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Ultra-sensitive SQUID systems for applications in biomagnetism and ultra-low field MRI

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***Abstract*—We present the use of our ultra-sensitive SQUID system in the field of biomagnetism and ultra-low field (ULF) MRI. A current sensor configuration is used where a pick-up coil is inductively coupled to the SQUID. A 1st-order axial gradiometer system, operated in a liquid He dewar with negligible noise, achieves a measured coupled energy sensitivity ϵ_c of 40 h and a white noise below 200 aT Hz$^{-1/2}$. As an example of its use in biomagnetism, we discuss single trial magnetoencephalography measurements of high frequency bursts at 600 Hz from the somatosensory cortex which are related to synchronized spiking activity of individual neurons.**

We also deploy this system for ultra-low field MRI where it is operated inside an MRI coil system with several fast-switchable field and gradient coils. This necessitates the use of a current limiter in the input circuit and a 2nd-order axial gradiometer leading to an increased noise of 380 aT Hz$^{-1/2}$. Here, we demonstrated full tensor current density imaging of impressed currents in phantoms. For further improvement of the noise, the fabrication process for the nanometer-sized Josephson junctions based on the HfTi self-shunted junction technology has been extended to a SIS process with AlOx as the insulating layer. We achieved noise levels of 330 nΦ_0 Hz$^{-1/2}$ and 550 nΦ_0 Hz$^{-1/2}$, corresponding to energy sensitivities of 5 h and 20 h for uncoupled and coupled SQUIDs, respectively.

***Index Terms*—SQUID, biomagnetism, MEG, ULF MRI, nano-Junctions**

I. Introduction

The use of SQUIDs in biomagnetism as very sensitive field sensors is well established. In magnetoencephalography (MEG) they measure the magnetic field originating from the brain and commercial systems show noise levels in the low fT Hz$^{-1/2}$-range. More recently, SQUIDs are also used as detectors in ultra-low field magnetic resonance (ULF MR) where they must withstand pulsed fields up to 150 mT and operate in the presence of microtesla imaging fields. In order to attain a better signal-to-noise ratio (SNR) custom-designed single-channel or few-channel SQUID systems with noise figures below 1 fT Hz$^{-1/2}$ have been built. In our latest system, the performance limiting thermal noise from the superinsulation and/or thermal shields of the fiberglass liquid helium (LHe) dewar could be avoided, resulting in about 150 aT Hz$^{-1/2}$ for a 45 mm diameter magnetometer pick-up coil [1]. In this work, we discuss its use in the field of biomagnetism and ULF MRI and present our development of SQUIDs based on nanometer-sized Josephson Juncions (JJs).

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II. The ultra-sensitive SQUID system

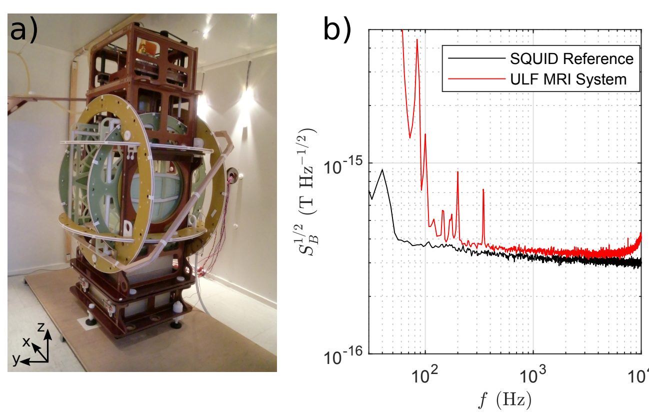

Fig. 1. a) ULF MRI system b) noise SQUID with 2nd-order gradiometer.

