Tunneling spectra of underdoped $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ intrinsic Josephson junctions*

Yuan Tao(袁 涛)[a)], Wang Xin-Qiang(王新强)[a)†], Ren Jian-Kun(任建坤)[b)], Lin De-Hua(林德华)[a)], Tian Ye(田 野)[b)], Ren Yu-Feng(任育峰)[b)], and Zhao Shi-Ping(赵士平)[b)‡]

[a)] *Department of Physics, Chongqing University, Chongqing* 400044, *China*

[b)] *Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*

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Mesa-structured submicron intrinsic Josephson junctions are successfully fabricated and well characterized on underdoped $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystals with a T_c of 80 K. Tunneling spectra at the temperatures ranging from 4.2 K to 295 K are measured. A pulse technique is used to reduce sample heating for the measurement near pseudogap opening temperature $T^* \sim 280$ K. Our experimental results show that the superconducting gap, the peak-dip separation, and the pseudogap opening temperature are all increased as compared with those from near optimally doped samples, which requires further theoretical analysis in the future.

Keywords: underdoped $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ superconductors, intrinsic Josephson junctions, tunneling spectra

PACC: 7450, 7430J, 7470V

1. Introduction

The pairing mechanism and the nature of the pseudogap[1] are the two most important unsolved issues in the study of high-T_c cuprate superconductors.[2] Various spectroscopic techniques, such as angle-resolved photo-emission spectroscopy (ARPES),[3] optical[4] and tunneling spectroscopy,[5] have been used to obtain a better understanding. Among these techniques, the tunneling experiment is unique, as it plays a central role in the case of conventional superconductors and provides the key test of the epoch-making microscopic BCS theory.[6,7]

In the tunneling studies of $Bi_2Sr_2CaCu_2O_{8+\delta}$ high-T_c superconductors, scanning tunneling microscope (STM),[5] break junctions (BJs),[8,9] and intrinsic Josephson junctions (IJJs)[10−15] have been used. Compared with STM and BJs, IJJs bear a closer resemblance to the conventional planar-type tunnel junctions[7] with the intrinsic double CuO_2 planes as the superconducting electrodes.[16,17] Being intrinsic, IJJs can provide stable and convenient temperature and magnetic-field-dependent measurements. It has been shown that submicron sized IJJs[12] exhibit tunneling spectra that are considerably different from those of micron sized IJJs[10,11] in which self-heating could be more influential (heating is known to increase as sample size increases).[18] Analysis of the tunneling spectra for near optimally doped submicron IJJs shows consistent pictures with those from BJs at low temperatures and from STM in the pseudogap phase at high temperatures.[14,15] Furthermore, analysis based on a self-energy model proposed by Norman *et al.*[19] demonstrates that within the precursor paring scenario the same Fermi arc behaviour as observed in ARPES experiment[20] can be obtained from the tunneling results of submicron IJJs.[15]

Tunneling studies of submicron IJJs have so far been limited to samples near optimal doping, and it is of much interest to extend the results to other doping levels. In this work, underdoped submicron IJJs are fabricated and spectra from 4.2 K up to above the pseudogap temperature T^* are presented. We describe our fabrication process and a pulse measurement technique that avoids increasing heating effect at the T^* near room temperature. Finally, the temperature dependent spectra and their comparison with previous tunneling results are discussed.

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†E-mail: xqwang@cqu.edu.cn

‡Corresponding author. E-mail: spzhao@aphy.iphy.ac.cn

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2. Experiment and results

Underdoped $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystals were used in our experiment, which were grown by the method described previously.[21] Compared with the variation of the oxygen content, the substitution of Y for Ca can lower the doping level quickly. Since hole density p equals δ for $Bi_2Sr_2CaCu_2O_{8+\delta}$ with ideal stoichiometry, it is likely that the underdoped phase is achieved with a smaller change in oxygen content, and thus less change of the tunnel barrier property than that of the optimally doped samples.

Mesa-structured IJJs were fabricated on the crystals, glued onto Si substrates, using a process similar to that in the previous reports.[12,22–24] In the experiment, special care was taken to avoid the deterioration of the superconducting properties of the topmost surface CuO_2 double-layer in the mesa during preparation so that all the layers in the mesa were as identical as possible. This was realized through the *in situ* low-temperature cleavage of the crystals, followed immediately by the evaporation of Au films at high speed.[23] One important change compared with our previous work is that instead of PMMA950, ZEP520 resist was used, which was found to be more resistant against Ar-ion milling, and the mesa structures with lateral dimensions down to submicron size could be easily fabricated with high reproducibility by electron beam lithography.

