Y-Ba-Cu-O / Au / Nb Ramp-type Josephson Junctions

Hendrik J.H. Smilde, Hans Hilgenkamp, Gerrit J. Gerritsma, Dave H.A. Blank, and Horst Rogalla

***Abstract*—Ramp-type junctions connecting the d-wave superconductor $YBa_2Cu_3O_{7-\delta}$ and the s-wave superconductor niobium are fabricated using a thin gold layer as a chemical barrier. High critical current densities exceeding 5 kA/cm² are obtained. The normal state resistivity (R_nA) values of the junctions are of the order of 0.1 μΩ cm². The magnetic field behavior of the critical current of junctions oriented in the [10ℓ]- and in the [11ℓ]-direction of the $YBa_2Cu_3O_{7-\delta}$ is explained in terms of a predominant $d_{x^2-y^2}$ order parameter in the high-T_c superconductor.**

***Index Terms*—Heterojunctions, high-temperature superconductors, hybrid integrated circuits, Josephson junctions.**

I. Introduction

The availability of contacts *between* high-T_c and low-T_c superconductors will bear a large promise for various applications, in superconducting electronics as well as for fundamental studies. For instance, the potential to create novel phase-devices by employing the unconventional order parameter symmetry of the high-T_c superconductors [1], and the possibility to connect electrically fast high-T_c Single Flux Quantum-logic to the easier manageable low-T_c technology, appear attractive features of such structures. Also, qubits, the key elements for quantum computation, have been proposed based on contacts between high-T_c and low-T_c superconductors [2], [3].

Using high-T_c single crystals, corner junctions and SQUIDs were fabricated between $YBa_2Cu_3O_{7-\delta}$ and low-T_c superconductors [4]-[6]. The electrical characteristics of these structures provided evidence for the $d_{x^2-y^2}$-symmetry of the order parameter of the high-T_c cuprates. Various groups have dedicated research towards the characterization and optimization of $YBa_2Cu_3O_{7-\delta}$ - Nb contacts [7]-[10]. A complete *in situ* process avoiding contamination was found to provide the best results from the point of view of I_cR_n-product and the critical current density (J_c) [9]. However, to our knowledge, no successful realization of all-thin-film Josephson junctions connecting controllably different crystal sides of $YBa_2Cu_3O_{7-\delta}$ to Nb in one device has been reported.

In conjunction with the attractive technological and fundamental aspects, our research has been focused towards the development of a versatile method for the fabrication of contacts between low-T_c superconductors and high-T_c superconductors along the a-b plane of the cuprate. Here, we present high-quality thin film Josephson contacts between Nb and $YBa_2Cu_3O_{7-\delta}$, in various crystal directions of the high-T_c material, using a ramp-type configuration.

II. Junction Preparation

For the preparation of high quality junctions between metallic superconductors, such as niobium, and the cuprate high-T_c superconductors, oxygen migration from the high-T_c to the low-T_c superconductor presents an important difficulty. A thin, but closed layer that serves as a chemical separation between both superconductors may avoid the oxygen migration, for which gold is found to be the most suitable material.

The ramp-type junction concept [11] forms the basis of the junctions in this work, employing its ability to controllably access different specified spatial directions of the $YBa_2Cu_3O_{7-\delta}$-crystal, as is indicated schematically in Fig. 1.

The optimized fabrication procedure of the junctions starts with the *in situ* pulsed laser deposition of a bi-layer of 150 nm $YBa_2Cu_3O_{7-\delta}$ and 100 nm $SrTiO_3$ on a single-crystal $SrTiO_3$ substrate. The deposition is carried out at 780 °C in a 0.30 mbar oxygen environment, with a laser spot intensity of 1.2 J/cm² and a repetition rate of the KrF excimer laser fixed at 4 Hz. The $SrTiO_3$ insulation layer is grown at 740 °C in 0.10 mbar of oxygen at similar laser spot parameters. The bi-layer is cooled down in 1 bar of oxygen, keeping the sample 15 minutes at 600 °C and 15 minutes at 450 °C before reaching room temperature. The c-axis oriented $YBa_2Cu_3O_{7-\delta}$