The SQUID system is described in detail in [1]. A current sensor configuration is used with a pick-up coil inductively coupled to the SQUID via an on-chip input coil of inductance L_i. Accordingly, the resolution of the current sensor depends on the flux noise $S_\Phi^{1/2}$ and on the coupling coefficient k between input coil and SQUID inductance L. A common figure of merit is the coupled energy resolution $\epsilon_c = \epsilon/k^2$,

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where $\epsilon = S_\Phi/2L$ is the energy resolution of the uncoupled SQUID. The equivalent field noise is given by $S_B^{1/2} = (2\epsilon_c/L_\mathrm{i})^{1/2} L_\mathrm{tot}/A_p$ where L_tot and A_p are the inductance of the input circuit and the area of the pick-up coil, respectively. Based on this scheme, we built a single-channel SQUID system which is operated in a modified fiberglass dewar with negligible thermal noise. It features a measured ϵ_c of $40\,h$ and a noise level below 200 aT Hz$^{-1/2}$ when connected to a 45 mm diameter 1$^\mathrm{st}$-gradiometer pick-up coil. The measured distance of the pick-up loop to the outside bottom of the dewar is 13 mm which makes this system suitable for applications in biomagnetism where the distance between source and pick-up coil needs to be minimal.

III. Applications in Biomagnetism

A. Single trial MEG

As an application in biomagnetism we show MEG of high frequency bursts at 600 Hz from the somatosensory cortex after electrostimulation of the median nerve. These so-called σ-bursts are related to synchronized spiking activity of individual neurons. While the MEG detection of averaged σ-bursts has been demonstrated before, single trial detection was impossible due to insufficient SNR. With our ultra-sensitive SQUID system utilizing a 1$^\mathrm{st}$-order axial gradiometer and pick-up diameter 45 mm, these high frequency bursts, shown in Fig. 2, could be detected at the single-trial level with a maximum SNR of 1.28. This is a prerequisite for the non-invasive study of the latencies in spiking activity and the influence on neuronal processing, for example.

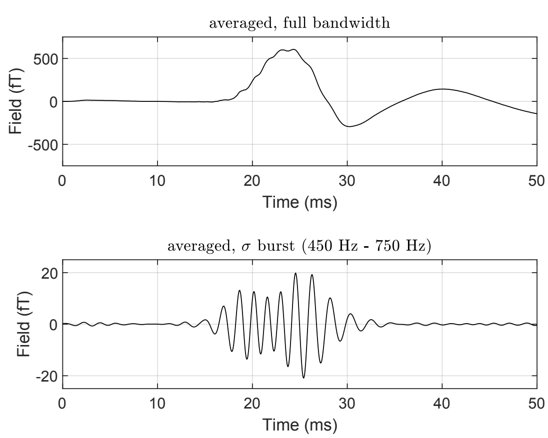

Fig. 2. MEG of somatosensory evoked activity. The σ-bursts in the bottom panel could be detected with a maximum SNR of 1.28 at the single trial level.

B. Ultra-low field MR

We also deploy this system for ultra-low field MRI where it is operated inside an MRI coil system with several fast-switchable field and gradient coils. This necessitates the use of a current limiter in the input circuit and a 2$^\mathrm{nd}$-order axial gradiometer inductively coupled to the SQUID which leads to an increased noise of 380 aT Hz$^{-1/2}$ as shown in Fig. 1b). Apart from anatomical imaging, we also investigate the imaging of impressed and intrinsic currents in the human head. The former is denoted current density imaging (CDI) and aims ultimately at the non-invasive *in vivo* determination of the conductivity σ of the human head tissue, a key parameter in the solution of the inverse problem in MEG and more importantly in EEG. Knowledge of σ would therefore improve localization accuracy in those methods, which could be improved even further by anatomical knowledge obtained with combined MEG-ULF MRI. We demonstrate in phantoms with close to physiological parameters that a suitable sequence can indeed determine the full current density tensor and discuss the required steps for the implementations of *in vivo* CDI [2].

