Spin-polarized quasiparticle tunnel injection in a YBa2Cu3Oy/Au/Co junction

Article *in* Applied Physics Letters · August 1999

DOI: 10.1063/1.124625

6 authors, including:

Kiejin Lee
Sogang University
156 PUBLICATIONS **1,337** CITATIONS

Wan Wang
Toshiba Corporation
6 PUBLICATIONS **118** CITATIONS

Barry A Friedman
Sam Houston State University
155 PUBLICATIONS **2,034** CITATIONS

Takayuki Ishibashi
Nagaoka University of Technology
181 PUBLICATIONS **1,370** CITATIONS

APPLIED PHYSICS LETTERS VOLUME 75, NUMBER 8 23 AUGUST 1999

Spin-polarized quasiparticle tunnel injection in a $YBa_2Cu_3O_y$/Au/Co junction

Kiejin Lee,[a] Wan Wang, and Ienari Iguchi
Department of Applied Physics, Tokyo Institute of Technology and CREST, Japan, and Science and Technology Corporation (JST), Oh-okayama, Meguro-ku, Tokyo 152-8551, Japan

Barry Friedman
Department of Physics, Sam Houston State University, Huntsville, Texas 77341, and Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba, 305-8568, Japan

Takayuki Ishibashi and Katsuaki Sato
Faculty of Technology, Tokyo Institute of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184, Japan

(Received 22 March 1999; accepted for publication 29 June 1999)

We report the strong suppression of $YBa_2Cu_3O_y$ (YBCO) supercurrent by injection of spin-polarized quasiparticles (QP) using a cobalt ferromagnetic injector. The injection of spin-polarized QP generates a substantially larger nonequilibrium population as compared with that of an unpolarized injection current. The observed current gain depends on the thickness of Au interlayer (d_{Au}) and is directly related to the nonequilibrium magnetization due to spin relaxation effects. For d_{Au} = 15 nm, the tunnel characteristic a YBCO/Au/Co junction exhibited a zero bias conductance peak, which may be interpreted by spin scattering processes at a ferromagnetic/*d*-wave superconductor junction. © *1999 American Institute of Physics.* [S0003-6951(99)02034-3]

The investigation of nonequilibrium superconductivity due to tunnel injection of spin-polarized quasiparticles (QP) provides useful information on the superconducting mechanism related to spin-dependent electronic properties[1] and may also lead to a new class of superconducting devices. The nonequilibrium state in a superconductor can be induced by injecting photons or phonons with energy greater than the superconducting energy gap or a tunnel current into it, so that the number of QP becomes greater than that in thermal equilibrium. One effective way to induce a strongly perturbed nonequilibrium state is tunnel injection of QP.[2] Some results on the QP injection effect into a high T_c superconductor (HTSC) have been reported previously.[3,4] However, compared to a low temperature superconductor, the current gain of HTSC was considerably smaller and about unity. However, quite recently, it has been reported by many authors that the spin-polarized QP injection from either a colossal magnetoresistance material[5,6] or a ferromagnetic material of permalloy[7] into a HTSC caused strong nonequilibrium effects. The experiments suggest that the high density of spin-polarized QP were injected into a superconductor and created a nonequilibrium state which was able to affect the electronic transport properties of the superconducting film.

In this letter, we report the Cooper-pair breaking effect in a HTSC superconductor due to the injection of spin-polarized QP into a YBCO film from a cobalt (Co) film and compare it to that of unpolarized QP from a nonmagnetic metallic gate. The dependence of the differential conductance of YBCO/Au/Co (superconductor/normal-metal/ferromagnetic: S/N/F) junctions on the voltage bias and the thickness of Au interlayer (d_{Au}) have been studied. The current gain of S/N/F junctions strongly depended on d_{Au}, which behavior is interpreted by a model of the nonequilibrium magnetization due to the spin relaxation effects. The properties of differential conductance of S/N/F junctions are interpreted by the spin scattering processes at a ferromagnetic/*d*-wave superconductor junction.

