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Controlled preparation of all high-T_c SNS-type edge junctions and DC SQUIDs

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High-T_c SNS-type Josephson junctions and DC SQUIDs were successfully fabricated using hetero-epitaxially grown multilayers of $YBa_2Cu_3O_x$ and $PrBa_2Cu_3O_x$. These layers are *c*-axis oriented and hence edges of the multilayers give rise to a current flow in the *ab*-plane between the electrodes of a Josephson junction. The necessary structuring was done by Ar ion beam etching. The individual junctions exhibit a supercurrent up to 80 K. The I_cR_n-product of these junctions usually has a lower limit of 8 mV at 4.2 K. Voltage modulation of the first DC SQUIDs can be observed up to 66 K. Details on the fabrication and measurements are presented.

1. Introduction

Due to its importance for superconducting electronic applications much effort has been spent on the preparation and study of high-T_c superconducting thin film Josephson junctions. The first high-T_c junction was made at IBM using thin films of $YBa_2Cu_3O_x$ (YBCO) [1], rapidly being followed by a number of others [2–4]. Shortly afterwards also junctions in TBCCO [5] and BSCCO [6] materials were fabricated. However, all these junctions depend on the weak-link behaviour of a more or less arbitrary number of naturally occurring grain boundaries in polycrystalline thin films. This prevents the controllable fabrication of junctions that is needed in most electronic applications. Therefore several research groups started working on multilayer techniques to create artificial barriers between two superconductors. Both normal metal as well as insulating barrier materials are used to fabricate SNS or SIS junctions. So far the first result reported in literature of a working SNS-like device was obtained by a group at Bellcore using laser deposited multilayers of YBCO/$PrBa_2Cu_3O_x$(PBCO)/YBCO/Au [7].

It is well known that the YBCO superconductor, having a perovskite structure, is highly anisotropic. The superconducting coherence length perpendicular to the *c*-axis is much longer than parallel to the *c*-axis. Hence the optimal direction for tunneling is perpendicular to the *c*-axis. Unfortunately nowadays most high quality YBCO thin films are *c*-axis oriented, namely the *c*-axis of the crystal structure is perpendicular to the substrate surface. Therefore sandwich type junctions, where current has to be transported in the *c*-axis direction, would mean tunneling parallel to the *c*-axis direction, which is supposed to be very difficult. At IBM, YBCO edge junction SQUIDs were fabricated using a barrier made by a plasma oxyfluoride process. The results are however not very reproducible [8]. In this paper we present preliminary results on the preparation of epitaxial YBCO/PBCO/YBCO Josephson edge junctions and quantum interference devices (SQUIDs). These controllable and reproducible edge junctions show a critical current up to quite high temperatures and could be operated at the boiling temperature of liquid nitrogen.

2. Junction fabrication

The high-T_c Josephson junctions have been fabricated from hetero-epitaxially grown multilayers. The multilayer structures include both thin barriers for junctions and insulating layers between the YBCO superconductors. A PBCO layer was used as normal conducting barrier layer in the SNS edge sandwich because of its isomorphic structure and similar lattice constant as YBCO [9]. Details about the preparation of YBCO thin films and YBCO/PBCO/YBCO multilayer have been published in previous papers [10,11]. Briefly, the YBCO and PBCO thin films have been deposited in situ by a modified off axis RF-magnetron sputter technique. A ground plate was mounted, facing the target at a 45° angle. This geometry makes the direct substrate bombardment improbable. Similar to ion beam sputtering, the sputter parameters can be controlled independently. Stoichiometric sintered YBCO and PBCO targets with a diameter of 50 mm were used. As substrates, we used (100) surfaces of yttrium-stabilized ZrO_2. The sputter gas was a mixture of argon and oxygen which consisted, in most cases, of 50% oxygen and 50% argon. Typical sputter gas pressures are between 5×10^{-2} and 3×10^{-1} mbar. During deposition the substrates were heated to temperatures between 640°C and 700°C. The incident RF-sputter power density was 2–5 W/cm^2.

