IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 5, NO. 2, JUNE 1995

Evidence for Tunneling and Magnetic Scattering at *In Situ* YBCO/Noble-Metal Interfaces

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***Abstract*—We report low-temperature conductance data for *in situ* $YBa_2Cu_3O_{7-\delta}$ (YBCO)/Ag, YBCO/Au, and YBCO/Pt planar *c*-axis interfaces. Analysis of the conductance data for these interfaces, which have resistivities as low as 1×10^{-8} Ω·cm², indicates that tunneling is the predominant transport mechanism. Zero-bias conductance peaks are present for all of the *in situ* interfaces. These peaks are analyzed in the framework of the Appelbaum model and are attributed to the presence of isolated magnetic spins at the interface. The presence and similarity of the peaks for each noble-metal overlayer supports the hypothesis that the magnetic spins are inherent to the YBCO surface.**

INTRODUCTION

Superconducting contact technology and superconductor/normal-metal/superconductor (SNS) device technology have advanced steadily in recent years, but both will benefit from an increased understanding and control of the interface transport mechanism in high-T_c superconductor (HTS)/N interfaces. Contact applications require a low interface resistivity and a mechanically stable interface. SNS device applications require a well-characterized, reproducible interface with strong proximity coupling. These requirements will be more readily met as interface transport is better understood.

Electrical transport at YBCO/N interfaces is complicated by extrinsic factors as well as intrinsic properties of the YBCO. A simple schematic of a *c*-axis, planar YBCO/N interface is illustrated in Fig. 1. First, YBCO has an anisotropic crystal structure and anisotropic effective masses; the effective mass along the *c*-direction, m_c, is approximately an order of magnitude larger than the effective mass in the *ab*-plane, m_{ab}. The YBCO surface also has anisotropic chemical reactivity and diffusion coefficients. Second, the surface of the YBCO is not atomically smooth, but consists of growth steps or spirals which allow the anisotropic properties to enter into the transport process. Third, the superconducting properties of the YBCO surface are very sensitive to oxygen stoichiometry and oxygen disorder, and oxygen disorder is readily induced by strain [1]. A likely consequence of this oxygen disorder is the presence of isolated magnetic spins, possibly Cu ions, at the YBCO surface. As discussed below, these spins have a significant effect on interface transport. Finally, *ex situ* YBCO surfaces exposed to various gases and etchants can form an amorphous reaction layer, which acts as a tunnel barrier and increases contact resistivity [2].

HTS/N interface transport has been the subject of many investigations. Most recently [3], we have shown evidence for direct tunneling and tunneling assisted by magnetic scattering for *c*-axis, planar YBCO/Ag interfaces having a wide range of interface preparations and contact resistivities. Even *in situ* contacts exhibited tunneling characteristics. Here the term "tunneling" refers generally to weakly-coupled transport where the transmission coefficient is << 1. We have not ruled out the possibility of conduction through microchannels [4]. The evidence for tunneling includes a parabolic conductance background, a gap-like conductance downturn, and a zero-bias conductance peak. This peak has been observed in other HTS-based junctions [5]-[7] and has been attributed to the presence of magnetic scattering at an interface. Our previous results [3] indicated that the magnetic scatterers are inherent to the YBCO surface, since the characteristics of the zero-bias conductance peak were not dependent upon the tunnel barrier thickness.

The purpose of this study is to see if the transport at YBCO/Au and YBCO/Pt interfaces is dominated by tunneling and magnetic scattering, as was observed for YBCO/Ag interfaces, in order to test the hypothesis that the magnetic scatterers are inherent to the YBCO surface. The results do indeed support this hypothesis. We found that YBCO/Au and YBCO/Pt interfaces produce zero-bias conductance peaks that are very similar to the peaks observed in YBCO/Ag, both in magnitude and voltage bias dependence. This is consistent with the magnetic scatterers originating at the YBCO surface.

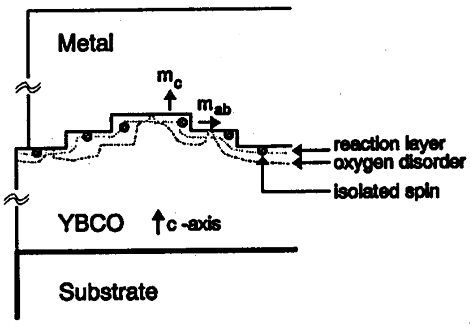

Fig. 1. Schematic drawing of a YBCO/normal-metal interface to illustrate some of the factors affecting interface electrical transport.

