Noise performance of SQUID magnetometers as a function of critical current value: a statistical-like approach

A Vettoliere¹, B Ruggiero¹, O Talamo¹, P Silvestrini², C Granata¹
¹ Institute of Applied Sciences and Intelligent Systems of National Research Council, via Campi Flegrei, 34 – 80078 Pozzuoli – Italy
² Department of mathematics and physics – University of Campania “L. Vanvitelli”, viale Abramo Lincoln, 5 – 81100 Caserta – Italy
antonio.vettoliere@cnr.it

Abstract. The critical current value is a key parameter of a Superconducting Quantum Interference Device. In this paper we investigate the effects of different critical current values on the noise performance of SQUID magnetometers. By using a statistical-like approach, we measure the spectral density of magnetic field noise of 200 magnetometers relating the values to the critical current change. The magnetometer consists of a dc-SQUID in a washer shape magnetically coupled to a square superconducting pickup coil. The fully integrated design includes a feedback coil to work in Flux Locked Loop mode and an Additional Positive Feedback circuit to increase its voltage responsivity. The main application field of these sensors is the magnetoencephalography that exploits multichannel systems based on SQUID magnetometers, in which the uniformity of noise performance of the sensors is needed. We found that a best value of critical current is 20 µA and also that a value spread ranging from 8 to 40 µm, does not affect in an evident way the sensitivity of such magnetometers. The corresponding noise spectral density remains within the range $2–6\ fT/\sqrt{Hz}$.

1. Introduction
The Superconducting QUantum Interference devices (SQUIDs) play a key role measuring a very small magnetic field, being able to measure a magnetic flux equivalent to few millionths of the elementary flux quantum, i.e. a quantity as low as few $10^{-21}$ Wb [1,2]. Thanks to its versatility, the SQUID can be designed to be used in measuring any physical quantity that can be converted in a magnetic flux [3]; moreover, it can be realized to achieve the suitable spatial resolution (NanoSQUID) to measure a single electron spin [4,5]. Since more than fifty years, the SQUID based magnetometer represents the elective sensor in the field of biomagnetism due to a suitable sensitivity and compactness to be used in complex multichannel systems. In particular, the magnetoencephalography (MEG), a brain functional imaging technique, exploits a large number of sensor that, in the advanced multichannel systems, can be exceed 200 units [6,7].
In these systems the SQUID sensors are used in magnetometer or gradiometer configuration in which a superconducting detection circuit is magnetically coupled to the SQUID. In the case of magnetometer, such a circuit consists of a planar superconducting flux transformer shaped as series of a pickup coil and a multiturn input coil with the latter magnetically coupled to a bare SQUID, a superconducting ring.
containing two Josephson junction, in a washer configuration [8]. To be employed in MEG systems, a sensor must have a magnetic field noise as low as few fT per bandwidth unit to detect the weak magnetic signal generated by the electrical neuronal activity. Furthermore, since most of the spectral content of brain activity falls within the first few tens of Hz, the corner at which the low frequency noise appears must be lower than few Hz [9-11]. Low temperature SQUID magnetometers meets all the above mentioned criteria exhibiting high excellent noise performance and, at same time, a good reliability and stability during the operation. Although such magnetometer are typically fabricated by using a reliable niobium technology, during the fabrication process of a large number of SQUID magnetometers, a value spread of some important SQUID parameters such as the critical current can occurs. In this paper, we present an experimental study of the effect of the critical current spread on the magnetic noise performance by using a statistical approach based on the characterization of large number of SQUID magnetometers. In particular, we will show that, if the magnetometer is properly designed and fabricated, a large critical current spread does not introduce a substantial degradation of the noise performance.

2. Device properties and fabrication

In the magnetometer the magnetic flux is collected by a square pickup coil and transferred to the SQUID loop, in a washer shape, via a multiturn input coil exploiting the Ketchen design [8]. To achieve a suitable magnetic field sensitivity a design based on a pickup coil area of about 65 mm² and a relative large area of SQUID washer (140×140 µm²) have been employed and to prevent both washer resonances and performance degradation due to a non-optimal β value, a damping resistor across the SQUID ring has been included [12,13]. To ensure the suitable linear dynamic range for biomagnetic signal measurements, a Feedback Locked Loop (FLL) scheme has been designed and a relative coil has been integrated on the same chip. Its double coil shape, in which the current flows in opposite directions, limits the crosstalk effect in the neighboring sensors [14]. The chip integrates also an additional positive feedback (APF) [15,16] circuit including a further square coil arranged in parallel to the SQUID via a resistor whose value can be select in a set of 7 resistors to optimize the loop gain (Fig. 1a) [17].

