Flux Motion in YBCO Biepitaxial Josephson Junctions

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Abstract—We have measured the current-voltage characteristics of overdamped long $\text{YBa}_2\text{Cu}_3\text{O}_7$ biepitaxial Josephson junctions. The velocity-matching step was observed in the current-voltage characteristics with an applied magnetic field. The presence of velocity-matching steps suggests that the biepitaxial Josephson junction is formed around a dielectric-like barrier between superconducting grains. Anomalous subharmonic voltage steps were found under microwave irradiation. The relations between anomaly steps and fluxon motion are discussed.

I. INTRODUCTION

The magnetic flux motion in a Josephson junction is a subject of increasing practical interest. Since it has been recognized that flux flow three-terminal superconducting devices theoretically can operate at frequencies up to several tens of gigahertz [1], [2]. This makes them attractive for high frequency applications. In a Josephson flux flow transistor, an external magnetic field is applied to the junction plane. The field penetrates into the junction in form of Josephson fluxons, each of them carrying one magnetic quantum Φ_0 . Ideally, if the bias current is less than the maximum Josephson current I_c , the phase difference of order parameter on opposite sides of the junction is time independent, and the fluxons are static. When the bias current exceeds I_c , a Lorentz force will drive fluxons moving along the junction. An electromagnetic (EM) wave also can be generated and propagated along the junction in a slowed velocity, or Swihart velocity [3], $\bar{c}$. In a long junction, there are two main modes of fluxon motion. First is the nonresonant fluxon motion, in which fluxons oscillate between the junction edges. In the second mode, so-called flux flow mode, fluxons are created at one edge of the junction, move along the junction once, and are annihilated at the other edge. When the fluxon velocity u approaches the EM wave phase velocity $\bar{c}$, the current-voltage (I - V) characteristic will show a current step. This step, often referred as the Eck peak [4] or velocity-matching (VM) step, has been observed in both low- T_c and high- T_c junctions [5].

This paper reports our observation of the VM step for YBCO biepitaxial Josephson junctions. From the step voltage, V_m , the intrinsic capacitance C and the quasiparticle loss α of the junctions can be estimated. By studying the response of these junctions to microwave radiation, we observed the anomaly subharmonic Shapiro steps. These steps are attributed to the synchronous interactions between microwave radiation and fluxon oscillation [6].

II. EXPERIMENTS

To fabricate biepitaxial Josephson junctions, a 50 nm-thickness CeO_2 buffer was first deposited onto the $\text{MgO}[100]$ substrate by rf sputtering. Part of the CeO_2 layer was removed from the surface of substrate by Ar ion milling, providing a smooth and sharp interface where the grain boundary will be located. Then, a 200 nm-thickness YBCO film was grown on the prepared substrate by rf sputtering. Finally, the YBCO film was patterned by standard photolithography and etched by Ar ion beam.

The electrical measurements were performed using the four-probe method. The current was supplied by a constant current source (Keithley model 220) and the voltage was measured by a nanovoltmeter (Keithley model 182). A magnetic field up to 20 G was applied perpendicular to the

Fig. 1 Current-voltage characteristics of a 30- μm YBCO biepitaxial Josephson at 57 K.

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sample plane from a calibrated solenoid wrapped around the sample. Microwaves were generated by a microwave generator (GigaTronics model 7200) and were introduced to the junction through a waveguide.

III. RESULTS AND DISCUSSION

With no applied magnetic fields or microwave, the I - V curves of our samples exhibit overdamped resistively shunted junction-like features at temperatures up to 80 K. Fig. 1 shows the typical I - V characteristics of a 30- μm long YBCO biepitaxial Josephson junction at 57 K. Due to the thermal activated phase slippage, the I - V characteristics show no zero slope at low current and noise rounding curve near the critical current [7].

