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AFM plough YBCO microbridges: Substrate effects

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***Abstract*— Atomic force microscope (AFM) nanolithography was used as a novel cutting technique to defined micro-size constrictions on $YBa_2Cu_3O_{7-x}$ striplines. $YBa_2Cu_3O_{7-x}$ (YBCO) thin films are deposited using an inverted cylindrical magnetron (ICM) sputtering technique. The films are then patterned into 8-10 micron width strips, using photolithography and dry etching. In order to understand the effects of substrates, we fabricated YBCO planar microbridges on MgO and STO substrates. We studied the substrate effects on Current-Voltage (I-V) characteristics and Shapiro-steps. We show that the observed Shapiro steps from the bridges on STO substrates are of poor quality, when compared to those on MgO substrates. This is because the STO substrate is 'microwave dirty' and it is well known that the substrate has resonant microwave losses at low temperatures.**

***Index Terms*—AFM lithography, Josephson junction, SrTiO3, YBCO**

I. Introduction

ONE of the essential factors to obtain epitaxial HTS thin films and to fabricate good quality thin-film electronic devices is the choice of substrate material. The substrates should have a clean smooth surface and a close lattice match with the films to ensure epitaxial growth. The thermal expansion coefficients of the substrate and the HTS film must be comparable over a large temperature range to avoid excess strain relaxation - significant differences in the thermal expansion coefficients will lead to cracking of the film [1]. Chemical compatibility between the substrate and the film is important and there should not be any chemical reaction, because such a reaction between the substrate and the film will inhibit good epitaxy and may prevent the formation of the superconductive phase.

There are many materials that have been tested as substrates for HTS cuprate thin-films, especially $YBa_2Cu_3O_{7-x}$ thin films. Generally, the substrates that are suitable for growth of YBCO can be categorized into two groups: Perovskite structures such as $SrTiO_3$, $LaAlO_3$, and $NdGaO_3$, and non-Perovskite structures such as MgO and Al_2O_3.

$SrTiO_3$ has a very small lattice mismatch with YBCO (2%), however, the substrate is unsuitable for high frequency applications due to its large dielectric constant (277 at room temperature). MgO substrates have a modest dielectric constant (9.65), it is readily available, and has a 9% lattice mismatch with YBCO [2]. A very low dielectric constant and the low cost make MgO a more suitable substrate for junctions for high frequency applications.

Planar Josephson junctions such as micron and nanobridges were successfully fabricated on high-temperature superconductors using focused ion beam (FIB) and electron beam lithography (EBL) [3, 4].

Recently we have demonstrated AFM ploughing as a novel way of fabricating YBCO planar constriction type micro-bridges [5]. In this paper, we report on the substrate effects on the I-V characteristics and Shapiro-steps in these recently fabricated micron size bridges, on MgO and STO substrates. Understanding the substrate effects on the performance of these microbridges is very important. For example, STO substrates exhibit severe microwave resonances in a range of temperatures from 60 K to 90K [6]. These resonances can interfere with the observation of Shapiro-steps. Our measurements show that microbridges fabricated on STO substrates show poor quality Shapiro-steps, as compared to those on the MgO substrates.

II. Experimental procedure

A. Thin film preparation

YBCO thin films were grown on (100) oriented MgO and $SrTiO_3$ substrates by Inverted Cylindrical Magnetron sputtering. Before the deposition, the thicknesses of the films were between 120 nm and 150 nm. The substrates were cleaned with acetone in an ultrasonic bath for 10 minutes, and then blown dry with nitrogen. The substrates were glued on a heater plate with silver paste. The YBCO ceramic target–substrate distance was 30mm. Pre-sputtering was applied for 15 minutes to eliminate any contamination on the surface of the target. The substrate temperature was 740° C, the total pressure of the 1:1 argon/oxygen gas mixture was 320 mTorr, and the dc sputtering power 72 W with a current of 400 mA and a voltage of 180V. The deposition rate was approximately 2.7 nm/min. After the deposition, the films were cooled and

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annealed at 460° C for 30 min in an oxygen environment, before it was allowed to cool down to room temperature.

The surface morphology of the films was characterized by AFM.