The fabrication process is based on all-refractory niobium technology and consists of several steps to obtain a fully integrated SQUID magnetometers [17-18]. The first step, consists of the Nb/Al-AlOx/Nb trilayer deposition on oxidized silicon wafer (3” in diameter) patterned by optical photolithography. The trilayer is made depositing three thin film without vacuum interruption by using 2 dedicated dc-magnetron sputtering (2” in diameter) housed in high vacuum station (A) in which up to 5 wafers can be processed thanks to a rotating substrate carrier driven by a programmable stepping motor. Both a turbomolecular pump and an ion pump unit guarantee a basic pressure of less than 3×10⁻³ Torr.

The sputtering process is performed in a plasma of argon, whose pressure is fine controlled by a quartz crystal valve keeping in the vacuum chamber a stable pressure of 1.5 mTorr. The Nb base layer, having a thickness of 200 nm, is deposited at a rate of 1.5 nm/s. After that the initial conditions restored, the aluminum layer having a thickness of 7 nm is deposited at an effective rate of 0.09 nm/s, by rotating the wafer carrier to ensure film uniformity. The AlOx tunnel barrier is achieved by thermal oxidation by filling in the vacuum chamber dry oxygen at pressure of 250 mbar for 1 hour. In such a way, a critical current density of 70 A/cm² is expected. Finally, the Nb top electrode, 350 nm thick, is deposited in the same conditions of base electrode. After the deposition, a lift-off process is performed in acetone to define a final trilayer geometry.

An optical photolithography step defines a square window type areas of 16 µm² where, by a Selective Niobium Anodization Process (SNAP), the Josephson junctions are realized. A further insulation is provided by a 120 nm thick SiO₂ film deposited in another vacuum system (B) equipped with a rf-magnetron sputtering. To remove top Nb in selected areas to prepare the contact pads for electrical wiring a Reactive Ion Etching (RIE) process in CF₄ plasma is performed. The next step realizes the shunt and damping resistors by using a dc-magnetron sputtering housed in vacuum system (B) depositing a thin film of Au-Pd having a thickness of 300 nm and deposited at a rate of 2.0 nm/s. Again the lift-off process defines a shape of these resistors. The sheet resistance is 1.0 Ω/sq at T = 4.2 K
resulting in a resistor value $R$ of about 3 Ω. The last fabrication step consists of wiring deposition including the realization of the SQUID washer; by using the System (B) provided of an ion gun, the etching cleaning process is carried out before to deposit by dc sputtering, a 500 nm thick Nb film at a rate of 1.0 nm/s, whose geometry is defined, as in the previous steps, by an optical photolithography step and a subsequent lift-off process.

This fabrication process allows to obtain all refractory niobium junction exhibiting a quality factor $V_M > 80$ mV at $T = 4.2$ K. Figure 1a shows a picture of a SQUID magnetometer while in figure 1b the sequence of the main steps of fabrication process is reported.

3. Methods and results

More than two hundred SQUID magnetometers has been characterized in liquid helium bath at 4.2 K by using a cryogenic insert provided of cylinder shield made of lead with a μ-metal cladding.

In particular, the measurement of spectral densities of magnetic field noise has been carried out by using a low noise readout electronics working at room temperature and connected to the magnetometer by a radio filtered connections [19]. The measurement scheme, in a direct coupling configuration, includes a feedback circuit, called Flux-Locked-Loop (FLL), to linearize the SQUID output increasing the linear dynamic range.

The measurement of the magnetometer critical currents has shown a value spread of about 30 μA ranging from 10 to 40 μA. The current values histogram is reported in fig. 2a and is centered at about 22 μA that corresponds to the expected value of current density of 70 A/cm$^2$ for a junction area of 16 μm$^2$. In correspondence of such spread, the $I_c$ values range from 1 to 5. The red line is a fit with a normal curve. Such a spread of critical current can be ascribed to differences in junction areas or in barrier thickness originated in the sample fabrication or in patterning by photolithography or in anodization process to realize the Josephson junctions. Exploiting such considerations, to obtain a quite wide value spread to give a significance in the statistical results we have varied the time illumination exposure during the photolithographic process and the end point voltage of the anodization process. Being the SQUID voltage swing proportional to $I_c$ via SQUID resistance, the spread of voltage swing (ΔV) also occurs. The figure 2b reports the spread of voltage swing that assumes a normal behavior ranging from 16 to 56 μV and centered at value of about 35 μV.

