Quantum Detection Applications of NanoSQUIDs fabricated by Focussed Ion Beam

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Abstract. The increasing demands of quantum metrology and nanoscience are driving the requirements for single particle detection capability across a wide variety of physics applications, including QIP, single photon detection, NEMS, nanomagnetism and spintronics. NanoSQUIDs represent a new manifestation of an old but exciting superconducting technology which addresses some of these requirements. We will describe a straightforward approach to fabricating Nb microbridge weak-links which may be used in nanoscale SQUIDs. These devices have demonstrated very low noise, even at operating temperatures above 4.2 K. We will also describe the performance of prototype devices made using this technique for energy resolving single photon detection, nanoparticle spin detection and NEMS resonator readout.

1. Introduction
SQUIDs (Superconducting QUantum Interference Devices) are macroscopic quantum objects which are capable of detecting and measuring a wide range of physical parameters with unequalled sensitivity. This extends from magnetic flux (the natural most straightforward quantity that a SQUID responds to directly) through spatial displacement to photon detection and mass detection, for example [1]. Interestingly the SQUID devices which were first developed and that demonstrated an approach to the standard quantum limit were of relatively macroscopic size (typically a millimetre or so in linear dimension). It is really only rather recently that it has been appreciated that SQUID size may be radically reduced towards the nanoscale and that such devices will not only retain exceptional sensitivity but will, through their size, find applications in a whole new range of detection and measurement areas [2,3,4,5,6].

In this paper we describe a particularly simple fabrication method for SQUIDs which we have applied to producing nanoscale SQUIDs, based on focussed ion beam fabrication. We further illustrate that the exceptional measurement sensitivity and low noise performance which has long been known from macroscopic devices extends down, unabated, to the nanoscale. We then go on to describe some prototype applications of these simple microbridge based nanoSQUIDs in the areas of single photon spectroscopy, nanomagnetic particle detection and nanoelectromechanical systems (NEMS) resonator readout. We close with some speculation on further applications and some limits to performance.

2. Fabrication
The fabrication process combines conventional optical lithography with an ion etch step followed by a subsequent focussed ion beam (FIB) milling step. The process both simplifies the fabrication of
nanoSQUIDs and allows the loop diameters to be reduced down to 200 nm, with the incorporation of microbridge junctions of the order of 60 nm width in a single lithography step on a bilayer Nb/W film. A Nb thin film (~200 nm thick) is first deposited by sputtering and patterned into a series of lines around 1–2 µm in width by conventional photolithography. An important part of our process involves the *in situ* deposition of a tungsten layer (~150 nm thick) by e-beam over the entire region to be patterned, immediately before the FIB milling. This use of a normal-metal layer affects the subsequent properties of the SQUID in three crucial aspects, as demonstrated by Lam and Tilbrook [7]: it initially provides a protective barrier to minimize ion beam damage to the Nb bridge, thus preserving its superconducting property; in the operation of the SQUID, the tungsten acts as both a thermal shunt, minimizing hot spot generation and the resulting thermal hysteresis, and as a resistive shunt, which limits the McCumber parameter:

\[
\beta = \frac{2 \pi R^2 C}{\phi_0}
\]

thus removing the effect of electrical hysteresis. Tungsten (W) was used as the overcoating material rather than, for example, Au [8] because of its resistivity, which is both high and temperature independent. These SQUIDs, which we estimate to have an inductance of ~0.6 pH, exhibit non-hysteretic current- voltage characteristics with critical currents of order of 50–300 µA in the temperature range of 5–9 K, with regular periodic \( I_c - B \) curves in magnetic fields up to 10 mT. More details of the fabrication process are given by Hao *et al.* [9, 10].

3. Noise Performance of Microbridge nanoSQUIDs

Figure 1 shows the I-V characteristic of one such FIB fabricated nanoSQUID, an SEM image of which is shown in the inset. Note that the characteristic accurately follows the predictions of the resistively shunted junction model (see for example [11]), with parameters \( I_c = 120 \mu A, R = 5.5 \Omega \).

Figure 1. The I-V characteristic of a FIB-fabricated nanoSQUID at 4.65K, an SEM image of nanoSQUID is shown in the inset and the internal loop diameter is approximately 300 nm.

