Biomedical Signal Processing and Control 46 (2018) 116–120

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

# Model design of a superconducting quantum interference device of magnetic field sensors for magnetocardiography

Bankole. I. Oladapo[a,*], S. Abolfazl Zahedi[a], Surya C. Chaluvadi[a], Satya S. Bollapalli[a], Muhammad Ismail[b]

[a] *School of Engineering and Sustainable Development, De Montfort University, Leicester, UK*
[b] *Department of Engineering, University of Leicester, Leicester, UK*

ARTICLE INFO

*Article history:*
Received 2 November 2017
Received in revised form 25 May 2018
Accepted 10 July 2018

*Keywords:*
Magnetic field sensor
Magnetocardiography
Electrocardiography
Superconducting quantum interference device

ABSTRACT

In recent years, there has been an increase in the study of magnetocardiography (MCG), complementary to electrocardiography (ECG) research, with the purpose of increasing accuracy in the diagnosis of heart and brain pathologies. This research proposes the physical infrastructure of an advanced technology that can be used to obtain heart and brain signals from a specifically designed magnetic field. A generated magnetic sensor is proposed to sense weak magnetic fields in order to detect magnetic heart and brain activity, using interferometry methods. The method of detection of the magnetic field in the sensor, known as a superconducting quantum interference device (SQUID), is found in the interference that occurs during transmission of feeding currents, and the induced currents in the sensor. The sensor consists of two Josephson junctions, connected in parallel. This research presents a fabrication method and the characteristics of thin superconducting films, as an advance in the construction of a SQUID sensor. An ablation chamber is designed, and the deposition of the superconductor on a copper substrate is explored, to obtain thin films at lower cost. The results obtained show good characteristics of superconductivity which can produce a good quality magnetic sensor. There is an intention to further decrease the roughness of the material for the photolithography process.

## 1. Introduction

Electrophysiology is a biomedical field dealing with the study of the electrical activity present in cardiac muscle fibre, the ion channels located within the cardiac cell membrane fibre, and its effect on the body. The opening of the various populations of ion channels in cardiac muscle fibre generates electrical currents mediated by various ionic species [1,2]. The electrical coupling between cardiac muscle fibres allows the potential action to propagate through cardiac muscular tissue. Catheter ablation of atrial fibrillation (AF) and detection of the dominant frequency (DF) has evolved rapidly this decade, in both the atria and the coronary sinus (CS). However, in patients with persistent AF, ablation therapy is still challenging because the arrhythmogenic substrate beyond the pulmonary veins (PVs) plays a role in the perpetuation of AF [3]. The electrical signal of the myocardium is the product of the sum of the action potentials of the muscle fibres which propagates passively and diffuses through the body. Because of the passive propagation of electrical signals, only a small part reaches the skin surface, where it can be measured using electrodes, electrocardiography (ECG) or magnetocardiography (MCG). In ECG or MCG, the voltage of the signal depends on how the electrodes are placed on the surface of the body and their proximity to the heart or brain [3–6].

The ECG test, however, has many limitations. Firstly, it can only measure cardiac electrical activity indirectly because the true signals from the heart are distorted by elements of electrical resistance that lie between the source of the signal in the heart or brain cells and the ECG electrodes placed on the skin surface. Secondly, the measurements are very directional in nature. Assuming that the ECG electrode is a window through which the heart or brain can be observed, misplaced electrodes give a different view of the heart or brain, and, indeed, a misplaced electrode can change a monophasic wave that is a hill on an ECG trace into a biphasic wave (hills and valleys). As mentioned, the electrical activity of the myocardium is a product of the transmembrane ion currents that occur in cardiac muscle fibres. But, according to the law of Biot-Savart, the charge flow induces a magnetic field, which generates an ionic current in the cardiac muscle fibres. The measurement and recording of these

---

* Corresponding author.
*E-mail address:* P17243433@my365.dmu.ac.uk (Bankole.I. Oladapo).

https://doi.org/10.1016/j.bspc.2018.07.007

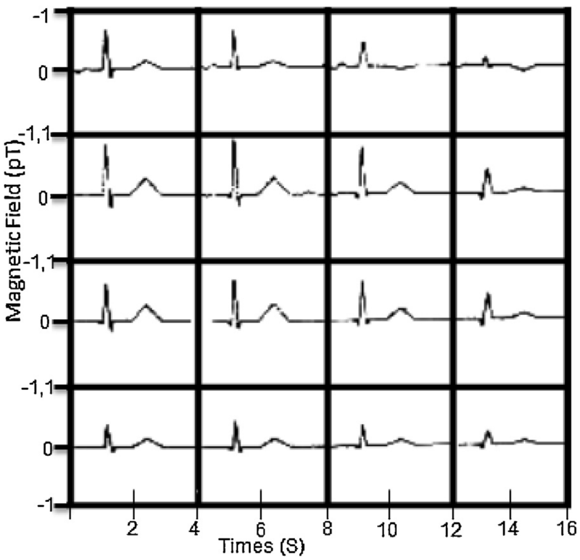

**Fig. 1.** MCG measurements of magnetic field signal components perpendicular to the plane, according to the mesh proposed by [1,5].

magnetic signals constitute MCG. In summary, the electrical activity of the heart is produced by transmembrane ionic currents. It generates a bioelectrical field detectable by ECG and a bio-magnetic field detectable by MCG.

