Focused Ion Beam NanoSQUIDs as Novel NEMS Resonator Readouts

Ling Hao, John C. Gallop, David Cox, Edward J. Romans, John Cameron Macfarlane, and Jie Chen, *Member, IEEE*

***Abstract*—Nano electromechanical systems (NEMS) represent an important new class of device with wide ranging applications. In this paper we report proposals and calculations for novel methods for excitation and readout of cantilever-style NEMS resonators which are applicable over a wide temperature range. We suggest a Lorentz force-based excitation method and discuss an ultrasensitive readout provided by a nanoSQUID, where the cantilever vibration modulates the inductance of the nanoSQUID loop, allowing potentially sub-picometer amplitude sensitivity to be achieved.**

***Index Terms*—Mechanical resonators, NanoSQUIDs, NEMS.**

I. Introduction

THE DOMINANCE of electronics may be coming to an end as hard limits emerge in terms of device density, power dissipation and speed. One of a very few promising new disruptive technologies is based on nano-scale electromechanical system (NEMS) resonators [1]–[4]. These NEMS resonators are expected to have a variety of applications, ranging from *ultra-sensors* for physical parameters (mass, force, charge, spin, chemical specificity), through single molecule bio-sensing, information storage and processing technologies, and even to nanoscale refrigerators. NEMS resonators are sufficiently small that mesoscopic quantum mechanical behavior is expected to appear at low temperatures, with the prospect of observing it at room temperature in the longer term, requiring all of the quantum metrology capabilities that have hitherto been applied in atomic and condensed matter physics.

In this paper we propose novel methods for exciting and reading out cantilever-style NEMS resonators which are applicable over a wide temperature range. We present calculations of the expected performance and preliminary device fabrication details for on a Lorentz force-based excitation method where the dc magnetic field could be provided by a miniature, high-strength ferromagnet. Here the conducting NEMS cantilever carries an ac current orthogonal to this field and vibrational excitation occurs along the third axis. We will present calculations which show that a sufficiently sensitive form of readout can be provided by our on-going development of nanoSQUIDs [5], [6]. Here a SQUID structure is fabricated, using focused ion beam etching, on the same chip as the NEMS resonator. The vibration of the cantilever modulates the inductance of the nanoSQUID loop, allowing potentially sub-picometer amplitude sensitivity to be achieved.

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L. Hao, J. C. Gallop and D. Cox are with the National Physical Laboratory, Teddington, U.K. (e-mail: ling.hao@npl.co.uk; john.gallop@npl.co.uk; David.cox@npl.co.uk).

E. J. Romans is with the London Centre for Nanotechnology, University College London, U.K. (e-mail: e.romans@ee.ucl.ac.uk).

J. C. Macfarlane is with the Physics Department, University of Strathclyde, Glasgow, U.K. (e-mail: j.c.macfarlane@strath.ac.uk).

J. Chen is with the School of Engineering and Design, Brunel University, Uxbridge, U.K. (e-mail: jie.chen@brunel.ac.uk).

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II. Operating Principles

To explore the quantum mechanical properties of a single mechanical resonator it is important to operate at an effective temperature where the thermal noise is less than the resonator's quantized vibrational energy, i.e.

$$(h/2\pi)\omega > k_{\mathrm{B}}T \tag{1}$$

where ω is the resonator's fundamental angular eigenfrequency, T is the temperature, and h and k_{B} are fundamental constants. To avoid the need to operate at ultra-low temperatures this implies that the maximum oscillatory frequency should be sought for the mechanical resonator (up to a few tens of GHz should be achievable). To achieve these high frequencies the resonator should be made of a material with as high a velocity of sound as possible, with low mechanical losses (to ensure sharp resonances), and be capable of fabrication on the smallest possible length scale. Our work involves research into the properties of a number of model systems based on nanofabricated structures, composed of single-crystal materials. Crystalline materials such as Si, $\mathrm{Si_3N_4}$ and particularly *carbon nanotubes* [7], [8] satisfy these requirements whilst also being suitable for deep-sub-micron lithography, using either electron or ion beam methods.

