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 YBa$_2$Cu$_3$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-$\Phi$ curves of SQUIDs can be characterized by the parameters of the first junctions if the SQUID is biased at $I = I_{c1}$ 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 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 $\mu$m. Gold pads were deposited onto the electrodes to reduce the contact resistance. The V-I and V-$\Phi$ curves were measured in a $\mu$-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.
(CPR) $I_c = I_c \sin \theta$ for $I < I_c$ 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

$$V = R_2 \left( I^2 - I_c^2 \right)^{1/2} - \frac{2\pi R_2 I_c}{\theta_c} \left[ \ln \left( \frac{1}{I_c - 1} \right) + 2\pi \theta_c \right],$$

where $R_2$ is the resistance and $I_c$ is the critical current of the second junction, and $\theta_c$ stands for the critical phase angle in the linear CPR. The supercurrent 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 $I_c = 1.25 \text{ mA}$ and $R_2 \approx 0.63 \Omega$ for $I > I_c$ as shown in the solid curve of Figure 1. This fitting can be also applied to the SQUID with $I_c \approx I_c$ to obtain $I_c / I_c$.

Figure 2 shows typical V-$\Phi$ 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]

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

where $I_{c1}$ is the critical current, and $R_1$ is the resistance of the first junction, $\beta = 2L_s I_{c2}/\Phi_0 R_1$, $L_s$ is inductance of the SQUID, $T$ is the temperature, $k_B$ is the Boltzmann constant, and $\Phi_0$ is the flux quantum. Putting $L_s = 40 \text{ pH}$, $I_{c1} = 289 \mu\text{A}$, $R_1 = 1.94 \Omega$, and $T = 20 \text{ K}$ into equation (2), we obtained $\Delta V = 56 \mu\text{V}$. This value is consistent with the measured modulation depth $\Delta V = 50 \mu\text{V}$ of the SQUID. In other words, the $\Delta V$ of the step-edge SQUID can be estimated by considering the first junction as the 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-$\Phi$ of the step-edge SQUIDs can be described with the RSJ model with a sinusoidal CPR for $I_{c1} < I < I_{c2}$.

**REFERENCES**