Spatial Resolution Assessment of Nano-SQUIDs Made by Focused Ion Beam

L. Hao, J. C. Macfarlane, J. C. Gallop, E. Romans, D. Cox, D. Hutson, and J. Chen

Abstract

The ability to reduce SQUID dimensions into the submicrometer or nanometer regime points the way towards novel applications, particularly in emerging fields such as quantum information processing, single-photon/particle detection, and experimental studies of nano-scale entities such as Bose–Einstein condensates. We report here on our ongoing work combining traditional thin-film and photolithographic fabrication processes with computer-aided-design software and focused ion beam milling to realize sub-micrometer superconducting structures. Their magnetic field sensitivity, noise behavior, spatial resolution, and prospects for magnetic spin detection are discussed.

L. Hao and J. C. Gallop are with the National Physical Laboratory, Teddington, TW11 0LW, UK (e-mail: ling.hao@npl.co.uk).

J. C. Macfarlane is with the National Physical Laboratory, Teddington, TW11 0LW, UK, and also with the Physics Department, University of Strathclyde, Glasgow G4 0NG, UK (e-mail: j.c.macfarlane@strath.ac.uk).

E. Romans is with the Physics Department, University of Strathclyde, Glasgow G4 0NG, UK and is now with London Center for Nanotechnology, University College London, WC1H 0AH UK (e-mail: e.romans@ee.ucl.ac.uk).

D. Cox is with ATI, Surrey University, Surrey, GU2 7XH, UK (e-mail: d.cox@surrey.ac.uk).

D. Hutson is with the Physics Department, University of Strathclyde, Glasgow G4 0NG, UK.

J. Chen is with School of Engineering and Design, Brunel University, Uxbridge, UB8 3PH, UK (e-mail: jie.chen@brunel.ac.uk).

I. INTRODUCTION

As the dimensions of superconducting thin-film devices approach the sub-micrometer scale, new rules for their design, fabrication and characterization come into play. For example, the London and Pearl penetration lengths become comparable with or greater than the device size. We demonstrate that deep sub-micron superconducting bridges of dimensions 80 nm, when inserted into a single-layer superconducting ring, can effectively replace traditional tri-layer junctions which, because of lithographic limitations and current density considerations, occupy an unacceptably large area when incorporated into nanometer-scale SQUIDs with loop dimensions down to 200 nm. For operation in the temperature range

100 mK–9 K, the bridges, typically of Nb or Al, are made by a combination of conventional photo-lithography followed by milling of the bridge and/or ion implantation, by focused Ga-ion beam. A proportion of the SQUID's effective area may consist of a reduced thickness film with suppressed λ_L , and this allows the effective area (i.e. inductance) of the SQUID to be controllably varied by up to a factor of 2 [1]. We report also [1] on the current-voltage characteristics of these junctions, together with the voltage-field transfer function and inductance/effective-area measurements of SQUIDs incorporating them, over a range of temperatures. The junction characteristics resemble the Dayem-bridge weaklink model and phase slip weak-link models, and when suitably shunted by an in-situ metallic layer, are free from hysteresis over a useful range of operating temperatures. The flux-noise of SQUID devices made in this way is experimentally measured and compared both with data from conventional devices and with predictions of available noise models. On the basis of these measurements, together with our calculations (Section II), an estimate is made of the spatial resolution of such a nano-SQUID when used to map the magnetic field arising from, for example, currents in closely-spaced nanowires, as a step towards an assessment of its sensitivity limit for magnetic moment detection. We infer that the spatial resolution estimated in this way for our nanoSQUIDs exceeds that of recent predictions based on results of Bose–Einstein Condensate magnetometers [2].

II. THEORETICAL BACKGROUND

It has long been understood that generally the limiting energy sensitivity of a SQUID is set by thermal noise in the junction shunt resistors. At sufficiently low temperatures the Uncertainty Principle provides an even stronger limit. Consider a 2D thin film (thickness d) in which is patterned a SQUID loop with radius r of area A and inductance L which may be scanned across a region to investigate the local magnetic properties.

Since a SQUID is in essence a magnetic flux sensor there is a clear trade-off between spatial resolution and magnetic field or moment sensitivity. The effective radius of the SQUID loop is enlarged by a factor $\sqrt{1 + \lambda_L^2/r^2}$ where λ_L is the Pearl penetration depth, applicable in the regime where $\lambda_L \gg \lambda_L$, and λ_L is the London penetration depth. The spatial resolution is set by the larger of the effective SQUID radius and the closest distance of approach. Thus in order to achieve high spatial resolution the Pearl length must be minimized by ensuring that $\lambda_L \ll r$. Fig. 1 indicates how λ_L changes with T at temperatures corresponding to 0.1 T_c and 0.95 T_c . In the classical thermal noise limit the minimum magnetic flux sensitivity may be expressed in terms of the SQUID loop inductance L , the junction capacitance C and the operating temperature T :

$$\delta\phi = \langle S_\phi^2 \rangle^{1/2} = (2\varepsilon L)^{\frac{1}{2}} = \left(32k_B T (LC)^{\frac{1}{2}} L \right)^{1/2} \quad (1)$$

Fig. 1. Plot of spatial resolution versus SQUID thin film thickness at two different temperatures. Solid line is for $T/T_c = 0.1$ and dashed line for $T/T_c = 0.95$.

