Superconducting Aluminium Contours with Applications to Magnetometry

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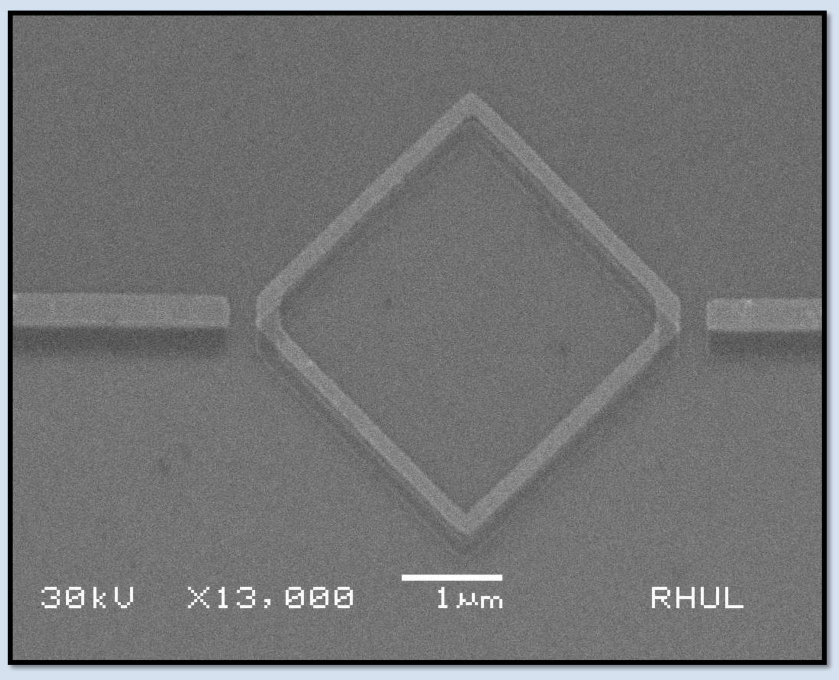
Abstract

Nanoscale asymmetric rings and a Differential Double Contour Interferometer (DDCI) were fabricated to explore sensors of weak magnetic fields and signals.

Measurements of output voltage as a function of magnetic field are carried out below T_c for arrays of asymmetric rings with increasing bias current.

Quantum oscillations were observed and from the gradient of output voltage vs magnetic flux it was found that the sensitivity (| ∂V/∂Φ |) was 420mV/Φ_o and 40mV/ Φ_o for the 200 rings at 1.25K and 1000 rings at 1.15K respectively.