Manuscript received October 17, 1994.

EXPERIMENT

For this study, YBCO films 200 nm thick were fabricated on 12 mm × 12 mm (100) MgO or (100) $LaAlO_3$ (LAO) substrates using pulsed laser deposition. Each substrate was heated to 730-750 °C in 26.7 Pa (200 mTorr) of O_2 during deposition, and then cooled to room temperature in 26.7 kPa of O_2. The resulting c-axis-oriented films had T_c's ranging from 86 to 91 K. Scanning tunneling microscopy has shown that films grown under these conditions on MgO have spiral growth steps, while those grown on LAO exhibit island growth [8]. In each case, the area of the exposed YBCO *ab*-edges is about 5% of the *c*-axis area. For this study, the YBCO films were coated *in situ* [9] with a 200 nm overlayer of Ag, Au, or Pt immediately after cooldown and before breaking vacuum. The YBCO surface, however, is exposed to a partial pressure of approximately 0.01 Pa (10^{-4} Torr) of contaminant gases for 30 minutes during cooldown in high O_2 pressure. Ag and Au were evaporated from a resistive hearth with the substrate in contact with a water-cooled platform; Pt was deposited using rf magnetron sputtering in 0.67 Pa (5 mTorr) of Ar onto an uncooled substrate. The films were then photolithographically patterned to define the planar interfaces ranging in size from 2 μm × 2 μm to 16 μm × 16 μm. A 500 nm-thick Ag layer was used to form the top electrode. Conductance curves were derived from the current-voltage data.

RESULTS AND DISCUSSION

Low-bias conductance curves for the three types of interfaces are compared in Fig. 2. The main feature of these data is the presence of zero-bias conductance peaks for all three interfaces. These peaks are very similar in character, with the normalized peak height $\Delta G_{p\text{-}p}/G_0$ ranging from 0.07 to 0.22, and full-width-at-half-maximum values of 3.7 to 5.6 mV. As discussed below, these conductance peaks are consistent with tunneling assisted by magnetic scattering at the interface. Their presence in all of these samples, independent of noble-metal type, indicates that the transport mechanism is independent of the particular noble metal and suggests that the magnetic scatterers are inherent to the YBCO surface.

Both the YBCO/Ag and YBCO/Pt samples produced asymmetrical conductance curves. Generally, a similar asymmetry is a observed for all devices on a particular chip, as shown in Fig. 3 for a YBCO/Ag sample having 4 μm × 4 μm, 8 μm × 8 μm, and 16 μm × 16 μm interfaces. This device-independent conductance is indicative of good interface uniformity across the chip. We do not understand the origin of the asymmetry in detail, but it is consistent with the presence of an asymmetrical tunnel barrier [10].

The zero-bias conductance peaks have been analyzed in the framework of the Appelbaum model [11], [12]. The Appelbaum model predicts a zero-bias conductance peak for

