Surface Tension-Powered Self-Assembly of Microstructures—The State-of-the-Art

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Abstract—Because of the low dimensional power of its force scaling law, surface tension is appropriate for carrying out reshaping and assembly in the microstructure size domain. This paper reviews work on surface tension powered self-assembly of microstructures. The existing theoretical approaches for rotational assembly are unified. The demonstrated fabrication processes are compared. Mechanisms for accurately determining the assembled shape are discussed, and the limits on accuracy and structural distortion are considered. Applications in optics, electronics and mechanics are described. More complex operations (including the combination of self-assembly and self-organization) are also reviewed. [926]

Index Terms—Capillary force, microelectromechanical systems (MEMS), microsystems, microoptoelectromechanical systems (MOEMS), self-assembly, surface tension.

I. INTRODUCTION

SURFACE tension is the force responsible for a variety of physical phenomena involving small volumes of liquid [1]. These include the rise of fluids in capillaries, the spherical shape of liquid droplets, the fragmentation of liquid jets into streams of droplets, and so on [2]–[5]. In the natural world, the shapes of many large organisms are dominated by body weight. However, gravitational forces scale with dimension cubed, while surface tension forces scale linearly with dimension [6]. Consequently, as overall size is reduced, there eventually comes a size regime in which surface tension forces dominate. The shape of smaller organisms is often dictated by considerations of surface force [7].

In the size domain of microstructures, surface forces are overwhelming. A variety of older applications for surface tension exist in microelectromechanical systems (MEMS). For example, reflow moulding has been used to reshape solder into balls, for improved alignment in flip-chip assembly, a widely used industrial process [8], [9]. These techniques have been adapted to the more demanding environment of optical packaging, in what is widely referred to as “silicon optical bench

technology”. Surface tension has been used for alignment of hybrid integrated semiconductor laser diodes [10], [11], silica based planar lightwave circuits [12], and photodiodes [13]. The first two applications involve coupling of waveguide components, when micron-level misalignment creates significant optical loss. In some cases, additional passive structural features have been used to assist alignment.

Remaining in the optical domain, spherical lenses have been formed by melting the ends of optical fibers for improved coupling to lasers. Lenslet arrays have been made by melting cylindrical pillars of photoresist [14], and by polymerising sessile drops constrained to lie on disc-shaped lands [15]. Waveguide losses have been reduced, by melting cores into a cylindrical section, removing sidewall roughness in the process [16]. Finally, within MEMS, surface tension forces are also responsible for the collapse of microstructures during removal of sacrificial layers [17].

Surface tension has also been used to carry out *directed* operations, in which microstructures are reconfigured. There are two types of operation: reorientation of precisely located parts into three-dimensional (3-D) structures, and aggregation of randomly oriented parts. Both are generically known as “self-assembly”, although the latter is closer to “self-organization”. Both are the topic of the present paper, which reviews the state-of-the-art.

Section II reviews surface micromachining processes, concentrating on those used to form 3-D microstructures. Several analytic tools relevant to surface tension problems are introduced in Section III. These are applied to a two-dimensional (2-D) geometry for powered rotation in Section IV, and a comparison is then made with a finite element approach capable of modeling 3-D liquid surfaces. Demonstrated processes for 3-D self-assembly are described in Section V, together with a discussion of the motion limiters needed to obtain accurate assemblies. Other mechanical issues such as stability and structural distortion are also considered. Mechanical, electrical and optical applications of rotational self-assembly are described in Section VI. Methods for increasing complexity by combining self-assembly with self-organization are then reviewed in Section VII, and conclusions are presented in Section VIII.

II. SURFACE MICROMACHINING

The rapid growth of MEMS since the late 1980s has been driven by the development of fabrication techniques capable of forming complex microstructures. A key enabler has been the

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Fig. 1. (a) Surface micromachining processes; (b) fold-out hinge; (c) assembled Fresnel lens (photos courtesy K. S. J. Pister and M. C. Wu).

methods of surface micromachining. A number of primary variants of this technology exist, as shown in Fig. 1(a). We now give a brief review of these.

A. Polysilicon Surface Micromachining

Surface micromachining exploits differences in properties of deposited materials to form quasi-3-D features. The original process combined complementary metal oxide semiconductor (CMOS) technology with the deposition of polycrystalline silicon (polysilicon) mechanical layers onto silica layers. The silica can be preferentially etched to form suspended structures [18]–[21]. The stress in the polysilicon can be made extremely

low. The layer thickness is, however, normally limited to a few microns, and the material properties are generally inferior to single crystal silicon.

The cycle of deposition, patterning and etching of each material can be repeated to build up multilayer structures, and the components of a structure can have a wide range of shapes. Polysilicon micromachining is widely used, and has been developed as multi-user processes in the United States at (for example) the Cronos foundry [22] and Sandia National Laboratories [23], who operate an IC-compatible five-level process [24].

B. Other Surface Micromachining Processes

Similar surface micromachining processes have been developed using electroplated metals such as nickel as the mechanical layer, and other metals or polymers as the sacrificial material [25], [26]. Feature heights have increased significantly with the development of new thick-layer resists [27], [28]. The main advantage of metal micromachining is its low temperature, which has allowed postprocessing of MEMS onto completed circuits [29].

Another promising process uses bonded silicon-on-insulator (BSOI). BSOI is a silicon wafer that is thermally bonded to an oxidised Si substrate and polished to the desired thickness ($5\text{ }\mu\text{m} - 200\text{ }\mu\text{m}$) [30], [31]. The bonded layer is then patterned by deep reactive ion etching (DRIE), which uses an inductively coupled plasma and specialised etch chemistry to form deep features with near-vertical walls [32], [33]. As with the processes above, movable structures are made by removal of the buried oxide. Etching of extremely deep structures is now well understood, both using the cyclic etch-passivate DRIE process [34] and with the alternative cryogenic DRIE process [35].

Although DRIE of BSOI often involves single-stage processing, rather than repetitive cycles, its end products are often similar to surface micromachined devices. Its advantages are improvements in thickness, surface flatness and mechanical properties of the structural layer. Processes are now being developed for DRIE of polysilicon [36], or for depositing polysilicon in deep etched silicon moulds to create high aspect ratio microstructures [37].

C. 3-D Structures

The structures obtained by surface patterning are only quasi three-dimensional. Attempts have been made to reconfigure microstructures, using thermal mechanisms or residual stress [38], [39]. Complex microstructures have also been assembled by hand [40]. A key advance was made with the realization that fully 3-D structures can be made by rotating parts out of the wafer plane, and latching them into position. Suitable hinges based on elastic links [41], [42] were rapidly superseded by polysilicon staple hinges [43]–[45]. These can easily be integrated into multi-user MEMS processes as shown in Fig. 1(b). Some structures have even been fixed after assembly using snap action microrivets [46].

An important application was then found in 3-D microoptoelectromechanical systems (MOEMS), in which rotational assembly is used to create small optical subsystems that process free space beams travelling above the surface of a chip [47]–[49]. 3-D MOEMS components developed to date

include refractive [50] and Fresnel lenses [51], corner cube reflectors [52], Fabry-Perot etalons [53], mirror scanners [54], and bar-code readers [55]. For example, Fig. (1c) shows a lens assembly consisting of a polysilicon frame carrying an etched Fresnel lens. The frame is held normal to the substrate by rotated latches.

In the telecommunications domain, 3-D MOEMS devices using moving mirrors have been shown to outperform conventional devices (for example, guided wave interferometers). A variety of switches have been developed, based on arrays of pop-up mirrors [56], [57] and single-axis [58], [59] and dual-axis [60] torsion mirrors. Of these, the best known is the Lucent Wavestar (Wavestar is a trademark of Lucent Technologies) micromirror, which uses a self-assembled, linked mechanism to space the mirrors away from the substrate and hence allow a large turn angle [61].

