Experimenting with magnetic sensors: 
Superconducting QUantum Interference Devices (SQUIDs)

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Abstract We review the main aspects of designing, fabricating, and operating a number of systems within the SQUID (Superconducting QUantum Interference Device). While this article is not intended to be an exhaustive review on the principles of coils and the underlying concepts behind the Josephson effect, a qualitative description of the operating principles of coils and the properties used to fabricate them is presented. Specific examples of input circuits and detection configuration for different applications and environments, along with expected performance, are described. In particular, anticipated signal strength, environment (applied field and external noise), and cryogenic requirements are discussed. Finally, a variety of applications of SQUID ultra-high magnetic sensors in areas of electromagnetic, material property, and geophysical and biomedical are reviewed.

1. Introduction

The magnetic sensing at nanoscale level is a promising and interesting research topic of nanoscience. Indeed, magnetic imaging is a powerful tool for probing biological, chemical and physical systems. The study of small spin cluster, like magnetic molecules and nanoparticles, single electron, cold atom clouds, is one of the most stimulating challenges of applied and basic research of the next years. In particular, the magnetic nanoparticle investigation plays a fundamental role for the modern material science and its relative technological applications like ferrofluids, magnetic refrigeration and biomedical applications, including drug delivery, hyperthermia cancer treatment and magnetic resonance imaging contrast-agent. Actually, one of the most ambitious goals of the high sensitivity magnetometry is the detection of elementary magnetic moment or spin. In this framework, several efforts have been devoted to the development of a high sensitivity magnetic nanosensor. Among the different magnetic sensors, Superconducting QUantum Interference Devices (SQUIDs) exhibit an ultra-high sensitivity and are widely employed in numerous applications. Basically, a SQUID consists of a superconducting ring (sensitive area) interrupted by two Josephson junctions. In the recent years, it has been proved that the magnetic response of nano-objects can be effectively measured by using a SQUID with a very small sensitive area (nanoSQUID). For this reason, SQUIDs have been progressively miniaturized in order to improve the sensitivity up to few spins per unit of bandwidth. With respect to other techniques, nanoSQUIDs offer the advantage of direct measurement of magnetization changes in small spin systems. In this review, we focus on SQUIDs and its applications. In particular, we will discuss the motivations, the theoretical aspects, the fabrication techniques.

2. Superconducting materials

The use of different materials for making products can be traced to prehistoric times when humans used stones and wood to make weapons or farming implements. The materials they used did not end with stone or wood but expanded with the discovery of metals in the Iron Age and subsequently synthetic (plastic) and composite materials. For centuries, materials with different properties have been used for manufacturing products. In today’s manufacturing industries, designers and engineers select materials for their products based on factors such as cost, availability, ease of manufacture, material properties, and environmental conditions in which the product will be used. As society continues to demand new products that can function under different...
conditions with optimum performance, finding new materials or changing the properties of materials has become necessary. One such change in properties is to make a material superconductive. Superconductors are materials that will conduct electricity without resistance below a certain critical temperature. Superconductivity was first observed in 1911 by Heike Kamerlingh Onnes. He observed that the electrical resistance of mercury wire dropped to zero when the wire was cooled in liquid helium below a certain critical temperature 4.2K (Kelvin Temperature). The research on superconductivity was advanced in 1957 by three American physicists, John Bardeen, Leon Cooper, and John Schriefer. Their theory of superconductivity, which became known as BCS theory, became the basis for discovering high temperature, 23K (degrees Kelvin) superconductors, materials which become superconductors at temperatures much higher than 10K (-268.8C). Since then much work has been done by other scientists to expand their research. There are two classifications of superconductors, type I and type II. Type I superconductors are metals and elements that show superconductivity at low temperatures. These include mercury, tin, aluminum, and zinc, all between 0.88K and 4.15K. Type II superconductors are metals and compounds that reach superconductivity at much higher temperatures. Examples of these compounds are ceramic superconductors composed of thallium (Tl), yttrium (Y), barium (Ba), copper (Cu), and oxygen (O)-molecular formula of YBa2Cu3O7, which achieves superconductivity at a critical temperature of 90K; Bi SrCaCuO at 105K; and TlBaCaCuO at 125K. The discovery of type II superconductors makes them materials of interest to scientists, designers, engineers, and manufacturers. As a result of this achievement, scientists do not doubt the possibility of room temperature superconductivity.