By means of this technique, we routinely obtain transition temperatures, $T_{c,zero}$, of about 90 K. The critical current density at 77 K of these YBCO thin films is found to be higher than 10^6 A/cm^2. For the YBCO/PBCO/YBCO multilayer the superconducting properties are not affected by the presence of the PBCO layer. On X-ray diffraction patterns, besides the substrate reflections, only (00*l*) peaks are present. The full width at half maximum of the (005) peak was observed to be 0.35°. It is somewhat broader than that which we found for single films (for YBCO thin films: $\Delta\vartheta_{50}=0.28°$, for PBCO thin films: $\Delta\vartheta_{50}=0.30°$), but still indicates that these multilayers are highly textured. This is confirmed by He-ion channeling on a trilayer and Auger sputter profiling. Within the depth resolution limits of RBS of about 5 nm, no interdiffusion between layers could be observed.

In order to obtain Y/P/Y junctions in the *ab*-plane we used a two step process. In the first step, a YBCO layer with a thickness of 30–200 nm and a PBCO toplayer have been grown in situ. This PBCO layer is relatively thick (around 150–250 nm) in order to avoid Josephson coupling between two YBCO layers along the *c*-axis direction. This however gives rise to resistive shunting between the two superconducting electrodes. So in some samples an extra ZrO_2 layer was used as insulator. The ZrO_2 insulating layer was deposited by ion beam sputtering. A focused ion gun of 3 cm diameter was used as ion source and argon at a pressure of 6×10^{-4} mbar was used as sputter gas. The voltage and current of the Ar^+ ion beam are 800 V and 20 mA, respectively. The resistance of this insulating layer is more than 10 MΩ. In this case, even though a higher decrease of transition temperature occurs, perhaps due to interdiffusion of ZrO_2, a zero resistance temperature above 80 K is still being achieved. Then a part of the multilayer is covered by a photoresist stencil and the unprotected area was etched by an argon ion beam with an incident angle of 45–65 degrees in order to fabricate an edge. Our ion beam parameters are typically 3.5 kV acceleration potential and 30 μA/cm^2 beam current density at the sample.

In the next step a thin PBCO barrier layer and YBCO top layer are deposited. To avoid contamination of the interfaces of the sandwich structures, the substrates could be turned to different targets without breaking the vacuum. The thickness of the barrier layer is between 6 and 30 nm, as estimated from sputter time. The samples were annealed at 400°C in one bar oxygen after film deposition. At the end four silver electrodes have been deposited by sputtering. The resulting edge junction is shown in fig. 1. In this way a whole series of junctions is fabricated with critical temperature up to 80 K. The edge junctions we prepared in this way typically have a height between 30 and 200 nm and a width between 10 and 1000 μm.

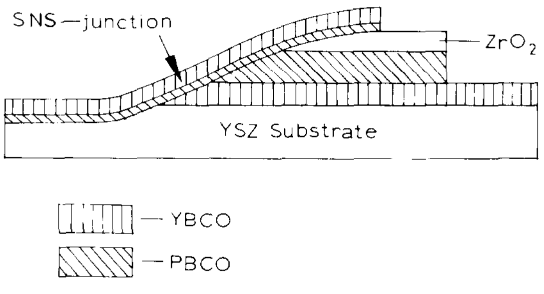

Fig. 1. Schematic diagram of the edge junction geometry.

3. Measurements

In fig. 2 we present the I–V-characteristics of one of these junctions, without insulating ZrO_2 layer, and hence being shunted. The PBCO barrier layer thickness was approximately 6 mm as estimated from sputtertime. The supercurrent vanishes around 80 K, as is typical for most of our junctions. This is about 10 K below the transition temperature of our YBCO thin films or YBCO/PBCO/YBCO multilayers. The critical current density of our best junction is approximately 1000 A/cm^2 at 77 K.

