Temperature dependent characteristics of step-edge YBCO SQUIDS

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In this report, the temperature dependent characteristics are investigated for the step-edge YBCO SQUID. The experimental results show a linear relationship between I_c and T . This reveals a SIS-like tunneling behavior for the step-edge YBCO SQUID. The peak-to-peak voltage V_{pp} in the V - Φ curve of the SQUID was found to decrease almost linearly when the temperature was raised from 10 K to 60 K. As the temperature approached to the T_c of the SQUID, the V_{pp} was reduced abruptly and deviated from the theoretically predicted curve. This deviation may be due to the variation of the inductance of the SQUID at various temperatures.

1. INTRODUCTION

Due to their great potential in applications, the characteristics of high- T_c SQUIDS have received increasing studies [1–6]. Most reports have focused on optimization of the SQUIDS and some significant results were obtained [1,2,6]. However, research on the temperature effects on the SQUID characteristics are still rare. Therefore, some properties of the step-edge YBCO SQUID are investigated at various temperatures in this work.

2. EXPERIMENTAL DETAILS

The SQUID investigated is a step-edge YBCO SQUID with a hole area of $20 \times 40 \mu\text{m}^2$. The fabrication of the SQUID was reported elsewhere [5]. For the electric measurements, the four-point method was used. The temperature was sensed by a diode thermometer and controlled by a temperature controller. To examine the magnetically modulated voltage oscillation of the SQUID, the SQUID was placed into a solenoid which provided a magnetic field perpendicular to the hole of the SQUID. The experimental details were illustrated in Ref. [6].

3. RESULTS AND DISCUSSION

The critical current I_c of the step-edge YBCO

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SQUID was obtained from the V - I curve with a criterion voltage of $1 \mu\text{V}$. By varying the temperature, the I_c as a function of the temperature T can be examined. The experimental temperature dependent normalized critical current $I_c(T)/I_c(0)$ is shown in Fig. 1 (denoted by dots). It was found that the critical current I_c almost remains constant at temperature T lower than 20 K. When the temperature is raised, I_c is reduced linearly down to zero as T reaches to the critical temperature. This linearity suggests that the weak link of the step-edge YBCO junctions is similar to a SIS junction behavior. A theoretical $I_c/I_c(0)$ - T relation for an ideal SIS Josephson junction was developed by Ambegokar-Baratoff to be [7]

$$I_c(T)/I_c(0) = [\Delta(T)/\Delta(0)] \tanh(\alpha T_c/2T), \quad (1)$$

here $\alpha = \Delta(0)/k_B T_c$, k_B is the Boltzmann constant

Fig. 1. Normalized critical current versus the temperature. The dots are the experimental data. The solid line is the theoretical curve [7].

and $\Delta(T)$ is the temperature dependent energy gap in the BCS theory. To fit the experimental results to the theoretical curve, the $\Delta(T)/\Delta(0)$ can be evaluated at the reduced temperature T/T_c with the help of the BCS functions tabulated in Ref. [8]. The theoretical curve with $\alpha = 0.85$ and $T_c = 80$ K is shown in Fig. 1 by the solid line. It was found that the experimental data almost follow the SIS-junction behavior. And also, with the fitted $\alpha(=\Delta(0)/k_B T_c)$ being 0.85 and T_c being 80 K, the $\Delta(0)$ was obtained to be 5.82 meV.

In addition to the temperature dependent critical current of the SQUID, the influence of the temperature on the magnetically modulated voltage oscillation (V - Φ curve) is also investigated. In Fig. 2, the peak-to-peak voltage V_{pp} of the V - Φ curve decreased almost linearly when the temperature was increased from 10 K to 60 K. An abrupt drop in the V_{pp} was found at the temperatures from 60 K to 77 K. Based on the RSJ model with thermal fluctuations for a SQUID, Enpuku derived a theoretical expression for the V_{pp} as [9]

$$V_{pp} = v \frac{I_c R_n}{1 + \beta_L} \left(1 - 3.57 \frac{\sqrt{k_B T L}}{\Phi_0} \right) \quad (2)$$

with $\beta_L = LI_c/\Phi_0$, where v is a bias current dependent variable, I_c is the critical current of the SQUID without thermal fluctuations, R_n is the normal state resistance of the SQUID, k_B is the Boltzmann constant, T is the working temperature and L is the inductance of the SQUID. For this case, the R_n equals 6 Ω . The range of the working temperature is from 10 K to 77 K and the I_c at each temperature is obtained from the V - I curve. In the experiment, the bias current for the maximum V_{pp} at a given temperature almost equals to the

Fig. 2. V_{pp} in the V - Φ curve of the SQUID as a function of temperature. The dots with error bars are data points, whereas the line was deviated by Enpuku et al. [9].

corresponding I_c . According to the published report [10], the suitable value for v is $7/\pi^2$. The only undetermined parameter in Eq. (2) is L . To find it, the experimental data $V_{pp}(T)$ are fitted to Eq. (2). The resulting curve with $L = 125$ pH is shown in Fig. 2 (denoted by the solid line). A good match between the experimental data and the theoretical prediction is obtained at temperatures lower than 60 K. Whereas an obvious deviation of the data from the fitted curve occurs at higher temperatures. This deviation may be due to the variation in the inductance L at higher temperature. This point is also supported by the published researches from other groups [11,12].

4. CONCLUSION

The I_c - T curve reveals SIS-like tunneling behavior for the step-edge YBCO SQUID. The V_{pp} in the V - Φ curve of the SQUID decreased with increasing the temperature. The V_{pp} - T curve is consistent with the theoretical prediction in the lower temperature range. At high temperatures, the deviation of the experimental V_{pp} - T curve from the theoretical prediction implies that the inductance of the SQUID is heavily temperature dependent at temperatures near T_c .

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