FIB Fabricated Micro-Paddle Resonator for Mass Detection

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Abstract, An experimental MEMS paddle resonator was made using focused ion beam (FIB) fabrication from a 200-nm-thick silicon nitride membrane and investigated using a laser vibrometer for resonant frequency detection. The fundamental mode was found to be torsional, as required, with resonant frequency of 1.38 MHz and Q of 1070 at a test pressure of 20μbar. The mass sensitivity was 55ag/Hz, close to the results of analytical and FEA modelling, demonstrating proof of principle.

Keywords: MEMS, mass sensor, resonator, FIB

1. Introduction

The use of microelectromechanical systems (MEMS) in information technology and the automotive and aviation industries is already well established. As the biomedical and security sectors are added, their impact could become extremely important. In particular, there is a major interest in the detection of a range of molecules and organisms, including viruses and related proteins. This requires systems capable of detecting masses on the femtogram or attogram scales. Scale up from a single detector to a massively parallel array for high sensitivity devices, capable of simultaneous detection of a range of species, will require the development of submicron devices approaching the nanoscale, *viz.* nanoelectromechanics or NEMS. A resonant mechanical "spring and mass" device is an obvious choice as a mass detector in such systems.

Many researchers have shown that microcantilevers are a major candidate for such a task, providing exceptionally high sensitivity to the addition of mass in the attogram range [1–7]. Microcantilever sensor/actuator structures have been produced by a range of fabrication methods including FIB [8]. We have previously proposed, as an alternative, a novel paddle resonator system in which the "spring" action is provided by the torsional forces generated in a pair of supporting shafts [9]. This is prototyped using FIB fabrication from a 200nm thick membrane of LPCVD silicon nitride [10].

2. Theory and Design

Our paddle resonator is a double-clamped beam with large plate at the mid-point, as shown in figure 1. It is intended to resonate at a high fundamental frequency in torsion through the beams. The design is asymmetrical about the in plane axis of rotation in order to promote the torsional mode over a vertical oscillation. The plate is to be coated with chemically selective polymer compounds for biochemical detection. This structure has several advantages over the more common microcantilever systems, including:

- Larger area of detection with similar sized structure with less intrinsic bending in the beams due to the weight of the detecting plate
- Near-linear response to added mass
- Utilisation of bending moment to drive hence less power is required for significant displacement

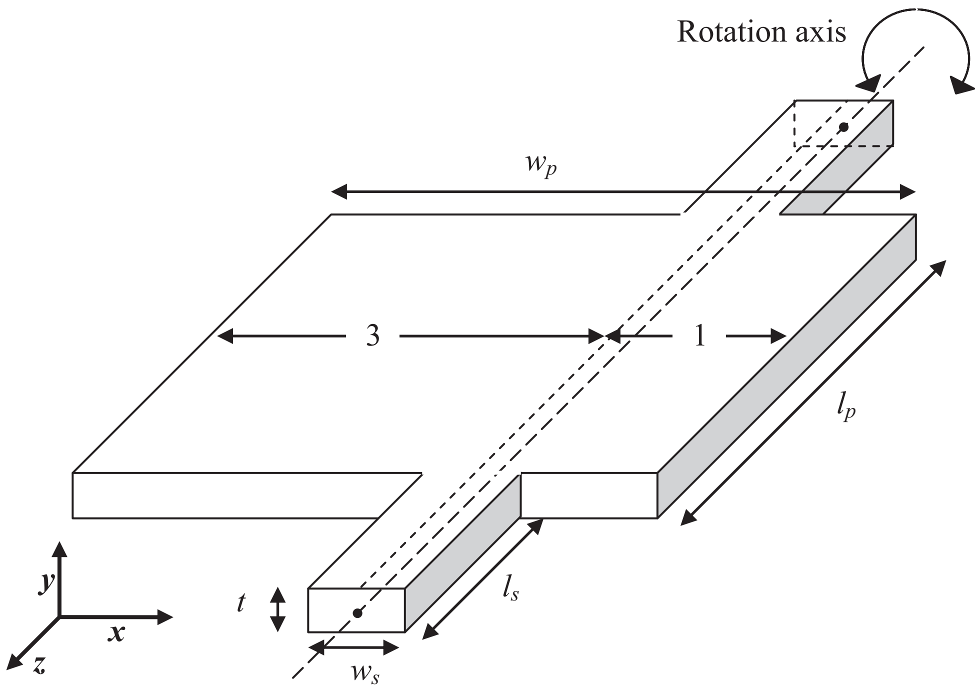

Figure 1 Schematic design of the asymmetrical paddle resonator.

