TUNING OF VIBRATING MICROMECHANICAL RESONATORS
USING A FOCUSED ION BEAM

D.F. Moore $^a$ and R.R.A. Syms $^b$

Abstract
The permanent tuning of the resonant frequency of in-plane vibrating micromechanical resonators is discussed, with particular reference to the tuning of the suspension stiffness rather than tuning of the mass. Iterative frequency tuning of laterally resonant electrostatic comb-drive microactuators by focused ion beam machining is demonstrated.

Introduction
The continuing large investment in silicon integrated circuits is leading to rapid advances in the technology to structure and modify material on the sub-micrometer scale. By-products of these technology developments include processes which have the potential to be used in a range of other engineering applications. One example is focused ion beam (FIB) technology which was primarily applied to (i) photomask modification and repair, and (ii) transmission electron microscope sample preparation. This paper describes novel FIB applications such as making cuts in silicon microbeams to tune the resonant frequency of mechanical microresonators.

Silicon Micromachining
Developments in micromachined silicon have recently been reviewed [1-4]. These include machining conventional silicon, the use of silicon-on-insulator starting material, and the application of deep profile lithographic processes and etching [5,6]. A wide range of devices and microsystems is emerging, and typical applications of micromachined silicon are in physical sensors [1].

D.F. Moore is with the Department of Engineering, University of Cambridge,
Trumpton Street, Cambridge CB2 1PZ U.K.
R.R.A. Syms is with the Department of Electronic and Electrical Engineering, Imperial College,
Exhibition Road, London SW7 2BT U.K.

$^a$ dfm1@iee.org $^b$ r.syms@ic.ac.uk
The use of frequency rather than amplitude to encode readout in a sensor gives good noise immunity. As a result, sensors based on vibrating elements have received considerable attention, and many physical and chemical parameters have been measured [1], including applications such as gyroscopes [7]. Resonant sensors are highly amenable to miniaturisation on silicon substrates; size reduction increases shock resistance, and the use of high-quality material reduces internal loss. Large quality-factors have been obtained from vibrating beams of both single-crystal silicon and polysilicon.

Defects and stresses can cause resonance shifts in vibrating microsystems, and methods of tuning must be made available [8-10]. In active tuning systems, stresses are applied electrostatically or electrothermally to elastic suspensions to change the resonant frequency. In passive tuning, dimensional changes are employed. Reactive ion etching has been used to apply dimensional changes globally, and focused ion beam machining to make local adjustments, for example to the size of a resonant mass. Recently, FIB machining has been used to adjust the stiffness of a comb drive electrostatic microactuator by making narrow cuts at the roots of a flexure suspension that effectively alter the suspension length [14].

Figure 1 is a schematic plan view of the microresonator. It comprises a light truss with a 2.6 mm span, supported by two flexures length 1.15 mm, thickness 7 μm and width 5 μm. The moving parts act as a mass spring system, and motion was excited by applying 13 V ac between the two halves of the comb drive. Figure 2 shows the frequency responses in air obtained each time FIB cuts were made. The simulated results given by the solid lines agree closely to the experimental data [14]. Figure 3(a) shows a secondary electron micrograph of the initial structure, and Figure 3(b) is after the first FIB cuts. This approach to processing has many possible applications because relatively delicate micromechanical structures can be cut with submicron precision. The application of focused ion beam processing enables submicrometer mechanical structures to be made [15].

A key application of passive frequency tuning may well be in frequency matching of coupled resonator systems. For example, coupled resonator gyroscopes operate by the coupling of energy between two different vibrational modes via coriolis forces [16]. Unfortunately, the coupling process rapidly becomes ineffective as the resonant frequencies of the two modes diverge. Because manufacturing tolerances often give rise to frequency variations, a method of passive tuning is therefore needed to restore synchronism. Using the approach above, we have now begun work on frequency matching of in-plane coupled resonator gyroscopes based on orthogonal electrostatic actuators cross-coupled by a flexible elastic suspension. Initial results show that similar frequency shifts may be achieved.
Conclusions
There are clearly many possible applications of tuning microresonators and the FIB approach is precise and versatile. The FIB is certainly useful for prototyping, and possibly for production.

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References
Figure 3. Electron micrographs of the resonator corresponding to Figure 2, taken in the FIB system using secondary electron imaging. (a) the untuned resonator, and (b) after the first FIB machining process.
Figure 1. Schematic plan view of the comb drive electrostatic microactuator used for the trimming tests. The freestanding structure is supported from two fixed lands, and the effective lengths of the two flexures can be increased by cutting slits at the machining sites on the fixed lands.

Figure 2. Displacement versus electrostatic drive frequency characteristics for the untuned resonator, the resonator after the first micromachining process, and after the second. The experimental data are plotted as points, and the simulation results are given as continuous lines.