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Spin injection and transport properties of $Co/Au/YBa_2Cu_3O_y$ tunnel junctions

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Abstract

We report the spin injection and transport properties of three terminal devices of $Co/Au/YBa_2Cu_3O_y$ (F/N/S) tunnel junctions by injection of spin-polarized quaiparticles using a cobalt ferromagnetic injector. The observed current gain depends on the thickness of Au interlayer and is directly related to the nonequilibrium magnetization due to spin relaxation effects. The tunnel characteristic of a F/N/S tunnel junctions exhibited a zero bias conductance peak (ZBCP). The suppression of the ZBCP was observed due to the suppression of Andreev reflection at the interface, which is due to the spin scattering processes at the interface between a ferromagnetic and a d-wave superconductor.

Keywords : spin injection, three terminal devices, $YBa_2Cu_3O_y$ tunnel junction, Andreev reflection, zero bias conductance peak

I. Introduction

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. One effective way to induce a strongly perturbed nonequilibrium state is tunnel injection of spin-polarized QP.[2] Recently, it has been reported by many authors that the spin-polarized QP injection from either a colossal magnetoresistance material [3,4] or a ferromagnetic material of permalloy [5] and cobalt [6] into a HTSC caused strong nonequilibrium effects. The experiments suggest that the high density of spin-polarized QP was injected into a superconductor and created a nonequilibrium state which was able to affect the electronic transport properties of the superconducting films.

In this report, we find that the spin-polarized QP injection suppresses the critical current of the superconductivity quite effectively, showing the importance of the Cooper-pair breaking effect by spin-polarized carrier injection. The temperature dependence of the current gain of $Co/Au/YBa_2Cu_3O_y$ (F/N/S) junctions and the thickness of Au interlayer (d_{Au}) has been studied. The current gain of S/N/F junctions strongly depends on d_{Au}, behavior of which is interpreted by a model of the nonequilibrium magnetization due to the spin relaxation effects. We studied the tunnel conductance of F/N/S tunnel junctions in order to investigate the spin tunneling process. Two types of samples, Co/Au/YBaCuO and Au/YBCO (N/S), were prepared in order to investigate the transport properties of spin-polarized quasiparticle into a *d*-wave superconductor.

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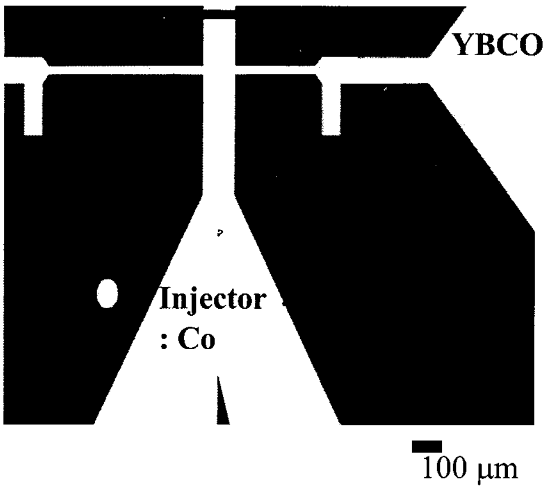

Fig. 1. Photograph of the Co/Au/YBCO tunnel junction.

II. Experiment

The YBCO films of 50-60 nm thick were prepared by pulsed-laser deposition technique on MgO (100) substrates. The resulting c-axis-oriented YBCO film had a transition temperature of 85-90 K. The device geometry is depicted in Fig. 1. The effective junction area was 100x20 μm^2 for both junctions. 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. The superconducting properties of YBCO films were always degraded when a Co layer was directly sputtered onto a YBCO film. The isolation effect of Au barrier at the S/F interface provided a noticeable change in superconductivity [5]. The tunnel junction resistance changed by about two orders of magnitude, nearly exponentially, with varying d_{Au} from zero to 10 nm. The deposition of a minimum 10 nm thickness of Au barrier layer was necessary to avoid the degradation of superconductivity of a YBCO film. The current gain is defined by the relation $\Delta I_c/I_{inj}$, where ΔI_c is the reduction of I_c and the criterion for I_c is taken to be the value $\pm 1\mu$V appearing at the *I-V* characteristics.

III. Results and Discussion

The temperature dependence of the current gain of S/N/F junctions on the Au thickness is shown in Fig. 2. Note that, the spin diffusion length was about ~1.5 μm for an Au film according to the measurement of the spin-injection-detection technique by Johnson and Silsbee [7], thus spin-polarized QP can diffuse into the Au interlayer without losing their spin orientation. We found that the observed current gain was directly related to d_{Au}. 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 nonequilibrium spin population in the YBCO film. Note that, in the steady state of the F/N tunnel 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

$$M=I_M\ T_s/A\ d_{Au}, \qquad (1)$$

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 Au interlayer($A\ d_{Au}$ is the volume occupied by the spin-polarized QP) [8]. 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 Au interlayer. Thus, the electrical impedance due to nonequilibrium magnetization effects 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 both as temperature is reduced, since the QP relaxation time is known to be longer at lower temperatures. Thus, as shown in Fig. 2, 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. 3.

