Measurement of Starting Torque in Surface Tension Self-Assembly of Microstructures

By

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Abstract

The torque available at the start of out-of-plane rotation in surface tension powered self-assembly of microstructures is measured by deformation of an elastic spring. Values confirm to theoretical estimates and show that surface tension torque can overwhelm the gravitational counter-torque for realistic components in the microstructure size regime.

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Surface tension powered self-assembly is a method of constructing three-dimensional microstructures. Movable parts are fabricated flat by surface patterning and sacrificial etching, and rotated out of the wafer plane by a surface tension torque obtained by heating small pads of meltable material linking moving parts to the substrate. The technique has been demonstrated using metal (Pb:Sn solder)3,4, glass (BPSG)7 and polymer (thick photoresist)6 as the meltable material, and single-crystal silicon3,7, bonded silicon8, polysilicon4 and electroplated Ni3 and Cu6 as the mechanical material.

Surprisingly large structures (e.g., the torsion mirror scanner shown in Figure 1a, whose frame has a height of 500 µm) can be assembled in this way. Physical considerations suggest that because of its advantageous size scaling, surface tension force (which scales as dimension) should overcome elastic forces (dimension squared) and self-weight (dimension cubed) if the size of a structure is sufficiently reduced. To identify the limits of surface tension self-assembly, it is important to measure the torque available. This can be done with an elastic torque gauge, as we now show.

Figure 2a shows the geometry, which consists of two self-assembling parts on a 1 mm baseline. Normally, the surface tension torque would cause these to rotate in opposite directions through 45°, until a mechanism engaged to prevent further movement (as in Figure 1a). However, in the experiment here, each movable part is linked to the fixed land near the hinge by a meander spring, formed from a series of short axial stubs joined by N long transverse beams, each of length L, breadth b and depth d. Rotation now ceases when the resisting torque of the spring balances the surface tension torque. If the spring stiffness is known, the surface tension torque may then be found from the final angle, and if this angle is small, the value thus obtained is the starting torque.

The parts are constructed by deep reactive ion etching through the 5 µm thick bonded Si layer
of a bonded silicon on insulator wafer. The movable parts are perforated with 4 μm square holes on a 20 μm pitch, to allow removal of a 2 μm sacrificial layer of SiO₂ using buffered HF. The movable and fixed parts are linked by 250 μm x 40 μm pads of 12 μm thick Hoechst AZ4562 resist. The springs have N = 12 transverse beams of breadth b = 6 μm, and depth d = 5 μm, and lengths of either L = 500 μm or L = 250 μm. Figure 1b shows a gauge with short springs, after melting the resist at 145°C for a time sufficient for normal assembly. Clearly, the springs limit the rotation drastically.

The heights of different parts above the substrate were measured using an optical microscope equipped with a x 50 objective lens and a Mitutoyo linear motion gauge. These data were used to calculate the angle of rotation of the odd numbered transverse beams in the spring, and the total angle. Figure 3 shows the variation of angle with beam number, for two springs with different beam lengths. In each case, the total angle of rotation is a few degrees. The angle varies linearly with position along each spring, and the stiffness provided by the longer beams is roughly half that of the shorter beams.

The torsion stiffness may be estimated by neglecting any twist in the short axial segments linking the transverse beams, and assuming that the beams distort only by bending. Symmetry aspects then dictate that the loading and deformation of each beam are as shown in the exaggerated diagram of a single beam in Figure 4a, which has one end clamped and one pinned, with a moment M applied to the pinned end. As a result, the deformation of the whole structure will be as in Figure 4b. Each transverse beam contributes a torsion stiffness of \( K_i = M/\theta = 4EI/L \) to the spring, where E is Young’s modulus (taken as 1.08 x 10¹¹ N/m² for Si) and \( I = bd^3/12 \) is the second moment of area. The overall torsion stiffness of the spring is then \( K = K_i/N \).

For L = 500 μm, the spring stiffness is \( K = 4.5 \times 10^{-9} \) Nm/rad, which corresponds to a torque of \( M = 2.88 \times 10^{-10} \) Nm for the angular deflection of 3.67° shown in Figure 3. Previous calculations have suggested that the maximum available starting torque in surface tension self-assembly is \( M' = \gamma w/2 \) per unit length of hinge driver pad, where \( \gamma \) is the surface tension coefficient and \( w \) is the half-width of the pad (here, 20 μm). Assuming a typical value of \( \gamma = 0.4 \) N/m, this corresponds to a total torque of \( 10^{-9} \) Nm from a pad of length 250 μm. The close correspondence between \( M \) and \( M' \) suggests that surface tension self-assembly operates essentially as predicted.

For a rectangular movable part of radial span \( L_p \), the gravitational counter-torque is \( M'' = \rho g L_p^2 d/2 \) per unit length, where \( \rho = 2330 \) kg/m³ is the density of Si, and \( g = 9.81 \) m/sec². For \( L_p = 700 \) μm (as here), this corresponds to a torque of \( 7.14 \times 10^{-12} \) Nm for a part of 250 μm width. The measured assembly torque is therefore \( \approx 40 \) times greater than the maximum likely gravitational counter-torque, and hence can overwhelm it. These two results confirm the essential features of surface tension self-assembly.
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References


Figure 1. a) Self-assembled 3D optical torsion mirror scanner; b) torque gauge.
Figure 2. Layout of surface tension powered assembly torque gauge.

Figure 3. Variation of rotation angle with beam number, for two different springs.

Figure 4. Simplified model for deformation of a) single beam element and b) entire spring.