Measurement and noise performance of nano-superconducting-quantuminterference devices fabricated by focused ion beam

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Science and industry demand ever more sensitive measurements on ever smaller systems, as exemplified by spintronics, nanoelectromechanical system, and spin-based quantum information processing, where single electronic spin detection poses a grand challenge. Superconducting quantum interference devices SQUIDs have yet to be effectively applied to nanoscale measurements. Here, we show that a simple bilayer deposition route, combining photolithography with focused ion beam patterning, produces high performance nanoscale SQUIDs. We present results of noise measurements on these nanoSQUIDs which correspond to a magnetic flux sensitivity of around $0.2 \mu_0 / \text{Hz}^{1/2}$. This represents one of the lowest noise values achieved for a SQUID device operating above 1 K.

The detection of a single electronic spin is a very challenging step for any superconducting quantum interference device (SQUID). It has been demonstrated¹ that in order to approach the sensitivity required to detect a single spin flip, the SQUID inductance has to be minimized, implying that the SQUID loop diameter will have to be reduced to submicrometer dimensions. Reassuringly, it has also been clear for some time that the noise performance of SQUIDs may be improved not only by reducing the operating temperature but also by reducing the SQUID inductance and junction capacitance. Both of the latter routes argue for the use of smaller SQUID devices.² Restrictions on operating ever smaller SQUIDs have arisen for several reasons. First, “traditional” SQUIDs, incorporating Josephson tunnel junctions, are generally found to have dimensions greater than 1 μm , due to junction current-density limitations. They also require a trilayer deposition route which requires an oxidation treatment. Second, tunnel junctions also possess significant capacitance, arising from their geometry. It has been recognized that the use of microbridge junctions would very effectively reduce the junction size and capacitance, thereby allowing smaller SQUID inductance. However, microbridge junctions have generally been regarded as too noisy for use at the highest sensitivity levels. In spite of this, a number of microSQUIDs using microbridge junctions have been described, notably by Jamet et al.,³ Cleuziou et al.,⁴⁻⁶ and Lam.⁷ A limitation of some of the devices produced by those processes has been the existence of thermal hysteresis in the SQUIDs’ characteristics, which has made them difficult to read out by standard methods and may have introduced excess noise. In this paper, we show that an alternative, simple bilayer, deposition route which combines photolithography with focused ion beam (FIB) patterning can provide nanoSQUIDs with some of the lowest noise achieved so far and, therefore, the potential for extremely high spin sensitivity.

The entire fabrication process combines conventional optical lithography/ion etch steps with a subsequent FIB milling step. This route 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 80 nm width in a single lithography step on the 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 using 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:⁸ 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 β_c parameter, thus removing the effect of electrical hysteresis. W was used as the overcoating material rather than, for example, Au,⁷ 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 nonhysteretic current-voltage characteristics with critical currents I_c of order of 50–300 μ A 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

Here, we report the results of measurements on our nanoSQUIDs operated in a variable temperature cryostat with a temperature range between 4.2 and 12 K. The nanoSQUIDs have been operated in a flux-locked loop FLL, with a 16 SQUID series array SSA_ Refs. 10 and 11_ at 4.2 K used to preamplify the nanoSQUID output signal. In Fig. 1, a schematic of the readout setup is shown. The SSA used has an equivalent input current noise of 10 pA/Hz^{1/2}. By using this system, we have been able to measure the noise performance of the nanoSQUID without being affected by noise contributions from the room temperature FLL electronics. Due to its submicron loop size, the nanoSQUID is highly insensitive to magnetic background fields as is also the SSA preamplifier, on account of its gradiometric design. It was, therefore, possible to operate the nanoSQUID readout system without magnetic shielding.

