

# Key elements for a sensitive 77 K direct current superconducting quantum interference device magnetometer

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We have made sensitive dc superconducting quantum interference device (SQUID) magnetometers that operate at 77 K have been made. By using bicrystal grain boundary Josephson junctions and a single layer of  $\text{YBa}_2\text{Cu}_3\text{O}_7$  thin film with optimized processing and an optimized directly coupled design, we have produced magnetometers with very low noise and a large transfer function. At 77 K, the transfer function is  $100 \mu\text{V}/\Phi_0$ ; the white field noise of the magnetometer is less than  $10 \text{ fT}/\sqrt{\text{Hz}}$  above 10 kHz, rising to  $26 \text{ fT}/\sqrt{\text{Hz}}$  at 1 Hz. The corresponding white noise energy has the low value of  $2 \times 10^{-31} \text{ J s}$ ; a value very similar to that of commercial Nb SQUIDS. Key elements required to achieve this performance are discussed. © 1995 American Institute of Physics.

In order to apply high  $T_c$  SQUID (superconducting quantum interference device) magnetometers that operate at 77 K in the areas of biomagnetism, geophysics, or remote magnetic detection, it is necessary for them to have field noise levels comparable to those attained by low-temperature Nb technology. For these applications, we also require good resolution at frequencies down to 0.1 Hz or less, so the levels of both the white and the  $1/f$  or “flicker” noise are important.<sup>1</sup> When fabricating low noise devices, we need to identify the major sources of noise. One source of  $1/f$  noise is fluctuations of the critical current of the Josephson junctions, which depend on the junction quality but can be reduced by a suitable bias modulation scheme.<sup>1</sup> Another source of  $1/f$  noise is the motion of flux lines trapped in the superconductor.<sup>1</sup> This varies widely with the structure of the superconducting films.

The impact of SQUID flux noise on the field noise of a magnetometer is determined by the effective area of the magnetometer,  $A_{\text{eff}} = \Phi_{\text{sq}}/B$ , where  $B$  is the applied field and  $\Phi_{\text{sq}}$  is the flux coupled to the SQUID.  $A_{\text{eff}}$  is determined by the design of the magnetometer. The largest values of  $A_{\text{eff}}$  have been obtained in multilayer devices, using either multiturn flux transformer coils to couple the pickup circuit to the SQUID<sup>2</sup> or a multiloop array of parallel-connected SQUID inductors which also serve as the pickup structure.<sup>16</sup> The first high-temperature superconductor (HTS) multilayer integrated SQUID magnetometer operating at 77 K, showed the potential of multilayered epitaxial technology,<sup>2</sup> but the noise of such magnetometers for practical applications remained to be improved. The *ex situ* multilayer deposition and patterning processes required make it difficult to maintain continuous heteroepitaxial multilayers that are highly aligned in both the growth direction and in-plane; consequently, the resulting structures exhibit excess low-frequency noise, even though they frequently have excellent electrical transport properties. Progress is being made in multilayer devices. Ludwig *et al.* recently reported noise at 77 K of  $37 \text{ fT}/\sqrt{\text{Hz}}$  at 1 Hz for a  $1 \text{ cm}^2$  multiloop device.<sup>3</sup>

While we and others are searching for ways to improve multilayer HTS devices, we are also making single-layer directly coupled dc SQUID magnetometers with optimized geometry. While  $A_{\text{eff}}$  for these devices is less than that of multilayer devices of the same overall size, we find that this loss is outweighed by the benefit we get from being able to use a single low-noise HTS film. In the directly coupled geometry, the large pickup loop is connected parallel with the much smaller inductance of the SQUID. The dynamics of the SQUID are thus determined by the smaller inductance, but flux linking the pickup loop induces a current which couples flux to the SQUID.

