

Low Noise HTS dc-SQUID Flip-Chip Magnetometers and Gradiometers

M. I. Faley, U. Poppe, K. Urban, D. N. Paulson, T. N. Starr, and R. L. Fagaly

Abstract—We have fabricated HTS dc-SQUID flip-chip sensors with a large area multilayer flux transformers. Different layouts of the flux transformers provide a large variety of magnetometers and planar gradiometers. For the magnetometers a resolution ~ 6 fT/ $\sqrt{\text{Hz}}$ and the planar gradiometers a resolution of about ~ 30 fT/cm/ $\sqrt{\text{Hz}}$ were routinely obtained at 77 K. The noise was nearly white down to frequencies of few Hz. The sensors were vacuum-tight encapsulated together with a heater and a feedback coil. This makes the handling of the sensors more reproducible and convenient. Production of the magnetometers and gradiometers in small series was proven.

Index Terms—HTS, magnetometer, gradiometer, multilayer structures

I. INTRODUCTION

MANY applications require measuring systems with an utmost sensitivity to magnetic fields. For example, an average R-wave magnitude of a fetal magnetocardiogram (fMCG) signal is ~ 2 pT. To measure the fMCG in a frequency bandwidth of about 100 Hz with a signal-to-noise ratio of ~ 10 one needs a system with a noise below of about 20 fT/ $\sqrt{\text{Hz}}$. Commercially available LTS dc-SQUID systems have a typical resolution ~ 5 fT/ $\sqrt{\text{Hz}}$ (for 20 mm \times 20 mm pick-up loop [1] of the sensor).

A straightforward upgrade of LTS measuring systems would be the use of HTS sensors of similar resolution. This would significantly simplify the operation and drastically increase the cryogen hold time of the systems. An unexpected and astonishing result of a decade of development of HTS SQUIDS is that the field resolution of the HTS magnetometers at 77 K was approaching and now overlaps some LTS magnetometers operating at 4.2 K. Cantor *et al.* [2] reported noise levels of 24 fT/ $\sqrt{\text{Hz}}$ at 1 Hz and of 14 fT/ $\sqrt{\text{Hz}}$ at 1 kHz using a single-layer, directly coupled magnetometer with a pickup loop 20 mm \times 20 mm. Dantsker *et al.* [3] achieved a resolution of 27 fT/ $\sqrt{\text{Hz}}$ at 1 Hz and 8.5 fT/ $\sqrt{\text{Hz}}$ at 1 kHz using a flip-chip magnetometer with a dc-SQUID inductively coupled to a multilayer flux transformer having a 9 mm \times 9 mm pickup loop. It is obvious, that the sensitivity and reproducibility of

the magnetometers could be additionally improved by a larger pick-up loop with the flux transformer made on a larger wafer.

To subtract high magnetic background noise one can use a gradiometric configuration of the pick-up coil. Tian *et al.* [4] have achieved a field gradient sensitivity of 73 fT/cm/ $\sqrt{\text{Hz}}$ in the white noise region and 596 fT/cm/ $\sqrt{\text{Hz}}$ at 1 Hz with a single layer gradiometric flux antenna on a 50 mm Si wafer. We have demonstrated [5] a planar HTS flip-chip gradiometer having multilayer gradiometric flux antenna prepared on a 30 mm wafer. A resolution of ~ 40 fT/cm/ $\sqrt{\text{Hz}}$ at frequencies above 10 Hz and ~ 100 fT/cm/ $\sqrt{\text{Hz}}$ at 1 Hz was achieved.

In the following, we describe our present flip-chip magnetometers and gradiometers. First we outline the ramp-, bicrystal-, PMMA-, and AZ-techniques, which were used for the preparation of the dc-SQUIDS and flux transformers. We have significantly improved our early-developed [6] technology based on a nonaqueous Br-ethanol etching to achieve the high sensitivity of the sensors especially at low frequencies.