Active methods used to power the rotation include scratch drive actuators [62]–[64], linear vibromotors [65] and micro-engines [66], [67]. Although these actuators allow dynamic adjustment and have good resolution, they are relatively inaccurate and cannot be used in open loop systems. They are also complex, consume a large chip area, and have not been proven to have sufficient reliability for practical devices.

More compact (and potentially parallel) actuation mechanisms include magnetic deflection [68], [69], thermal shrinkage of polymers such as polyimide [70], [71], and electrochemical shrinkage of conducting polymers such as polypyrrole [72], [73]. However, for one-time assembly, surface tension force (the subject of this paper) has been one of the most powerful drivers.

D. Stiction

Although MEMS reliability has improved, stiction remains a problem. Stiction can arise through collapse during sacrificial etching [17], or by the contact of moving parts [74]. Many anti-stiction treatments have been developed, including hydrophobic fluorocarbon coatings [75], Teflon-like coatings [76], self-assembled monolayers [77] and anodization [78]. Controlling surface tension is thus of considerable importance in MEMS.

III. SURFACE TENSION

In this section, we review some standard analyses of surface tension effects. We first demonstrate the existence of a pressure difference between a droplet and its surround, and show that this pressure is uniform in equilibrium. We verify the advantageous size scaling of surface tension. Finally, we discuss boundary conditions relevant to self-assembly, and the magnitude of the surface tension coefficient.

A. The Laplace Pressure

Initially, we consider a small, roughly rectangular element of a convex curved surface, the interface between a liquid and a vapor [see Fig. 2(a)]. The lengths of its sides are L_1 and L_2 , so that its surface area is $s \approx L_1 L_2$. Its surface energy is defined as $U_s = \gamma s$, where γ is the surface free energy of the liquid-vapor interface per unit area. We first use virtual work to show that the surface curvature causes a pressure difference ΔP (the Laplace

pressure) between the liquid and the vapor [1]. If we ignore gravity, and assume the surface moves parallel to itself by a distance δ , some work $dW = \Delta P dv$ must be done against the Laplace pressure, where dv is the change in the liquid volume beneath the element. If the surface area changes in the process by ds , the surface energy will also change by $dU_s = \gamma ds$. Since dU_s and dW must be equal, we may write

$$dU_s - \Delta P dv = 0. \quad (1)$$

Assuming that the length L_1 changes to $L_1 + dL_1$, and so on, the change in area of the element is $ds \approx \{L_1 dL_2 + L_2 dL_1\}$. Now, the surface may be described locally in terms of two orthogonal radii of curvature r_1 and r_2 , so we may write $dL_1 = L_1(\delta/r_1)$, and so on. The change in area is therefore given by $ds \approx \delta L_1 L_2 \{1/r_1 + 1/r_2\}$. It is trivial to show that $dv \approx \delta L_1 L_2$. Substituting into (1), we find that the Laplace pressure is given by

$$\Delta P = \gamma \left\{ \frac{1}{r_1} + \frac{1}{r_2} \right\} \quad (2)$$

Two simple results emerge from (2): for a cylindrically curved surface, one radius of curvature is infinite (so we can write $\Delta P = \gamma/r$), while for a spherically curved surface, both radii are equal (so that $\Delta P = 2\gamma/r$). The Laplace pressure is therefore inversely proportional to curvature, so that large pressures can arise for small droplet radii. A concave surface (which has negative radii of curvature) has a negative Laplace pressure.

B. Conditions for Global Equilibrium in Droplets

Generally, a liquid droplet will assume a shape that minimizes its surface free energy. For a closed surface S , the total surface energy is:

$$U_s = \gamma \int_S ds. \quad (3)$$

At a minimum in surface energy, U_s is stationary. We now use virtual work to show that this condition is consistent with an alternative statement of equilibrium, namely that a droplet of incompressible fluid will assume a shape that eliminates pressure gradients. For example, if the surface moves parallel to itself by a distance δ that is now *variable* over the surface, the work dW done against a Laplace pressure ΔP (also now assumed variable) is

$$dW = \int_S \int \Delta P \delta ds. \quad (4)$$

Equating dW with dU_s once again, we obtain $dW = 0$. However, the total change in volume dv arising from this displacement is

$$dv = \int_S \int \delta ds. \quad (5)$$

Since the liquid is assumed to be incompressible, we must have $dv = 0$. If this condition is met, dW will automatically be zero if $\int_S \int \Delta P \delta ds = \Delta P \int_S \int \delta ds$, i.e., if the Laplace pressure is constant. Note that, from (2), the condition for constant Laplace

Fig. 2. a) Geometry for calculation of Laplace pressure; b) force balance in a hemispherical droplet; c) liquid droplets on different surfaces.

pressure is that $((1/r_1) + (1/r_2))$ is constant. A spherical droplet is the simplest that satisfies this criterion. However, there are other possibilities, and many cylindrically symmetric droplets were described by Plateau in the 19th century [3]. The degree of stability of these alternatives will depend on their Laplace pressure, as higher values will involve higher strain energies.

C. Scaling of Surface Tension Forces With Size

Results of this type may be arrived at more simply. For example, consider a spherical droplet, which has been bisected as shown in Fig. 2(b). Due to the surface tension, a force $F_\gamma = \gamma 2\pi r$ acts on the circumference of each hemisphere. Due to the Laplace pressure, a force $F_P = \Delta P \cdot \pi r^2$ acts on the base. In

TABLE I
SURFACE TENSION COEFFICIENTS OF COMMON MATERIALS

Material	γ (N/m)	θ (°C)	Ref.
Water	0.07275		[79]
<i>Organic Liquids</i>			
Benzene (in air)	0.029	20°	[80]
Ethyl Alcohol (in air)	0.023	20°	[80]
Methyl Alcohol (in air)	0.023	20°	[80]
n-Propyl Alcohol (in vapour)	0.024	20°	[80]
<i>Common Elements</i>			
Antimony	0.382	630°	[81]
Bismuth	0.378	270°	[81]
Gold	1.07	1200°	[80]
Indium	0.561	160°	[81]
Mercury	0.472	RT	[79]
Silver	0.944	960°	[81]
Lead	0.465	327°	[81]
Tin	0.574	232°	[81]
<i>Lead-Tin Solders in Inert Atmosphere</i>			
Pb:Sn 80:20 (mass)	0.454	350°	[82]
Pb:Sn 60:40 (mass)	0.466	350°	[82]
Pb:Sn 40:60 (mass)	0.482	350°	[82]
Pb:Sn 20:80 (mass)	0.503	350°	[82]
<i>Lead-Tin Solders in Colophony Flux Atmosphere (chlorine content 1%)</i>			
Pb:Sn 40:60 (mass)	0.34	250°	[83]
<i>Lead-Free Solder Alloys in Air</i>			
Sn-3.5Ag	0.431	271°	[84]
Sn-0.7Cu	0.491	277°	[84]
Sn-0.58Bi	0.319	188°	[84]
Sn-9Zn	0.518	249°	[84]
<i>Silicate Glasses</i>			
Molten vitreous silica	0.3	1800°	[85]
Sodium silicate (32.9 mol % Na ₂ O)	0.2864	1000°	[86]
Aluminosilicate (20 wt % Al ₂ O ₃)	0.405	1700°	[86]
Sodium borosilicate (16:8:76 molar)	0.287	1300°	[86]
<i>Polymers</i>			
Poly (propylene)	0.029	RT	[87]
Poly (styrene) (MW 9300)	0.039	RT	[87]
Poly (tetrafluoroethylene)	0.024	RT	[87]
Poly (methyl methacrylate)	0.041	RT	[87]
Nylon 66 (MW 17000)	0.047	RT	[87]

equilibrium, these forces balance, leading again to $\Delta P = 2\gamma/r$. Each force component clearly scales as the dimension, while the Laplace pressure itself scales inversely with the dimension.

