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PROPERTIES OF THE YBCO THIN FILM INTERFEROMETERS FABRICATED ON ZrO_2 BICRYSTAL SUBSTRATES

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Abstract

Properties of the dc SQUIDs made of YBCO thin film deposited on ZrO_2 bicrystal substrate and nature of the fabricated Josephson junctions have been studied. It is found that the characteristics of the junctions are similar to that of the *SNS* structures with paramagnetic impurities in the N layer. The level of the interferometer noise close to $5\times10^{-4}\ \Phi_o/Hz^{1/2}$ and magnetic field sensitivity $\delta B \sim 10^{-10}\ T/Hz^{1/2}$ at frequencies higher than 25 Hz in the usual feedback mode of the SQUID operation has been achieved at 77 K.

Introduction

In a short time after the discovery of the high-T_c superconductivity of copper oxides, a number of research groups have fabricated by different technologies the simple single level YBCO thin film dc SQUID interferometers.[1-4] However good performances of the interferometers have not been achieved yet. The main difficulty is the absence of the technology for making the reproducible artificial Josephson junctions. Hence, only the junctions naturally occurring on thin film grain boundaries are usually used for forming the SQUIDs.

Unfortunately in the structures made of high-quality thin films with the critical current density about 10^5-10^6 A/cm^2 the traces of the Josephson effect have been found very rarely.[4] When interferometers are made from the YBCO thin film with the average grain size close to 1 μm and critical current density of the order of 10^2-10^3 A/cm^2 at 77 K the Josephson effect and quasi-periodic response of the interferometer voltage to magnetic field are usually recorded.[5,6]

In this case the number of the grain boundaries in the current concentration area in the vicinity of the interferometer's microbridges is usually much more than the required two around the loop. Thus a lot of the flux-quantizing loops arise and the smallest of them produce more pronounced peaks in the interferometer voltage vs. flux pattern.[5] For this reason it is difficult to couple the interferometer to the external field and an intensive noise appears.

These difficulties could be avoided by using the bicrystal substrates.[7] This provides a possibility to fabricate two high quality thin film superconductor electrodes separated by a spatially localized weak link with the critical current density much less than that of the electrodes.

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The goal of this work was the fabrication of the single-level dc SQUIDs made on the bicrystal ZrO_2 substrates and investigation of their properties with studying the nature of the Josephson junctions made by developed technology.

Thin films

Thin films of YBCO were deposited by laser sputtering of bulk ceramics targets on ZrO_2 bicrystal substrates with the misorientation angle in the basal plane close to 35-40°.

A pair of solid state lasers and a pair of targets were used, so that the streams of the evaporated material from the each target collided and the indirect well-mixed stream reaches the substrate. The oxygen pressure in the chamber was regulated in the range 0.1-1.0 Torr, the substrate temperature was 650-800°C and the evaporation rate was 30-120 nm/s.

A specific resistance ρ of the films with a thickness d = 0.3-0.5 μm in the normal state at 100 K was close to 130 μΩ×cm. The films exhibited a sharp ($\Delta T \sim 1$ K) resistive transition to the superconducting state at T = 82-89 K.

The X-ray diffraction pattern of the films showed usually only (001)-type reflexes corresponding to a well-oriented thin film with the c axis perpendicular to the substrate.

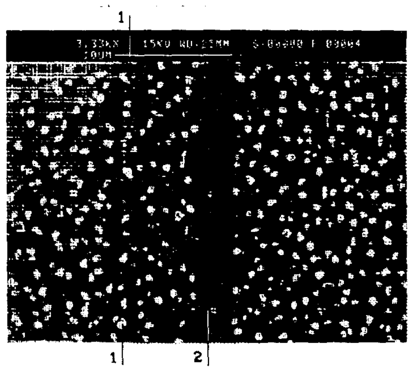

Figure 1. Scanning electron micrograph of YBCO thin film deposited on ZrO_2 bicrystal substrate. Arrows (1) show the place where the two parts of the substrate are sintered. Arrow (2) shows a cut made by a laser beam. The square grid visible at the film surface is a result of the SEM image treatment by computer.

The deposited films had usually the mirror-like surface. The SEM image (Fig. 1) shows the two blocks of the film separated by a sharp boundary. The small (1 - 2 μm) particles on the film surface have slightly different stoichiometry than the film itself. The blocks look like dark and light areas when the polarizer and the analyzer are used in the optical microscope. These qualitative data together with the data of the X-ray analysis allow us to suppose the film blocks to be epitaxially aligned with the orientation of the substrate parts.

