11 Superconductivity and SQUID magnetometer

Basic knowledge

Superconductivity (critical temperature, BCS-Theory, Cooper pairs, Type 1 and Type 2 superconductor, Penetration Depth, Meissner-Ochsenfeld effect, etc), High temperature superconductors, Weak links and Josephson effects (DC and AC), the voltage-current $U(I)$ characteristic, SQUID: structure, applications, sensitivity, functionality, screening current, voltage-magnetic flux characteristic)

Literature

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[8] http://www.physnet.uni-hamburg.de/home/vms/reimer/htc/pt3.html

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Content:

1. Introduction

The aim of the present experiment is to give an insight into the main properties of superconductivity in connection with the description of SQUID.

Superconductivity is a unique property of certain materials which is mainly characterized by:
- Zero resistance to the flow of DC electrical current;
- The ability to screen out magnetic fields (perfect diamagnetism);
- Quantum mechanical coherence effects – magnetic flux quantization and the Josephson effects.

SQUIDs (**S**uperconducting **Q**uantum **I**nterferometer **D**evices) are the most sensitive sensors for magnetic fluxes. According to John Clarke, one of the developers of the concept, the SQUID magnetometers may be the most sensitive measurement device known to man. He evokes the following images to illustrate its sensitivity:
- It can measure magnetic flux on the order of one flux quantum. A flux quantum can be visualized as the magnetic flux of the Earth's magnetic field (0.5 Gauss = 0.5 x 10^{-4} Tesla) through a single human red blood cell (diameter about 7 microns).
- It can measure extremely tiny magnetic fields. The energy associated with the smallest detectable change in a second, about 10^{-32} Joules, is about equivalent to the work required to raise a single electron 1 millimeter in the Earth' gravitational field.

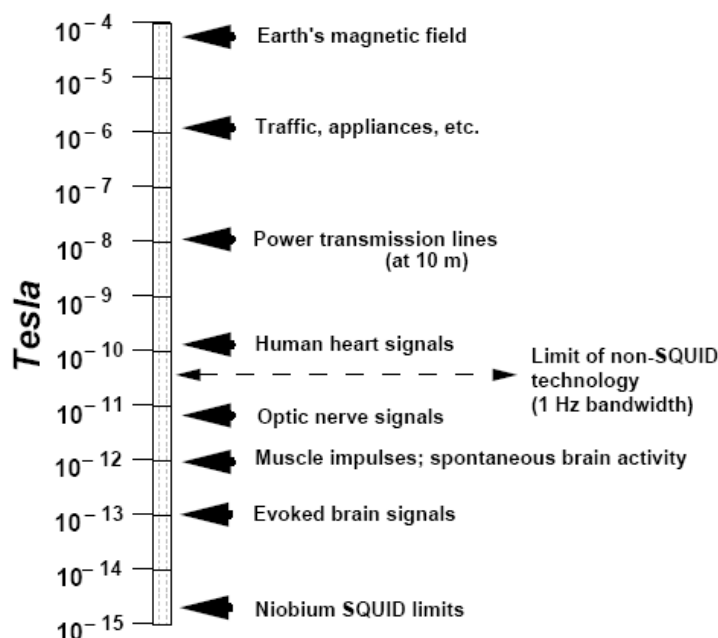Figure 1 shows a comparative chart highlighting the SQUID sensitivity.

Fig. 1: Comparison: magnetic field levels of various sources – SQUID sensitivity.

In addition to the magnetic fluxes, other physical values such as electrical current (sensitivity of 10^{-12} A) and electrical resistance (sensitivity of 10^{-12} Ω) can be measured with a SQUID if they can be adapted into the magnetic flux.

There is a great variety of **SQUID applications** either under investigation or commercially available. The most relevant SQUID applications are: laboratory instrumentation, biomedical

applications (magnetoencephalography, magnetocardiology, etc), military applications (for submarine and mine detection), in geophysics (from prospecting for oil and minerals to earthquake prediction) and in non-destructive evaluations.

A great revolution in superconductivity came in 1986 when the era of high-temperature ($\geq$ 90K) superconductivity (HTS) began.
Our experimental setup, Mr. SQUID®, is a HTS DC SQUID magnetometer and can therefore be used to detect small magnetic signals if they are properly coupled to the SQUID. Because its modulation coils are not superconducting, Mr. SQUID® does not have the sensitivity of high-performance laboratory SQUIDs. Hence, it cannot be used to detect truly minute signals such as those generated by the human brain. However, it enables us to demonstrate the most relevant SQUID characteristics.

2. Basic knowledge (Superconductivity and SQUID)

Superconductivity, discovered in 1911 by H. Kammerlingh Onnes, is a phenomenon occurring in certain materials at extremely low temperatures, characterized by zero electrical resistance, exclusion of the interior magnetic fields and quantum mechanical coherence effects.

The resistivity of a metallic conductor decreases gradually as the temperature is lowered. On the other hand, the resistance of a superconductor decreases gradually as the temperature is lowered and drops abruptly to zero when the material is cooled below its **critical temperature, T_C**. A sketch of the above effects is shown in Fig. 2. The value of T_C varies from material to material. Conventional superconductors usually have T_C ranging from less than 1 K to about 23 K. T_C of HTS ranges from about 90 K to about 138 K.
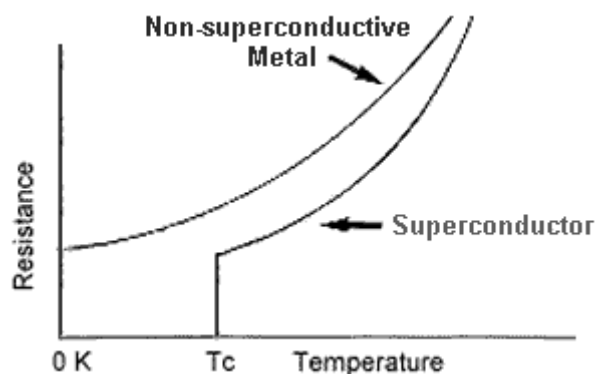

Fig. 2: Temperature dependence of the resistance of a normal metal and of a superconductor.

