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Physica C 282–287 (1997) 1493–1494

PHYSICA C

Zero-bias anomaly in the tunneling spectroscopy of high-Tc superconducting films

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The Coulomb staircase structure observed in the tunneling current-voltage characteristics (IVC's) of superconducting $YBa_2Cu_3O_{7-\delta}$(YBCO) films have been found to exhibit an extra feature of zero-bias anomaly (ZBA), with $\Delta V_0 \approx 1.5\Delta V_n$ when the bias voltage exceeded a certain threshold value. Where ΔV_0 and ΔV_n (which remains essentially constant) are the widths of the voltage step across zero bias and other higher order steps, respectively. Comparisons made with $TlBa_2Ca_2Cu_3O_{9\pm\delta}$(Tl-1223) films under similar conditions indicate that the effects of surface layer polarization might be the primary reason responsible for the ZBA observed in YBCO films.

1. INTRODUCTION

With the advent of nanoscale technology flourished recently, the understanding of single electron charging effects have become more and more prominent in the field of mesoscopic physics and devices[1]. As indicated by McGreer et al.[2], the STM tip and the embedded nanoscale grains in a granular can be modeled as two tunnel junctions coupled in series to exhibit incremental charging effects in their IVCs. Such Coulomb staircase structures have been evidently observed in laser ablated YBCO films, even at room temperatures[3]. However, it was observed that, there exists a zero-bias anomaly (ZBA) as the bias voltage exceeded a certain threshold. In that the width of the voltage step across zero-bias is wider than the expected value of e/C by about 50%. Such effect has been tentatively attributed to the effect of residual charge induced by the polarization of the dielectric layers[3-4]. In this paper, we show further evidence in supporting to this interpretation by comparing the detailed Coulomb staircase structure and polarization characteristics obtained on both YBCO and Tl-1223 films.

2. EXPERIMENTAL

The YBCO films used in this study were prepared by in-situ pulsed laser deposition on MgO, $LaAlO_3$, $NdGaO_3$, and $SrTiO_3$ with respectively optimized conditions[5]. The Tl-1223 films, were prepared by single target dc-sputtering followed by postannealing[6]. The films were all c-axis oriented with typical Tc of 87- 90 K and 105-108K for YBCO and Tl-1223, respectively. It is noted that, although the films all have Jc(77 K) above 10^6 A/cm^2, the grain morphology on the surface, as revealed by both STM and AFM, was consisted of grains with average diameter of about 100Å[3]. Thus, on the scale of tunneling measurements, they are granular in nature.

Both topographic and spectroscopic information were obtained simultaneously by operating the STM system (Park Science Ins.®) under the scanning probe mode. In this mode, a fixed bias voltage Vt was first chosen to set the tip-surface distance, and then the IVCs were taken by ramping the tip voltage from -Vt to Vt with the feedback circuit disabled. In this way, the tip-surface distance was fixed while taking the IVC. All the IVC results reported here were measured at room temperature and in the ambient environment.

The polarization measurements were performed using a Sawyer-Tower circuit. Two droplets (≈2mm in diameter) of silver paint were first applied onto the film surface as the probe contacts. The polarization density P underneath the area covered by sliver paint was calculated and was used to estimate the effective residual charge in the junction.

3. RESULTS AND DISCUSSION

The IVCs which evidently displayed all the features of Coulomb staircase structure were reported previously[3]. Briefly, the main features of the IVCs observed were consistent with that expected from the model of two mesoscopic tunnel junctions coupled in series. In particular, at a certain bias voltage, the step width of the staircase ΔV_n has a constant value of ΔV_n=e/C in virtually every film investigated. The typical junction capacitance C as derived from ΔV_n gives C ≈ $10^{-17}-10^{-18}$ F and varied linearly with increasing bias voltage and hence inversely proportional to the tip-surface distance.

