We report interface transport results for planar, c-axis-oriented YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO)/normal-metal interfaces in which the interface resistivities vary from $10^{-8}$ to $10^{-3}$ $\Omega$ cm$^2$. This wide range of resistivities was obtained by systematically exposing the YBCO films to various surface treatments, such as subjecting to air, N$_2$, or CO$_2$, or etching with Br-methanol or an Ar-ion beam, prior to depositing an Ag overlayer. In situ interfaces (in which the Ag overlayer was deposited immediately after fabricating the YBCO film and without breaking vacuum) gave the lowest contact resistivity,$^1$ while ex situ interfaces$^2$ formed after ion etching the YBCO surface gave the largest contact resistivity. The central result of this letter is that tunneling through an insulating layer between the YBCO and Ag appears to be the dominant interface transport mechanism, at low temperatures, even for the in situ interfaces. Moreover, zero-bias conductance peaks having similar characteristics are observed over the entire range of interface resistivities. These conductance peaks suggest that magnetic scattering contributes significantly to the interface transport in these samples. Although we have not yet identified the particular magnetic scatterers, the similar peak characteristics over the large range of contact resistivities suggest that the magnetic scatterers giving rise to the peaks are present at the "intrinsic" degraded YBCO surface.

Understanding, predicting, and controlling electrical transport at thin-film YBCO/normal-metal interfaces is required for advances in superconductive devices based on proximity or Josephson effects, as well as superconducting microcircuit transmission line applications. Many groups have fabricated SN and SNS devices based on high-$T_c$ superconductors, and progress has been steady.$^3$–$^7$ For applications that use a large number (up to thousands) of junctions or contact interfaces on a single chip, however, uniformity and reproducibility of junction critical currents and resistivities are crucial requirements which have yet to be adequately obtained, and the interface resistivity often dominates the device resistivity. A deeper understanding of the transport mechanisms across YBCO/normal-metal interfaces is required to control or minimize interface resistivity.

There are a number of papers on interface transport and tunneling measurements between high-\textit{T}_c superconductors and normal metals in the literature. Many report zero-bias peaks in the conductance versus voltage (\textit{G-V}) characteristics, often called zero-bias anomalies (ZBAs). Recent papers$^8$–$^{10}$ have reported more detailed studies of ZBAs, and several explanations for the origin of ZBAs in YBCO/normal-metal interfaces have been offered. The most frequently invoked explanation for conductance ZBAs is that of tunneling assisted by scattering from isolated (noninteracting) magnetic impurities (spins) in the interface. This was originally modeled for metal-insulator-metal junctions by Appelbaum$^{11}$ and Anderson.$^{12}$ Most of the samples in the ZBA studies reported to date have had large interface resistances due to "natural barriers" formed by air exposure before counter electrodes deposition, and often the geometry of the contact areas was not well defined. These sample characteristics limit to some degree the information that can be obtained from these transport experiments, the origin of the isolated magnetic spins being an example.

For this study, YBCO films 200 nm thick were fabricated on polished (100) MgO or (100) LaAlO$_3$ substrates by pulsed laser deposition.$^2$ The chamber base pressure with the substrate at deposition temperature was $\sim 10^{-7}$–$10^{-4}$ Pa ($\sim 10^{-7}$–$10^{-6}$ Torr). Following YBCO deposition, films were cooled to room temperature in an oxygen ambient of 26.7 kPa (200 Torr). The resulting $c$-axis-oriented films [which had full width at half-maximum (FWHM) $< 0.5^\circ$ for the 005 rocking curves] had $T_c$'s ranging from 86–91 K and $J_c$'s of $\sim 3.5 \times 10^6$ A/cm$^2$ at $T = 77$ K. Scanning tunneling microscopy data taken on separate films prepared under identical conditions show spiral growth for YBCO on MgO and island growth for YBCO on LaAlO$_3$, with the area of the YBCO $a$-$b$ edges about 5% of the $c$-axis area.$^{13}$ After cool down, the YBCO films were either coated immediately with a 200 nm overlayer of evaporated Ag (to study interfaces formed \textit{in situ})$^1$ or subjected to a selected surface treatment.$^2$ The YBCO surface treatments included air, CO$_2$, or N$_2$ exposures, or Br-methanol or Ar-ion etches. The Br-methanol and 200 V Ar-ion etches were calibrated to remove the top
was exposed to $N_2$ gas prior to Ag deposition. A nearly para-
YBCO/Ag interfaces measured, including
in situ
having
normal state,14 and are observed in all of our samples where
conductance backgrounds are indicative of tunneling in the
parabolic background at high biases is clearly evident. Parabolic
interfaces has not been conclusively ruled out. None of the
samples investigated thus far have shown signs of Andreev
reflections,17 which are expected in the clean interface limit 18
in the case of the YBCO/barrier/Pb samples, it is likely that any exposed a-b edges
are oxygen reduced at a relatively rapid rate due to the prox-
imity of the Pb, which would diminish the conductance from the a-b edges. This is in contrast to our situation, in which
the counterelectrode is a noble metal with low oxygen affin-
ity.