In turn we can calculate the minimum detectable magnetic field change in unit bandwidth

$$\delta B = \left[\frac{32k_B T C^{1/2} L^{3/2}}{\pi^2 a^4} \right]^{1/2} \quad (2)$$

For an extensive thin film with a hole of radius , we may relate the inductance to by the approximate expression

$$L \sim 2.5\mu_0 a \quad (3)$$

So finally we estimate in terms of the spatial resolution and other scale-independent parameters

$$\delta B^2 b^{5/2} \sim 4^{5/2} \pi k_B T \mu_0^{3/2} C^{1/2} \quad (4)$$

Note that as b decreases δB increases, as expected intuitively. For a realistic operating temperature of 1 K and a junction capacitance of 10^{-15} F (estimated from junction dimensions), this predicts that for a spatial resolution of 10 nm the product of spatial resolution and field sensitivity is around 2 orders of magnitude better than recent results reported for a BEC magnetometer [2]. It should be pointed out here that the superconducting penetration depth sets a lower limit on the spatial resolution achievable with nano-SQUIDs.

For most bulk materials at temperatures well below their T_c this is in the range 50 –150 nm with Al having the lowest value for elemental superconductors. The film thickness required to allow the Pearl length to approach λ_L will thus be required to be in this range also.

III. EXPERIMENTAL APPROACH

In addition to the advantages gained by the use of nano-bridge junctions, as outlined in Section I, we see from the above estimate that the minimum spatial resolution can be improved by the reduction in capacitance offered by the single-layer, low-dimensional properties of these junctions. We note also, however, that the penetration of electromagnetic fields into superconducting structures presents a further set of unavoidable problems for nanoscale applications, because the penetration length varies strongly with temperature, frequency and film thickness.

Fig. 2. SEM image of an actual Nb nano-SQUID with loop diameter 371 nm, weak-link junctions 65 nm $\times$ 80 nm and Nb film thickness is 150 nm.

Moreover, the magnetic properties of thin films and devices made from them are extremely sensitive to the deposition conditions and thickness of the films. We proposed elsewhere [1] a non-invasive, in-situ technique for measurement of the temperature-dependent magnetic properties of ultra-thin superconducting structures, and we have taken account of the finite penetration depth in our theoretical analysis in Section II.

IV. FILM DEPOSITION AND FABRICATION

Niobium films are deposited by dc magnetron sputtering from a 99.999% pure target onto oxidized silicon wafers or other suitable substrates (eg MgO or) held near room temperature in an ultra-high vacuum chamber with base pressure around . For the SQUID devices used in the presently reported work, Josephson junctions of weak-link or Dayembridge type are used. This simplifies the fabrication process, compared with the traditional tri-layer technique where an aluminum film and oxidation stage followed by a second Nb deposition were required. When the overall device structures have been delineated by photolithography and reactive-ion etching, the critical sub-micrometer Dayem-bridge regions are

individually prepared by focused-ion-beam milling (see Fig. 2). The FEI Nova Nanolab 600 dual beam FIB, as used in this work, is capable of defining nanoscale structures down to 50 nm. However Ga ion implantation can poison superconducting thin films (lowering or even destroying superconductivity). To avoid this problem our approach is to deposit W(CO) using an e-beam over the Nb tracks, giving a pad 150 nm thick. This thickness provides a protective layer to prevent Ga ion implantation in the Nb junction during milling and also this W layer provides a shunt resistor for junctions. The ion beam current is kept as low as possible (5 nA) to minimize poisoning. During milling the sample is imaged with the e-beam so that milling may be stopped as soon as all the Nb is removed. Live imaging is possible provided the e-beam current exceeds the ion beam current. Because the FIB milling is performed under computer control, once the process has been optimized a success rate of better than 80% can be achieved.

Fig. 3. Current-voltage curves for Nb nano-SQUID shown in Fig. 2. The voltage modulation is due to applied magnetic fields in the range 0–1 mT. The operating temperature is $T = 7.34$ K, and the critical current density is ~ 1 MA/cm². The sinusoidal voltage vs. field dependence of nano-bridge junction SQUIDs is shown in Ref. [1].

Fig. 4. Temperature dependence of critical current. The curve is a fit to the points: I_c (1 $\square$ $T=T_c$), and $T = 8.5$ K.

V. SQUID PARAMETERS AND NOISE

Measurements of nano-SQUID parameters and noise performance have been carried out in a variable temperature cryostat inside a shielded enclosure. For the Nb weak-link junctions considered here, at K, critical current A, normal resistance , the dynamic resistance is at the operating point. A theoretical (optimum) value for is given by mV , where is the flux quantum, but the experimental value, estimated from the critical- current modulation depth shown in Fig. 3, is only around 100 V . The inductance of the SQUID loop (assumed to be a circular aperture of diameter 370 nm), is estimated by a standard formula, to be 0.2 pH. To this is added the kinetic inductance of the weak links (0.1 pH), so pH. The parameter , based on the above values, is calculated to be 0.27 at the indicated temperature, although, at lower temperatures it will increase with the critical current which is quite strongly temperature-dependent as shown in Fig. 4.