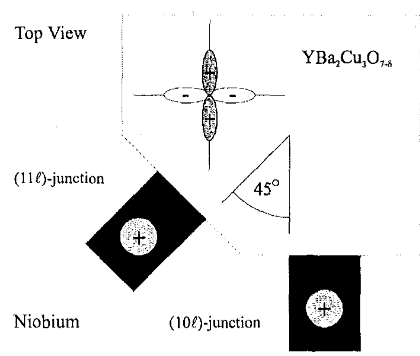

Fig. 1. Experimental layout for probing the order parameter symmetry of the cuprate superconductors in different crystal directions. A junction in the direction of one of the principal crystal axes of the high-T_c superconductor to the isotropic low-T_c superconductor and one rotated 45° with respect to the first are depicted.

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films have a zero-resistance transition temperature $T_{c,0}$ of 89 to 90 K.

Using a photoresist stencil, a ramp is etched in the bi-layer by 500 eV Ar-ion milling under 35° with the substrate surface. The ramp is aligned along the [100]-direction of the $YBa_2Cu_3O_{7-\delta}$, or aligned along the [110]-direction. Due to differences in etch-rate between the photoresist and the perovskite bi-layer, the obtained ramp angles are between 15° and 20°. After removal of the photoresist a short low-voltage ion-milling cleaning step is carried out in order to remove possible non-stoichiometric phases [12]. To limit the roughness of the re-crystallizing ramp surface to a minimum, an anneal step is carried out for 30 minutes at 740 °C in a 0.30 mbar oxygen environment [13]. Furthermore, to provide a fresh high-quality surface for the barrier deposition, a thin $YBa_2Cu_3O_{7-\delta}$ interlayer of a few unit-cells is grown on top of the ramp without breaking the vacuum and at standard deposition circumstances. From separate control experiments it is expected that no significant current passes through this thin interlayer underneath the – to be deposited – Au / Nb bi-layer except for the $YBa_2Cu_3O_{7-\delta}$ material deposited locally at the ramp area. Subsequently, *in situ* a thin Au layer of 7 to 8 nm is deposited over the ramp with pulsed laser deposition in an argon environment of 0.22 mbar and with an energy density of 4 J/cm^2.

After applying a photoresist lift-off stencil onto the sample, a short sputter-etch step is carried out removing ~ 2 nm Au, before *in situ* 80 nm of Nb is dc-sputtered to form the low-T_c counter electrode. The Nb films have standard T_c-values of 8.7 to 9.2 K. The last steps in the fabrication-process are the lift-off of the Nb, and the removal of the overlap of Au on top of the $YBa_2Cu_3O_{7-\delta}$ / $SrTiO_3$ bi-layer by standard photolithography and Ar-ion milling.

Junctions were fabricated in this way with widths ranging from 5 to 200 μm. Their electrical characteristics are recorded in a shielded cryostat using a standard 4-probe measurement set-up. The normal state resistivity (R_nA) value as well as the critical current density (J_c) are calculated with the real contact area of the junctions, by taking the ramp-angle into account.

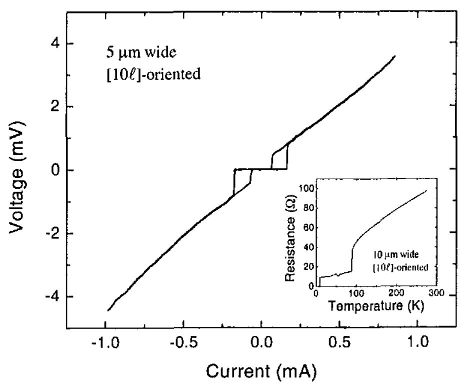

Fig. 2. Current-Voltage characteristic of a 5 μm wide [10ℓ]-oriented ramp-type $YBa_2Cu_3O_{7-\delta}$ / Au / Nb junction at $T = 4.2$ K. The inset shows a typical R-T curve of a similar 10 μm wide junction using a bias current of 1 μA.