(l_p= 8 µm, w_p = 10 µm, l_s = 2.5 µm, w_s = 1 µm, t = 200 nm)

The movement in the beams can be described by the torque-deflection equation [11]

$$T = GJ_t \frac{\partial \theta}{\partial x} \qquad (1)$$

Where T is the applied torque, G is the shear modulus of the membrane, θ the angle of twist and x the distance along the beam.

J_t is the *Torsional Parameter* of a non-circular bar which is defined as [12]

$$J_t = ab^3\left[\frac{16}{3} - 3.36\frac{b}{a}\left(1 - \frac{b^4}{12a^4}\right)\right] \qquad (2)$$

for a beam of rectangular cross-section (a ≥ b).

By considering a uniform shaft segment of length l_s, the *torsional stiffness* K_t may be written as

$$K_t = \frac{T}{\theta} = \frac{GJ_t}{l_s} \qquad (3)$$

During vibration, it is assumed that the plate is a rigid structure rotating about the weightless shafts. The plate is of density ρ and thickness t with rotational axis through the mid plane at ¾ of the width from the left and generates *Polar Mass Moment Of Inertia* J_P, given by

$$J_p = \rho l_p t \int_{-\frac{3w}{4}}^{\frac{w}{4}} \int_{-\frac{t}{2}}^{\frac{t}{2}} (x^2 + y^2) dxdy \qquad (4)$$

where l_p is the length of the plane and w its width, which gives

$$J_P = \frac{m_P}{48}\left(7w^2 + 4t^2\right) \qquad (5)$$

The natural or fundamental frequency f_n of the device is

$$f_n = \frac{1}{2\pi}\sqrt{\frac{2K_t}{J_P}} \qquad (6)$$

The fundamental frequency is dependent on the material properties. It is notoriously difficult to measure properties such as modulus and density for thin film membranes and the values will vary with chemical composition and manufacturing conditions. It was, therefore, decided use literature values, which were found *a posteriori* from modelling and experiments to be acceptable (see section 4, below). Poisson's ratio and density of LPCVD silicon nitride were found in the literature to be 0.27 and 3000 kgm^{-3} with little variation [13]. The Young's and shear moduli of the LPCVD silicon nitride are 101.5GPa and 40.0GPa respectively [13–16]. Using these values, the predicted fundamental frequency of the paddle resonator is 1.642 MHz.

A commercial finite element analysis package [17] was used to check the results of the above analytical model. It confirms that the fundamental mode is torsional and predicts a fundamental frequency of 1.508 MHz (see figure 2.). The difference between the analytical and FEA models is largely due to the deformation at the shaft-plate interface, shown in figure 3, which is ignored in the simple analytical model.

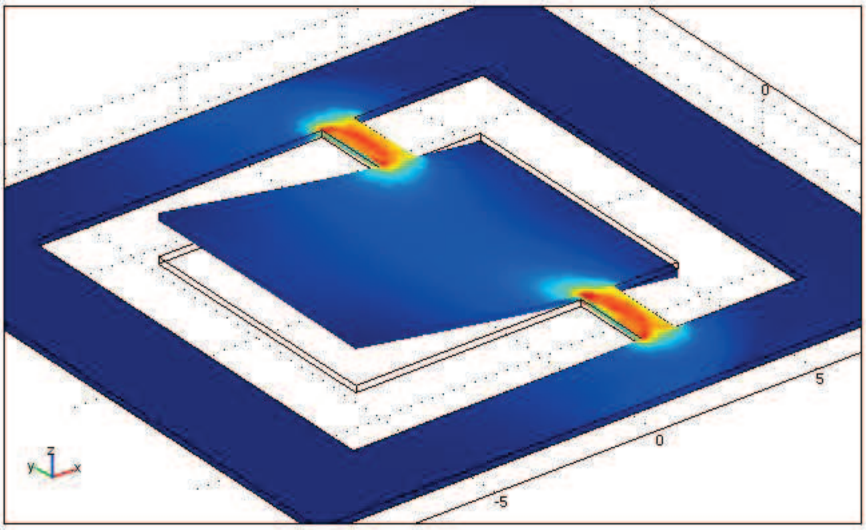

Figure 2 FEA model showing paddle displacement for fundamental mode, f_n = 1.508 MHz.