Three-terminal configuration was used for measuring resistance $R(T)$ and I–V curves in our experiments. The top Au electrode was used as both the current and the voltage leads. I–V curves were recorded by using a dc, or pulse method, or by a digital oscilloscope, and $\mathrm{d}I/\mathrm{d}V$ spectra were obtained by their numerical differentiation. In Fig. 1(a), we show the I–V characteristic in a voltage range below 300 mV, in which branches from 10 IJJs can be seen. The mesa had an area of 4×4 μm^2. The temperature dependence of the resistance R across the mesa is plotted in Fig. 1(b), where superconducting transition occurs at $T_c = 80$ K and above T_c, R decreases monotonically with temperature increasing. From the $R \sim T$ and I–V characteristics, we can see that the topmost surface CuO_2 double-layer has nearly the same T_c as the inner layers in the mesa and critical current I_c of the surface IJJ is close to those of the inner IJJs.

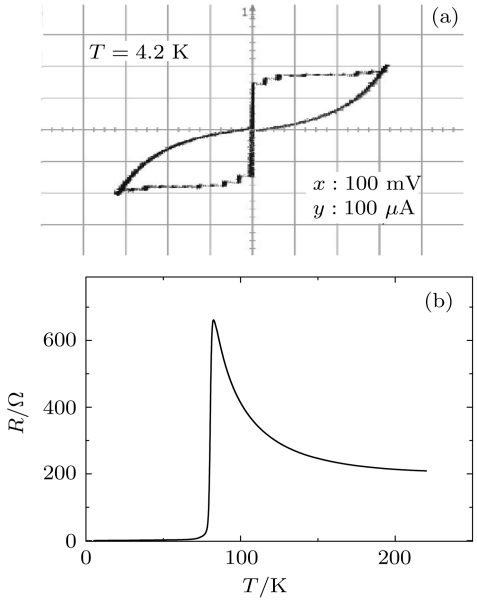


Fig. 1. (a) I–V curve branches of an underdoped $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ mesa, 4 μm in size and containing 10 IJJs, and (b) resistance across the mesa measured using 1-μA excitation current, showing a T_c of 80 K.

The $\mathrm{d}I/\mathrm{d}V$ tunneling spectra of a mesa with an area of 0.6×0.6 μm^2 fabricated on the same crystal are presented in Fig. 2 as indicated by solid lines. The temperature ranges from 4.2 K up to 295 K, which is above pseudogap opening temperature $T^* \sim 280$ K. The voltage is divided by IJJs number so it represents the value per IJJ. In the figure, we see that the curve at 4.2 K has a well-known peak-dip-hump structure. At 75 K near T_c, the dip-hump disappears while the pseudogap persists with temperature increasing until $T^* \sim 280$ K (not shown here for clarity). The curve at 295 K $> T^*$ is seen to be gapless.

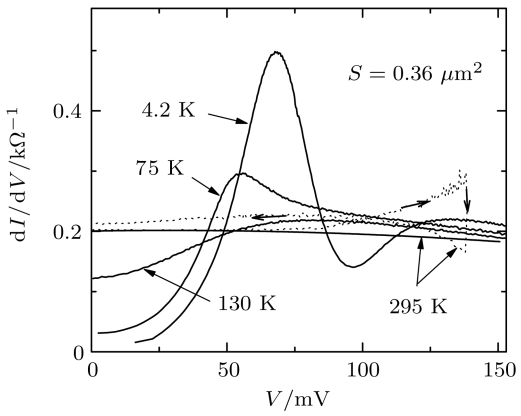


Fig. 2. Tunneling spectra (solid curves) of a mesa 0.6 μm in size on the same crystal as that in Fig. 1. V is the voltage per IJJ. The solid curve at 295 K, which is above $T^* \sim 280$ K so pseudogap vanishes, is obtained from pulse measurement, while the dotted line at the same temperature exhibits hysteresis due to heating.

The dot line in Fig. 2 was obtained at 295 K in the same way as those at lower temperatures but it shows a hysteresis when the bias current I is sweeping up and down. It turns out that the sample's heating was the cause for such a strange behaviour. In Fig. 3(a), we exaggerate the heating effect by biasing the mesa at two current values and the voltage per IJJ is plotted against time. It can be seen that at $I = 200$ μA, the voltage has a clear decrease with time in a scale of 1 or 2 min, which results from sample temperature rise (compared with the temperature dependence of R in Fig. 1). The temperature rise from self-heating becomes more severe when I increases to 300 μA as can be seen in the figure.