The YBCO films of 50–60 nm thickness were prepared by pulsed-laser deposition technique on MgO (100) substrates. Note that, the surface morphology of the YBCO thin film is crucial in S/N/F spin injection experiment. We investigated the surface of the deposited YBCO films using an atomic force microscope. The typical surface roughness of 50-nm-thick YBCO film has an average roughness of about 7 nm. Thus, we can rule out the expected material effect due to a rough surface of the YBCO film. Two types of samples with different counter electrodes were prepared in order to compare the injection effect of spin-polarized QP with that of unpolarized QP; one structure has a S/N/F structure and the other has a S/N structure. The effective junction area was $100\times 20\,\mu m^2$ for both junctions. For S/N junctions, the thickness of the deposited Au layer was about 50 nm. For S/N/F junctions, we deposited an Au barrier film on the YBCO film to avoid the formation of a spin-glass phase at the S/F interface.[8] The superconducting properties of YBCO films were always degraded when a Co layer was directly sputtered onto a YBCO film as shown in Fig. 1(a). The isolation effect of Au barrier at the S/F interface provided a noticeable change in superconductivity. With this sandwiched structure, the tunnel junction resistance changed. The deposition of a minimum 10 nm thickness of the Au barrier layer was necessary to avoid the degradation of superconductivity of a YBCO film. The device geometry is depicted in Fig. 1(b). Two currents were fed into a YBCO film: one is the injection current (I_{inj}) and the other is the transport current (I_T) through a YBCO film. The I_{inj} goes from the ferromagnetic Co film to the YBCO film through an insulating

---

[a] Corresponding author. Electronic mail: klee@htsc.ap.titech.ac.jp

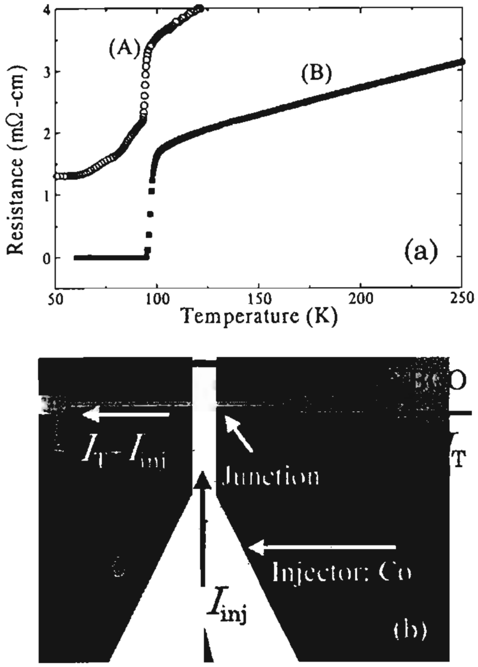

FIG. 1. (a) Resistive transition of $YBa_2Cu_3O_y$ films for a $YBa_2Cu_3O_y$/Au/Co tunnel junction (A) without a Au interlayer (d_{Au}) and (B) with d_{Au} = 10 nm. (b) Photograph of the $YBa_2Cu_3O_y$/Au/Co tunnel junction.

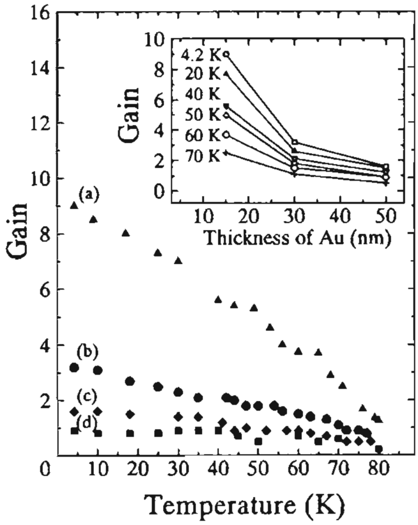

FIG. 3. Temperature dependence of current gain of $YBa_2Cu_3O_y$/Au/Co of (a) d_{Au} = 15 nm, (b) d_{Au} = 30 nm, (c) d_{Au} = 50 nm, and (d) $YBa_2Cu_3O_y$/Au (d_{Au} = 50 nm) tunnel junctions. The inset shows the temperature dependence of the current gain of $YBa_2Cu_3O_y$/Au/Co on the Au thickness.

tunnel barrier (I) formed at the S/I/N/F boundary.

