Effect of spin-polarized current injection on pair tunneling properties of $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions

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Abstract

We studied the effect of spin injection on tunneling conduction properties of intrinsic Josephson junctions formed in $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals. Properties of an identical stack (10×5.0×0.030 μm^3) of intrinsic Josephson junctions were compared for the bias current injected through Au and Co electrodes. The suppression of the superconducting gap in the CuO_2 double layers and the interlayer Josephson critical current was manifested in the tunneling current-voltage characteristics of the stacks. This effect appears to be caused by the pair breaking associated with spin-polarized carriers injected from the Co electrode into the $Bi_2Sr_2CaCu_2O_{8+x}$ single crystal. This study may provide valuable information on clarifying the mechanism of high-T_c superconductivity.

Keywords : spin-dependent tunneling properties, pair breaking, intrinsic Josephson junctions, Bi-2212 superconductors

I. Introduction

Investigation of the nonequilibrium superconductivity by tunneling injection of spin-polarized quasiparticles provides useful information on the spin-dependent superconducting properties [1] and may also lead to a new class of superconducting devices. In fact, the tunneling injection of spin-polarized quasiparticles is one of the most effective means of inducing a strongly perturbed nonequilibrium quasiparticle state [2]. Recently, it has been reported that the spin-polarized quasiparticle injection from either colossal magnetoresistance materials [3,4] or ferromagnetic materials such as permalloy [5] or cobalt [6] into high-T_c superconductors causes strong nonequilibrium effects. Experimental results suggest that high density spin-polarized quasiparticles injected into a superconductor create a nonequilibrium state, which affects the electric transport properties of the superconductors.

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In this study, we investigated the tunneling transport properties of spin-polarized quasiparticles into a $Bi_2Sr_2CaCu_2O_{8+x}$ single crystal. To that end, properties of an identical stack (10×0.5×0.030 μm^3) of intrinsic Josephson junctions (IJJs) formed on the surface of the $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals were compared for the bias currents injected though Au and Co electrodes [refer to the inset of Fig. 1(b)]. Clear quasiparticle branches in tunneling current-voltage (*I-V*) curves from the IJJs in the stack were observed for an unpolarized bias current though the Au electrode. On the other hand, spin injection though the Co electrode to the same stack caused pair breaking in the CuO_2 double layers, which led to the reduction of the Josephson critical current density J_c and the superconducting gap $\Delta(T)$ revealed in the tunneling *I-V* curves. The critical current density J_c for the spin injection, however, stayed almost constant while the superconducting gap kept dropping with increasing temperature. This behavior is in clear contrast to that of the conventional superconductors where the variation of the tunneling critical current density is closely related with that of the superconducting gap.

II. Experimental

Slightly overdoped as-grown Bi-2212 single crystals were grown by the solid-state reaction method. A single crystal with the typical lateral size of ~ 0.5 mm^2 was glued on a sapphire substrate using negative a photoresist (Tokyo OMR-83-60) and cleaved with a piece of adhesive tape to obtain an optically smooth surface. A 300-Å-thick Au film was then thermally deposited on the cleaved crystal surface to protect it during the ensuing microfabrication processes. Three 450-Å-deep (including the thickness of the Au film) rectangular stacks were prepared on the crystal surface by micro-patterning and ion-beam etching. The central mesa was 10 μm wide and 40 μm long. On one side of the top of the mesa a 4 μm-long and 800-Å-thick Co layer was thermally prepared as a spin-injecting electrode [refer to the inset of Fig. 1(b)]. Au contact leads of the same length and thickness as the Co layer were then connected to the other side of the central mesa and the two outer mesas. The Co and the Au electrodes on the central mesa were about 2 μm apart. The top of the central mesa was then divided into two by dry-etching the center of the mesa just deep enough to remove the first-deposited Au layer. It leaves a four-terminal-measurement geometry. The thin (100 Å thick) Au layer between Bi-2212 and the Co electrode prevented the formation of the possible spin-glass phase at the interface [6], thus reducing the interfacial spin-flip scatterings.

The inset of Fig. 1(b) illustrates the four-terminal measurement configuration for the spin-polarized current injection. The spin-degenerate current injection was realized for the current biasing through the Au electrode by switching the current and voltage electrodes. In both cases the measurement configuration allowed one to monitor the voltages along the same stack of IJJs in the central mesa.

III. Results and Discussion

The electrical current injected from the Co layer acts as spin pumping which drives a nonequilibrium current of spin-polarized quasipartices into the Au interlayer and the Bi-2212 stack. In previous studies