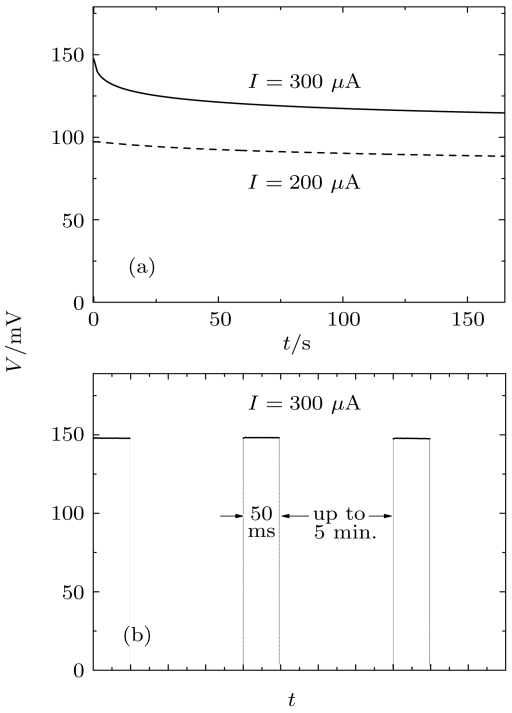


Fig. 3. Pulse measurement at 295 K used to reduce heating. (a) Voltage per IJJ versus time for two indicated constant currents, and (b) voltage per IJJ versus time for 300-μA current pulse of 50-ms width.

We note that for the near optimally doped sample with the same area, the influence of heating is already small for temperatures near and below $T^* \sim 230$ K.[12] That the problem of heating becomes more serious in the present case can be explained as follows. First, thermal conductivity for the Bi-based cuprates becomes smaller as the material is more underdoped.[25] Secondly, T^* increases from 230 K to 280 K which is near room temperature. In this temperature range, thermal conductivity of the Si substrate below the $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ crystal has a large decrease with temperature increasing[26] while that of Au film above the crystal mesa also decreases slightly. Therefore, thermal conduction for nearly all the materials in concern becomes poorer in the present measurement as compared with the case in Ref. [12].

To solve the self-heating problem, we performed the pulse measurement as previously used by Anagawa *et al.*[27] The principle of this method is that the bias current I for the measurement sustains for only a short period of time before heating becomes obvious and the temperature rise is observable. In Fig. 3(b), we show the results of $I = 300$ μA with a pulse width of 50 ms. We can see that the change of the voltage per IJJ is already negligible from pulse to pulse for a width of 50 ms that can be easily prepared. The solid line at 295 K in Fig. 2 is the result obtained by using the pulse measurement.

3. Discussion

It is interesting to compare the experimental spectra in Fig. 2 with those from the sample with near optimal doping.[12,14,15] At a low temperature of T = 4.2 K, the present result shows a superconducing peak position at 68.4 mV (thus the energy gap $\Delta \sim$ 34.2 meV) and a dip position at 96.4 mV, which are larger than 63.1 mV and 84 mV from the near optimally doped mesa with the same area.[12] In Ref. [9], the spectral dip feature was attributed to the coupling of bosonic excitations (either phonons or spin fluctuations served as a glue to the superconducting pairing) to the electronic system. Under such a consideration, the dip is located at an energy of $2\Delta + \Omega$, where Ω roughly corresponds to the energy of the bosonic excitations. In the present case, we have $\Omega \approx 28$ meV, which is greater than $\Omega \approx 23$ meV for the near optimally doped sample. The increases in Δ and Ω are consistent with the reported values of Refs. [8] and [9], respectively.

Turning to the high temperature side, we have pseudogap opening temperature $T^* \sim 280$ K, which is higher than the value of 230 K from the near optimally doped sample.[14,15] The increase of T^* as doping level decreases is observed in the previous STM and BJs experiments.[5] The value of $T^* \sim 280$ K is close to that of the STM results but is considerably higher than that from the BJs experiment for samples with a similar doping level. More detailed analyses as performed for the near optimally doped samples[14,15] are required to have a further understanding of these experimental results.