3. Superconductivity

The Josephson Effect is an example of macroscopic quantum phenomenon in superconductivity. In 1962, Brian Josephson predicted that Cooper Pair could tunnel between superconductors separated by the insulating layer, with the same possibility as that of an ordinary electron. There is a possibility of both of them (super electrons and normal electrons) tunneling across an insulating barrier. When a thin layer of insulating material separates two superconductors, electron pairs are able to tunnel through the insulator from one superconductor to the other. This phenomenon is called the Josephson Effect and is analogous to quantum mechanical tunneling. There are 4 possible modes of Cooper Pair tunneling through a Josephson Junction that will produce the dc Josephson effect: (1) in which a dc current can flow across the junction in the absence of electric field without the need for an applied voltage, (2) the ac Josephson effect, where an ac current can flow through the junction with an applied voltage across the junction, (3) the inverse ac Josephson effect, whereby dc voltages are induced across an unbiased junction by an impressed rf current, and (4) macroscopic quantum interference effect. To get superconductivity, electrons must cooperate in pairs, called Cooper pairs. The pairs obey a different statistical law from single electrons, making resistanceless passage possible. In low-temperature superconductors the pairs form through an interaction with an acoustical wave in the crystal lattice called a phonon. As an electron proceeds through the crystal, it draws the atomic nuclei toward itself. As it passes, the nuclei move back to their previous position. Thus, the lattice ripples as the electron moves along. A proper interaction between two such ripples brings the electrons into a Cooper pair.

5. SQUID

SQUIDs are used to sense extremely small magnetic fields created by currents flowing around loops fabricated in the SQUID circuitry. In 1986, the discovery of a new class of oxide materials opened up a broad range of applications in conventional electronics. These materials, known as high-temperature superconductors, have critical temperatures in the 77[degrees] K range. As a result, liquid nitrogen a far more viable coolant can cool these oxides. Today, there are two camps of superconductor research and development high temperature superconductors (HTSs) and low temperature superconductors (LTSs). HTS materials are those that remain superconductive above 30 K; LTS materials remain superconductive below 30 K. Within both camps, there are several.
known materials that can achieve superconductivity. Thallium is the highest temperature material used for HTS material; YBCO (ytterbium barium copper oxide) has a somewhat lower operating temperature, but is more common. Niobium is the most common material used for LTS materials. Because of the difficulties associated with cooling, LTS materials have found only restricted use. LTS applications are primarily found in the medical area, where they are used for magnets in large MRI (magnetic resonance imaging) diagnostic machines and in scientific equipment. The superconducting quantum interference device consists of two Josephson junctions inserted into a superconducting loop. The device is extraordinarily sensitive to changes in electromagnetic fields. When a SQUID is operated at 4 K, thermal noise is virtually eliminated and the SQUID’s sensitivity approaches the fundamental limits imposed by quantum mechanics. No other technology comes close, comparing the performance of superconducting SQUIDs with conventional magnetic sensors.

10. Experiment

10.1. The mK System
Since we hope to measure the magnetic properties of materials we want to eliminate all possible additional magnetic fields in the system. Non-magnetized Connectors:
The pins that were initially used in this device were magnetic, so we replaced them with non-magnetic pins.

10.2. Assembling the Measurement System
Inductive components of different core coil geometries and wire technologies are taken into account. Rigorous analytical modeling was applied to achieve minimization of the possibility of breaking the signal wire and to ensure that the full system is submerged in the liquid He3 to maintain its superconducting properties. The system includes a dedicated self-testing/calibrating controller, AC and DC magnetic sensor: Pick-up coil: enables us to measure the magnetic field around our sample. It’s made of NbTi, is 70mm in diameter and has a length of 215mm. The pick-up coil is made such that the current
induced by the magnetic field with no sample should be 0. The technique we using in winding the Nb wire around the Coil allowed us to cancel out the current induced by the coil, which is then placed into the cylindrical solenoid.

Offset coil: Used to make up for the fact that any asymmetry in our system can lead to large errors in our calculations. The off-set, is designed and correctly placed between the Hall Element and the Pick Up Coil, it is used to correct any asymmetry.

Hall Probe: The Niobium wire connects the pick-up coil to the Off-set correction system and to the the Hall Probe.

The wire is glued well against the coils and everything is attached tightly to ensure no noise fluctuation and to enable good measure of the magnetic field accurate to the nT scale. The assembly is then cooled down in the UHV chamber, which has a field less than 20 nT inside it, and immersed in LHe to obtain both static and dynamic alternating current field measurements. Actual tests performed on Niobium and Titanium thin film validate the viability of the proposed sensor system.

11. Experimental results

![Temperature dependence of resistance.](image)

![Temperature dependence of magnetic field. Noise level was too large for measuring the Meissner effect.](image)
fig. 3. *Time dependence of magnetic field*

*Dynamic range of offset adjustment: 20 µT; too small! Measured offset: 5 µT.*

### 11. conclusion

Noise level of Hall element was too large for measuring the Meissner effect; Offset adjustment can work well, however, the dynamic range is lower than offset signal; Pick-up coil worked well. As futur plans we would like to: optimize the dynamic range of magnetic field’s strength, also the device features loud noise which makes the makes the analyses illisible. Enhance the sensitivity of Hall element and augmente dynamic range of offset adjustment system.

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