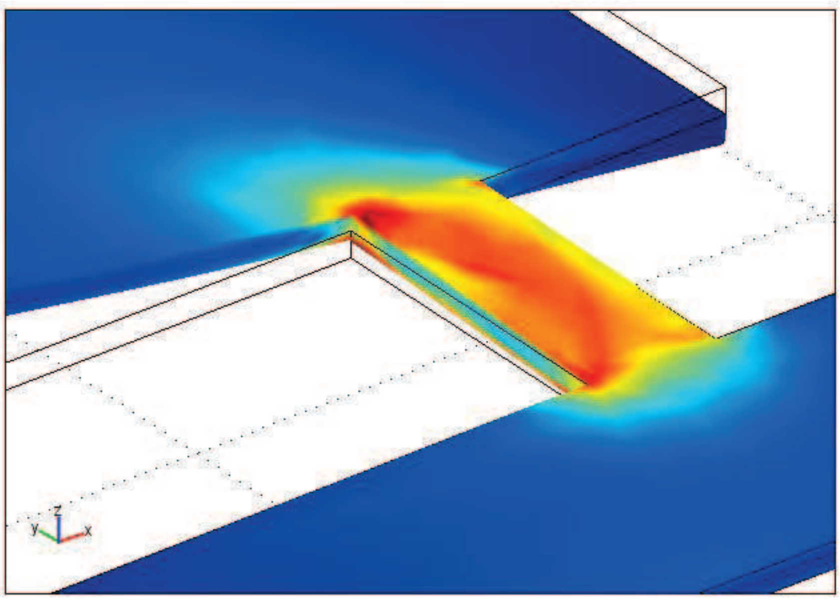

Figure 3 FEA analysis showing deformation at the shaft-plate interface.

An adsorbed mass of 1000 fg is chosen as representative of typical experiments. It is assumed that the detected mass is considerably less than the mass of the plate and equally spread to form a monolayer on the plate, which will be insignificant relative to the thickness of the plate. Hence the model must be modified to include the additional moment of intertia term ΔJ_p, due to the layer of thickness δ, where

$$\Delta J_p = \rho' l_p \int_{-\frac{3w}{4}}^{\frac{w}{4}} \int_{t}^{t+\delta} (x^2 + y^2) dx dy \qquad (7)$$

where ρ' is the density of Pt. This is evaluated using a first order expansion in $\frac{\delta}{t}$, justified since δ is small compared to t, to give

$$\Delta J_p = \frac{m_d}{48}(7w^2 + 12t^2) \tag{8}$$

The paddle is so thin that the terms in t^2 in equations (5) and (8) may be ignored giving a final modified polar moment of inertia to a good approximation as

$$J'_p \approx \frac{7(m_p + m_d)w^2}{48} \tag{9}$$

3. Fabrication

The material used to make the test device was a 200 nm-thick LPCVD silicon nitride membrane window supplied by Silson Ltd. [10]. All fabrication was done using the FEI Strata DB 235 Dualbeam™ FIB/SEM system at Birmingham [18]. The paddle was made by computer controlled FIB etching of the LPCVD silicon nitride membrane to produce a suspended structure, followed by platinum (Pt) deposition to simulate mass adsorption in operation. FIB etching and deposition was done using a beam of energy 30keV at probe currents of 300pA and 1pA respectively. The process exhibits good reproducibility for multiple-device-manufacturing capability. With 1000fg of controlled FIB Pt deposition, equation (9) predicts that the resonant frequency should decrease by approximately 16.8 kHz, giving a mass sensitivity value of 59.5ag/Hz. The FIB-deposited platinum appears as a light region in figure 4(b), compared with the virgin paddle (figure 4(a)).