The understanding of superconductivity was advanced in 1957 through the so called **BCS** (Bardeen-Cooper-Schrieffer) **theory**, which explains the superconductivity at temperatures close to absolute zero. According to BCS theory the atomic lattice vibrations force the electrons to pair up into teams that could pass all of the obstacles which caused resistance in the conductor. These teams of electrons are known as **Cooper pairs**. In other words, two electrons couple together over a range of tens-hundreds of nanometers through their wave functions and form a Cooper pair. The Cooper pairs possess the character of bosons and condense into the ground state.

According to the BCS theory, as one negatively charged electron passes by positively charged ions in the lattice of the superconductor, the lattice distorts (see Fig. 3-(a)). This causes phonons to be emitted which form a trough of positive charges around the electron. Figure 3-(a) illustrates a wave of lattice distortion due to attraction to a moving electron. Before the electron passes by and before the lattice springs back to its normal position a second electron is drawn into the trough. It is through this process that two electrons, which should repel one another, link up. The forces exerted by the phonons overcome the electrons' natural repulsion. The electron pairs are coherent with one another as they pass through the conductor in unison. When one of the electrons that make up a Cooper pair passes close to an ion in the crystal lattice, the attraction between the negative electron and the positive ion cause a vibration to pass from ion to ion until the other electron of the pair absorbs the vibration. The net effect is that the electron has emitted a phonon and the other electron has absorbed the phonon. It is this exchange that keeps the Cooper pairs together. The pairs are constantly
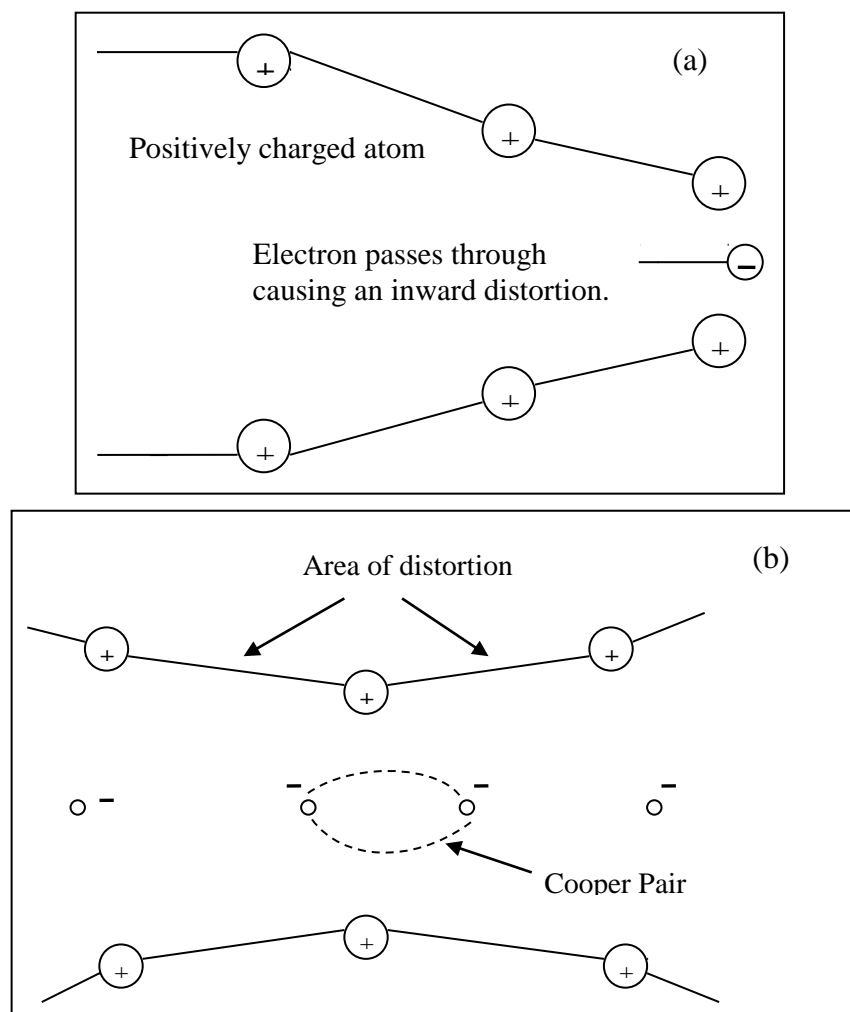

Fig. 3-(a): Illustration of a wave of lattice distortion due to attraction to a moving electron;
(b) the formation of Cooper pairs

breaking and reforming. Because electrons are indistinguishable particles, it is easier to consider them as permanently paired. Fig. 3-(b) illustrates how two electrons become locked together.

Since in the normal conductive state the wavefunctions describing the electrons are not related to one another, in the superconducting state a single wavefunction describes the entire population of Cooper pairs. As long as the superconductor is cooled to very low temperatures,

the Cooper pairs stay intact, due to the reduced molecular motion. As the superconductor gains thermal energy the vibrations in the lattice become more violent and break the pairs. As they break, superconductivity diminishes at T_C.