III. Experimental Results

The junctions prepared in this work are oriented in two different directions with respect to $YBa_2Cu_3O_{7-\delta}$ crystal-axes: along the [10ℓ]-direction and along the [11ℓ]-direction of the $YBa_2Cu_3O_{7-\delta}$. The former are expected to face a lobe in the superconducting order parameter of high-T_c superconductor, the latter a node, as is indicated schematically in Fig. 1.

First, the electrical properties of both differently oriented junctions will be presented in sections *A* and *B*. A particular interesting aspect is presented by the behavior of the critical currents of both types of junctions in the presence of an applied magnetic field, as will be shown in section C.

A. Junctions aligned with the a- or b-axis of the $YBa_2Cu_3O_{7-\delta}$

The resistance versus temperature curves of the [10ℓ]-junctions (see the inset of Fig. 2) show clearly the transitions of both electrodes, with transition temperatures of 90 K and 9 K for $YBa_2Cu_3O_{7-\delta}$ and Nb respectively. The resistance increases linearly with temperature in the range between 9 and 90 K, indicative for the Nb behavior, as well as in the range above 90 K, dominated by the $YBa_2Cu_3O_{7-\delta}$ material.

All [10ℓ]-oriented junctions show hysteretic current-voltage characteristics at T = 4.2 K and at zero magnetic field. The observed J_c's at liquid helium temperatures exceed 5 kA/cm^2. This result demonstrates that indeed high J_c-values are attainable with this class of ramp-type junctions.

An estimation of the Josephson penetration depth results in λ_J ~ 5 μm. This is in correspondence with the observation that the critical current I_c scales well with the junction-width up to 20 μm including, while for the 50, 100 and 200 μm wide junctions J_c deviates to lower values down to 2 kA/cm^2.

Applying a magnetic flux density of the order of several tenth of μT to the junctions suppresses the I_c completely, which indicates that the structures function indeed as Josephson contacts. The magnetic field dependence of the supercurrent will be discussed in more detail below.

The observed R_nA-values are typically 1 to $2 \cdot 10^{-7}$ Ω cm^2 and remain constant in the temperature range between the T_c of the junction and 3.5 K.

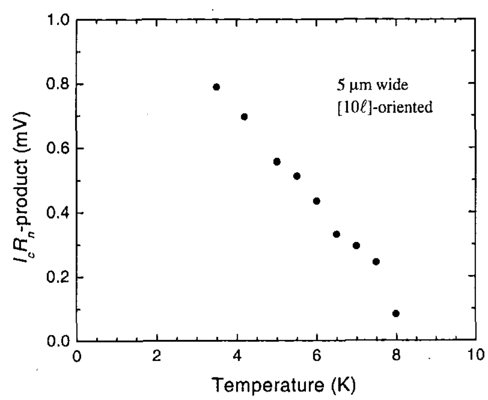

Fig. 3. I_cR_n-product as a function of the temperature for a 5 μm wide $YBa_2Cu_3O_{7-\delta}$ / Au / Nb ramp-type junction oriented in the [10ℓ]-direction.

The hysteretic nature of the current-voltage characteristics is understood by considering the overlap of the top electrode over the bottom electrode, which acts as a shunting capacitance in parallel with the junction. This effect is even enhanced by the used isolator, $SrTiO_3$, which has a high dielectric constant ε_r. Applying the analyses of Zappe [14] to the ratio of the maximum I_c and the minimum return current, and given the overlap length of 7 μm, the ε_r-value of the $SrTiO_3$ at $T = 4.2$ K is estimated to be of the order of 200. This is in correspondence with typical reported data for thin films [15], [16].

An important measure for the quality of the Josephson contacts is the I_cR_n-product. The [10ℓ]-junctions have values of 0.5 to 0.7 mV at $T = 4.2$ K. The obtained values compare very well with the best *in situ* fabricated $YBa_2Cu_3O_{7-\delta}$ / normal metal / Nb contacts reported in literature [7]-[10]. A typical temperature dependence of I_cR_n-product is presented in Fig. 3. A rapid increase below the T_c of the junction is observed, which is presumably due to the fact that the $YBa_2Cu_3O_{7-\delta}$ order parameter has already reached a high value at this temperature. Below, a regime of nearly linear raise in I_cR_n with decreasing temperature is observed.