Fig. 5. (a) Calculated noise curve based on (5) using experimental values for R , R and I ; (b) experimental noise curve at 40 kHz
(see text).

The theoretical thermal white voltage noise spectral density of a Josephson junction can be calculated by the Likharev- Semenov equation [3]:

$$S_V = \frac{4k_B T}{R_n} (R_d)^2 \left(1 + \frac{1}{2} \left(\frac{I_c}{I} \right)^2 \right) \quad (5)$$

The dynamic resistance of a SQUID when measured as a function of bias current and inserted into (5), leads to a predicted noise curve as shown in Fig. 5(a). Clearly the predicted levels of noise spectral density are well below the noise floor of any conventional room temperature amplifier. However, a method which we have described elsewhere [4] using a tuned low-temperature transformer allows the noise curve vs. bias current to be acquired at a particular frequency (here it is 40 kHz), shown in Fig. 5(b). The experimental and theoretical peak values (55 pV/Hz and 60 pV/Hz respectively) are in good order-of-magnitude agreement. The discrepancy at voltages above the peak is attributed to the damping of the transformer resonance by the junctions' normal resistance. We conclude from these measurements that, at 40 kHz, the measured noise peak is indistinguishable from the expected thermal noise floor, indicating that there is no significant excess noise at this relatively high frequency. Using the noise figure of 55 pV/Hz at 40 kHz (Fig. 5(b)) together with the estimated of 100 V as indicated in Fig. 3 it is seen that this voltage noise level represents a flux noise of 0.55 Hz.

Fig. 6. Voltage noise spectral density S of nano-SQUID at low frequencies: (a) SQUID bias current at operating point; (b) SQUID bias current = 0. Measured with STAR Cryoelectronics SA132 SQUID-array amplifier. The values of S have been corrected for system voltage gain of 2×10 .

These results suggest that the flux noise in nano-SQUIDs made by the present FIB technique are comparable to those recently reported [5] for similar structures made by electron-beam lithography. To acquire noise data at low frequencies, the tuned-transformer technique is no longer useful, and room-temperature amplifiers are likely to be themselves too noisy. Instead we used a SQUID array amplifier [6]. The results of noise measurements with this set-up are shown in Fig. 6. When the SQUID is

biased at its operating point, evidence of $1/f$ noise (Fig. 6(a)) can be seen below 1 kHz. Allowing for the apparent system noise floor of pV/Hz as obtained with the SQUID in its zero-bias current state (Fig. 6(b)), we can estimate the nano-SQUID noise at 10 Hz to be of the order 500 pV/Hz. We further note that, in Fig. 6(a) the downward trend of the noise floor above 100 Hz is consistent with the figure of 55 pV/Hz obtained at the 40 kHz spot frequency.

VI. DISCUSSION AND CONCLUSION

The design and fabrication of single-layer nano-scale SQUIDs by Focused-Ion-Beam techniques have been demonstrated, and the characteristics of several prototype structures have been investigated. For our nano-SQUID effective area of, as described above, the level of white flux noise at 40 kHz, 0.55 Hz, corresponds to a field resolution of order 10 nT. According to our calculation (4), a spatial resolution of substantially less than 0.5 μ m should then be available with these devices. This estimate is considerably better than the nano-scale magnetic field sensing performance which has been reported elsewhere. The spatial resolution and magnetic moment sensitivity of our FIB nanoSQUID devices will be further tested in ongoing work.

REFERENCES

- [1] L. Hao, J. C. Macfarlane, and J. C. Gallop, "Direct measurement of the penetration depth in ultra-thin and/or mesoscopic superconducting structures," *J. Appl. Phys.*, vol. 99, p. 123916, 2006.
- [2] S. Wildermuth, S. Hofferberth, I. Lesanovsky, S. Groth, P. Krüger, J. Schmiedmayer, and I. Bar-Joseph, "Sensing electric and magnetic fields with Bose-Einstein condensates," *Appl. Phys. Lett.*, vol. 88, p. 264103, 2006.
- [3] K. K. Likharev and V. K. Semenov, "Fluctuation spectrum in superconducting point contact junction," *JETP Lett.*, vol. 15, pp. 442–445, 1972.
- [4] L. Hao, J. C. Macfarlane, and C. M. Pegrum, "Excess noise in YBCO thin film Josephson junctions and devices," *Supercond. Sci. Technol.*, vol. 9, pp. 678–687, 1996.
- [5] S. K. H. Lam, "Noise properties of SQUIDs made from nanobridges," *Supercond. Sci. and Technol.*, vol. 19, pp. 963–967, 2006.
- [6] SQUID Array Amplifier SA132, STAR Cryoelectronics, Santa Fe, NM 87508-1412, 2006.