SURFACE FORCE INDUCED FAILURES IN MICROELECTROMECHANICAL SYSTEMS

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Abstract. Over the past decade much work has been devoted to the realization of practical microelectromechanical systems (MEMS). These systems combine electronic circuits with microfabricated mechanical transducers on a miniature substrate to perform a wide range of sensing and actuation functions. MEMS are currently used to process acceleration, pressure, heat, sound, and chemical signals in a generalized manner. Because mechanical structures used in MEMS are made of thin films suspended a few micrometers off the substrate, these structures are highly susceptible to surface forces which can substantially and sometimes catastrophically degrade their manufacturing yield and reliability. This paper discusses some of the common failure mechanisms present in these devices due to adhesion forces. In particular, adhesion-related failures occur in MEMS when suspended elastic members unexpectedly collapse and stick to their substrates. This type of device failure develops during device fabrication and operation hence is one of the dominant sources of yield loss in MEMS. The physical mechanisms responsible for the failure are discussed, and normalized elastic member dimension bounds for prevention of collapse and sticking as well as other practical failure prevention schemes are presented.

1. Introduction

Microelectromechanical systems are micrometer-size systems capable of interfacing electrical and mechanical forces. Because these devices must react to mechanical signals, many of these use construction topologies that require physical motion. For example, an accelerometer translates the motion
of a suspended proof mass into capacitance which is later converted to a voltage output. Suspended microstructures such as plates and beams are commonly used in the manufacturing of pressure (Burns 1988, Kung and Lee 1991) and acceleration sensors (Ristic, Gutteridge, Dunn, Mietus and Bennett 1992). These structures are typically made by forming a layer of the plate or beam material on top of a sacrificial layer of another material and etching the sacrificial layer (Guckel and Burns 1989, Lysko, Stolarski and Jachowicz 1991).

Typically these suspended elastic structures have large areas, yet are constructed a few microns off their substrate. The presence of these very narrow gaps makes these structures very susceptible to surface induced phenomena such as capillarity and adhesion forces. Nathanson (Nathanson and Guldberg 1975) first reported that small electroformed elastic structures are influenced by surface tension forces. If these forces were sufficiently high the elastic member could collapse and permanently adhere to the substrate causing a device failure.

Surface forces can be present both during the device manufacture as well as during their normal operation hence their path to failure must be carefully studied. During processing, adhesion can occur when the suspended member is exposed to an aqueous rinse and dry cycle. Guckel (Guckel and Burns 1989) observed that when microscopic elastic plates are rinsed and dried, the capillary forces acting on these are large enough to bring them in contact with their underlying substrate. They also observed that, after complete drying, some of them remain pinned to the substrate held by attractive forces. Similar results have been observed by numerous researchers (Guckel, Sniegoeski and Christenson 1989, Scheeper, Voorthuyzen and Bergveld 1990, Orpana and Korhonen 1991, Takeshima, Gabriel, Ozaki, Takashashi, Horiguchi and Fujita 1991). Capillarity induced collapse can also develop when the device is under normal operation if it is exposed to high humidity conditions leading to capillary condensation (Israelachvili 1985) and the formation of a water droplet in the gap.

The route to sticking failure is hence divided into two phases. In the collapse phase the structure is brought in contact with the substrate, and in the adhesion phase, the structure is affixed to the substrate. If any of these two phases is eliminated, the adhesion failure does not occur. Either phase can be eliminated if the stiffness of the microstructure is sufficiently high yielding a characteristic stiffness threshold for the onset of failure. This threshold is observed experimentally in an array of progressively weaker suspended elements. Figure 1 shows a photograph of an array of micromachined polysilicon cantilever beams showing clearly the onset of failure at a particular beam length. The same phenomena develops in other types of suspended micromachined structures such as doubly supported beams and
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Figure 1. SEM of micromachined polysilicon cantilever beams of increasing length. The photograph shows the onset of pinning for beams longer than 34 μm.

Figure 2. SEM of an array of suspended polysilicon circular plates. The two large plates have collapsed.

A third yet possible adhesion failure mode develops if the suspended member is placed in contact with another surface by an external force or by accidental shock. This is especially important in deformable mirror devices (Hornbeck 1995) and other dynamical systems where mechanical contact is intrinsic. Recently, intermittent sticking failures have been observed in
microengines (Tanner, Smith, Bowman, Eaton and Peterson 1997, Miller, Vigne, Rodgers, Sniejowski, Walters and McWorther 1997) and surface micromachined accelerometers. Figure 3 shows a photograph of the Sandia microengine (Garcia and Sniejowski 1995). This device consists of a small rotating polysilicon pinion gear driven by two perpendicular linear comb drives (not shown) moving 90° out of phase. In the figure the gear drives a larger diameter rotational mechanical safety lock. During the engine opera-

![Diagram of pinion gear, comb drive, pin lock, and trouble regions]

*Figure 3.* SEM of Sandia’s microengine showing dynamic sticking failure. While in operation one of the fingers of the driving comb drives collapsed.

