Studying Shunted SQUID Measurements in a Controlled Magnetic Field Setting

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Abstract

In recent years, the study of nanodevices such as superconducting quantum interference devices (SQUIDs) has increased in popularity due to their usage in magnetometry, for example of the magnetism of nanoparticles. Particularly, SQUIDs have the capability of measuring small changes in magnetic field and changes in magnetization at the level of a few Bohr magnetons. Electrical measurements of a SQUID, which is shunted with an on-chip Au resistor, are shown in the normal and superconducting states, at temperatures down to 4 K. Stable critical currents and hysteretic voltage-current characteristics are observed. The SQUID holder is fitted within a custom-made solenoid to control the magnetic flux passing through the SQUID. Data and corresponding theory showing the dependence on the device's critical current is presented as well as a discussion of these results.

Motivation

An example of a superconducting nano-device is a SQUID[1][2] (Fig. 1), or Super-conducting QUantum Interference Device.

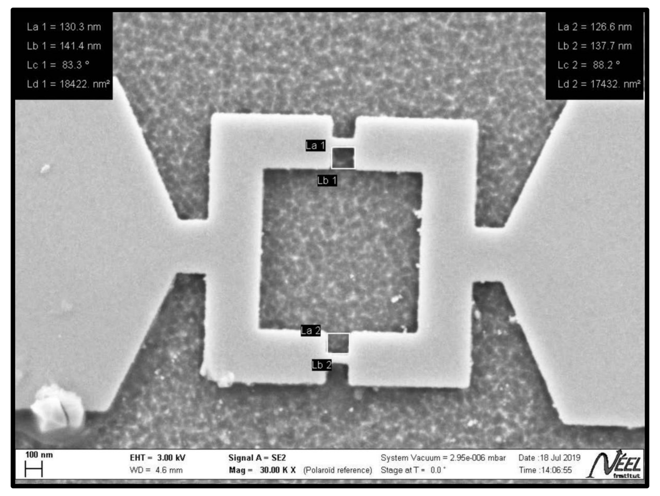


Figure 1: SQUID loop fabricated at Néel Institute imaged under SEM. Area of loop calculated to be **0.983** μm^2

The device uses Josephson Junctions[5] to create detectable interference patterns in electric current.

Applying magnetic flux through a SQUID loop (Fig. 1) induces a current, so we can see the effect of B-field on electronic samples.

Preparation

Our SQUID has the following specs:

- Si substrate
- 20nm Nb deposition
- < 1200Ω normal mode resistance
- T_c ~7K
- Loop area ~ $1\mu m^2$
- Gold shunting
  - This stops electrostatic discharge from killing the device
- Critical current near 0.5mA

Dipstick now harnesses a solenoid to supply B-field to sample.

1. Sample is loaded into the stage
2. Cap is connected and sealed
3. Vacuum is pumped within, filled with He exchange gas
4. Sample connected electronically and grounded
5. Dipstick immersed in a liquid He dewar