Masuda *et al.* fabricated the first HTS directly coupled dc SQUID magnetometers, using Bi–Sr–Ca–Cu oxide films.<sup>4</sup> With a structure  $\sim 4 \text{ mm}$  square, they obtained  $A_{\text{eff}} = 0.14 \text{ mm}^2$ . At 4.2 K, the noise was  $2 \times 10^{-4} \Phi_0/\sqrt{\text{Hz}}$  at 1 Hz, corresponding to  $2.9 \text{ pT}/\sqrt{\text{Hz}}$ . Greatly improved directly coupled dc SQUID magnetometers with (YBCO) thin films have been demonstrated in the last few years. Koelle *et al.*<sup>5,6</sup> have achieved a magnetic field noise of  $105 \text{ fT}/\sqrt{\text{Hz}}$  at 1 kHz, increasing to  $145 \text{ fT}/\sqrt{\text{Hz}}$  at 1 Hz for devices  $1 \text{ cm}^2$  in size at 77 K. Using a large washer rf SQUID, Zang *et al.* have reported a magnetic field noise as low as  $170 \text{ fT}/\sqrt{\text{Hz}}$  at 1 Hz for a  $1 \text{ cm}^2$  device at 77 K.<sup>7</sup> Lee *et al.* recently reported a magnetic field noise of  $35 \text{ fT}/\sqrt{\text{Hz}}$  at 1 kHz, increasing to  $65 \text{ fT}/\sqrt{\text{Hz}}$  at 1 Hz for a dc SQUID magnetometer ( $1 \text{ cm}^2$  in size) at 77 K.<sup>8</sup> In this letter, we discuss the decisions we took in making our high performance directly coupled magnetometers and report on their performance.

Our HTS films are high-quality epitaxial YBCO grown by laser ablation on  $\text{SrTiO}_3$  substrates with various heteroepitaxial and/or homoepitaxial buffer layers. According to SEM observations and AFM measurements, the films have a roughness of less than 4 nm; distinct large grains or  $a$ -axis oriented material were not detected. We check the film noise by placing a sample of the film in close proximity to a small HTC SQUID. We find that it is possible to reduce the  $1/f$  noise of a film by achieving high crystalline quality. Many of our films show flux noise of less than  $10 \mu\Phi_0/\sqrt{\text{Hz}}$  at 1 Hz.

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This shows the importance of the macro- and microstructure of the thin film for low noise device fabrication. A detailed study of noise versus the crystalline quality and morphology of YBCO thin films with homoepitaxial and heteroepitaxial buffer layers will be published elsewhere.<sup>9</sup>

We have found the best choice of junction type for low-noise SQUIDs to be the simple and reproducible grain boundary junctions grown on bicrystal substrates.<sup>10,11</sup> Even though the  $1/f$  noise of grain boundary junctions is considered ubiquitous and not well understood, it is related to the quality of the film itself and so is reduced as the film noise is reduced.<sup>9</sup> Thus far, most HTS junction technologies have produced junction shunt resistances of less than a few  $\Omega$ .<sup>4-6,10,11</sup> However, we are able to achieve junction resistances as large as  $20 \Omega$  with a  $2 \mu\text{m}$  linewidth. This is beneficial both to the device noise and its transfer function. We can improve the SQUID performance further by increasing junction resistance if we use submicron geometry while maintaining a high  $I_c R$  product.

The SQUID design rules set out by Tesche and Clarke<sup>1,12</sup> constrain the choice of parameters. For the junction coupling strength to be greater than thermal energies, we require that  $I_c \Phi_0 / 2\pi \approx 5 k_B T$ , where  $I_c$  is the junction critical current,  $\Phi_0$  the flux quantum, and  $T$  is the temperature. At 77 K,  $I_c \approx 17 \mu\text{A}$  is sufficient. Optimum SQUID performance is obtained when  $\beta_L = 2LI_c / \Phi_0 \approx 1$ , where  $L$  is the SQUID inductance; thus  $L$  should be no larger than 59 pH. This restricts our freedom to obtain large  $A_{\text{eff}}$  by using a single large  $L$ . To ensure nonhysteretic characteristics we require  $\beta_c = 2\pi I_c R^2 C / \Phi_0 \leq 1$ , where  $R$  and  $C$  are the junction shunt resistance and capacitance.<sup>13,14</sup> Since the size of the SQUID transfer function  $dV/d\phi$  is approximately  $R/L$ , and the spectral density of the thermal voltage noise is  $S_v \approx 16k_B TR$ , the thermal flux noise density is  $S_v / (dV/d\Phi)^2 \approx 16k_B TL^2 / R$ . Therefore, we can reduce the thermal flux noise by making  $R$  as large as possible, so long as  $C$  is kept small enough to satisfy the condition on  $\beta_c$ . In this connection, it is important to realize that planar grain boundary junctions in HTS technology can have a capacitance of  $<10$  fF, much smaller than that of typical Nb trilayer junctions ( $\approx 1$  pF), or of trilayer or edges SNS junctions with  $2 \mu\text{m}$  linewidth. The grain boundary junction is frequently considered to be a limiting factor in HTS technology; but if we take advantage of it properly it may have important applications to HTS SQUIDs and digital electronics. For example, we can equal the energy resolution of commercial Nb SQUIDs with HTS at 77 K. In cases where  $C$  is critical, it would be best to use a substrate with a lower dielectric constant than  $\text{SrTiO}_3$ ; we have found yttria-stabilized zirconia to be acceptable.

