Neon focussed-ion beams for fabrication of superconducting nanowires

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***Abstract*—We have used a neon focused-ion beam to fabricate both nanoscale Nb Dayem bridges and NbN phase-slip nanowires located at the end of quarter-wavelength coplanar waveguide resonators. The Dayem bridge devices show flux-tuneability and intrinsic quality factor exceeding 10,000 at 300 mK up to local fields of at least 60 mT. The NbN nanowires show signatures of incoherent quantum tunnelling of flux at 300 mK.**

***Keywords*— nanofabrication, superconducting nanowires, quantum electronics, flux tunnelling**

I. Introduction

Superconducting nanowires with cross-sectional dimensions comparable to or less than the coherence length display non-linear transport characteristics which can be exploited in a quantum and classical electronics applications. The Dayem bridge [1] consists of a short region of suppressed superconducting order between two fully superconducting electrodes. Josephson coupling between the electrodes results in it behaving as a non-linear inductor. If the superconducting nanowire has a high degree of structural disorder then the physics may be dominated by coherent quantum phase-slips (CQPS) [2]. The CQPS nanowire is the dual of the Josephson junction and it behaves as a non-linear capacitor.

For quantum device applications it is critical that dissipative loss mechanisms (which, for example, suppress the T_1 coherence lifetime) are minimised. The technological challenge is therefore to fabricate superconducting nanowires without significantly increasing the dissipative loss rate above that of the "bulk" unpatterned film. Focussed-ion-beams (FIB) are widely used for nanofabrication of superconductors. Traditionally FIB patterning made use of gallium ions from a liquid metal ion source. Gallium implanted into the nanowire however may result in increased dissipation [3]. Gallium also has high solid-state mobility, leading to long-timescale variability in the device characteristics. More recently the gas-field ion source has been used to generate both helium and neon ion-beams, with the latter having sufficient mass to perform FIB milling of metallic thin films.

Here we demonstrate the use of neon FIB milling for fabrication of superconducting nanowires. We have created nanoscale superconducting loops containing either (a) Dayem bridges in Nb films or (b) phase-slip nanowires (operating here in the incoherent regime) in disordered NbN films. To quantify dissipative losses in these nanowires the loop is located at the end of a quarter-wavelength superconducting coplanar waveguide (CPW) resonator. Measurements of the resonant frequency and quality factor of the resonator enable the non-linear properties of and losses in the nanowires to be extracted respectively.

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II. Nanowire-terminated transmission lines

A SQUID has flux-tuneable inductance given by

$$L_k=\frac{\Phi_0}{4\pi I_c\left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|}, \quad (1)$$

where I_c is the SQUID critical current at zero flux, Φ is the applied flux and Φ_0 is the flux quantum. The impedance seen at the input to a transmission line of length l and impedance Z_0 which is terminated by a SQUID of impedance $Z_L = i2\pi\nu L_k$ is

$$Z_{in}=Z_0\frac{Z_L+iZ_0\tan(2\pi\nu l/c)}{Z_0+iZ_L\tan(2\pi\nu l/c)}, \quad (2)$$

where ν is the frequency and c is the phase velocity. At resonance the imaginary part of Z_{in} is zero. Hence flux-modulation of the SQUID (load) inductance is manifested as a change in the resonant frequency of the transmission line.

If the Josephson junctions of the SQUID are replaced by two phase-slip nanowires then the form of the flux-modulation of the total inductive load is modified. In this case the kinetic inductance of both the nanowires, L_{k1}, and the wider part of the loop, L_{k2}, depend quadratically on the persistent current I. The total kinetic inductance is now given by

$$L_k=L_{k1}\left(1+\frac{I^2}{I_{*1}^2}\right)+L_{k2}\left(1+\frac{I^2}{I_{*2}^2}\right), \quad (3)$$

where I_{*1} and I_{*2} are the current scales which characterise the nonlinearity of the nanowires and the wider part of the loop

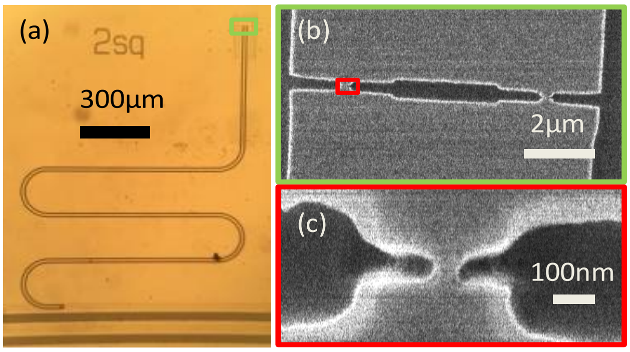

Fig. 1. Nb Dayem-bridge device. (a) Optical micrograph of the CPW meander resonator with feedline at the bottom of the image; (b) Helium FIB image of the highlighted region in (a) showing the SQUID loop; (c) Helium FIB image of the highlighted region in (b) showing a single Dayem bridge. In all images the Nb is bright and the exposed Si substrate is dark. Reproduced from [5].

respectively. Noting that $I = \Phi / L_k$, the flux-dependence of the total kinetic inductance can now be calculated.