Interferometer configuration

The configuration of the interferometer (Fig.2) was obtained by the laser ablation process.[5] At the first step the cuts (1) and (3) are produced for the fabrication of the wide Dayem-type microbridge across the boundary. The typical values of the critical temperature T_{cm} and critical current density j_{cm} differ from that of the film (T_c ~ 87 K, $j_c \sim 6\times10^4$ A/cm^2 at 77 K). At this stage of the fabrication of the interferometer No. 604-1 (shown in Fig. 2a) the parameters of the bridge are equal to T_{cm} = (78±0.2) K, $j_{cm} = (1.5\pm0.2)\times10^2$ A/cm^2.

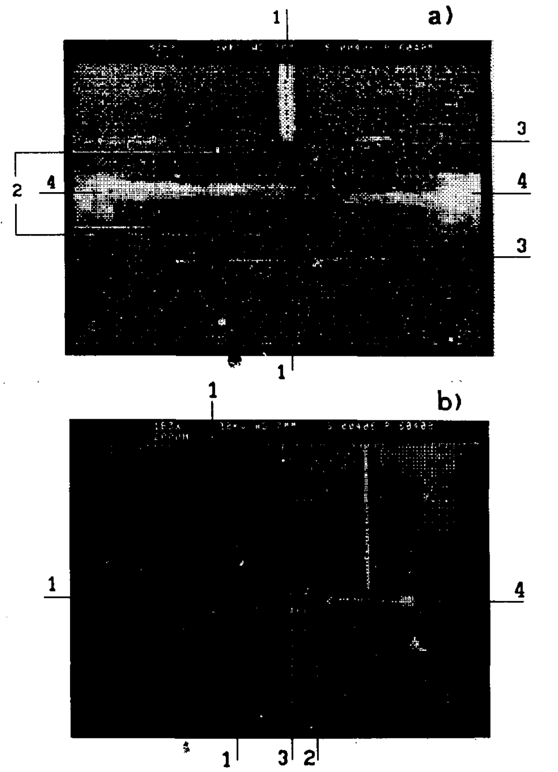

Figure 2. Scanning electron micrograph of the fabricated interferometer - (a). Arrows (1) and (3) show the laser beam cuts picked out the Dayem-type microbridges (2). Arrows (4) indicate the window in the film forming the loop of the interferometer.

Top image of the interferometer (4) - the right (light) side of the picture - and the part of the magnetic flux autotransformer (1) - dark region of the left side of micrograph - (b). The additional cut (3) causes the induced current flow close to the interferometer through the film strip (2).

At the second stage the interferometer loop was fabricated by cutting the central part of the microbridge (4). For the sample No. 604-1 the loop area was equal to 1600 μm^2 and the widths of the microbridges $W_{1,2}$ ~ 12 μm. At the last stage the magnetic flux autotransformer primary loop was fabricated (see Fig.2 b)

DC I-V curves of the interferometer and the weak link model

The I-V curve of the sample No. 604-1 recorded at 77.3 K (see Fig. 3) shows a considerable excess current I_{ex} in high voltage region that is typical for the Josephson junctions with metallic conductivity.[8] Shapiro steps at quantized voltages V_n = $(hf/2e)\times25\times n$ μV (see Fig. 3), arising under microwave irradiation also confirm the existence of the Josephson effect in the junctions.

The experimentally observed monotonous growth of I_{ex} with decreasing the temperature (see Fig. 4) indirectly indicates that the boundaries between the superconducting electrodes and weak link material possess rather high transparency. The temperature dependence of the interferometer critical current $I_c(T)$ is shown in Fig. 4. I_c value is nearly constant in the range 45 K < T < 60 K, and rise up at T < 40 K.

Figure 4 shows also the temperature dependence of the interferometer normal resistance R_n (defined as differential resistance R_d at $I \gg I_c$). At low temperatures T < 40 K the magnitude of R_n is constant (R_n ~ 0.47 Ohm) and specific surface resistance ρ_o = $R_n\times W\times d \sim 5\times10^{-8}$ Ohm×cm^2 is close to the typical value of the grain boundary junctions. Increasing the temperature leads to rising up R_n at T > 40 K and to its sharp jump up to ~ 100 Ohm when the temperature has achieved T_{cm}.