...tion, adhesion to the substrate can occur at the pin assembly joints (Tanner et al. 1997) and at the comb drive fingers causing failure (Figure 3(b)).

This paper discusses the conditions necessary for the onset of the adhesion failure and several techniques used to eliminate it. The material for
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the manuscript was extracted from several of my papers in the subject as well as a recent longer review discussing this topic (Mastrangelo 1997). Other important related reviews are found in (Maboudian and Howe 1997, Komvopoulos 1996, Bhushan 1997, Kaneko 1991).

2. Collapse by Capillary Forces

The behavior of elastic structures under capillary forces has been studied in (Mastrangelo and Hsu 1993). Here, as an illustrative example, we analyze the lumped elastic structure of Figure 4. This simple structure contains all the general phenomena present in continuous elastic microstructures under a capillary pull. The plate represents the suspended member surface, the spring its stiffness, and the gap the distance between the member and the substrate.

![Diagram](image)

*Figure 4.* Deflection of a rigid plate attached to a spring by capillary forces

In Figure 4, a rigid circular plate of radius \( r_o \) is suspended above a substrate. The substrate is fixed, and the top plate is attached to a spring of constant \( \kappa \). If the weight of the plate is negligible, the original plate separation is \( z = h \) when the spring is relaxed. A liquid bridge of volume \( V_l \) is trapped between the plate and substrate. In order to simulate the drying process, the equilibrium positions assumed by the plate as the liquid is gradually removed are considered. Initially, the liquid spreads to a radius \( r_i \) with a volume \( V_l = \pi r_i^2 z \). The maximum volume that the liquid assumes without overflowing is \( V_o = \pi r_o^2 h \). The surface energy \( U_S \) of the spring-plate-liquid system is

\[
U_S = \begin{cases} 
  U_{S_o} + 2\pi \gamma_l \cos \theta_c \left( r_o^2 - V_l / \pi z \right) & z \geq z^* \\
  U_{S_o} + \pi \gamma_l \left( \cos \theta_c - 1 \right) \left( r_o^2 - V_l / \pi z \right) & z < z^* 
\end{cases},
\]

(1)
where $U_{S_o}$ is a constant, $\theta_c$ is the contact angle, $\gamma_l$ is the liquid surface tension, and $z^* = V_l/\pi r_o^2$ is the plate separation assumed when the liquid completely wets the surface of the top plate. This equation neglects the complicated nature of the small liquid-air meniscus area (Fortes 1982, Carter 1988, Finn 1986, Padday, Pitt and Pashley 1974, Matijevic 1969) since the liquid-air area is small. At $z = z^*$, $U_S$ has a breakpoint, and for $z < z^*$, the liquid overflows. Initially, the total energy is

$$U_T = U_S + U_E$$

$$= U_{S_o} + 2\pi \gamma_l \cos \theta_c \left( r_o^2 - \frac{V_l}{\pi h} \right) + \frac{1}{2} \kappa (h - z)^2$$

The equilibrium plate spacing minimizes $U_T$. Figure 5 shows plots of $U_T$ for different liquid volumes. The curve has one or two minima. One of

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Figure 5. (a) Total energy of the two-plate system. (b) Activation energy separating the minima

these develops at the breakpoint of $U_S$ implying that the equilibrium liquid
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radius is $r_o$. The other results when $dU_T/dz = 0$ or from Eq. (2) along the curve

$$z^2(z - h) - \frac{2\gamma_0 \cos \theta_c V_i}{k} = 0. \quad (3)$$

The path traced by the reachable minimum of $U_T$ as the liquid volume decreases from $V_i = V_0$ to $V_i = 0$ determines the equilibrium position and final state of the plate. This path is known as the equilibrium trajectory, and a reachable minimum of a potential system is that at which the system rests from a known starting state. Conceptually, this minimum is determined by placing an imaginary golf ball on the energy curve at any starting position and letting it roll to the most favorable energy well. As internal control parameters change, the shape of the curve and its minima shift making the ball slide toward one side or the other (see Figure 6). Sudden changes or

![Diagram](image)

*Figure 6.* (a) Reachable minima of a potential system. (b) Catastrophe.

**Catastrophes** may occur in the equilibrium for those values of the parameters at which a local minimum disappears when it merges with a local maximum (Arnold 1986, Saunders 1990, Poston and Stewart 1978, El Naschie 1990).