IV. Nanometer-sized Josephson Junctions

A. Junction technology

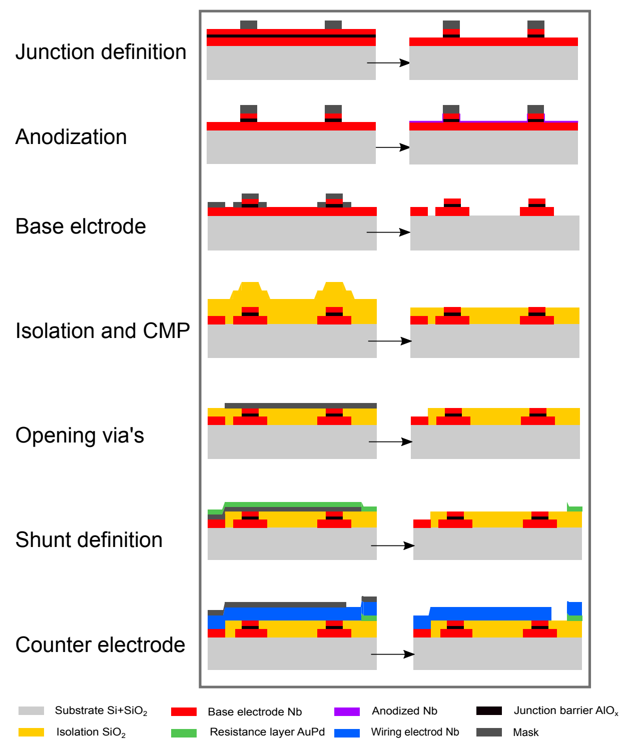

Fig. 3. Technology for producing the nanometer-size Josephson Junctions.

For further improvement in the noise performance of our SQUIDs, the fabrication process for the nanometer-sized JJs based on the HfTi self-shunted junction technology has been extended to a superconductor-insulator-superconductor process with AlOx as the insulating layer. The technology, indicated in Fig. 3, was adopted from an established SNS process [3] and utilizes e-beam lithography and a chemical mechanical planarization (CMP). An SEM image of a (700×700) nm^{2}AlOx junction is shown in Fig. 4.

B. Performance

For the evaluation of the Nb-AlOx-Nb nano-junction process miniature SQUID magnetometers were fabricated. These devices have square junctions with side lengths between 500

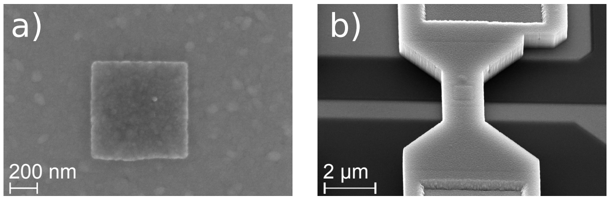

Fig. 4. SEM image of a (700×700) nm^2 AlOx junction. a) after anodization b) with counter electrode

and 800 nm. The 800 nm square junctions had a critical current I_0 of about 6.4 μA and shunt resistance R_N between 18 Ω and 48 Ω. The self-inductance of the SQUID loop was 70 pH. The noise performance is shown in Fig. 5. At 4.2 K the measured white flux noise was about 330 nΦ_0 Hz$^{-1/2}$ corresponding to an ϵ of 5 h. which is a factor almost 10 better compared to our conventional technology with junction sizes of $(2.5{\times}2.5)$ μm^2. The noise increases at lower frequencies with a typical value of 900 nΦ_0 Hz$^{-1/2}$ at 1 Hz.

