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Characteristics of $\text{YBa}_2\text{Cu}_3\text{O}_y$ step-edge Josephson junctions on MgO substrate

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Abstract

We fabricated and characterized $\text{YBa}_2\text{Cu}_3\text{O}_y$ step-edge Josephson junctions and DC SQUID's on MgO (001) substrates. Sharp steps on MgO (001) were obtained by the techniques of photolithography and Ar-ion milling with step heights varying from 300 to 350 nm. The current-voltage (I - V) characteristic of the junction is consistent with the resistively shunted junction (RSJ) model. We obtained $J_c = 1.0 \times 10^5 \text{ A/cm}^2$ and $I_c R_n = 110 \mu\text{V}$ at 77 K. In addition to the conventional Shapiro steps resulting from the AC Josephson effect, half-integral steps were observed. The width of these half-integral steps was sensitive to the RF power and the magnetic field. DC SQUID's have been operated below 78 K and the observed voltage modulation agrees with the expected value.

1. Introduction

The growth of high- T_c superconducting thin films over a sharp step on a substrate can create a superconducting weak link [1–4]. Well-characterized Josephson junctions were fabricated by depositing $\text{YBa}_2\text{Cu}_3\text{O}_y$ (YBCO) films on SrTiO_3 and MgO bicrystals [5–7]. However, to integrate these junctions to a large-scale integrated circuit is not easy because their locations are limited by the grain boundary in the substrate. Step-edge junctions, as we report here, are suitable for integration, and reproducible. To date, such weak links have been used by many groups to make quantum interferometers (SQUID's), and show low $1/f$ noise [8,9] at liquid nitrogen temperature. Because of the good performance, ease of fabri-

cation and integrability, step-edge junctions have received revived interest.

2. Experiments

The fabrication processes of our junction are simple compared with those of other groups [4,8] who used a metal mask to etch a step on substrates. Our method starts from creating a sharp step on a MgO (001) substrate, using an AZ1350J photoresist mask. Ar-ions impinge at an angle of 45° with respect to normal incidence and perpendicularly to the line of the step. The ion-beam energy is 500 eV, the beam current density is 2.8 mA/cm^2 , and the Ar pressure is 2×10^{-4} Torr. The step height was calibrated by measurement with a Dektak Surface Profilometer

(3030ST). Typically, a step height of 300 nm on MgO required four minutes of ion milling. In order to prevent damage of the photoresist during ion milling, we cooled the substrate block with running water. After ion-beam etching, we removed the photoresist with acetone, then annealed the substrate at about 1000°C for one hour to reduce the ion beam damage on the surface of the MgO substrate. Next, we deposited a YBCO film 150 nm thick by an off-axis RF magnetron sputtering system. We used a standard photolithography technique to make a pattern in the YBCO thin film with a directional ion beam of lower energy (280 eV). Finally, Ag contact pads were defined by the lift-off technique.

Our sample was bonded with wire and mounted into a small solenoid which provides an ambient magnetic field up to 30 G normal to the plane of the substrate. A four-point method was used for all electrical measurements. The voltage criterion 1 μV was used to define the critical current. Normal state resistance R_n of the junction was determined from the slope of the current–voltage curve at a high biased voltage.

3. Results and discussion

YBCO films as grown show a preferred orientation with the crystal c -axis perpendicular to the substrate. The critical temperature T_c of the YBCO film on the ion-milled MgO substrate was near 85 K and the critical current density J_c exceeded $7 \times 10^5 \text{ A/cm}^2$ at 77 K. Fig. 1 shows the current–voltage (I – V) characteristic of a junction 5 μm wide at 80 K that is consistent

Fig. 1. I – V characteristics of a step-edge junction. The width of the junction is 5 μm .

with the prediction of the resistively shunted junction (RSJ) model [10,11]. When the temperature was near T_c , a rounding of the I – V characteristics was observed, due to thermally activated phase slippage [12]. We obtained $J_c = 1.0 \times 10^5 \text{ A/cm}^2$, $I_c R_n = 110 \mu\text{V}$ at 77 K and $J_c = 6.4 \times 10^6 \text{ A/cm}^2$ at 4.2 K. The critical current density and the $I_c R_n$ product of our junction are much greater than published data for the step-edge junction. R_n was found to be independent of temperature between T_c and 60 K. Typically, for bridge widths of 10 or 20 μm and step height 300 nm, the junctions had a critical current density varying from 1×10^4 to $1 \times 10^5 \text{ A/cm}^2$ at 77 K.

A dipole antenna was used to couple microwave radiation into the junction. I – V characteristics were examined with the microwave irradiation of frequencies 1–15 GHz. Fig. 2 shows the expected voltage steps, or Shapiro steps at integral multiples of $h\nu/2e$, in which h is the Planck constant, ν is the frequency of the applied microwaves and e is the charge of an electron. The amplitude of the Shapiro steps was modulated by the microwave power. This was in good agreement with the prediction of the RF current-source model [13,14], which is more appropriate than the voltage-source model in our experimental condition because the impedance of free space is much greater than that of the junction. A detailed discussion of the amplitude of Shapiro steps modulated by microwave and magnetic fields will be reported subsequently.

Fig. 2. I – V characteristics of a junction with a width 40 μm under microwave irradiation at 7.5 GHz and 60 K. As the microwave power was increased, the width of the Shapiro step oscillated.