Figure 2 shows the I_c suppression versus injection current for a S/N/F junction with d_{Au} = 30 nm at 4.2 K. Note that, in the absence of tunnel barrier and nonequilibrium effect, a current gain of unity arises solely from current pair breaking. Here, the solid straight line corresponds to the expected curve from the current pair-breaking model when only the distributed current summation effect is considered. It is clearly that there is a large deviation from this straight line, indicating that a nonequilibrium effect takes place due to the spin-polarized QP injection into the YBCO film. To rule out heating effects, we used the simple heating model assuming that only the injection current has the effect of raising the film temperature, and calculated the expected simple heating curve for this junction as shown by the dashed line in Fig. 2. The curve was calculated in the following way: under QP injection, the nonequilibrium state is described by an effective temperature T^*, then the injector power P becomes proportional to $T^{*4} - T^4$, where T is the bath temperature.[9] Then, for a given I_{inj}, T^{*4} is given by the expression $T^{*4} = T_c^4 I_{inj}^2 / I_{inj}^{*2}$. Note that, when $I_{inj} = I_{inj}^*$, $T^* = T_c$. From the expression of the film critical current, the value of I_c corresponding to I_{inj}^* was obtained $I_c = I_{c0}(1 - I_{inj}/I_{inj}^*)^{3/2}(1 + (I_{inj}/I_{inj}^*))^{1/2}$, where I_{c0} is the unperturbed I_c at $T = 0$. The qualitative discrepancy between the data and the calculated curve is evident, indicating that a nonequilibrium state different from simple heating is established.

Figure 3 shows the temperature dependence of the current gain for S/N/F and S/N junctions. The current gain is defined as the relation $\Delta I_c / \Delta I_{inj}$, where ΔI_c is the reduction of I_c and the criterion for I_c is taken to be the value ±1 μV appearing at the current–voltage characteristics. The current gain of the S/N/F junction, which decreases with increasing temperature, can be explained by the suppression of the order parameter of superconductor and the decrease of the spin polarization of the injected carrier with increasing temperature up to T_c. In the whole temperature range, the current gain of S/N/F junction is 5–10 times larger than that of the S/N junction. For S/N junctions, the current gain was about unity. Note that the current gain strongly depended on the junction geometry[3] and the QP injection direction into a HTSC.[10] However, for a simple cross-type tunnel junction structure, it was almost unity. Hence, the high current gain of a S/N/F junction may be attributed to an additional nonequilibrium effect due to the injection of spin-polarized QP into the superconductor.

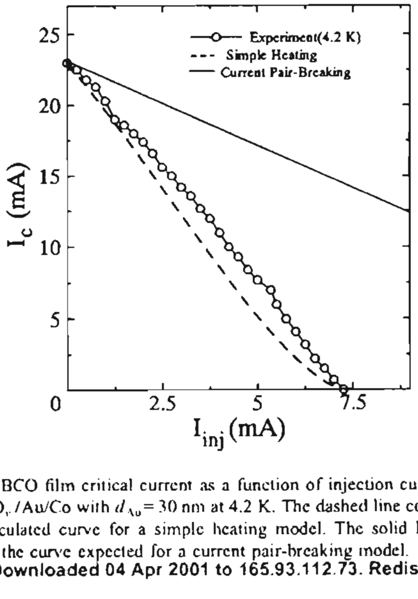

FIG. 2. YBCO film critical current as a function of injection current for a $YBa_2Cu_3O_y$/Au/Co with d_{Au} = 30 nm at 4.2 K. The dashed line corresponds to the calculated curve for a simple heating model. The solid line corresponds to the curve expected for a current pair-breaking model.

