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Tunneling properties of in-situ-fabricated intrinsic Josephson junctions in $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals

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Abstract

Stacks of intrinsic Josephson junctions were fabricated on the surface of $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals, using photolithography and Ar-ion etching. The number of junctions in a stack was controlled by the etching time, while the c-axis I–V and R versus T curves were measured in-situ in a vacuum chamber for T down to ~ 13 K. The tunneling resistance and the I–V curves are scaled by the surface junction resistance. The superconductivity of the surface conducting plane in contact with a Au electrode is weakened by the proximity to the normal metal. In a low-bias region, main tunneling properties of a junction are not affected by the presence of other junctions in a stack.

Keywords: In-situ fabrication; Intrinsic Josephson effects; Bi-2212; Surface junction

Highly anisotropic high-T_c materials such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) can be considered as series of arrays of intrinsic Josephson junctions (IJs) along the c-axis [1]. Tunneling measurements on a small-sized stack including a few IJs provide valuable information on the superconducting gap and the order-parameter symmetry as well as the interlayer tunneling characteristics [2].

In this study, we vary the number of IJs in a stack by progressively increasing the height of the stack by ion-beam etching, while monitoring their tunneling characteristics. It is found that the c-axis I–V and $R(T)$ curves are scaled by the surface junction resistance and tunneling properties of nearby junctions are not correlated at least in a low-bias and low-dissipation regime.

We took the following in-situ etching and measurements steps [3]. Firstly, a narrow and long base mesa with a Au electric pad was fabricated on the surface of BSCCO single crystals using photolithography and ion-beam etching [4,5]. A thin Au film was intentionally left on the top surface of the base mesa between the electric pads to prevent the premature formation of small stack structures. The next stage was in-situ-controlled fabrication of a small stack in a vacuum chamber equipped with a liquid-helium cooling pot as well as an ion-beam etching system. The Au electric pads acted as masks for the in-situ ion-beam etching of the small stacks to define its lateral size, 15×12 μm^2. We used a three-terminal measurement configuration.

Fig. 1 shows the progressive evolution of the c-axis tunneling resistance $R_c(T)$ with increasing the total etching time t_e. To eliminate the extrinsic effect due to change of the junction area with increasing t_e, $R_c(T)$ was normalized by $R_c(T_c)$, the resistance at the bulk superconducting transition temperature, $T_c(\simeq 86.5$ K). Below T_c, $R_c(T)$ gradually increases to the secondary resistance maximum at $T'_{c,\mathrm{on}}$ and then drops sharply to 0.1 Ω at T'_c and below. The secondary resistance peak below T_c is attributed to the weak surface junction consisting of the topmost Cu–O bilayer in the normal state and the adjacent inner Cu–O bilayer in the superconducting state [5]. We can then consider $R_c(T_c)$ as the normal-state resistance of the surface junction. Thus, for $T'_{c,\mathrm{on}} < T < T_c$, the corresponding resistance of the normal-metal/insulator/d-wave superconductor (N′ID) junction can be

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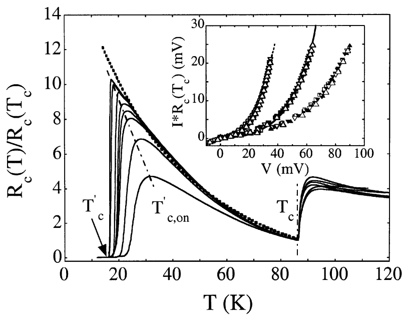

Fig. 1. $R_c(T)/R_c(T_c)$ curves with increasing t_e. Total number of branches is $n = 4$, 5, 5, 6, 8, 9, 10 and 12 for $t_e = 6.5$, 10, 12, 15, 19, 22, 26, and 30 min, from bottom to top. The contact resistance was not subtracted. Inset: the rescaled first three branches below T_c' at the corresponding t_e. The dotted line is a fit to D′ID tunneling, and the solid line is a fit to DID tunneling.

written as

$$R_{N'ID}(T) = \left[\lim_{V\to 0} \frac{dI}{dV}\right]^{-1} = \left\{\lim_{V\to 0} \frac{d}{dV}\frac{1}{eR_n'} \times \int_{-\infty}^{\infty} N(E,\Delta)[f(E) - f(E+eV)]\,dE\right\}^{-1}, \tag{1}$$

where R_n' is the junction resistance, Δ the energy gap, $f(E)$ the Fermi distribution function, and $N(E,\Delta)$ the normalized density of states of d-wave superconductor [6]. The best fit of Eq. (1) to the secondary resistance peak is denoted as the dotted curve using $\Delta_0 = \Delta(T=0) = 32$ meV with the assumption of the BCS-type temperature dependence of the gap. Insensitivity of the rescaled $R_c(T)$ to the number of IJs in a stack indicates that only one N′ID junction exists, presumably on the surface of the stack.

The inset shows the first three quasiparticle branches of I–V curves below T_c'. The current axis was rescaled by multiplying $R_c(T_c)$ corresponding to t_e. Remarkably, all the three branches fall into three merging curves, irrespective of the number of junctions in a stack, which implies a negligble correlation effect among the IJs. The first branch is due to the surface D′ID (D′ means the suppressed superconductivity of d-wave superconductor) junction [5]. By fitting the first branch to the I–V relation in Ref. [6], we obtained the best fit value of the suppressed gap $\Delta_0' = 15.3$ meV. However, the doping-dependent correlation [7] between Δ and T_c indicates that Δ_0' should be larger than $1.3\Delta_0$ for $T_c' = 30$ K. The only way to eliminate the inconsistency is to assume that the suppression of Δ_0' and T_c' of the surface layer is not caused by the reduction of the doping level, but by its proximity contact to the Au normal-metal pad.

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