Next, we describe the layouts, encapsulations, and properties of the magnetometers and gradiometers. Important is that the present stage of the technology allows a reproducible preparation of the HTS sensors with a properties at 77 K similar to the properties of some LTS ones operating at 4.2 K.

II. EXPERIMENTAL

A. Multilayer structures

The flip-chip sensor consisted of a dc-SQUID and a multilayer flux transformer made on a separate substrate. Single- or 30° bicrystal 1 cm \times 1 cm SrTiO₃ substrates were used for the preparation of the dc-SQUIDS. For the preparation of the flux transformers we have used single crystal 10 mm \times 10 mm SrTiO₃ substrates and \varnothing 30 mm LaAlO₃ or SrTiO₃ wafers.

The structures were prepared from YBa₂Cu₃O_{7-x} (YBCO) and PrBa₂Cu₃O_{7-x} (PrBCO) *c*-oriented films by a high-oxygen-pressure dc-sputtering technique [7]. The YBCO films show typical critical current densities I_c of about 5×10^6 A/cm² at 77 K and a transition temperature T_c above 91 K. A high quality of ceramic films was found to be very important for good operation parameters of the HTS sensors. Films without outgrowths and with a surface roughness on

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the level of about 3 nm (peak-to-peak) or with a well-defined growth spirals can be prepared by this method (see Fig.1).

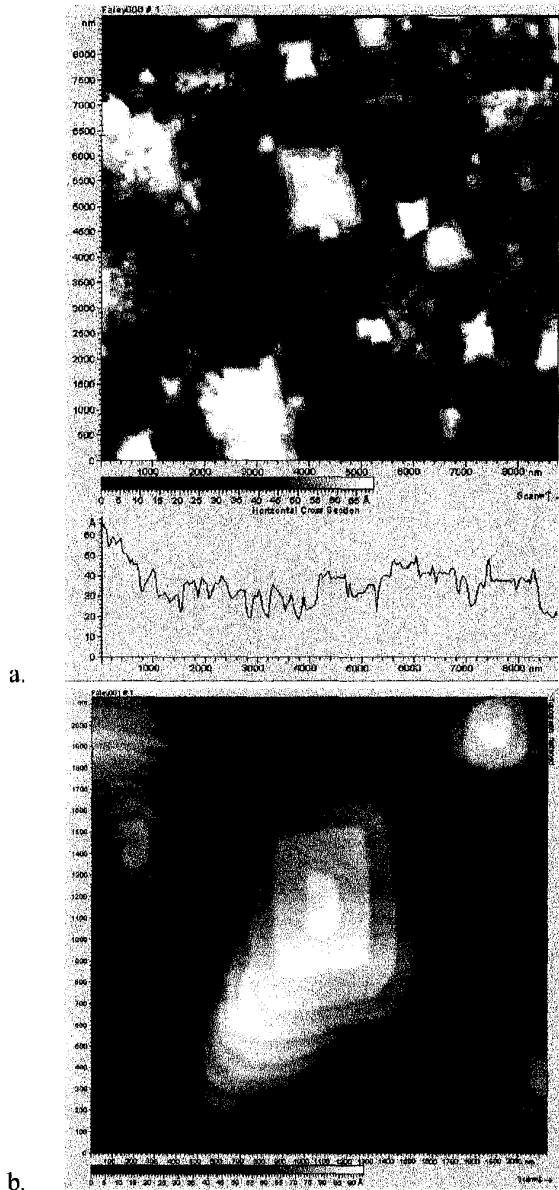


Fig. 1. AFM images of the surface of a 200 nm thick PrBCO film demonstrating: a) a possibility to prepare the films with 3 nm (peak-to-peak) surface roughness on a length of about 10 μm; and b) spirals, double-spirals, and islands observed on the film surface.

The HTS Josephson junctions for the dc-SQUIDs were two types: ramp-junctions [6] and 30° bicrystal [8] ones. The junctions had a width of about 2 μm and a critical current of about (10 - 50) μA at 77 K.

