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SPIN DEPENDENCE OF PAIR TUNNELING PROPERTIES OF $Bi_2Sr_2CaCu_2O_{8+x}$ INTRINSIC JOSEPHSON JUNCTIONS

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Detailed tunneling characteristics of a stack of intrinsic Josephson junctions in a $Bi_2Sr_2CaCu_2O_{8+x}$ single crystal were obtained both in spin-degenerate and spin-polarized bias configurations. Injection of the spin-polarized quasiparticles effectively weakened the in-plane superconducting strength and the interlayer Jospehson coupling. The superconducting gap and the Josephson critical current of the stack were, in general, further suppressed by an external field applied in parallel with the *c*-axis direction. Study of the spin-dependent tunneling characteristics may provide valuable information on clarifying the mechanism of high-T_c superconductivity as well as the interlayer phase fluctuation induced by the "pancake vortices" on CuO_2 layers.

Keywords: Spin-polarized tunneling; intrinsic Josephson junctions; pair breaking; interlayer Josephson coupling; interlayer phase fluctuation.

1. Introduction

The *c*-axis tunneling transport properties in highly anisotropic high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) and $Tl_2Ba_2Ca_2Cu_3O_{10+\delta}$ (Tl-2223) were studied extensively. It has been established that adjacent superconducting CuO_2 double layers in the materials are coupled by the Josephson effect and, thus, a Bi-2212 or a Tl-2223 crystal is equivalent to a stack of Josephson tunnel junctions.[1] It is also known that, since superconducting CuO_2 layers are only 0.3 nm thick, the materials show a very large nonequilibrium effect, with the sensitive reduction of the superconducting order to the influx of excessive quasiparticles to the layers. This nonequilibrium effect is expected to become more effective for the injection of spin-polarized quasiparticles,[2,3,4,5,6] because it causes strong pair breaking along with the appreciable suppression of the superconducting strength in the CuO_2 layers.

In this study, we investigated the influence of the spin injection on the *c*-axis tunneling characteristics of a Bi-2212 crystal as functions of temperature and magnetic field H applied in parallel with the c axis. For accurate measurements we fabricated, by the electron beam micropatterning and the Ar-ion-beam etching technique, a rectangular mesa with a dimension of $3\times12\times0.065$ μm^3 on the cleaved surface of a Bi-2212 single crystal. Three Au contact leads and a Co contact lead (all with the lateral dimension of 0.8×10 μm^2) that was to be used as a spin-injecting electrode were prepared on the mesa structure by e-beam micropatterning and e-gun evaporation. Based on our previous study we assume that the Co contact lead with the dimension used was in a single-domain state.[7] Three 65-nm-high rectangular stacks were formed on the mesa structure by ion-beam etching, where two outer stacks were used as connection electrodes and the tunneling characteristics were examined for the central stack with the lateral dimension of 3×2 μm^2. The top of the central stack was divided into two by ion-beam etching its center just deep enough to remove the predeposited Au layer and an upper part of Bi-2212 to get a four-probe-measurement geometry [see the inset of Fig. 1(b)]. The configuration shown in the inset of Fig. 1(b) is for the spin-degenerate (SD) current injection through the Au electrode. On the other hand, a spin-polarized (SP) current was injected through the Co electrode by switching the current and voltage measurement leads in the configuration of Fig. 1(b) from outside during the measurement.

2. Results and Discussion

Many of the quasiparticle branches are seen in the tunneling $I - V$ curves shown in Fig. 1(a) for both SD and SP bias configurations at 4.2 K in the absence of a magnetic field. The quasiparticle branches were traced out by sweeping the bias up and down repeatedly (not all the branches were traced out). The $I - V$ curves exhibit approximately 45 resistive quasiparticle branches, the number of which coincides with the estimated mesa thickness of 65 nm divided by the spacing between neighboring CuO_2 double layers, 1.5 nm.