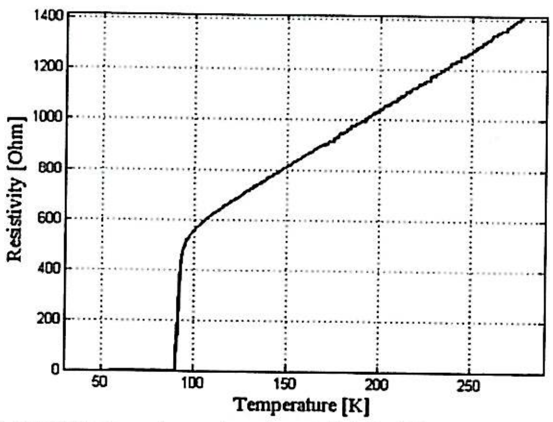

Fig. 1. Resistance versus temperature characteristic for 100 nm YBCO film.

The resistive behaviour of the films was measured. Silver (Ag) contact pads with thicknesses of 400 nm were evaporated onto the films surface and subsequently annealed at 470° C in a 1 atm oxygen environment for 30 min, in order to obtain low-resistivity contacts.

B. Microbridge fabrication

The YBCO film was patterned into microstrips with 8–10 μm widths, using standard photolithography and argon ion milling.

Photoresist (ma-P 1225) was spun onto the film surface at 4000 rpm to a thickness of 2 μm, and soft-baked on a hot-plate at 100° C for 5 min. The resist was exposed to 360 nm UV through a chrome contact mask for 25 sec, and then developed for 50 sec in ma-D 331 developer. The resist was then hard-baked at 110° C for 15 min.

Argon ion milling was performed using a Kaufman-type ion source with an incidence angle of 45° to the film surface. The rf power was 50 W, the argon gas pressure 0.25 mTorr, and the voltages of the electrodes were 750 V.

In order to minimize the loss of oxygen from the superconducting layers during the milling process, the film was mounted on a water-cooled copper sample holder with thermal paste.

The etching was terminated when an open circuit on the substrate at the sides of the YBCO striplines was measured.

Photoresist residue was removed by immersing the film in mr-Rem 660 photoresist remover for 10 min, and then immersing it in acetone for 10 min in an ultrasonic bath.

We used a diamond coated tip as a cutting tool to define the plough. The AFM was operated in contact mode, with the tip vertically displaced toward the YBCO surface with a loading force of 11 μN, sufficient to completely remove the YBCO layers.

The YBCO stripline is imaged first, and then the middle of the stripline is moved to the centre of the image. At the start of the nanolithography process the tip is placed at the centre of the image at the centre of the stripline width. The constriction width W is controlled by displacing the tip by

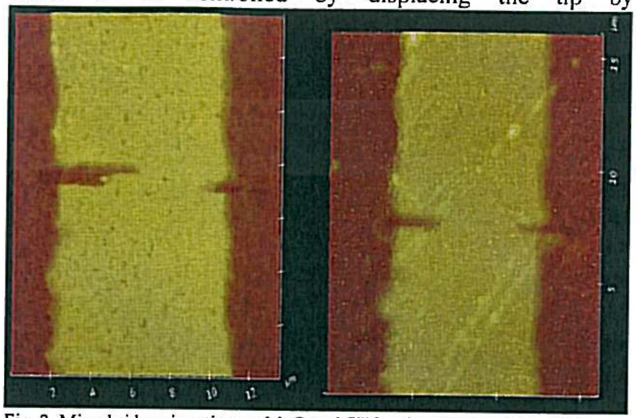

Fig. 2. Microbridges junction on MgO and STO substrates made by AFM.

W/2 to the left side on the stripline. The tip is then driven into the YBCO surface, and displaced on the same line for a few hundred cycles. The tip velocity was 4 μm/s. The constriction is completed by applying the same nanolithography on the right side of the stripline. Constrictions with fully controlled width and depth were achieved by adjusting the tip movement and the scan speed of the plowing operation. The YBCO residuals from the cuts were cleaned by dipping the film in acetone in an ultrasonic bath for a few minutes. The drawback of this technique is the wear and resolution degradation of the tips after it has been used for a few times in the lithography.