However, as shown in Fig. 1(a1) and 1(a2), when the bias voltage was increased from 0.1 to 0.3 Volt there appears an anomaly widening for the zero-bias step, while the width of other steps remains essentially unchanged. This ZBA was observed for all the YBCO

0921-4534/97/$17.00
PII S0921-4534(97)00853-8

films studied and appeared to be independent of substrate used as well as the details of film superconducting properties.

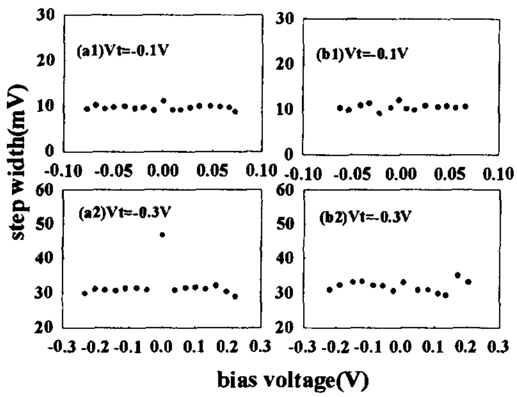

Fig.1:The voltage step width as a function of Vt for YBCO and Tl-1223 films.

It is also noted that every data point shown in Fig. 1 is representing an average of 16 IVCs taken over an area of about $100\times100Å^2$. Since it has been well established that the top few layers of the YBCO films are apt to be degraded when exposed to the ambient, it was speculated that this ZBA might be resulted from the polarization of those layers, leading to a change in the effective barrier of initial Coulomb blockade[3-4]. In order to elucidate this speculation, similar measurements were performed on Tl-1223 films, whose surface is believed to be relatively immune from ambient degradation. Indeed, as shown in Fig. 1(b1) and (b2), there is no ZBA observed under similar conditions. It is noted that, under the same bias voltages, the ΔV_n values were essentially the same in both YBCO and Tl-1223 films. This indicates that the same mechanisms were prevailing in both cases and is consistent with the notion that single charge tunneling should be dependent only on the nanoscale nature of the system and not on details of the electrode materials.

To further verify that the ZBA in YBCO films was indeed resulted from the nature of film surface, we have made preliminary surface polarization measurements on both type of films. As shown in Fig. 2, they did display dramatic differences in surface polarization. For Tl-1223 films, it is clear that there is no saturation for surface polarization within range of the applied voltages and the hysteresis loop obtained is believed to arise from the phase-lag of the instruments. However, quantitative analyses on the polarization hysteresis curves are needed to clarify this point. On the other hand, the results for the YBCO films are unambiguous for an apparent surface polarization. A rough estimate, taking the saturation voltage Vs≈0.4 V and the build-in reference capacitance C=10nF, gives $P\approx[0.4(V)\times10^{-8}(F)]/4mm\approx10^{-7}C/cm^2$. Thus the averaged polarization density for a grain with 100Å in diameter should have an effective polarization-induced residual charge $Q_{eff}\approx10^{-7}(C/cm^2)\times\pi$ $(50Å)^2\approx7.9\times10^{-20}C$. It might be fortuitous, however, the obtained values(e/2) is about the value expected to give a step width widening of $0.5\Delta V_n$.

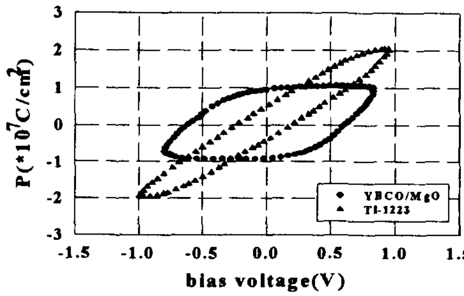

Fig.2:The P-E curves for YBCO and Tl-1223 films.

4. SUMMARY

In this report, we have shown that, although similar Coulomb staircase structure of tunneling IVCs were evidently observed in both YBCO and Tl-1223 films, the zero-bias anomaly previously seen in YBCO did not appear in Tl-1223 films. The surface polarization measurements performed on both type of films did show dramatic qualitative differences, suggesting that the ZBA observed in YBCO films were due primarily to the degraded surface layers commonly encountered in this material.

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