Enhanced transparency ramp-type Josephson contacts through interlayer deposition

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A thin interlayer is incorporated in ramp-type Josephson junctions to obtain an increased transparency. The interlayer restores the surface damaged by ion milling and has the advantage of an all *in situ* barrier deposition between two superconductors, leading to clean and well-defined interfaces. The method has been applied to Josephson junctions between high ($YBa_2Cu_3O_{7-\delta}$) and low temperature (Nb) superconductors, separated by a Au barrier. Transmission electron microscopy images of these junctions reveal crystalline $YBa_2Cu_3O_{7-\delta}$ up to the interface with the Au barrier. The junctions have improved critical current density values exceeding 20 kA/cm^2, normal state resistances of $3\times10^{-8}\ \Omega\ \mathrm{cm}^2$ and I_cR_n products of 0.7 mV at 4.2 K. Furthermore, the junction properties can be controlled by varying the Au barrier thickness. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1485305]

For vias and Josephson contacts in thin film devices involving high temperature superconductors, the ramp-type[1–3] interface configuration is frequently used, exploiting the maximal superconducting coherence length and charge density of states in the ab plane of the cuprates. A further advantage of the ramp-type geometry is the opportunity to tailor junction properties by the choice of the barrier material and its thickness. A crucial step in the preparation of ramp-type interfaces is the structuring of the beveled edge in the superconducting base electrode. Unfortunately, this procedure can severely degrade the quality of the base electrode near the interface. Transmission electron microscopy (TEM) studies of $YBa_2Cu_3O_{7-\delta}$/Au ramp-type interfaces[4] clearly show an amorphous layer with a thickness up to 2 nm at the ramp edge between the high-T_c base electrode and the Au layer deposited at the freshly milled ramp edge. From energy-dispersive x-ray analysis it is concluded that the Cu content of this amorphous layer is nearly zero. Interestingly, the damage invoked by the ion beam can also be used to create a Josephson barrier between two high-T_c superconducting electrodes, as is done in the interface engineered junctions[5] (IEJs). Wen *et al.*[4] found that in this all-high-T_c IEJ-technology nonsuperconducting Ba-based perovskite structures are apt to form at the interface, most likely during the deposition of the counter electrode, which takes place at elevated temperatures. Although with IEJs results comparable to the early high-T_c ramp-type junctions have been obtained, these junctions are based on structural damage, which is less favorable in the quest to achieve high controllability and reproducibility of junction properties. In order to study the influences of the ion mill on the ramp edge interface, and to derive ways to reduce their effects on the transport properties, we have investigated $YBa_2Cu_3O_{7-\delta}$/Au/Nb ramp-type junctions. In this configuration, an inert noble metal is used to cover the freshly milled ramp edge, this in contrast to the all-high-T_c ramp-type junction where a complex oxide barrier like $PrBa_2Cu_3O_7$ is used.

Initially, $YBa_2Cu_3O_{7-\delta}$/Au/Nb ramp-type junctions were made following usual procedures developed for the preparation of all-high-T_c ramp-type junctions. Bilayers of 150 nm [001]-oriented $YBa_2Cu_3O_{7-\delta}$ and 100 nm $SrTiO_3$ are grown by pulsed laser deposition on [001]-oriented $SrTiO_3$ single crystal substrates. In these films, beveled edges (ramps) are etched by Ar-ion milling under an angle of 45° using a photoresist stencil, yielding ramps with an angle of ~20° with the substrate plane.[6] In order to facilitate a good alignment of the junction with the $YBa_2Cu_3O_{7-\delta}$ ⟨100⟩-axes, edge-aligned substrates are used, with an alignment accuracy better than 1°. After stripping of the photoresist, a low-voltage ion mill step is applied to clean the surface, *in situ* followed by an annealing step and the deposition of Au. The anneal procedure is introduced to recrystallize residual amorphous material present at the ramp edge. To avoid large outgrowths the sample is heated at ~35 °C/min to 740 °C in a 0.30 mbar oxygen environment, and annealed for 30 min at these conditions.[7] Due to the reduced mobility of the particles at the ramp surface compared to the 780 °C deposition temperature of $YBa_2Cu_3O_{7-\delta}$, crystallization occurs only on a small length scale. After deposition of the Au-barrier layer with a thickness ranging from 8 to 120 nm, a photoresist lift-off stencil is applied to define the junction area. Before Nb deposition, maximally 2 nm of the Au layer is removed by rf-sputter etching, followed *in situ* by dc-sputter deposition of 150 nm Nb. After lift-off, the redundant uncovered Au is removed using ion milling.

