Research Activities on Microengineering at Imperial College, London

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Work on microengineering commenced at Imperial College in 1992, following contact with Japanese researchers associated with the instigation of the MITI Large Scale Micromachine Project. Since then, this activity has grown in parallel with the two other main interests of the Section – integrated optics and microelectronics – allowing an extremely useful technical cross-fertilisation to take place. Links have been maintained with Japan, through exchange of personnel with the AIST Mechanical Engineering Laboratory, Tsukuba, and through project sponsorship by the Micromachine Center. The Section is equipped for device fabrication, having several clean rooms containing semiconductor processing equipment, chemical processing areas and test laboratories. Our current research ranges from the development of new fabrication processes to devices and systems, including the following:

- **Silicon Micromachining and Microactuators**

  We have devised a method of fabricating silicon MEMS based on a combination of surface and bulk micromachining. Only single-crystal material is used, and electrical isolation is provided by back-to-back p-n junctions. The devices are large compared with conventional surface micromachined components (several mm span, suspended 100 μm above the substrate), and have correspondingly large motions that may easily be observed in an optical microscope. Figure 1 shows a typical device. We have demonstrated wide-range electrothermal tuning of mechanical resonances, and are currently developing a coupled-resonator gyroscope incorporating an active frequency-matching system.

- **Piezoelectric Materials and Microactuators**

  We have been investigating different chemical routes for the fabrication of piezoelectric ceramics, for use as actuating layers on silicon microstructures. We have recently found an alternative to the sol-gel process, based on metal-organic decomposition. This allows rapid and reliable production of thick PZT films with good ferroelectric properties, and we are now fabricating bimorph cantilevers based on this material. We have also obtained preliminary results for a new type of microactuator operating by the electrical control of surface tension forces (electro-wetting).

- **3-D Microforming**

  We have devised low-cost alternatives to LIGA processing based on simple lithography tools. Deep metal microstructures may be built up by repeated application of a standard process cycle comprising 1) deposition of a conducting seed layer, 2) deposition of photoresist, 3) lithography, and 4) metal electroforming. By using this approach, and combining UV contact lithography with excimer laser micromachining, we have realised complex devices such as the six-level nickel microturbine shown in Figure 2, which has structural heights in the range 30 μm to 100 μm per level.

![Fig. 2. Six-level electroformed microturbine fabricated using resist moulds formed by UV lithography and excimer laser micromachining (shaft dia.: 200 μm).](image)

- **Parallel Assembly**

  We are interested in the generic problems of the handling of small components and their assembly into microsystems. We have recently demonstrated a wafer-scale parallel assembly process, in which elec-
troformed components supported on optically transparent carriers are detached by using pulsed laser irradiation through the rear side of the carrier to ablate an intermediate polymer layer. Transfer of components from one wafer to mate with components on another is then achieved simply by bringing the two wafers into proximity, aligning them, and then exposing the reverse side of the carrier to detach the required components. Figure 3 shows a typical motor structure, in which the rotor has been mounted on the stator by laser-assisted assembly.

Fig. 3. Wobble motor based on a rotor and stator that have been fabricated on separate substrates and brought together by laser-assisted assembly (rotor dia.: 1 mm).

• Self-Assembly of Three-Dimensional Microstructures

We are also studying methods for fabricating truly three-dimensional structures that cannot be made by lithography and etching (which form only quasi-3D structures). We have demonstrated a method of self-assembly based on out-of-plane rotation and fixing of flat parts. Rotation is powered by the surface tension force provided by pads of meltable material linking each movable part to the substrate. Rotation through a fixed angle (say, 90°) may be achieved using a simple mechanical limiter. Figure 4 shows a typical self-assembled structure, based on silicon micromachined parts and pads of low-melting point borophosphate glass. We are now developing applications of self-assembly, such as a folded inductor for high-Q microwave circuits.

• Optical and Optomechanical Devices

Over a number of years, we have developed a unique process for fabricating thick glass layers on silicon substrates, based on the sol-gel technique and the iterative use of spin-coating and rapid thermal annealing. This has allowed us to fabricate silicon-on-silicon waveguide components such as couplers and thermo-optic switches, and also to investigate novel materials for enhanced functionality. We have demonstrated optical nonlinearity in a semiconductor-doped glass waveguide, and are also investigating rare-earth doping for optical amplification. Our latest project involves combining waveguide components with microactuators for optical scanning and reading applications.

• Microanalysis Systems

We are attempting to construct silicon-based microanalysis systems. Anisotropic etching of (100) Si substrates is often used to form precision alignment features for locating optical fibres in ribbon connectors. We have used a similar approach to fabricate an alignment assembly for cylindrical electrodes. Figure 5 shows four electrodes arranged in the geometry of an electrostatic quadrupole lens. This lens can be used as an imaging element in an ion optical system. It can also be used as the mass analyser in a miniaturised mass spectrometer, and preliminary demonstrations of mass selection have recently been performed.

Fig. 4. 3-D microstructure fabricated by out-of-plane rotation of surface micromachined Si flaps using surface tension forces provided by pads of a low-melting point glass (flap height: 300 μm).

Fig. 5. Quadrupole electrostatic lens based on anisotropic etching of Si (electrode dia.: 500 μm).

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