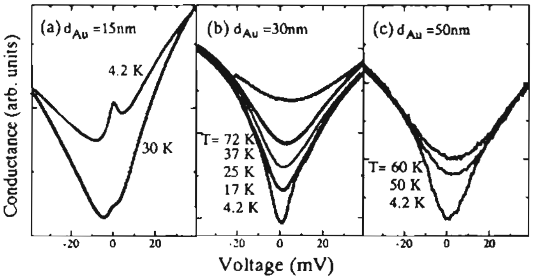

FIG. 4. Temperature dependence of the differential conductance for a YBa_2Cu_3O, Au/Co junction with a Au interlayer (d_{Au}) of (a) d_{Au} = 15 nm, (b) d_{Au} = 30 nm, and (c) d_{Au} = 50 nm.

Note that the spin diffusion length was about $\sim 1.5\ \mu m$ for an Au film according to the measurement of the spin-injection-detection technique by Johnson and Silsbee.[11] We found that the observed current gain was directly related to d_{Au}, as shown in the inset of Fig. 3. As d_{Au} was increased, the spin-polarized QP injection effect might be weakened due to spin relaxation effects in the Au interlayer. The observed current gain seems to be directly related to the non-equilibrium spin population in the YBCO film. Note that, in the steady state of the N/F junction, spins enter Au interlayer by a random relaxation process. The electric current driven from a Co layer acts as a spin pump which drives a nonequilibrium density of spin-polarized QP in the Au interlayer. The nonequilibrium magnetization due to the spin relaxation effects in the Au interlayer is given by $M = I_M T_s / A d_{Au}$, where I_M is the current of magnetization, T_s is the spin relaxation time, A is the area of electrode of F, and d_{Au} is the thickness of the Au interlayer.[11] Thus, the electrical impedance of the polarized current due to the nonequilibrium magnetization effects increased as the thickness of d_{Au} was decreased. This fact means that the volume occupied by spin-polarized QP is directly related to the current gain. The steady-state nonequilibrium magnetization effects may build up in the YBCO film because the spin relaxation time in a YBCO film is shorter than that of the Au interlayer. Thus, the nonequilibrium electrical impedance of the S/N/F varied with d_{Au}. Note that, the temperature dependence of current gain may originate from nonequilibrium spin magnetization effects. It is expected that the spin relaxation time T_s becomes longer as temperature is reduced, since the quasiparticle relaxation time is known to be longer at lower temperatures. Thus, as shown in Fig. 3, we found that lowering the temperature increases the current gain.

In order to investigate the Au barrier dependence of the transport properties, we studied the tunnel conductance of S/N/F junctions. The temperature dependence of the differential conductance of a S/N/F junction with $d_{Au} = 15$ nm is shown in Fig. 4(a). The asymmetric zero bias conductance (ZBCP) started to appear at 30 K and its amplitude increased with decreasing temperature. For $d_{Au} = 30$ and 50 nm, it showed a dip structure around zero bias as shown in Figs. 4(b) and 4(c), corresponding to a typical c-axis tunneling conductance characteristic for a YBCO junction. Note that, for tunneling along the c-axis of YBCO, a ZBCP is not expected. Thus, the c-axis tunnel injection in the S/N/F junction with $d_{Au} = 30$ and 50 nm may not be much affected by spin polarization. The results indicate that the differential conductance characteristics in the S/N/F junction with $d_{Au} = 15$ nm are strongly affected by the effective interfacial boundary and the degree of spin polarization of the injector. A number of model calculations have recently been done which describe the transport properties between a ferromagnet and an anisotropic d-wave superconductor.[12–14] These calculations are based on the ideas of Ref. 14 where a ferromagnet s-wave superconductor junction is treated. The models indicate that what will be observed in experiment depends strongly on the orientation of the surface, the normal scattering properties of the surface, whether it is reflective or transparent, and the degree of spin polarization of the ferromagnet. For a transparent surface and a strongly polarized ferromagnet, there is a zero bias resistance peak.[13] This effect has been observed in a $La_{2/3}Ba_{1/3}MnO_3/DyBa_2Cu_3O_7$ junction.[15] For more reflective surfaces and $[mnp]$ (n, m, and p; integer) interfaces with both m and n not equal to zero, a ZBCP is expected unless the ferromagnet is quite close to being completely polarized.[13] For S/N/F junctions with $d_{Au} = 15$ nm, the degree of polarization is not large and, due to an oxide layer, the surface is not very transparent. We therefore expect for non-c-axis oriented interfaces a ZBCP.