B. Junctions rotated 45° with respect to the a- and b-axes of the $YBa_2Cu_3O_{7-\delta}$

Junctions rotated 45° with respect to the a- and b-crystal axes of the $YBa_2Cu_3O_{7-\delta}$ electrode typically do not show a clear scaling behavior of I_c with the junction size, which is in contrast with the aligned ones. Zero field J_c's vary between 50 and 500 A/cm^2 at $T = 4.2$ K, which is at least a factor of 10 below the aligned-junction value. The R_nA-values vary between 2 and $6\cdot10^{-7}$ Ω cm^2. The large spread in J_c is reflected in that of the I_cR_n-product for these junctions, which varies from 0.01 to 0.3 mV at $T = 4.2$ K.

Fig. 4 displays a typical *I-V* characteristic of a [11ℓ]-oriented junction. Generally, non-hysteretic curves are observed for these orientations. An estimation of the McCumber parameter β_c based on the derived ε_r values of the deposited $SrTiO_3$ layers of the [10ℓ]-oriented junctions, yields $\beta_c \leq 1$ for these junctions, which is in agreement with this observation.

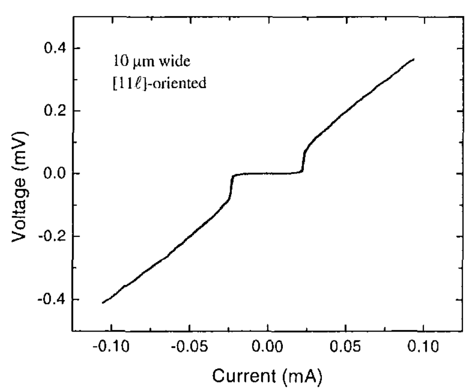

Fig. 4. Current-Voltage characteristic of a 10 μm wide [11ℓ]-oriented ramp-type $YBa_2Cu_3O_{7-\delta}$ / Au / Nb junction at liquid helium temperature.

C. Magnetic field dependence of the critical current

The dependence of the critical current on the applied magnetic field $I_c(B)$, for the two different types of junctions, presents particularly interesting aspects. Typical $I_c(B)$-dependencies are shown in Fig. 5 for the [10ℓ]- and [11ℓ]-oriented junctions.

The magnetic field is applied perpendicular to the substrate surface, creating in this way identical situations for both differently oriented junctions. The patterns are symmetric around zero field as well as for positive and negative voltage bias, indicating that the trapped flux is insignificant in all presented cases.