In order to enhance the sensitivity to magnetic fields with a single layer device, the SQUID inductance  $L$  is connected in parallel with the much larger pickup loop of inductance  $L_p$ . The effective area of a directly coupled SQUID magnetometer is given by  $A_{\text{eff}} = A_s + \alpha A_p (L/L_p) \approx \alpha A_p (L/L_p)$ , where  $A_s$  is the effective area of the SQUID inductance and  $A_p$  is the effective area of the pickup loop. For  $A_s$  and  $A_p$ , "effective area" implies that flux focusing is taken into account.  $\alpha$  is a coupling constant which is unity

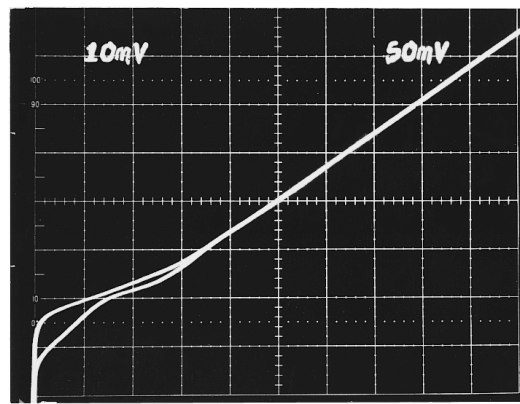


FIG. 1. Current-voltage characteristic of a dc SQUID magnetometer at 77 K with applied flux  $\Phi=0$  (upper curve) and  $\Phi=\Phi_0/2$  (lower curve). V:  $10 \mu\text{A}/\text{div}$ . H:  $5 \mu\text{V}/\text{div}$ .

when the current in  $L_p$  produces the maximum possible flux in  $L$ .  $L$  includes the inductance of the SQUID loop and the parasitic inductance associated with the junction region. In our design,  $L$  has a total value of about 50 pH.

Finally, our pickup loop is in the form of a square washer with outer side length  $a$  and inner side length  $d$ . In this geometry, the ratio  $A_p/L_p$  approaches a maximum in the limit  $a \gg d$ . In this limit,  $A_p = ad$  and  $L_p = 1.25 \mu_0 d$ .<sup>15</sup> On our  $20 \times 20 \text{ mm}^2$  substrates, we used  $a = 19 \text{ mm}$  and  $d = 6 \text{ mm}$ . We estimate  $A_{\text{eff}} = 0.51 \text{ mm}^2$ . For all the inductive elements, it is important to be aware of the role of film thickness and penetration depth in determining the kinetic contribution to the inductance.

We have fabricated our magnetometers with 150–300 nm thick YBCO films on  $1 \times 1 \text{ cm}^2$  or  $2 \times 2 \text{ cm}^2$   $\text{SrTiO}_3$  bicrystal substrates with a  $24^\circ$  misorientation angle. The complete structure was patterned by ion beam etching and normal metallization was done by ion beam sputtering of Ag/Au after ion beam cleaning through a photoresist liftoff stencil. The current-voltage characteristic of one such dc SQUID magnetometer at 77 K with applied flux  $\Phi=0$  and  $\Phi=\Phi_0/2$  is shown in Fig. 1. In this case,  $I_c = 8 \mu\text{A}$  and

