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Low noise operation of integrated $YBa_2Cu_3O_7$ magnetometers in static magnetic fields

S. Krey[a)]
Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Universität Hamburg, Jungiusstraße 11, D-20355 Hamburg, Germany

B. David and R. Eckart
Philips GmbH Forschungslaboratorien, Abteilung Technische Systeme Hamburg, Röntgenstraße 24, D-22335 Hamburg, Germany

O. Dössel
Institut für Biomedizinische Technik, Universität Karlsruhe, Kaiserstraße 12, D-76128 Karlsruhe, Germany

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The noise of two integrated $YBa_2Cu_3O_7$-$SrTiO_3$-$YBa_2Cu_3O_7$ multilayer magnetometers in static magnetic fields up to 110 μT is investigated: An inductively coupled magnetometer with integrated flux transformer and a multiloop magnetometer. In both samples, only a moderate increase of the low frequency flux noise is found in high fields, due to the high epitaxial quality of the involved multilayer films. So for moderately shielded or unshielded applications in the earth's magnetic field, high-quality integrated $YBa_2Cu_3O_7$ magnetometers can be operated with low excess noise. © *1998 American Institute of Physics.* [S0003-6951(98)01924-X]

The most sensitive superconducting quantum interference devices (SQUIDs) from high transition temperature (T_c) superconductors are integrated magnetometers from $YBa_2Cu_3O_7$ (YBCO) multilayers. Today, the noise level of these devices has reached a level close to that achieved with commercial low-T_c systems.[1,2] However, this sensitivity was obtained in heavily shielded settings which often cannot be used for economical or practical reasons. So, for many applications SQUID magnetometers have to be operated in moderately shielded or unshielded environment, where they are influenced by the earth's magnetic field of about 50 μT. The performance of high-T_c devices usually suffers from increased flux noise, if they are cooled through T_c in a magnetic field B_0. This causes flux vortices to be trapped in the superconducting thin films, and excess noise is generated by the thermally activated random hopping of the vortices between their pinning sites.[3] The spectral density S_Φ of the excess flux noise typically scales with $1/f$ as a function of the frequency f and therefore adversely affects low frequency applications such as biomagnetism or geophysical measurements. The number of vortices is proportional to the applied field, and one expects $S_\Phi(f)$ to scale linearly with B_0 if the vortex motion is uncorrelated.

At present, only measurements on single layer devices in a magnetic field have been reported. Miklich *et al.*[4] investigated the performance of a bare SQUID and a directly coupled magnetometer in static magnetic fields. They found an increase of the $1/f$ noise at 1 Hz by an order of magnitude for $B_0 = 50\ \mu$T. Similar measurements were made by Faley *et al.*[5] and Schmidt *et al.*,[6] but they did not observe any significant increase of flux noise up to 100 μT. Recently, Dantsker *et al.*[7] examined the influence of the device geometry on the excess noise. For washer SQUIDs, they found a large increase of the flux noise of more than one order of magnitude, if the devices were cooled in fields up to 60 μT. By reducing the washer's linewidth, they could keep the flux noise low up to a threshold field of 33 μT, but at higher fields the noise rapidly increased. In Ref. 8 they further showed that this threshold field can be shifted towards higher values, if the SQUID washer is provided with slots or holes, giving sufficiently small structure widths to prevent vortex penetration.

Here we present the first noise measurements on two integrated multilayer devices operated in static magnetic fields: An inductively coupled magnetometer with integrated flux transformer and a multiloop magnetometer. Each device is patterned on $10\times 10\ \mathrm{mm}^2$ $SrTiO_3$ (STO) substrate and incorporates YBCO step-edge junctions. The YBCO-STO-YBCO multilayer fabrication process is described in detail elsewhere.[9] We deposit the YBCO films and the intermediate STO insulation layer by high oxygen pressure off-axis rf magnetron sputtering and pattern them by standard photolithography and Ar-ion beam etching. The magnitude of the low frequency flux noise in YBCO thin films strongly depends on their epitaxial quality and degree of c-axis orientation,[10] usually leading to a higher excess noise level in a multilayer device, if the upper film contains areas of lower quality.[11,12] This in mind, we generally pattern the large superconducting areas from the lower YBCO film, directly grown on the substrate. The steep step required for the junctions is milled under normal incidence into the insulation layer and the Josephson junctions are patterned from the upper YBCO film.

The inductively coupled magnetometer is described in detail in Ref. 13. The $10\frac{1}{2}$ turn input coil is placed on a $700\times 700\ \mu\mathrm{m}^2$ square washer and connected to a pickup loop with 8.8 mm outer diameter and a pickup area of $A_p = 54\ \mathrm{mm}^2$. The estimated SQUID inductance is $L_S = 85\ p$H. The multiloop layout used in this study is an im-

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[a)] Electronic mail: krey@physnet.uni-hamburg.de

TABLE I. Transport properties of the investigated inductively coupled and the multiloop magnetometer measured at the temperature $T=77$ K.