Even though special care was taken to obtain clean interfaces with the above preparation procedure, critical current densities did not exceed 1 A/cm^2 at $T=4.2$ K, with normal state resistance (R_nA) values of the order of $10^{-4}\ \Omega\ \mathrm{cm}^2$.[8] This poor interface transparency is attributed

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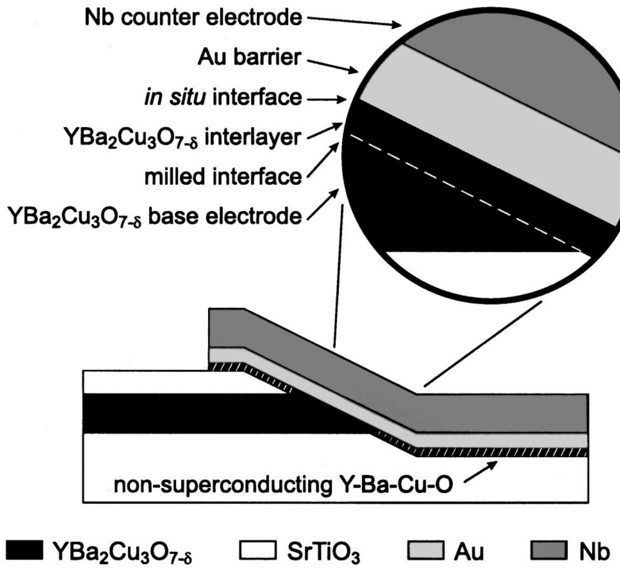

FIG. 1. Schematic cross section of the $YBa_2Cu_3O_{7-\delta}$/Au/Nb ramp-type junction including the interlayer.

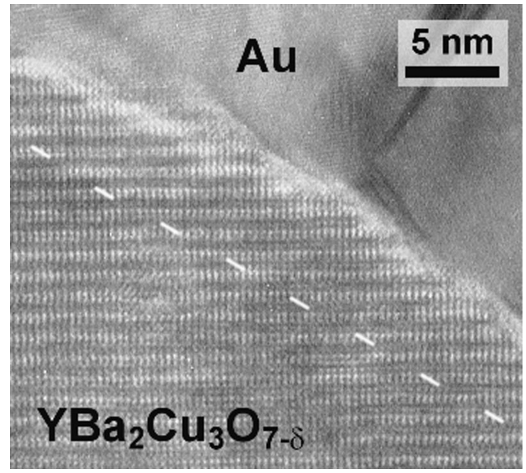

FIG. 2. Bright-field transmission electron microscopy image of the $YBa_2Cu_3O_{7-\delta}$/Au interface at the ramp-edge area, including an interlayer of 6 nm deposited $YBa_2Cu_3O_{7-\delta}$. Crystalline $YBa_2Cu_3O_{7-\delta}$ material is observed up to the Au interface, while no clear interface is observed between the base electrode and the interlayer (dashed line).