III. Neon Focussed-Ion-Beam

A GFIS source [4] consists of a metallic (typically tungsten) tip which is cooled to below 100 K and sharpened by field emission to atomic dimensions. He or Ne gas is admitted to a pressure of ~10^{-6} mbar. The potential applied to the tip is adjusted so that the electric field is only sufficiently large to ionise the inert gas atoms at the apex of the tip. This results in an inert gas beam of very high brightness which emerges from three atoms in the tip, one of which is selected as an atomic ion source. The ions are then accelerated and focussed onto the sample using conventional ion-beam optics. Typical neon beams in commercially-available FIB systems have energy up to 35 kV, current up to 10 pA and beam diameter at the sample of 2nm. The sputter yield is typically three times lower than that of Ga ions of equivalent energy. The maximum beam current, however, is more than three orders of magnitude lower than that of commercially-available gallium FIB systems, leading to significantly reduced volume milling rates for neon by comparison with gallium.

IV. Experimental Details

Films were grown by d.c. magnetron sputtering from a Nb target onto silicon (in the case of Nb) or c-axis oriented sapphire (in the case of NbN) substrates. For Nb deposition the sputter atmosphere is 100% argon, whereas for NbN deposition it is 50% argon – 50% nitrogen. The film thickness is ~ 50 nm for the Nb films and ~ 10 nm for NbN as the CQPS rate is enhanced in thinner films. The larger-scale features of our devices were created by using electron-beam lithography and reactive-ion-etching in SF_6. The nanowires were created by FIB milling using a 15 kV Ne beam with a current of a few pA. Measurements were performed in a 3He cryostat at a temperature T ~ 300 mK using an r.f. vector network analyser.

V. Niobium Dayem Bridges

In Fig. 1 we show a Nb Dayem-bridge SQUID loop coupled to a λ/4 resonator. The width of the two bridges is

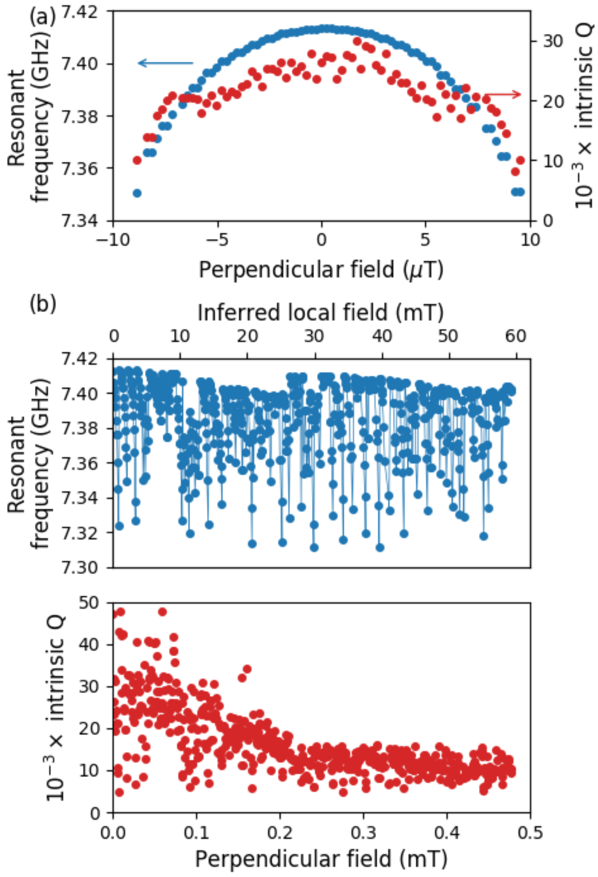

Fig. 2. (a) Dependence of the resonant frequency (blue, left axis) and intrinsic quality factor (red, right axis) of the Nb Dayem-bridge device on a magnetic field applied perpendicular to the SQUID loop. (b) The same measurements extended to higher field. The lower axis shows the applied field and the upper axis shows the inferred local field at the SQUID. The line is a guide to the eye.

around 50 nm. The field-dependence of the resonant frequency and quality factor of this structure at T = 300 mK are shown in Fig. 2(a). In an applied field of 10 μT the resonant frequency is tuned by ~60 MHz from its zero-field value of 7.41 GHz. The intrinsic Q of the resonance has a zero-field value of around 25,000. Another similar device fabricated on the same wafer has an intrinsic Q of 120,000 [5]. To our knowledge this is the highest reported Q of a SQUID-tuneable resonator. Comparison with other on-chip resonators which do not include SQUIDs [5] confirms that the Q in these devices is limited by losses in the "bulk" superconducting films, and that the additional losses due to presence of the nanowires are negligible by comparison.