Device		Inductively coupled	Multiloop	
Voltage swing	ΔV	6.8	6.9	μV
Critical current[a]	I_0	42	13	μA
Normal resistance[a]	R_n	2.6	5.3	Ω
Sensitivity	B/Φ	1.290	0.897	nT/Φ_0
Effective area	$A_{\text{eff}}=\Phi/B$	1.60	2.31	mm^2

[a] Values given per junction.

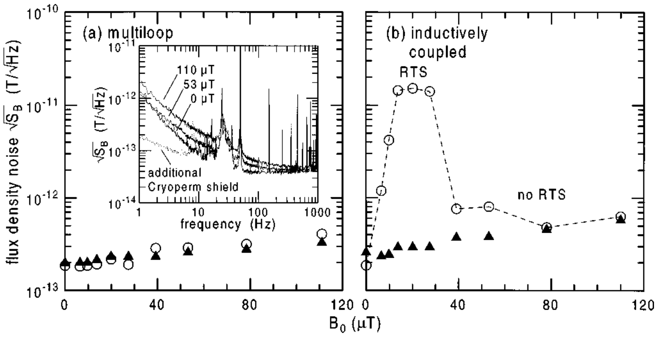

FIG. 1. (a) Flux density noise of the multiloop and (b) the inductively coupled magnetometer as a function of the cooling field B_0. Filled symbols indicate measurements in the permanent field, open symbols mark measurements with the field switched off. The inductively coupled device shows a random telegraph signal (RTS) for $B_0<40\ \mu$T, induced by the switching transients. The inset of (a) depicts three noise spectra recorded in zero field with the field cooled multiloop magnetometer for $B_0=0$, 53, and 110 μT. The spikes are due to microphonic pickup and power line interference.

proved version of the WH1 layout described in Ref. 14. We enlarged the outer diameter to a value of 8.5 mm and adjusted the pickup coil width w_p and total spoke width D_s to give the maximum effective area while keeping the SQUID inductance constant at $L_S=145\ p$H. With $w_p=1095\ \mu$m and $D_s=280\ \mu$m, we obtain a measured effective area of $A_{\text{eff}}=2.31\ \text{mm}^2$ in good agreement with the calculated value of $2.35\ \text{mm}^2$. This is, as far as we know, the largest effective area reported yet for a high-T_c SQUID magnetometer on a $1\times 1\ \text{cm}^2$ substrate. The transport properties of both magnetometers are listed in Table I.

All noise measurements were performed inside a magnetically shielded room, where the magnetometers were installed in a low noise cryostat for biomagnetic measurements, filled with liquid nitrogen. The intrinsic noise characteristic of both devices was measured with an additional Cryoperm shield, using the standard flux locked loop (FLL) technique. For the multiloop magnetometer we found $\sqrt{S_B}(1\ \text{kHz})=39\ \text{fT}/\sqrt{\text{Hz}}$ in the white noise regime and $\sqrt{S_B}(5\ \text{Hz})=92\ \text{fT}/\sqrt{\text{Hz}}$ for the low frequency noise. No further noise reduction with bias current reversal (ac bias) could be achieved at 5 Hz, due to residual ambient noise. Despite a comparable voltage swing ΔV, the inductively coupled magnetometer showed a higher white noise level of $\sqrt{S_B}(1\ \text{kHz})=66\ \text{fT}/\sqrt{\text{Hz}}$, which raised to $85\ \text{fT}/\sqrt{\text{Hz}}$ with bias current reversal. We attribute this to the resonant flux voltage characteristic of this device, which is often observed for magnetometers with integrated flux transformers.[1] It prevents the optimal adjustment of the flux-modulation scheme, especially with bias reversal. However, with ac bias the low frequency noise was reduced from $\sqrt{S_B}(5\ \text{Hz})=188$ to $161\ \text{fT}/\sqrt{\text{Hz}}$, indicating that the former value includes a contribution from critical current fluctuations in the junctions.