The resonator support structure and its surroundings are important in that these will determine the energy transfer between the resonator and the environment, both wanted and unwanted. Characterization of the resonator properties can be carried out using a range of conventional techniques such as electrical and thermal transport methods. A *disruptive technology* such as NEMS brings new requirements for enabling technologies. It is necessary to excite and detect the resonant modes of the NEMS resonator. The sub-wavelength size of the resonators relative to optical wavelengths means that the simple optical readout which is conventionally used in, for example, atomic force microscopes will not be appropriate.

III. Excitation Methods

The implementation of resonant NEMS systems requires development across many areas of physics and engineering.

NEMS are electromechanical devices which allow electromagnetic energy to be converted into mechanical energy. Any system may be treated as consisting of four sub-systems: an excitation system, the NEMS resonator itself, a readout system and a control/feedback element. The excitation system (which is primarily an input transducer) converts electrical energy into mechanical energy by exciting a resonant mode of the resonator mechanical element. The mechanical displacement is transduced back into electrical signals by the readout system. There are several potential excitation methods which we are considering, two of which are outlined in the following sections.

A. Electromagnetic: Lorentz Force Excitation

The Lorentz force F due to a static magnetic field B acting on a straight wire of length L which carries current i is:

$$\boldsymbol{F} = i\boldsymbol{L} \times \boldsymbol{B} \tag{2}$$

If a resonator structure carries a current then this can produce a significant deflecting force—for instance with an applied magnetic field of 3.5 T, a 10 μm long wire carrying a current of 100 μA will experience $F \sim 3.5 \times 10^{-9}$ N. This is clearly applicable to conducting *double-clamped* resonators, rather than diving board types, except where these could be configured in a horse-shoe geometry. Moving to nanoscale structures, metallic carbon nanotubes can exhibit ballistic electrical conduction at room temperature over lengths greater than 1 μm. They are also capable of carrying large current densities before suffering electrical breakdown [9]. If a nanotube is connected to a 50 Ω high frequency (i.e. rf or microwave) current source and an orthogonal *static* magnetic field B applied then the ac Lorentz force can be sufficient to excite significant transverse vibration amplitude in the tube.

B. Magnetic Excitation: Ferromagnetic Particle Excitation

A small ferromagnetic particle attached to a NEMS resonator can provide a local excitation force when placed in a time varying magnetic field gradient. (For a nanotube this could be a catalyst particle, made of Fe, Ni or Co.) For certain ferromagnetic materials the super-paramagnetic limit only sets in for particle sizes less than ~5 nm, even at room temperature. Consider a particle of radius a with magnetic dipole moment $\boldsymbol{m}$. If each constituent atom has a typical moment μ_{B} with lattice spacing a_0 the particle moment is given by

$$m = \frac{4\pi\mu_B}{3}\left(\frac{a}{a_0}\right)^3 \tag{3}$$

The force F on a particle in an alternating magnetic field gradient $(\mathrm{d}B_z/\mathrm{d}z)sin(\omega t)$ is given by $\boldsymbol{F} = (\boldsymbol{m}.\boldsymbol{\nabla})\boldsymbol{B}$. The magnetic field could be generated by rf or microwave current flowing in a coplanar line, with the gap between conductors situated close to (distance d from) the magnetic particle (see inset to Fig. 1). Since the width, $2w$, of the gap is much greater than either $d(\sim w)$ or the radius of the particle, a, the only nonzero component of the transverse magnetic field gradient will be $\mathrm{d}B_z/\mathrm{d}z$ where x is the direction of propagation. For a microwave current amplitude i_0 the force $F_{\mathrm{z}}(z)$ on the particle, calculated from (4) and (5),