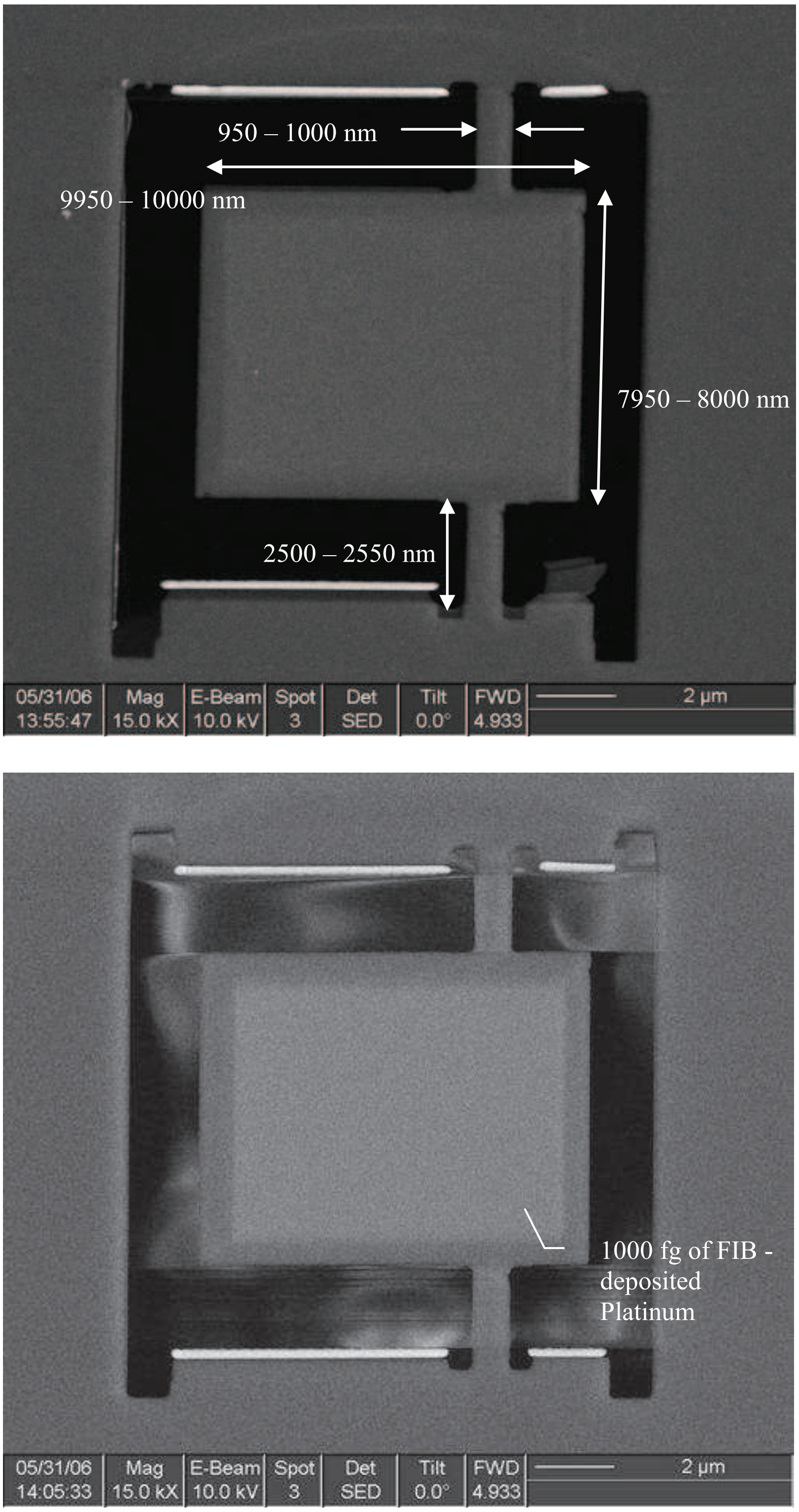

Figure 4 SEM image of (a) FIB-fabricated paddle resonator (b) with 1000fg Pt deposition to simulate mass adsorption.