The behavior of the spring-plate-liquid system during the drying cycle is evident when the branches of the local extrema of $U_T$ are plotted as a function of the control parameter $V_i$ in a branching diagram. Letting $\xi = V_i/V_0$, $\lambda = z/h$ and $V_0 = \pi r_0^2 h$, the first branch $B_\infty$ associated with an extremum in $U_S$ is

$$B_\infty : V_i = \pi r_0^2 \xi , \text{ or } \xi = \lambda. \quad (4)$$
The second branch $B_\xi$ is found from Eq. (3)

$$B_\xi : \quad \xi = \left( \frac{\kappa h^2}{2\pi \gamma \cos \theta_c r_0^2} \right) (1 - \lambda) \lambda^2 = N_C (1 - \lambda) \lambda^2 ,$$

where the non-dimensional number $N_C = \kappa h^2 / 2\pi \gamma \cos \theta_c r_0^2$. Branch $B_\xi$ is a minimum of $U_T$ for $\lambda > 2/3$ and a maximum for $\lambda < 2/3$. Figure 7 shows three branching diagrams for fixed $N_C$. The arrows show the direction of the equilibrium trajectories.

In Figure 7(a), the equilibrium trajectory begins at $A$ with $(\xi, \lambda) = (1, 1)$. If $N_C$ is low, branches $B_\infty$ and $B_\xi$ do not intersect. As $V_1$ decreases, the trajectory follows branch $B_\infty$ from points $A$ to $B$. At $\xi(B)$ a second minimum $C$ from $B_\xi$ emerges in the energy curve. This new minimum is not reachable since an energy barrier $\Delta U_B \rightarrow C$ is present between the two minima as shown in Figure 5(b). In the limit as $V_1 \rightarrow 0$, the trajectory ends at $D$ with $(\xi, \lambda) = (0, 0)$. The final plate separation is $z = 0$, and the plate remains pinned to the substrate.

$N_C$ can be adjusted such that $B_\infty$ and $B_\xi$ intersect in a segment as in Figure 7(b). Setting $B_\infty(\lambda) = B_\xi(\lambda)$ one finds

$$\xi = (\lambda_1, \lambda_2) = \frac{1}{2} \pm \left( \frac{1}{4} - \frac{1}{N_C} \right)^{1/2} .$$

When $\lambda_1$ and $\lambda_2$ are real, the segments of $B_\infty$ and $B_\xi$ in $\lambda_1 \leq \lambda \leq \lambda_2$ combine thus disappearing from the extremum set. The equilibrium trajectory starts at $A$ following branch $B_\infty$ to $B$. At $\xi(B)$, the trajectory jumps abruptly to the now global minimum at point $C$ and continues along $B_\xi$ to point $D$ where the minimum $E$ from $B_\xi$ reappears. Point $E$ is is not reachable because of the barrier $\Delta U_D \rightarrow E$; thus, for lower $V_1$, the trajectory follows $B_\xi$ ending at $F$ with $(\xi, \lambda) = (0, 1)$. The final plate separation is $z = h$, and the plate is free.

There is a threshold value in $N_C$, defined as $N_T$, that determines the final state. Trajectories with $N_C < 4$ follow $B_\infty$ throughout the cycle, yielding pinned plates. Trajectories with $N_C$ slightly larger than 4 are routed to branch $B_\xi$ after a catastrophe yielding free plates. For $N_C \geq 9/2$ and $\lambda_2 \geq 2/3$, the trajectory is a smooth curve (Figure 7(c)) yielding free plates; thus $N_T = 4$.

It is convenient to define an elastocapillary number, $N_{EC}$, such that the plate is free for $N_{EC} > 1$ and pinned for $N_{EC} < 1$. Thus

$$N_{EC} = \frac{N_C}{N_T} = \left( \frac{\kappa h^2}{8\pi \gamma \cos \theta_c r_0^2} \right) .$$

The analysis of the spring-plate-liquid system shows a bifurcation of the equilibrium trajectory, and a non-dimensional number which determines
Figure 7. Branching diagrams for the spring-plate-liquid system