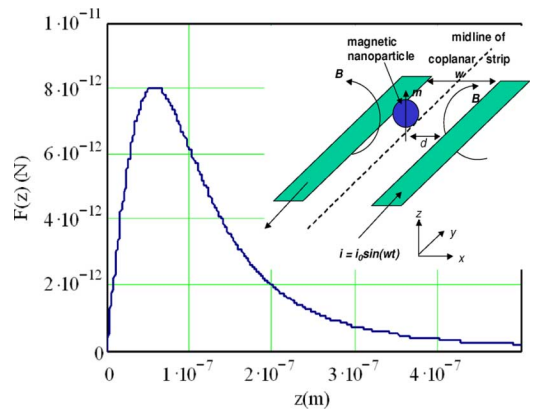

Fig. 1. Force produced on a 50 nm ferromagnetic particle by a 1 μA rf current versus the vertical separation z of particle and coplanar line. In the inset, d represents the lateral distance between the coplanar line and the ferromagnetic nanoparticle.

$$F_z(z) = m.\left(\frac{d}{dz}B_z(z)\right) \tag{4}$$

where

$$B_z(z) = \frac{-(\mu_0 i_0 w)}{\pi(w^2 + z^2)} \tag{5}$$

is plotted in Fig. 1 as a function of z, the height of the particle above the line. For a separation $z = 50$ nm a vertical movement of ~0.1 pm should be easily detected by a SQUID-based readout (see Section V-E below), whereas the displacement produced by this method would be as great as 100 pm for a typical NEMS resonator spring constant.

IV. Prototype Device Fabrication and Modeling

We have designed and fabricated several prototype devices based on scheme A with Lorentz force excitation and readout using a SQUID. To test the principle of the readout method we have chosen to fabricate the prototype device to operate at MHz frequencies, rather than attempting to go directly to the GHz range. The first fabrication stage involved depositing an Nb superconducting thin film (~ 200 nm thick) on an oxidized Si substrate. This was then patterned into the overall geometry of a SQUID loop using conventional photolithography. Then two nanobridge Josephson junctions were etched into the loop using Focused Ion Beam (FIB) milling, producing constrictions down to a width of 80 nm [6].

To provide good mechanical/magnetic coupling between the NEMS resonator and the SQUID readout, we fabricated a mechanical resonator on the same substrate, directly above the SQUID loop. The mechanical resonator consists of a central Si beam 40 μm in length, 1 μm wide and of thickness 800 nm. At its center is a circular paddle 15 μm in diameter; the whole of this resonator is coated (before attachment to the SQUID) with 40 nm of Al to allow current to flow. Fig. 2 shows an SEM image

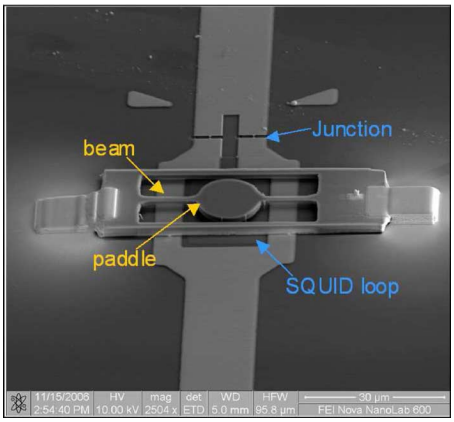

Fig. 2. SEM micrograph of an Al-coated Si paddle NEMS resonator e-beam welded to the substrate and coupled to a nanobridge dc SQUID. (Electrical connections were subsequently added to the resonator.)

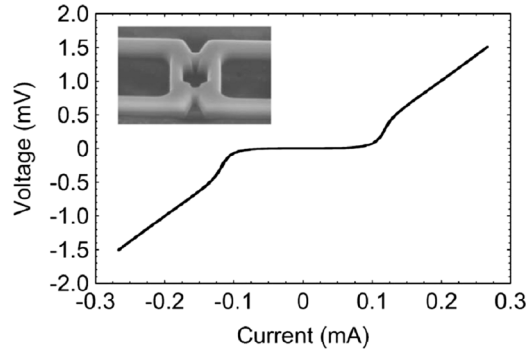

Fig. 3. SEM micrograph of a Nb nanoSQUID and its RSJ-like current-voltage characteristic [10]. The internal loop diameter is approximately 300 nm.

of the device. The center paddle of this design provides maximum inductive coupling between resonator and SQUID loop.