Figure 2 shows a typical I-V characteristic for one of our devices at a temperature of 4.65 K with no applied magnetic field and critical current $I_c=95$ μ A. The physical layout of the nanoSQUID is shown in the inset. The total thickness of the Nb/W film in this example is 350 nm, the loop diameter is 370 nm, the microbridge junctions are 65 nm wide by 80 nm long, and the four-terminal superconducting leads are shown. The normal state resistance of the device is 6.25. The effective shunt resistance of the tungsten film that is described above was measured to be 5.8 in the case of an identical

device, which had open-circuited junctions, independent of temperature from 4.2 to 30 K. The estimated inductance of the SQUID, based on a simple geometric model, is $L_s \sim 0.6$ pH. The general shape of the characteristics closely approximates the resistively shunted junction model. Note also the absence of hysteresis and of any structure, which might be associated with microwave self-resonances in the SQUID, at least up to the maximum voltage displayed of 1.5 mV. The absence of hysteresis and microwave resonances below ~ 700 GHz, as deduced from the lack of structure in the IV characteristics, implies that the capacitance of each microbridge junction must be less than 0.1 pF. This is expected to be a significant overestimate. The inset in Fig. 3 shows the current-flux characteristic of the SQUID. The feedback current through the nanoSQUID measured with the FLL operated with respect to SSA is plotted as a function of an applied external magnetic field. The applied field periodicity of the response implies an effective area of $0.30 \mu\text{m}^2$, in reasonable agreement with our estimate of the device's geometric area of $0.20 \mu\text{m}^2$. In Fig. 4, the measured magnetic flux noise spectral density S_Φ expressed in units of the flux quantum $\Phi_0/\text{Hz}^{1/2}$, as a function of frequency from 0.1 Hz to 100 kHz is depicted. Note that there is a region at low frequency where the noise spectrum has a $1/f^2$ form, but above 1 Hz, there is a much weaker frequency dependence. Even at 1 Hz, the spectral density is as low as $0.8 \Phi_0/\text{Hz}^{1/2}$, while in the white noise region around 1 kHz, this has fallen to $0.2 \Phi_0/\text{Hz}^{1/2}$. The frequency roll off at higher frequencies represents the result of filtering in the readout electronics.

In summary, we have described a rather straightforward technique for the production of nanoSQUIDs from a single bilayer thin film of Nb/W, having the following desirable properties: *i* inductance of order of 0.6 pH; *ii* < 0.1 pF junction capacitance, *iii* hysteresis-free I-V characteristics at temperatures from 5 to 9 K and *iv* demonstrated flux noise level of less than $1 \Phi_0/\text{Hz}^{1/2}$ at 1 Hz and a white noise level at $f \sim 1$ kHz of $0.2 \Phi_0/\text{Hz}^{1/2}$. Beyond the $1/f$ dominated region and making the assumption of optimal coupling,¹² this white flux noise level corresponds to a predicted spin sensitivity of ~ 2 in units of electron spins per $\text{Hz}^{1/2}$. This is a factor of around 8 times lower than the value deduced in Ref. 7, having corrected for that author's more pessimistic coupling assumption. These devices exceed the noise performance of conventional SQUID devices made from conventional tunnel Josephson junctions at operating temperatures

of 4 K and above. The flexibility of the lithographic and FIB techniques, combined with the advantage of using single-layer Nb films suitably overlaid where necessary by in situ tungsten films, ensures good reproducibility of the process. There is a scope for further miniaturization of the devices and for tuning the operating temperature by using different materials. These nanoSQUIDs have important applications in nanomagnetic particle detection and measurement, aimed at spintronics studies, readout of NEMS devices, and in quantum information processing. Our experimental results suggest the suitability of the technique for the further development of detectors that will approach the goal of single electron spin detection.

FIG. 3. NanoSQUID current-flux characteristics with $I_b=60 \text{ } \mu\text{A}$ and $T=6.8 \text{ K}$.

FIG. 4. Flux noise spectral density S_ϕ vs frequency f at $T=6.8 \text{ K}$ with bias current of $60 \text{ } \mu\text{A}$.

This work was funded through the Pathfinder Metrology Programme of the National Measurement System Policy Unit of the Department of Innovation, University and Skills DIUS, UK, and the PTB Visiting Scientist Programme.

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