Available online at www.sciencedirect.com
SCIENCE DIRECT®
Sensors and Actuators A 129 (2006) 146–149
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Field line distribution in a mixed sensor

M. Pannetier [a,*], C. Fermon [a], P. Vedrine [b], M.S. Welling [c], R.J. Wijngaarden [c]

[a] *Service de Physique de l'Etat Condensé (CNRS URA 2464), DSM/DRECAM/SPEC, CEA Saclay, 91191 Gif Sur Yvette Cedex, France*
[b] *SACM/DAPNIA, CEA Saclay 91191 Gif-Sur-Yvette, France*
[c] *Condensed Matter Physics, Department of Physics and Astronomy, Faculty of Sciences, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*

Received 4 July 2004; received in revised form 30 September 2004; accepted 22 November 2005
Available online 25 January 2006

Abstract

We have demonstrated that a very low magnetic field can be detected by a sensor combining a superconducting pick-up loop and a GMR element [1,2]. In this device, the excitation field applied to the superconductor generates a supercurrent running through the loop. This current is driven through a constriction, where it generates high density magnetic field lines that can be detected by the GMR sensor.

We have performed magneto-optical imaging on a YBCO ring with a constriction to estimate the magnetic field—enhancement and the localization of the field lines in this design for applied fields down to 1 μT. The obtained measurements give the vertical component of the local magnetic field. Locally the field lines are enhanced by a factor larger than 200 for fields small enough to induce a current lower than the critical current. A decrease of the gain for higher applied fields is observed, when the critical current is reached.

We present also a calculation of the gain, taking into account the precise distribution of current in the rectangular section of the superconductor [3] and the inductance of the loop. These results are in agreement with finite element modeling. The gain for various dimensions and aspect ratio's is given and compared to the experimental results. An optimized design is given for magnetoencephalography applications, in order to replace low-T_c SQUIDs used in the present apparatus. The expected sensitivity of this system is calculated to be in the range of a few fT/$\sqrt{\text{Hz}}$.

PACS: 07.55.Ge; 75.47.De; 73.50.Td

Keywords: Biomagnetism; Magnetoresistive sensors; Superconductors

1. Introduction

Mixed sensors are based on the association of a superconducting flux-to-field transformer with a magnetoresistive element. They provide a very sensitive measurement of low field. Experimental results on $YBa_2Cu_3O_{7-\delta}$-based devices have shown a level of noise of 35 fT/$\sqrt{\text{Hz}}$ [1,2]. To achieve a high sensitivity, both the magnetoresistance performance and the transformer design play key roles. For the magnetoresistive sensor we use a Giant Magnetoresistance material with low noise level. Use of TMR or CMR materials may improve the device in the future. The transformer must be designed such that a large amount of flux is captured, which is achieved by using a sufficient area, and by concentrating the supercurrent induced by the applied field through a narrow constriction where the field lines will be locally very high. These requirements are advantageously fulfilled with a wide loop of typically few mm to 2 cm in diameter, containing a micron-sized constriction.

In order to understand and optimize the mixed sensor devices, we have performed magneto-optical imaging on a superconducting loop at the position of the constriction and compared the obtained results with precise modeling of the field line distribution in the relevant directions of field.

2. Sample

The sample is a commercial [4] 100 nm thick $YBa_2Cu_3O_{7-\delta}$ thin film sputtered on a sapphire substrate. Patterning is achieved using conventional lithography techniques and dry-etching. The pattern is a square loop, of 3 mm outer diameter and 0.7 mm wide. One side of the loop exhibits a constricted area, as shown in schematic of Fig. 1, with a constriction of 25 μm in

* Corresponding author. Tel.: +33 1 69 08 7410; fax: +33 1 69 08 8786.
E-mail address: mpannetier@cea.fr (M. Pannetier).