There is a certain maximum current that a superconductor can carry, above which they stop being superconductors. If too much current is pushed through a superconductor, it will revert to the normal state even though it may be below its T_C.

When a superconductor is cooled below its T_C and a magnetic field is increased around it, the magnetic field remains around the superconductor. If the magnetic field is increased to a given point the superconductor will go to the normal resistive state. The maximum value for the magnetic field at a given temperature is known as the critical magnetic field H_C. For all superconductors there exist a region of temperatures and magnetic fields within which the material is superconducting. Outside this region the material is a normal conductor.
The superconductors are usually divided in two classes: Type I and Type II.

Type I superconductors are pure metals. They exhibit zero resistivity below T_C, zero internal magnetic field (Meissner effect), and a critical magnetic field above which the superconductivity ceases. The superconductivity in Type I superconductors is modeled well by the BCS theory. They are also characterized by very small values of T_C (< ~11 K) and H_C (they are called also "soft" superconductors), which make them not attractive for applications. Figure 4-(a) shows the induced magnetic field of a Type I superconductor versus applied magnetic field. When an external magnetic field (abscissa) is applied to a Type I superconductor the induced magnetic field (ordinate) exactly cancels that applied field until there is an abrupt change from the superconducting state to the normal state.
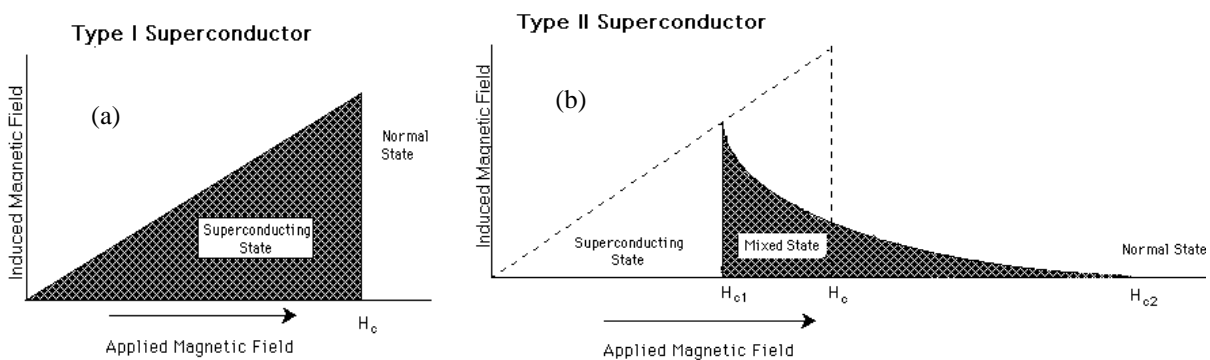

Fig. 4: Induced magnetic field versus applied magnetic field of a
(a) Type I superconductor and (b) Type II superconductor

Type II superconductors are alloys and they incorporate also the new subclass of HTS. They are characterized by higher values of T_C (up to 23 K for conventional superconductors and up to 138 K for HTS) and much higher critical fields which allows them to carry much higher current densities while remaining in the superconductive state. Fig. 4-b shows the induced magnetic field of a Type II superconductor versus applied field. This graph contains two critical fields, H_{C1} and H_{C2}. Below H_{C1} the superconductor excludes all magnetic field lines (Meissner effect). At field strengths between H_{C1} and H_{C2} the field begins to intrude into the material. When this occurs the material is said to be in the mixed state, with some of the material in the normal state and part still superconducting. Type II superconductors show a slow transition to the normal conductive state, in contrast to the Type I superconductors.

Meissner effect (or Meissner-Ochsenfeld effect) is the effect by which a weak magnetic field decays rapidly to zero in the interior of a superconductor. For example, a superconducting ring excludes the magnetic field lines from its interior. The distance to which the field is active is known as the London penetration depth and is on the order of 100 nm. An illustration of the Meissner effect is given in Fig. 5. One can see that when the temperature is lowered to below T_C, the superconductor will "push" the field out of itself. It does this by creating surface currents in itself which produces a magnetic field exactly countering the external field, producing a "magnetic mirror". The superconductor becomes perfectly diamagnetic, cancelling all magnetic flux in its interior.
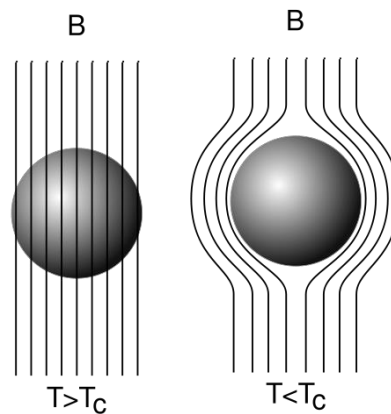

Fig. 5: Illustration of the Meissner effect

Weak links and Josephson effects

Any weak coupling between two regions of superconductor – such as tiny constrictions, microscopic point contacts, weakly conducting layers, or certain crystallographic grain boundaries – gives rise to a structure called **Josephson junction** or **weak-link**. The term "weak-link" comes from the fact that Josephson junctions generally have a much lower critical current (which is the maximum current that can be carried before resistance begins to appear) than that of the two superconducting regions that it connects.
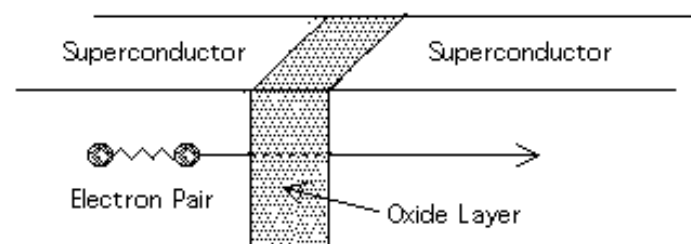

Fig. 6: Schematic representation of a weak link in which the Josephson tunneling takes place.