Results



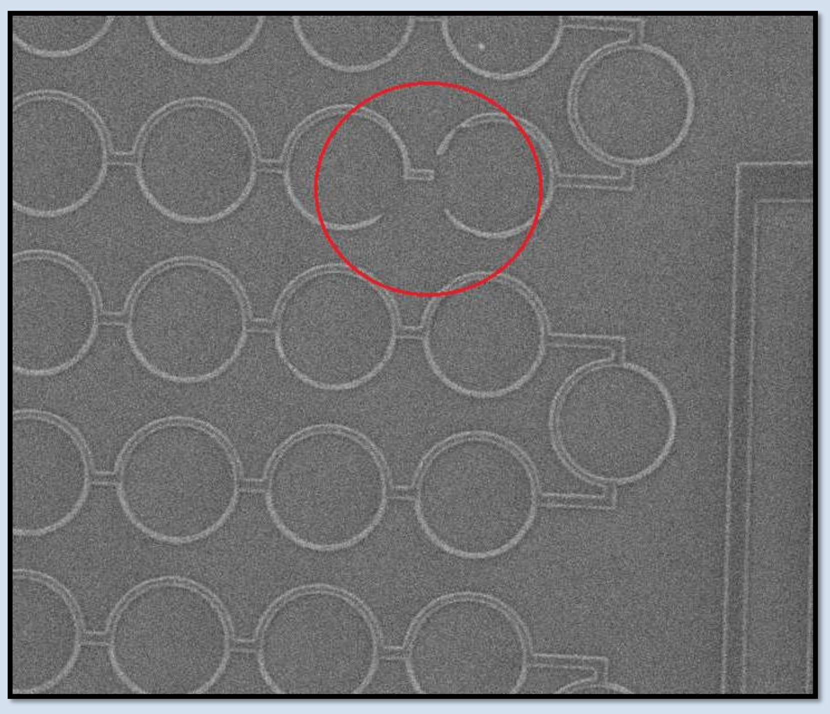
Fabrication Outcome

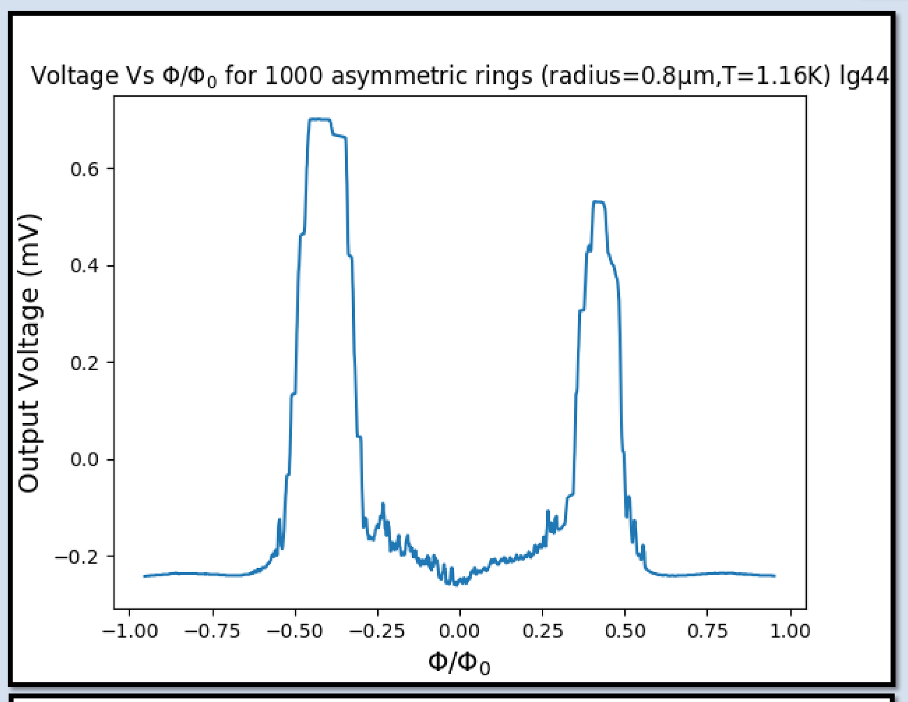
SEM image (left) of the unsuccessful DDCI sample of palladium / aluminium contours. The second (Al) contour is of a lower contrast.

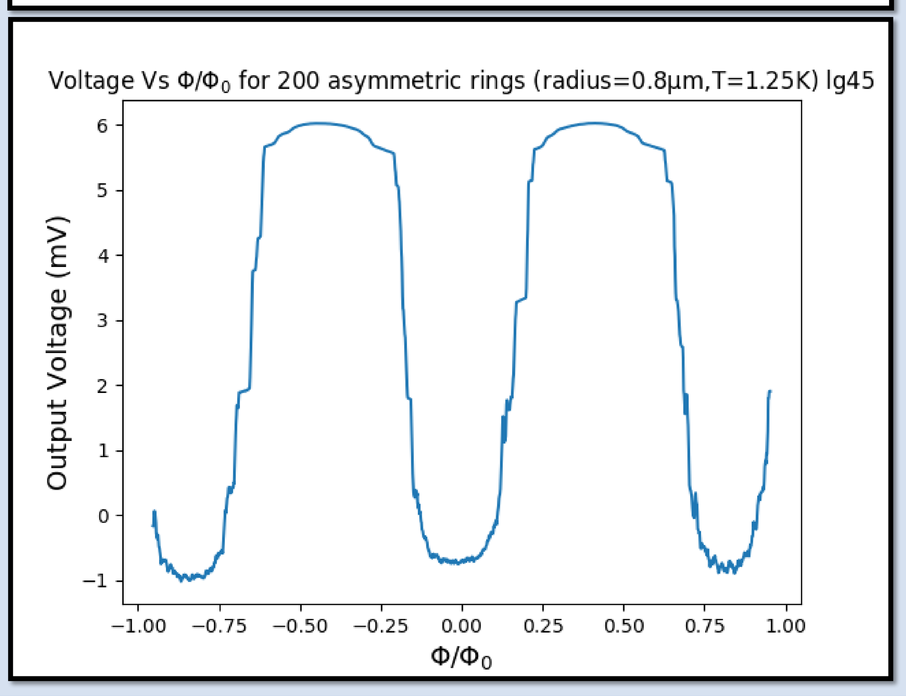
The sample was loaded at a 90◦ offset and it also appears that the deposition angle of 20◦ was not sufficient; the fabrication was unsuccessful due to human error.