The multiloop flux transformers were prepared with a similar technique [6] using the PrBCO film as an insulation layer between the windings and the return strip. First two layers were patterned with deep-UV lithography using a PMMA-photoresist and a Br-ethanol etching. Top layer,

containing the μ-size structures was patterned with a conventional AZ-photoresist and an ion-beam etching. The PrBCO film prevents superconducting shortage and provides a normal conducting shunt of the flux transformer to avoid high frequency resonances in the coil structure.

A high quality of the crossovers and vias in the multilayer multiturn coil of the flux transformer is essential to obtain high values of the induced supercurrent. Mainly the critical current of the flux transformer limits the dynamic range of the sensors. Due to the damage-free interfaces and gently sloping edges produced by a Br-ethanol etching we have achieved a critical current for the transformer inner coil of about 100 mA at 77 K. For the 8 mm HTM-8 magnetometer (see Fig. 2a) the pick-up loop has an inductance ~ 20 nH. The dynamic range of the magnetometer limited by the critical current of the flux transformer is about 60 μT (peak-to-peak). This allows sensitive measurements with the HTM-8 magnetometer even after a movement in earth's field.

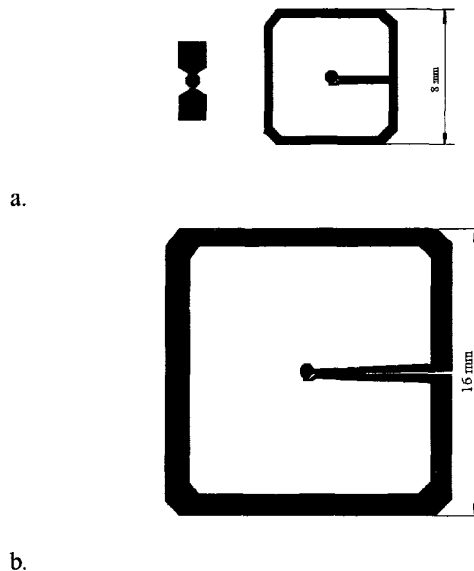


Fig. 2. a) The dc-SQUID and 8 mm multilayer flux transformer (HTM-8) used for the flip-chip magnetometers; b) The layout of the 16 mm flux transformer (HTM-16).

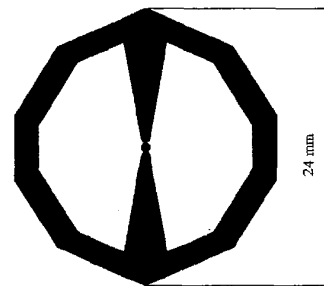


Fig. 3. The gradiometric flux transformer used for HTG-10R. The 1 mm multi-turn coil is placed in the middle of the flux transformers.

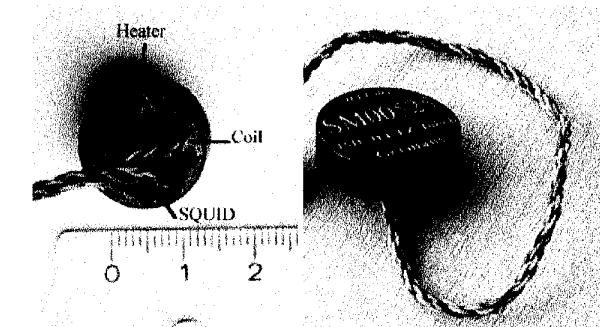
Some layouts of the magnetometers and of the gradiometric flux transformers are presented in Fig. 2 and 3 respectively. The gradiometric flux transformers have a length of about 24 mm and a baseline of about 10 mm.

