Voltage Modulation of High- T_c SQUIDs with Step-edge Junctions

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We studied the V-I characteristics and the voltage modulation of washer-type step-edge $\text{YBa}_2\text{Cu}_3\text{O}_y$ dc SQUIDs. It was found that the banks of the SQUID were composed of two junctions in series. The V-I curve can be fitted to the RSJ model with a sinusoidal current phase relation for the first grain-boundary junction while the second junction show a non-sinusoidal current phase relation. The V- Φ curves of SQUIDs can be characterized by the parameters of the first junctions if the SQUID is biased at $I \sim I_{c1}$ where I_{c1} is the critical current of the first junction. The implications of the data are discussed.

1. INTRODUCTION

The characteristics of the step-edge junction (SEJ) have been extensively studied in recent years [1–3]. In general, the SEJ consists of multiple grain boundaries in series [1]. The V-I curve of the SEJ can be fitted to the RSJ model with excess supercurrents [2]. However, the characteristics of the multiple grain boundary junctions in the SQUIDs are rarely discussed. In this work, we report the effects of grain boundaries on the V-I curve and the voltage-flux modulation of the junctions and the washer-type dc SQUIDs.

2. EXPERIMENTAL DETAILS

The $\text{SrTiO}_3(001)$ step-edge substrate used for the fabrication of the SEJ's and the dc SQUIDs has a step angle greater than 70° . The junctions and SQUIDs were fabricated using a photolithography process followed by an Ar^+ ion milling. The junction width was $3 \mu\text{m}$. Gold pads were deposited onto the electrodes to reduce the contact resistance. The V-I and V- Φ curves were measured in a μ -metal shielded cryostat.

3. RESULTS AND DISCUSSION

Figure 1 shows a typical V-I curve of the SEJ in a zero applied field. The first kink in the V-I curve

was attributed to the first junction, while the second kink was caused by the second junction [3]. The currents at the kinks were identified as the critical current I_{c1} and I_{c2} of the first and the second junctions respectively. I_{c1} and I_{c2} were found to show linear temperature dependence as shown in the inset of Figure 1. The V-I curve of the first junction can be fitted to the resistively shunted junction (RSJ) model [4] with a sinusoidal current-phase relation

Figure 1. V-I curve of the SEJ fits the RSJ model with a sinusoidal CPR for first junction and a linear CPR for second junction. The temperature dependent critical currents for these junctions are shown in the inset.

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(CPR) $I_s = I_c \sin \theta$ for $I < I_{c2}$ as shown in the dashed curve of Figure 1. In contrast to the first junction, it was found that the V-I curve of the second junction could not be fit to the RSJ model with a sinusoidal CPR due to the substantial excess supercurrent. It has been shown that a junction with an excess supercurrent may be simulated with the RSJ model with a linear CPR [5]. In this case, the equation for the V-I curve of the SEJ is given by

$$V = R_1(I^2 - I_{c1}^2)^{1/2} - \left[\frac{2\pi R_2 I_{c2}}{\theta_c} \right] \left/ \ln \left(\frac{I/I_{c2} - 1}{I/I_{c2} - 1 + 2\pi/\theta_c} \right) \right. \quad (1)$$

where R_2 is the resistance and I_{c2} is the critical current of the second junction, and θ_c stands for the critical phase angle in the linear CPR. The supercurrent current in the second junction was assumed to increase linearly until the phase angle $\theta = \theta_c$ [5]. Choosing the critical phase angle $\theta_c = 7\pi$, we can fit the V-I curve to equation (1) with $I_{c2} \approx 1.25$ mA and $R_2 \approx 0.63 \Omega$ for $I > I_{c2}$ as shown in the solid curve of Figure 1. This fitting can be also applied to the SQUID with $I_{c1} \approx I_{c2}$ to obtain I_{c1} / I_{c2} .

Figure 2 shows typical V- Φ and V-I curves of a SQUID at different bias currents. R_1 is the resistance of the first junction derived from the RSJ model with a sinusoidal CPR while R_2 is the resistance of the second junction obtained from the RSJ model with a linear CPR. It was found that the external magnetic field modulates both I_{c1} and I_{c2} of the SQUID. However, the effect of the field on the modulation of I_{c2} is negligible if the SQUID is biased at a current near $2I_{c1}$ and if the $I_{c2} \gg I_{c1}$. Neglecting the second junction, we can estimate the voltage modulation depth by using the following equation [6]

$$\Delta V = \frac{4 I_{c1} R_1}{\pi (1 + \beta_L)} \left(1 - 3.57 \frac{\sqrt{k_B T L_s}}{\Phi_0} \right) \quad (2)$$

where I_{c1} is the critical current, and R_1 is the resistance of the first junction, $\beta_L = 2I_{c1}L_s/\Phi_0 R_1$, L_s is inductance of the SQUID, T is the temperature, k_B is the Boltzmann constant, and Φ_0 is the flux quantum. Putting $L_s = 40$ pH, $I_{c1} = 289 \mu A$, $R_1 = 1.94 \Omega$, and $T = 20$ K into equation (2), we obtained $\Delta V = 56 \mu V$. This value is consistent with the measured modulation depth $\Delta V \approx 50 \mu V$ of the SQUID. In other words, the ΔV of the step-edge SQUID can be estimated by considering the first junction as the

Figure 2. The typical V-I curve of the step-edge SQUID at 20 K. The voltage modulation of the SQUID by the applied magnetic flux at various bias currents is shown at the bottom of the figure.

effective junctions in the SQUID. Therefore, the behavior of the step-edge SQUID may be described with the RSJ model with a sinusoidal CPR for the first junction instead of the non-sinusoidal CPR for the SEJ [2].

4. CONCLUSION

In summary, the V-I characteristics of step-edge junctions can be fit to the RSJ model with a sinusoidal CPR for the first junction and a non-sinusoidal CPR for the second junction. The V- Φ of the step-edge SQUIDS can be described with the RSJ model with a sinusoidal CPR for $I_{c1} < I < I_{c2}$.

REFERENCES

1. K.Herrmann, G.Kunkel, M.Siegel, J.Schubert, W.Zandr, A.I.Brangiski, C.L.Jia, B.Kabius and K.Urban, J. Appl. Phys. 78 (1995) 1131.
2. V.Foglietti, R.H.Koch, J.Z.Sun, R.B.Laibowitz, and W.J.Gallagher, J. Appl. Phys., 77(1995) 378.
3. H.E.Hornig, S.Y.Yang, J.T.Jeng, J.M.Wu, J.H.Chen and H.C.Yang, IEEE Trans. Appl. Supercond. 9 (1999) 3986.
4. T.Van Duzer and C.W.Turner, "Principles of Superconductive Devices and Circuits", 1981.
5. L.D.Jackel, W.H.Henkels, J.M.Warlaumont, and R.A.Buhrman, Appl. Phys. Lett. 29 (1976) 214.
6. K.Enpuku, Y.Shimomura, and T.Kisu, J. Appl. Phys. 73, (1993) 7929.