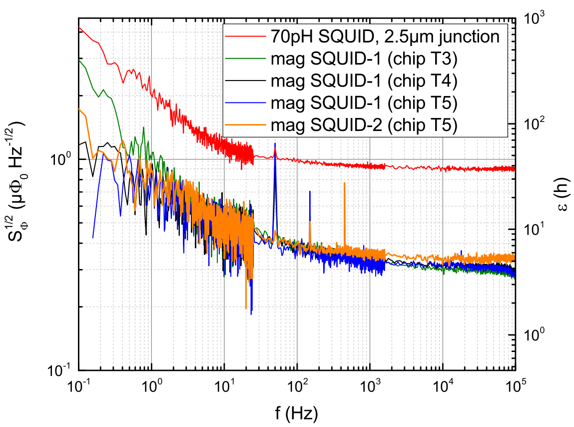

Fig. 5. Flux noise and energy resolution of 4 separate magnetometer SQUIDs with (800×800) nm^2 (SQUID-1: $R_N = 48\,\Omega$, SQUID-2: $R_N = 32\,\Omega$) and one SQUID with (2.5×2.5) μm^2 JJs.

Based on these results, integrated current sensors were designed and fabricated having a SQUID inductance of 80 pH. For the input circuit consisting of a 400 nH input coil, a proven double-transformer design was used with a coupling coefficient of $k = 0.75$. The expected coupled energy resolution of this design is approximately 10 h at 4.2 K. In Fig. 6 the results show that we achieve an ϵ_c of 20 h. The mismatch is probably due to a parasitic resistance between SQUID and input coil of 75 Ω. Clearly, future fabrications need to avoid this issue.

V. Future 11-channel ULF MRI system

We are currently building a 11-channel system for ULF MRI in order to reduce acquisition time by making use of parallel imaging. It will be operated in an upgraded commercial fiberglas LHe dewar with negligible noise so that its performance will be limited by the SQUIDs. As it is to be used for imaging, the main pick-up coils consist of 2$^{\text{nd}}$ order axial gradiometers; 7 small and 1 surrounding large pick-up similar to our earlier design [4]. A triplet of small magnetometers, sensitive in all

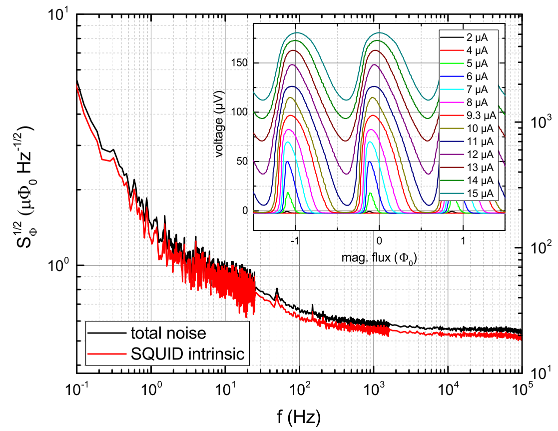

Fig. 6. Flux noise and coupled energy resolution of fully integrated current sensor SQUID with (700×700) nm^2 JJs.

three spatial directions, is also installed. Table I gives the expected performance for the various pick-up coils.

TABLE I
Expected performance of 11-channel SQUID system

Sensor	Diameter	Noise (ϵ_c= 20 h)	Noise (ϵ_c= 10 h)
1 × 2$^{\text{nd}}$-order gradiometer	69.5 mm	100 aT Hz$^{-1/2}$	70 aT Hz$^{-1/2}$
7 × 2$^{\text{nd}}$-order gradiometer	22 mm	509 aT Hz$^{-1/2}$	360 aT Hz$^{-1/2}$
3×magnetometer triplet (x, y, z)	17.1 mm	448 aT Hz$^{-1/2}$	317 aT Hz$^{-1/2}$

A. Conclusions

In this work we presented that with an ultra-sensitive SQUID system new techniques in biomagnetism become possible. The main issue of dewar noise can be avoided by careful design. With such a system we demonstrated single-trial MEG of high frequency bursts due to synchronized neuronal spiking activity. Adapted to ULF MRI, we showed that full tensor current density imaging is also possible. With a new generation of sensors based on nanometer-sized JJs the performance can further be improved. First results on test devices validated the concept which will be used in our future 11-channel system.

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