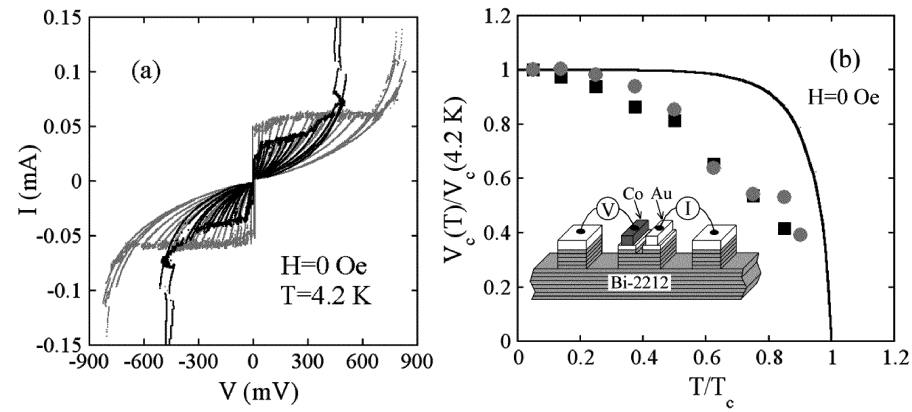

Fig. 1. (a) Tunneling current-voltage characteristics of the central stack of intrinsic Josephson junctions for spin-degenerate (gray curves) and spin-polarized (black curves) bias configurations at 4.2 K. (b) Temperature dependence of the normalized sum-gap voltages for the two configurations [with the same color convention as in (a)] and the expected temperature variation of the gap for the $d_{x^2-y^2}$-wave symmetry (solid line). Inset; a schematic layout illustrating the four-probe tunneling measurements.

Fig. 1(a) shows the $I - V$ characteristics both in the SD and in the SP bias configurations at 4.2 K. For the spin injection as in Fig. 1(a) both the voltage of the outermost resistive quasiparticle branch and the Josephson critical current (I_c) of each junction are suppressed in comparison with the SD case. The voltage of the outermost quasiparticle branch corresponds to the sum-gap voltage (V_c) of the superconducting CuO_2 layers.[8] The reduction of the sum-gap voltage was caused by the pair breaking in the CuO_2 double layers as the spin-polarized quasiparticles were injected from Co electrode, which in turn weakened the interlayer coupling between the adjacent superconducting layers, thus reducing the tunneling critical current as well. The sum-gap voltages for both the SD and the SP bias cases, when normalized by the 4.2-K values, have almost the same temperature dependence [see Fig. 1(b)]. The temperature dependence of the normalized sum-gap voltage for both configurations, however, deviates significantly from the approximate empirical temperature dependence of the gap, which is valid for materials with the $d_{x^2-y^2}$-wave symmetry[9] [see Fig. 1(b)]. The discrepancy may have been caused by the significant reduction of the superconducting order due to excessive nonequilibrium quasiparticle effect in 0.3-nm-thin CuO_2 layers at higher temperatures.

We now turn to the tunneling characteristics in various magnetic fields at 4.2 K for the two bias configurations. Figs. 2(a) and 2(b) illustrate the magnetic-field dependencies of the $I - V$ curves, in the SD and SP configurations, respectively, for the field increasing stepwise up to 400 Oe, which is much lower than upper critical field of the material. Since the bias was swept up and down one time for these sets of data the quasiparticles branches were not traced out in detail. At the highest magnetic field $I - V$ curves were still highly hysteretic. For the injection of spin-degenerate tunneling quasiparticles both the Josephson critical current and the superconducting gap as manifested in the sum-gap voltage decrease with increasing magnetic field [Fig. 2(a)]. This feature is in clear contrast with the behavior of the spin-injection case as shown in Fig. 2(b), where only the Josephson current is reduced with increasing field. The reduction of the Josephson critical current for a nonequilibrium bias current may be understood in terms of generation of the "pancake vortices" in the perpendicular magnetic fields. Pancake vortices are in general misaligned along the *c*-axis direction because of the thermal disorder and induce the phase fluctuation between the neighboring CuO_2 layers, thus reducing the Josephson critical current.[10,11,12] The Josephson critical current is expected to be more reduced with increasing magnetic field and temperature due to the increased interlayer phase disorder. The reduction of the sum-gap voltage for the SD configuration in Fig. 2(a) in fields much lower than the upper critical field, however, is not well understood.