its final state. These characteristics are also present in continuous elastic structures. In (Mastrangelo and Hsu 1993), expressions for the elastocapillary numbers for continuous elastic beams and plates have been calculated using a variational energy approach that includes the balance of elastic, po-
<table>
<thead>
<tr>
<th>Structure</th>
<th>Approximate Elasticity Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>cantilever beam</td>
<td>( \frac{2 E h^2 t^3}{9 \eta \cos \theta_e t^4 (1 + l/w)} )</td>
</tr>
<tr>
<td>doubly supported beam</td>
<td>( \frac{128 E h^2 t^3}{15 \eta \cos \theta_e t^4 (1 + l/w)} \left[ 1 + \frac{3(1 - \nu^2)}{4} \frac{\sigma_R w^2}{E t^2} + \frac{2177}{2560} \left( \frac{h^2}{t^2} \right)^{3/4} \right] )</td>
</tr>
<tr>
<td>circular plate</td>
<td>( \frac{10}{9} \left( \frac{E h^2 t^3}{\eta \cos \theta_e (1 - \nu^2) t^4} \right) \left[ 1 + \frac{3(1 - \nu^2)}{4} \frac{\sigma_R w^2}{E t^2} + \frac{2177}{2560} \left( \frac{h^2}{t^2} \right)^{3/4} \right] )</td>
</tr>
<tr>
<td>square plate</td>
<td>( \frac{20}{9} \left( \frac{E h^2 t^3}{\eta \cos \theta_e (1 - \nu^2) w^4} \right) \left[ 1 + \frac{2(1 - \nu^2)}{9} \frac{\sigma_R w^2}{E t^2} + \frac{5}{12} \frac{h^2}{t^2} \right] )</td>
</tr>
</tbody>
</table>

Potential, and surface energies. The results for different microstructures are shown in Table I, where \( E \) is the Young modulus, \( t \) the member thickness, \( h \) the gap, \( \nu \) is Poisson's ratio, \( \sigma_R \) the member residual tensile stress, and \( l, w, r_0 \) are the member length, width, and radius.

3. Adhesion by Intersolid Contact Forces

The second the phenomena in the failure path is a strong intersolid adhesion force between the microstructure and the substrate overcomes the elastic restoring force of the deflected suspension member. The intersolid adhesion force is a consequence of the change in the energy stored at the contact area with respect to the member deformation. The magnitude this the adhesion energy depends on the nature of the interface and the presence of surface contamination. In pure crystalline solids this energy is high (500-2000 mJm\(^{-2}\)), and in soft polymers it is much lower (5-100 mJm\(^{-2}\)).

It has been reported that the adhesion between two microstructure surfaces is also dependent on the roughness of the surface (Komvopoulos 1996). In practice, the proper treatment of this parameter is difficult as the interfacial roughness for a microstructure is by no means a-priori certain, and its influence on the onset of sticking failure is largely not understood. Therefore for all calculations that follow this energy represents an effective empirical quantity.

In this section we consider the equilibrium between these two opposing
forces using an energy function formulation that includes the adhesion and elastic energy of the deformed suspension member.

The simplest problem is that of the peeling of an elastic cantilever beam from an adhesive surface. This problem is related to the peeling of sticky tapes (Kendall 1971) and the cleavage of crystals (Maszara, Goetz and McKitterick 1988, Gillis and Gilman 1964, Gilman 1960). Figure 8 shows a cross section of a cantilever beam of length $l$, width $w$, thickness $t$, height $h$, and Young’s modulus $E$. The beam is adhering to its substrate a distance $d = (l - s)$ from its tip. The stored elastic energy of the beam in the segment $0 \leq x \leq s$ induces a restoring force that tends to peel the beam from the adhering substrate. The energy of adhesion stored in the segment $s \leq x \leq l$ induces another force that holds the beam in contact with the substrate. The equilibrium peel distance $s^*$ is determined by the balance of these two energies. At equilibrium, $s^*$ minimizes the the total energy of the system (bending plus adhesion energies) (Kendall 1971).

Since there are no external forces acting on the beam for $0 \leq x \leq s$, its deflection $u(x)$ is the solution of

$$E I \frac{d^4 u}{dx^4} = 0 \quad , \quad I = \frac{wt^3}{12} , \quad (8)$$

where $I$ is the moment of inertia of the beam respect to the $z$ axis. Equation (8) is solved subject to the boundary conditions

$$\frac{du}{dx} \bigg|_0 = \frac{du}{dx} \bigg|_s = 0 \quad , \quad u(0) = 0 \quad , \quad u(s) = h \quad . \quad (9)$$

which ignores the effects of finite compliance at the step-up posts (Mullen, Mehrengany, Omar and Ko 1991, Meng, Mehrengany and Mullen 1993). Equation (8) has the solution

$$u = h f(\eta) = h \eta^2 \left( 3 - 2 \eta \right) \quad , \quad \eta = \frac{x}{s} . \quad (10)$$
The bending energy stored in the beam is

\[ U_E = \frac{EI}{2} \int_0^l \left( \frac{d^2 u}{dx^2} \right)^2 \, dx = \frac{6EIh^2}{s^3} . \]  

(11)

The interfacial energy stored in \( s \leq x \leq l \) is simply the surface energy per unit area of the bond \( \gamma_s \) times the area of contact

\[ U_S = -\gamma_s w (l - s) . \]  

(12)