When surface tension effects are exploited in MEMS, the aim will often be to use a combination of the surface tension and Laplace pressure for actuation. At equilibrium, these bal-

ance each other. They may, however, differ in other circumstances. When out of equilibrium, and especially with small drops, the resulting forces can be very strong. For sufficiently small droplets, surface tension is often the dominant contributor to the free energy, and may (for example) overwhelm gravitational forces.

Fig. 3. Two-dimensional geometry for surface tension powered rotation.

D. Boundary Conditions in Surface Tension Problems

Liquid droplets may be attached to solid surfaces as shown in Fig. 2(c). In this case, three coefficients of surface tension must be considered: γ_{LV} , for the liquid-vapor interface, γ_{LS} , for the liquid-solid interface, and γ_{SV} for the solid-vapor interface. The term γ_{LV} is equivalent to γ above. In the three upper diagrams, we distinguish three cases: first, when the solid surface is uniformly wettable and flat; second, when the surface is modified to provide a wettable land, surrounded by an un-wettable area, and third, where the surface is uniformly wettable, but contains steps. In the first case, consideration of the forces acting indicates that a drop will spread until a definite contact angle θ_c is obtained. In the second and third, the liquid will be confined to the central area, so that the contact angle depends on the liquid volume. Our analysis will consider this latter geometry. Other cases are clearly possible; the two lower diagrams show droplets in wells with different wetting conditions. In the first, the droplet will pin at the top of the well; in the second, it will only pin at certain volumes.

E. The Surface Tension Coefficient

Table I lists values of the surface tension coefficient, for materials of interest in microfabrication [79]–[87]. Generally, γ lies in the rough range $2 \times 10^{-2} \text{ N/m}$ to 1 N/m . Of interest are the low surface tension coefficients of organic solvents and poly-tetrafluoroethylene (exploited in reducing surface tension collapse and stiction, respectively), and the high surface tension coefficients of metals (which may power alignment or actuation).

IV. ROTATION POWERED BY SURFACE TENSION

In this section, we consider how surface tension may power out-of-plane rotation. We first use a simple two-dimensional model to demonstrate the existence of a torque, and find the variation of torque with angle, showing that the torque will vanish at a particular angle. We compare the torque with the gravitational counter-torque, and show that the surface tension torque will be much the greater for drops with micrometer sizes. We then compare the model with a three-dimensional finite-element analysis, and finally consider assembly speed.

A. 2-D Analysis

We begin with the 2-D geometry shown in Fig. 3(a) [88]. Here a movable flap (of breadth b and thickness d) is attached by a flexible hinge (of length $2w$) to a fixed base-plate. This geometry may be constructed by sacrificial processing. A meltable pad (originally solder) is deposited on the hinge to a height h ; this material wets the hinge but not the surround, so that the hinge acts as a land.

If the pad is melted, the free surface will deform as shown in Fig. 3(b). At this point, the free surface perimeter of the liquid is s . The perimeter is reduced by rotation of the hinge, as shown in Fig. 3(c), and its decrease lowers the surface energy. The decrease in free energy may exceed the work needed to rotate the flap. The geometry will stabilise when a balance among torques is achieved. The pad may then be resolidified as in Fig. 3(d).

In the original analysis, all forces other than surface tension were neglected. A cylindrical free liquid boundary was assumed, with constant radius of curvature r . The net torque on

the flap was then found by two different methods, both giving the same result. First, the surface energy U_s per unit length was found in terms of the angles ϕ and θ as

$$U_s = \gamma w \left\{ \frac{\phi \cos(\frac{\theta}{2})}{\sin(\frac{\phi}{2})} \right\}. \quad (6)$$

By virtual work, the torque can be found by differentiation, as $T = -\partial U_s / \partial \theta$. Alternatively, it can be found as the difference between a torque $T_\gamma = \gamma w \cos(\alpha)$ per unit length (due to the surface tension force), and an opposing torque $T_p = Pw^2/2$ (due to the Laplace pressure). Since $\alpha = (\pi - \theta - \phi)/2$ and $r = w \cos(\theta/2) / \sin(\phi/2)$, the net torque was obtained as

$$T = \gamma w \left\{ \sin \left\{ \frac{(\theta + \phi)}{2} \right\} - \frac{\sin(\frac{\phi}{2})}{2 \cos(\frac{\theta}{2})} \right\}. \quad (7)$$

A relation between the angles θ and ϕ was then found by assuming incompressibility in the liquid. Equating the initial pad volume $2wh$ per unit length with the corresponding value after rotation of the flap, the following result was obtained [88]:

$$\cos^2 \left(\frac{\theta}{2} \right) \{ \phi - \sin(\phi) \} - \sin^2 \left(\frac{\phi}{2} \right) \{ 4\eta - \sin(\theta) \} = 0. \quad (8)$$

Here $\eta = h/w$ is an important new parameter, the normalized pad height.

Equation (8) was originally solved numerically, to find ϕ for a given value of θ . The result was substituted into (6) and (7) to yield the surface energy and torque. Fig. 4(a) shows their variation with flap angle, for a particular normalized pad height of $\eta = 0.6427$. The surface energy is a slowly varying function of angle, with a minimum at $\theta = 90^\circ$. The torque is also a slowly varying function, which is initially finite and falls to zero at the surface energy minimum. These results suggest that the flap will rotate from a horizontal to an upright position, at which point the driving torque will disappear.

The analysis above says little about the geometry *during* rotation. In fact, for small values of η , the situation is complex, because the free surface of the liquid may become concave at intermediate angles. However, it is trivial to show that it cannot ever become concave for $\eta > 0.25$. This range includes most final angles of practical interest.

B. Control of the Final Angle

In [88], it was shown numerically that the final angle could be controlled by the thickness of the meltable pad. Later on, the equilibrium shape of the droplet was found analytically [89]. The shape is shown in Fig. 4(b), for three different liquid cross-sections. In each case, the free boundary is an arc of a circle centred on the point O and passing through the ends of the lands (points A and B) and the hinge (point C).

Because of the simple equilibrium geometry, there is a simple relation between the angles ϕ and ψ at the final angle, namely $\phi_e = 2\psi_e$, where “e” denotes equilibrium. The value

a)

b)

c)

Fig. 4. a) Variation of surface energy and torque with angle, for $\eta = 0.6427$; b) equilibrium shapes for different pad heights; c) variation of final angle and starting torque with pad height.

of η needed for a given θ_e can be found by substituting into (8) to obtain

$$\eta(\theta_e) = \frac{\{\sin^3(\theta_e) + \{1 + \cos(\theta_e)\} \{\pi - \theta_e + \sin(\theta_e) \cos(\theta_e)\}\}}{4 \sin^2(\theta_e)}. \quad (9)$$

Fig. 4(c) shows the variation of η with θ_e . The normalized pad height increases slowly, as the final angle reduces. For the special case of $\theta_e = \pi/2$, (9) reduces to $\eta = (2 + \pi)/8 = 0.6427$, in agreement with the prediction of Fig. 4(a).

C. Comparison With the Gravitational Counter-Torque

Returning to (7), the initial torque (when $\theta = 0$) is given by

$$T_0 = \left(\frac{\gamma w}{2} \right) \sin \left(\frac{\phi_0}{2} \right). \quad (10)$$

Here ϕ_0 is the value of ϕ at $\theta = 0$. Consequently, the starting torque has a maximum value of $T_{0(\max)} = \gamma w/2$ [88]. At this point, the liquid cross-section is semicircular, so that $\eta = \pi/4$ or 0.7854. Fig. 4(c) shows the variation of the normalized starting torque $T_0/\gamma w$ with η . T_0 is still close to its maximum value when $\eta = 0.6427$, showing that 90° rotation can be achieved with a near-optimum starting torque.

The value of the torque may be estimated as follows. For lead-tin solder (for example), the surface tension coefficient depends on alloy composition and temperature. For 80% lead and 20% tin, it is ≈ 0.454 N/m at a temperature of 350°C [82]. For a typical land width of $w = 10\ \mu\text{m}$, we then obtain $T_{0(\max)} = 2.27\ \mu\text{Nm}$ per unit length. A hinge of length (say) $500\ \mu\text{m}$ would then exert a maximum torque of $1.135\ \text{nNm}$.