In fig. 3 we plotted the critical current I_c versus $1-T/T_c$ on a double logarithmic scale. Most of the data points lie on a straight line having a slope of two. This is characteristic of a SNS-junction where the critical current is given by [12]

$$I_c(T)=A|F_0(T)|^2[\xi_n(T)/\xi_{GL}(T)]^2 \times\exp[-L/\xi_n(T)]\,,$$

where A is a temperature independent constant, ξ_{GL} the Ginzburg-Landau coherence length, ξ_n the effective coherence length in the normal metal, F_0 the amplitude of Cooper-pairs in the electrodes and L the length of the normal metal path from one superconducting electrode to the other. As $\xi_{GL}(T)$ and $F_0(T)$ vary approximately as $(1-T/T_c)^{-1/2}$ and $(1-T/T_c)^{1/2}$ for $T/T_c \geq 0.5$ and as $\xi_n(T)$ varies only slowly, the critical current I_c is proportional to $(1-T/T_c)^2$. In order to observe phase coherence across the junction, additional experiments are required.

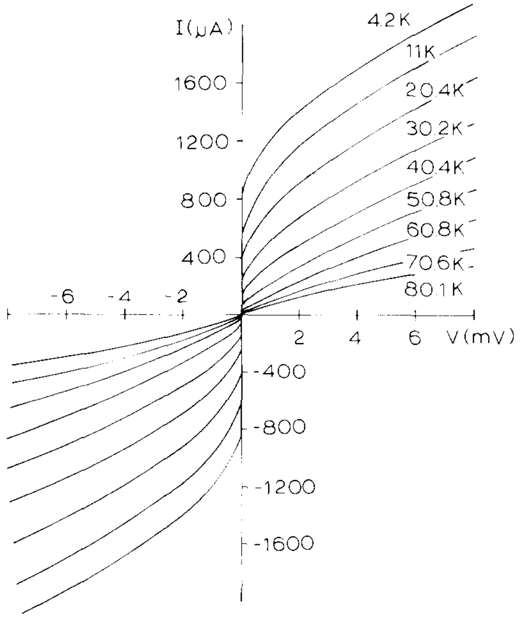

Fig. 2. Current–voltage characteristics of one of our edge junctions without ZrO_2 layer at different temperatures. This junction is shunted.

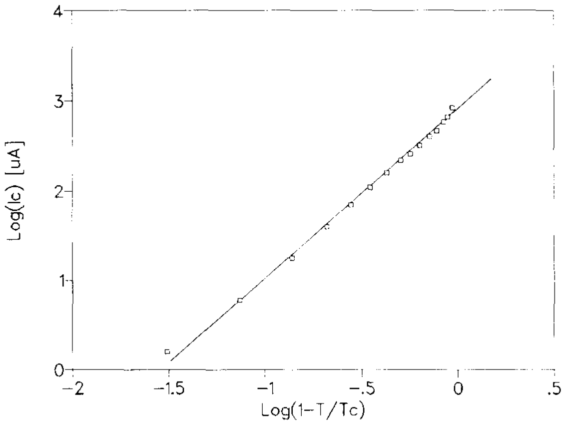

Fig. 3. The critical current I_c as function of $(1-T/T_c)$ for the junction of fig. 2. A slope of two has been observed. This indicates SNS behaviour.

For the proof of the existence of phase coherence, DC SQUIDs are fabricated from these junctions in order to observe voltage modulation. In this case we used a barrier layer thickness of 20 nm in order to minimize the probability of having shorts between the junction electrodes. Furthermore only ZrO_2 was used to separate the top and bottom electrode in order to prevent resistive shunting of the junction and hence to maximize the DC SQUID voltage modulation. A hole of 5×150 μm^2 was etched across the edge using photolithography and ion beam etching. In fig. 4 we present the flux voltage characteristics of one of our DC SQUIDs in the temperature range from 4.2 to 66 K. The height of this edge junction is 120 nm whereas the width is 15 μm and the critical current density at 4.2 K is approximately 150 A/cm^2. The normal state resistance is about 20 Ω and is almost independent of temperature. The V–ϕ curves are well periodic up to an applied flux of several tens of flux quanta. Even above 66 K some modulation

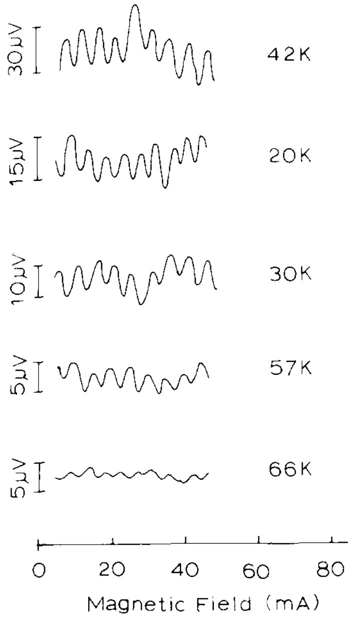

Fig. 4. Voltage vs. magnetic field for one of the edge junction DC SQUIDs at different temperatures. The magnetic field is plotted in units of current through the magnet coil and 20 mA current yields approximately 7 flux quanta in the loop.