0924-4247/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2005.11.057

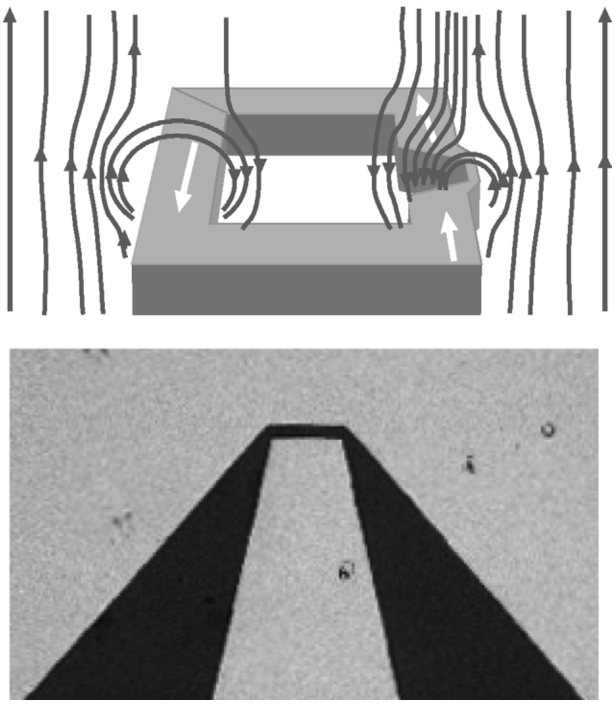

Fig. 1. (Top) Schematic in perspective of a superconducting flux-to-field transformer. The main loop has a diameter of 3 mm, 0.7 mm wide, and contains a constriction of 25 μm long, 7 μm large. The external field is applied perpendicular to the sample (bottom) SEM picture of the constriction.

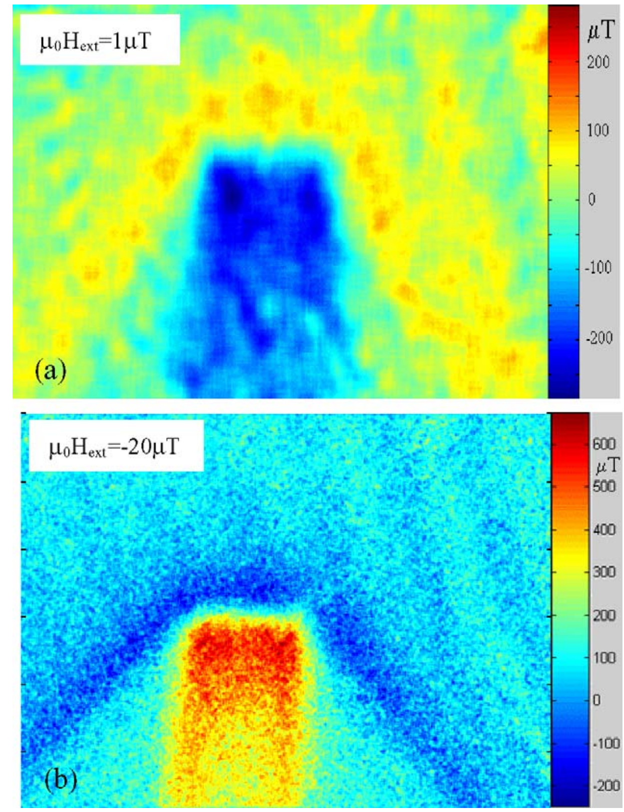

Fig. 2. Magneto-optical imaging of a superconducting constriction in the 3 mm diameter loop of Fig. 1, for an applied field of 1 μT (panel a) and −20 μT (panel b). Both images are obtained after a zero field cooling down to 4.2 K. The size of the bridge is 25 μm in length and 7 μm in width. The color scale bar on the right side gives the local field perpendicularly to the film (z-component).

length, 7 μm wide. The imaging is focused on this constriction area.

3. Magneto-optical imaging

Magneto-optical imaging is a powerful technique that allows visualizing and measuring the magnetic field distribution in a sample. This method, based on the Faraday effect, is widely used for studying superconductors [5]. The local magnetic field is detected using a Bi-doped yttrium iron garnet film with an in-plane anisotropy, exhibiting a large Faraday effect, typically 0.06°/mT. The magneto-optical image lock-in technique used [6] has a magnetic resolution for the perpendicular field of $0.7\ \mathrm{mT}/\sqrt{\mathrm{Hz}}$ and a spatial resolution of 0.5 μm, while the sign of the field is determined unambiguously.

The garnet indicator is placed on top of the sample and mounted on a devoted cryogenic polarization microscope. The applied field is perpendicular to the film, i.e. parallel to the c-axis of the sample. The image is detected by a digital camera, with a magneto-optical image lock-in amplifier.

The experiment is performed at 4.2 K in a field varying from zero to few mT. The images are recorded in a static mode, after the field has been swept to the targeted value.