This torque may be compared with the torque T_f due to the weight of the flap, given by

$$T_f = \left\{ \frac{\rho b^2 d g}{2} \right\} \cos(\theta). \quad (11)$$

Here ρ is the density of the flap material. T_f has a maximum value T_{f0} when $\theta = 0$; at this angle, it must be overcome by the starting torque T_0 if the flap is to rotate. Assuming that $T_0 \approx T_{0(\max)}$, that the hinge width is comparable to the flap thickness (both might be $\approx 10\ \mu\text{m}$), and that gravitational terms due to the shape of the drop can be neglected, we obtain a simple expression for the maximum breadth of flap that can be lifted

$$b_{\max} \approx \sqrt{\left\{ \frac{\gamma}{\rho g} \right\}}. \quad (12)$$

For silicon, $\rho = 2.33 \times 10^3\text{kg/m}^3$. This gives $b_{\max} = 4.46 \times 10^{-3}\text{m}$, or roughly 5 mm. Note that $b_{\max}$ is the breadth at which T_0 and T_{f0} are comparable. For breadths ten times smaller, the surface tension torque will be ≈ 100 times larger than the gravitational torque, which is then effectively negligible. The mechanism is therefore useful for microstructures.

Although surface tension force (which scales as dimension¹) can easily overcome gravitational forces (which scale as dimension³) in the microstructure size domain, it has less success against elastic forces (which scale as dimension²). As a result, it was quickly realized that it would be difficult to bend or deform an elastic hinge linking the fixed and moving parts. Attention was therefore directed to a so-called ‘‘hingeless’’ geometry, in which the elastic link was omitted [89].

D. Hingeless Structures

In the absence of a structural link, a second free liquid surface must exist in the gap g between the fixed and moving parts as shown in the 2-D geometry of Fig. 5(a). Here the liquid is assumed to wet the two lands, but be pinned at the edges. Although it does not modify the torque, the second liquid surface causes an additional force to act on the flap. The sum of all the forces yields a net force F in the ζ -direction [89]. This force tends to hold the gap closed, so that there is no need for the elastic link.

Fig. 5(b) shows the variation of the force F with angle, for different final angles θ_e . The force is large at the start of rotation, but falls to zero at equilibrium. The explanation is provided by Fig. 5(c). Here, the LH diagram shows the liquid cross

Fig. 5. a) Geometry of hinge-less structure; b) variation of gap closure force with angle; c) definition of over-rotation.

section for $\theta_e = 90^\circ$. The RH diagram shows the flap rotating further, opening the gap. Because the two shapes have the same free-boundary lengths and liquid cross-sectional areas, they are similar energy states. Thus, there is no barrier to further rotation once equilibrium has been reached. This is an important drawback, which requires the addition of mechanical limiters.

A similar effect occurs when the drop is spherical and the lands are circular discs.

E. 3-D Analysis

Three-dimensional finite-element (FE) models that include surface tension and gravity are widely used to predict the shape of reflowed BGA solder [90], [91] and of lenses formed by polymerization [92]. Three-dimensional modeling of self-assembly has been carried out using Surface Evolver, a public domain FE package developed by Brakke of the University of Minnesota [93]. Surface Evolver can include complex geometries and boundary conditions, together with a finite liquid density. Given an initial user-defined surface and a set of boundaries and constraints, the program uses a gradient descent algorithm to evolve the free surface toward a state of minimum energy.

The results obtained using Surface Evolver are similar to those of the 2-D model [94]–[97]. For example, Fig. 6(a) shows a simulated surface at different angles of rotation [94]. Fig. 6(b) shows the variation of the surface area with angle for the case where the wettable lands on each part are rectangular. The lands have a width and length of $300\ \mu\text{m}$ (i.e., a very different shape from an infinite strip). However, the surface energy again has a clearly defined minimum. The liquid volume used is $3.5 \times 10^{-5}\ \text{cm}^3$, so that the initial height is $h = 194.4\ \mu\text{m}$ and $\eta = 0.648$. The equilibrium angle is 87.4° , close to the desired value of 90° [94].

The 3-D model has been validated by experiment. Fig. 6(c) shows a comparison between experiment and theory for the variation of ψ_e with liquid volume. The data are obtained using carefully measured volumes of solder, and there is close correlation with theory [94]. The difference between model and experiment is within 2° , with the error mainly caused by slight variations in the volume of deposited solder.

F. Speed of Assembly

Little has been reported on the speed of surface tension self-assembly. Here we present a brief analysis, neglecting gravity. In Fig. 3(c), the driving torque $T_s(\theta)$ from the liquid is resisted by inertia and by two drag components, due to air resistance and hinge viscosity, with damping coefficients D_a and D_h , respectively. The equation of motion is

$$T_s(\theta) = \frac{I_f d^2\theta}{dt^2} + \{D_a + D_h\} \frac{d\theta}{dt}. \quad (13)$$

Here $I_f = \rho b d^3/3$ is the angular moment of inertia of the flap and torques are per unit length.

The assembly speed depends on which terms dominate. The variation $T_s(\theta)$ is shown in Fig. 4(a) for $\theta_e = \pi/2$; it is close to the starting value $\gamma w/2$ for the first 40° , and then falls monotonically. If inertial forces dominate, and we assume constant driving torque, (13) reduces to $d^2\theta/dt^2 \approx 3\gamma w/2\rho b d^3$. Integrating from $\theta = 0$ to $\theta = \pi/2$ yields

$$t = \sqrt{\left\{ \frac{2\rho b d^3}{3\gamma w} \right\}}. \quad (14)$$

For $w = b, d = 500\ \mu\text{m}$, $\gamma = 0.45\ \text{N/m}$ (solder) and $\rho = 2.33 \times 10^3\ \text{kg/m}^3$ (Si), $t \approx 1\ \text{ms}$.

We can estimate air damping from a MEMS scanner in [120]. Here a Si mirror measuring $500 \times 500 \times 5\ \mu\text{m}$ has a resonant half-width $\Delta f \approx 25\ \text{Hz}$. The damping coefficient is $D_m = 2\pi I \cdot \Delta f \approx 2 \times 10^{-11}\ \text{Ns}$. Angular velocities well above $1\ \text{rad/ms}$ are then needed for $D_m d\theta/dt$ to be comparable to $\gamma w/2$, suggesting that air damping is negligible in assembly.

An estimate of liquid damping can be obtained from a simpler problem. If a plate of area A moves at a velocity v in a liquid against a transverse velocity gradient dv/dx , the power used is $P = \eta A v dv/dx$, where η is the viscosity. Knowing the driving force, the time for a given displacement can be found. Adapting the analysis to the rotational assembly geometry, we have obtained the time t for 90° rotation as

$$t \approx \frac{0.5\eta w}{\gamma}. \quad (15)$$

For the previous parameters, and using $\eta \approx 2 \times 10^{-3}\ \text{Pa} \cdot \text{s}$ for molten solder [82], times in the sub- μs range are indicated. However, these may rise if incomplete melting, alloying or oxidation occur. For polymers and glass, viscosities are far higher. For example, photoresist hinges were used in [102]. At the melt temperature of 145°C , a similar polymer (PMMA) has a viscosity of $\approx 3 \times 10^6\ \text{Pa} \cdot \text{s}$ [98]. Assuming that $w = 10\ \mu\text{m}$ and $\gamma = 0.04\ \text{N/m}$ (from Table I), (15) gives $t = 375\ \text{s}$, corresponding well with experiment.

V. SELF-ASSEMBLY USING SURFACE TENSION

The first demonstration of powered assembly used macroscopic parts formed from flexible printed circuit board, with solder as a meltable material [89]. Since then, microstructure assembly has been demonstrated many times. Because the mechanical parts lie beneath the meltable pads, they must be fabricated first on a sacrificial structure. All processes require distinct mechanical, meltable, and sacrificial materials, and further interlayers may be needed for adhesion. All except the sacrificial material must be immune to the undercut etchant, and all except the meltable material unaffected by high temperature.

