A low-temperature process for mass-parallel self-assembly of three-dimensional micro-opto-electro-mechanical systems is described. The devices are fabricated by dry etching of bonded silicon-on-insulator wafers, and self-assembled by out-of-plane rotation powered by a surface tension torque obtained by melting thick pads of photoresist. Fixed optical mirrors oriented at 45° and 90° to the substrate are demonstrated, and electrostatically-driven resonant torsion mirror scanners with a wide angle of deflection are described.

INTRODUCTION

Three-dimensional (3-D) micro-opto-electro-mechanical systems (MOEMS) are miniature optical breadboards that process free-space optical beams travelling parallel to the surface of a silicon chip (1). The beams are typically 100 µm in diameter, and may travel short distances without appreciable diffraction. They are processed by optical components such as micro-lenses (2), mirrors and scanners (3, 4), that are initially fabricated flat by surface micromachining of polysilicon and silica, and are then rotated out of plane on flexible hinges (5).

The original processes were developed at Berkeley Sensors and Actuators Center (BSAC), and are now available commercially from Cronos Integrated Microsystems (6). Although the multi-user MEMS process (MUMPS) is now highly developed, it is complex (involving 7 layers: 1 isolation nitride; 3 structural polysilicon; 2 sacrificial silica and 1 metal), and the mechanical parts are fabricated from thin (2 µm) polysilicon. Furthermore, the MOEMS structures must be assembled manually or using further subsystems such as linear vibromotors (7).
Alternative MEMS fabrication processes have been developed based on the use of bonded silicon-on-insulator (BSOI). BSOI consists of an oxidised silicon wafer carrying an extremely thick bonded silicon layer (the device layer), and is now the material of choice for deep etched micromechanical devices, since it allows virtually strain free mechanical parts to be made in single crystal Si layers with thickness up to several hundred µm (8,9).

Processes for mass-parallel self-assembly of micromachined parts have also been developed at Imperial College, using out-of-plane rotation powered by surface tension forces of pads of a meltable material (10). Due to the advantageous size scaling of surface tension force compared with gravitational force, surprisingly large microstructures can be manipulated in this way, and processes powered by solder (11, 12) and low melting point glass (13) have been demonstrated. Recently, we have developed a simple two-mask process based on parts formed from 4” industry-standard bonded silicon-on-insulator wafers and meltable pads of thick commercial photoresist (14). Here, we describe its application to 3-D MOEMS devices.

BSOI PROCESS FOR SURFACE TENSION POWERED SELF-ASSEMBLY

Figure 1 shows the process. Bonded silicon-on-insulator material consisting of 4” (100) Si substrates carrying 6 µm thick bonded Si layers on 2 µm thick thermal oxide was manufactured by BCO Technology. The mechanical parts were first formed by reactive ion etching through the bonded layer with a parallel plate etcher (Plasma Technology RIE80), using CHF₃, O₂ and Ar gas. The etched wafer was then annealed to promote adhesion, spin-coated with Hoechst AZ4562 photoresist, pre-baked, exposed using a standard UV mask aligner, and developed. A spin speed of 1400 rpm yielded hinge driver pad thicknesses of 11.5 µm.

Previous work [10] has shown that the optimum ratio between the height h of the hinge driver pads and their width 2w for 90° rotation is \( \eta = \frac{h}{w} = \frac{\pi + 2}{8} = 0.6427 \), and that thicker pads yield smaller final rotation angles. To ensure at least 90° rotation, a width of 2w = 36 µm was used, corresponding to \( \eta = 0.639 \) for 11.5 µm resist thickness. The hinge gap is fixed at 2.5 µm, and the hinge drivers were segmented into 250 µm sections to ensure complete undercut during sacrificial layer etching.

