The SQUID

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Abstract

In this experiment, various properties of the SQUID were investigated. The SQUID resistance at room temperature was found to be $290 \pm 20\Omega$ which is within the expected value. The first part of the experiment was carried out using the V-I curve. The resistance of each Josephson junction, R_N, was found to be $4.5 \pm 0.5\Omega$ and the critical current, I_C to be $6.2 \pm 0.4\mu A$. R_N is within the accepted range, whereas the value of I_C measured was smaller than expected. The second part of the experiment used the V-Φ curve. Using two methods, the maximum peak voltage ΔV_{max} was found to be $29\pm10\mu V$ and $28\pm2\mu V$ respectively. The inductance, L, was found to be 75±8pH. Finally, the β_L parameter was calculated using different expressions. These were found to be 0.44±0.11 and 0.28±0.08 All expected values were given in the user manual.

Introduction and Theory

A SQUID is a Superconducting QUantum Interference Device, a very sensitive magnetometer that can be used to measure extremely weak magnetic fields. There are two different types of SQUID, the direct current (DC) and the radio frequency (RF). For this experiment the DC SQUID was used.

The SQUID works based off of two concepts, superconducting loops and Josephson junctions.

The basic premise is as follows:

- Two identical Josephson junctions are placed in parallel in a superconducting loop. Without any outside magnetic influence interacting with this device, the input current, I, is split evenly between the junctions.
- If an external magnetic flux is applied it will induce a screening current in the superconducting loop. This screening current, I_S, will oppose the current through one of the junctions and add to the current in the other junction.
- In addition, when the applied flux is increased past $\frac{\Phi_0}{2}$, the direction of I_S flips. This is due to the loop attempting to add to the flux to bring it to an integer multiple of Φ_0.

- As the induced current depends on the applied flux, the critical current of the SQUID, I_C, oscillates as a function of Φ.

By measure the coltage, current and flux through the probe it is possible to calculate several important parameters of the SQUID. This is helped by the ability to adjust the applied bias current, and to apply a bias flux as well.

For this experiment, the V-I and V-Φ curves were measured and used to find the values for various properties of the SQUID.

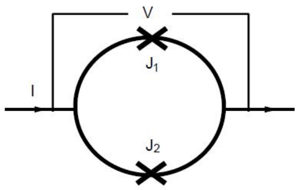

Figure 1: Josephson Junctions

Experimental Setup

The apparatus for this experiment was the Mr. SQUID magnetometer system. This consisted of:

- A probe wtih a high-temperature superconductor (HTS) thin film SQUID sensor chip
- A cryogenic probe with a removable magnetic shield
- A battery-operated electronic control box
- An oscilloscope to display the output signals from the control box

The probe is designed to be immersed in a liquid nitrogen bath in the enclosed dewar flask. Initial measurements were taken at room temperature after which the probe is cooled to 77K using the liquid nitrogen.

Results and Conclusions

The $V - I$ curve

Room Temperature

The $V - I$ characteristic curve was measured at room temperature and can been seen in Graph 1. Using the graph, the resistance of the SQUID at room temperature was determined using the fact that the slope of the graph is equal to $\frac{R}{2}$.

	Value	Adjusted	Uncertainty
V	15.2V	1.52mV	$\pm$0.04mV
I	104mV	10.4μA	$\pm$0.4μA
R	146Ω	292Ω	$\pm$20Ω

The resistance was found to be $290 \pm 20\Omega$ at room temperature. This is in line with an expected value of $\sim 300\Omega$

Cooled to 77K

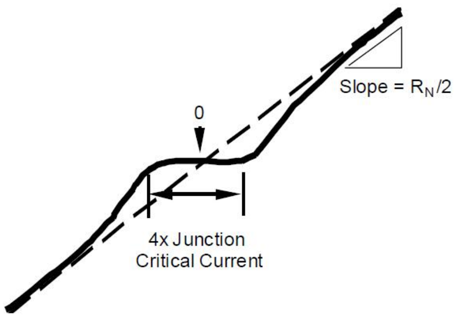

Figure 2: Calculating I_C and R_N

The SQUID was cooled to 77K using liquid nitrogen and the $V-I$ curve was measured again. Initially the flux bias was adjusted until a maximum value of I was observed. This occurs at values of $\Phi = n\Phi_0$ for some integer n. From this, Graph 2, the junction resistance, R_N, was found using the slope. In addition the critical current, I_C, was also found from the width of the flat region of the curve.
$R_N = 4.5 \pm 0.5\Omega$
$I_C = 6.2 \pm 0.4\mu$A

The expected value of R_N is 4-6Ω so this is correct. I_C is somewhat smaller than the expected $\sim 15\mu A$. This is almost certainly due to magnetic flux trapping. This occurs when external magnetic flux gets trapped in the SQUID loop or in the junctions as it is being cooled to 77K. The magnetic shielding on the probe is not perfect and the mobile phones and computers in the area are possibly the causes for the trapped flux.