The three features illustrated in Fig. 1, the parabolic
background, gaplike feature, and ZBA, indicate that interface
transport is occurring by tunneling. The contact resistivity
results reported in Ref. 2 also contain evidence for tunneling
for these interfaces. An exponential dependence of the contact
resistivity on air exposure time2 translates into an exponential
dependence of the effective (tunnel) barrier layer
thickness.15 A relatively weak temperature dependence be-
low $T_c$ was also observed.2 Taken together, these features
provide strong evidence for tunneling as the dominant low
temperature interface transport mechanism in these samples,
although conduction through microchannels16 at the in situ
interfaces has not been conclusively ruled out. None of the
samples investigated thus far have shown signs of Andreev
reflections,17 which are expected in the clean interface limit18
and have been observed in some point-contact tunneling
studies of YBCO.19,20

The ZBA can be qualitatively explained in terms of the
Appelbaum model11,12 for magnetic scattering off isolated
spins located at the interface region in a metal-insulator-
metal tunnel junction. The model consists of three terms for
the conductance: direct tunneling ($G_1$), tunneling with spin

FIG. 1. $G$-$V$ for a planar, c-axis YBCO/Ag interface formed after exposing
the YBCO surface to $N_2$ gas for 1000 min at room temperature. Inset:
Low-bias data indicating the similarity of the zero-bias peaks for YBCO/Ag
interfaces having nearly four orders of magnitude difference in their resis-
tivities. The top data set is for a 4 $\mu$m x 4 $\mu$m in situ interface, and the bottom
data set is for an 8 $\mu$m x 8 $\mu$m ex situ interface.

1-3 nm of YBCO. Following the Ag overlayer evaporation,
the samples were photolithographically patterned to define
planar interfaces (square contact areas having 2, 4, 8, and 16
$\mu$m sides) between the YBCO and the Ag overlayer. A 500-
nm-thick Ag top electrode was used to contact the devices.
Conductance curves were obtained by differentiating the
$I$-$V$ data using a sliding three-point fit.

Several features of the conductance data for the
YBCO/Ag interfaces indicate that tunneling is the dominant
transport mechanism at low temperatures. Figure 1 shows
$G$-$V$ data for a YBCO/Ag interface in which the YBCO film
was exposed to $N_2$ gas prior to Ag deposition. A nearly para-
B1-A1/A2 interfaces producing zero-bias dips. The
discrepancy might be due to the fact that our nominally
c-axis samples could have a more significant conductance
contribution from the a-b edges, which constitute about 5%
of the total interface area in our samples having spiral or
island growth morphology.13 Also in the case of the YBCO/
barrier/Pb samples, it is likely that any exposed a-b edges
are oxygen reduced at a relatively rapid rate due to the prox-
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FIG. 2. Summary plot illustrating the character of the normalized peak-to-
peak zero-bias conductance for planar YBCO/Ag interfaces.

mV wide and had normalized peak-to-peak heights
($\Delta G_{pp}/G_0$) of 4%-22%, as shown in Fig. 2.

Whereas we observe zero-bias conductance peaks in our
c-axis YBCO/Ag interfaces, Lesueur et al.9 observed such
peaks only in (100) or (103) YBCO/Pb interfaces, with
c-axis YBCO/Pb interfaces producing zero-bias dips. The
discrepancy might be due to the fact that our nominally
c-axis samples could have a more significant conductance
contribution from the a-b edges, which constitute about 5%
of the total interface area in our samples having spiral or
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ity.
flip ($G_2$), and tunneling and reflection with spin flip ($G_3$). The latter term is responsible for the ZBA, and it has a logarithmic temperature and voltage dependence.

Figure 3 shows the temperature dependence of the conductance for an in situ interface. The zero-bias conductance peak diminishes as temperature is increased from 4 to 55 K. The inset indicates a logarithmic temperature dependence of the peak amplitude, consistent with the Appelbaum model. We also observe a logarithmic voltage dependence of the conductance over the range $4 \leq eV/kT \leq 10$, with thermal smearing observed at lower voltages. Figure 3 also shows that for $V > 20$ mV, the data lie on a temperature-independent background, making the gaplike feature near $V = 20$ mV more apparent.

The application of an external magnetic field perpendicular to an in situ interface caused a reduction in the conductance peak amplitude also, as shown in Fig. 4. The peak-to-peak conductance decreased by 30% as the field was increased from 0 to 12 T. Subtracting the zero-field conductance peak amplitude also, as shown in Fig. 4, the tunneling and reflection with spin flip ($G_3$).

with the isolated magnetic spins originating at the YBCO surface, since the ZBA characteristics are independent of the barrier thickness.

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