Microstructure and Josephson phenomenology in 45° tilt and twist YBa$_2$Cu$_3$O$_{7-\delta}$ artificial grain boundaries

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I. INTRODUCTION

The investigation of the relation between microstructure and transport properties in high-temperature superconducting (HTSC) grain-boundary (GB) Josephson junctions (JJ’s) is considered fundamental both for the basic understanding of the order-parameter symmetry in high critical current superconductors and for the implementation of reliable technologies based on Josephson junctions. Several kinds of artificial grain boundaries (AGB’s) have been produced since the discovery of high-$T_c$ superconductivity, and their microstructure has been thoroughly investigated. Artificial grain boundaries (AGB’s) in YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) characterized by a tilt in the a-b plane (i.e., a rotation around the c axis) have been realized on bicrystals or by biepitaxial fabrication techniques, and have been investigated in detail. The transport properties of the wide class of GB’s characterized by an orientation difference between the c axes are still mostly unexplored. Only 90° tilt boundaries produced on artificial substrate steps have been analyzed in detail.

The available experimental results indicate that the transport properties of GB’s depend on many factors. Beside the relative orientation of the electrodes, the orientation of the interface plane plays a major role, as emphasized by the comparison between symmetric and asymmetric bicrystal junctions. Furthermore, the “macroscopic” orientation of the interface, as determined by the fabrication parameters, describes only roughly the actual meandering of the GB revealed by microstructural analyses, which is determined by partly controlled factors such as growth mode, growth velocities and faceting. Meandering GB’s, exhibiting different kinds of interfaces, are actually found in bicrystal, biepitaxial, and step-edge junctions.

YBCO junctions based on AGB’s characterized by a 45° relative misalignment of the c axes and realized by a biepitaxial technique have been produced recently. The AGB is obtained at the interface between a (103) film deposited over a (110) SrTiO$_3$ substrate and a c-axis film deposited over a MgO seed layer (Fig. 1). Junctions associated with this AGB exhibit promising Josephson properties. Two different AGB’s characterized by a 45° tilt or twist of the c axis across the GB are considered. We will refer to them in the following as “tilt” or “twist” AGB’s, respectively. As shown below, this technique exploits the anisotropic properties of YBCO. It offers a unique possibility to modify the structure and transport properties of the AGB by controlling the orientation of the AGB and the order-parameter symmetry in high critical current superconductors.
entation of the interface, which is defined by the fabrication process.

The aim of the present work is to investigate some almost unexplored configurations of the wide class of GB’s characterized by a misalignment of the c axes, looking for a direct correlation between the grain-boundary microstructure and superconducting properties. This is of great interest for the understanding of the nature of transport in superconducting GB’s, which is still an open issue. Furthermore, it allows the investigation of the order-parameter symmetry in HTSC’s, by taking advantage of the anisotropic and easily tunable properties of the proposed structure. Finally, we will show that the technology we implemented provides a Josephson structure able to offer some advantages, in terms of applications, over junctions obtained by other techniques. Some examples are ease of integration for circuit design and high transport property characterization of these AGB Josephson junctions. A microstructural characterization, along with detailed measurements of the Josephson phenomenology is reported. The differences between the transport properties of the two AGB are discussed in terms of a qualitative growth model.

II. JUNCTION FABRICATION PROCEDURE AND EXPERIMENTAL SETUP

The fabrication process involves the deposition of MgO and YBCO thin films and ion-milling procedures. (110)-oriented MgO thin films are deposited by rf magnetron sputtering from a stoichiometric oxide target on (110) SrTiO$_3$ (STO) substrates. Details of the optimization of (110) MgO seed layers suitable for YBCO growth have been reported elsewhere. In the present case a thin MgO seed layer (20 nm) was deposited at a substrate temperature of 600 °C. A standard lithographic procedure, employing a Nb mask, ion milling, and reactive ion etching, was used to pattern the seed layer. YBa$_2$Cu$_3$O$_{7-x}$ films with a thickness of 120 nm were deposited by inverted cylindrical magnetron sputtering in an Ar/O$_2$ atmosphere ($P_{O_2} = P_{Ar} = 50$ Pa) at a temperature of 780 °C. Finally, microbridges having widths ranging from 4 to 8 μm were fabricated by H$_3$PO$_4$ and HF wet etching.

Cross section (CS) as well as plan view samples for electron microscopy have been prepared by standard mechanical polishing and ion milling. High-resolution electron microscopy (HREM) observations were performed in a Jeol 4000 EX microscope with a point resolution of 0.17 nm.