For the measurements in static fields, we removed the additional shield. Instead, we centered the magnetometer within a copper coil, fed by a high capacity lead-acid accumulator in series with an appropriate resistor for the field B_0. For $B_0=0$ but without the extra shield, we found a higher low frequency noise level that increased faster than $1/f$ with approximately $S_B \propto f^{-2.4}$ and a corner frequency of about 18 Hz, due to ambient noise penetrating the shielded room. The magnetometers were enclosed in capsules of glasfiber epoxy together with two heating resistors in close contact to the substrate. With a heating power of 0.7 W, we were able to rise the magnetometer's temperature above T_c in about 2 min. With the magnetometer in normal conducting state, we applied the magnetic field B_0 and subsequently switched off the heating current. In two different experiments we measured the noise of the field cooled magnetometers either after switching off the magnetic field or in the permanent field. In the first case, both magnetometers presented here should behave differently. In a changing magnetic field a shielding current is generated in the pickup loop of the device that can induce vortices into the film by the Lorentz force. The multiloop magnetometer contains an *intrinsic* flux dam,[15] limiting the shielding currents in the loops, because they are forced across the Josephson junctions, whereas the current within the flux transformer of the inductively coupled device can become much larger.

Figure 1(a) shows the measured flux density noise $\sqrt{S_B(f)}$ of the multiloop magnetometer as a function of the cooling field B_0. For both experiments, a continuous increase in low frequency noise with nearly the same noise levels is found, indicating that our current source for the coil does not contribute significantly to the noise. Also the device's critical currents were not markedly reduced in the field. The inset of Fig. 1(a) depicts three noise spectra recorded in zero field with the field cooled multiloop magnetometer for $B_0=0$, 53, and 110 μT. In the permanent field $B_0=110\ \mu$T we measured $\sqrt{S_B}(5\ \text{Hz})=340\ \text{fT}/\sqrt{\text{Hz}}$, which includes an environmental contribution of about $\sqrt{S_{B,\text{env}}}(5\ \text{Hz})=144\ \text{fT}/\sqrt{\text{Hz}}$, yielding a net increase of $[S_B(B_0)-S_{B,\text{env}}]^{1/2}=308\ \text{fT}/\sqrt{\text{Hz}}$ at 5 Hz. This is about a factor 3.3 above the value taken with the additional shielding. In zero field, this excess noise could always be removed by the heating procedure. For the inductively coupled device, we found a much stronger increase of the low frequency noise in low fields, if we switched off the field prior the measurements. We measured a random telegraph signal (RTS) that was probably caused by the switching transients.[16] Interestingly, for larger field changes than 40 μT this RTS was not observed anymore and the device stayed much quieter. We presume, that the stronger Lorentz force due to the larger shielding currents prevents the vortices from escaping from their metastable pinning sites.

Figures 2(a) and 2(b) show the spectral density of the excess flux noise $S_{\Phi,\text{exc}}(B_0)=S_\Phi(B_0)-S_{\Phi,\text{env}}$ as a function of B_0 in the permanent field, not including the environmental contribution. For both magnetometers we find an overall linear increase of $S_{\Phi,\text{exc}}$ with B_0. No threshold field for flux

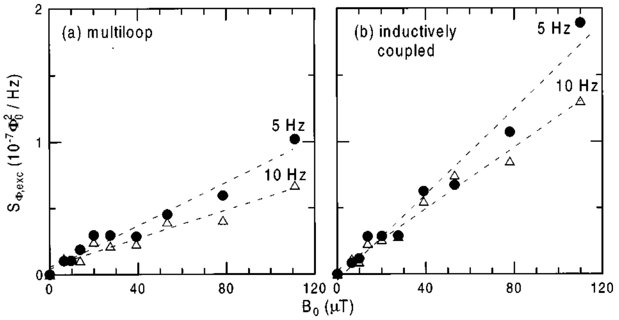

FIG. 2. Spectral density of the excess flux noise $S_{\Phi,\mathrm{exc}}(B_0)=S_\Phi(B_0)-S_{\Phi,\mathrm{env}}$, due to the cooling field B_0, not including the environmental contribution $S_{\Phi,\mathrm{env}}$. Dashed lines are least-squares fits to the data. Measured at 5 Hz (solid symbols) and 10 Hz (open symbols).

entry is observed, probably due to the large linewidths of the magnetometers. The slope at 5 Hz is about twice as large for the inductively coupled device, what may suggest that the latter is more sensitive to flux entry if we assume the same mechanism for flux noise as in Ref. 4. The main candidate for flux penetration may be the input coil of the flux transformer which is patterned from the upper YBCO layer and which is the most crucial part of the inductively coupled device, due to its many edges and narrow crossovers. Moreover, flux lines moving there couple very effectively into the SQUID. However, both devices show a performance that is not seriously affected by fields up to 110 μT. The induced low frequency flux noise is of the same order as the ambient noise penetrating the shielded room.

In summary, we have measured the noise levels of a multiloop magnetometer and an inductively coupled magnetometer from YBCO-STO-YBCO multilayers in static magnetic fields up to 110 μT. Both devices show only a moderate increase of the low frequency flux noise that underlines the high quality of the involved thin-films. The good performance of both devices in high fields, together with their large effective area at a small chip size makes multilayer devices attractive for future multichannel applications in moderately shielded or unshielded environment.

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