SEM image (right) of the asymmetric rings used in measurements of 0.8μm radius. A large number of samples were produced successfully but fabrication at this scale generally has a certain failure rate.

The red circle indicates broken parts of the sample due to metal that hasn't adhered to the substrate either due to contamination or mishandling of the sample.







Measurements

Output voltage was measured as a function of solenoid current which has been converted to magnetic flux for different bias currents.

The figures on the left show the quantum oscillations that are maximised when the bias current is near the critical current for two arrays of connected asymmetric rings (200,1000 rings). The direct effects of the number of rings and temperature isn't clear and requires more data.

It is observed that the system closer to the transition temperature had the largest sensitivity (gradient) of 420mV/Φ_o. A more pronounced asymmetry is observed for the lower temperature sample which may be linked to an observed hysteresis in the IV characteristics (not pictured).

Conclusions

The failure of the DDCI has highlighted improvements to the fabrication process as well as the importance to avoid human error. The deposition angle of 20◦ was inadequate and was calculated to be closer to 27◦ . This could be calculated with greater accuracy and precision if the thicknesses of resist layers are measured before evaporation.

Quantum oscillations, centred near ±0.5 Φ_o , emerge as the bias current approaches the critical current which is expected for a superconducting state. The sensitivity (|∂V/∂Φ|) is maximised before the transition to the normal state which was found to be 420mV/Φ_o and 40mV/Φ_o . The difference could either be due to the number of rings or the proximity of the sample to T_c . An asymmetry between peaks may be linked to a hysteresis effect of the I-V characteristics at lower temperature. A larger range of temperature measurements could help confirm this and perhaps derive a relation between them.

There is insufficient data to draw many meaningful conclusions although it does provide a direction for study in maximising the sensitivity and understanding the hysteresis of the I-V characteristics and the asymmetry of the magnetic dependence. The number of rings, the temperature and the radius should be varied independently.

Introduction

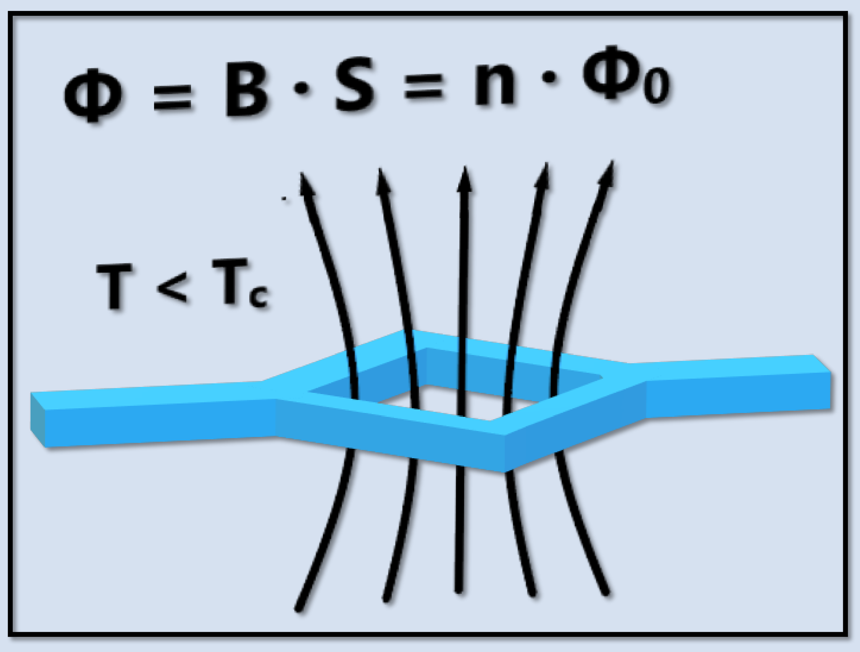
Aims

- Develop knowledge and practical skills of nanofabrication techniques and processes in a cleanroom environment
- Fabricate a DDCI and a selection of nanoscale asymmetric rings
- Observe how these systems can act as sensitive magnetometers