III. EXPERIMENTAL RESULTS

A. General description of the AGB

In order to study the differences between the 45° tilt and twist AGB’s, schematically shown in Fig. 1, the morphological, microstructural, and transport properties were analyzed and compared. The morphology of twist and tilt AGB’s is shown in the SEM micrographs of Figs. 2(a) and 2(b), respectively. The most striking morphological difference between the two cases is the different orientation of the needlelike (103) grains, which are elongated along the [110]$_{STO}$ direction, with respect to the interface. The needlelike morphology of (103) grains in the twist junction of Fig. 2(a) is slightly less evident than Fig. 2(b), and is indicative of a slightly vicinal cut of the (110) STO substrate. The expected microstructure of the grain boundary, in the ideal case of a vertical interface, is schematically represented in Figs. 3. In Fig. 3(a) the rotation between the two electrodes is around an axis parallel to the interface (tilt case). In Fig. 3(b), the rotation axis is perpendicular to the interface (twist case). Mea-
measurements of current vs voltage have been performed as a
function of temperature and externally applied magnetic
field. They are presented in Sec. III B, where evidence of the
Josephson behavior of the two AGB’s is given. A detailed
analysis of the interface has also been performed based on
HREM investigations and is reported in Sec. III C.

B. Current-voltage characteristics and the Josephson effect

From the typical I-V characteristics at \( T = 4.2 \) K of a twist
and a tilt junction, shown in Fig. 4, one can clearly distin-
guish two different regimes in terms of the critical current
densities \( J_C \) and the normal-state specific conductances \( \sigma_N \),
corresponding to the two types of AGB’s. In both cases the
maximum working temperature \( T_C \) of the devices is typically
higher than 77 K. Twist AGB junctions typically have \( J_C \)
values in the range 0.1–4.0 \( \times 10^5 \) (A/cm²) and \( \sigma_N \) values in
the range 20–120 \( \mu \Omega \) cm\(^{-1} \) at \( T = 4.2 \) K. Tilt AGB
junctions have lower \( J_C \) and higher \( \sigma_N \) values, in the ranges
0.5–10 \( \times 10^3 \) (A/cm²) and 1–10 \( \mu \Omega \) cm\(^{-1} \), respectively.
For both types of GB’s these values were estimated using the
nominal junction width. They can be changed by a factor of
2, in the worst case, by the presence of impurities at the
junction interface,\(^{12} \) which can reduce the actual width. \( J_C \)
and \( \sigma_N \) values fall in the ranges typical for in-plane GB JJ’s,
usually fabricated using bicrystal or conventional biepitaxial
techniques.\(^{13} \) The \( I_C R_N \) values are high in both cases, of the
order of 1–2 mV at \( T = 4.2 \) K These are plotted as a function of
\( J_C \) and compared with those from other types of
junctions\(^{13} \) in the inset of Fig. 4. They are larger for the
corresponding \( J_C \) values than those provided by conven-
tional biepitaxials and are of the same order of magnitude as
in bicrystal and step-edge junctions. At \( T = 77 \) K, \( I_C R_N \) is
approximately 50 \( \mu \)V.

The Josephson nature of the junctions has been verified
by applying an external magnetic field \( H \). A typical \( I_C(H) \)
pattern measured at \( T = 4.2 \) K is shown in Fig. 5(a), where
\( I-V \) curves are plotted as a function of \( H \). A Fraunhofer-like
dependence of \( I_C \) on \( H \) is evident, as well as slight deviations
manifested in the fact that \( I_C \) does not modulate down to
zero. The pattern is symmetric around zero magnetic field,
and in all samples the absolute maximum of \( I_C \) occurs at
zero magnetic field.\(^{14} \) In Fig. 5(b), \( I-V \) curves are given for
different values of the magnetic field. The appearance of
steps at finite voltages can be clearly distinguished. This be-
behavior will be briefly considered in the next section.

C. Interface features in the artificial grain boundaries

The cross section (CS) HREM images shown in Figs. 6,
7, and 8 confirm the expected nature of the AGB, but reveal
in addition the presence of more complex interfaces between
the two orientations.