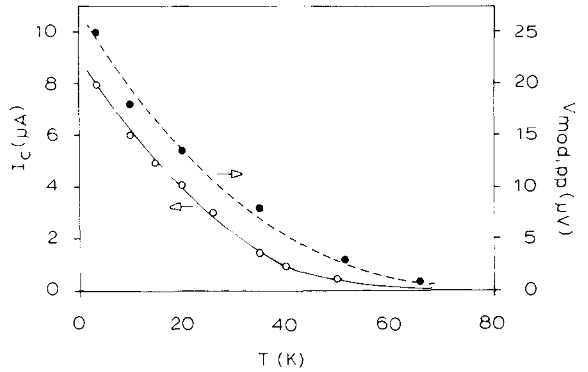

Fig 5. Temperature dependence of the modulation voltage as well as the critical current.

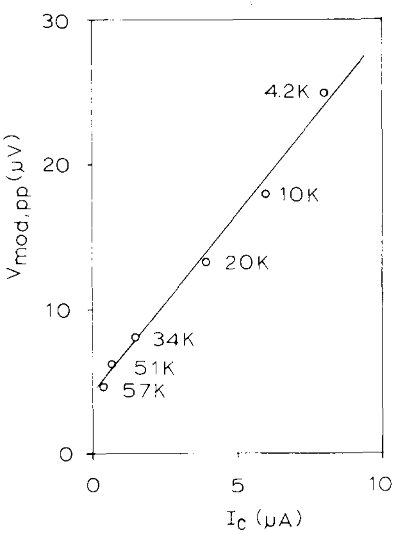

Fig. 6. The modulation voltage as function of the critical current.

could be observed, but the signal is too small and noisy for practical applications. It should however be noted that these measurements were carried out in an unshielded environment. The modulation period corresponds to approximately one flux quantum in the SQUID loop. The total modulation depth $m = \Delta I_c / I_c$ is roughly 20% of the critical current and the modulation voltage at 4.2 K and 66 K are typically 25 μV and 2 μV, respectively. The LI_c-product is roughly $0.2\Phi_0$ as calculated from the geometrical data of the SQUID.

The temperature dependence of the modulation voltage has been studied as well as the critical current (see fig. 5). A linear dependence of modulation voltage on critical current has been observed (fig. 6). Although up to now the practical operation temperature of these first SQUIDs is still lower than the boiling temperature of liquid nitrogen it seems, however, there is no serious difficulty to obtain useful SQUIDs which could be operated at 77 K in the near future. The important thing here is, that the supercurrent of these artificial barrier edge junctions flows through a well controlled PBCO layer in the *ab*-plane of the YBCO layer. It gains a remarkable advantage over the usual multilayer junctions in terms of reproducibility and controllability. Furthermore it should be noted that we could increase the bias current of our DC SQUID up to 1 mA at 4.2 K without any change in I–V characteristics. From this we conclude that the Josephson effect is not caused by shorts across the barrier layer as was found for the edge junctions of Laibowitz et al. [8]. At present we are engaged in measuring the noise properties of our DC SQUIDs, the results of which will be published in a forthcoming article.

4. Conclusions

In summary, we have successfully fabricated artificial barrier edge junctions and DC-SQUIDs of YBCO material with a good reproducibility. These junctions are based on high-T_c epi-heterostructures in which the superconducting layers still keep good superconducting properties. Voltage modulation with applied flux has been observed up to 66 K. Especially the supercurrent can flow in the *ab*-plane of the YBCO layer through a well controlled PBCO barrier. We think such edge junction SQUIDs will provide genuine applications for high-T_c superconductors, especially where low critical current and small capacitances are required.

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