A. Microfabrication Processes

So far, mechanical parts have been fabricated in silicon, polysilicon and metal, and silicon, silica and resist have been used as sacrificial materials. The range of meltable materials has included polymer, solder, and glass, as shown in Table II.

The first microfabrication process used electroplated nickel parts and Pb : Sn solder, with bulk silicon as the sacrificial material [99]. Because the undercut etchant (ethylene diamine pyrocatechol) attacked the metals, this process had a low yield. Some instability in the solder pads (known from Rayleigh's studies of cylindrical droplets [4], [5]) was also seen.

A more reliable bulk micromachining process was therefore developed, using B⁺-doped Si as the mechanical material and borophosphosilicate (BPSG) glass as the meltable one [100]. The BPSG was deposited by repetitive spin-coating and rapid thermal annealing of sol-gel glass [101]. Unfortunately,

Fig. 6. a) FE simulation of surface tension powered rotation; b) variation of surface energy with angle, as predicted by the FE method; c) comparison between experiment and theory for the variation of final angle with liquid volume.

assembly involved very high temperatures (1050 °C). For some time, advances awaited more practical processes.

At least four reliable surface micromachining processes now exist. Fig. 7(a) shows a process developed at Imperial College, based on mechanical parts formed in BSOI (with a 5 μm thick bonded layer patterned by DRIE), with photoresist as the

meltable material [102], [103]. This process has been used to assemble parts with spans of up to 1 mm, using very compact driver pads (with lengths of 250 μm , widths $2w \approx 40 \mu\text{m}$ and heights $h \approx 12 \mu\text{m}$). Because the parts are formed in single crystal silicon, and the melt temperature of the photoresist is low (160 °C), the parts remain flat after assembly. The

TABLE II
MELTABLE MATERIALS USED IN SURFACE TENSION POWERED SELF-ASSEMBLY

Meltable material	Type	Method of deposition	MPT °C	CTE $\times 10^{-6}/^{\circ}\text{C}$	Reflow environment	Reference
Solder	Small Parts Inc., LMA-117 Bi:Pb:In:Sn:Cd	Dip-coat	47	-9.1	Aqueous sol'n (KBr + acetic acid)	108, 142, 144, 145, 146, 148
Polymer	Hoechst AZ4562 photoresist	Spin coat	150-165	High [†]	Air, convection oven	102, 103, 110, 113, 120, 122
Solder	Technic Inc. 37Pb : 63Sn	Electroplate	183	25	Nitrogen and formic acid gas	99, 104, 116 - 119
Solder	Taiwan Sunball Int. Tech. Co. 63Sn-Pb37	BGA spheres	183	25	Nitrogen and formic acid gas	94-97, 105-107, 111, 114, 115
Glass	BPSG 5.25 mol% B ₂ O ₃ 6.75 mol% P ₂ O ₃	Spin coat + RTA of sol-gel	950-1050	0.5	Oxygen, RTA	100, 101

process is therefore appropriate for MOEMS. The assembled structure must be metallised to restore electrical connection to the substrate, or to increase optical reflectivity.

Fig. 7(b) shows an alternative Imperial College process, based on multilayer electroplated Cu parts and Pb: Sn solder [104]. Because the mechanical and meltable parts are formed from metals, the process is appropriate for electrical MEMS. The use of photoresist as a sacrificial material avoids corrosion by acid undercut etchants, and the low melt temperature of the solder allows the structures to be postprocessed onto circuits. To avoid oxidation of the solder, melting is performed in a reducing atmosphere.

Fig. 8(a) shows a solder-based process developed at Boulder [105], [106]. The mechanical parts are formed in 1.5–3.5 μm thick polysilicon, and the solder lands are 0.5 μm thick gold. The solder used is either deposited by plating, evaporation and lithography (lift-off) or as precision, premanufactured spheres. The polysilicon parts can be fabricated by a standard foundry method. Using multilayer processing it is simple to incorporate staple hinges. Resistive point heaters have been developed to allow local control of assembly [107]. The main disadvantages are that the solder spheres are relatively large (100 μm – 400 μm), suffer from size variation ($\pm 25 \mu\text{m}$) and require precision placement [94]. However, placement can be automated using pick-and-place mechanisms.

A final solder-based process has been developed at Harvard University, as shown in Fig. 8(b) [108]. The mechanical parts are metal, fabricated by electroplating in a mould. A prior plating step is used to inset a surface pattern. The parts are designed to be detached from the substrate by removing a sacrificial layer [109]. Another distinguishing feature is that the whole metal surface is covered in solder, by dip coating.

The use of photoresist (either as a meltable material, or as mould for electrodeposited solder) has largely solved the

problem of forming hinge driver pads with accurate dimensions and placement. Photoresist and solder are compatible with wet undercut etches, and melt at low temperatures. Significant challenges that need to be addressed are the mismatch in thermal expansion coefficient (which may be large with photoresist), and the stability of the meltable material (which may require an inert gas environment). Desirable process developments include dry release (for improved yield) and solders with a higher melting point than Pb: Sn (to allow postprocesses that also involve soldering).

The majority of self-assembly experiments have been performed using solder. A universal conclusion is that the solder surface must be clean, if results are to be repeatable. The earliest experiments used hinge-less metal plated structures. Although these demonstrated the idea, as shown in Fig. 9(a), the control of angle was poor, and the parts often rotated past 90°, as shown in Fig. 9(b) [99]. Further experiments and modeling have shown that the misalignment of linked assemblies may be considerable. This is illustrated by Fig. 9(d), which shows the cumulative error in the tip position of the 5-bar linkage in Fig. 9(c), obtained from the error distribution of each link [97]. The main sources of error are hinge play and imprecision in the amount of solder.

B. Limiter Mechanisms

Considerable attention has been devoted to mechanical limiters that would allow a finite driving torque to be retained throughout rotation, provide a definite end-stop, and enable the process to be determined by lithography rather than the volume of meltable material. Fig. 10 shows several latches, divided into below- and above-substrate types.

For bulk micromachined devices, there may be considerable clearance (up to 100 μm) beneath the suspended parts, allowing a mechanism to hang beneath. The latch in Fig. 10(a) uses

Fig. 7. Self-assembly processes using a) BSOI and photoresist and b) plated metal and solder.

single-layer parts [100]. The movable part is provided with a pair of cranks, and the fixed part with a pair of catches. Although there is a gap between the cranks and catches, the offset crank reduces the gap as the part rotates, eventually preventing rotation. To limit rotation to 90° , the separation

d should equal the part thickness. In this case, inaccuracy in defining this thickness limited the angular precision to $\pm 3.75^\circ$.

For surface micromachined parts, the clearance is reduced to a few μm , but this distance may be more accurately known. Fig. 10(b) shows a mechanical limiter that uses the substrate

Fig. 8. Self-assembly processes using a) polysilicon and solder spheres and b) plated metal and dip-coated solder.

itself as an end-stop [110]. This mechanism is very compact, and thus suitable for assembling small parts, but its small lever arm again makes it inaccurate.

To obtain high precision, a lever arm comparable to the part size must be used. Fig. 10(c) shows a mechanism for

90° rotation [111], derived from work on unpowered surface-micromachined structures [51]. Here a separate mechanical support has been constructed in polysilicon. The support is also attached to the substrate by a staple hinge, and is raised by the movable part until an end-stop is reached. The accuracy

Fig. 9. a) 90° rotation and b) over-rotation in hingeless structures (photos courtesy P. W. Green); c) 5-bar multiple link assembly, and d) simulation of assembly accuracy.

of this type of mechanism is restricted by clearance in the hinges.

