Unger Nr. 80

Physics and Technology of High Temperature Superconducting Josephson Junctions

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Abstract— **The controllable fabrication of reliable HTS Josephson junctions with sufficiently small spread of their characteristic parameters has not yet been achieved and prevents the successful use of HTS Josephson junctions in complex integrated circuits. The problems in HTS junction fabrication certainly are related to the specific properties of the cuprate superconductors, which make the fabrication of high quality interfaces in HTS junctions employing artificial barrier layers extremely difficult. Therefore, several types of HTS Josephson junctions make use of so-called intrinsic interfaces originating from grain boundaries or the intrinsic layer structure of the cuprates. Beyond the fabrication technology, the physics of HTS Josephson junctions is not well understood. In particular, the detailed mechanisms of charge transport in the various junctions types and the impact of an unconventional symmetry of the superconducting order parameter are unsettled issues. We summarize the key issues regarding the physics and technology of HTS Josephson junctions and discuss possible routes to a useful HTS junction technology.**

I. Introduction

There is encouraging progress in the fabrication of useful high temperature superconducting (HTS) devices based on Josephson junctions (JJs) (see e.g. [1]–[5]). However, until now the ideal approach in HTS-JJ technology satisfying all requirements for complex integrated circuits such as sufficiently small spread of critical current still cannot be identified [2]. For the metallic low temperature superconductors (LTS) the most successfully used junction technology is based on a more or less complex planar layer structure consisting of two superconducting (S) electrodes separated by an artificial barrier layer, which may be a normal metal (N), an insulator (I), or a semiconductor (Se). In such a junction technology the *extrinsic* interfaces between the electrodes and the barrier layer as well as the quality and homogeneity of the artificial barrier layer determine the junction properties. For HTS the fabrication of such layer structure is very difficult. Firstly, in contrast to LTS for HTS a fully epitaxial layer structure is required. Secondly, the short coherence length (only about 1 - 2 nm in *ab*-direction and less than 0.2 nm in *c*-axis direction) and the strong sensitivity of the HTS to structural and chemical changes imply that interfaces in such structures must be perfect on an atomic scale. However, at present the engineering and precise control of interfaces in the commonly used fabrication processes as well as the detailed understanding of the physics and chemistry of interfaces in HTS systems are still lacking. This so far prevents the controllable and reproducible fabrication of HTS-JJs with sufficiently small spread of their characteristic parameters.

Due to the difficulties related to the fabrication of HTS-JJs involving *extrinsic* interfaces, in HTS-JJ technology methods exploiting the special properties of HTS materials such as the intrinsic Josephson effect in *c*-axis direction or the use of the controlled grain boundary nucleation for grain boundary Josephson junctions (GBJs) still appear favorable. In this approach the junction properties are determined by *intrinsic* interfaces and/or barrier layers. However, also in this case the fabrication of junctions, which are useful in complex circuits, requires the optimization and precise control of the intrinsic interfaces/barriers what has not been achieved so far. Furthermore, in this approach it is more difficult to vary the junction properties such as the critical current density over a wide range.

At present there are a few key problems regarding physics and technology of HTS-JJs. Without any doubt a key question is related to the quality and uniformity of interfaces and barrier layers. A viable JJ-technology requires perfect interfaces and a spatially homogeneous, uniform barrier to allow the control and specific variation of the junction properties and to achieve good reproducibility. However, so far the structural and electrical transport properties of most JJs indicate the presence of spatially inhomogeneous and in some cases heterogeneous interfaces and barrier layers. There is no doubt, that research aiming at the improvement of HTS-JJ technology primarily has to attack this problem. In this context the spatially resolved analysis of the junction properties is highly important to get information on the nature and the characteristic length scales of the non-uniformities. A further important issue refers to the nature of charge transport in HTS-JJs. Due to the complicated nature of both interface layers and barrier materials, for most HTS-JJs the detailed transport mechanism has not yet been identified. Since HTS materials are close to the metal-insulator transition, the transport mechanism in these materials can vary strongly over a few lattice constants due to variations of the oxygen content, oxygen disorder, strain, or chemical reactions. Hence, the possible transport mechanisms across intrinsic and extrinsic interfaces may in-

Manuscript received August 26, 1996.
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This work was supported by the BMBF, project No.: 13N6434 and the Deutsche Forschungsgemeinschaft.

clude direct tunneling, resonant tunneling, hopping, or diffusion, depending on the amount of degradation of the HTS material and the length scale of the degraded region. Finally, beyond the problems related to interface engineering and materials technology there are more fundamental issues such as the two-dimensional nature of the HTS, the possibly unconventional symmetry of the superconducting order parameter, or a strong mismatch of the carrier density and the Fermi velocity between the HTS electrodes and a N-barrier that have to be taken into account in the development of HTS Josephson junctions.

