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McMillan–Rowell oscillations observed in c-axis $Au/Bi_2Sr_2CaCu_2O_{8+\delta}$ junctions

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Abstract

We observed periodic oscillations in the differential resistance vs. voltage curves of $Au/Bi_2Sr_2CaCu_2O_{8+x}$ (Au/Bi2212) junctions near the bulk superconducting transition temperature T_c of the Bi2212 single crystals. The oscillations can be explained in terms of the McMillan–Rowell coherent states resulting from the Andreev-reflected quasiparticles in the normal-metallic layer. This is the first observation of the McMillan–Rowell oscillations in the *c*-axis transport of the Bi2212 material.

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As we reported previously [1], when the surface of a freshly cleaved $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) single crystal is deposited immediately by novel metals such as Au, the superconductivity of the surface CuO_2 bilayer gets suppressed due to the proximity effect. Thus the surface CuO_2 bilayer remains normal down to the temperature T_c' below the bulk transition temperature T_c. Reduction of this transition temperature of the surface CuO_2 layer depends on the oxygen doping level of the mother crystal [2]. The *c*-axis transport properties of the Bi2212 single crystals can be well understood in terms of an array of intrinsic Josephson junctions (IJJs) [3], where the CuO_2 bilayers serve as thin superconducting electrodes, and the Bi–O and Sr–O layers in-between as a whole as an insulating barrier. The presence of this insulating barrier, well below T_c, suppresses the Andreev reflection (AR) for *c*-axis quasiparticle (QP) transport. Approaching T_c, however, the barrier strength of the insulating layer weakens considerably [4] and AR appears below the gap voltage [2].

In this study we present the consequences of the AR above the gap voltage in Au/Bi2212 *c*-axis junctions, which appeared as periodic peaks, equally spaced along the bias-voltage axis in the differential-resistance (dV/dI) curves. The peaks were identified as the McMillan–Rowell oscillations (MRO) [5,6], that arose from the geometrical resonance of QPs in the normal-metallic Au layer. To our knowledge, this is the first observation of the MRO in Bi2212 single crystals where the QP transport is along the *c*-axis of the crystal. Weakening of the barrier strength of the insulating layer between adjacent CuO_2 bilayers with increasing temperature constrains the MRO to appear only close to T_c. The resulting renormalized Fermi velocity v_F' turned out to be about 1.1×10^6 m/s, which was close to the known free-electron-limit value in Au.

The Bi2212 single crystals and Au/Bi2212 mesa junctions were prepared as described in Ref. [2]. The typical size of the mesas were 10×13–15×40 μm^2 in lateral dimension and 10–20 nm in thickness. As depicted in the inset of Fig. 1(a), the measurement configuration restricts the QP transport mainly along the *c*-axis of the crystal. T_c, defined as the superconducting onset temperature of the Bi2212 single-crystal mesas, ranged from about 82 to 89 K.

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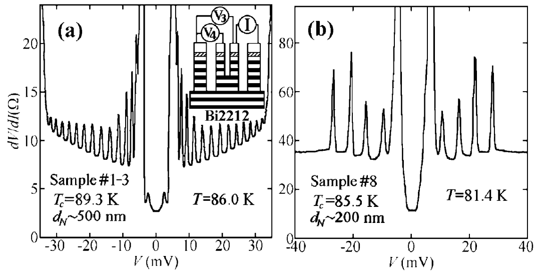

Fig. 1. Dynamic resistance curves near but below T_c of (a) Sample#1–3 and (b) Sample#8, with Au layers of thickness $d_N \sim 500$ and ~ 200 nm, respectively. Inset: the 3-probe (V_3) and the 4-probe (V_4) measurement configuration.