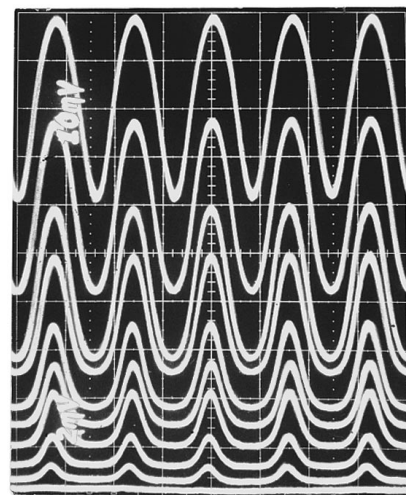


FIG. 2. Voltage-flux characteristic at 77 K with different bias currents. V:  $10 \mu\text{V}/\text{div}$ .

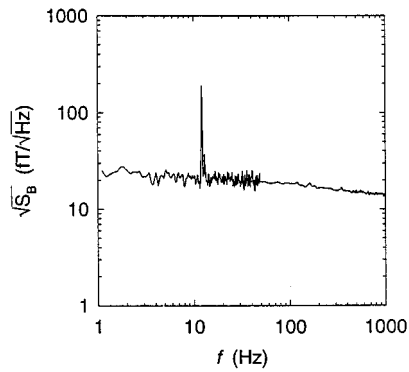


FIG. 3. Measured rms magnetic field noise  $S_B^{1/2}(f)$ . The spike at 12 Hz is a microphonic effect.

$R=14.2 \Omega$ . Resonant structures can be seen in our magnetometers on  $\text{SrTiO}_3$ . Figure 2 shows the voltage-flux characteristic of a dc SQUID magnetometer measured at different values of bias current at 77 K. We find the ratio of field to flux is  $4.6 \text{ nT}/\Phi_0$ , hence  $A_{\text{eff}}=0.43 \text{ mm}^2$ , compared with our theoretical value of  $0.51 \text{ mm}^2$ . Many of these devices operating at 77 K show a peak-to-peak voltage modulation in excess of  $30 \mu\text{V}$ , corresponding to a maximum  $dV/d\Phi \approx 100 \mu\text{V}/\Phi_0$ , a particular benefit of the large resistance.

Figure 3 shows the best measured rms magnetic field noise density  $S_B^{1/2}(f)$  at 77 K in zero field, obtained using flux-locked loop electronics with bias current reversal at 2 kHz. The white field noise of the magnetometer (of size  $2 \times 2 \text{ cm}^2$ ) is less than  $10 \text{ fT}/\sqrt{\text{Hz}}$  above 10 kHz, rising to  $26 \text{ fT}/\sqrt{\text{Hz}}$  at 1 Hz, corresponding to a flux noise  $S_\Phi^{1/2}(f)$  of  $2.2 \mu\Phi_0/\sqrt{\text{Hz}}$  above 10 kHz and  $5.7 \mu\Phi_0/\sqrt{\text{Hz}}$  at 1 Hz. The corresponding white noise energy,  $S_\Phi/2L \approx 2 \times 10^{-31} \text{ J s}$ , is a value very similar to that of commercial Nb SQUIDs.

We have made more than 60 SQUID magnetometers following the methods described here. They all have a white noise of less than  $10 \mu\Phi_0/\sqrt{\text{Hz}}$  at 1 kHz and 62% of them have a  $1/f$  noise of less than  $10 \mu\Phi_0/\sqrt{\text{Hz}}$  at 1 Hz. The SQUID properties are reproducible on thermal cycling. The SQUID magnetometers require no special handling, other than vibration isolation to eliminate microphonic noise caused by their motion in the ambient field.

To conclude, we have fabricated dc SQUID magnetometers that operate at liquid nitrogen temperature and have a very low 1 Hz field noise and a large transfer function. For a single-layer dc SQUID magnetometer operating at 77 K, the magnetic field noise is believed to be the lowest reported to date. Moreover, we have demonstrated that it is possible to attain at 77 K, the high energy sensitivity normally associated with Nb technology at 4.2 K. The advantages of these single layer devices are fewer fabrication steps and high yields. We hope this result will increase the acceptance of HTS thin-film technology for many practical applications.

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