V. SQUID Readout

Our proposed technique involves the use of nanoSQUIDs (Superconducting Quantum Interference Devices) developed at NPL [5], [6] as readouts. This will require operation at cryogenic temperatures but this is already necessary to satisfy inequality (1). Close inductive coupling between SQUID and resonator 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 resonator, i.e. eventually approaching the nanoscale. There are different ways the readout could actually operate:

A. Inductance Modulation

By positioning a metallic (or especially superconducting) coated NEMS resonator close to the sensing loop of a nanoSQUID, the mutual inductance of the SQUID will be modified. The SQUID readout will then carry sideband information concerning the time dependent movement of the resonator.

B. Flux Modulation

If a ferromagnetic particle is attached to the vibrating cantilever the adjacent SQUID can detect the enclosed magnetic flux change as the particle moves. Alternatively, for the case of a conducting cantilever clamped at both ends, a direct current flowing through the cantilever produces a magnetic flux at the SQUID loop which will be modulated by the cantilever movement producing an alternating output signal.

C. NanoSQUID Fabrication

We have already demonstrated nanoSQUIDs with a loop size as small as 200–300 nm [6]—see Fig. 3 inset. It is also important for high sensitivity that the cantilever can be brought sufficiently close to the SQUID loop to maximize 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 superconductor-coated cantilever might be incorporated 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.

D. Modeling of Vibrational Modes

To model the vibrational modes of the beam and paddle combination we used COMSOL finite element software. For the physical parameters appropriate for bulk Si (Young's modulus $E = 170\ \mathrm{GPa}$ and density $\rho = 2329\ \mathrm{kg/m^3}$) the lowest mode frequency is found to be about 2.119 MHz with spring constant $k \sim 30\ \mathrm{N/m}$. This pure transverse oscillation of the paddle in the z-direction, and a simple torsional mode, are shown in Fig. 4. We have also modeled the same structure with the addition of a 40 nm Al coating, which results in only a small shift in the eigenfrequencies (see Table I).

E. Estimation of Displacement Sensitivity

Using the same finite element method 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 characterize the inductance variation as a result of the oscillation at a given amplitude. As an example consider a torsional mode of the paddle resonator shown in Fig. 2. For an angle ϕ between the plane of the SQUID loop and the paddle and an angle dependent self-inductance $L(\phi)$ of the SQUID loop the minimum detectable angular displacement $\delta\phi$ is related to the minimum detectable magnetic flux change of the SQUID $\delta\Phi$ by

$$\delta\phi = \delta\Phi L(\phi)\left[\frac{dL(\phi)}{d\phi}\right]^{-1} \tag{6}$$

. For our FIB patterned microbridge SQUIDs the measured flux noise (see Fig. 5) is not a strong function of the SQUID loop size, being predominantly determined by electronic noise voltage in the system. We therefore estimate for this resonator,