The parameter \( \gamma_s \) has units of J m\(^{-2}\) or N m\(^{-1}\). The sign of \( U_S \) is negative because it is a binding energy. The total energy (or free energy) of the system is the sum of the elastic plus surface energies

\[ U_T = U_E + U_S = \frac{6EIh^2}{s^3} - \gamma_s w (l - s) . \]  

(13)

Figure 9 shows a typical curve of \( U_T(s) \). This curve has a single minimum corresponding to the equilibrium \( s^* \). This is found by setting \( dU_T/ds = 0 \)

\[ s^* = \left( \frac{3 E^3 h^2}{2} \right)^{1/4} \gamma_s . \]  

(14)

The energy curve has a single equilibrium point if \( s^* < l \) and no equilibrium point if \( s^* > l \). Thus the beam is pinned to the substrate if \( s^* < l \), and it is free if \( s^* > l \).
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\[ \theta = 0 \]

\[ \theta > 0 \]

\[ (a) \]

\[ (b) \]

\[ (c) \]

Figure 10. Pivoting of cantilever tip near detachment.

The slope boundary condition \( du/dx = 0 \) at \( x = s \) does not allow for shear deformations of the tip of the beam. Shear deformations are particularly important for \( s \to l \) since when \( d = (l - s) \) is very small, the tip of the cantilever “pivots” changing its elastic energy substantially just before detachment as shown in Figure 10. This effect is taken into consideration by dividing the beam into two regions. The region of the beam for \( 0 < x < s \) has no external forces acting on it, so Eq. (8) is solved subject to the boundary conditions of Eq. (9) and the modified slope condition at \( x = s \),

\[
\frac{du}{dx} \bigg|_s = \theta = \frac{hm}{s} .
\]

where \( \theta \) is the shear angle of the tip, and \( m \) is a non dimensional number. The deflection \( u(x) \) and elastic energy of the beam segment are

\[
u = h \eta^2 \left( (m - 2) \eta + (3 - m) \right) ,
\]

\[
U_E = \frac{6EIh^2}{s^3} \left( 1 - m + \frac{1}{3} m^2 \right) .
\]

Note that \( U_E \) decreases with increasing \( m \) (and \( \theta \)) for \( 0 \leq m \leq 3/2 \). The short segment \( s \leq x \leq l \) corresponding to the beam tip experiences shear deformations which determine \( m \). The solution of the coupled problem is
<table>
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<th>Approximate Peel Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>cantilever beam</td>
<td>$\frac{3 , E , t^3 , h^2}{8 , \gamma_s , l^4}$</td>
</tr>
</tbody>
</table>
| doubly supported     | \[
\begin{align*}
\left( \frac{128 E h^2 \, t^3}{5 \, \gamma_s \, l^4} \right) \left[ 1 + \frac{4 \, \sigma_R \, \ell}{21 \, E \, t^2} + \frac{256}{2205} \left( \frac{h}{t} \right)^2 \right]
\end{align*}
\] |
| circular plate       | \[
\frac{40}{3} \left( \frac{E \, h^2 \, t^3}{(1 - \nu^2) \, \gamma_s \, r^2} \right) \left[ 1 + \frac{51 (1 - \nu^2)}{160} \left( \frac{\sigma_R \, r^2}{E \, t^2} + \frac{63}{200} \frac{h^2}{t^2} \right) \right]
\] |
| square plate         | \[
\frac{186 \, E \, h^2 \, t^3}{(1 - \nu^2) \, \gamma_s \, w^4} \left[ 1 + \frac{27 (1 - \nu^2)}{310} \left( \frac{\sigma_R \, w^2}{E \, t^2} + \frac{12 \, h^2}{31 \, t^2} \right) \right]
\]

Given in reference (Mastrangelo and Hsu 1992) yielding

\[
m(s) = \frac{16}{5} \left( \frac{t}{d} \right)^3 \left( \frac{t}{s} \right) \left[ 1 + \frac{15}{32} \left( \frac{d}{t} \right)^2 \frac{E}{G} \right] + \frac{32}{15} \left( \frac{t}{d} \right)^3 \left( \frac{t}{s} \right) \left[ 1 + \frac{15}{32} \left( \frac{d}{t} \right)^2 \frac{E}{G} \right] \quad (17)
\]

where $G = E / (2(1 + \nu))$ is the beam shear modulus.

The beam detaches from its substrate when

\[
l = s^* = \left( \frac{3 \, E \, t^3 \, h^2}{8 \, \gamma_s} \right)^{1/4}
\]  

(18)

Therefore we can define a peeling bound, $N_P$ such that the beam remains in contact with the substrate for $N_P < 1$ and free for $N_P > 1$. Thus

\[
N_P = \frac{3 \, E \, t^3 \, h^2}{8 \, \gamma_s \, l^4}
\]

(19)

Using the same techniques, peel bounds for doubly-supported beams and plates have been calculated. These bounds are shown in Table II.

