2.373J/3.48/6.778J/10.584/16.288J/SMA5108/4I6

# YIELD AND RELIABILITY OF MEMS

28 April 2003


## V. T. Srikar and S. Mark Spearing

Massachusetts Institute of Technology

## John Williams

Cambridge University Engineering Department


## Yield and Reliability

**Reliability: Measure of the probability of failure of a device in service - due to any cause**

**Yield: Measure of the number of devices (or component parts) produced vs. the expected number given the amount of incoming material/devices started**

## (Some) Yield and Reliability Concerns in MEMS

**Reliability Concerns**:

**Stiction**

Fracture ✓

Delamination ✓

Fatigue ✓

**Wear**

**Yield Concerns**:

**Stiction**

Particle contamination

Residual Stress and gradients ✓

Fracture ✓

## MEMS Reliability concerns not discussed here

- Moisture diffusion
- Gas diffusion
- Thermal runaways
- Creep/relaxation (particularly polymers, soft metals)
- Electrical breakdown (shorting, sparking)
- Interconnect reliability
- EM Fields
- Radiation
- ……

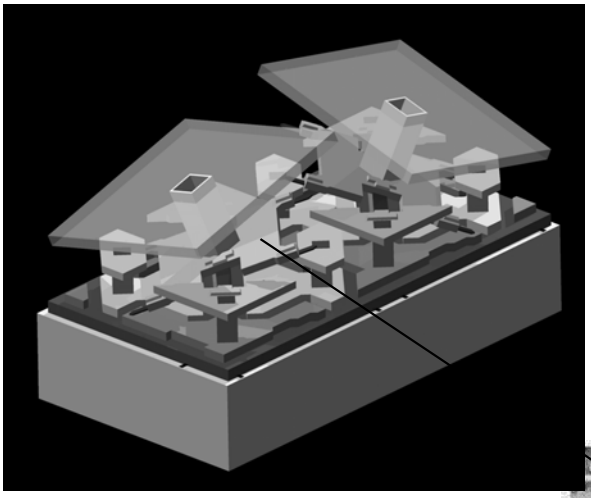
*If it can fail, it will (Murphy's law), but application of common sense, and proactive failure mode analysis can ease reliability issues (ask the "what if?" questions and perform tests)*

## MEMS Yield issues/remedies not discussed here

- Achieving designed tolerances in processes
- Interfaces (bonds, interconnects, joints)
- Residual stresses
- Gross errors (tool settings
- Yields multiply ($0.99^{100}$=0.37)
- Back end processes are particularly crucial
  - – packaging, wafer bonding, interconnects
- Application of statistical process control, process capability, total quality management, 10 x process improvement

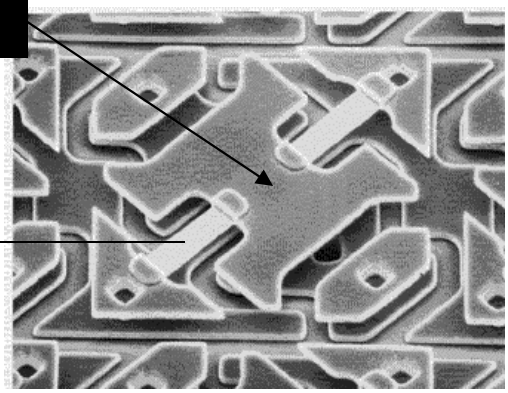
*Devices can be designed for manufacturability, but processes have to be managed with yield as an objective function*