Using a 1 μV criterion, the I_c is estimated to be about 330 μA , the $I_c R_n$ is about 12 μV , and $J_c = 5.5 \text{ kA/cm}^2$ at $T = 57 \text{ K}$. However, these parameters can be raised to 2 mA, 70 μV , and 33 kA/cm^2 respectively at 25 K. To confirm that the junction is long, we evaluated the Josephson penetration depth

$$\lambda_j = (\Phi_0 / 2\pi\mu_0 J_c (t + 2\lambda_L))^{1/2},$$

where μ_0 is the vacuum permeability, t is the thickness of junction barrier, and λ_L is London penetration depth. Take a value of $\lambda_L = 140 \text{ nm}$ for the YBCO film [8] and $t + 2\lambda_L \approx 2\lambda_L$, thus the λ_j is about 4 μm and much small than the junction length. The magnetic field dependence of critical current at 25 K is illustrated in Fig. 2. It can be seen that the $I_c(B)$ dependence shows pronounced deviations from the Fraunhofer pattern. The non-Fraunhofer-like $I_c(B)$ characteristic has been attributed to crystalline microstructure and $d_{x^2-y^2}$ symmetry [9], [10]. Since the applied magnetic field is perpendicular to the substrate, the magnetic focus must be considered. Although the curve has lost the regularity of Fraunhofer pattern, the simulation results in [9] show that the separation between the two nearby dips in $I_c(B)$

Fig. 2. Critical current as a function of applied magnetic field at 25 K for the junction with junction length $L = 30 \mu\text{m}$. Dots are the experimental data. The lines are guides to the eye.

curve is still roughly about one flux quantum in the junction. From Fig. 2, we obtain 0.7 G is approximately corresponding to penetration of one flux quantum into the junction. Thus the flux focus factor F due to the perpendicular applied magnetic field is about 4.

In order to study flux motion in long YBCO biepitaxial junctions, we applied a magnetic field to a 30- μm junction to study I - V characteristics in flux flow state. Fig. 3 (a) shows some results at 57 K. Since the YBCO biepitaxial junctions are overdamped, the VM steps may be obscure in the I - V data. Therefore, we plot the excess current I_s versus V to reveal the increase of supercurrent, as the dashed lines in Fig. 3 (a) show. Here $I_s = I - V/R_n$ is the space average dc supercurrent across the junction. Figure 3 (b) shows that the voltage of the increased supercurrent is linearly dependent on the applied field B , and dV_m/dB is about 22 $\mu\text{V/G}$. Hence we relate these voltages to the VM steps. According to [5], the relation of VM step voltage and applied magnetic field can be written as

$$V_m = (t + 2\lambda_L) \bar{c} F B.$$

From the value of dV_m/dB , we estimate that the EM wave propagation velocity in YBCO biepitaxial junctions is approximately $2 \times 10^5 \text{ m/s}$. This is only about 1/50 of value reported in YBCO/YSZ 0-32° [001] tilt bicrystal junctions [5]. Since the Swihart velocity is the upper limit of flux flow

Fig. 3. (a) I - V curves of a 30- μm junction with different applied magnetic fields B_1, B_2, B_3, B_4 at 57 K. The average supercurrent I_s vs. V curves are shown as dash lines. The arrows indicate the V_m voltages where flux flow resonances occur. $B_1 = 0.31 \text{ G}$, $B_2 = 0.40 \text{ G}$, $B_3 = 0.58 \text{ G}$, $B_4 = 0.67 \text{ G}$. (b) VM step voltage V_m versus applied magnetic field B of the 30- μm junction. The solid line is the linear fit.

Fig. 4 I - V curves of a 10- μm junction irradiated with different microwave frequencies at 67 K. The inset shows the first step voltage as a function of production of microwave frequency and flux quantum $v\Phi_0$. The solid line shows linear fitting curve.

velocity, the maximum operation frequency of Josephson flux flow devices is about 20 GHz.