In a weak link, the phases of the Cooper pairs in the two regions of superconductor are related. In other words, the Copper pairs can tunnel through the weak link without breaking them up, resulting in an electrical current which can flow between the two regions of the superconductor with zero resistance. A schematic representation of a Josephson contact, in which the quantum mechanical tunneling (Josephson tunneling) of the Cooper pairs takes place is shown in Figure 6.

The DC (direct current) and the AC (alternating current) Josephson effects are the two fundamental phenomena which occur in a Josephson contact:

DC Josephson effect:

There is an electrical direct current flowing through a Josephson contact even in the absence of an external voltage. This current is given by $\mathbf{I = I_0 \sin \delta = I_0 \sin(\Theta_2 - \Theta_1)}$, where δ is the phase difference of the Cooper pairs wave functions on both sides of the Josephson contact and I_0 is the maximum supercurrent.

AC Josephson effect:

By applying a direct voltage on the Josephson contact an oscillating current flow is generated with the frequency $\omega = \frac{2eV}{\hbar}$.

The **voltage-current $U(I)$ characteristic** is one of the most important characteristic of a Josephson contact. Fig. 7 shows the voltage-current characteristic of a weak link. The horizontal part of this characteristic, where the resistance is zero, corresponds with the superconductive state of the Josephson junction. The maximum current which can flow through the weak link without resistance, called the critical current I_C, can be estimated from the $U(I)$ characteristic as being half of the horizontal plateau. For $I > I_C$ the Cooper pairs break into two electrons and a resistance appear. This corresponds with the transition from the superconductive state to the normal conductive state. The slope of the $U(I)$ characteristic in the normal conductive regime represents the resistance in the normal conductive state, R_n. The product of the critical current I_C and R_n, $U_C = I_C \cdot R_n$, is called the critical voltage U_C which is another important parameter of the weak link.
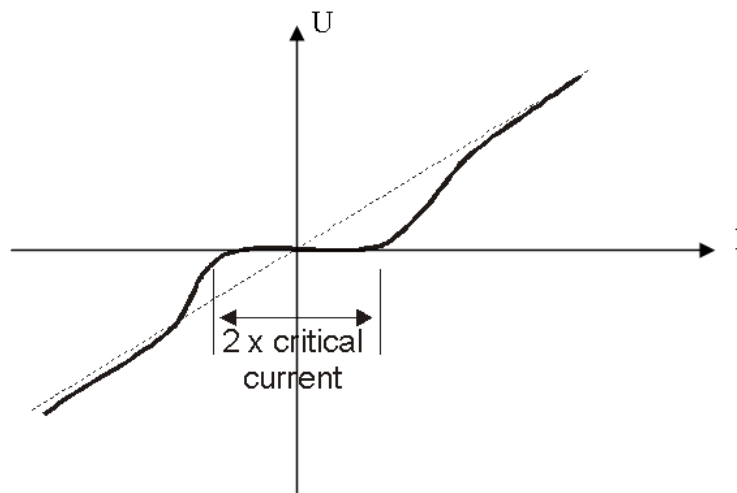

Fig. 7: The voltage-current characteristic of a weak link

Josephson junctions are the essential active devices of superconductive electronics. One of the most useful circuit made from Josephson junctions is the DC SQUID.

DC SQUID

SQUID consists of two Josephson junctions connected in parallel on a closed superconducting loop. A fundamental property of superconducting rings is that they can enclose magnetic flux only in multiples of a universal constant called the flux quantum ϕ_0. This is a very important

quantum condition which plays a crucial role in understanding the functionality of SQUID. In other words, an external magnetic field can penetrate a superconductive loop if and only if the magnetic field is an integer multiple of the magnetic flux quantum ϕ_0:

$$\phi_0 = \frac{h}{2e} = 2 \times 10^{-15} Wb$$

Because the flux quantum is the smallest quantity of the magnetic flux, this physical effect can be exploited to produce an extraordinarily sensitive magnetic detector known as SQUID. SQUIDs actually function as magnetic flux-to-voltage transducers, because they convert the magnetic flux, which is hard to measure, into voltage, which is easy to measure.

Let us suppose that a constant current, known as a bias current, is passed through a SQUID. If the SQUID is symmetrical and the junctions are identical, the bias current will split equally, half on each side. A DC SQUID is generally represented schematically as shown in Figure 8. A supercurrent will flow through the SQUID, as long as the total current flowing through it does not exceed the critical current of the Josephson junctions, which have a lower critical current than the rest of the superconducting ring. The critical current is the maximum zero–resistance current which the SQUID can carry, or the current at which a voltage across it develops. When the two junctions in the SQUID are identical, the loop is symmetrical, and the applied field is zero, both junctions will develop a voltage at the same time. So, the critical current of the SQUID is simply twice the critical current of one of its junctions. If the critical current of each junction is 5 μA, for example, then the critical current of the SQUID is 10 μA. The voltage-current characteristic, or *V-I* curve, of a SQUID, looks very much like the *V-I* curve of a bulk superconductor, shown in Fig. 7.