## Example 1: TI Micromirror



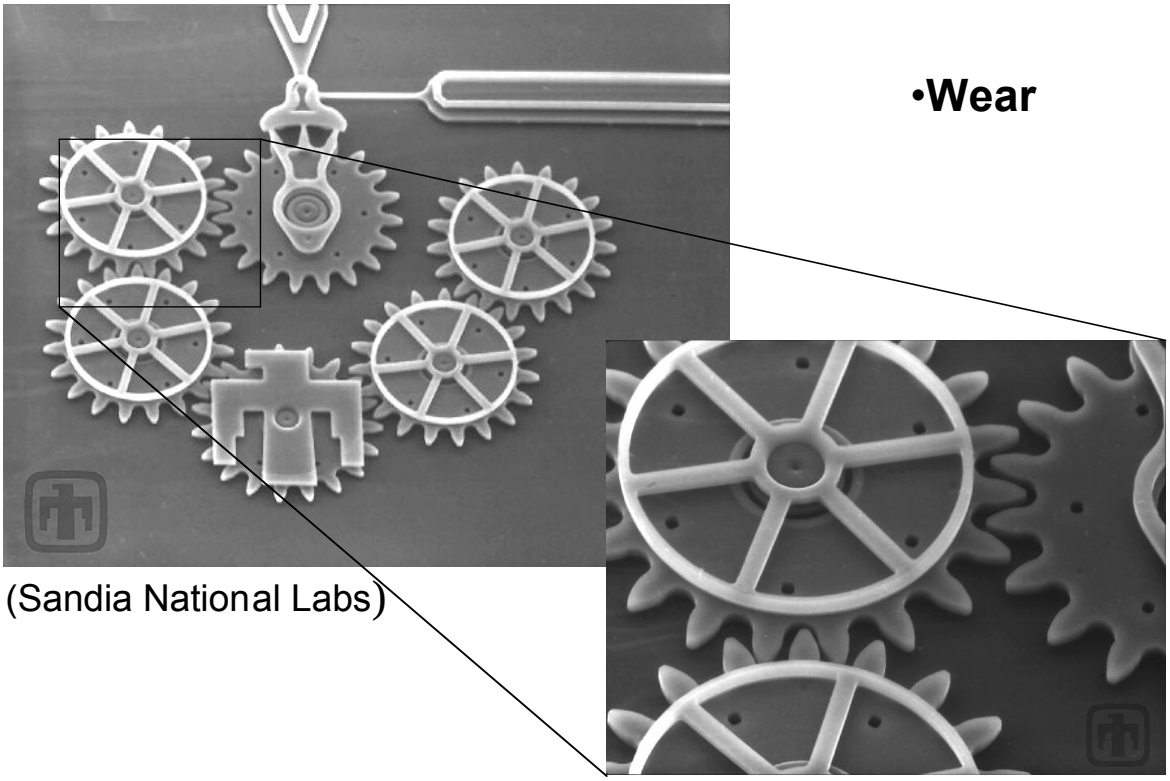
(Texas Instruments)

- **Particle contamination**
  (Package in Class 10 room)
- **Fatigue**
  (No failures after $10^{12}$ cycles!)



Torsional hinge

## Example 2: Sandia Gear Chains



•**Wear**

(Sandia National Labs)

## Stiction

•*Undesirable Immobilization of Mechanical Structures*

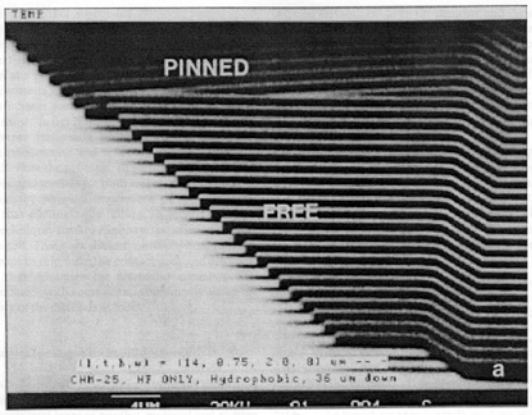



Fig. 1. SEM of micromachined polysilicon cantilever beams of increasing length. The photograph shows clearly the onset of the pin for beams longer than 34 μm.