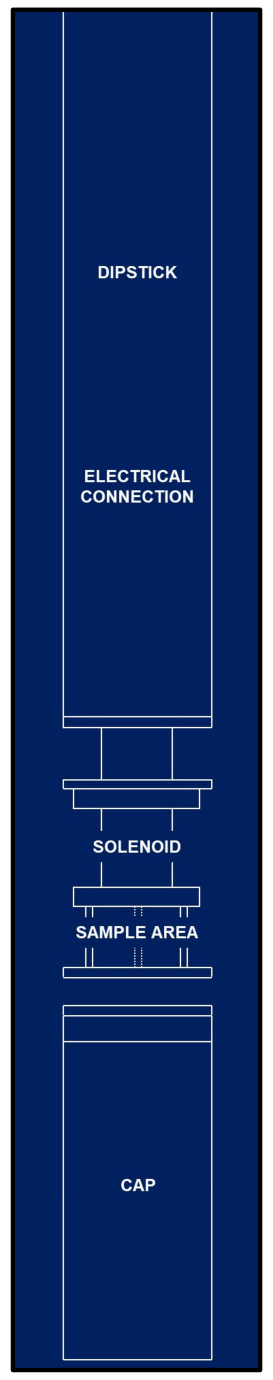


Figure 2: Schematic of the configured dipstick

Superconductivity

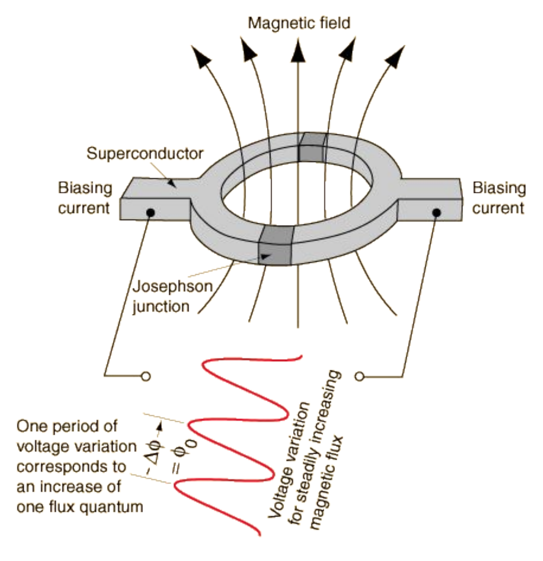


Figure 3: Schematic of the SQUID at work. Josephson assumed $V(t) = \frac{\phi_0}{2\pi}\frac{d\varphi}{dt}$. Taken from [6]

- I_c – critical current, above which $V \neq 0$
- ϕ – magnetic flux through SQUID loop
- $\phi_0 = h/2e$ – magnetic flux quantum
- $I_{max} = I_{c1} + I_{c2}$ – max. of interfering I_c's

$$I_c = I_{max}\left|\cos\frac{\pi\phi}{\phi_0}\right|$$

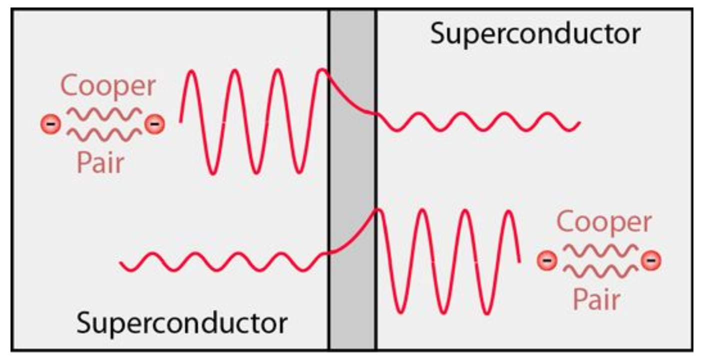


Figure 4: As dictated by BCS theory[5], Cooper pairs of electrons tunnel through the junction barrier. Although the typical boundary conditions are met, the phase of the electron's wavefunction may change. Property of [6].