Images for an applied field of 1 μT and for −20 μT are shown in Fig. 2a and b; to enhance the contrast and to remove the influence from the Earth's magnetic field, an image taken at 0 μT was subtracted.

In a previous work [7], the field profile in a ring has been extensively studied for a wider range of fields, high enough to destroy the Meissner state and to allow penetration of vortices. Here, we can observe from the image obtained at 1 μT that locally, the field lines reach 250 μT, due to the supercurrent running in the bottleneck created by the constriction. When increasing the applied field, the supercurrent reaches its critical value, first at the edges, then propagating to the centre of the constriction, up to the point where the field is no longer enhanced by the supercurrent field lines, but only shifted by the applied field. In particular at −20 μT, one can already observe that the maximum local field reaches 600 μT, leading to an enhancement factor of only 30, indicating that the critical current has been already reached in the constriction. Table 1 gives the enhancement factor as a function of the applied field, extracted from the magneto-optical data.

Table 1
Local enhancement of the perpendicular magnetic field determined from the magneto-optical imaging as the ratio between the maximum local field value and the externally applied field

Applied field (μT)	Local enhancement
1	250
10	200
100	60
1000	4

Table 2
Comparison of expected and measured gain for mixed sensors

External radius (mm)	Width (mm)	Constriction width (μm)	Expected gain	Measured gain	Experiment	Material
3	0.7	7	240[a]	250	MO	YBCO
3.25	2.75	7	131	108	Mixed sensor [1]	Niobium
2	1	6	132	100	Mixed sensor [1]	YBCO
12.5	5	6	516	500	Mixed sensor [8]	Niobium

[a] Expected gain for the vertical component of the field, as detected by the MO setup. In all the other cases, the gain is given for the planar component of the field, as sensed by the GMR. Except for the magneto-optics, where it is irrelevant, the expected gain takes into account the partial coverage between the superconducting constriction and the GMR sensor.

4. Modeling of the field line distribution

To correlate these experimental results with design optimization, one needs to calculate the expected field profile in various sizes and aspect ratio configuration. Furthermore, the magneto-optical technique gives quantitative information on the z-component of the field, while the MR sensor will be sensitive to the in-plane x-component.

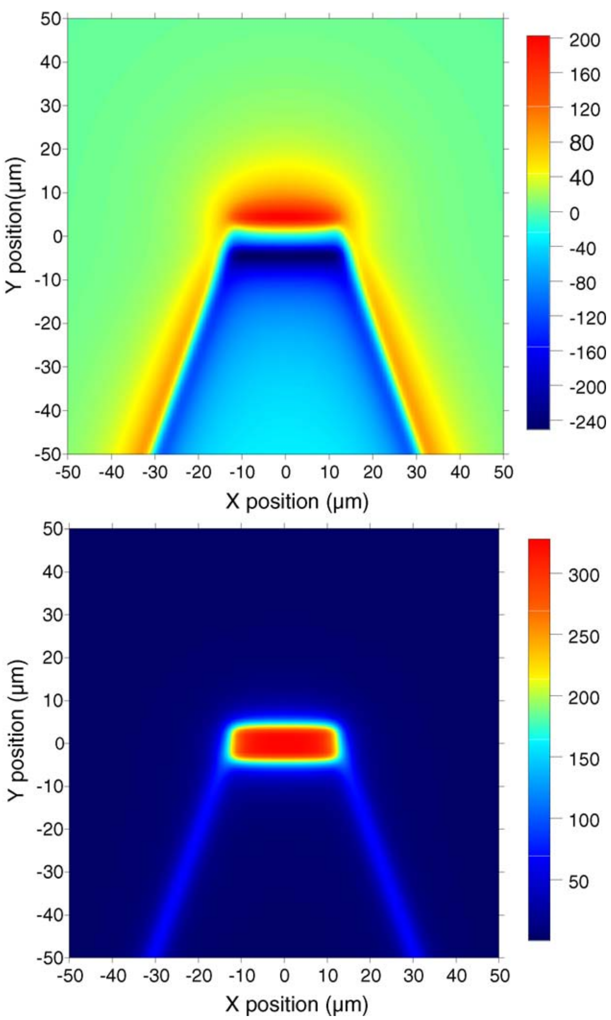

Fig. 3. Field line distribution calculated for a 7 μm wide and 25 μm long constriction with 70° links to a main loop: (a) gives a calculation of the out-of-plane field component (that is measured by the magneto-optical experiment, see Fig. 2a) and (b) gives a calculation of the in-plane field component (that is experienced by the GMR sensor). Field lines are given for a height of 2 μm above the sample.