In order to understand how the SQUID works let us bias the SQUID with a current well below its critical current. Then, if we apply a tiny magnetic field to the SQUID, the magnetic field wants to change the superconducting wave function. Therefore, the superconducting loop opposes the applied magnetic field by generating a screening current I_S, that flows around the loop (see Figure 8). The screening current creates a magnetic field equal but opposite to the applied field, effectively cancelling out the net flux in the ring.

The applied magnetic field has lowered the effective critical current of the SQUID — in other words it has reduced the amount of bias current we can pass through the SQUID without generating a voltage. The reason is that the screening current superimposes itself on top of the bias current so that: the effective critical current of the top junction decreases with the quantity of I_S and the effective critical current of the bottom junction has to decrease also with I_S, in order for the bottom junction to be in the superconductive state (if the effective critical current of the bottom junction does not decrease, the addition of I_S to the initial critical current gives rise to a new current bigger than the critical current of the junction → normal conductive regime). As a consequence I_{bias} decreases with $2 \cdot I_S$. Suppose the critical current of each junction is 5 microamps and the screening current is 1 microamp. Since the junction on the bottom has to carry 1 microamp of screening current, it can now carry only 4 microamps of
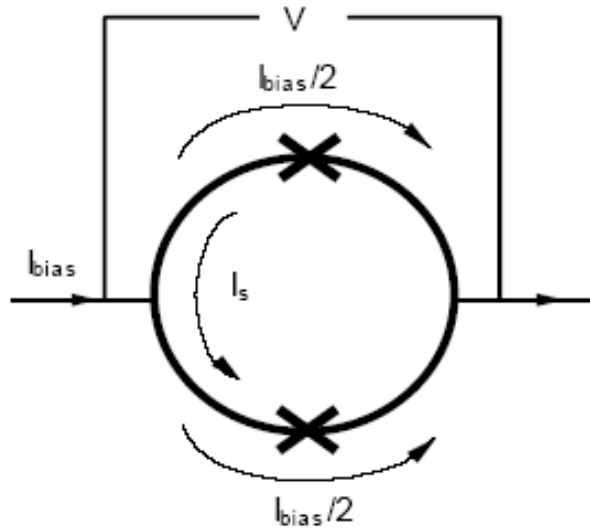
Fig. 8: A DC SQUID in the presence of an applied field

bias current before it becomes resistive. It does not distinguish between bias currents and screening currents; it just detects the flow of the electron pairs. When it carries a total of 5 microamps, it becomes resistive.

SQUID magnetometers are biased with a constant bias current slightly greater than the critical current. When the junction on the bottom goes normal, all the current goes through the junction on the top, which makes it go normal. That means both paths are now resistive, so a voltmeter will register a voltage across the SQUID. As we increase the applied magnetic flux, the screening current increases. But when the applied magnetic flux reaches half a flux quantum, something interesting happens. The junctions momentarily go normal. The continuity of the superconducting loop is destroyed long enough for one quantum of magnetic flux to pop inside the loop. Then superconductivity around the loop is restored. (This is illustrated in Figure 9.) Thus, the junctions serve as gates that allow magnetic flux to enter (or leave) the loop.

The above phenomena can be understood easier by considering the following example: rather than generating enough screening current to keep 0.51 flux quanta out, now all the SQUID has to do is generate enough screening current to keep 0.49 flux quanta in, which is, of
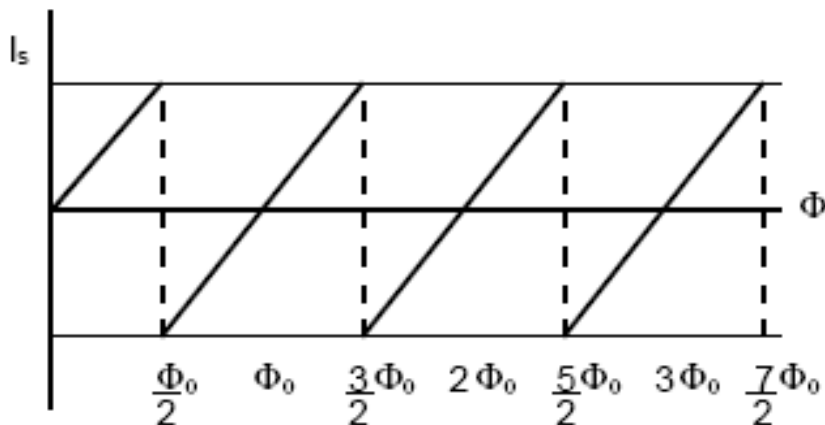

Figure 9: Relationship between screening current and applied magnetic flux.

course, a little easier (that is, lower in energy.) Of course, the screening current has to change direction, as shown in Fig. 9 and Fig. 10.

If we consider the behaviour of the screening current as more and more magnetic flux is applied, we would obtain the plot shown in Fig. 9. The screening current changes sign when the applied flux reaches half of a flux quantum. As the applied flux goes from half a flux quantum toward one flux quantum, the screening current decreases.
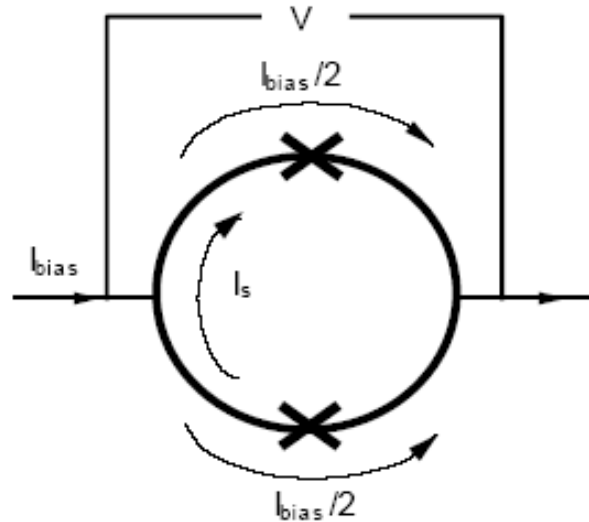

Figure 10: The screening current I_S has reversed its direction.