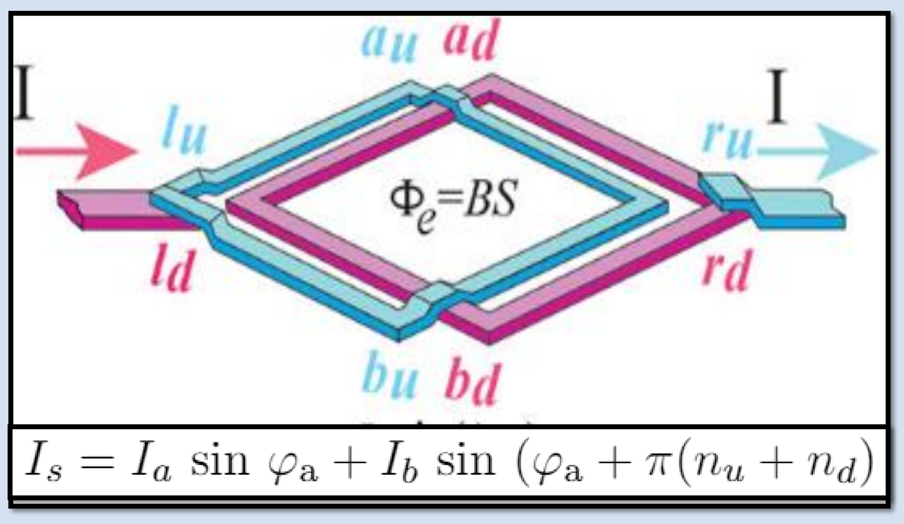
Flux quantisation

In a superconducting state the aluminium actively expels an external magnetic field (the Meissner effect). This is due to a screening current being induced in the ring which is persistent due to zero resistance. This current changes to satisfy the condition that flux inside the loop is constant.

By considering Ginzburg-Landau theorem the flux through the ring is actually quantised as an integer number of flux quanta. If the superconducting state is interrupted by a normal state additional flux quanta can tunnel into the ring.



Flux quantisation (*Φ*) in the asymmetric contours in magnetic field *B* of area *S* below T_c.



DDCI of area *S*, bias current *I*, external flux Φ_e and Josephson junctions a and b. The junctions modulate the supercurrent so it takes the form shown above. Flux can tunnel into the loops so that *n* changes by one when part of the loop turns to normal state. The parity of the quantum numbers leads to full modulation of the current [1].

Magnetometry

Both the DDCI (pictured left) and the asymmetric rings (above) allow tunnelling of additional flux as a section of the contours briefly turns to a normal state due to thermal fluctuations about T_c [1]. This causes a change in voltage as the screening current changes to account for this flux. This can be used to detect changes in flux where the sensitivity is |∂V/∂Φ |.

The DDCI in particular was designed to modulate the current using Josephson junctions to create a more sensitive sensor than a SQUID. The equation for the superconducting current is shown to the left and shows the DDCI is a detector of quantum states related to this tunnelling.