In Fig. 2(b,c) we show the field-dependence of the resonant frequency and Q of the same device at higher applied fields. Jumps in the resonant frequency occur at the insertion of each additional flux quantum to the SQUID loop. From the data we extract a lower bound of 3.4 for the normalised inductance, $\beta_L = 2L_kI_c/\Phi_0$. From the field-periodicity of the discontinuities we estimate the flux focussing factor (arising from the superconducting ground planes) to be F = 124. This allows us to rescale the field axis in Fig. 2(b,c) to give the local flux

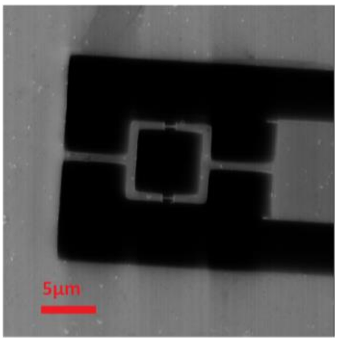

Fig. 3. Helium FIB image of a NbN phase-slip nanowire device. NbN is bright and the exposed sapphire substrate is dark.

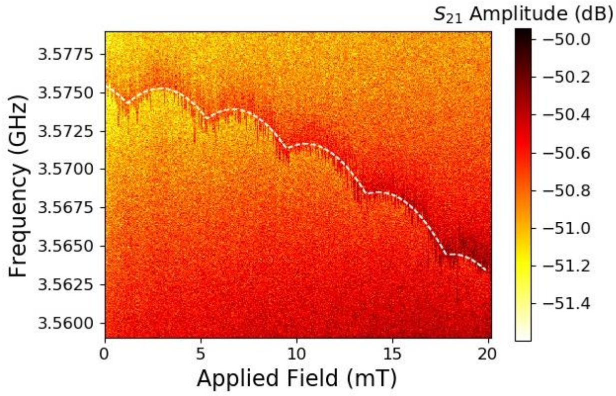

Fig. 4. Dependence of the transmission of the nanowire phase-slip device upon frequency and magnetic field applied perpendicular to the plane of the superconducting loop. The white dashed line shows the fit to the resonant frequency using (2) and (3).

density, $B_{local} = FB_{applied}$. At local fields higher than 30 mT the device not only retains its flux-tuneability but also the Q is flux-independent (within the noise level) and exceeds 10,000.

VI. Niobium Nitride Phase-Slip Nanowires

Fig. 3 shows a typical fabricated device structure for investigation of phase-slip physics in NbN nanowires. In what follows we report measurements of such a device containing nanowires of length 200 nm and width 35 nm at T = 300 mK. The transition temperature of the NbN was measured to be 8.5 K. Our measurements therefore are made at temperatures far below the predicted value of the crossover temperature below which the rate of quantum activation of phase slips exceeds the thermal rate [6]. The intrinsic Q for this device is 2,000 whereas, prior to the neon FIB milling stage, it was 13,000. The higher loss in the NbN devices by comparison with the Nb devices discussed above may be associated with the high level of structural disorder and low film thickness, both of which are necessary to maximise the CQPS rate. Nevertheless the Q of the neon-milled devices is two orders of magnitude larger than previously reported CPQS devices based on indium oxide films [7] and somewhat larger than other NbN CQPS devices [8].

The magnetic-field dependence of the spectral response of this device is shown in Fig. 4. We observe two effects: (i) a parabolic decrease of the resonant frequency as the field increases. This results from the field-dependence of the kinetic inductance of the "bulk" NbN film, which (unlike for the Nb devices reported above) is larger than the geometric inductance; (ii) a periodic modulation of the resonant frequency with period 4.15 mT. This arises from incoherent quantum phase-slip events occurring in the NbN nanowires, allowing a single flux quantum to tunnel into the loop. The dashed line in Fig. 5 shows a fit to the data using (2) and (3), modified to include the parabolic field-dependence parametrised by a phenomenological field-scale B*. The fitting parameters are the flux focussing factor and B*. The goodness of this fit, coupled with the absence of any signature of an avoided level-crossing, confirms that incoherent quantum phase slips are occurring in the nanowires.

VII. Conclusions

We used neon FIB to fabricate nanowires of width less than 50 nm which exhibit non-linear quantum effects whilst maintaining low loss. The field resilience of the Nb Dayem bridges (shown here up to a perpendicular local field of 60 mT) suggests that they may be useful for application as a readout technology for spin qubits [5]. Additionally measurements of incoherent flux tunnelling in NbN nanowires at 300 mK are a key milestone towards measuring coherent quantum phase slips. Future work will focus on minimising the losses at dilution-refrigerator temperatures where we expect CQPS phenomena to be observable.

Acknowledgment

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References

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