to the fact that just an anneal procedure will not recover the correct stoichiometry at the ramp-edge surface. To improve the transparency it is desirable to separate the barrier formation to the base electrode and the effect of the ion mill on the ramp edge. Therefore, it is proposed to deposit a thin interlayer of 5–7 nm $YBa_2Cu_3O_{7-\delta}$ at standard conditions after cleaning and annealing of the ramp edge, before depositing the Au layer. This interlayer is expected to stabilize the off-stoichiometric etched surface of the base electrode and enables *in situ* formation of the interfaces between the electrodes and barrier, leading to a much cleaner interface. It is remarked that application of the low-voltage ion mill results in a negligible reduction of the superconducting coupling between the bottom electrode and the high-T_c cuprate interlayer.[9]

A schematic of the junction obtained in this way is presented in Fig. 1. The interlayer concept employs the difference in homoepitaxial and heteroepitaxial growth of high-T_c material. The thin interlayer is anticipated to be superconducting only if deposited on the $YBa_2Cu_3O_{7-\delta}$ the ramp area, whereas on the $SrTiO_3$ substrate and isolation layer it is anticipated not to become superconducting. This is, e.g., due to the strain as a result of the lattice mismatch. On $SrTiO_3$ it takes about 7 nm to obtain the superconducting orthorhombic phase.[10,11] Moreover, roughening of the $SrTiO_3$ substrate surface, due to the ion milling, is unfavorable for growing very thin superconducting $YBa_2Cu_3O_{7-\delta}$.

Figure 2 presents a TEM micrograph of the ramp edge area near the $YBa_2Cu_3O_{7-\delta}$/Au interface. Because of the application of the thin $YBa_2Cu_3O_{7-\delta}$ interlayer, crystalline high-T_c material extends up to the Au barrier, and an amorphous layer was never observed. The interface between the base electrode and the interlayer could not be distinguished by TEM, indicating nearly perfect homoepitaxial growth. Observation of the interlayer, Au barrier, and Nb top electrode grown on top of the bare (ion milled) $SrTiO_3$ substrate shows that, besides amorphous material, only small isolated spots in the interlayer contain crystalline material. These areas were very sensitive to the electron beam used in the TEM analysis, and become amorphous in a few seconds during the observation, indicating an unstable Y–Ba–Cu–O phase.

In order to investigate whether the interlayer deposited on the bare substrate becomes superconducting nevertheless, a 10 μm wide bridge is structured along with the prepared ramp-edge junctions. This trilayer bridge consists of the $YBa_2Cu_3O_{7-\delta}$ interlayer, Au barrier and Nb top electrode, and is prepared simultaneously with the ramp-edge junctions. Such a bridge is characterized electrically using a bias current of $I_{bias} \sim 0.1\ \mu A$. Indications of superconductivity in the interlayer on the bare substrate were never observed, and therefore it is concluded that the interlayer is not shunting the junction underneath the Nb contact paths.

The ramp-type $YBa_2Cu_3O_{7-\delta}$/Au/Nb junctions, which are oriented along the $\langle 100 \rangle$ directions of the high-T_c crystal, are characterized for their electrical properties. A minimum interlayer thickness of 5 nm is found to improve the critical current density considerably to values beyond 20 kA/cm^2, which is well comparable with the best all *in situ* fabricated a-axis-oriented trilayer junctions[12] obtained with these materials. In Fig. 3 the critical current density as a function of the Au-barrier thickness at $T = 4.2$ K is given, using a 7 nm $YBa_2Cu_3O_{7-\delta}$ interlayer. By modifying the Au-barrier thickness, junction properties, such as the critical current density, can be adjusted. The minimum Au barrier thickness to be used turns out to be 8 nm. For thinner barriers, it appears that the Au layer is not closed completely and the Nb reacts with the base electrode material forming niobium oxides. The reaction leads to a significant decrease in critical current density and barrier transparency at low temperatures. This observation is in agreement with TEM analysis, exhibiting areas in the base electrode, where such a reaction seems to have taken place.