The intention of this review is to briefly summarize the present knowledge on the physics and technology of HTS-JJs. Since it is impossible to consider all the different facets of this wide field of research, we try to work out only the most general and fundamental aspects of HTS-JJs. In particular, our survey will focus on the technological demands and the electrical properties common to most types of HTS-JJs. In addition, we discuss the present knowledge on the transport mechanisms and address the problem of spatially inhomogeneous junction properties. Finally, we point out that this overview gives our personal view of a field that still is discussed controversially. It only intends to be representative of literature, but cannot be exhaustive.

II. Survey on HTS Josephson Junctions

A. Classification

It is well known that the Josephson effect exists between any weakly-coupled superconductors [6]. There are different ways to classify HTS weak links. Traditionally, Josephson junctions were classified into tunnel junctions, proximity effect coupled junctions and constriction type junctions depending on whether the weak coupling is established by a thin insulating tunnel barrier, a normal metal or a narrow geometrical constriction, respectively. In the former junction type the transport mechanism is tunneling, whereas diffusive transport is present in the latter junctions. Unfortunately, for many HTS-JJs it is difficult to assign them unambiguously to one of these classes, since the detailed transport mechanism (e.g. tunneling, resonant tunneling, hopping, diffusion) is not known. Initially most types of HTS junctions were considered to be proximity coupled junctions and their transport properties have been interpreted with reference to conventional proximity effect theory. However, for GBJs it has been shown quite early by Gross *et al.* that their transport properties are better described by tunneling and resonant tunneling across an insulating grain boundary barrier containing a large density of localized states (LS) [3], [7], [8]. Very recently, a detailed analysis by Delin *et al.* [5] showed that almost none of the HTS-JJs passes the ultimate tests for simple proximity effect theory.

Alternatively, due to the importance of interfaces in HTS junction technology, it is more natural to classify HTS-JJs into:

1) junctions without interfaces: Constriction type junctions such as nanobridges (NBs) and weakened structure junctions (WSJs), where the weak coupling is achieved by locally degrading the superconducting properties of a HTS thin film microbridge by focused electron or ion beam irradiation, have no (at least no well defined) interfaces. These junctions are based on a single layer technology and therefore are simple to fabricate. The fabrication of WSJs is based on the strong sensitivity of HTS to structural changes as well as to oxygen deficiency and disorder. At present, the direct electron beam writing technique developed at Stony Brook [9] and in Cambridge [10] allows the reproducible fabrication of HTS junctions with parameter spreads as small as 10% (3σ) on chip. However, these junctions still do not show the necessary long-term stability, although considerable improvement in this direction has been achieved [10]. The HTS junctions based on local oxygen ion implantation (100 keV) have been pioneered by Tinchev [11]. Recently, a more systematic study of junctions implanted by O^+, Ar^+, and Ga^+ has been performed [12]. Beyond the simplicity of fabrication and the absence of any topological limitations, the possibility to dial in the desired J_c-value of the junctions by varying the ion fluence makes this junction type attractive. However, a further improvement of their I_cR_n products ($< 50\mu V$ at 77 K) is still required.

2) junctions with intrinsic interfaces/barriers: Although the special properties of HTS-materials so far prevent the fabrication of useful SIS-type planar junctions, they allow the fabrication of a new class of JJs based on intrinsic interfaces/barriers. This type of junction is not known for the metallic superconductors. It is interesting to note that despite a considerable technological effort the interfaces and barrier layers in these junctions, which are given by nature, so far are superior to those generated artificially. This new class of junctions is formed by the different GBJs such as bicrystal (BC-GBJs), step-edge (SE-GBJs) and biepitaxial (BE-GBJs) as well as the intrinsic Josephson junctions (IJs).