B. Capsulations

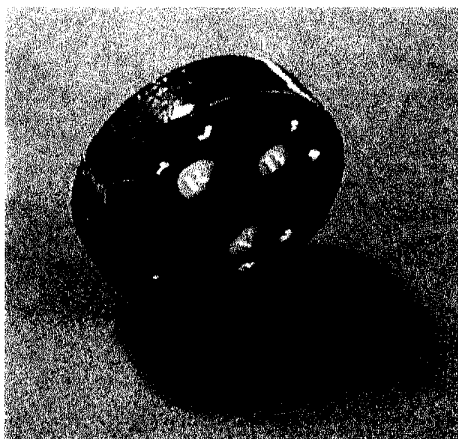
The sensors need to be encapsulated to ensure a long and reliable service life. We enclose the sensors in fiber-glass epoxy capsulations. The capsulations are vacuum-tight sealed to prevent the HTS films from degradation by ambient atmosphere and humidity.

A modulation coil and nonmagnetic Pt resistor are integrated inside the capsulation. The latter one is fixed to the SQUID and serves both as a thermometer or as a heater. The heater allows easy removal of trapped magnetic flux to improve the noise properties of the magnetometer. The encapsulation significantly simplifies the handling of the magnetometers during characterization, applications, and for the end-users. The capsulations can be adapted to the specific measuring systems intended for different applications. Standard dimensions of the capsulations are listed in Table 1.

Encapsulated HTM-8 and HTM-8-90 sensors were displayed in Fig. 2 of Ref. 9. The standard encapsulated gradiometer HTG-10 was displayed in Fig. 3 of Ref. 5. The capsulations for the magnetometers (HTM-8, HTM-16) and for the gradiometer (HTG-10R) are shown in Fig. 4.



a.



b.

Fig. 4. The standard capsulations of (a) magnetometers HTM-8 and HTM-16 and (b) gradiometer HTG-10R.

TABLE 1
SIZES OF THE STANDARD CAPSULATIONS FOR THE FLIP-CHIP SENSORS

Sensor type	Diameter (mm)	Thickness (mm)
HTM-8	18	7
HTM-16	27	8
HTG-10R	40	10

The flux noise of the sensors was measured inside an open cylinder YBCO shield in combination with a 3-layer μ -metal shield.

III. RESULTS

We have observed that the flip-chip arrangement significantly reduces the effective SQUID inductance and provides a high effective area for the sensors. The effective inductance of the present SQUIDs inductively coupled to the flux transformers is about 100 pH. In Fig. 5 the flux sensitivity of the flip-chip magnetometers is compared with the direct-coupled magnetometers described in references [2] and [10].

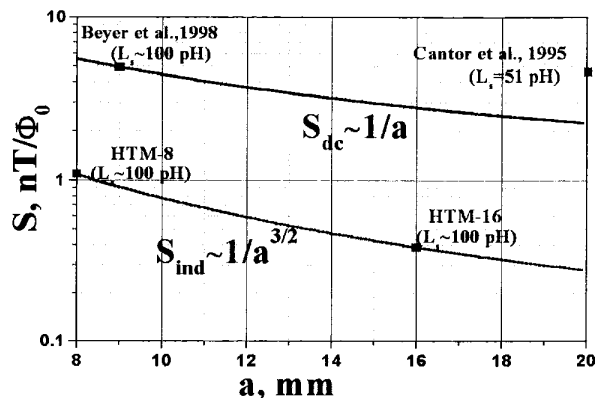


Fig. 5. Flux sensitivity "S" vs pick-up loop size "a" for direct coupled (S_{dc}) and inductively (flip-chip) coupled (S_{ind}) magnetometers.

The effective area A_{eff} of a direct-coupled magnetometers is proportional to $A_{pickup}/L_{pu} \sim a$, where "a" corresponds to size; $A_{pickup} \sim a^2$ to area; and $L_{pickup} \sim a$ to inductance of the pickup coil. For an inductive coupled magnetometer with an optimized multiturn input coil for the flux transformer, the effective area $A_{eff} \sim A_{pickup}/\sqrt{L_{pickup}} \sim a^{3/2}$. Flux sensitivity $S(nT/\Phi_0)=1/A_{eff}$. In the case of a large area pickup coil the flip-chip magnetometer have a significant advantage in flux sensitivity compared to direct-coupled magnetometer.