III. Results and Discussion

A. Thin film characterization

The surface morphology of the YBCO thin films was investigated using AFM. The films had smooth surfaces, with surface roughness values between 4 to 6 nm. No droplets or outgrowths were observed on the surface of the films.

Fig. 1 shows the temperature dependence of the electrical resistance. The films show metallic-like resistive behaviour in the normal state and have sharp superconducting transitions.

The residual resistance ratio R (300)/R (100) was 2.83, the zero resistance temperature (T_{C0}) was 90.2 K, and the width of the superconducting transition about 1 K. These results confirmed that the films had good superconducting properties.

B. Josephson-effect measurements on microbridges

After the successful fabrication of the microbridges with AFM nanolithography (see Fig. 2), the film was mounted on a PC board. Gold wires were bonded from the silver contact pads to the copper striplines on the PCB. The sample was then positioned inside the cold finger cryocooler unit for testing.

We used the Mr. SQUID Electronics unit [7] as excitation source. It generates a triangular waveform to test the device, and we monitored the I-V response on the oscilloscope window.

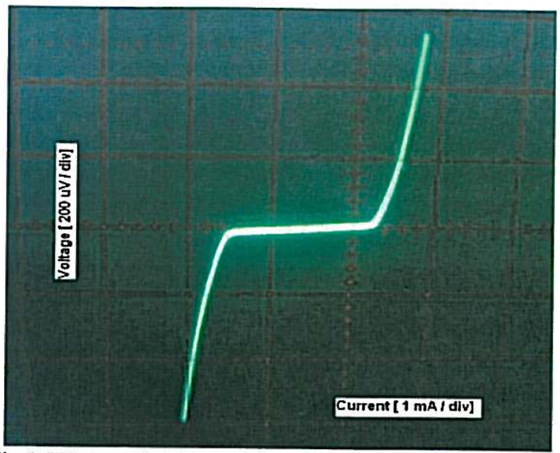

Fig. 3. I-V curve of a 3.6 μm microbridge junction on MgO substrate.

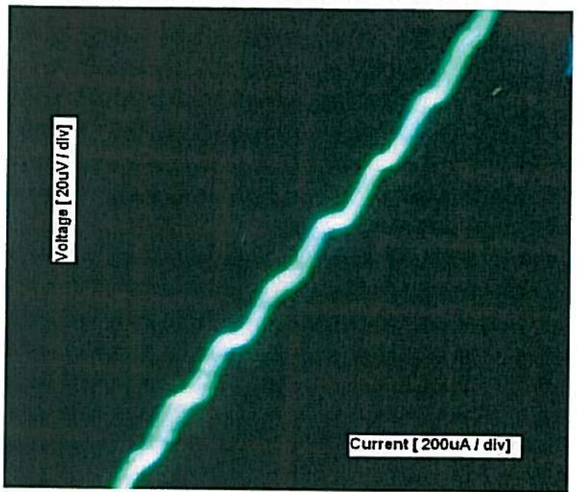

Fig. 4.a. Shapiro-steps of the same constriction junction (Fig. 3) exposed to 8.1522 GHz MW power.

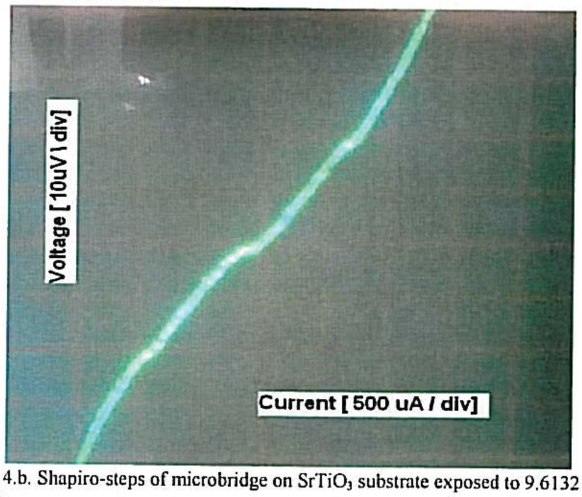

Fig. 4.b. Shapiro-steps of microbridge on $SrTiO_3$ substrate exposed to 9.6132 GHz.