The GBJ-technology is based on the pioneering work of the IBM group on BC-GBJs [13]–[15]. An overview on BC-GBJs can be found in [3], [4]. In this technique the grain boundary present in the bicrystal substrate ($SrTiO_3$, MgO, $NdGaO_3$, YSZ, sapphire, Si) is replicated in the epitaxial HTS film deposited on top. The grain boundary angle and symmetry is determined by the substrate. Up to now BC-GBJs have been fabricated using epitaxial YBCO (see e.g. [3]), BSCCO[17]–[19], TBCCO[20], HBCCO [21], LSCO[22], and BKBO[23], [24] films. The critical current density of BC-GBJs decays about exponentially with increasing misorientation angle [7], [16] most likely caused by an increase of the thickness of the grain boundary barrier with increasing misorientation angle θ [3]. Therefore, the J_c-values of BC-GBJs can be varied over several orders of magnitude ($10 - 10^4 A/cm^2$ at 77 K) by changing θ. Since the position of BC-GBJs is bound to the grain boundary in the substrate other types of GBJs have been developed. Simon *et al.* [25] proposed the fabrication of GBJs at steep substrate steps. The understanding of these SE-GBJs has been developed by the Jülich group [26], [27] and in many follow-up studies. Inspired by bicrystal GBJs, Char *et al.* [28] developed the biepitaxial technique that allows the fabrication of asymmetric 45° GBJs by using an extremely thin epitaxial template layer to rotate the in-plane orientation of the HTS film by 45° in selected substrate areas. At present the GBJs are the most studied and best understood HTS-JJs. They have reasonable I_cR_n products (up to 400μV at 77 K) and can be fabricated at high yield. The spread of their characteristic parameters (typically 10 - 15% on chip) already allows their use in simple circuits.

It has been shown by Kleiner *et al.* [29], [30] that the small misorientation angles.

Secondly, the presence of a $d_{x^2-y^2}$-wave symmetry of the order parameter in conjunction with rough or faceted junction barriers may result in considerable inhomogeneities of the critical current density. This is due to the fact that the tunneling direction is changing along the junction resulting in a different J_c value, which is proportional to the magnitude of the pair potential in the tunneling direction. For GBJs the detailed analysis of spatial variations of J_c has shown that there are inhomogeneities on all length scales down to 1 nm with a probability distribution $p(a) \propto 1/a^{1.5}$ for the characteristic length scale a [55]. These inhomogeneities most likely are related to the faceted grain boundary interface and the presence of a $d_{x^2-y^2}$-wave symmetry of the order parameter in the superconducting grains. Then, in order to avoid these inhomogeneities perfectly smooth interfaces are required what put strong demands on the fabrication technology.

Thirdly, as predicted by Kashiwaya and Tanaka *et al.* [84], [85] zero-energy bound states are expected for JJs formed by *d*-wave superconductors, since quasiparticles experience different signs of the pair potential depending on the direction of their motion. Including the effect of zero-energy bound states in the theory of JJs a zero bias conductance peak (ZBCP) is expected. Such zero bias conductance peak (see Fig. 4) has been observed for YBCO, BSCCO, and LSCO-GBJs [86]. In contrast, in our experiments with NCCO-GBJs no such peak could be observed [87]. This is expected if one suggests that NCCO has a *s*-wave order parameter as supposed by measurements of the London penetration depth. In addition to a ZBCP a strong upturn of the $I_c(T)$ dependence at low temperatures is predicted for GBJs with certain misorientation angles [85]. This could not be observed so far experimentally most likely due to the strong faceting of the grain boundaries washing out the effect.

V. Summary

There is considerable progress in the fabrication and understanding of HTS-JJs. With respect to junction technology the improvement of the spread of the junction parameters is the key issue. This requires to put more effort on the control and atomic engineering of interfaces and barrier layers. The main transport mechanism in most HTS-JJs is direct tunneling for the Cooper pairs and elastic and inelastic tunneling via localized states in the junction barrier for the quasiparticles. For these junctions a further improvement of their characteristic voltage requires the removal of the localized states in the barrier. Whereas for GBJs this may be difficult to achieve, for REJs the use of suitable barrier materials may improve the situation. So far there are only a few junction types representing true proximity effect SNS junctions due to the problem of getting high quality interfaces with low boundary resistance. An unconventional symmetry of the order parameter in HTS is expected to have considerable implications on the characteristics of HTS-JJs. The detailed understanding of the Josephson effect in superconductors with unconventional pairing symmetry and the possible effects on HTS-JJ technology requires more future theoretical and experimental work.

Acknowledgment

The authors thank A. Braginski, A. A. Golubov, Halbritter, M. Yu. Kupriyanov, J. Mannhart, P. Seid M. Siegel, and D. Winkler for stimulating discussions.

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