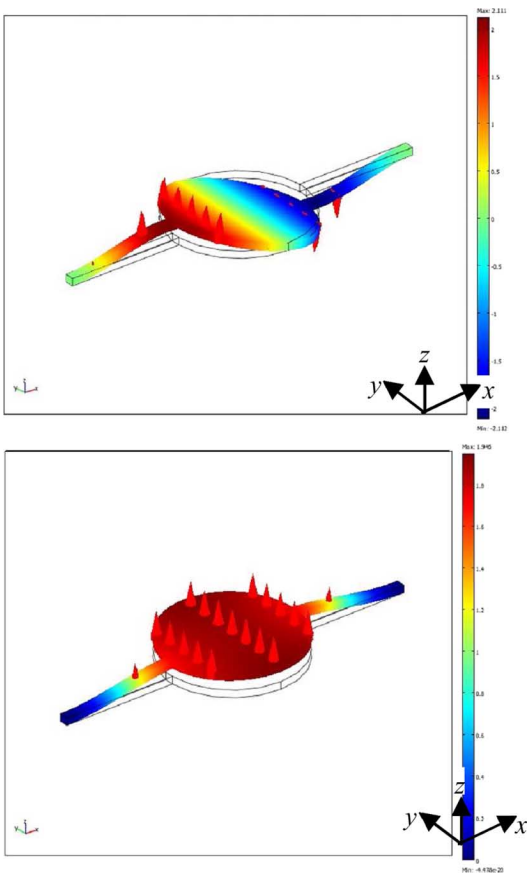

Fig. 4. Models showing (top) transverse and (bottom) torsional vibration modes for the paddle-shaped resonator. Black/white outline shows undistorted beam and paddle and arrows represent direction and amplitude of displacement.

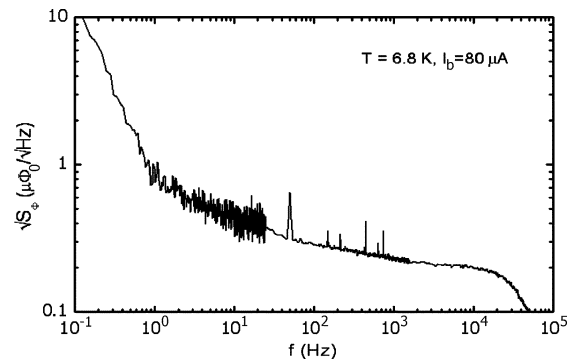

Fig. 5. Flux noise versus frequency for a Nb nanoSQUID at 6.8 K [10].

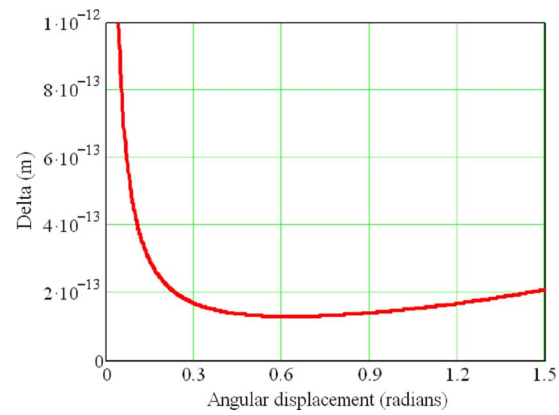

Fig. 6. Paddle edge displacement sensitivity in a 1 Hz bandwidth as a function of mean displacement angle in radians.

TABLE I
EIGENFREQUENCIES FOR Si BEAM/PADDLE AND Al COATED Si BEAM/PADDLE

Mode Number	f(MHz) for Al coated Si beam/paddle	f(MHz) for Si beam/paddle	Notes
1	2.1927	2.1192	z-displacement
2	2.2786	2.3693	x-torsion
3	3.0277	3.0738	x-torsion
4	7.6711	7.5811	x-torsion
5	7.8482	7.7684	y-torsion
6	27.339	26.365	high mode

with a filling factor of around 80% of the nanoSQUID loop, a flux sensitivity $\delta\Phi$ of $< 1\ \mu\Phi_0/\mathrm{Hz}^{1/2}$ so the displacement sensitivity of the paddle edge for this torsional oscillation mode is expected to be $< 10^{-13}\ \mathrm{m/Hz}^{1/2}$. The variation of displacement sensitivity of the paddle edge as a function of mean angle ϕ is shown in Fig. 6.

VI. CONCLUSIONS

NanoSQUIDs have been finding increasing range of applications in recent years (for a recent review see [11]). In this paper we have proposed and evaluated another potential use. The extreme sensitivity of SQUIDs, matched to the size of NEMS devices, should provide the highest sensitivity for future mass, force and displacement sensing.

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