Moreover, the Swihart velocity can be established as

$$\bar{c} = c \left(\frac{\epsilon_0}{C(2\lambda_L + t)} \right)^{1/2}$$

where c is the light velocity in vacuum, ϵ_0 is the permittivity of vacuum, and C is the intrinsic capacitance per unit area of the junction. Accordingly, we obtain $C = 70 \text{ pF}/\mu\text{m}^2$, and a junction capacitance of 420 pF. Since our junctions show no hysteresis, this corresponds to a Stewart-McCumber parameter β_c of less than one. Indeed, the β_c we calculated is $0.5 < 1$, and is consistent with non-hysteresis I - V curves. Furthermore, the quasiparticle loss $\alpha = (1/I_c R_n)(J_c \Phi_0 / 2\pi C)^{1/2} \approx 1.3$ at 57 K. This confirms that the EM wave can propagate in the junction, and flux flow can be sustained.

Finally, in Fig. 4, we report the I - V characteristics of a 10- μm junction irradiated with different microwave frequencies at 67 K. The I - V curves show some constant voltage steps, such as the well known Shapiro steps. However, the value of the first step voltage V_1 divided by the product of microwave frequency and flux quantum $v\Phi_0$ is 0.35, as shown in the inset of Fig. 4. There are several mechanisms to explain subharmonic steps. Non-integral steps have been observed in the YBCO biepitaxial junctions [11], and interpreted as the effect of parallel junctions. However, parallel junctions can describe the 1/2, 1/3 steps, and this is not the case here. Two-dimensional Josephson arrays can cause subharmonic steps when the applied field is such that the number of flux quanta per unit cell is not an integer [12]. However, the applied magnetic field does not affect the step voltages in our sample. Other possibilities are the nonsinusoidal current-phase

relation (CPR) [13], [14] and the effect of flux motion in a long junction. The nonsinusoidal CPR for 45° grain boundary YBCO junctions was observed by Il'ichev *et al.* [15]. Thus, we cannot rule out the prospect in our YBCO biepitaxial junctions. On the other hand, since we have observed flux flow resonance in the 30- μm junction, it is reasonable to examine the effect of flux motion.

For microwave radiation at powers less than the threshold for flux flow, constant voltage steps can be induced at [6]

$$V_{n/m} = (n/m)(v\Phi_0).$$

These voltage steps are due to the synchronous coupling that occurs when the fluxon couples to the n th harmonic of the incident radiation for every m trips across the junction. In other words, the condition for which $V_{n/m}$ appears is $v_\phi = (n/m)v$, where v_ϕ is the frequency of fluxon oscillation in the junction. If the anomalous subharmonic voltage steps we observed are caused by interaction between microwave radiation and fluxon oscillation in the long junction, then the average velocity of flux motion $\bar{u}$ can be calculated using $\bar{u} = Lv_\phi$, where L is the junction length. With the ratio $n/m = 0.35$, we obtained the $\bar{u} = 2.1 \times 10^4 \text{ m/s}$ for a YBCO biepitaxial junction at 6 GHz microwave irradiation. Although the average velocity $\bar{u}$ is consistent with the upper limit of fluxon velocity in the above discussion, additional experiments are necessary, such as to determine the dependence between junction length and step voltage.

In conclusion, we have studied the I - V characteristics of YBCO biepitaxial Josephson junctions under magnetic fields and microwave irradiation. The VM steps were observed in the 30- μm junctions at 57 K. This suggests that EM waves can propagate along the junction, and the junction capacitance cannot be neglected. However, the Stewart-McCumber parameter of the junction is about 0.5, which still satisfies the non-hysteresis I - V characteristics shown in our junctions. Finally, we observed the anomalous subharmonic voltage steps in the microwave irradiated I - V curves. The anomaly cannot be attributed to the effects of parallel junctions or 2D junction arrays. However, the other two possible mechanisms, flux motion in a long junction and nonsinusoidal CPR, require further experiments in order to determine which is the cause.

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