The inset of Fig. 2(a) shows the magnetic-field dependence of the Josephson critical current I_c, for both bias configurations. The values of I_c were determined by extrapolating the almost linearly varying portion of the critical current in the bias range of 50 mV$\leq V \leq$250 mV and finding the intercept value in the current

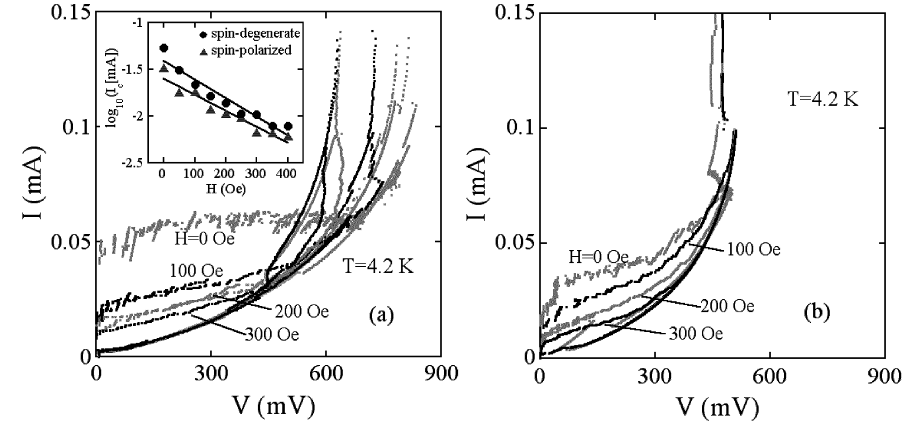

Fig. 2. Tunneling current-voltage characteristics of the central stack for (a) the spin-degenerate and (b) the spin-polarized bias configurations at 4.2 K and various magnetic fields. Inset; the field dependence of the Josephson critical current for the two bias configurations.

axis. The zero-field values of I_c were 0.049 and 0.018 A/cm^2, for the SD and SP bias configurations, respectively. The value of I_c for the spin-injection case in a given field is reduced by about a factor of 2.5 from that of SD configuration. As seen in the inset of Fig. 2(a), however, the temperature sensitivity of the variation of I_c is not much different from each other for both configurations. As denoted by the best-fit lines in the inset of Fig. 2(a) the Josephson current I_c reduces exponentially by the field satisfying the relation, $I_c(H) \sim I_0\text{exp}(-\alpha H)$, where α=0.0046 and 0.0040 Oe^{-1} [with H in Oe] for the SD and SP configurations, respectively. This exponential reduction of the critical current by the c-axis magnetic field is in agreement with the theoretical prediction by the pancake-vortex-induced interlayer phase disorder.[10,11] The influence of a magnetic field on the Jospehson critical current between the neighboring CuO_2 layers with reduced superconducting strength due to spin injection, however, has not been theoretically treated yet. Since the field direction was perpendicular to the plane of Co electrode the observed field dependencies could not be the domain-alignment effect.

3. Conclusion

We observed the significant reduction in the in-plane superconducting order as manifested in the sum-gap voltage of intrinsic Josephson junctions in a Bi-2212 single crystal and the reduction in the interlayer coupling by the tunneling injection of spin-polarized quasiparticles. Studying the change in the tunneling characteristics for the spin-injection configuration in comparison with the spin-degenerate one for an identical stack of intrinsic Josephson junctions, as in this study, may shed light on the mechanism of the high-T_c superconductivity. It is not clear at this stage of the study, however, whether the observed distinctive characteristics between the two different configurations are inherent to high-T_c superconducting materials or not.

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