3.1. Observation of the half-integral constant voltage steps

In addition to the typical integral Shapiro steps we observed “half-integral” steps for some samples, shown in Fig. 3. Constant voltage steps in the I - V curves occurred at exactly half the voltage value of the Shapiro steps expected from the AC Josephson effect. The I - V curve of the junction showed no hysteresis and $I_c R_n = 0.11$ mV at 77 K. These anomalous “half-integral” steps appeared on the I - V curve when microwaves at 5–10 GHz irradiated these junctions. Then we obtained $\Omega \equiv h\nu/2eI_c R_n = 0.17$ and the McCumber parameter $\beta_c \equiv 2eCI_c R_n^2/\hbar < 1$. (The I - V curve is hysteretic [11] for $\beta_c > 1$.) These half-integral steps are anomalous because their occurrence cannot be explained by the current-source model [13,14] and AC Josephson effect. A detailed observation of I - V curves near these half-integral steps reveals no additional step structure.

The widths of these half-integral steps can be modulated by the microwave power, as shown in Fig. 4. Also, a small applied magnetic field (< 2 Oe) would affect the widths of these half-integral steps in a complicated way that cannot be reproduced. This fact suggested that the trapped magnetic flux is important.

The cause of these half-integral steps is unclear. Nevertheless, it may be a crucial fact that the I - V characteristics of the junctions show a significant deviation from the prediction of the RSJ model at a greater DC bias. Fig. 5 shows a typical one. The published results of earlier experiments [15,16] on ob-

Fig. 3. Anomalous half-integral constant voltage steps were observed on a junction of width 5 μ m. This junction shows $I_c R_n = 0.11$ mV at 77 K.

(a) 5.5 dbm (b) 6.5 dbm (c) 8 dbm (d) 9 dbm

Fig. 4. Half-integral steps modulated by varied intensities of microwaves at 70 K.

Fig. 5. I - V characteristics of the junction deviate from the prediction of the RSJ model at a more greatly biased current.

serving non-integral steps from single-junction effect indicated that they occurred only when $\beta_c > 1$ or $\Omega > 1$ or both. This is not in agreement with our results. Another possibility is the multiple-junctions effect, viewing the entire step-edge junction as multiple small junctions in parallel [17]. This consideration is reasonable because the wide grain boundary junction is non-uniform. Our junction can be viewed as a wide junction [18], too. However, the voltage output of our junction biased at a constant current $I > I_c$ showed no SQUID-like behavior under small applied magnetic field ($H < 3$ Oe).

3.2. Magnetic field effects

The critical current of a single junction generally modulates with the applied magnetic field normal to

the substrate plane in a complicated way. Fig. 6 shows the critical current I_c as a function of magnetic field for a junction $10\text{ }\mu\text{m}$ wide. The overall shape of the $I_c(B)$ curve roughly agrees with that expected for a wide Josephson junction [19], but the critical current did not vary smoothly as the applied magnetic field was increased. There is much unexplained fine structure in the measured $I_c(B)$ curve. This characteristic shape is most likely correlated to the presence of a spatially inhomogeneous critical current density along the step edge. Furthermore, the measured $I_c(B)$ dependence also depended on the history of the magnetic field. These effects are caused by the trapping of magnetic flux near the step edge.

3.3. Characteristics of the DC SQUID's

These step-edge junctions were incorporated into DC SQUID's that consist of two microbridges in parallel enclosing a loop of area $625\text{ }\mu\text{m}^2$, a schematic top view of which is shown in Fig. 7. According to

Fig. 6. Critical current of a step-edge junction as a function of applied field. The width of the junction is $10\text{ }\mu\text{m}$.

Fig. 7. Schematic representation of a DC SQUID with a hole size $25 \times 25\text{ }\mu\text{m}^2$.

our numerical calculation, the geometric loop inductance of the DC SQUID $L = 40\text{ pH}$ [20]. The voltage output of a SQUID as a function of the applied magnetic field with a DC current bias slightly greater than I_c is shown in Fig. 8 ($V-\Phi$ curve). The period of the voltage modulation is constant and independent of temperature. The period is consistent with the geometric loop area and the flux focusing factor is about 5.

At 65 K , we obtained the data $I_c = 627\text{ }\mu\text{A}$, $R_n = 290\text{ m}\Omega$; then the shielding parameter $\beta_L = LI_c/\Phi_0 = 24.0$. According to the prediction of Clarke et al. [21], with the optimized direct current bias, the voltage modulation peak to peak is $\Delta V = I_c R_n / (1 + \beta_L) = 7.8\text{ }\mu\text{V}$. In our experiment we obtained $\Delta V = 7.5\text{ }\mu\text{V}$ which is consistent with their prediction. When the applied field exceeded 200 mG (about 15 times the period of voltage modulation), the $V-\Phi$ curve became distorted, because the magnetic flux entering each junction modulated the critical current of the DC SQUID, and the result is shown in Fig. 9.

4. Conclusion

We successfully fabricated step-edge Josephson junctions and DC SQUID's that show current-voltage characteristics expected from the RSJ model. However, half-integral steps were once observed on the $I-V$ curve of a single junction, which cannot be explained by the typical current-source model and AC Josephson effect. By suitably controlling the crucial fabrication parameters, the step height, the sharpness

Fig. 8. A DC SQUID shows voltage modulation under applied magnetic fields.

Fig. 9. Voltage modulation of a DC SQUID under large magnetic fields.

of the step, and the film thickness, the junctions were highly reproducible. According to simple processes, we can fabricate Josephson junctions that show similar or even better performances compared with junctions fabricated from bicrystal substrates. The present method allows junctions to be designed at will on large-scale integrated circuits.

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