When the applied flux reaches exactly one flux quantum, the screening current goes to zero. At that point, the magnetic flux inside the loop and the magnetic flux applied to the loop are equal, so there is no need for a screening current. If you increase the applied magnetic flux a little more, a small screening current starts to flow in the positive direction, and the cycle begins again. The screening current is periodic in the applied flux, with a period equal to one flux quantum.

Since:
   o   The screening current of a SQUID is periodic in the applied flux, and
   o   The critical current of a SQUID depends on the screening current,
it makes sense that a SQUID's critical current is also periodic in the applied magnetic flux. The critical current goes through maxima when the applied magnetic flux is an integer multiple of the flux quantum, because that is when the screening current is zero. It goes through minima when the applied magnetic flux is an integer of the flux quantum plus one half, because that is when the screening current is largest. Because the critical current of the SQUID is periodic, the *V-I* curve of a SQUID oscillates periodically between two extremes as shown in Figure 11.

The rightmost *V-I* curve in Fig. 11 corresponds to the case when the applied magnetic flux is a multiple of one flux quantum. The *V-I* curve on the left corresponds to the case when the applied magnetic flux is a multiple of one flux quantum plus one half. As the magnetic flux increases continuously from zero, the SQUID *V-I* curve oscillates continuously between these two extremes with a period of one flux quantum.
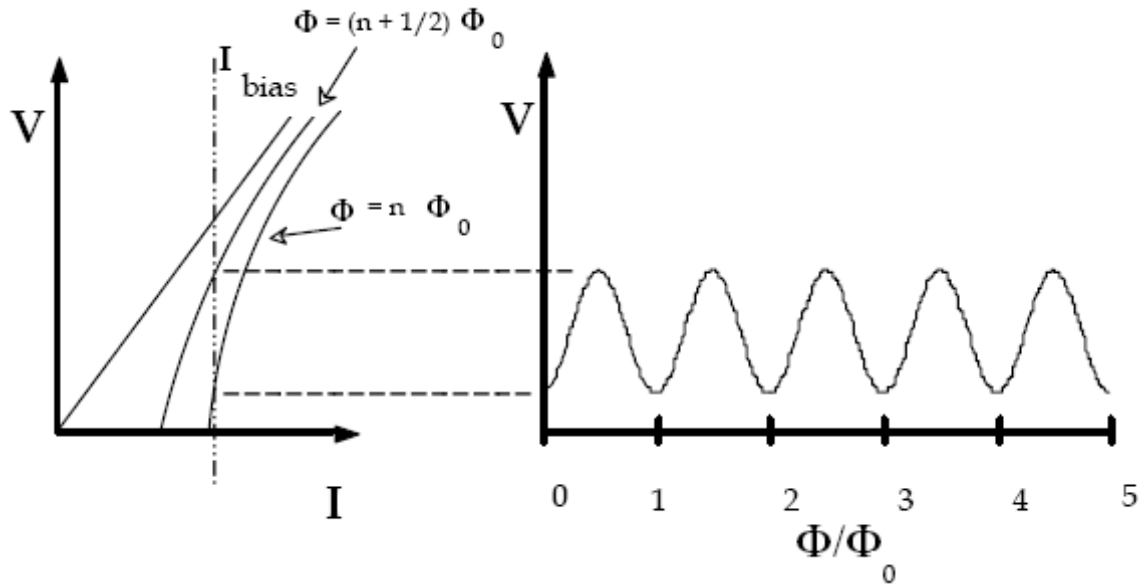
Figure 11: Periodic dependence of the SQUID voltage on applied flux.

To make a magnetometer, or magnetic field detector, the SQUID has to operate with a constant bias current slightly greater than the critical current, so that the SQUID is always resistive. Under these conditions, there is a periodic relationship between the voltage across the SQUID and the applied magnetic flux, with a period of one flux quantum. At fixed bias current, the voltage across the SQUID is a maximum when the critical current is a minimum, and vice versa. The relationship between the input flux and the output voltage across the SQUID looks like the right side of Fig. 11. This is the phenomenon scientists and engineers exploit to create the world's most sensitive magnetic field detectors.

A SQUID is a Superconducting QUantum Interference Device. The curve showing how the critical current of the SQUID varies with applied flux is an interference pattern, analogous to an optical interference pattern. If you pass a current through a DC SQUID, you see maxima and minima of critical current as you raise or lower the applied flux, because the macroscopic quantum wave functions at the two junctions interfere with each other.

3. Experimental setup

The *"Mr. SQUID"* of the company *"Conductus"* consists of the following components:

- Electronic control unit (power supply: two 9V batteries)
- Sample holder and SQUID sensor
- Dewar for liquid nitrogen
- Two-channel oscilloscope

The sample is a high-temperature superconductor (HTS):
$Yba_2Cu_3O_{7-x}$ (x ≈ 0 – 0.2, "YBCO").

Additionally, a Pt-100 resistor, an Ohmmeter and a thermometer for measuring the room temperature are available.

Fig. 12: An operating Mr. SQUID® system

4. Experiment

4.1 Preparing the SQUID

4.1.1 Introduction

The SQUID has to be cooled down to the temperature of liquid nitrogen under **zero-field** conditions.
Avoid the presence of any magnetic field (such as produced by a permanent magnet) and electromagnetic influences in the SQUID area!