Figure 6 shows a 45° twist AGB observed in CS along the
[1 1 0] MgO/STO direction. The edge of the MgO seed layer
is indicated. The (001) film protrudes over the MgO edge.
This is a consequence of the high growth velocities of (001)
YBCO grains in the \( a-b \) plane, a well-known feature of the
YBCO growth mode.\(^{10,15} \) No spurious phases appear at the
AGB interface in this case. The interface is sharply defined,
implying that it is oriented normal to the image plane on the
length scale of the sample thickness. Beside a basal plane
(BP) facet close to the MgO edge, indicated by (001) in Fig.
6, the interface is rounded and seems to follow the growth
front of the (001)-oriented film, rather than following a pre-
cise crystallographic orientation.

For the case of tilt AGB’s we have observed different
kinds of interface planes. In Fig. 7, a highly perfect faceted
interface is shown, separating the (001) basal plane (BP) of the (103)-oriented film and the (001) film. In Fig. 8 the tilt AGB exhibits an irregularly stepped interface. The orientation of the (103) domains at the interface is different in Figs. 7 and 8, as shown by the arrows indicating the [001] YBCO direction. Beside the small facet close to the substrate (which again separates the BP of the (103)-oriented film and the (03) plane of the c-axis film), the interface in Fig. 8 does not show any clear geometrical relation with the YBCO axes of either crystal. The Moiré interference pattern at the AGB indicates that the interface is also meandering along the electron beam direction (i.e., along the [001] STO direction). A qualitative model explaining the different morphologies of the tilt AGB shown in Figs. 7 and 8 is presented in the next section.

Quite unexpectedly we found that the position of the grain boundary can be shifted away from the MgO edge over the MgO seed layer. An extreme case is shown in Fig. 9, where the distance between the edge in MgO and the grain boundary is about 200 nm. The presence of the Y$_2$O$_3$ precipitate at the MgO edge is not relevant for the shift since other cases without Y$_2$O$_3$ have been observed too. The possible origin of such a shift is discussed in the next section.

**D. Structural properties of the (001) and (103) films**

We separately investigated the properties of (001) and (103) YBCO films in regions far from grain boundary. Spurious phases are found both on (103) and (001) films. Their nature and growth will be discussed in detail in a separate paper. In some cases, precipitation of spurious phases at the AGB was observed. Data obtained from the (001) YBCO film confirmed the high structural quality achieved for YBCO growth on (110) MgO (as already demonstrated in Ref. 9). Figure 10 shows a CS HREM image of the (103) film. It clearly demonstrates the presence of a domain structure of (103) and (03) grains separated by 90° tilt intrinsic grain boundaries (IGB’s). Microbridges patterned perpen-
IV. DISCUSSION

In this section we explore the correlation between GB transport properties and the GB microstructure by analyzing the junction barrier properties. Data presented in the previous section indicate that these structures, despite some lack of uniformity on the scale of tens of nm, exhibit clear Josephson phenomena originating from the grain-boundary barrier region. We describe the junction under study within the framework of the phenomenology of other HTSC GB Josephson junctions. Finally, we analyze the GB formation from the point of view of YBCO growth habits and propose modifications of the manufacturing process that could allow to select a single type of atomically clean interface.

A. I-V characteristics and the junction barrier

The I-V curves usually exhibited resistively shunted junction-like behavior, although in some cases deviations related to the presence of an excess current $I_{\text{exc}}$ were observed (Fig. 4). A general correlation between the presence of $I_{\text{exc}}$ and high critical current densities has been demonstrated. $I_{\text{exc}}$ could be directly related to supercurrents with a nonzero time average and to the fact that the junction is long. A transition from the long to the short junction limit is normally induced by increasing the temperature in both low- and high-$T_C$ superconductor Josephson junctions. More recently the disappearance of $I_{\text{exc}}$ has been obtained by irradiating HTSC GB junctions by an electron beam, by decreasing the critical current density and increasing the Josephson penetration depth. Another explanation of the presence of $I_{\text{exc}}$ could be based on the proximity effect in the barrier region and the nonequilibrium state of quasiparticles in the superconducting electrode.