4. Testing

The resonances of the paddle resonator, with and without the Pt coating, were measured using the Polytec OFV 501 laser vibrometer at Newcastle University [19] with an environmental pressure of 20µbar. The system utilises a 632nm wavelength He-Ne laser producing a focused spot with diameter below 10µm. The resonator design allows ultimately for an integrated electromagnetic actuator, but, in the meantime, an external piezoelectric transducer was used to excite resonance. The paddle was driven by a piezoelectric stage, which was scanned through the predicted resonance. Figure 5 shows the frequency scan response of the intrinsic paddle resonator with the fundamental frequency at 1.378 MHz with a quality factor of $Q = 1070$, calculated from figure 5, using $Q = \frac{f_{resonance}}{\Delta f_{@-3dB}}$. The experimental frequency is lower than, but close to, the value of 1.642 MHz predicted by analytical modelling and the FEA value of 1.508 MHz. (There is an uncertainty of 50 nm in paddle width – see figure 4 – which corresponds to an error ~0.3 % in the calculated frequency.)

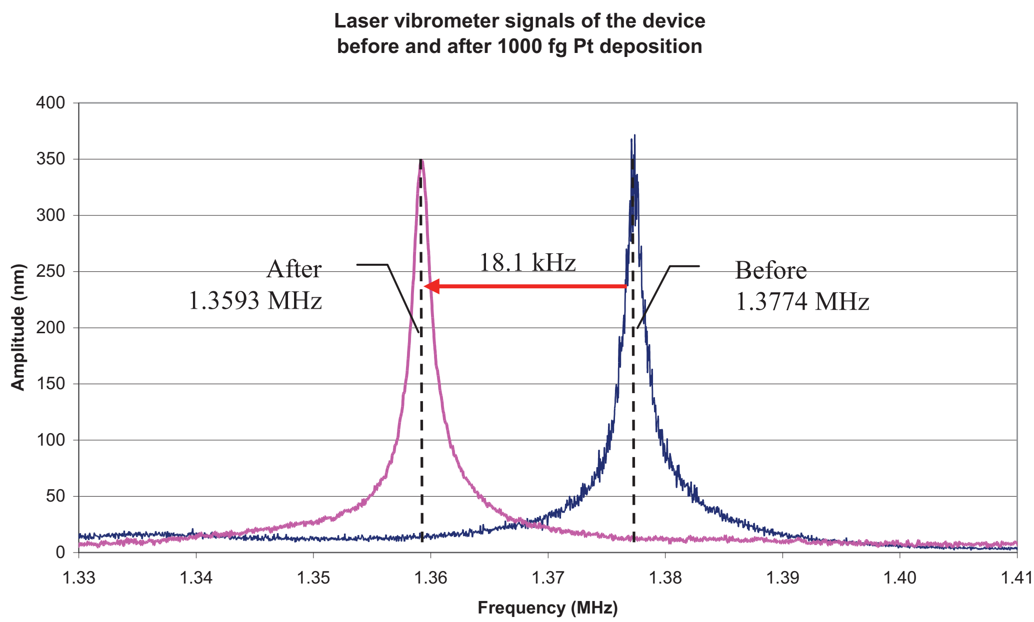

Figure 5 Experimental resonance scan results before and after 1000 fg Pt deposition.

The paddle with added mass of 1000 fg produced a shift in the frequency response curve, as also shown in figure 5. The shape of the shifted resonance peak is essentially the same with an insignificant change in Q to 1054. The resonant frequency was reduced by 18.1 kHz, corresponding to a mass sensitivity of 55ag/Hz, which is very close to the initially predicted value of 59.5ag/Hz (see section 3). The agreement with theory justifies the values for density etc. assumed *ab initio* in section 2.

The piezoelectric drive mechanism is useful for proof of principle experiments such as those described above, but, for a fully developed packaged device, an alternative integrated drive is necessary. This is also true of the readout where a replacement for the laser system must be found. An initial design study has been carried out, showing how an electromagnetic drive using the Lorenz Force can be incorporated into the device to produce the necessary resonance scan. The readout signal will be generated by a Faraday-Lenz electromagnetic coil induction system. This work will be reported in a future publication.

6. Conclusions

The paddle microresonator mass detector has considerable potential as a mass detection system, *inter alia* for biomedical and security applications, with several advantages over microcantilever devices. The design and theoretical analysis of such a system has been completed, showing good agreement between analytical and FEA models. An FIB tool has been used to fabricate devices in a 200-nm thick LPCVD silicon nitride membrane. FIB-generated test deposits of Pt have been used to mimic the effects of added mass in the 1000 fg range. Proof of principle has been demonstrated experimentally with frequency shifts close to those predicted. Integrated drive and readout capabilities are under development.

7. References

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