4. Conclusion

Mesa-structured submicron IJJs are successfully fabricated and well characterized on underdoped $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+\delta}$ single crystals, which has a T_c of 80 K. Tunneling spectra in a temperature range of 4.2 K–295 K are measured. It is found that near the pseudogap opening temperature $T^* \sim 280$ K, thermal conductions of the mesa IJJs and the surrounding materials become poor compared with those in the case of near optimally doped samples so self-heating causes obvious distortion of the tunneling spectra. In order to reduce heating, a pulse measurement technique is used and the result without distortion is obtained. The present tunneling spectra show that the superconducting gap, the peak-dip separation, and the pseudogap opening temperature are increased as compared with those from the near optimally doped samples, which requires further theoretical analysis in the future.

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References

[1] Timusk T and Statt B 1999 *Rep. Prog. Phys.* **62** 61
[2] Lee P A, Nagaosa N and Wen X G 2006 *Rev. Mod. Phys.* **78** 17
[3] Damascelli A, Hussain Z and Shen Z X 2003 *Rev. Mod. Phys.* **75** 473
[4] Basov D N and Timusk T 2005 *Rev. Mod. Phys.* **77** 721
[5] Fischer ϕ, Kugler M, Maggio-Aprile I, Berthod C and Renner C 2007 *Rev. Mod. Phys.* **79** 353
[6] Schrieffer J R 1964 *Theory of Superconductivity* (New York: Benjamin)
[7] Wolf E L 1985 *Principles of Electron Tunneling Spectroscopy* (New York: Oxford University Press)
[8] Miyakawa N, Guptasarma P, Zasadzinski J F, Hinks D G and Gray K E 1998 *Phys. Rev. Lett.* **80** 157
[9] Zasadzinski J F, Ozyuzer L, Coffey L, Gray K E, Hinks D G and Kendziora C 2006 *Phys. Rev. Lett.* **96** 017004
[10] Krasnov V M, Yurgens A, Winkler D, Delsing P and Claseson T 2000 *Phys. Rev. Lett.* **84** 5860
[11] Suzuki M and Watanabe T 2000 *Phys. Rev. Lett.* **85** 4787
[12] Zhu X B, Wei Y F, Zhao S P, Chen G H, Yang H F, Jin A Z and Gu C Z 2006 *Phys. Rev.* B **73** 224501
[13] Li S X, Qiu W, Han S Y, Wei Y F, Zhu X B, Gu C Z, Zhao S P and Wang H B 2007 *Phys. Rev. Lett.* **99** 037002
[14] Zhao S P, Zhu X B and Wei Y F 2007 arXiv:cond-mat/0703177v2
[15] Zhao S P, Zhu X B and Tang H 2009 *Eur. Phys. J.* B **71** 195
[16] Kleiner R, Steinmeyer F, Kunkel G and Müller P 1992 *Phys. Rev. Lett.* **68** 2934
[17] Kleiner R and Müller P 1994 *Phys. Rev.* B **49** 1327
[18] Krasnov V M, Yurgens A, Winkler D and Delsing P 2001 *J. Appl. Phys.* **89** 5578
[19] Norman M R, Randeria M, Ding H and Campuzano J C 1998 *Phys. Rev.* B **57** R11093
[20] Kanigel A, Chatterjee U, Randeria M, Norman M R, Souma S, Shi M, Li Z Z, Raffy H and Campuzano J C 2007 *Phys. Rev. Lett.* **99** 157001
[21] Wang N L, Buschinger B, Geibel C and Steglich F 1996 *Phys. Rev.* B **54** 7445
[22] Zhu X B, Wei Y F, Zhao S P, Chen G H and Yang Q S 2004 *Chin. Phys.* **13** 529
[23] Zhao S P, Zhu X B, Wei Y F, Chen G H, Yang Q S and Lin C T 2005 *Phys. Rev.* B **72** 184511
[24] Cui D J, Lin D H, Yu H F, Peng Z H, Zhu X B, Zheng D N, Jing X N, Lu L and Zhao S P 2008 *Acta Phys. Sin.* **57** 5933 (in Chinese)
[25] Crommie M F and Zettl A 1990 *Phys. Rev.* B **41** 10978
[26] Glassbrenner C J and Slack G A 1964 *Phys. Rev.* **134** A1058
[27] Anagawa K, Yamada Y, Shibauchi T, Suzuki M and Watanabe T 2003 *Appl. Phys. Lett.* **83** 2381