Figures 11-12 shows experimental plots of the effectiveness of some of the bounds for different structures. The best fit occurs for cantilever beams because of the lack of residual and elongation stresses. The surface energies have been determined from the slope of the plot. Surface energies ranging
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![Graph showing detachment length as a function of (h^2 l^3)^{1/7} (μm)^{5/7}]

**Figure 11.** Peel bound for polysilicon cantilever beams

![Graph showing detachment length as a function of (h^2 l^3)^{1/7} (μm)^{5/7}]

**Figure 12.** Peel bound for doubly supported beams

between 100-300 mJm⁻² have been measured for polysilicon microstructures (Mastrangelo and Hsu 1993).

4. **Some Failure Prevention Methods**

While these bounds are useful for detecting the onset of adhesion failures in MEMS devices, many practical devices require dimensions that fall within
the failure range. A number of schemes have been developed to eliminate the failure both during the fabrication and device operation. Roughly, these schemes fall within two categories. Physical schemes aim at modifying the shape of the structure to minimize the collapsing or contact force. Chemical schemes aim toward the chemical modification of the contact surfaces through the use of low-energy coatings.

4.1. ELIMINATION OF COLLAPSING FORCE

A large number of adhesion failures occur during the fabrication of the devices themselves. These failures are related to the capillary force that develops when the structures are released by wet chemical etches.

4.1.1. Freeze-Drying Methods:
The capillary pull force can be eliminated if the liquid phase is not present. The rinse solution can be removed by freezing the solution and sublimation. This freeze-drying (Flosdorf 1982, Holler 1979, Mellor 1978) technique can be used to eliminate the capillary pull by first freezing the sample and then exposing it to a heated vacuum environment. This idea was first applied to the release of MEMS devices by Guckel and Burns (Guckel and Burns 1989). A well known disadvantage of the freeze-drying method is the fact that the rinse solution can undergo a significant volume change. This volume change can create a stress sufficient to destroy the sample. To alleviate this problem, Guckel used a rinse solution consisting of a mixture of methanol and water that minimized the volume change. A similar process was developed by Takeshima et al. (Takeshima et al. 1991) who replaced the rinse solution through a gradual series of dilutions with t-butyl alcohoh. This compound freezes at 25.6°C and is much softer than Guckel's icy mixture; however the sublimated vapors are highly toxic.

4.1.2. Supercritical Drying:
Another method of eliminating the capillary pull is by the use of supercritical drying techniques. In this technique, the rinse solution is gradually replaced by liquid CO₂ at elevated pressures inside a high-pressure chamber. The sample is then taken to the critical point of CO₂ where the interface between the liquid and gas does not exists. The technique is highly successful with nearly 100% yields (Mulhern, Soane and Howe 1993). Commercial supercritical drying equipment has been available for more than 20 years (Dawes 1988) for small samples, and large scale equipment construction has been planned. The main difficulty with the technique resides in the safety considerations because of the very high (≈ 72 Atm) pressures required to take the samples to the critical point. This technique is more widely accepted than the freeze-drying method.
4.1.3. **Dry Etching:**
A number of schemes have been proposed which are based on dry etching of the sacrificial layer. This operation is often difficult if the sacrificial layer is silicon based (such as silicon dioxide) because it requires strong etchants that do not have good selectivities with respect to the suspended element material. Vapor-phase HF etching (Watanabe, Ohnishi, Honma, Kitajima, Ono, Wilhelm and Sophie 1995) at elevated temperatures (Wong, Moslehi and Bowling 1993, Ruzillo, Torek, Daffron, Grant and Novak 1993) has been often used for this purpose with a high rate of attack of silicon nitride films. The structure can also be easily released by plasma etching if the sacrificial layer is silicon (Hirano, Furuhata and Fujita n.d.).

A more successful series of techniques are based upon the replacement of the sacrificial layer with a weaker solid that can be later removed by a harmless dry etching. These schemes involve primarily the replacement of sacrificial layers with plastics that can be then be etched using O₂ plasma or ozone which are harmless to silicon-based materials. Techniques based on conformal vapor deposited polymer supports (p-xylene) (Figures 13-15) (Mastrangelo and Saloka n.d.) have been successful in releasing polysilicon plates that as large as $3000 \times 3000 \times 1 \, \mu m^3$. A technique that is based

![Figure 13. Top view of polymer support feet on a polysilicon plate](image)

upon the replacement of the rinse solution with resist through a series of dilutions was developed by Orpana and Korhonen (Orpana and Korhonen 1991). Other techniques include the replacement of the rinse solution with
monomers that polymerize in a short time as well as plasma-polymerized fluorinated plastics (Kozlowski, Lindmair, Scheiter, Hierold and Lang 1995, Jansen, Gardeniers, Elders, Tilmans and Elwenspoek 1994).