Fig. 10(d) shows the most accurate limiter developed to date [102]. The mechanism allows 45° rotation, and consists of two parts, which rotate simultaneously in opposite directions until their extremities catch. The hinges are $2L$ apart, and the catching surfaces are $L/\sqrt{2}$ from their respective hinges. Assuming symmetry, the catches follow circular trajectories, and engage when the parts have rotated through the same angle.

Alignment accuracy may be estimated by assuming that the main source of error lies in the definition of the mechanical parts. Assuming that a symmetric 45° triangular structure is formed from parts of length L_p , on a baseline of length $2L$ as in Fig. 10(d), the angular error $d\theta$ may be related to dimensional errors dL_p and dL by $d\theta = -\{dL - dL_p/\sqrt{2}\}/L$. Errors caused by (say) etching will affect dL (since the surfaces that define L have anti-parallel normal vectors) but not dL_p (since the surfaces defining L_p have parallel normals). Thus, the error simplifies to $d\theta = -dL/L$. Clearly, low error requires a large baseline.

For $L = 500 \mu\text{m}$ (a reasonable maximum) and $dL = 0.1 \mu\text{m}$ (a realistic minimum), we obtain $d\theta = 2 \times 10^{-4}$ rads, or 0.69 minutes of arc.

More advanced operations may be used to form other 3-D structures. Fig. 10(e) shows a multiply linked mechanism used to ensure parallel rotation of several parts. Here, only one hinge need be powered; additional unpowered hinges ensure correct motion of the linked parts. More complex links have been used to allow unpowered, single-step assembly of orthogonal features such as corner cube reflectors [112].

The structures shown so far involve rotation of individual parts, or simultaneous assembly of multiple parts. Sequential assembly allows other geometries. For example, Fig. 10(f) shows the construction of a 90° rotated structure. Here, the mechanism of Fig. 10(d) is first used to construct a “stop” above the substrate, which limits rotation of the central part after it has rotated through 90°. Assembly is sequential, because the central part must rotate further than the others. However, the timings are not crucial; the stop must simply be formed before the central part reaches it [103].

Fig. 10. (a) and (b) Below-substrate limiters; (c) and (d) above-substrate limiters; (e) and (f) complex mechanisms.

C. Accuracy and Speed

The alignment accuracy achievable using surface tension self-assembly has been steadily improving. The best method is cur-

rently the BSOI process of Fig. 7(a). Angular errors as low as a few minutes of arc (similar to the estimate in Section V-B) have been obtained for 45° and 90° rotated structures using this

Fig. 11. (a) Overall view and (b) enlargement of the latch, in a 45° mirror; (c) time variation of angle for counterrotating parts; (d) schematic and (e) SEM view of torque gauge.

process, when combined with the limiters shown in Fig. 10(d) and (f) [103]. There are three reasons for this high precision.

First, single-layer patterning and advanced etching allow accurate definition of all dimensions. Second, hinge-less geometries

allow any clearance in the hinge to be eliminated by the gap closure force, thus fixing one end of the movable part. Finally, a long lever arm allows the other end also to be well defined. For example, Fig. 11(a) shows a scanning electron microscope view

of a 45° mirror, with an overall height of 0.5 mm. Fig. 11(b) shows an enlarged view of the catches. The errors in position are clearly submicron, despite the large difference in mass of the moving parts.

One conclusion is that the assembly process must be dictated by a balance between the surface tension torque and a torque other than one due to gravity. Video recordings of macroscopic and microscopic solder-powered self-assembly operations have now been made. In each case, these show assembly times of a few seconds [89]. Slightly longer times have been measured for glass-powered assembly, using rapid heating [100].

For polymer-powered assembly, times can be many minutes at low temperatures [102]. For example, Fig. 11(c) shows part of the time variation of angle of the two parts in Fig. 10(d), which demonstrates their synchronicity. At this slow rate, it is clear that the additional torque is due to viscous friction, as discussed in Section IV-F. Consequently, by ensuring uniformity of the hinge driver pads, assembly can be independent of the size and shape of the parts, a major advantage. Viscous friction also serves to delay the fragmentation of the molten, cylindrical hinge driver into spherical droplets [5].

D. Structural Deformation

The ability to rotate large movable parts clearly demonstrates the existence of a surface tension torque. The starting torque has been measured directly for photoresist, by deflecting a torsion spring as shown in Fig. 11(d) and (e) [113]. Although there is uncertainty in the surface tension coefficient, and in the contribution of shrinkage, the prediction of (10) appears broadly correct.

The existence of a torque throughout assembly allows viscous friction to be overcome, making sure the final angle is reached. The torque will, however, act against the structure when the limiter has engaged, tending to deform it. For example, Fig. 12(a) shows a polysilicon structure assembled using solder spheres [111]. Fig. 12(b) shows a finite element model of half of the structure, illustrating the deformation [97]. Because of the large relative size of the solder sphere, the distortions are caused by the Laplace pressure at the centre of the part and surface tension force near the edge.

For larger parts and smaller meltable pads, the distortions are caused by the global action of the torque acting at the hinge. As a result, they are mainly due to bending, and close agreement may be reached with the prediction of simple structural models, which take this into account [103]. Minimizing deformation is important for applications such as MOEMS. One method is to assemble several parts that are connected by linkages, so that the optical surface has no direct stresses on it, as shown in Fig. 12(c).

E. Complex 3-D Structures

Entirely closed structures have been demonstrated by the Harvard Group. For example, Fig. 13 shows a range of polyhedra including pyramids with 4 and 5 faces, cubes (with 6), and hexagonal sections (with 8) constructed from detached parts that are covered in and connected by solder [108]. Although models for the assembly process and liquid shape do not yet exist, there is an obvious minimum energy geometry, in which the interior

(a)

(b)

(c)

Fig. 12. (a) Geometry and (b) predicted deformation of flap assembled using solder spheres; (c) mirrors assembled using solder self-assembly but attached via linkages.

is filled with solder except for a spherical cavity. More complicated structures have been fabricated by manual assembly of patterned sheets, in a manner analogous to origami. Fig. 14(a) shows micro-origami arches and birds, constructed from thin

Fig. 13. (a) Metallic 2-D structures prior to folding; (b) 2-D precursors after dip-coating with solder; (c) completed polyhedra, ranging in size from 100 to 300 μm per side.

metal sheets carrying slotted fold lines as shown in Fig. 14(b) [109].

VI. APPLICATIONS OF ROTATIONAL ASSEMBLY

Rotational assembly is generally used in 3-D microstructures carrying out-of-plane features. Surface tension is a particularly advantageous form of energy to use in powering rotation when one-time assembly is required by a simple, compact mechanism. We illustrate the applications with examples from mechanical, electrical, and optical MEMS.

A. Mechanical MEMS

The earliest examples of 3-D mechanical structures assembled by surface tension are walking micro-robots, with out-of-plane legs [111]. More recently, an elegant microfan has been constructed in polysilicon [114], [115]. Fig. 15(a) shows the layout of the parts before assembly, and Fig. 15(b) an SEM view of a completed fan. The rotor is parallel to the substrate, and

carries shaped blades that are rotated out-of-plane to a specified angle by Pb: Sn solder spheres. In this case, surface tension is an appropriate method of assembly, because it can still be carried out on a moving part such as a rotor.

The rotor is driven by a set of scratch drive actuators, powered using 30–150 V sinusoidal signals at frequencies of 2–15 kHz, giving overall rotational speeds of up to 180 rpm. The main application envisaged is gas or liquid transport in fluidic microsystems, and the creation of an air-flow normal to the substrate has been verified using smoke visualization.