The instrument for obtaining MCG is more complex than that used for ECG [7]. Because of this complexity, a theoretical and experimental investigation is developed. According to Helmholtz theorem, ECG and MCG are mathematically independent. Therefore, it would be expected that MCG can generate a lot more information than ECG. In practice, the electrical and magnetic signals are detected partially and independently, which reduces the amount of new information that MCG can detect [8]. However, the information that MCG can provide has made it extremely useful. The ECG and MCG statistical information are complementary, but, overall, the human mind is responsible for accurate diagnosis. When both ECG and MCG data are used in analysis and diagnosis, errors in the diagnosis of cardiac pathologies can be reduced by half, compared to using ECG only [9–12]. Additionally, the effectiveness of MCG has been validated in patients with various cardiac abnormalities such as ischemia, cardiomyopathies, atrial and ventricular arrhythmias, etc. Prototypes have been developed that obtain MCG in a stress test, similar to those performed for ECG.

## 2. Materials and methods

MCG conforms to a vectorial relation, which can provide information according to three-dimensional cardiac magnetic activity. It generally takes the component perpendicular to the chest [13–16]. Unlike ECG, MCG has little interaction with the skin, and it is not necessary to have a reference. Similar to the derivations proposed by Eithoven in ECG, Maslennikov et al. propose a 4 × 4 mesh which constitutes standard MCG. Fig. 1 shows the recorded measurements of typical MCG of the head taken with a SQUID4 sensor [1,5].

Magnetic field measures are the most appropriate technique for measuring extremely weak magnetic fields, such as cardiac fields, and utilize SQUID. This is one the most sensitive devices that exist for MCG [4,16]. The SQUID16 is an extremely sensitive magnetometer, used to measure extremely subtle magnetic fields based on superconducting loops containing a Josephson junction that converts magnetic flux to voltage. The output voltage is a periodic magnetic flux as follows:

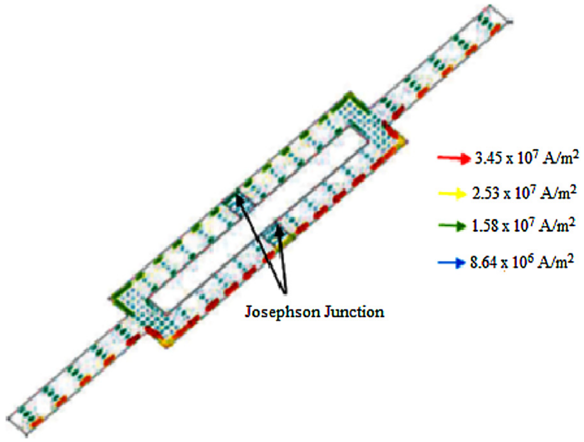

**Fig. 2.** A force microscope SQUID sensor of an atom of current density distribution in a superconducting state.

$$\emptyset_0 = \frac{h}{2e} = 2.07 \times 10^{-15}\,\text{weber(wb)} \qquad (1)$$

Where $\emptyset_0$ representsmagnetic flux, $h$ is the Plank constant and $e$ is the charge of the electron. In this way, the output voltage detects signals corresponding to a change in the lower flow $\emptyset_0$. For its function in SQUID, it combines two physical phenomena: magnetization of magnetic flux; $\emptyset$ magnetic flux in a closed superconducting circuit recast of $\emptyset_0$ and the tunnel of the Josephson effect. The directcurrent (DC) SQUID consists of two Josephson junctions, connected in parallel in a circuit superconductor. It is called a DC SQUID because it operates using a DC current [17–20].

### 2.1. DC SQUID

This transducer is comprised of two Josephson junctions, coconnected in parallel to form a type of washer. In the arrangement shown in Fig. 2, there is a function wave of common electron pairs at both the top and bottom of the array. For a symmetric, and in the absence of an external, magnetic field arrangement, the phase differences can be seen via the joints. When a charge is applied perpendicular to the magnetic plane of the array a difference in phase arises between the joints. If the critical currents $I_1$ and $I_2$ are equal, the following expression can be derived [21–23].

$$I = 2 \times I_2 \times \cos\left(\frac{\pi \times \emptyset_{ext}}{\emptyset_0}\right) \qquad (2)$$

The Josephson junction connections shown in Fig. 2 are structurally parallel to one another. I is the current supply of the system, $\emptyset_{ext}$ represents the external magnetic flux, and the phase differences of the current through the union is represented by input an output of the Josephson junctions. The constant $\emptyset_0$ corresponding to the magnetic flux (equation 1). If we feed the SQUID with a constant current and apply a magnetic flux to the circuit uniformly, the voltage across the SQUID oscillates for a period given by $n\emptyset_0$ (with $n = 0, 1, 2, \ldots$). If the external field increases slowly, it results in a voltage, the period of which is a multiple of $n\emptyset_0$, which makes it possible to measure magnetic fields smaller than a quantum of magnetic flux. Fig. 2 shows a SQUID sensor. Despite the advantages of SQUID sensors, the use in MCG for clinical purposes, as in the case of ECG, is limited because it is a subject of research and technological development [6].

The measurement of weak magnetic signals, such as those induced by the electrical activity of the heart, requires a technology only available in a few countries [24,25]. In order to cover this