4.1.4. **Hydrophobic Coatings:**

The capillary pull can become a push if the contact angle is made larger than 90°. Oxidized silicon surfaces are hydrophilic with contact angles ranging from 0 - 39° depending on the type of oxide and surface treatment.
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Bare silicon surfaces obtained by the removal of native oxide using HF are hydrophobic. The hydrophobicity has been attributed to possible hydrogen groups (Graf, Grunder, Schulz and Muhlhoff 1990) attached to the silicon. Contact angles (Gould and Irene 1988) as high as 78° have been reported; however, the native oxide is known to regrow in both water and when exposed to air (Watanabe, Hamano and Harazono 1989, Morita, Ohmi, Hagesawa, Kawakami and Suma 1989); thus complete hydrophobicity is difficult to achieve. In order to obtain a higher contact angle, a chemical change in the surface of the suspended member is required. Recently, a number of well-known (Ulman 1991) hydrophobic self-assembled monolayers (SAM) have been grown on silicon surfaces with successful results (Alley, Howe and Komvopoulos 1992, Houston, Maboudian and Howe 1996). These layers are based on the silanization of silicon surfaces with organic groups by treating the surface with octadecyltrichlorosilane (OTS) precursor molecule (C₁₈H₃₇SiCl₃). The procedure first involves the replacement of the aqueous rinse with an organic solvent through a series of dilution steps. The SAM is next grown, and then the solvent is replaced by water through the reverse series of dilutions. Because the silanized surfaces have a very high contact angle (≈ 114°), at this stage the water recedes from the surfaces resulting in a sample that emerges dry from the rinse. Cantilever beams at least as long as 1000 μm long were successfully released using this technique with beams as long as 400 μm passing the “in-use” stiction contact test (Figure 16). More recently, self-assembled fluorinated layers have been used for

Figure 16. Sticking probability for cantilever beams that were given different treatments.

the same purpose with improved results (Srinivasan, Houston, Howe and Maboudian 1997).
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Most of these techniques (with the exception of coatings) can only eliminate the capillary pull or its effects during its fabrication process. After the sample is packaged, if it is exposed to a high-humidity environment or a shock, the pinning may return hence becoming a reliability issue. Therefore these techniques are insufficient to effectively eliminate the adhesion failure but rather delay it. A permanent solution to the problem also requires additional treatments that attempt to reduce the intersolid adhesion.

4.2. REDUCTION OF INTERSOLID ADHESION

The permanent elimination of the adhesion failure requires the reduction of the intersolid surface adhesion. Several techniques have been developed toward this goal. The main ones are listed below.

4.2.1. Textured Surfaces:
The adhesion force can be decreased if the contact area between the elastic member and the substrate is reduced. This can be accomplished by texturing the contact surface through the generation of a rough interface (Alley, Mai, Komvopoulos and Howe 1993, Yee, Chun and Lee 1995). Yee (Yee et al. 1995) reported an increase in the detachment length of approximately two by the oxidation and dry etching of a polysilicon supporting surface.

Texturing can also be introduced by constructing a periodic array of small supporting post, commonly known as “dimples”. These supports are constructed by etching small indentations into the sacrificial layer before the deposition of the suspended member as shown in Figures 17-18. This method was first used by L. S. Fan (Fan 1990) for the construction of a micromotor, and later applied to comb drives (Tang, Nguyen and Howe n.d.). The force required to detach a semi-spherical dimple of radius \( R \) is (Johnson, Kendall and Roberts 1971, Johnson 1987)

\[
F = \frac{3}{2} \pi \gamma_s R
\]

hence it becomes zero as \( R \rightarrow 0 \). This technique is very simple but it suffers from two drawbacks. First, the dimple method cannot be applied for microstructures with flat surfaces as required in many transducer designs. Second, the adhesion of the dimple is often larger than that anticipated by Eq. (20) when drying out the sample. This is attributed to the formation of a solid bridge of \( \text{SiO}_2 \) as water evaporates (Watanabe et al. 1989).

4.2.2. Low-Energy Monolayer Coatings:
These coatings are the same hydrogenated and OTS-type monolayers discussed above. If their intersolid adhesion energy is sufficiently low, this
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Figure 17. Construction of dimple posts.