B. Electrical MEMS

The earliest examples of 3-D electrical components assembled by surface tension are inductors [104], [116]–[119]. Here the aim is to prevent the magnetic and electric fields from penetrating the substrate (which is generally conducting), and hence reduce the eddy current losses and parasitic capacitance to ground that degrade performance at RF frequencies. Out-of-plane rotation is preferable to etching the substrate,

Fig. 14. (a) Fold patterns and (b) completed structures for two micro-origami figures.

because it does not significantly reduce the available chip area. A compact assembly mechanism is required to prevent the introduction of parasitics. Fig. 16(a) and (b) show self-assem-

bled inductors with meander and spiral layouts, respectively. Each is formed in electroplated Cu, and assembled by electroplated pads of Pb: Sn solder. The spiral inductor has a larger

Fig. 15. a) Microfan layout and b) SEM of assembled fan.

inductance, but requires two additional layers of masking and plating.

Fig. 16(c) shows the de-embedded variation of quality factor (Q-factor) with frequency for a 4 1/2 turn meander inductor, at a number of different angles. The Q-factor rises with angle, as the inductor is rotated out-of plane. So far, inductances of 1.5 to 2.5 nH and Q-factor increases from 4 to 20 have been achieved [118], and the assembled components appear mechanically stable [119].

C. Optical MEMS

Many optical microsystems use light beams that travel parallel to the substrate to obtain a long path. In this case, optical elements such as mirrors and lenses must be set up normal to the substrate. Surface tension provides a simple method of assembly, and the accuracy required in a passively aligned system. Many self-assembled MOEMS devices have now been constructed. The simplest are 45° mirrors, as shown in Fig. 11(a). These have 1 mm $\times$ 1 mm areas, and are flat to $\pm\lambda/2$ at 1.5 μm wavelength [103].

More complicated components include mirror scanners and lenses. Fig. 17(a) shows a 45° scanner. This “Type 1” scanner has its torsion and assembly axes parallel [120]. The structure consists of a frame carrying a small mirror mounted on a torsion bar. Its design is therefore a simple modification to a fixed mirror, with a skewed electrostatic comb drive at the base. A surface map of the main part of the frame is shown in Fig. 17(b). Because the mirror is supported only by the torsion bar, it is unaffected by the structural distortion caused by assembly. Instead, the dish shape is characteristic of metallization stress. The device is resonant, and a peak deflection angle of 16° was obtained at a frequency of 2.6 kHz, using a drive voltage of 175 V p-p. The Q-factor of the resonance was ≈ 60 .

The alternative “Type 2” scanner shown in Fig. 17(c) has perpendicular torsion and assembly axes [110]. To avoid the electrodes clashing when the mirror turns, the fixed half of the drive is also rotated through 45° as shown in Fig. 10(b) to obtain a staggered comb drive. A similar approach has been adopted in a conventional torsion mirror [121].

Other optical components such as microlenses have also been demonstrated. Fig. 17(d) shows a self-assembled frame, which

(a)

(b)

(c)

Fig. 16. (a) Meander and (b) spiral self-assembled inductors (photos courtesy G.Dahlmann); (c) variation of Q-factor with frequency, for meander inductors at fixed angles.

has been used to locate a plate at 90° to the substrate [122]. The plate carries an array of lenses, which are also formed during assembly, by reflow molding of cylindrical photoresist pads

into spherical surfaces. For an optical aperture of $60 \mu\text{m}$, focal lengths of the order of $30 \mu\text{m}$ have been obtained. Components of this type may be used to collimate the outputs of optical fiber arrays.

VII. SELF-ORGANIZATION AND SELF-ALIGNMENT

Surface tension has also been used to create structures through the parallel assembly and orientation of detached parts. We now review a number of such approaches, which typically involve a combination of surface tension, agitation and evaporation. Many of the approaches are chemically or biologically inspired, and analogies with self-assembly in nature have been described in recent reviews [123], [124].

A. Crystallization by Surface Tension

One early demonstration of self-organization involved the tessellation of micro-machined parts floating on a liquid surface, as shown in Fig. 18(a) [125]. In these experiments, bonding was based on the weak attractive force resulting from the modification of the surrounding menisci by the weight and shape of the parts, while motion of the liquid or magnetic actuation provided the agitation needed to work through the possible orientations. Using this method, 2-D “crystals” were constructed as shown in Fig. 18(b).

The forces responsible for bonding suspended parts may be estimated as follows [125], [126]. Including the hydrostatic pressure of an open liquid surface of variable height z above a reference as shown in Fig. 18 (c), we may write (2) as

$$\gamma \left\{ \frac{1}{r_1} + \frac{1}{r_2} \right\} = \Delta \rho g z. \quad (16)$$

Here $\Delta \rho$ is the difference in density between the suspension liquid and the vapor or liquid above. Because the curvature of the liquid surface is often small, the exact differential expression for curvature may be approximated in (say) the x -direction as

$$\frac{1}{r_x} = \frac{\frac{d^2 z}{dx^2}}{\left\{ 1 + \left(\frac{dz}{dx} \right)^2 \right\}^{\frac{3}{2}}} \approx \frac{d^2 z}{dx^2}. \quad (17)$$

With this approximation, (16) may be written as

$$\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} = \frac{z}{l_c^2}. \quad (18)$$

Here l_c is the so-called critical length, given by

$$l_c^2 = \frac{\gamma}{\Delta \rho g}. \quad (19)$$

For an interface between (for example) the hydrophobic liquid perfluorodecalin (PFD) and water, the critical length is $l_c = 2.4 \text{ mm}$. The total energy may be found as the sum of the surface and gravitational components, as

$$U = \iint_S \{U_S + U_G\} ds. \quad (20)$$

Fig. 17. (a) Type I torsion mirror scanner; (b) flatness map of mirror surface; (c) Type II scanner; (d) reflow molded microlens array.

Here, the individual energy terms may be found to first order as

$$U_S = \gamma \frac{\left\{ \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right\}}{2} \quad \text{and} \quad U_G = \frac{\Delta \rho g z^2}{2}. \quad (21)$$

The attractive forces between suspended parts may then be found by differentiating the total energy U as a function of the part separation. In general, this calculation is hard to perform analytically, and great simplification is obtained by reducing the geometry. For example, in one dimension, (18) becomes:

$$\frac{d^2 z}{dx^2} = \frac{z}{l_c^2}. \quad (22)$$

Analytic solutions may be found for limiting cases of perfectly hydrophobic or hydrophilic surfaces. For example, for two objects with faces coated as shown in A of Fig. 18(d) and separated by a distance $2x_0$, the intervening meniscus may be considered to be pinned at a height $z_{\max}$ at $x = \pm x_0$ and vary symmetrically between the objects. In this case, a symmetric solution to (22) may be obtained as [126]

$$z(x) = z_{\max} \frac{\cosh\left(\frac{x}{l_c}\right)}{\cosh\left(\frac{x_0}{l_c}\right)}. \quad (23)$$

A similar antisymmetric solution may be obtained when the two objects have faces as shown in B of Fig. 18(d). Equation (23) may then be substituted into (20) and (21) to evaluate the contributions of surface energy and gravitational energy to the total.

The minimum energy is obtained in A when the separation $2x_0$ is zero, so that two such objects attract each other. In the alternative geometry of B, they repel each other. The prediction of this theory has again been verified, using Surface Evolver [126]. The forces are powerful for objects in the millimeter size range, i.e., comparable to l_c . However, for smaller objects, the contributions of gravity become negligible, and no menisci are formed, unless hydrophobic and hydrophilic effects are more carefully manipulated.

Considerable effort has been expended on increasing the bonding force above that obtained from the combination of gravity and surface energy. For example, bridging flocculation of a dilute solution of a polymer (polyacrylamide) has been used to bond surfaces with complementary surface shapes [127]. The Harvard Group have used additional coatings, and patterned the coatings independently of the shape of the parts. The original work involved assembly of millimetric plates of polydimethylsiloxane (PMD) floating at the interface between

Fig. 18. (a) Arrangement for capillary self-organization; (b) assembled structures; (c) water surface round a floating object; (d) attraction and repulsion of floating objects.

water and PFD. The shape of the local menisci could be tailored by changing the part shape, patterning hydrophobic strips on the edges of the parts, and using chiral patterns for the hydrophobic areas [128], [129]. In later work performed with polyurethane rods, the effects were enhanced by having

one side coated with hydrophobic lubricant, and the other side rendered hydrophilic by exposure to an oxygen plasma [130].