Field lines can be calculated from the supercurrent distribution in the constriction. The total value of the current circulating in the constriction depends on the shape of the pick-up loop. Its optimization is given in Ref. [2].

In the case of a thin film with a rectangular cross-section, the current density is not described in the Meissner state as a uniform supercurrent running in the constriction. The current density as function of the position in the constriction can be calculated using the analytic solution given in Ref. [3]. In our case, the thickness of the film is much lower than the width of the constriction and the calculation of the current can be simplified [3]. For the simulations, we have neglected the variation over the thickness of the constriction, which is rather small.

The x and z-component of the magnetic field for the geometry and size of a sample similar to that studied in magneto-optics are shown in Fig. 3a and b. Model and experiments are in good agreement for the z-component. From the x-component simulation, we observe that the maximum field is located immediately above the constriction [3]. From these figures, it is possible to calculate the gain of a mixed sensor by integrating the planar field at the surface of the GMR sensor. These gains are in good agreement with the measured ones on various niobium and $YBa_2Cu_3O_{7-\delta}$ mixed sensors (Table 2).

The GMR sensor contains a soft bilayer of 3.5 nm of NiFe and 2.4 nm of CoFe. This bilayer interacts with the field created by the supercurrent in the constriction. In order to evaluate this effect, 3D finite element modeling using the software Cast3M [9] has been performed. It appears that there is a deformation of the flux lines in the vicinity of this very thin soft magnetic layer but there is hardly any modification of the field around the superconducting constriction. This insures the validity of the approach. Hence, even in presence of this soft magnetic layer, the current distribution used to model our sensor is valid.

5. Conclusion

We have given a complete description of the determination of the gain of a mixed sensor, taking into account the current distribution in the superconductor and the variation of the inductance of the loop as a function of its dimensions.

Measured gains are in agreement with the calculated ones for different loop sizes and widths.

A gain of 4000 can theoretically be achieved with a 25 mm diameter loop and a 1 μm constriction width. These values are achievable by standard lithography techniques and would lead to a overall sensitivity of about 1 fT/$\sqrt{\text{Hz}}$.

Acknowledgement

This work was supported in part by the European MAG-NOISE Network No. IST-1999-10486.

References

[1] M. Pannetier, C. Fermon, G. Le Goff, J. Simola, E. Kerr, Science 304 (2004) 1648.
[2] M. Pannetier, C. Fermon, G. Le Goff, E. Kerr, 129 (2006) 247–250.
[3] E.H. Brandt, G.P. Mikitik, Phys. Rev. Lett. 85 (2000) 4164.
[4] The YBCO sample used in the magneto-optical experiment is a commercial one deposited by Theva GmbH, Germany.
[5] M.R. Koblischka, R.J. Wijngaarden, Supercond. Sci. Technol. 8 (1995) 199.
[6] R.J. Wijngaarden, et al., Rev. Sci. Instrum. 72 (2001) 2661.
[7] M. Pannetier, et al., Phys. Rev. B 67 (2003) 212501.
[8] M. Pannetier, et al., unpublished.
[9] P. Vedrine, private communication, http://www.cast3M.fr.

Biographies

Myriam Pannetier received her PhD from the University of Caen, France, in 1999, on vortex dynamics in superconducting bridges. She had been working as a post-doctoral fellow on magneto-optical imaging for 2 years at the Condensed Matter Physics Laboratory at the Vrije Universiteit Amsterdam. Since 2001, she is working at the CEA in Saclay, France. Her research subjects include magnetoresistive sensors and nanomagnetism.

Claude Fermon received his PhD in 1986 on nuclear magnetic ordering. He currently works in CEA, Saclay, France on NMR, neutrons and nanomagnetism.

Pierre Vedrine has been graduated from the Arts et Metiers Engineering School in 1988. Since 1994, he is working in CEA, Saclay, France, on superconducting magnets modeling, in particular for the Large Hadron Collider.

Marco S. Welling received his PhD in 2004 at the Vrije Universiteit Amsterdam, for a work on magnetic field patterns in superconductors using magneto-optics.

Rinke J. Wijngaarden received his PhD in 1982. He currently works at the Vrije Universiteit Amsterdam in the field of pattern formation in granular materials and superconductors.