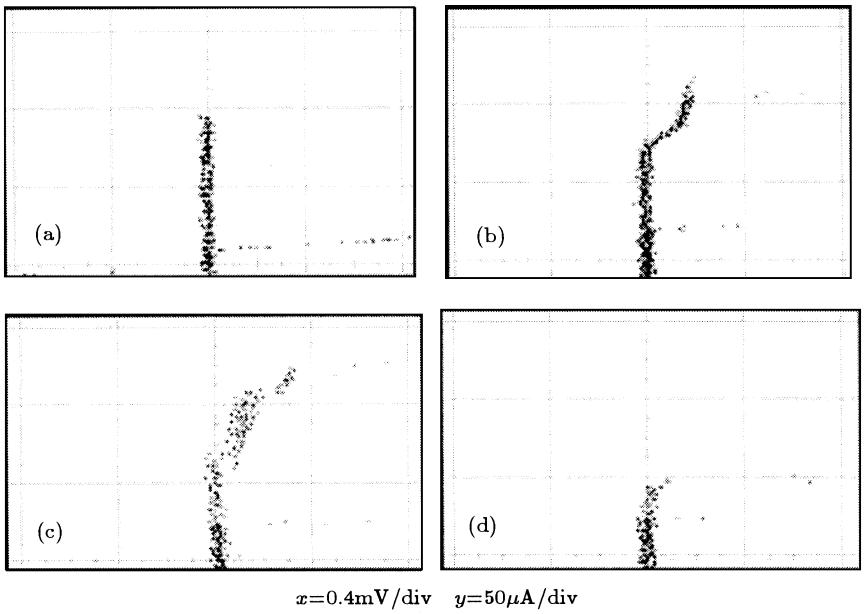


Fig.2. (a) Current–voltage characteristic of the surface IJJ at 4.2K without external magnetic field, in which the critical current I_c' is about 90μA and the return current I_r' is about 10μA. (b) When the magnetic field B is increased from zero, I_c' decreases and for B=0.18T, a clear resonant step (Fiske step) appears at about 150μV. (c) For B=0.36T another resonant step appears at about 300μV. (d) For B=0.54T the I_c' decreases to about 40μA and the Fiske steps vanish.

As is well known, Fiske steps in IVCs are caused by an interaction (geometric resonance) of the ac Josephson effect with electromagnetic cavity modes in the transmission line formed by the junction.[8] If the Josephson frequency matches the frequency of the cavity modes, a zero-frequency current step appears. As the Josephson current is spatially modulated, due to the applied magnetic field, a series of steps are found in the IVCs at voltages

$$V_n = n\Phi_0 c_0/2L, \tag{1}$$

where L is the junction width (5μm in our mesa), Φ_0 is the flux quantum, c_0 is the Swihart velocity of the single junction, and n is an integer. However, according to the stacked Josephson junction model, N-stacked junctions will have N different characteristic velocities of electromagnetic modes in them, which are given by the following formula:[1,2]

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

where $c_0 = c\sqrt{td/2\lambda^2\varepsilon}$, c is the velocity of light in vacuum, and ε is the dielectric constant of the tunnel barrier. It should be noted that Eq.(2) is based on a phenomenological description of IJJs as a series of SJJs with the following parameters: d and λ are respectively the thickness and London penetration depth of superconducting layers; t is the thickness

of the tunnel barrier between the neighbouring CuO_2 layers; $s = t + d$ is the space periodicity of the stack; and we should further assume $\lambda \gg s$. So, c_0 has a different expression from that of a usual single Josephson junction where the thickness of the superconducting layers is larger than the London penetration depth.

To calculate c_0 and c_n, we first evaluate C_j, or ε, of the IJJs. C_j can be calculated using the relation [9]

$$\beta_c = \frac{2\pi I_c' R_n^2 C_j}{\Phi_0}\left(\frac{4I_c'}{\pi I_r'}\right)^2 \qquad (3)$$

in the limit $\beta_c \gg 1$, based on the resistively shunted junction model. Here I_r' is the return current and β_c is the McCumber parameter. Using I_c'=90μA, I_r'=10μA, and $R_n = 20\Omega$, we obtain $\beta_c = 131.3$ and C_j=1.2pF (ε=6.5). Then, with $\lambda_{ab} = \lambda\sqrt{s/d}$, the effective London penetration depth of the stack,[10] the expression of c_0 can be rewritten as

$$c_0 = c\sqrt{ts/2\lambda_{ab}^2\varepsilon}. \qquad (4)$$

Using this value of ε and typical parameters t=1.2nm, s=1.55nm, and λ_{ab}=170nm [3] for BSCCO, we obtain $c_0 = 6.7 \times 10^5$m/s and c_n of five stacked junctions are in the range from 1.8×10^6m/s for n=1 (the highest mode) to 4.9×10^5m/s for n=5 (the lowest mode).

Since ΔV_n is about 150μV, we know from Eq.(1) that the velocity of the electromagnetic wave in the surface IJJ is 7.2×10^5m/s, which is quite close to the above estimated value of c_0. This result shows that the surface IJJ is more like a single Josephson junction since the most possible Fiske step will occur when all the stacked IJJs are synchronized at the lowest cavity mode branch, but the Fiske steps in our sample are only observed at voltages corresponding to the velocity mode of a single junction. This can be understood since the Josephson critical current of the inner IJJs is six times larger than that of the surface IJJs. As the magnetic field B is applied in the range concerned, the critical current is subject to a much less change so the inner IJJs may simply serve as a superconducting electrode.

In summary, Fiske steps in the IVCs under magnetic fields have been successfully observed in the surface IJJs of the BSCCO crystal. The Swihart velocity for our sample is 7.2×10^5m/s, which corresponds to the velocity mode of a single junction. These results will be helpful to understand the properties of stacked IJJs.

We are grateful to Professor H J Tao for kindly providing us with the BSCCO crystals used in this work and for Y F Ren, H W Yu and Professor F Z Xu for their technical help during sample preparations.

References

[1] Kleiner R and Müller P 1994 *Phys. Rev.* B **49** 1327
[2] Sakai S, Ustinov A V, Kohlstedt H, Petraglia P and Pedersen N F 1994 *Phys. Rev.* B **50** 12905
[3] Krasnov V M, Mros N, Yurgens A and Winkler D 1999 *Phys. Rev.* B **59** 8463
[4] Kim N, Doh Y J, Chang H S and Lee H J 1999 *Phys. Rev.* B **59** 14639
[5] Zhu X B, Zhao S P, Yu H W, Chen G H, Xie S S and Yang Q S 2002 *Sing. J. Phys.* **18** 83
Zhu X B, Zhao S P, Chen G H, Xie S S and Yang Q S 2002 *Chin. Phys. Lett.* **19** 1859
Zhu X B, Zhao S P, Yu H W, Chen G H, Xie S S and Yang Q S *Physica* C (revised)
[6] Irie A, Hirai Y and Oga G 1998 *Appl. Phys. Lett.* **72** 2159
[7] Krasnov V M, Mros N, Yurgens A and Winkler D 2000 *Physica* B **284** 1856
[8] Fiske M D 1964 *Rev. Mod. Phys.* **36** 221
[9] Likharev K K 1986 *Dynamics of Josephson Junctions and Circuits* (Philadelphia, PA: Gordon and Breach)
[10] Clem J and Coffey M 1990 *Phys. Rev.* B **42** 6209