The behavior of self-assembling systems with selective bonds can be described by chemical formulae and analyzed by rate equations [127]. Such systems also demonstrate emergent be-

havior. In recent experiments, self-assembly was used to create tilings (periodic checkerboards, aperiodic Penrose tilings and simulated cellular automata) [131]. The dynamic patterns obtained when the parts are actually *powered* (using an ‘engine’, operating by the decomposition of hydrogen peroxide solution by the catalytic action of a small platinum coating fixed to each part) have also been explored [132].

B. Alignment by Surface Tension

Systematic experiments on surface tension attachment and alignment are now being conducted for MEMS applications. The accuracy obtained when capillary forces are used to align wettable parts onto wettable lands has been characterized [133]. In this case, the parts required individual placement. In a more parallel self-assembly experiment, magnetic forces were used to assemble microscopic metal disks suspended in water onto substrates patterned with arrays of nickel dots [134]. Although the parts attached correctly to the substrate, no orientation of the parts was obtained.

A more sophisticated, and cycleable process that combines mass-parallel binding and alignment has been developed [135], [136]. The process uses *active* assembly sites consisting of hydrophobic surfaces of gold coated in an alkanethiol self-assembled monolayer (SAM) and *inactive* sites of hydrophilic gold. The parts are suspended in an aqueous solution, and randomly attracted, aligned and anchored to the sites by a heat curable lubricant as shown in Fig. 19(a). Electrochemical reduction of the SAM (e.g., following $\text{CH}_3(\text{CH}_2)_n\text{SAu} + \text{e}^- \rightarrow \text{Au} + \text{CH}_3(\text{CH}_2)_n\text{S}^-$) is used to return selected sites to their inactive, hydrophilic state [137]. The process can be repeated with different parts. Fig. 19(b) shows two sets of square dies (polished, and unpolished) that have been located using two separate assembly cycles [136]. The alignment forces have again been modeled using Surface Evolver [138].

Surface tension has also been used to carry out assembly based on shape recognition, by aligning parts with defined 2-D shape to matching binding sites [139], [140]. The parts are again suspended in fluid, and randomly attracted to the site by a hydrocarbon lubricant. Once at the site, they rotate and translate to minimize the free surface of the lubricant. The minimum is obtained when the perimeters of the part and the binding site align. For polygonal perimeters, the parts can be aligned to an accuracy of 0.3° with a yield of 100%, an impressive achievement. The method has been used to attach hexagonal dielectric mirrors to MEMS actuators [141], as shown in Fig. 19(d).

Electrical functionality has also been obtained using self-attached parts. Working displays have been constructed by attaching LED dies to cylindrical substrates as shown in Fig. 19(e). The LEDs are connected by electrodes on the substrate, and by additional self-aligned top electrodes [142]. In trials, up to 1560 dummy silicon dies were attached to solder receptors in less than 3 min, with 98% coverage.

With nonpolygonal shapes, lower yield is obtained. For example, the two parts (“dee” and “comma”) in the LHS of Fig. 19(c) have aligned correctly. In the RHS, an alternative local energy minimum has resulted in incorrect alignment [140]. Algorithms for optimising the shape of binding sites to avoid such local minima are now being developed [136].

C. 3-D Structures

The use of local binding sites has been extended to allow the formation of 3-D regular “crystals”. Mechanical stability can be obtained by using a photocurable adhesive to generate the interfaces whose initial minimization causes self-assembly to occur. The adhesive can then be polymerised to form a solid structure [143], [144].

The most dramatic demonstrations have been carried out using polyurethane parts coated with a low-melting point metallic alloy (Bi-Pb-In-Sn-Cd solder, mpt 47°) and floating in an aqueous KBr solution. A variety of 3-D lattices have been assembled from polyhedra, with selected faces solder-coated, and helical lattices have also been created from chiral parts [144]–[146]. By patterning the solder into distributions of dots, highly selective bonds have been formed. These can be selective between different parts, different facets and different orientations of facets. Polygonal structures carrying suitable bond patterns may be created by combining the techniques previously described, namely formation of flat, patterned parts (in some cases by plating into a mould, followed by rotational assembly).

These techniques are sufficiently advanced to create functional devices. For example, Fig. 20(a) shows how a set of polyhedra carrying elementary circuitry (a light-emitting diode) may be self-assembled using solder bonding pads. These pads act as conducting links between the polyhedra, so that the entire structure acts as a circuit, with all the LED’s connected together as shown in Fig. 20(b) [145]. Similar techniques have been used to build circuitry on a helical pitch, using structures and assembly processes modeled on the tobacco mosaic virus [146]. In this case, wedge-shaped polyhedra were used. Each wedge provided 66° of rotation of the structure, so that assembly of six pieces generated 1.1 turns of the helix.

Other 3-D processes have used parts joined by flexible wire links, which self-assemble in a manner analogous to protein folding [147]. Electrical devices have again been formed by this method. Precursors have been constructed from chains of triangular prisms, each bearing circuitry and linked by flexible wires. In one example, each prism carried an inverter, resistors and capacitors and an LED. Self-assembly of the prisms into a circular pentameric structure yielded a ring oscillator. Replacement of the inverters by flip-flops and alteration of the orientation of alternate prisms generated a structure that folded into a linear arrangement and functioned as a shift register [148].

D. Alignment and Crystallization by Surface Tension and Evaporation

Surface tension has also been combined with evaporation to perform parallel assembly operations. An early example involved the insertion of diode chips by an evaporating liquid into wells etched in a silicon substrate [149]. This approach has been exploited industrially, in the mass-production of RF ID tags on plastic substrates [150].

Nagayama and others have used the capillary forces obtained at the meniscus of a liquid evaporating on a surface to assemble and order suspended particles into two-dimensional crystals

Fig. 19. (a) Alignment by surface tension force; (b) arrays of different parts after 2-step self-alignment (photos courtesy X. Xiong and K. Bohringer); (c) correctly (LH) and incorrectly (RH) aligned parts after shape-matching self-assembly; (d) self-assembled hexagonal MEMS mirror (photos courtesy U. Srinivasan and R. Howe); (e) self-assembled cylindrical LED display.

[151], [152]. The particles are driven toward the meniscus by convective flow, as shown in Fig. 21(a), and are packed together into hexagonal arrays by the long-range force between particles induced by surface tension at the film surface. Size-dependent separation of particles has been demonstrated [153], and near-perfect arrays have been constructed over large areas by

gradually withdrawing the surface from the liquid [154]. The capillary forces have been characterized [155], and measured directly using a torsion microbalance [156]. Similar results have been obtained by spin-coating dispersions of polystyrene beads, which are packed together by the evaporating liquid into close-packed arrays [157], [158].

Fig. 20. a) Procedure to form electrical networks in 3-D by self-assembly. b) Assembled $2 \times 2 \times 3$ aggregate containing 12 truncated octahedra and showing parallel connectivity.

Parallel-sided cells formed using resist or Mylar spacers have been used to define the overall shape of the crystal [159]. The lattice nucleates and grows from the edges of the cell as a result of solvent depletion through channels between the Mylar and the glass substrate. Alignment may be assisted by sonification, and the number of (111) planes in the lattice may be controlled by variation of film thickness. Moulded capillaries and templated surfaces have also been used to define the overall crystal shape. For example, Fig. 21(b) shows an array constructed inside a capillary [160]. Cylindrical holes have been used as tem-

plates for ring structures, which have then been released from the substrate [161].

The resulting films can act directly as photonic band gap structures, with applications in optical filtering [162], [163]. Further processing may be used to construct alternative surface patterns, with the same periodicity but a smaller or different feature size. For example, two-dimensional micropatterns have been used as microlens arrays in projection lithography [164]. Metal films have also been evaporated through the openings between the beads. Successive evaporations, with the substrate

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