Figure 18. SEM photograph of a dimple on a polysilicon plate.

option is very attractive since it eliminates both failure originating mechanisms. Houston et al. (Houston et al. 1996) performed contact tests in silicon microstructures with surfaces that were terminated with hydrogen bonds, and coated with OTS self-assembled monolayers. Preliminary tests suggested that cantilever beams as long as 1000 μm-long exhibited about 50% sticking probability on OTS-coated samples after they are brought in contact with the substrate (Figure 16). These films have been reported to
show an extremely low effective adhesion energy (3 \( \mu \text{Jm}^{-2} \)). More recently, coatings of perfluorinated alkyltrichlorosilane or FDTS (\( \text{C}_{10}\text{H}_{4}\text{F}_{17}\text{SiCl}_{3} \)) have been used for elimination of adhesion (Srinivasan et al. 1997).

The main difficulty associated with many of these films is their fragility. Because the SAM films are extremely thin (\( \approx 2.5 \) nm), they have a high tendency to degrade at elevated temperatures, as shown in Figure 19. (Houston et al. 1996). The aging behavior of hydrogen terminated surfaces has also been observed by Houston et al. (Houston, Maboudian and Howe 1995) indicating that these surfaces degrade over time. FDTS films are less reactive than OTS films hence can withstand much longer periods at atmospheric conditions and at elevated temperatures. Figure 19 shows the comparison of water contact angles on the film surfaces when exposed to elevated temperatures for a brief time.

Recent experiments by Kluth et. al. (Kluth, Sunag and Maboudian 1997) suggest that these films are also susceptible to thermal desorption; hence their long term effectiveness remains an open question. These films however will remain effective inside sealed, controlled packaged environments at thermal equilibrium where degradation reactions cannot take place, and any vaporization is henceforth followed by a redeposition. Simi-
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lar monolayer films are currently used in sealed deformable mirror displays under this strictly controlled environment (Hornbeck 1995).

4.2.3. Fluorinated Coatings:
Fluorinated hydrocarbon coatings consisting of CF\textsubscript{x} chains have very low surface energies; hence they are likely candidates coatings for the reduction of intersolid adhesion. PTFE-like layers can be grown in many different ways (Licari 1970). A common way to grow these films is by plasma polymerization (Yasuda and Hsu 1977, Yasuda and Hsu 1978, Yasuda 1985). Often the growth of these films is highly directional with most of the growth occurring in the surfaces exposed to the plasma (Jansen et al. 1994). In order for these films to be effective, the film must grow under a covered surface.

Fluorinated films can also be grown at a much reduced rate in zones which are not directly exposed to the plasma (Buzzard 1978). In this regime, the deposition rate is a diffusion-limited process which is not subject to the rapid decay of the plasma density resulting in a much more uniform deposition. This idea has been recently exploited by Man et al. (Man, Gogoi and Mastrangelo n.d., Man, Gogoi and Mastrangelo March 1997) to deposit PTFE-like films on silicon microstructures with much improved conformality In this technique, the deposition takes place inside a Faraday cage that prevents the plasma from directly reaching the sample.

![Figure 20. Cross section of poly plate showing PTFE film coverage](image)

The fluorinated films can be quite thick (> 20 nm) hence durable and have a contact angle of about 108 °.
Figure 21. Example polysilicon plate coated with PTFE

Figure 22. Uniformity of TFE-like films on the underside of suspended plates. The front of the plate has approximately twice the thickness as the underside.

Periodic wear and temperature tests were performed in these films as shown in Figure 25. The results predict a projected mean time to failure (determined by a loss in the hydrophobicity) greater than 10 years at 150 °C in atmospheric conditions. The films remain hydrophobic even at very high temperatures and display little wear even after $10^7$ contact cycles.

Of all the above adhesion prevention methods, low-energy coatings are the most effective and reliable. In addition, both SAM (Deng 1994) and thicker fluorinated coatings have proved effective in the reduction of wear and friction in dynamic microstructures (Smith, Sniegowski and LaVigne 1997). The monolayer technique is very attractive since it solves both capillary pull and adhesion problems with only one application, but it requires a sealed package to maintain the long term monolayer integrity. Thicker films are more robust and can survive atmospheric conditions for
many years but these require the use of a complementary technique to eliminate the capillary pull during the device fabrication. So far the best solution seems to be a combination of both techniques.
5. Conclusion

This paper reviews the causes and solutions for surface force induced sticking failures in microelectromechanical systems. The failures originate from the extreme susceptibility of suspended MEMS devices to surface forces due to their close proximity to their substrates. The failure route requires the presence of a collapsing force followed by a strong intersolid adhesion. The behavior of the microstructure under these two forces has been examined and several practical techniques for the elimination of failure are discussed.

References


Deng, K.: 1994, PhD thesis, Case Western Reserve University, Cleveland, OH.


*Figure 5*. Degradation of TFE-like plasma polymerized coatings under atmospheric conditions at different temperatures. These films remain on the sample for many years.
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