Minimum critical bias

The flux bias was then adjusted so as to give a minimum critical bias current and is shown in Graph 3. This was found to be I=1.5$\pm$0.2μA using the same method as above. The maximum change in voltage was found by comparing the two graphs. This was quite difficult to do due to the small size, and therefore there is a large error associated with it:
ΔV_{max}=20$\pm$10μV

The $V - \Phi$ curve

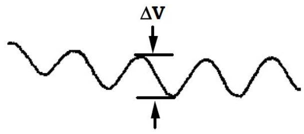

Figure 3: Calculating ΔV

The SQUID was then switched to $V - \Phi$ mode and the characteristic curve was obtained. This is shown in Graph 4.4 The Bias current was adjusted to give a maximal modulation depth. This is at the 'knee' of the $V - I$ curve, where the variation in voltage with repsect to flux is highest. The amplitude of the oscillations give ΔV_{max}. This was found to be ΔV_{max}=28$\pm$2μV, which is in agreement with the value found in the previous experiment.

The change, ΔI, required for the flux to change by one quantum is simply the period of the wave. In this case it was found as: ΔI=45$\pm$5μA

Additional Analysis

The mutual inductance, M, of the SQUID is given by:

$$M = \Phi_0/\Delta I$$

And the SQUID inductance, L, is simply 1.6M in this case. Another parameter, β_L can be determined in two ways. Either from L or from R_N:

$$\beta_{L_1} = 2I_C L/\Phi_0 \tag{1}$$

$$\beta_{L_2} = \frac{4I_C R_N}{\pi \Delta V} - 1 \tag{2}$$

Results found were:

	Value	Error
ΔI	45μA	$\pm$5μA
M	46pH	$\pm$5pH
L	75pH	$\pm$8pH
I_C	6.2 μA	$\pm$0.4μA
R_N	4.5Ω	$\pm$0.5Ω
ΔV_{max}	28μV	$\pm$1μV
β_{L_1}	0.44	$\pm$0.11
β_{L_2}	0.28	$\pm$0.08

While the β_L values are different by a factor of 0.6, however this is not unusual. From a sample of SQUID devices, the β_L values from equation 1 is generally $\sim$2 times larger than the value calcuted using equation 2. This is shown in Fig. 4

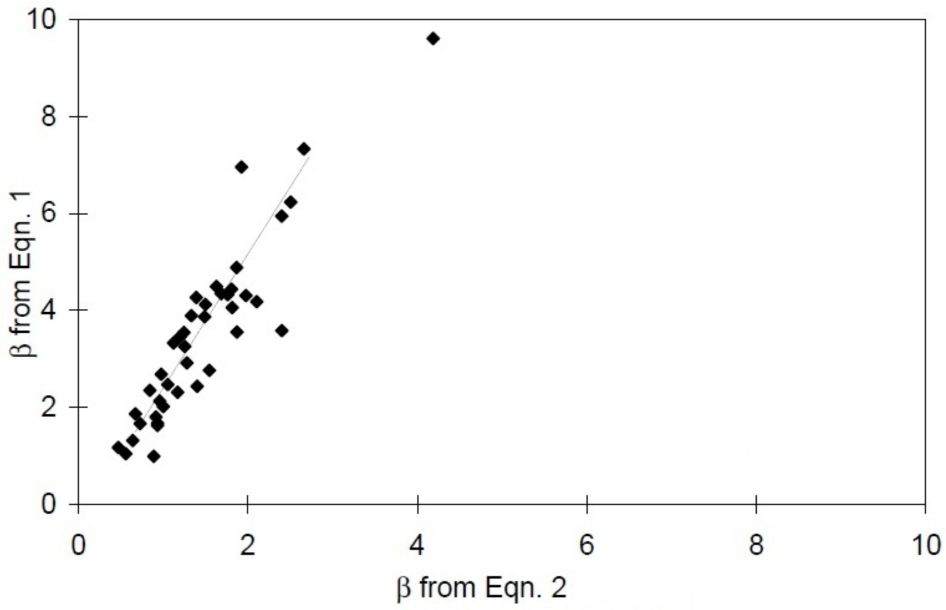

Figure 4: Differing β_L Values

Earth's Magnetic Field

Finally, the effect of the Earth's magnetic field on the SQUID device was measured by rotating it through 180°. A change of $0.4\Phi_0$ was observed. Given that the area of the probe is $90\mu m \times 90\mu m$ with a $50\mu m \times 50\mu m$ hole in the middle, and the permeability of the shielding at 77K is 4500, this corresponds to a field of $\sim 650\mu T$. The accepted value for the Earth's magnetic field is approximately $50\mu T$, so a 180° turn would correspond to an effective change of $100\mu T$ and this is within an order of magnitude to the correct result.

References

Star Cryoelectrics, Mr. SQUID User's Guide
Hook + Hall, Solid State Physics