TABLE 2
FLUX SENSITIVITIES AND NOISE ACHIEVED FOR THE FLIP-CHIP SENSORS

Sensor type	Flux sensitivity	Noise at 1 kHz
HTM-8	1 nT/ Φ_0	20 fT/ \sqrt{Hz}
HTM-16	0.4 nT/ Φ_0	6 fT/ \sqrt{Hz}
HTG-10	2.2 nT/cm Φ_0	40 fT/cm \sqrt{Hz}
HTG-10R	1.7 nT/cm Φ_0	30 fT/cm \sqrt{Hz}

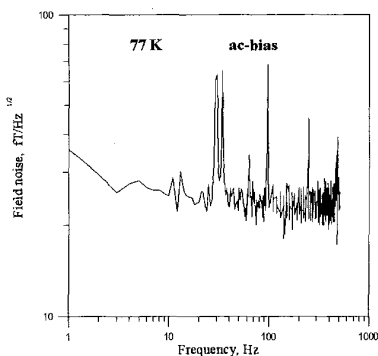


Fig. 6. Noise spectrum for HTM-8, measured inside a 3-layer μ -metal shield and a superconducting shield.

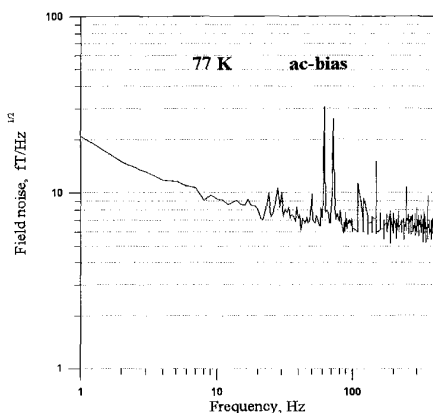


Fig. 7. Noise spectrum for HTM-16, measured inside a 3-layer μ -metal shield and a superconducting shield.

Typical sensitivities and noise achieved for the flip-chip sensors are listed in the Table 2. The noise spectra for the HTM-8 and HTM-16 magnetometers are presented in Fig. 6 and 7, correspondingly. The noise spectrum for HTG-10 gradiometer was demonstrated in Ref. 5. Recently, the noise data of our magnetometers were independently confirmed using STL-electronics [11] in the new shielded room of PTB (Berlin).

The flux noise of the HTM-16 is about $15 \mu\Phi_0/\sqrt{\text{Hz}}$. For the 100 pH 30° bicrystal HTS dc-SQUIDs a flux noise $\sim 5 \mu\Phi_0/\sqrt{\text{Hz}}$ was achieved (see, e.g., [8]). This means that there is a significant potential for further improvements in field and field gradient resolution for our sensors even with the present layouts. A resolution of the HTM-16 magnetometers of about 2 fT/ $\sqrt{\text{Hz}}$ seems possible in future. Similar field noise originates from Al-coated Mylar foil used for a thermal insulation in fiber-glass cryostats intended for operation with liquid helium (4.2 K). Improvement of the liquid nitrogen cryostats can be achieved using a modified thermal insulation without such foil. Thus, one can expect to achieve a field resolution below 1 fT/ $\sqrt{\text{Hz}}$ for the HTS system operating at 77 K. For this purpose magnetometers with a larger pickup coils (~ 30 mm) need to be developed.

IV. SUMMARY

The HTS sensors reported here have a sensitivity and reliability sufficient for many applications. The magnetometers achieved a white noise of about 6 fT/ $\sqrt{\text{Hz}}$ and the planar gradiometers achieved a gradient resolution of about 30 fT/cm- $\sqrt{\text{Hz}}$ at 77 K. The resolution of the sensors can be further improved in the future. The magnetometers and gradiometers are able to operate without magnetic shielding. The user-friendly capsulation for the sensors makes handling of the sensors safe, reproducible, and convenient. Production of both magnetometers and gradiometers in small numbers has been demonstrated and is sufficient for the construction of multichannel HTS systems.

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