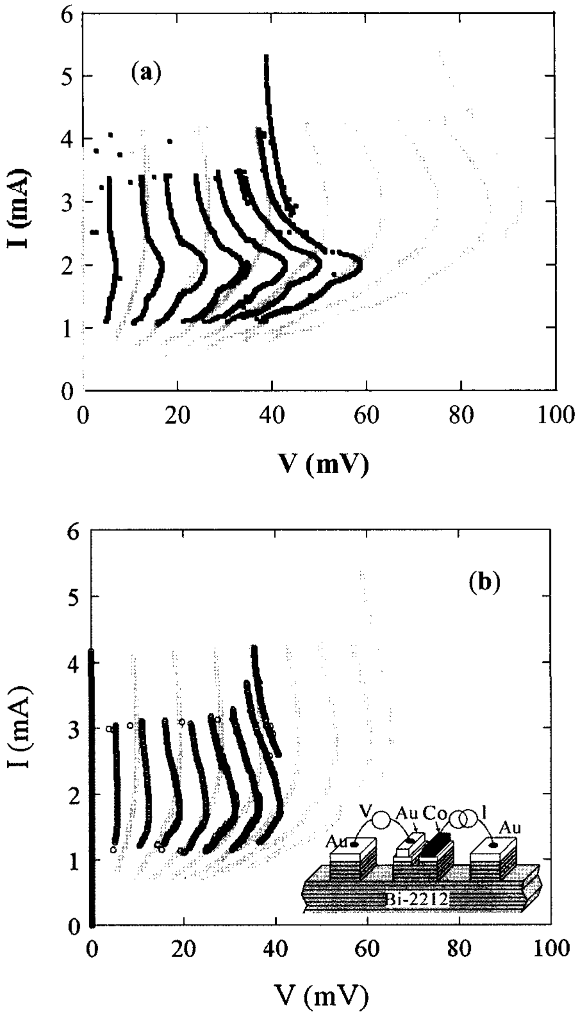

Fig. 1. Tunneling current-voltage characteristics of a mesa for the spin-degenerate (gray curves) and the spin-polarized (black curves) bias configuration at different temperatures below T_c at (a) 10 K and at (b) 30 K.

[7] the spin diffusion length was observed to be about 1.5 μm in an Au film. Thus spin-polarized quasipartices can diffuse into the Au interlayer without losing their spin orientation with the negligible spin relaxation.

The temperature dependencies of tunneling *I-V* curves for both the spin-degenerate (gray curves) and the spin-polarized (black curves) bias configurations at temperatures far below T_c are shown in Fig. 1. In both cases at two temperatures the *I-V* characteristics show clear and highly hysteretic quasiparticle branches. Since each branch corresponds to an intrinsic Josephson junction in the stack the number of the quasiparticle branches indicates that the stack contained 8 IJJs (or equivalently 8 CuO_2 double layers).

As seen in Fig. 1 the tunneling critical current is more or less uniform at both temperatures, which is the typical feature of an intrinsic Josephson junction. The voltage interval between the neighboring quasiparticle branches indicates the size of the superconducting gap in the corresponding CuO_2 bilayers. We observe that the superconducting gap values are also quite uniform.

The critical current at 10 K in Fig. 1(a) for the spin injection (the black curve) is reduced to about 75% of that of the spin-degenerate current injection (the gray curve). By contrast, the superconducting gap is reduced by half by the spin injection. The reduction in the superconducting gap was caused by the pair breaking in the CuO_2 double layers as the spin-polarized quasiparticles were injected. The injection also weakened the interlayer coupling between the neighboring CuO_2 double layers, thus reducing the tunneling critical current as well. At 30 K, as shown in Fig. 1(b), both the critical current and the gap value for the spin injection case are reduced further. For the spin-degenerate current injection, however, the critical current remains almost the same as for 10 K while the gap value is further reduced.

The trends of the temperature dependence of both the tunneling critical current and the superconducting gap are more clearly demonstrated in Fig. 2. Although the tunneling critical current for the spin injection case is reduced from the value of the spin-degenerate case by a certain amount the temperature dependencies for both cases remain almost temperature independent. By contrast, the gap values for both cases keep dropping with temperature in the range between 10 and 50 K. These trends are in clear contrast with the relation between the tunneling critical current and the gap value in a Josephson junction consisting of conventional superconductors, where the tunneling critical current is intimately related with the gap value. We believe this may have important implication to the mechanism of high-T_c superconductivity and it may provide clues on whether the ordering in high-T_c superconductors is spin dependent or not. More rigorous study is required with a single-domain ferromagnetic electrode for the spin injection.

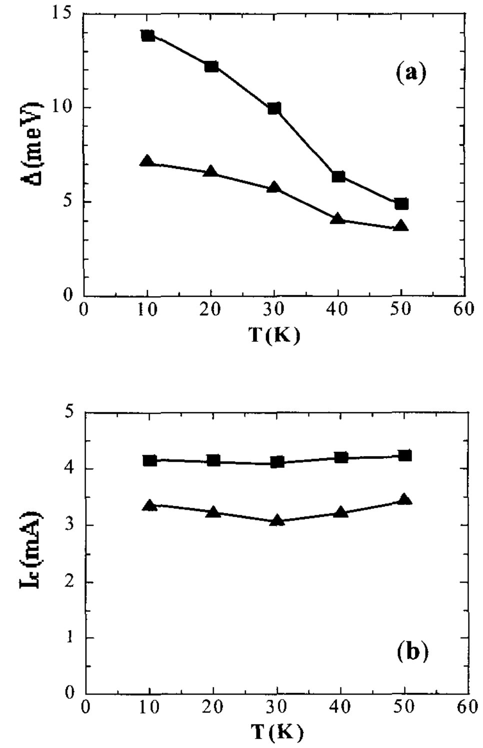

Fig. 2. Temperature dependencies of (a) the superconducting energy gap and (b) the interlayer Josephson critical current below T_c for the bias configuration of no spin injection (filled squares) and of the spin injection (filled triangles).

Acknowledgments

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