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Depression of the interlayer Josephson coupling in $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals by spin-polarized current injection along the *c*-axis

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Abstract

We studied the effect of spin-injection on tunneling conduction properties of intrinsic Josephson junctions (IJJs) formed in $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals. Properties of an identical stack ($10\times5\times0.030$ μm^3) of IJJs were compared for the bias current injection through Au and Co electrodes. Clear quasiparticle branches in tunneling current–voltage (*I*–*V*) curves from the IJJs in the stack were observed for an unpolarized bias current through the Au electrode. Spin-injection through the Co electrode caused pair breaking in the CuO_2 double layers, which led to reduction of the Josephson critical current and the superconducting gap revealed in the tunneling *I*–*V* curves.

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Keywords: Spin-polarized tunneling; Intrinsic Josephson junctions; Pair breaking; Interlayer Josephson coupling

The spin-polarized current injection (SPCI) to a superconductor has attracted much research interest [1–3] because it can provide key information on superconducting (SC) as well as normal-state properties of a material under study. It is also important for applications to spin-dependent SC devices [2]. Recently the reduction of the critical current by SPCI to $YBa_2Cu_3O_7$ (Y-123) epitaxial thin films along the *c*-axis direction has been reported [3]. SPCI into high-T_c superconductors, such as Y-123 and $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) superconductors, is expected to provide new information on the nature of *c*-axis transport properties and that of quasiparticle excitations [4].

In this study we investigate the effect of spin-injection along the *c*-axis direction of Bi-2212 single crystals, using mesas of stacked intrinsic Josephson junctions (IJJs) prepared on the crystal surface. We injected spins to the mesa through a ferromagnetic Co electrode [5] deposited on the surface of a mesa. The measurement configuration allowed us to compare the tunneling characteristics between the spin-polarized and spin-degenerate bias configurations for an identical stack of IJJs. Compared to the spin-degenerate case, the tunneling critical current and the SC gap in CuO_2 layers for the SPCI configuration is significantly reduced due to pair breaking in extremely thin CuO_2 layers.

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 photoresist 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 from the ensuing sample fabrication processes. In a sample three 450 Å deep (including the thickness of the Au film) rectangular mesas were prepared by micropatterning and ion-beam etching (refer to the inset of Fig. 1(c)). The central mesa was 10 μm wide and 40 μm long. On one side of the top of the central mesa a 4 μm long and 800 Å thick Co layer was thermally prepared as a spin-injecting electrode. Au contact leads of the same length and thickness as the Co layer were then deposited to the other side of the top of the

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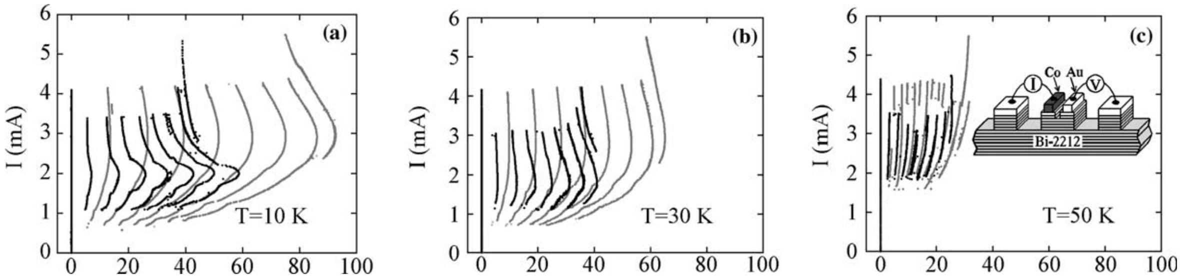

Fig. 1. Tunneling current–voltage characteristics of a mesa for spin-degenerate (gray curves) and spin-polarized (black curves) bias configurations at different temperatures below T_c.

central mesa and the two outer mesas. The Co and 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 region between the Co and Au electrodes just deep enough to remove the first-deposited Au layer, leaving a four-terminal-measurement geometry. The thin Au layer between Bi-2212 and the Co electrode prevented the formation of the possible spin-glass phase at the interface [6], thus reducing interfacial spin-flip scatterings.

The inset of Fig. 1(c) illustrates the four-terminal measurement configuration for the SPCI. The spin-degenerate current injection was realized through the Au electrode by switching the current and voltage electrodes. In both cases the voltages along the same stack of IJJs in the central mesa were monitored.

As seen in Fig. 1, tunneling current–voltage curves for both spin-degenerate (gray curves) and spin-polarized (black curves) bias configurations show very clear and highly hysteretic quasiparticle branches with fairly uniform critical currents at different temperatures below T_c. Since each quasiparticle branch is from an individual IJJ in the mesa the number of branches indicates that the central mesa contained 8 IJJs. Except for the highest-voltage branch at 10 and 30 K the voltage difference between the adjacent branches is quite uniform also. Variation of this voltage difference with temperature is a good indication of the change in the SC gap, although the actual gap value is larger than the voltage interval by about a factor of 2. The gray curves indicate that the interlayer Josephson coupling strength, represented by the values of the critical current, for the spin-degenerate bias configuration does not vary much with increasing temperature from 10 to 50 K. By contrast, the SC strength, represented by the voltage interval, reduces significantly with increasing temperature in the same range.

For the SPCI, the critical current reduces by about 20% for the three temperatures shown. By spin-injection the voltage interval reduces almost by half at 10 K. But the reduction of the voltage interval, or equivalently the gap voltage, becomes less effective with increasing temperature and becomes insignificant at 50 K, although the reduction of the critical current remains almost unaltered at this temperature. At higher temperatures thermal pair breaking may predominate the spin-induced pair breaking, which was likely to cause the spin-induced pair breaking less effective at 50 K. In both cases, however, the usual close correlation between the Josephson coupling and the SC strength in the electrodes was not followed. This may have a significant implication to the mechanism of high-T_c superconductivity. More rigorous study is required, however, with a narrower spin-injecting electrode, because apparently the Co electrode of size 4×10 μm^2 used in this study should not have been single crystalline.

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