Results

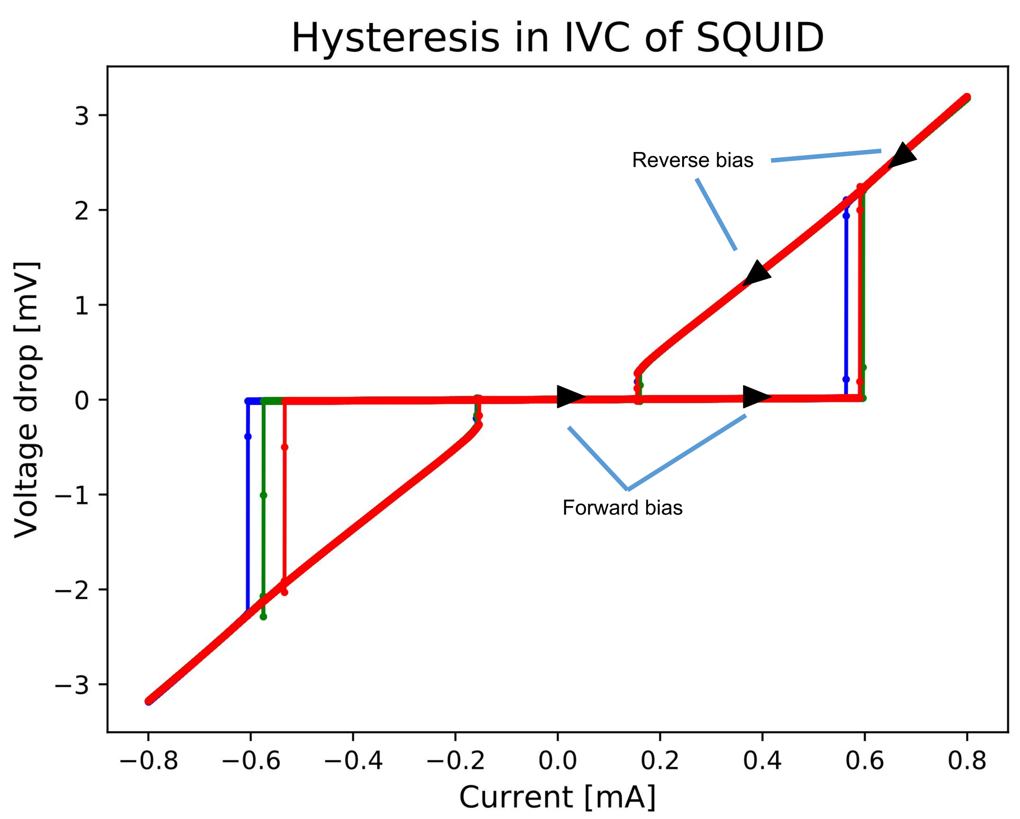


Figure 5: Example IVC plot of the device, displaying a hysteretic loop (highlighted in red) upon reversing the current bias. We find a critical current of $\boldsymbol{I_c = 0.58mA}$ ($0.16mA$ in reverse bias)

Screening parameter (β_L) tells how relevant is the self-inductance of SQUID (L)[4]. $\beta_L \ll 1 \Rightarrow$ can easily ignore self-inductance in SQUID model.

$$\beta_L \stackrel{\text{def}}{=} \frac{2LI_c}{\phi_0} \qquad \& \qquad \frac{I_{max}}{2I_c} \approx 1 - \frac{2\phi}{\phi_0}\frac{1}{\beta_L}$$

So, $\boldsymbol{\beta_L = 3.1 \Rightarrow L = 5.8 \cdot 10^{-12}\ H}$
Expected self-inductance*: $5 \cdot 10^{-13} H \leq L \leq 5 \cdot 10^{-11}\ H$

*Depending on the thickness of the wire taken: 20nm from Nb deposition or 315μm width of concentric squares (Fig. 1)