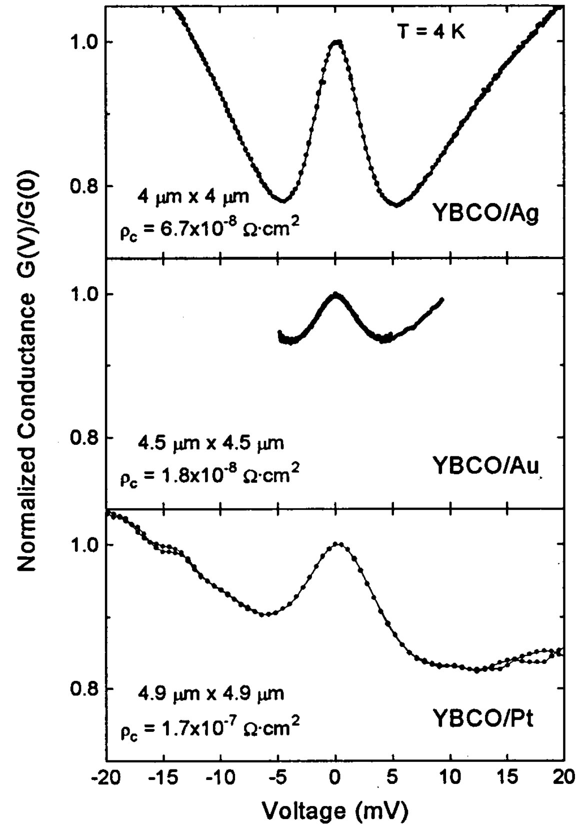

Fig. 2. Normalized conductance as a function of voltage for *in situ* interfaces having different noble-metal overlayers. The similarity of the zero-bias peaks suggests that the source of the peaks is the YBCO surface. (Conductance for the YBCO/Au sample is not shown for large negative voltages because the device failed at +10 mV, which corresponded to a current density of 10^7 A/cm^2 in the underlying YBCO film.)

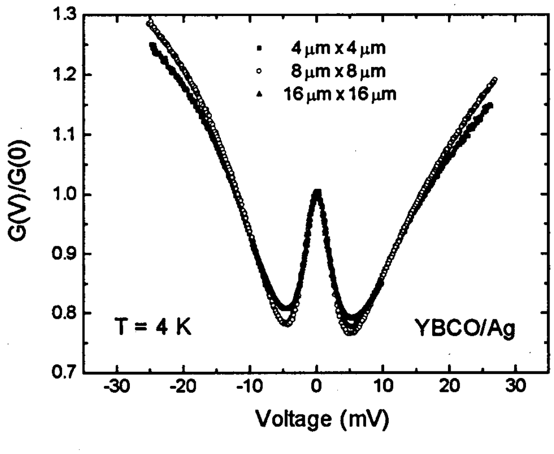

Fig. 3. Normalized conductance for three YBCO/Ag test structures on the same chip. The shape of the curve is nearly independent of area, indicating chip-wide uniformity of the interface.

metal-insulator-metal tunnel junctions having isolated magnetic impurities located in the barrier but relatively close to one of the metal electrodes. (We have not attempted to modify the model for the case where one of the electrodes is superconducting.) In this model there are three terms in the expression for conductance from metal A to metal B:

$$G = G_1 + G_2 + G_3. \tag{1}$$

G_1 is a term containing the contribution due to direct tunneling, with no exchange interaction between electron and the impurity. G_2 is a term proportional to T_J^2, which is the tunneling matrix element for an electron tunneling from metal A to metal B after undergoing a spin exchange with the magnetic impurity. The term

$$G_3(V,T) \propto N_a T_J^2 J \rho_A \rho_B (\rho_A + \rho_B) S(S+1) \ln\left(\frac{eV + nkT}{E_0}\right) \tag{2}$$

is responsible for the zero-bias conductance peak. Here, N_a is the areal density of the isolated magnetic spins, J and T_J^2 are the exchange and exchange tunneling interactions between the local moment and the metals (J is the exchange scattering amplitude for an electron reflected back toward the original electrode), ρ_A and ρ_B are the electron densities of states for the respective metals, S is the total spin of the magnetic impurity, n is a numerical constant on the order of 1, and E_0 is a cutoff energy. The factor $T_J^2 J$ represents an interference between the reflected and transmitted exchange-scattered currents. The isolated magnetic spins are favorable energy states and effectively open a tunnel channel capable of carrying an appreciable fraction of the tunnel current [6]. This term is the tunneling analogy of the Kondo effect [13] for low-temperature resistivity in dilute magnetic alloys.

The logarithmic voltage dependence of the zero-bias peak predicted by Appelbaum has been observed in a YBCO/Ag interface, as shown in Fig. 4. The conductance at $T = 4$ K is logarithmic for $4 < eV/kT < 12$, with thermal smearing at lower voltages. A logarithmic temperature dependence has also been observed for this interface [3].