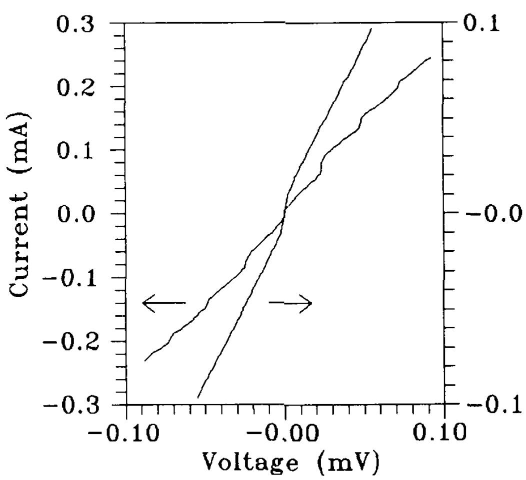

Figure 3. DC current-voltage characteristics of the interferometer No. 604-1 at the 77.3 K and Shapiro steps appeared at I-V curve at 70 K under 12 GHz microwave irradiation.

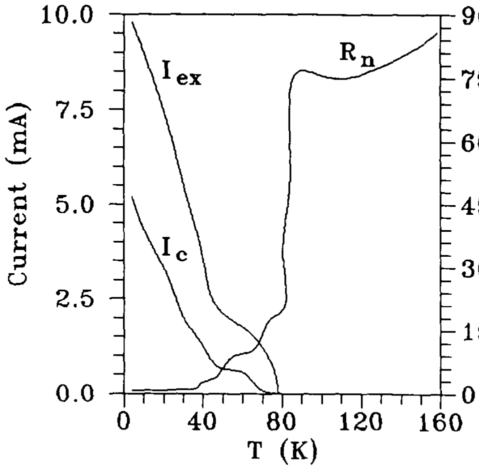

Figure 4. Excess current I_{ex}, critical current I_c, and normal resistance R_n of the interferometer vs. temperature.

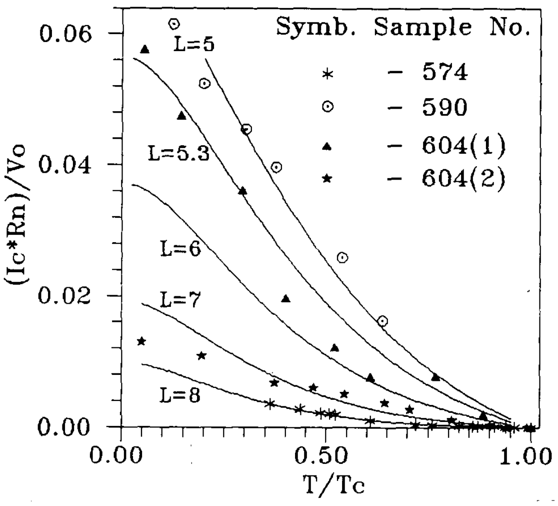

Figure 5. Normalized characteristic Josephson voltage $V_c = I_c R_n$ of the different weak links vs. temperature. Normalized factor $V_o = 2\pi k_B T_c / e$.

Figure 5 shows the temperature dependences of the characteristic voltage $V_c = I_c R_n$ of the fabricated structures. The maximum value of the parameter $V_c \sim 2.5$ mV achieved at $T \sim 4.2$ K is much lower than $V_c \sim \Delta(T)/e \sim 30$ mV allowed by the BCS-based theories for the perfect Josephson junctions.

The results of the calculations of the $V_c(T)$ dependences for the "dirty" SNS sandwiches with the "rigid" boundary conditions at the SN interface[9] for different values of the N layer thickness L/ξ_N and $\pi T_c \tau_s / \hbar = 0.5$ are shown in Fig. 5 by solid lines. A reasonable agreement between experimental and theoretical data has been obtained when the existence of the temperature-independent depairing mechanism (for instance electrons scattering on the localized magnetic moments characterized by spin-flip time τ_s) in the weak link material was supposed.

The I vs. H measurements in the range of magnetic field $H \sim 50\times10^{-4}$ T do not show expected behavior of the critical current. This fact can be explained if the real cross-section area $S = \rho \times L/R_n$ of the junction is much less than geometrical one $S_g = (W_1 + W_2)\times d$. The simple estimates show that if the weak link material has the transport properties close to those of superconducting electrodes (i.e. the coherence length $\xi_N \sim 1$ nm, $\rho \sim 10$ Ohm×cm) the ratio $S/S_g \sim 10^{-3}$ are really low. This estimate does not contradict the information obtained from the large scale SEM image of the boundary.

