Single-layer 2nd-order SQUID gradiometer and fabrication of YBa$_2$Cu$_3$O$_7$ nanobridges as the Josephson elements

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Abstract. We have studied fabrication of second-order SQUID gradiometers from single-layer of high-$T_c$ film. The gradiometer contains three parallel-connected pickup coils which are directly coupled to a step-edge junction SQUID. In the study of short-baseline devices, we achieved an unshielded noise of 0.84 pT/Hz$^{1/2}$ at 1 Hz for a well-balanced gradiometer. As Josephson elements of lone-baseline devices we made submicron YBCO bridges by using a focused ion beam method. In temperature-dependent critical currents, $I_c(T)$, and normal state resistances, $R_N(T)$, the bridge showed an SIS-type behavior, which is believed to be due to naturally formed grain boundaries crossing the bridges.

1. Introduction

SQUID measurements require special measures to eliminate external noises that are typically several orders of magnitude larger than signals to be detected. A magnetically shielded room is a sure solution. However, measurement in unshielded environments is necessary for some applications, such as nondestructive tests and clinical MCG. In such cases a gradiometer type SQUID sensor is an alternative solution because of the immunity to uniform field noises, whose sources are usually located relatively farther from the sensor and thus almost uniform at the sensor position.

The Nb SQUID gradiometer fabricated by the multilayer thin-film process has long been developed. However, a stable and reproducible multilayer process is not available yet for the high-$T_c$ oxides. Thus, most of the high-$T_c$ junction devices are made from the single superconducting layer. Directly coupled first-order SQUID gradiometer from a single-layer superconductor was developed by Knappe et al. [1]. We developed the 2nd-order SQUID gradiometer from a single layer of superconducting film on a single substrate for the first time [2]. Gradiometers of flip-chip coupling types were also developed. An asymmetric 1st-order SQUID gradiometer with a flip-chip coupling of the pickup coil to the SQUID was developed by Dantsker et al. [3]. The flip-chip coupled 2nd-order high $T_c$ SQUID gradiometer was also developed by Kittel et al. [4]. On the other hand, electronic gradiometers based on electronic subtraction of outputs of magnetometers located at different positions were developed. Koch et al. invented three-SQUID gradiometer with a reference SQUID for baseline field subtraction.
Tarvin et al. developed a second-order gradiometer composed of 3 independent sets of SQUID magnetometers [6]. In our previous works we have studied feasibility of the single-layer 2nd-order SQUID gradiometer in MCG application [2], [7]-[9]. In this work, we have studied fabrication of YBCO nanobridges for long-baseline single-layer 2nd-order SQUID gradiometer.

2. Short-baseline second-order SQUID gradiometer

Schematic of the design is shown in Fig. 1. Under a uniform field, the screening currents induced by the flux threading through the side loops flow in opposition direction to that of the center loop in the SQUID loop. When the following condition is satisfied, the flux coupled to the SQUID is zero. That is, $\alpha A/L = -\alpha_c A_c/L_c + A_s/L_s$, where $\alpha_c$ is the coupling of the center loop to the SQUID. $A (A_c, A_s)$ and $L (L_c, L_s)$ are the effective area and inductance of the side (center, SQUID) loop, respectively. For a balanced gradiometer, the gradient sensitivity is calculated to be $(\delta^2 B_z/\delta x^2) = \phi_0 L_c/\alpha_c^2 A_c L_s$, where $\phi_0$ is the intrinsic SQUID noise.

The gradiometer was 17.6 mm $\times$ 6 mm in overall size. The side (center) pickup loop has an inner dimension of 3.6 mm (2.0 mm) with a line width of 1.2 mm (1.134 mm). Effective area and inductance are 21.6 mm$^2$ (8.54 mm$^2$) and 8.98 nH (3.60 nH) for the side (center) loop. SQUID inductance is calculated to be 35 pH. Baseline is 5.8 mm. The balancing conditions were obtained by investigating balancing factor for different values of $\alpha$ around the calculated optimum value. For 5.8 mm baseline device, optimum value was $\alpha = 1.134$ mm with a balancing factor of $1.6 \times 10^3$.

The measured noise spectra are shown in Fig. 2. One can notice that the spectra are ‘white’ all the way down to 1 Hz for both shielded and unshielded cases, which is in comparison with the usual $1/f$ dependence at low frequencies. Second-order gradient noise is 0.45 pT/cm$^2$/Hz$^{1/2}$ for the shielded measurement and 0.84 pT/cm$^2$/Hz$^{1/2}$ for the unshielded case. Equivalent field noises are 150 fT/Hz$^{1/2}$ and 280 fT/Hz$^{1/2}$, respectively. Intrinsic flux noise of the SQUID ($\phi_0$) is estimated to be $1 \times 10^{-5} \phi_0 / Hz^{1/2}$ for the shielded and $1.9 \times 10^{-5} \phi_0 / Hz^{1/2}$ for the unshielded case, which is very low presumably due to the very large common mode rejection of the gradiometer.