A discriminating test of the Appelbaum model is magnetic-field dependence of the zero-bias peak [14]. The Appelbaum model predicts that the effect of a strong magnetic field on the G_2 term is the formation of a zero-bias conductance well $2g\mu_B H$ wide, where g is the Landé g-factor of the isolated spin, μ_B is the Bohr magneton, and H is the field. The magnetic field causes a Zeeman splitting of $\pm g\mu_B H$ in the energy levels of the isolated spins. This is the energy required for an electron to flip the impurity spin and arrive at an unoccupied state in metal B. The effect of field on the G_3 term (the zero-bias Kondo peak) is a peak splitting, where the zero-bias peak is split into two peaks separated by $2g\mu_B H$.

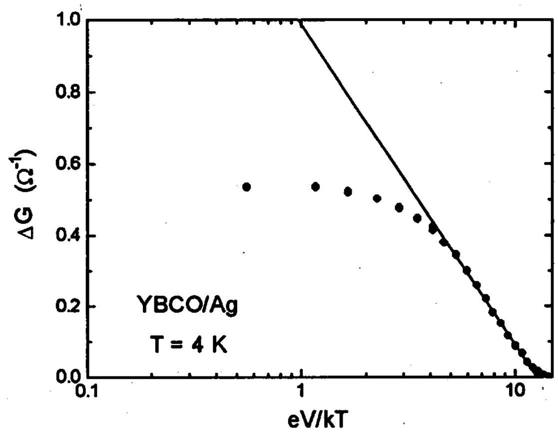

Fig. 4. Logarithmic voltage dependence of the conductance for an *in situ* YBCO/Ag interface at $T = 4$ K.

Fig. 5 illustrates the effect of magnetic field on the zero-bias conductance peak for an *in situ* YBCO/Ag interface. The zero-field conductance has been subtracted to emphasize the field effect. As predicted by the Appelbaum model, we observe a dip in the zero-bias conductance and the formation of two conductance shoulders with increasing magnetic field. This is convincing evidence for the presence of magnetic scatterers at these *in situ* interfaces. We have previously noted that determining the g-factor of the magnetic spins is not straightforward, since it is field dependent [3].

A likely source of isolated magnetic scatterers is Cu ions located at the oxygen-disordered YBCO surface. The YBCO surface appears to be responsible for the zero-bias conductance peaks, since they are observed regardless of

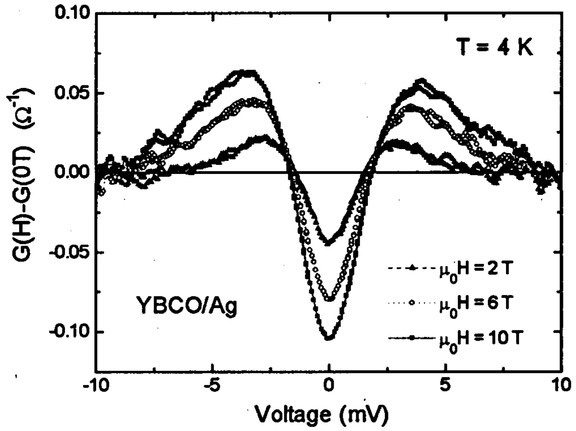

Fig. 5. Field dependence of the zero-bias conductance for an in situ YBCO/Ag sample. The zero-field conductance has been subtracted.

barrier thickness [3] or noble-metal type. The implication is that if the YBCO surface can be stabilized with good oxygen order, then the tunneling behavior we have observed may be minimized or controlled such that SNS devices and contacts can be fabricated more reproducibly with lower interface resistivities. Indications that this is possible have been reported for YBCO/doped-YBCO interfaces [15], and for YBCO/Au interfaces in which the YBCO surface was treated with atomic oxygen prior to metallization [16]. These types of interfaces warrant further study to elucidate the electrical transport mechanisms involved.

CONCLUSION

Conductance peaks for *in situ* YBCO/noble-metal interfaces at low temperatures are attributed to tunneling assisted by magnetic scattering. The similarity of the peaks for Ag, Au, and Pt overlayers indicates that the magnetic scatterers are not associated with a particular noble metal or overlayer deposition process. This complements previous data on *in situ* and *ex situ* YBCO/Ag interfaces having a wide range of interface preparations [3] and reinforces the hypothesis that the magnetic scatterers are inherent to the YBCO surface.

ACKNOWLEDGMENT

This work was supported by ARPA under contract 7975-01 and the NIST High-T_c Program. We also acknowledge discussions and support from F. Fickett.

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