From the data we could come to the conclusion that the characteristics of the fabricated Josephson structures could be explained in the framework of the SNS junction model[10] taking into account the temperature-independent pair breaking mechanisms in the N layer.

V-Φ_e curves and noise properties

Figure 6 shows the V vs. Φ_e dependence of the interferometer coupled to the autotransformer recorded at 4.2 K. The period of the V-Φ_e curve is determined by the area of the interferometer. The voltage-to-flux transfer factor at $T = 4.2$ K is of order of 60 $\mu V/\Phi_o$. At 77 K the dc V-Φ_e curve is smeared by noise. Nevertheless the proper response to the magnetic field exists if the feedback mode of the SQUID operation is used.

The density of the flux noise of the fabricated interferometer at 77 K is shown in Fig. 7 (curve 1). The measurements have been made in a flux-locked loop and the flux-to-voltage factor was determined from the magnitude of the minimal jump of the SQUID output voltage. One can see that $S_\phi \sim 2\times10^{-3}$ $\Phi_o/Hz^{1/2}$ for frequencies higher then 25 Hz and increases approximately as 1/f for lower frequencies.

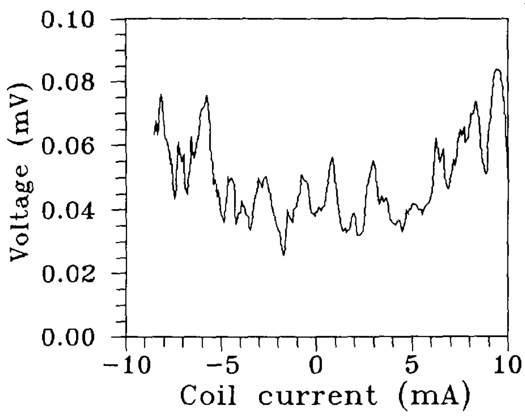

Figure 6. Voltage vs. flux curve for the interferometer No. 604-1 at 4.2 K.

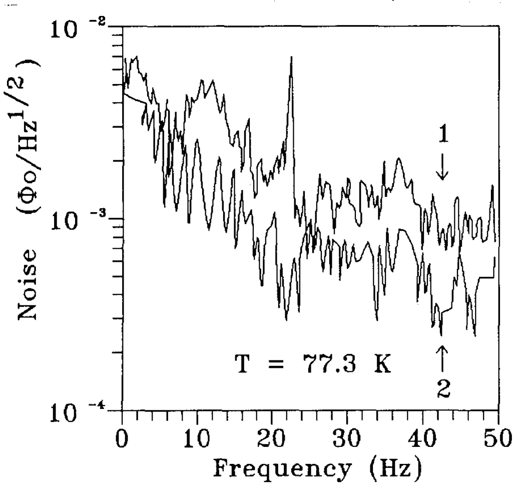

Figure 7. Noise vs. frequency for high-T_c dc SQUID operated in feedback mode at 77.3 K before curve 1) and after reducing in the amount of superconducting material near the interferometer loop (curve 2).

After the laser ablation of the unnecessary part of the film in the vicinity of the interferometer the noise level fell down to 5×10^{-4} $\Phi_o/Hz^{1/2}$ (curve 2 in Fig. 7). This noise level corresponds to field sensitivity close to 1×10^{-10} $T/Hz^{1/2}$ at f > 25 Hz.

Conclusion

The results show that interferometers made of YBCO thin films deposited on the bicrystal substrates have better characteristics then the devices fabricated from homogeneous high-T_c thin films. In this case the difficulties arising due to internal quantizing loops are avoided and the good coupling of the external magnetic field to the interferometer is achieved.

The developed technology could not guarantee the reproducibility of the parameters of the Josephson junctions but gives the possibilities to adjust I_c in some range by varying the bridge width. The properties of the junctions are close to weak link structures with paramagnetic impurities in N layer.

The achieved level of the magnetic field sensitivity $\delta B \sim 10^{-10}$ $T/Hz^{1/2}$ at 77 K could be improved by using reproducible artificial junctions[11] with high quality epitaxial film electrodes and multiturn high-T_c thin film input coil.[12]

Acknowledgments

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