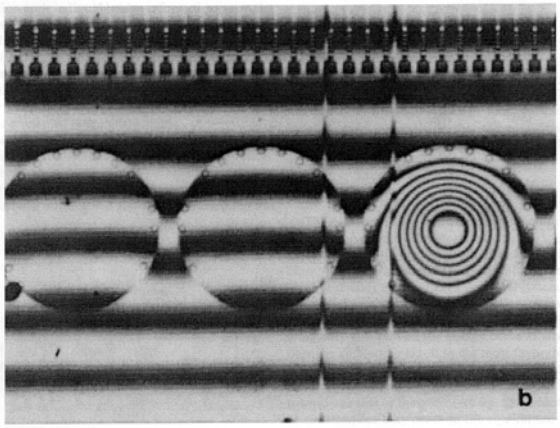
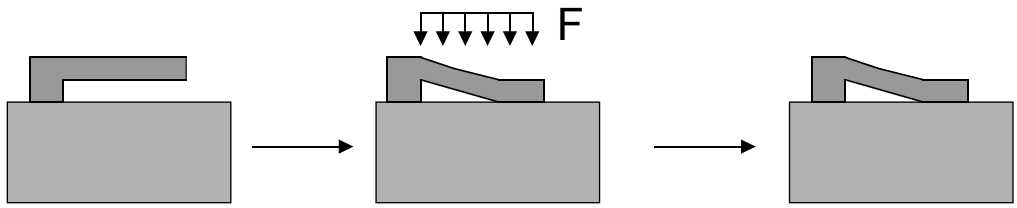



Fig. 2. Interferometric microphotograph of an array of micromachined polysilicon circular plates. The structures with circular interference patterns are pinned to the substrate. The first pinned plate is 252 μm in diameter.

(Mastrangelo)

## Necessary Ingredients for Stiction

•*Collapsing force and Solid-solid adhesion*




*Initial State* → ***Mechanical Collapse*** → ***Solid-Solid Adhesion***

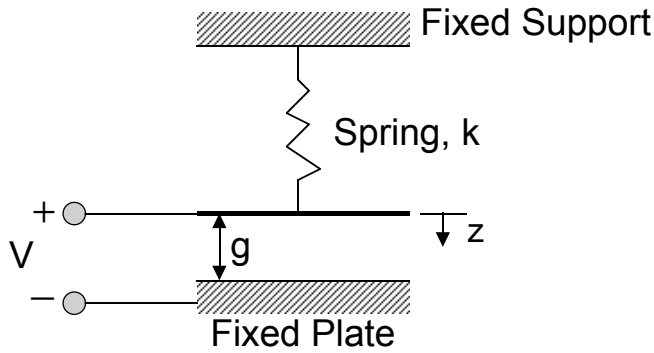
(During Fabrication or Operation)
- •Electrostatic forces
- •Capillary forces
- •Shock loads

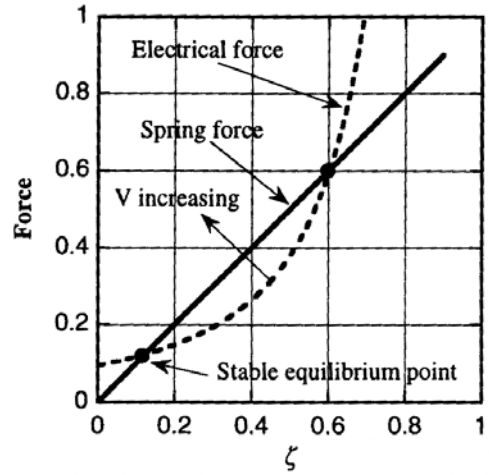
•Note similarities with Wafer-Bonding

## Outline of Stiction

- Nature of collapsing forces
  - -- Electrostatic
  - -- Capillary
  - -- Mechanical (Shock)
- Techniques to reduce collapsing forces
- Nature of solid-solid adhesion
- Techniques to reduce adhesion
  - -- Dimples
  - -- Self-Assembled Monolayers (SAM)
- Recovery after stiction
  - -- Mechanical forces
  - -- Lorentz forces

## 1. Electrostatic Forces: Pull-In



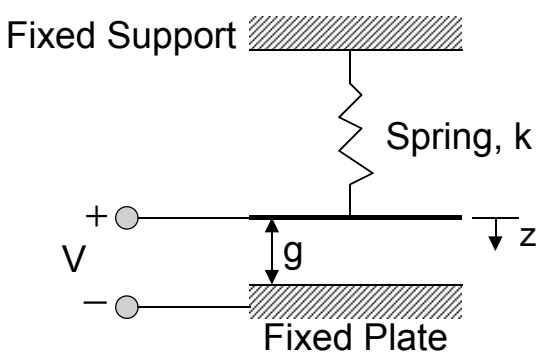

$$F_{net} = F_{electrostatic} + F_{elastic} = \frac{-\varepsilon A V^2}{2g^2} + k(g - g_0)$$