4.1.2 Experiment

During the work with liquid nitrogen safety glasses and goggles have to be used! The liquid nitrogen is transferred into the dewar by the tutor!

a) *Battery check*
   Press the battery check button of the control unit. The LED should be illuminated.

b) *Calibration of the Pt-100 resistance*
   The measurement of the temperature of the YBCO-SQUID is performed by a Pt-100 resistance attached on the backside of the SQUID-Chip. This resistance has to be calibrated. For this purpose the resistance of the Pt-100 has to be determined at two accurately defined temperatures (LN_2, room temperature) assuming a linear temperature dependence of the resistance. The calibration of the Pt-100 resistance can be performed either separately, as the first step of the experiment or together with the next step of the experiment (determination of T_C), performing only one cooling down of the SQUID.

c) *Connecting the electronic components*
   Connect the sample holder to the control unit. After that, the oscilloscope has to be connected. The oscilloscope has to be operated in x-y mode. The x-output (current) should be linked to the horizontal axis, the y-output (voltage) to the vertical axis of the oscilloscope.

d) *Presettings*
   Use the OSC mode of the control unit. Set the controllers FLUX-BIAS and CURRENT-BIAS to central position (zero) and turn the knob AMPLITUDE to the left (i.e. minimal amplitude). Set the function selection switch on "V-I" mode. Move the spot on the oscilloscope to central position by using the offset controller. The CURRENT-BIAS controller regulates the SQUID current. By turning the controller, the $U(I)$ curve of the SQUID (in the normal conductive state, at this moment) can be displayed on the oscilloscope. This can be done automatically if the CURRENT-BIAS controller is turned to its medium position and the AMPLITUDE knob is turned clockwise on.

4.2 Determination of the critical temperature T$_C$ of the YBCO-SQUID

In the following we determine the characteristic: SQUID resistance vs. temperature. From this characteristic the critical temperature of the YBCO-superconductor can be determined. For this purpose the SQUID temperature has to be varied from room temperature to the temperature of liquid nitrogen (77 K). Therefore, the dewar has to be filled to the half with liquid nitrogen.

By taking advantage of the temperature gradient over the liquid nitrogen surface the sample holder containing the SQUID sensor can be cooled down gradually. Move down the sample holder slowly (in steps of 2-4 mm) and wait for temperature stabilization. At each step the SQUID resistance has to be measured from the oscilloscope. The SQUID resistance is given by the slope of the U-I-curve on the oscilloscope (x-axis: current I, y-axis: voltage U). The resistance in the temperature range slightly above T$_C$ has to be measured very accurately. The SQUID resistance is equal to half of the resistance of one Josephson weak link. (Why?)

The measured data has to be plotted R$_{SQUID}$ vs. T. From this plot the critical temperature of the YBCO has to be deduced. Below T$_C$ the two Josephson contacts show the well-known U-I-characteristic. By rotating the sample holder the curve on the oscilloscope can be changed. (Why?)

DO NOT REMOVE THE SQUID FROM THE LIQUID NITROGEN AFTER YOU REACH THE SUPERCONDUCTING STATE! The next step of the experiment starts from this point.

4.3 Measurement of the SQUID voltage – current characteristic

4.3.1 Experiment

At the end of the previous step, the SQUID has to be at the temperature of liquid nitrogen (submerged in liquid nitrogen). This ensures us that the SQUID is in the superconductive state. As a consequence the *U(I)* characteristic of SQUID in the superconducting state has to be displayed on the oscilloscope. The shape of the curve you see on the oscilloscope has to be like the one in Fig. 7. Please distinguish between the quantitative values of the parameters which characterize a Josephson contact and respectively a SQUID.

4.3.2 Calculation of the critical current

a) *Read out the oscilloscope*
   The voltage appearing at the x-terminal of the control unit (x-axis of the oscilloscope) is developed across a 10 kΩ resistor (in the control unit) through which the SQUID current flows. To determine the current through the SQUID, divide the measured voltage on the x-axis of the oscilloscope by 10 kΩ.
   The voltage which appears at the y-terminal of the control un it (y-axis of the oscilloscope) represents the voltage coming from the SQUID, which is amplified by a factor of 10000. Therefore to determine the real voltage on the SQUID divide the measured voltage on the y-axis of the oscilloscope by 10000.

b) *Determination of the critical current*
   The critical current of the SQUID *I*$_C$ corresponds to half of the horizontal part of the *U-I*-characteristic displayed on the oscilloscope. The CURRENT-BIAS control can be used to balance the trace, if necessary. To maximize *I*$_C$ a small magnetic field can be applied and

controlled by using the FLUX-BIAS controller. How big is the critical current of a Josephson junction?

(If the critical current you see on the oscilloscope is very small, the likely cause is flux trapping. Try thermally cycling the probe with the control box off to restore the maximum critical current. Under some circumstances, several attempts may be necessary.)

c) *Determination of the characteristic voltage*
The critical voltage V_C of SQUID, which is the product of the SQUID critical current I_C and the SQUID resistance in the normal conductive regime R_n is another important SQUID parameter which has to be determined. R_n is given by the slope of the $U(I)$-curve in the normal conductive regime, $I > I_C$. How big is the resistance of a Josephson junction in the normal conductive regime?

Observation:
The *U(I)* characteristic have to be copied from the oscilloscope to transparencies available in the laboratory. Instead of this, you may also take a picture of the *U(I)* characteristic by using a photo digital camera. Ask the tutor!

