Tech 101 project 2: SQUIDs

Notes

Introduction

A SQUID – or Superconducting QUantum Interference Device – is a very sensitive magnetometer (device for measuring magnetic fields) based on quantum effects in a superconducting loop. SQUIDs have a wide range of uses in physics, biology and medicine.

History

SQUIDs were invented in 1962 by the British physicist Brian David Josephson, along with the Josephson junction which is vital to their operation. Josephson won the 1973 Nobel Prize for Physics (along with Leo Esaki and Ivar Giaever) for his discovery of the Josephson effect.

Operation

The Josephson effect – which is important to the operation of a SQUID[, and may also be used in future quantum computers] – occurs when an electric current (in the form of Cooper pairs) flows between two superconductors separated by a thin (a few atoms thick) non-superconducting (possibly insulating) layer through quantum tunnelling. Such a junction between two superconductors is called a Josephson junction. A Josephson junction can only support a certain maximum current in a superconducting state; this maximum current is called the critical current.

The most common types of Josephson junctions are tunnel junctions, where the barrier is an oxide insulator; semiconductor junctions; and Dayem bridge junctions, which are based on a constriction. Other types of junctions are rarely used.

A SQUID consists of a loop of superconductor with one or more Josephson junctions, called weak links. The inner diameter of the loop is typically about 100 µm. It is generally made from either an alloy of lead and gold or indium, or pure niobium. The use of ceramic superconductors such as yttrium-barium-copper-oxide (which have the advantage of higher critical temperatures) is also possible, but Josephson junctions from such materials are more difficult to manufacture.

There are two main types of SQUID: RF SQUIDs (also known as AC SQUIDs), which have only one Josephson junction; and DC SQUIDs, which have two or more junctions. DC SQUIDs are significantly more sensitive but also more expensive.

In a DC SQUID, a current is made to flow around the loop through both Josephson junctions. The electrons tunnel through the parallel junctions and interfere with each other. A magnetic field through the loop causes a phase difference between the electrons, which affects the current through the loop. Basically, a flux through the loop induces a current around the loop. This affects the current flowing through the loop, because the net current through each junction is no longer the same, resulting in a potential difference across the loop. The voltage across the loop can then be measured.

RF SQUIDs work on a similar principle, but use a radio frequency oscillating current and measure interactions between the superconducting ring and an external circuit, and only require one Josephson junction. The external circuit consists of an inductor and capacitor, forming a resonant LC circuit. The inductor is placed so as to induce a current in the SQUID ring, and when the Josephson junction enters the resistive state (which depends on the external magnetic flux) this draws energy from the LC circuit and damps it. This effect can then be measured.

Because SQUIDs are so sensitive, background magnetic fields can be a problem. Operating the SQUID in a shielded room helps, but can be expensive and means that the SQUID cannot easily be moved. Another solution is to use a *gradiometer* which measures the gradient of the field rather than its absolute value, by using several connected loops. This works because interfering magnetic sources are generally much further away, and so vary less. Other options are to measure the ambient magnetic field and subtract this from measurements, or to use damping coils to cancel out the background field. Another problem is Johnson noise, which is the magnetic field created by thermal motion of surrounding particles.

[Field / flux transformer?]

Applications

Biomagnetism

Various processes in animals produce small magnetic fields (on the order of 10^{-12} – 10^{-9} tesla), which can be detected by a SQUID. Of particular interest are the fields associated with neural activity. These can be imaged by machines based on an array of SQUIDs, in a technique known as magnetoencephalography (MEG). Such systems generally use gradiometer DC SQUIDs. An important advantage of SQUIDs over other systems used for similar purposes in imaging brain function is higher temporal resolution – MEG images can be acquired in millisecond intervals, and respond rapidly to changes in neural activity. For comparison, PET and MRI have a temporal resolution on the order of 1 second as they rely on blood and oxygen flows, but higher spatial resolution.

SQUIDs can also be used to measure heartbeat; such a measurement is called a magnetocardiogram.

Scanning SQUID microscopy

By scanning a SQUID probe over a sample in a similar manner to a scanning tunnelling microscope or atomic force microscope, a high-resolution image of its magnetic field structure can be obtained.

Image: Ultrahigh Resolution Scanning SQUID Microscope images of a 1 mm thick slice of martian meteorite ALH84001 (Caltech); SQUID microscope used.

Geophysical applications

SQUIDs have been used by geophysicists to measure movement of the Earth's magnetic poles and variations in the thickness of the crust. SQUIDs are also used in oil prospecting, earthquake prediction and geothermal energy surveying. Such uses require portable containers with sufficient insulation to carry liquid helium, and methods of reducing magnetic noise. Magnetic shielding is not practical, but other methods discussed earlier such as the use of gradiometers can be helpful. The use of high temperature superconductors would help solve some of these problems, as liquid nitrogen can be used for cooling rather than helium.

Conclusions

SQUIDs are likely to be used increasingly in the future as they become cheaper and more versatile due to the development of high-temperature superconductors and better cooling systems.