The dependence of the critical current $I_C$ on the temperature provides information on the nature and morphology of the junction and its transport mechanism. Typical dependences of the critical current $I_C$ on the temperature $T$ are reported in Fig. 11 and compared with the results on 10° and 15° tilt YBCO bicrystal Josephson junctions from Ref. 1. Here, the $I_C$ curves were normalized to the corresponding value at $T=0.2T_C$ and plotted as functions of the reduced temperature $T/T_C$. We first notice from the plots in Fig. 11 that the tilt and twist cases are quite different from each other, especially at lower temperatures. In the case of the 45° tilt junctions, $I_C$ tends to saturate at lower temperatures. This behavior resembles more the dependence for traditional weak links characterized by low values of the ratio $L/\xi_N$ (where $L$ is the barrier thickness and $\xi_N$ is the coherence length at $T=T_C$ in the normal barrier) and a barrier transparency that can be very low. Within this framework, the proximity effect would be expected to play a fundamental role. In the case of the 45° twist, an approximately linear increase of $I_C$ is observed over a wide range of temperature down to 0.2$T_C$. This is similar to the bicrystal case, as shown in Fig. 11. Such a behavior is typical of the HTSC junctions that deviate from the ideal Josephson dependence. Moreover, the values of the normalized $I_C$ of c-axis 45° tilt junctions are always lower than those corresponding to in-plane 10° and 15° tilt GB junctions in the whole temperature range 0.2$T_C$. The normal-state resistances are slightly affected by the temperature both for the tilt and the twist case.

When an external magnetic field is applied, apart from the modulation of the critical current (see below), the appearance of steps at finite voltages is clearly observed [see Fig. 5(b)]. These are frequently observed in HTSC GB’s Josephson junctions and are related to Fiske resonances. They give some evidence of the presence of a dielectric layer at the GB of the junction and quantitative information on the ratio between the barrier thickness $s_B$ and the relative dielectric constant $\varepsilon_r$. The nonlinear interaction of the ac Josephson current with the cavity causes self-induced resonances of order $n$ at voltages $V_n=n\Phi_0c/2W$, where $c=c_0/(\Phi_0/2\varepsilon_r\lambda_L)^{1/2}$ is the Swihart velocity, $c_0$ is the vacuum velocity, and $\lambda_L$ is the London penetration depth. We observed the first resonance structure at voltages $V_1$ typically ranging from 200 to 300 $\mu$V for 5 $\mu$m wide junctions. If we apply a Fiske mode...
analysis, for a value of \( \lambda_f = 150 \text{ nm} \), these resonances roughly correspond to \( t_R/e \) values ranging from 0.015 to 0.05 nm. These results are consistent with measurements on other types of GB junctions, characterized by low values of the critical current density. Additional information on Fiske steps and the barrier structure have been obtained by irradiating the junctions with an electron beam, demonstrating the tunability of the phase velocity for the electromagnetic wave and vortex propagation in the YBCO GB junctions.

As far as the magnetic-field dependence of the critical current, an example has already been given in Fig. 5(a). The observed magnetic modulation of \( I_C \) is quite different from those of asymmetric in-plane 45° (001) tilt bicrystal and biepitaxial junctions, in which the absolute \( I_C \) maximum is observed for \( H \parallel 0 \). On the other hand, the two behaviors reflect different GB microstructures and their influence on transport properties. An explanation could be found within the framework of a \( d \)-wave symmetry order parameter. In fact, the presence of the absolute \( I_C \) maximum for \( H \parallel 0 \) has been shown to be consistent with an interpretation based on \( d_{x^2-y^2} \)-wave symmetry and on grain-boundary faceting. Among other effects, the \( d_{x^2-y^2} \) symmetry component causes order-parameter depression at the grain boundary, inhomogeneous current distributions in the junctions and reduced \( I_C R_N \) products. In Fig. 12 we illustrate the \( d \)-wave order-parameter orientations for our junction configuration, and compare them with the ones in the asymmetric 45° tilt bicrystal, taking into account the intrinsic faceting. Apart from the previously discussed difference related to the orientation of the interface with respect to the \( c \) axis, a fundamental difference is that the order parameter orientations do not produce an additional \( \pi \) phase shift along our junction in contrast with the 45° tilt bicrystal junctions. When additional \( \pi \) phase shifts arise, as in the 45° tilt bicrystal junctions, the Josephson current across the facets flows in the direction opposite to that of the current across other facets (“negative” critical current density). This situation does not occur in our junction configuration, independently of the details of the interface orientation. We also note that the absence of “negative” critical current density also occurs if we consider the influences of the grain-boundary plane with respect to the substrate normal. On this basis we can argue that no unquantized magnetic flux would be expected in our junctions and low-frequency \( 1/f \) noise could be lower than in the asymmetric in-plane 45° (001) tilt bicrystal and biepitaxial junctions. Our structure could, therefore, allow one to explore further the order-parameter symmetry in a junction configuration.