4.4 Measurement of the SQUID voltage – magnetic flux characteristic

4.4.1 Output of the U-ϕ-characteristic

a) *Setting the current*
Leave the function selection switch in V-I mode. After the critical current has been maximized, the controller AMPLITUDE has to be turned down, anticlockwise. Just one spot appears on the oscilloscope. Use the CURRENT-BIAS controller to move this spot in the range where $I = I_C$. At this point the SQUID voltage is very sensitive to changes of the external magnetic field.

b) *Display the U(ϕ)-curve*
Set the function selection on V-ϕ. To display as many $U(\phi)$ periods as possible turn the AMPLITUDE knob clockwise on.

c) *Optimize oscilloscope settings*
While running the control unit in the V-ϕ mode it may be recommendable to switch the oscilloscope to AC mode.

d) *Optimize settings of the control unit*
The voltage amplitude can be maximized by using the CURRENT-BIAS controller.
By adjusting the FLUX-BIAS controller the center of the oscillations of the magnetic flux can be shifted.

4.4.2 Calculation of the SQUID parameter b_L

a) *What is b_L?*
This parameter, called also the modulation parameter, determines the maximum extent to which circulating current in the SQUID can shield the applied flux. B_L is given by:

$$b_L = 2 I_C \frac{L}{\phi_0} \tag{4}$$

,where L is the SQUID inductivity.

b) *Determination of b_L via amplitude modulation*
The modulation parameter can also be determined using the equation below, in which we need to determine the modulation amplitude ΔV.

$$b_L = \left(\frac{I_C R_n}{\Delta V} \right) - 1 \tag{5}$$

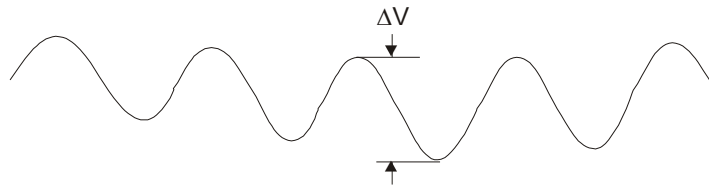ΔV can be determined as the peak to peak amplitude of the $U(\phi)$ characteristic, as shown below:

Fig. 13: Schematic illustration of the modulation amplitude.

4.4.3 Determination of the magnetic flux quantum

The SQUID inductivity is approximated by: $L = 300$ pH

Using the b_L parameter calculated from Eq. (5), the magnetic flux quantum ϕ_0 can be calculated from Eq. (4). The calculated value of ϕ_0 has to be compared with the theoretical value of $\phi_0 = 2.07 \times 10^{-15}$ Wb.

Observation:
The $U(\phi)$-characteristic have to be copied from the oscilloscope to transparencies available in the laboratory. Instead of this, you may also take a picture of the $U(\phi)$-characteristic by using a photo digital camera. Ask the tutor!

4.5 Qualitative experiments

4.5.1 Introduction

The following qualitative experiments demonstrate how sensitive a SQUID reacts on external magnetic fluxes. For this purpose, the $U(I)$ SQUID characteristic has to be displayed on the oscilloscope. DO NOT BRING ANY PERMANENT MAGNET IN THE SQUID VICINITY!

a) *SQUID with shielding*
Move various metallic objects back and forth in the SQUID vicinity (in the dewar vicinity). Do you see any influence on the $U(I)$ characteristic of the SQUID? If yes, explain what are the influences you observe on the $U(I)$ characteristic, which metallic objects influences the $U(I)$ characteristic and why. Try to move/rotate easily the SQUID holder. Do you see any influence on the $U(I)$ characteristic of the SQUID? Comment the observations!

b) SQUID without shielding

The sample is protected against external magnetic fields by a cylindrical shielding. Take the sample holder out of the liquid nitrogen und remove this cylinder by loosening the screw very carefully.

ATTENTION: The sample holder is very cold. Switch off all electronic equipment before you remove the shielding. During the work with liquid nitrogen safety glasses and goggles have to be used!

Put back slowly the sample holder into the liquid nitrogen. Try to display the *U(I)* curve again (it may need to slowly rotate the sample holder) and to measure the critical current. By moving the sample holder the *U(I)* curve changes. How can you explain this?
Put again some metallic items close to the dewar. Do you see any influence on the *U(I)* characteristic of the SQUID? Explain why not every metallic item influences the *U(I)* characteristic of the SQUID. How can you explain these effects?

5. Schedule and analysis

1. Calibration of the Pt-100 resistance for the temperature measurement

2. Determination of the critical temperature of the YBCO-SQUID

3. Determination of the SQUID critical current I_C

4. Determination of the SQUID resistance in the normal conductive state R_n

5. Determination of I_C and R_n of a Josephson junction

6. Calculation of the SQUID characteristic voltage V_C

7. Determination of the modulation amplitude ΔV

8. Determination of b_L

9. Determination of ϕ_0 deduced from the inductivity

10. Qualitative experiments

11. Description and explanation of the observed effects

12. Answer the following questions!

Questions

1. Describe the *U(I)* curve of a Ohmic resistance, of a diode and of a Josephson contact? Drawing!

2. How can the critical current I_C and the normal conductive resistance R_n of a Josephson contact be deduced from the *U(I)* curve of the SQUID? Drawing!

3. If the critical current I_C of one Josephson contact equals 5 µA and an applied field induces a screening current of 1 µA what is the magnitude of the critical current of the SQUID in the superconducting state?

4. Why does the SQUID react very sensitive on metallic items? Does the SQUID react on every kind of metal?