In summary, we have reported the strong suppression of the supercurrent of YBCO by injection of spin-polarized QP from a ferromagnetic injector. The observed current gain depended on the thickness of Au interlayer and was directly related to the nonequilibrium magnetization due to the spin relaxation effects. The differential conductance of a YBCO/Au/Co junction is affected by the spin-polarized QP injection current. The above phenomena are of great importance in developing nonequilibrium three-terminal superconducting devices.

[1] Q. Si, Phys. Rev. Lett. **78**, 1767 (1997).
[2] *Nonequilibrium Superconductivity, Phonon and Kapitza Boundaries*, edited by K. E. Gray (Plenum, New York, 1981).
[3] I. Iguchi, K. Nukui, and K. Lee, Phys. Rev. B **50**, 457 (1994).
[4] Yu. M. Boguslavskij, K. Joosse, A. G. Sivakov, F. J. G. Roesthuis, G. J. Gerritsma, and H. Rogalla, Physica C **220**, 195 (1994).
[5] V. A. Vas'ko, V. A. Larkin, P. A. Kraus, K. R. Nikolaev, D. E. Grupp, C. A. Nordman, and A. M. Goldman, Phys. Rev. Lett. **78**, 1134 (1997).
[6] Z. W. Dong, R. Ramesh, T. Venkatesan, M. Johnson, Z. Y. Chen, S. P. Pai, V. Talyansky, R. P. Sharma, R. Shreekala, C. J. Lobb, and R. L. Greene, Appl. Phys. Lett. **71**, 1720 (1997).
[7] D. B. Chrisey, M. S. Osofsky, J. S. Horwitz, R. J. Soulen, B. Woodfield, J. Byers, G. M. Daly, P. C. Dorsey, J. M. Pond, M. Johnson, and R. C. Y. Auyeung, IEEE Trans. Appl. Supercond. **7**, 2067 (1997).
[8] M. Rubinstein, P. Lubitz, W. E. Carolos, P. R. Broussard, D. B. Chrisey, J. Horwitz, and J. J. Krebs, Phys. Rev. B **47**, 15350 (1993).
[9] W. H. Parker, Phys. Rev. B **12**, 3667 (1975).
[10] K. Lee, H. Yamaguchi, W. Wang, H. Kume, and I. Iguchi, Appl. Phys. Lett. **73**, 2375 (1999).
[11] M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985); M. Johnson, *ibid.* **70**, 2142 (1993).
[12] J.-X. Zhu, B. Friedman, and C. S. Ting, Phys. Rev. B **59**, 9558 (1999).
[13] S. Kashiwaya, Y. Tanaka, N. Yoshida, and M. R. Beasley, Phys. Rev. B **60**, 3572 (1999).
[14] M. J. M. de Jong and C. W. J. Beenakker, Phys. Rev. Lett. **74**, 1657 (1995).
[15] V. A. Vas'ko, K. R. Mikolaev, V. A. Larkin, P. A. Kraus, and A. M. Goldman, Appl. Phys. Lett. **73**, 844 (1998).