The thermal rounding parameter \( \Gamma \) is given by

\[
\Gamma = \frac{2 \pi k_B T_{\text{eff}}}{\phi_0 I_c}
\]
and, treating the effective temperature $T_{\text{eff}}$ as a fitting parameter the result is $T_{\text{eff}} \sim 55\text{K}$, well above the operating temperature, suggesting that higher temperature black-body radiation or other artificial electromagnetic interference is incident on the SQUID. Improved filtering of the bias leads and shielding may be expected to reduce this effective temperature. The absence of observed hysteresis predicts that $\beta < 1$, implying that the junction capacitance $C < 0.1\text{pF}$. The effective flux noise in this SQUID (that is the noise observed at the output, converted to an effective flux noise at the input) is shown in figure 2. This was measured at PTB (Berlin) using a series SQUID array (SSA) [12] as a cryogenic preamplifier. This work has been reported in more detail elsewhere [4]. Note that in the white noise regime around 1kHz the flux noise $\delta \Phi \sim 2 \times 10^{-7} \Phi_0 / \text{Hz}^{1/2}$. A classical analysis of thermal noise arising in the shunt resistors of the Josephson junctions implies that the limiting flux noise $\Phi_n$ is set by the expression

$$\frac{\Phi_n^2}{2L} = \epsilon = 16k_BT(\frac{L}{C})^{1/2}$$

(3)

where $\epsilon$ is the minimum detectable energy in unit bandwidth [11]. The thermal noise predicted by equation (3) for this device is about $6.6 \times 10^9 \Phi_0 / \text{Hz}^{1/2}$ at 6.8K, which is about 30 times lower than the observed white noise value.

Figure 2. Flux noise spectral density in a nanoSQUID, as a function of frequency from 10mHz to 100kHz.

4. Inductive Superconducting Transition Edge Detection (ISTED)

SQUIDs using the type of microbridge junctions described above have been developed as a novel form of sensitive bolometer for energy resolving single photon measurements. The basic principle of the ISTED has some common features with superconducting transition edge detectors (TEDs). The device consists of a photon absorber which is inductively coupled to a SQUID (the absorber generally consists of a thin film of superconductor with a transition temperature $T_c$ somewhat less than that of the SQUID) (see figure 3). When this thin film absorbs an incident photon an appreciable temperature rise is produced, due to the low heat capacity of the absorber. As a result pairs dissociate, reducing the pair density $n_s$ and thus resulting in an increase in the absorber superconducting penetration depth $\lambda(T)$. This in turn results in an increased inductance of the SQUID and a resulting change in the voltage read out from the SQUID. Unlike a TED detector the SQUID and absorber both remain below their $T_c$ and consequently there is no added Johnson noise associated with the detection process.
Figure 3. (a) SEM image of ISTED sensor with 50x50 µm$^2$. The FIB-bed junctions are shown close to the arrow marks near the bottom of the image. (b) A single junction is shown enlarged and the width of junction is about 80nm.

The ISTED process has been analysed in some detail elsewhere [13]. Here we present new data demonstrating single photon energy resolution using an ISTED. The pulse height output from a SQUID surrounding a 50 µm absorber, operated at 8.15 K was analysed for 3 different situations. First it was irradiated with a weak source from a 633 nm laser, coupled from room temperature via an optical fibre. Next the noise was measured with the laser off but the fibre still coupled to the ISTED. Finally the warm end of the fibre was cooled to 77 K, with the laser still not connected. The results for the pulse height histograms in the three situations are shown in figure 4. The energy resolution is estimated from this data to be ~0.2 eV, even at this high operating temperature of 8.15 K. The noise equivalent power has been estimated as $1 \times 10^{-17}$ W/Hz$^{1/2}$. It has not proved possible to accurately measure the quantum efficiency of the device at present but it has been estimated to be only around 0.3%. This low figure is partly due to the relatively high optical reflectance and transmission of the Nb thin film absorber, which is only ~60-80 nm thick.

Figure 4. Histograms of pulse height distributions for three different situations: a) weak 633nm laser irradiating the ISTED through a room temperature fibre (black bars), b) the same fibre with the laser turned off (grey bars) and c) with the laser turned off and the open end of the fibre cooled to 77K (white bars).
Further work is planned to try to optimise absorber performance to improve the quantum efficiency of this type of device.

5. NanoSQUIDs as Nanomagnetic Particle Detectors

With the increasing importance of the spin component of electron transport for future devices as manifested in the coming spintronics revolution the optimization of SQUID capability for spin or magnetization detection becomes highly desirable [14-18]. Ultimately, a nanoSQUID may enable single electronic spin flips to be detected, allowing electronic spin resonance (ESR) and other spin manipulations to be done on a single spin. Recently single spin detection has been achieved using a mechanical magnetic resonance detection device [19], but this technique is rather specialized and of limited applicability. As well as setting the lower limiting size of a single magnetic domain storage element, single spins are also regarded as one of the most promising possible realizations of the *qubits* on which quantum computation will depend [20], if it becomes feasible. In such a single-spin detection situation the input coil and flux transformer are dispensed with and a ‘bare’ SQUID is used.