Note that, the devices having a critical current in a neighborhood of 22 μA coincide with those having a swing voltage in the range 35-37 μV.
Figure 2. Histograms of the critical current (a) and voltage swing (b) of the SQUID calculated on 200 sensors. The peak value occurs at 22 µA for the critical current and at 35 µV for the voltage swing. The dashed curves represent a Gaussian guidelines.

We can calculate the expected value for voltage swing carrying out a theoretical prediction by using the formula [12-13]:

\[
\Delta V = \frac{3-2\sqrt{\beta \gamma - \beta \gamma}}{\pi(1+\beta_{\text{eff}})} I_c R
\]

Where: \( \beta = \frac{2LL_I}{\Phi_0} \), \( \gamma = \frac{2\pi k_T}{I_c \Phi_0} \) and \( \beta_{\text{eff}} = \frac{\beta}{1+\beta} \)

Here, \( 2I_c \) denotes the SQUID critical current, \( L \) and \( R \) are its inductance and resistance respectively.

Note that the presence of a damping resistors introduces a \( \beta_{\text{eff}} \) that tends to one for large \( \beta \) i.e. the increase of critical current does not leads to the voltage swing decreasing. By entering the SQUID peak values in the formula (1): \( 2I_c = 22 \mu A, R = 1.5 \Omega \) and \( L = 260 \mu\Phi \), a voltage swing value of 34.6 µV is obtained in excellent agreement with the experimental one, confirming the reliability of the fabrication process.

In the figure 3, we report the voltage-magnetic flux characteristics (V-\( \Phi \)) which refer to three magnetometers having different critical current values. It is worth to note the effect of the APF circuit that produces a curve distortion obtaining an asymmetric increasing of slope and, as a consequence, an increase of the responsivity (\( \partial V/\partial \Phi \)) by selecting the suitable working point [20]. In this way, for the devices mentioned above, the maximum responsivity of 0.69, 0.86, and 1.18 mV/\( \Phi_0 \) can be obtained at the point of maximum slope. In such a way, the noise contribution of the voltage amplifier can be neglected. In fact, being the voltage noise spectral density of the amplifier \( \sqrt{S_V} = 0.5 \) nV/\( \sqrt{\text{Hz}} \) its contribution to overall magnetic flux noise is respectively 0.72, 0.58 and 0.42 µ\( \Phi_0/\sqrt{\text{Hz}} \). Such values are much smaller than those measured.

Since the noise performance of a SQUID working as magnetometer is the most important parameter, we have measured the magnetic flux noise of about 200 sensors to study the relationship with a critical current change.

In figure 4a, the values of the spectral density of magnetic field noise in the white region (\( \sqrt{S_B} \)) for each magnetometer as a function of its relative critical current is reported. The values of magnetic field spectral density have been obtained by taking the spectra in terms of magnetic flux noise multiplying them by flux-to-field transfer factor (\( B_\Phi \)), which depends on sensor design and, in our case, it is worth 0.7 nT/\( \Phi_0 \).
Figure 3. Voltage-magnetic flux characteristics (V-\(\Phi\)) of three SQUID magnetometers having different critical current values in ascending order. The red (bottom) curve correspond to the lowest value. The measurement was performed at liquid helium temperature (T=4.2 K).

This can be ascribed to low voltage swing for low critical current that leads to a poor responsivity and, as a consequence, an increase of field noise. Instead, high critical current value produces an instability of the APF circuit due to an excessive gain increasing the noise. In any case, although the spread of the critical current is quite large, this do not affect appreciably the magnetic field noise performance. In fact, the magnetic field sensitivity ranges from about 2 to 6 \(\text{fT}/\sqrt{\text{Hz}}\) in correspondence of critical current variation up to a factor 5. Such slight dependence is due to damping resistors which reduces the effects of the growth of inductance parameter \(\beta\) due to the increase of critical current. Furthermore, the integrated resistor network allow us to set the APF gain to avoid unstable behavior.