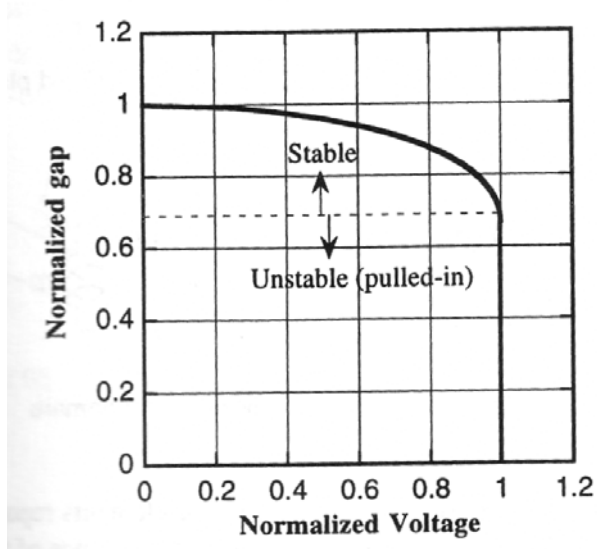
$$F_{net} = 0 \qquad \text{(Equilibrium)}$$

$$\delta F = \frac{\partial F_{net}}{\partial g}\delta g \qquad \text{(Stability of equilibrium)}$$

(Senturia)

## 1. Electrostatic Forces: Pull-In



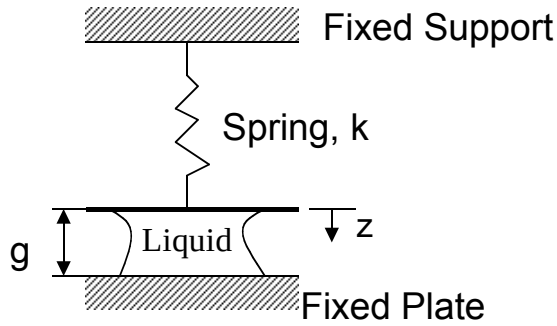

$$V_{PI} = \sqrt{\frac{8k\,g_0^3}{27\varepsilon A}}$$

$$g_{PI} = \frac{2g_0}{3}$$

Collapse for $V > V_{PI}$

(Senturia)