3. YBCO nanobridges for long-baseline gradiometer

For applications such as MCG, longer-baseline gradiometers are needed. We designed gradiometers with a much longer baseline, 30 mm. The design was based on the same rules as those of the shorter ones. Overall size is 70.2 mm $\times$ 10.6 mm with each pickup loop of the outer dimension of 10 mm $\times$ 10 mm. Expected gradient noise is calculated to be 18 fT/cm$^2$/Hz$^{1/2}$ for an intrinsic SQUID flux noise of $10^{-5} \phi_0 / Hz^{1/2}$. Unlike the shorter baselines, longer ones were to be made on sapphire substrates, in case of which fabrication of high quality Josephson junctions is the key issue.
We have fabricated submicron bridges by using focused ion beam (FIB). Two types were fabricated, which were variable thickness bridge (VTB) and constant thickness bridge (CTB). Both were patterned from YBCO(300 nm)/Au(50 nm) on sapphire substrates. Fig. 3 shows schematic of the bridges. VTB is 200 nm thick, 300 nm wide and 30 nm long, and CTB 100 nm wide and 30 nm long with Au layer on top intact.

We measured current-voltage ($I-V$) curves and obtained temperature-dependent critical current, $I_c(T)$, and normal state junction resistance, $R_N(T)$. Fig. 4 shows $I-V$ curves measured at 77 K. One can clearly notice excess current in CTB. Since the coherence length $\xi_{ab} \sim 1.5$ nm is much shorter than all the bridge dimensions, the bridges are basically in the flux flow regime. Critical currents are 4.3 mA and 70 μA for VTB and CTB, respectively. Critical current is not proportional to the cross sectional area of the bridge, which is believed due to nonuniform property of the bridge area. We believe that Josephson junction was formed by natural grain boundaries crossing the bridges. The following $I_c(T)$ and $R_N(T)$ data support this conclusion.

Fig. 5 and 6 show temperature-dependent critical current and normal state resistance data. $I_c(T) \sim (1-T/T_c)^{3/2}$ of VTB implies an insulating barrier, that is, the bridge behaves as an ‘SIS’ junction. On the other hand, CTB has $I_c(T) \sim (1-T/T_c)^{2}$, implying a normal barrier, which is obvious because of the Au layer on top. Normal state resistance data, $R_N(T)$, increases for VTB and decreases for CTB as temperature decreases below $T_c$. These results also support that VTB is an SIS and CTB an ‘SNS’ junction. Magnitudes of $R_N$ further support this conclusion. In the study of the electron-beam-damaged YBCO nanobridge by Booij et al. [11], the bridge became normal due to the damage and showed

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**Fig. 3.** Schematics of VTB (top) and CTB (bottom)

**Fig. 4.** I-V of VTB and CTB at 77 K.

**Fig. 5.** Critical current versus temperature.

**Fig. 6.** Normal resistance vs. temperature.
proximity junction behavior, that is, \( I_c(T) \sim (1 - T/T_c)^{3/2} \). But in the bridges of current study, no artificial damage was made, and thus no direct comparison can be made.

Since the bridge dimensions are much larger than the superconducting coherence length \( \xi_{ab} \sim 1.5 \text{ nm} \), the bridges are in the flux flow regime [10]. In such a case, the bridge behaves like a normal metal barrier. However, our data imply nonmetallic barrier as shown above. We believe that the bridges are crossed by grain boundaries which are naturally abundant in YBCO films. In other words, the bridges are grain boundary (GB) junctions with GB as a nonmetallic barrier. In case of CTB, the bridge is shunted by a 50 nm thick Au layer and thus becomes an ‘SNS’ weak link. Significant reduction in the normal state resistance \( R_N \), and its temperature dependence support our conclusion.

4. Conclusion
We have studied fabrication of single-layer second-order high-\( T_c \) SQUID gradiometer. For a well-balanced short-baseline YBCO gradiometer, the unshielded gradient noise was measured to be 0.84 pT/cm²/Hz^{1/2} at 1 Hz. As Josephson elements for long-baseline devices we made two types of submicron bridges by using a focused ion beam (FIB) patterning method. \( I_c(T) \) and \( R_N(T) \) data were SIS-like for VTB and SNS-like for CTB. We believe that those characteristics are ascribed to naturally formed grain boundaries crossing the bridges.

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