Reducing the loop area of the SQUID, which reduces its inductance, can increase the energy sensitivity of the device to near quantum limit operation. Furthermore, a device incorporating a SQUID of small loop area has a reduced sensitivity to external magnetic fields, making it an ideal probe of samples situated within the SQUID loop. When it comes to measuring magnetization of a small particle the SQUID design requirements are in some sense the opposite to those for magnetic field sensing. It is preferable to use the SQUID loop to directly sense the magnetisation rather than employing a separate flux transformer. In addition the SQUID loop area should be minimized, in order to approach optimal coupling [21-23]. There are two major issues which must be taken into account. First, achieving optimal coupling, given the physical size, geometric shape and expected magnetisation of the particles to be detected and second, a method for bringing the magnetic nanoparticle and the SQUID into close proximity. Since the SQUID only detects relative, not absolute, flux changes it is preferable to be able to manipulate either the position or the magnetization direction of the magnetic particle.

The electronic spin sensitivity is given by

\[ S_n = d \left( \frac{S_\Phi}{2\pi\mu_B\mu_0} \right)^{1/2} \]  

in units of spins (of moment $\mu_B$) per $\sqrt{\text{Hz}}$, where $S_\Phi$ is the power spectral density of flux noise, related to the energy resolution by $S_\Phi = 2eL$, and $d$ is the dimension of the SQUID loop, scaled by a geometry-dependent factor between 1 and 10. In measurements made on a set of Nb dc SQUID devices ranging from $d = 100 \mu m$ down to $3 \mu m$ [16] it has been demonstrated that the flux noise sensitivity exhibits the expected linear scaling with $d$. The smallest device has a spin sensitivity of about 40 spins in a 1 Hz bandwidth limited by noise in the first-stage room temperature preamplifier. Extension of this scaling to SQUIDs with $d = 200 \text{ nm}$, as demonstrated in the section on noise performance above, should enable single electronic spin flips to be detected.

We are considering a number of ways of reading out the spin flip of a nanomagnetic particle placed in close proximity to a nanoscale SQUID loop. All of these configurations require manipulation of single nanoparticles close to the SQUID loop. This may be achieved most simply by mounting the particle on a scanned probe system. Modelling supports the common sense realisation that the particle should be asymmetrically placed with respect to the axis through the centre of the SQUID loop. Recently we have demonstrated that a micromanipulator mounted in a scanning electron microscope (SEM) can be used to attach (see inset to figure. 6) and then remove a nanomagnetic particle from a nanoSQUID, without affecting the SQUID performance or physical parameters [24].
Figure 6. (a) Schematic layout of various methods for nanomagnetic spin flip detection using a nanoSQUID, directly coupled to the magnetisation. (b) SEM image of a nano-SQUID with a single magnetic particle bead attached. The nano-SQUID loop size is ~ 350 nm, junction size ~50 nm x 80nm. The particle diameter is ~ 120 nm.

6. Nano-Electromechanical Systems (NEMS) Resonator Readout
As electromechanical system devices become smaller, approaching the nanoscale, the oscillation displacement amplitude scales down in proportion to size. Thus ultra-sensitive transducer techniques and low dissipation excitation schemes are needed to operate NEMS sensors. Developing suitable excitation and readout methods is crucial and may have spin-offs into a number of other nanotechnology applications. We propose here a novel form of NEMS displacement readout provided by our on-going development of nanoSQUIDs [4,13,25]. As in the ISTD this readout is based on the modulation of the SQUID loop inductance by the movement of the NEMS resonator in its vicinity.

The resonator support structure and its surroundings are important in that they will determine the energy transfer between the resonator and the environment, both wanted and unwanted. Characterisation of the resonator’s properties can be carried out using a range of conventional techniques such as electrical and thermal transport methods. A disruptive technology such as nanomechanical resonators (NMRs) brings new requirements for enabling technologies. It is necessary to excite and detect the resonant modes of the NMRs. The sub-wavelength size of the resonators relative to optical wavelengths means that the simple optical readout which is conventionally used in, for example, scanned probe microscopes will not be appropriate. But a generic technique, expected to be even more sensitive than any other, involves the use of the novel nanoSQUID readout method under development at NPL. By positioning an electrically conducting NMR close to the sensing loop of a nanoSQUID the mutual inductance between NMR and SQUID loop will be modulated by their relative movement. This in turn will modulate the loop inductance of the SQUID, leading to a change in output voltage, arising from either (or both) an external flux applied to the SQUID or the internally generated flux arising from an asymmetric bias current distribution. The SQUID readout will then carry sideband information concerning the time dependent movement of the NMR. We estimate sub picometre sensitivity will be readily achievable by this method.