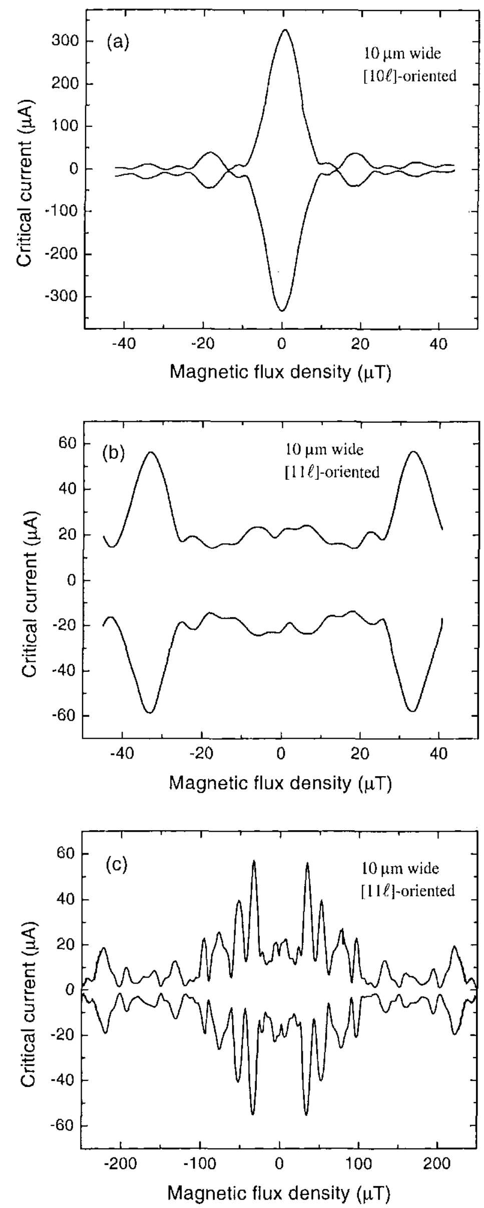

Fig. 5. $I_c(B)$-dependences of 10 μm wide ramp-type $YBa_2Cu_3O_{7-\delta}$ / Au / Nb junctions at $T = 4.2$ K and with a voltage bias of 5 μV: (a) [10ℓ]-oriented, (b) [11ℓ]-oriented, and (c) the same junction as in (b) for a wider scan in the magnetic field.

For the aligned junctions, I_c shows a maximum at zero field, while the magnetic field dependence yields the expected Fraunhofer-like pattern. Very irregular, though symmetric, $I_c(B)$-patterns are obtained for the nodal-oriented junctions. No declining envelope nor any obvious periodicity is found in the $I_c(B)$-pattern. An important observation is the fact that the maximum critical currents are clearly at $B \neq 0$, which can only be achieved from interference effects in junctions containing regions with 'negative' critical current densities (π-regions) [17].

A wider scan in the magnetic field of the same junction is presented in Fig. 5c. Interestingly, the characteristics of these 45° rotated samples look similar to those obtained for asymmetric 45° [001]-tilt grain boundaries in $YBa_2Cu_3O_{7-\delta}$ [17]-[19]. An explanation is provided for that system by considered faceting of the grain boundary and the predominant $d_{x^2-y^2}$ symmetry of the order parameter, leading to an array of 0- and π-facets along the interface.

IV. Discussion

Supposing a predominant $d_{x^2-y^2}$ order parameter symmetry, the huge experimentally observed difference between [10ℓ]-oriented and [11ℓ]-oriented junctions can be well understood. The overlap of the niobium order parameter with the $YBa_2Cu_3O_{7-\delta}$ order parameter is maximally established in the [10ℓ]-case; the magnitude of the lobe of the $YBa_2Cu_3O_{7-\delta}$ reaches its highest value in this direction in the a-b plane (the [01ℓ]-orientation is assumed to be an equivalent direction). For connections in the [11ℓ]-direction, a vanishing critical current is expected in first order due to the node in the superconducting gap of the $YBa_2Cu_3O_{7-\delta}$ electrode. The observed remaining Josephson current, and its magnetic field dependence, may arise as an effect of irregularities in the ramp microstructure. This leads to analogue effects as observed for the 45°-grain boundary junctions mentioned before. Also contributions due to coupling in the c-axis direction, or to possible admixtures of other symmetry components to the $YBa_2Cu_3O_{7-\delta}$ order parameter may play a role.

V. Conclusion

Summarizing, $YBa_2Cu_3O_{7-\delta}$ / Au / Nb Josephson junctions have been prepared successfully in ramp-type technology, allowing on one chip junctions having different orientations with respect to the cuprate crystal axes. High critical current densities are observed with the [10ℓ]-oriented junctions, exceeding 5 kA/cm^2, while the I_cR_n-product of over half a millivolt at liquid helium temperatures compares to the best values, found for all-*in situ* tri-layer contacts, reported in literature. The observed $I_c(B)$-patterns for differently oriented junctions are consistent with a predominant $d_{x^2-y^2}$-symmetry of the order parameter of the $YBa_2Cu_3O_{7-\delta}$. The successful implementation of these flexibly oriented junctions demonstrates the feasibility to fabricate novel phase-devices, such as theoretically proposed qubit-structures [2], [3] and complementary Josephson electronics [20].

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