In figure 4b, the same values of magnetic field noise of each of 200 magnetometers as a function of both its critical current and voltage swing are reported. The figure shows that the most frequent values of magnetic field noise range between 2.5 and 3.5 \(\text{fT}/\sqrt{\text{Hz}}\) and such values occur for critical current values in the range 18 – 26 \(\mu\text{A}\) and for a voltage swing falling in the range 25 – 40 \(\mu\text{V}\).

Figure 4. Magnetic field noise value in the white region of each magnetometers referred to its critical current (a) and to both its critical current and voltage swing (b). The blue line represent an eye guideline.
4. Conclusions

In conclusion, we carried out an experimental study to define the effects of critical current spread on the performance of SQUID in a magnetometer configuration. By using a statistical approach, we have characterized a batch of 200 magnetometers by measuring the critical currents, the voltage vs. magnetic flux characteristics and the magnetic field noise spectral densities. On this basis, we can conclude that, if the SQUID magnetometer is properly designed, a wide critical current spread does not affect appreciably the SQUID performance so that such magnetometers can be used to realize a high sensitivity system based on large number of sensors for many applications like the biomagnetism, guaranteeing the needed performance uniformity.

References

[1] Clarke J, Braginski A I (Eds.) 2004 The SQUID Handbook Vol I: Fundamentals and Technology of SQUIDs and SQUID Systems, Wiley-VCH Verlag GmbH &Co. KgaA, Weinheim.
[2] Seidel P (Ed.) 2015 Applied Superconductivity: Handbook on Devices and Applications, Wiley, Weinheim.
[3] Clarke J, Braginski A I (Eds.) 2006 The SQUID Handbook Vol II: Fundamentals and Technology of SQUIDs and SQUID Systems, Wiley-VCH Verlag GmbH &Co. KgaA, Weinheim.
[4] Granata C and Vettoliere A 2016 Phys. Rep. 614 p 1-69.
[5] Granata C, Russo R, Esposito E, Vettoliere A, Russo M, Musinu A, Peddis D and Fiorani D 2013 Eur. Phys. J. B 86 p 272.
[6] Pizzella V, Della Penna S, Del Gratta C and Romani G L 2001 Supercond. Sci. Technol. 14 R79
[7] Rombetto S, Granata C, Vettoliere A and Russo M 2014 Sensors 14 pp 12114-12126.
[8] Ketchen M B and Jaycox J M 1982 Appl. Phys. Lett. 40 pp 736-738.
[9] Hämäläinen M, Hari R, Ilmoniemi R, Knuutila J and Lounasmaa O 1993 Rev. Mod Phys. 65 pp 413-497.
[10] Cohen D and Halgren E 2009 Magnetoencephalography, Encyclopedia Neurosci. 5 pp 615-622.
[11] Del Gratta C, Pizzella V, Tecchi F and Romani G L 2001 Rep. Progr. Phys. 64 pp 1759-1814.
[12] Enpuku K, Shimomura Y and Kisu T 1993 J. Appl. Phys. 73 p 7929.
[13] Drung D, Knappe S and Koch H 1995 J. Appl. Phys. 77 p 4088.
[14] Granata C, Vettoliere A and Russo M 2006 Appl. Phys. Lett. 88 p 212506.
[15] Drung D and Koch H 1994 Supercond. Sci. Technol. 7 p 242-245.
[16] Drung D 1996 Advanced SQUID Read-Out Electronics. In: Weinstock H. (Eds.) SQUID Sensors: Fundamentals, Fabrication and Applications. NATO ASI Series (Series E: Applied Sciences), vol 329. Springer, Dordrecht pp 63-116
[17] Granata C, Vettoliere A and Russo M 2007 Appl. Phys. Lett. 91 p 122509.
[18] Granata C, Vettoliere A and Russo M 2011 Rev. Sci. Instrum. 82 p 013901.
[19] Ruggiero B, Delsing P, Granata C, Pashkin Y N and Silvestrini P (Eds.) 2006 Quantum Computing in Solid State Systems, London:Springer-Verlag.
[20] Vettoliere A, Granata C, Esposito E, Russo R, Petti L, Ruggiero B and Russo 2009 IEEE Trans. Appl. Supercond. 19 pp 702-705.