Although the detailed nature of the boundary is not addressed here, in summary our results suggest that the barrier, arising from the 45° tilt and twist of the \( c \) axis, can be dielectric in nature, and that there is a depression of the order parameter of the regions facing the grain boundary. We also speculate that the symmetry of the order parameter can generate a peculiar phenomenology in our junction configuration.

B. Grain boundary as a tunable barrier

Data presented in the previous section on tilt and twist AGB’s confirm that the orientation of the interface strongly affects transport properties, such as critical currents, normal-state resistance, etc. It can, therefore, be expected that the properties of our junctions can be changed by continuously varying the orientation of the MgO edge between the two limiting configurations explored in the present work. The barrier properties can therefore be tuned by the method described above.

This possibility of modifying the AGB macroscopic interface plane by controlling the orientation of the seed layer’s edge is somehow equivalent to the degree of freedom offered by bicrystal technology to create symmetric or asymmetric AGB’s. In both cases, the average orientation of the interface is modified while keeping the relative misorientation between the electrodes unaltered. The very strong impact of the interface orientation on transport properties is specific to our case, differently from bicrystals. Furthermore, the control of the interface orientation is obtained in our case by photolithographic means alone.

The HREM micrographs indicate that the fabrication procedure (i.e., the control over the orientation of the MgO edge) does not allow us to control with accuracy the microstructure of the interface at the atomic level. A variety of different interfaces exist for both 45° tilt and twist boundaries. As a consequence, the homogeneity of our junctions (as inferred by \( I_C \) modulation in an applied magnetic field) and the reproducibility of junction parameters is not as yet comparable with the best results which are achieved by resorting to better established AGB techniques. In order to assess clearly the weak-link behavior of one specific kind of boundary and to obtain reliable Josephson devices, the controlled growth of a clean homogeneous interface across the whole section of the microbridge is required. Such a requirement has not been reproducibly fulfilled, to date, by any of the known AGB fabrication technologies.

On the basis of the HREM data, the only well-defined interfaces obtained in 45° or 90° c-axis tilt and twist boundaries are interfaces bound by the basal plane (BP) of one electrode. It would be highly desirable to employ the degrees of freedom of our fabrication process to select the formation of such an interface. For this purpose we model the interface...
formation between (001) and (103) films and discuss the factors that can lead to the formation of a specific interface plane. First we need to model the growth of (103) films.

C. Qualitative model for the growth of (103) films

On the basis of our HREM images and the present knowledge of the morphology and growth of YBCO grains, the (103) nuclei before coalescence can be depicted as shown in Fig. 13. Let us now analyze the growth and the coalescence of such grains. The following considerations will allow a joint analysis of the tilt intrinsic grain boundaries and tilt AGB’s.

We believe that the side of the (103) nuclei terminated by the basal plane face, marked BPF in Fig. 13(a), is a slow growing side, due to the layered growth mode of YBCO and to the lack of favorable sites for the nucleation of new layers. The opposite side (let us call it the rough side) should grow relatively quickly, due to the abundance of steps and kinks provided either by the grain morphology or by the angle at the grain-substrate interface. The presence of two differently oriented grains as shown in Fig. 13(a) is usually accounted for by the double notation (103) and (103). Both domains differ by a 90° tilt rotation. Referring to Fig. 13(a), we will identify (103) domains with their basal plane face on the right side as BPF-R (basal plane face right). Accordingly, the (103) grains will be called BPF-L, basal plane face on the left side.

In the early stage of growth, BPF-R and BPF-L nuclei expand along the [11̅0] direction, as well as in the fast growing [001] direction, corresponding to the [010] direction. On the basis of the former hypothesis, BPF-R (BPF-L) nuclei expand faster on the left (right) side. When a BPF-R nucleus growing on the right and a BPF-L nucleus growing on the left meet, they will form a 90° tilt boundary. Boundaries are determined more by the growth dynamic (i.e., by the shape and growth mode of coalescing grains) than by the surface energy minimization, since the process takes place far from equilibrium. The boundary formed in this phase are roughly symmetric on a “macroscopic” scale, due to the similar shapes of the rough sides of coalescing grains [Fig. 13(b)]. On the atomic scale, they appear to be stepped and characterized by facets where the BP of one grain meets the (100)/(010) facets of the other grain.