Method

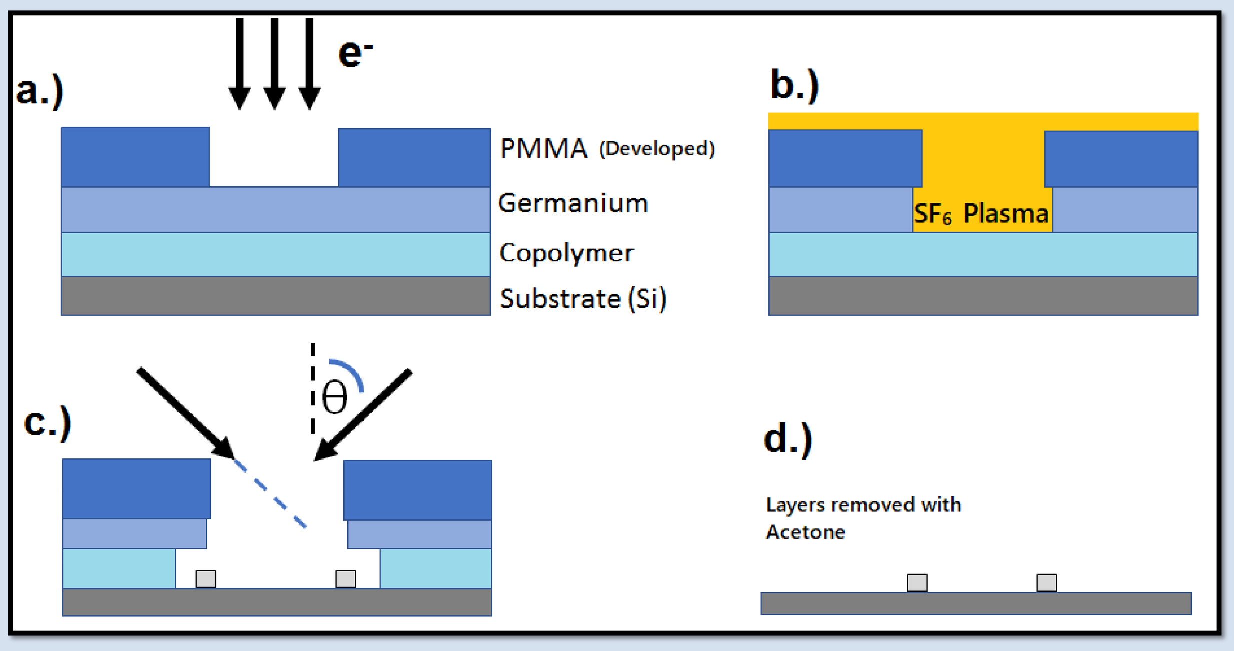


Diagram of the fabrication process of the DDCI. a.) Exposure and development of top layer after spin-coating
b.) Reactive ion etching with SF_6 / O_2 plasma mix
c.) Shadow evaporation of metals d.) Lift-off of remaining resist with acetone.

Fabrication Overview

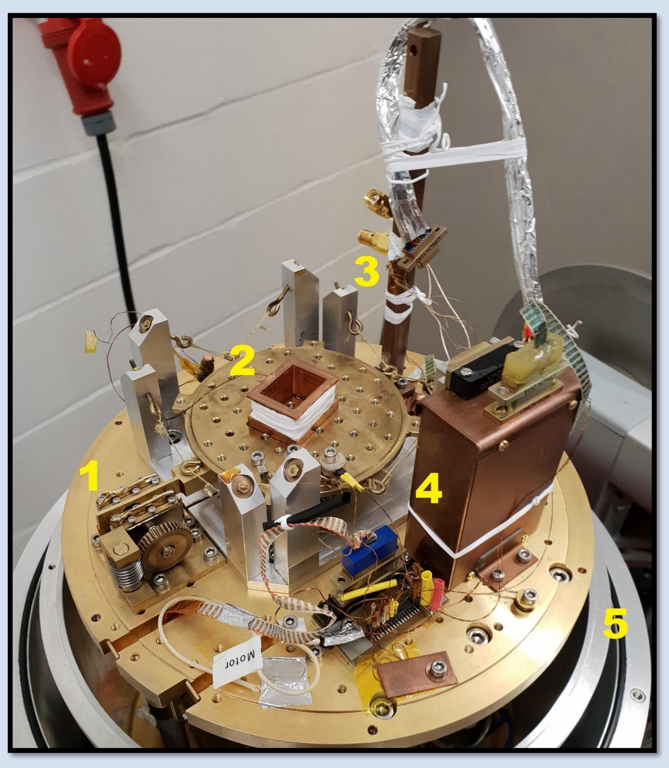
Fabrication of nanoscale samples involves the spin-coating of one or more layers of electron sensitive 'resists'. These are exposed to a beam of electrons in a process called electron beam lithography which traces out the desired pattern which weakens the polymers in a resist. The weakened areas can then be dissolved with a developer so metal can be deposited into the pattern to form the device. The remaining resist is removed during lift-off using strong solvents such as acetone, leaving the deposited metal behind.

Shadow Evaporation

A vital process in forming the DDCI is shadow evaporation where the sample is tilted by an angle ±θ during metal deposition to form two overlapping contours. An undercut must be developed in a two (or more) layer resist system by using a more sensitive bottom resist.

Experimental Setup

Samples are placed in a sub-1K cryostat (shown to the right) suspended within a superconducting solenoid for varying external magnetic flux at low temperatures. Amplifiers, resistors, voltmeters and ammeters are used to enable measurements.



Internals of the cryostat. 1.) Probe that 'pinches' to take measurements from the isolated stage 2.) Isolated stage which is cooled below 1K to which the sample is attached 3.) Rigging to suspend the sample and solenoid 4.) Internal circuitry that enables measurements 5.) Thermally isolated layers which are each at a lower temperature progressively inwards

[1] Vladimir L. Gurtovoi et al. Development of a superconducting differential double contour interferometer. *Nano letters*, 17(11):6516–6519, Nov 8, 2017. ISBN 1530-6984. URL: https://www.ncbi.nlm.nih.gov/pubmed/28991481.