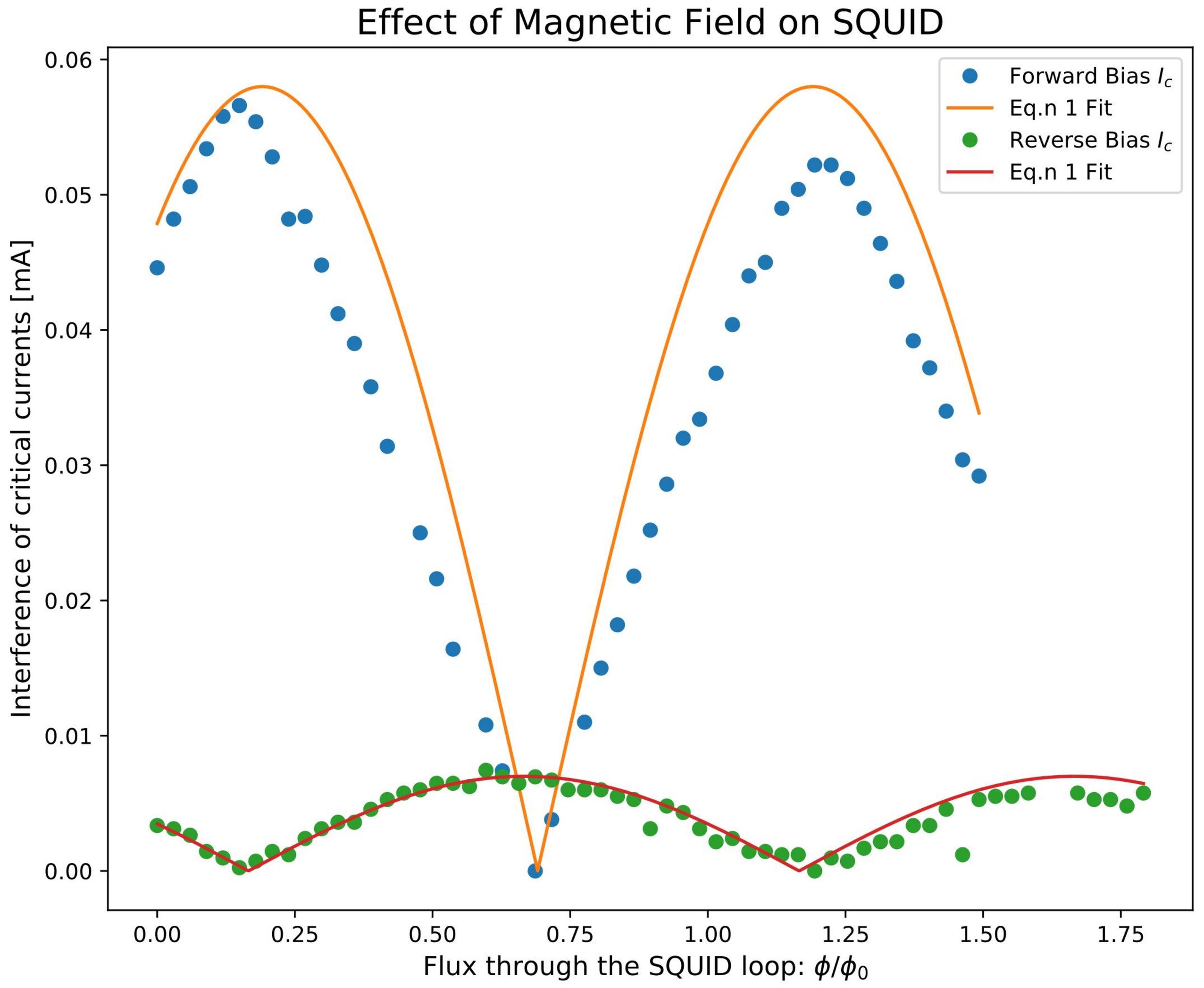


Figure 6: Magnetic field was changed to observe the effect on critical current. Normalized by $I_{c1} - I_{c2} = 0$

Observations

Sinusoidal pattern of I_c vs. ϕ (Eq. 1)

- Not very accurate: we have relatively large $\beta_L = 3.1 \Rightarrow$ need better modelling[1]
- Heating can also occur at high field[2]

Normal & re-trapping I_c are completely out of phase

Initial phase lag likely caused by external magnetic fields, mutual inductance with coil

$\phi_0 = 1$ to calibrate.

- Tells us 1V of input to solenoid generates 40mT of B-field at the sample

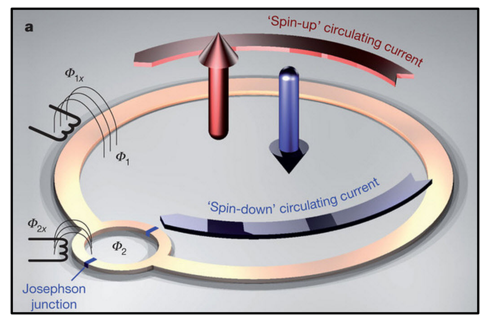
Conclusions

Cooldown from room temp. to 4K can take ~30 mins instead of hours or days in dilution fridge.

- Magnetic field is calibrated and may be used to accurately measure the effect of magnetic fluxes.
- Inversely, we can detect small magnetic fluxes generated by currents driven through our nanodevices.

- Fabrication expected values (*Preparation*) are in good comparison.
- Results from current-flux measurements match the basic theory[3][4][5] quite well, given such high β_L.

The fabricated SQUID can now be sent off to do work in "real-world" applications:



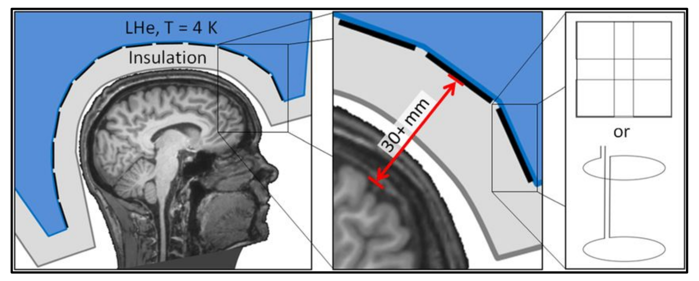


Figure 7 (left): SQUID being used in D-Wave quantum computer[7].
Figure 8 (above): SQUID array being used in MRI machine[8]

Future Work

- Use the apparatus in full on new sample devices
  - The dipstick has since been used to measure resistance values of superconducting carbon fibers (R. Ganguly)
- Consider angled flux and penetration depth for more accurate loop area
- Include self-inductance of the loop[2] and mutual inductance with solenoid
- Perform multiple calibrations with different samples

References

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