Alternatively a SQUID may be used as a sensitive displacement sensor in a number of other ways [26]. For example if a ferromagnetic particle is attached to the vibrating element of the NMR cantilever the adjacent SQUID can detect the enclosed magnetic flux change as the particle moves.
There is another possible SQUID detection method for the case of a conducting NMR cantilever clamped at both ends. A direct current flowing through the cantilever will produce a magnetic flux at the SQUID loop which will be modulated by cantilever movement. This would produce an alternating output signal from the SQUID.

Close inductive coupling between SQUID and NMR will be necessary, regardless of the specific readout mechanism implemented. This implies that the SQUID loop should be comparable in size to the linear dimension of the NMR, i.e of nanoscale dimensions. We have already demonstrated how to make SQUIDs with a loop size as small as 200 nm [13] and more recently have shown that these SQUIDs have exceptional low noise properties at relatively high operating temperatures [4]. It is also important for high sensitivity that the cantilever may be brought sufficiently close to the SQUID loop to maximise the change in inductance or coupled magnetic flux change. With this in mind it appears clear that the cantilever and SQUID would best be deposited, mounted or grown on the same substrate. The cantilever displacement could be read out by any of the methods outlined above which do not need connections to a conducting cantilever.

A second possibility incorporates the cantilever (superconductor coated) directly into the SQUID loop, allowing rf current excitation to be driven through the cantilever without significantly affecting the SQUID bias. Multi-layer deposition is also quite straightforward so much more complex systems are possible in principle.

In order to test these ideas a prototype SQUID structure has been fabricated, using FIB milling, on the same chip as a paddle-shaped Si NEMS resonator (see figure 7). The vibration of the paddle will modulate the inductance of the nanoSQUID loop, allowing sub picometre amplitude sensitivity to be achieved, according to a simple model of expected coupling between the two components. We will present elsewhere detailed calculations of the performance of these readout and excitation methods and also preliminary device fabrication details [27].

It is straightforward to give an estimate of the potential sensitivity of the inductively coupled nanoSQUID readout system. Using finite element modelling techniques we may readily estimate the self-inductance of a SQUID loop and how it is affected by the presence of a conducting cantilever. Movement of this cantilever element corresponding to a chosen expected vibrational mode can be factored in to this model to characterise the inductance variation as a result of the oscillation at a given amplitude. For an angle $\phi$ between the plane of the SQUID loop and the paddle and an angle dependent self-inductance $L(\phi)$ of the SQUID loop (see figure 9a) it is straightforward to estimate that the minimum detectable angular displacement $\delta\phi$ is related to the minimum detectable magnetic flux change of the SQUID $\delta\Phi$ by the relationship

Figure 7. SEM micrograph of Si paddle NEMS resonator coupled microbridge d.c. SQUID.
\[ \delta \phi = \delta \Phi L(\phi) \left[ \frac{dL(\phi)}{d\phi} \right]^{-1} \]  

(5)

For a paddle shaped resonator we assume a filling factor of around 80\% of the SQUID loop and a nanoSQUID with a flux sensitivity \( \delta \Phi \) of around 1 \( \mu \Phi_0/\text{Hz}^{1/2} \) (a realistic value for a nanoSQUID). Then the spatial movement detection sensitivity to a torsional oscillation mode is expected to be better than \( 10^{-13} \text{m/Hz}^{1/2} \). The variation of displacement sensitivity of the paddle edge as a function of mean angle \( \phi \) is shown in figure 9b).

Figure 8. (a) Schematic of paddle SQUID in torsional motion b) dependence of inductive SQUID signal on angle of rotation \( \phi \). (b) Variation of minimum displacement sensitivity as a function of \( \phi \) calculated from equations 4 and 5.

7. Future Prospects
SQUIDs have found widespread applications in metrology over the past thirty years. Other applications in medicine and instrument development have also emerged. Much more recently the growing importance of nanoscience and technology has led to a realisation that SQUIDs reduced to nanoscale size have an entire new range of applications. In this paper we have summarised some preliminary developments at NPL in producing nanoscale SQUIDs with weak-link microbridge junctions fabricated by focussed ion beam milling. We have demonstrated the low-noise properties of these detectors and shown that they may be used for exceptional bolometric performance. We also present some initial work on using these nanoSQUIDs for magnetic nanoparticle detection with the long term aim of being able to detect single electronic spin flips, a goal which would be of potential importance in QIP. SQUID displacement sensors have been known for many years (see for example Harry et al. [28]) but the idea of using nanoSQUIDs to sense NEMS readout is proposed and modelled here. We expect to provide experimental evidence for this sensitivity in the near future.

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