Fig. 1 shows typical dV/dI vs. voltage curves with periodic peaks when measured in the three-probe (I–V_3) configuration as illustrated in the inset of Fig. 1(a). The peaks were always observed only in a narrow temperature window near but below T_c, similar to the c-axis AR effect we observed previously [2]. Since the barrier strength of the intrinsic insulating layer weakens considerably, as T_c is approached from below, an IJJ behaves as a superconductor(SC)/normal-metal/SC (SNS) junction rather than a SC/insulator/SC (SIS) junction [2,4]. Therefore, the uniformly spaced dV/dI peaks can possibly be interpreted either by the Tomasch oscillation (TO) [5,7] or by the MRO [5,6].

The coherent interference, inside the SC of an NS junction, between a hole-like QP and an Andreev-reflected electron-like QP with energies higher than the superconducting gap energy Δ is responsible for the TO. On the other hand, when a QP with its energy higher than Δ is incident from the N side to the NS interface, the following four processes can occur sequentially as the QP traverses the N layer: (1) AR at the NS interface (e $\rightarrow$ h); (2) normal reflection (NR) at the opposite side of N (h $\rightarrow$ h′); (3) AR (h′ $\rightarrow$ e′); (4) NR (e′ $\rightarrow$ e″), where e and h denote electrons and holes, respectively. The MRO is due to the consequent coherent states between e and e″ in the N layer. Both TO and MRO are geometrical resonance and the voltage interval ΔV between the dV/dI peaks is inversely proportional to the thickness of the layer where the oscillations occur [5,6]. The fact that no such oscillations were observed in the four-probe configuration [I–V_4 in the inset of Fig. 1(a)], and the dependence of ΔV ($\sim$2.4, $\sim$5.8 mV) on the Au thickness ($\sim$500, $\sim$200 nm) in Fig. 1 makes us conjecture that the observed peaks were from MRO in the normal layer (including the top CuO_2 layer) of the Au/Bi2212 junction, the part denoted by 'd_N' in the inset of Fig. 2(a).

In the case of MRO, the voltage interval ΔV between the peaks in the dV/dI curves can be expressed as [6]

$$\Delta V = \frac{hv'_F}{4ed_N}, \tag{1}$$

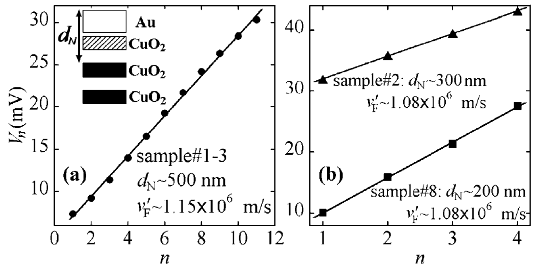

Fig. 2. The nth peak voltage V_n vs. n for (a) Sample#1–3 (●), (b) Sample#2 (▲) and Sample#8 (■). The resultant renormalized Fermi velocity was $v'_F \sim 1.1 \times 10^6$ m/s.

where v'_F and d_N are the renormalized Fermi velocity and the thickness of the N layer, respectively. Defining V_n as the averaged absolute value of the nth negative and positive peak voltages, a linear relation between V_n and n is obtained as shown in Fig. 2, where the slope yields an averaged ΔV. Using Eq. (1), the resultant renormalized Fermi velocity v'_F turned out to be $\sim 1.15 \times 10^6$ m/s and $\sim 1.08 \times 10^6$ ($\sim 1.08 \times 10^6$) m/s in junctions with the Au layers of thickness $d_N \sim 500$ nm and $\sim$200 ($\sim$300) nm, respectively. The value of v'_F in the junction with the thicker Au layer is closer to the free-electron-limit value in Au ($v_F \sim 1.40 \times 10^6$ m/s), consistent with the results of Ref. [8].

In summary, the dV/dI peaks spaced uniformly along the voltage axis, as observed in our Au/Bi2212 junctions, can be explained in terms of McMillan–Rowell oscillations (MRO) occurring in the normal-metallic Au layer combined with the proximity-coupled top CuO_2 bilayer. The observation of the MRO confirms that the barrier strength of the insulating layer keeps being weakened in IJJs formed in Bi2212 single crystals as temperature approaches T_c of the bulk crystal, consistent with our previous observation.

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