For junctions with closed Au barriers, a clear Fraunhofer-like magnetic field dependence of the critical current is observed. A typical example is shown in the inset of Fig. 3. Such nearly ideal magnetic field dependences indicate a good homogeneity of the critical current density along the junction.

From separate resistance measurements of pulsed laser

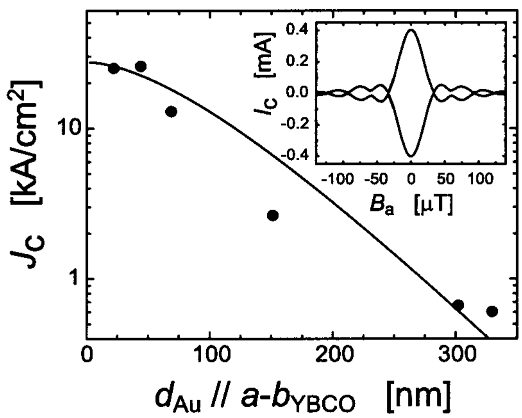

FIG. 3. Average critical current density as a function of the Au barrier thickness at $T=4.2$ K using a $YBa_2Cu_3O_{7-\delta}$ interlayer thickness of 7 nm. The solid line is a fit for a proximity effect Josephson junction based on a dirty limit Au coherence length of $\xi_{nd}=49$ nm and assuming electrical transport in the Au barrier parallel to the $a-b$ plane of the high-T_c superconductor. The inset shows a typical magnetic field dependence of the critical current of a 10 μm wide $YBa_2Cu_3O_{7-\delta}$/Au/Nb ramp-type junction oriented along the ⟨100⟩-crystal axis of the $YBa_2Cu_3O_{7-\delta}$ material, measured with a bias voltage of $V_{bias}=3$ μV.

deposited Au thin films, yielding a resistivity of $\rho_{Au}=4.6$ $\mu\Omega$ cm at $T=4.2$ K, a dirty limit normal metal coherence length of $\xi_{nd}\sim 49$ nm is deduced.[13,14] The solid line in Fig. 3 represents the calculated critical current density of an $S-N-S$ junction in the dirty limit[15] based on this coherence length, where dominant transport is assumed in the Au barrier parallel to the $a-b$ direction of the $YBa_2Cu_3O_{7-\delta}$ base electrode. With this independently determined normal state coherence length, the reduction in critical current density for increasing Au barrier thickness is well in agreement with the measured data, and the observed exponential decay of J_c with increasing Au-barrier thickness is consistent with theory on proximity effect junctions.

At 4.2 K, an average R_nA value of 3.0×10^{-8} Ω cm^2 is observed. Such a value is an improvement with a factor of 10 000 compared to ramp-type $YBa_2Cu_3O_{7-\delta}$/Au/Nb contacts prepared so far. The normal state resistance is dominated by the interface resistance between the $YBa_2Cu_3O_{7-\delta}$ and Au, being constant as a function of the Au-barrier thickness. The values correspond well to estimates based on band bending in the high-T_c cuprates[16] near a normal metal interface. The ramp-type junctions demonstrate characteristic I_cR_n products of 0.7 mV at 4.2 K for 8 nm thin Au barriers, and are dominated by the variation in critical current density for increasing barrier thickness.

In summary, introducing a thin interlayer on top of the ion-beam structured high-T_c base electrode and before deposition of a barrier and top electrode, high transparency ramp-type interfaces have been realized. Crystalline $YBa_2Cu_3O_{7-\delta}$ is observed up to the interface with the Au barrier material. Applying this technique to Josephson junctions between high-T_c and low-T_c superconductors improved the R_nA value by 10^4, and reproducible J_c values exceeding 20 kA/cm^2 were obtained. Besides the fact that the obtained R_nA values are in agreement with approximations based on band bending, the introduction of the interlayer improves the controllability of the junction properties in ramp-type technology significantly.[17] This technique is not restricted to this type of Josephson junction and is expected to be useful for all-high-T_c ramp-type junctions as well.

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