The dimensions of the movable parts were 250 µm to 1000 µm parallel to the axis of rotation, and up to 720 µm orthogonal to it. The clearance between the moving parts was fixed at 4 µm. To free the movable parts, the oxide was removed by etching in 7 : 1 buffered HF, which penetrated through 4 µm square holes on 20 µm centres. The etch time was determined by the half-width of the hinge driver pads, and for the dimension above was 7.5 hrs. To ensure adhesion of the resist pads, they were premelted at 110°C for 30 mins. Figure 2a shows typical structures at this stage of processing. The meltable photoresist pad, whose length is 250 µm, has clearly formed into a semi-cylindrical cross-section except near its end.
After washing, samples were freeze dried in a mixture of Aristar methanol and distilled water. Assembly was carried out by melting in a convection oven at temperatures in the range 130 - 150°C. To improve optical reflectivity, and to provide electrical connection to the movable parts across the insulating resist pads, samples were then metallised by sputter coating with 500 Å of Al. Figure 2b shows the structure of Figure 2a after self-assembly; the part in view has rotated out-of-plane through an angle of 45°. No warpage is apparent, implying very low stress and high mechanical quality in the BSOI material. The hinge gap is closed, confirming that surface tension has held the structure together during assembly.

3D MICRO-OPTOMECHANICAL DEVICES

The process described above has proved capable of parallel assembly of a variety of MOEMS structures, including symmetric and asymmetric 45° mirrors, electrostatically driven wide-angle torsional mirror scanners and 90° mirrors. Figure 3 shows assembly of 45° mirrors, which requires simultaneous rotation of a pair of flaps. The two flaps rotate in opposite directions, powered by the surface tension torque of two sets of hinge driver pads. After 45° rotation, further movement is prevented by a pair of simple mechanical latches, which are fabricated coplanar with the remainder of the structure. Here the largest mirror has a base width of 1000 µm and a height of 500 µm orthogonal to the wafer plane.

For structures in this size range, the influence of gravitational torque appears negligible. Similarly, at moderate melt temperatures, assembly dynamics are dominated by the viscosity of the resist rather than the inertia of the parts. Consequently, accurate assembly may be achieved with both symmetric and asymmetric structures, suggesting considerable design flexibility. Goniometer measurements show an average alignment error of ≈ 0.5° in correctly-assembled structures.

These structures may be modified to form scanning devices by replacing the fixed mirror with a frame carrying a smaller movable mirror mounted on a torsion bar, as shown in Figure 4. Here, the movable mirror measures 456 µm parallel to and 496 mm perpendicular to the axis of rotation. Each half of the torsion bar is 324 µm long, 8 µm wide and 6 µm deep. Oscillation at the torsional resonant frequency may be excited electrostatically, using a skewed electrostatic comb drive located at the base of the mirror. The moving half of the comb contains 19 fingers, each 8 µm wide and 60 µm long, and the electrode gap is 4 µm. The frequency response is typical of a single-degree of freedom resonant structure, with a Q-factor of ≈ 60, and optical scan angles of ≈ 10° may easily be obtained. Performance is comparable to that of devices fabricated by BSAC [4,5], although the drive voltage is currently somewhat higher.

Assembly of 90° rotated structures requires further modification, combining simultaneous and sequential self-assembly. Figure 5 shows the principle: simultaneous
rotation is used to construct a pair of 45° rotated assemblies, which now merely carry mechanical limiters designed to prevent rotation past 90° of an additional mirror flap, which completes its rotation only after the supporting structure has assembled.

CONCLUSIONS

Surface tension self-assembly has been shown to be a versatile technique for accurate, mass-parallel assembly of 3D microengineered structures. It is particularly suited for construction of devices which require features to be patterned and set up out of the wafer plane, such as MOEMS components. However, analogous applications exist for beam processing elements in microengineered electron and ion optical systems, for example in vacuum microanalysis devices such as mass spectrometers.

REFERENCES

Figure 1. Process sequence for surface tension self-assembly of BSOI microstructures.

Figure 2. BSOI microstructures a) flat, before sacrificial etching; b) after self-assembly.
Figure 3. a) CAD pattern and b) structure of self-assembled 45° mirrors.

Figure 4. a) 3D electrostatic resonant torsion mirror scanner; b) frequency response.

Figure 5. a) CAD pattern and b) structure of 90° mirrors formed by sequential assembly.