The current-voltage (I-V) characteristics of a 3.6 μm width microbridge on a MgO substrate, in the absence of microwave power, at 57 K are shown in Fig. 3. The critical current was measured to be 1.58 mA at 47 K. This temperature was the lowest that the specific crycooler could reach. The normal resistance of the junction was 1.2 Ω, and the I_cR_n-product was 90 μV at 77 K.

As a result of thermal fluctuations or flux flow a rounding effect can be present in the I-V characteristics of a junction [8]. However, our I-V curves exhibit sharp knees, possibly ruling out any thermal fluctuations or flux flow effects. This means that the I-V curves are most probably representing true Josephson behaviour.

However, a mere observation of I-V characteristics with dc currents may not necessarily mean the demonstration of the Josephson-effect. In order to establish the Josephson-effect, one should demonstrate ac and dc Josephson-effects, and the magnetic modulation of critical currents. In this paper we adopt the method of the observation of Shapiro-steps, which is a direct consequence of the Josephson-effect. Accordingly, measurements on the I-V characteristics of the microbridge junctions have been performed in the presence of an external microwave power source. Here we should emphasize that the substrate can have an influence. For example STO has microwave surface impedance resonances in the temperature range 60K to 90K [5]. This can interfere with the Shapiro-step quality in the microbridges fabricated on STO. MgO is supposed to be relatively microwave silent in this temperature range. In fact, we did observe poor quality Shapiro-steps in the case of microbridges fabricated on STO substrates, as compared to that of MgO substrate, as shown in Fig. 4 (a) and (b).

We applied 3 dBm microwave power in the 2 – 18 GHz range via a coaxial cable terminated with an antenna above the device. We observed well defined Shapiro-steps on the I-V curve of the microbridge on a MgO substrate at 8.1522 GHz (see Figure 4(a)). The response of the constriction to microwave radiations (Shapiro-steps) clearly gives positive evidence of the Josephson-effect. This is because the observed step size satisfies (1), which can only be derived from the fundamental Josephson-effect.

The step sizes can be used to calculate the theoretical constant $\frac{e}{h}$.

The voltage step is expressed as

$$V_0 = n\left(\frac{\Phi_0}{2\pi}\right)\omega_s \quad (1)$$

which is equivalent to

$$V_0 = n\left(\frac{h\omega_s}{4\pi e}\right) = n\frac{hf_s}{2e} \quad (2)$$

where $\Phi_0 = \frac{h}{2e}$. This equation can be rewritten to yield the theoretical constant $\frac{e}{h} = 2.41796\times10^{14}\,Hz/V$ as:

$$\frac{e}{h} = n\left(\frac{f_s}{2V_0}\right). \quad (3)$$

The voltage V_0 is approximately $17\mu V$ with some degree of uncertainty and the frequency f_s =8.1522 GHz. Substitution of these values into (3) results in $\frac{e}{h} = 2.3977\times10^{14}\ Hz/V$. This value corresponds quite well with the theoretically predicted value, constituting positive evidence for the Josephson-effect.

Fig. 4(b) shows Shapiro-steps on the I-V curve of a microbridge fabricated on a $SrTiO_3$ substrate. The voltage step height is about $20\mu V$ at a frequency f_s = 9.6132 GHz, resulting in $\frac{e}{h} = 2.403\times10^{14}\ Hz/V$.

The Shapiro-steps of our junction on a $SrTiO_3$ substrate are not clear compared to the steps on the MgO substrate. Nevertheless, the critical current is larger in the microbridge made on the $SrTiO_3$ substrate.

IV. Conclusion

In conclusion, we have produced planar micron-size bridge type junctions on YBCO thin films by AFM lithography. The junctions were tested for the Josephson-effect, and we have observed I-V characteristics and Shapiro-steps with external microwave irradiation of the microbridges on both MgO and STO substrates. The voltage steps are well defined on the MgO substrate, which demonstrate the Josephson-effect in these junctions. The voltage step value corresponds well with the predicted theoretical constant for Shapiro-steps.

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