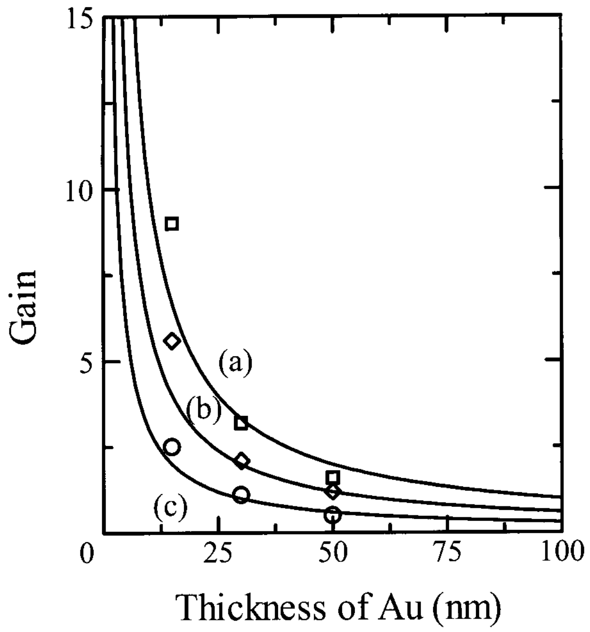

Fig. 2. Temperature dependence of current gain of $YBa_2Cu_3O_y$/Au/Co on the Au thickness (d_{Au}); (a) 4.2 K, (b) 40 K, and (c) 70 K. Solid line gives the theoretical fit with the $1/d_{Au}$ law.

The asymmetric ZBCP started to appear up to 30 K and its amplitude increased with decreasing temperature. Note that, for d_{Au}=30 nm (not shown in this paper), it showed a dip at zero bias. The curves show a typical c-axis tunneling conductance characteristic for a YBCO junction. Tunneling characteristics along the *c*-axis for most of the S/N junctions have a V-shape gap opening structure. Note that for tunneling along the c-axis of YBCO, ZBCP is not expected. The results indicate that the differential conductance characteristics for 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. First of all, to ensure that the ZBCP, as observed in Fig. 3 (a), is due to the spin-polarized QP injection effect into the superconductor, we fabricated and measured the differential conductance of a N/F junction with the same geometry as a S/N/F junction. It did not exhibit a zero bias anomaly or a dip at zero bias, resulting in and exhibiting only flat conductance behavior. This fact indicates that the ZBCP

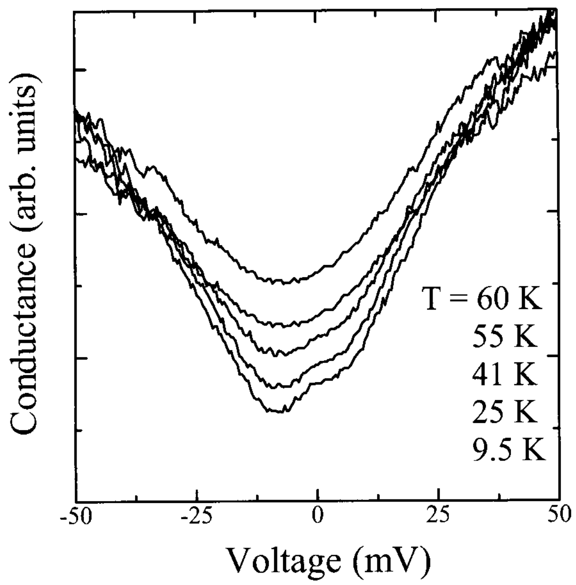

Fig. 3. Temperature dependence of differential conductance of the CO/Au/YBCO tunnel junction with d_{Au}=15 nm.

observed in this experiment originates from the transport properties of a S/N/F junction boundary. According to the recent theory of spin transport property between a ferromagnet material and an anisotropic d-wave superconductor, one may expect that the Andreev reflection would be significantly suppressed [8, 9]. In addition, the ZBCP might be influenced by the magnitude of the spin-polarization [8]. For CMR materials with the degree of polarization of the charge carriers close to unity, using a $La_{2/3}Ba_{1/3}MnO_3/DyBa_2Cu_3O_7$ tunnel junction, the appearance of a zero-bias resistance peak has been reported, which is in qualitative agreement with the theory of the suppressed Andreev reflection[10].

However, quite recently, Zhu et al, have calculated the conductance spectra of a ferromagnet/d-wave superconductor junction for various barrier strengths [11]. When a strong interfacial barrier scattering was introduced, the ZBCP is produced by Andreev reflection even if there is a ferromagnetic layer. When the ferromagnet is not too much polarized as compared to the CMR materials, the barrier scattering at the boundary is pretty strong. Thus, the barrier scattering may cause an anomaly in the conductance of a F/N/S junction. As the thickness of Au interlayer was increased, the ZBCP disappeared. The suppression of ZBCP for the thicker Au interlayer indicates that the barrier scattering process of spin-polarized QP decreased, leading to a typical c-axis tunneling behavior. The c-axis tunnel injection for the S/N/F tunnel junction was not much affected by spin polarization [12]. For the S/N/F junction (d_{Au}=15 nm), there is a non-(n0m) surface (n, m; integer) and a mid gap state since the ZBCP is observable. For the current gain due to spin-polarized QP injection, only S/N/F tunnel junctions with d_{Au} =15 nm give high current gain. These facts indicate that the high current gain may only be obtained by the spin-polarized QP injection into junctions with mid gap states, in contrast to the unpolarized QP injection effects into $ErBa_2Cu_3O_y$ [13]. We, therefore, conjecture that the current gain due to spin-polarized QP injection is related to the tunneling into the mid gap states.

In summary, we report the spin injection and transport properties of YBCO by injection of spin-polarized QP from a ferromagnetic injector, showing that the injection of spin-polarized QP generates a substantially large nonequilibrium population. 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. We have also reported the transport properties of the Co/Au/YBCO and the Co/Au/BSCCO tunnel junctions. The conductance spectra between ferromagnet and high-T_c superconductor showed ZBCP, reflecting the charge transport in the [110] surface. For N/S tunnel junctions, clear ZBCP directly related to the Andreev bound states was observed for the [110] surface. The observed results may be interpreted by the directional-oriented spin scattering processes in a ferromagnet/d-wave superconductor tunnel junction. The above phenomena are important in developing nonequilibrium three-terminal devices

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