If the two meeting grains have roughly the same height, they will form a triangular grain bounded by slowly growing (001) surface. In this configuration, the growth velocity along the [1̅1̅0] substrate direction will be further reduced with respect to the [001] direction, thus contributing to the elongated shape of (103) films shown in Figs. 2(a) and 2(b). During the following stages of film growth, the triangular grain might be covered and embedded by bigger nuclei expanding either in the [̅110] or in the [1̅10] direction [Fig. 13(c)]. Our qualitative model accounts for the observed microstructure and the intrinsic grain boundaries of the (103) film.

D. Different kinds of 45° c-axis tilt boundaries

Let us now analyze the contact of a c-axis grain growing on the left side and a BPF-R or a BPF-L growing on the right side. The expected growth of the grain boundary with increasing film thickness is qualitatively sketched in Figs. 14(a) and 14(b), respectively. The depicted evolution of the growing grains is based on the arguments of the former subsection and on established knowledge about the YBCO growth mechanism. One can see that the situations shown in Figs. 14(a) and 14(b), respectively, correspond to the AGB’s of the HREM images of Figs. 7 and 8. The contact of the c-axis grain with a BPF-L (103) grain leads to the formation of an almost perfect interface that might be suitable for the fabrication of homogeneous Josephson junctions. The contact of the c-axis grain with a BPF-R (103) grain instead to the formation of a rough irregular interface. These configurations are different not only because of the roughness which influences the uniformity of the junction but also for the microstructure, which could give rise to different transport properties.

On the base of simple symmetry arguments, we estimate that the (103) side of the actual GB interface is equally divided into BPF-L and BPF-R grains. However, note that (103) films containing only BPF-R or only BPF-L grains can be grown by using vicinal (110) substrates (namely, with the normal tilted off [110] axis towards the [010] direction). Therefore, from the analysis of HREM data, we suggest that the structure of the GB could indeed be tailored by suitably controlling the fabrication parameters, and that high-quality uniform BPF 45° tilt AGB’s might be obtained by this technique.

E. Shift of the grain boundary with respect to the MgO edge

The positions of the grain boundary, which is found in Fig. 9 on top of the MgO layer rather than on the edge, is unexpected. At first sight, the HREM images reported in Fig.
9 seem to suggest that a (103) grain nucleated on the right of the edge has overlapped the substrates by 200 nm growing in the STO direction. Under this hypothesis, the orientation would be preserved over the MgO seed layer because of lateral self-epitaxy of YBCO on the growing front of the grain. There are nevertheless two arguments against this interpretation.

1. The overlapping would be justified if the growth velocity of (103) grains in the STO direction exceeded the in-plane growth velocity of the (001) film. In fact, anisotropy of growth velocities in YBCO suggests the opposite to be true.

2. The presence of IGB’s in the (103) does not agree with the hypothesis of lateral self-epitaxy from the right. Rather, we believe that the cross section shown in Fig. 9 is due to the waviness of the MgO edge, as depicted in Fig. 15. According to this interpretation, the (103) grains shown in Fig. 9 would consist of BPF-R and BPF-L domains nucleated in a recess of a seed layer edge that have overlapped the MgO growing in the “fast” [001] STO direction. According to this interpretation, the shift of the grain-boundary position could be reduced by reducing the waviness of the MgO edge with suitable improvements in lithography.

FIG. 14. (a) A schematic representation of the formation of a 45° tilt AGB with a basal plane of the (103) film as interface plane. This type of interface occurs when a BPF-L (103) oriented grain meets the (001) film. (b) When a BPF-R (103) grain meets the (001) film a rough irregular interface is formed.

V. CONCLUSIONS

The Josephson properties and the microstructure of grain-boundary junctions characterized by a 45° relative misalignment of the c axes (45° tilt and twist) have been investigated. On the basis of HREM data, the nature and the orientation of the different GB interfaces that can be found in our junctions have been analyzed and discussed in detail. The dependence of the microstructure on the details of the growth process, and the influence of microstructure on the transport properties have been also investigated.

We have analyzed the properties of our junctions, with particular attention to the differences with asymmetric in-plane 45° (001) tilt bicrystal and biepitaxial grain-boundary Josephson junctions. The analysis indicates that one could employ the junctions described in this paper in applications and for fundamental studies on the symmetry of the order parameter. We argue that no unquantized magnetic flux would be expected in our junctions. Potential improvements of interface quality, based on a careful control of the film growth, are also discussed. It is inferred that the growth of atomically clean interfaces could be selected by employing vicinal substrates.

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