## 2. Capillary Forces



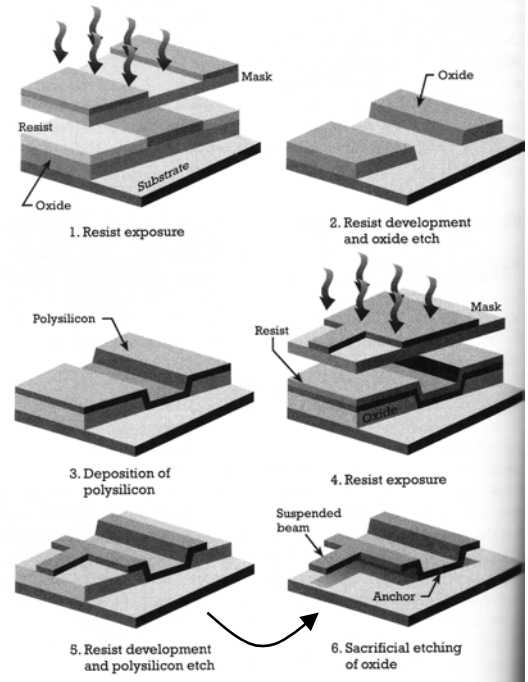



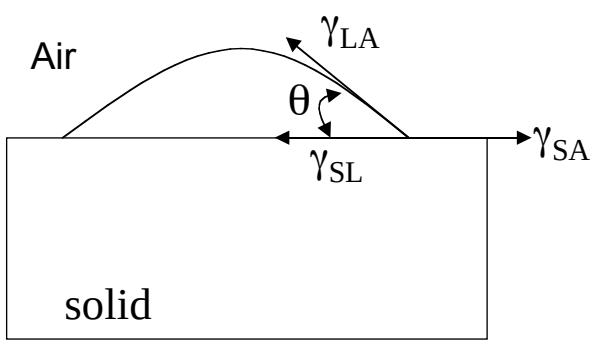

**Figure 3.20** Schematic illustration of the basic process steps in surface micromachining.

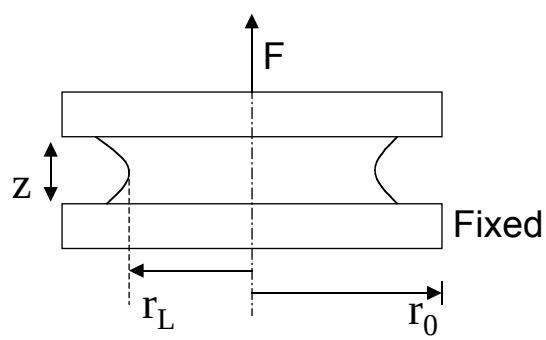
(Maluf)

- Sacrificial release etch
- Condensation in humid environments

(Mastrangelo and Hsu)

## 2. Capillary Forces




$$\gamma_{SA} = \gamma_{SL} + \gamma_{LA}\cos(\theta)$$

$$U_S = 2\left[A_{SA}\gamma_{SA} + A_{SL}\gamma_{SL}\right] = 2\pi\left[r_0^2\gamma_{SA} - r_L^2\gamma_{LA}\cos(\theta)\right]$$

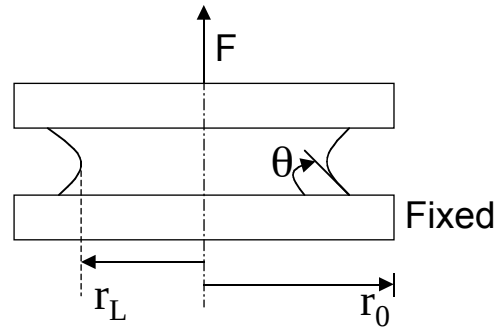
$$F = -\left(\frac{dU}{dz}\right) = -\left(\frac{dU}{dr_L}\right)\left(\frac{dr_L}{dz}\right) = \frac{-2\pi r_L^2\gamma_{LA}\cos(\theta)}{z}$$

(Mastrangelo and Hsu)

## 2. Capillary Forces

$$\Delta p_{LA} = \frac{-2\gamma_{LA}\cos(\theta)}{z}$$

(Laplace equation)

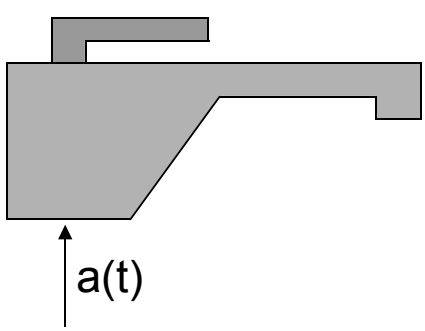


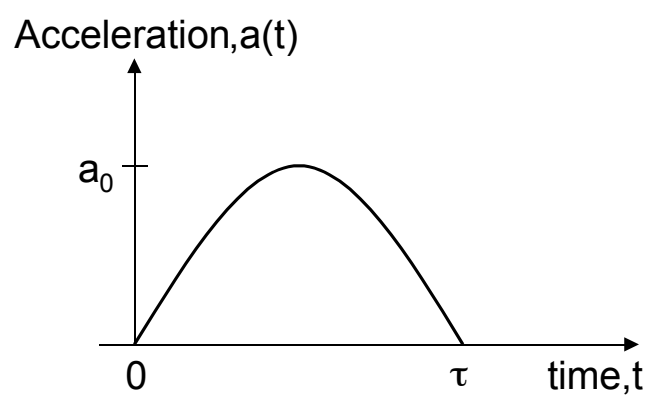

$$F = \Delta p_{LA} A = \frac{-2\pi r_L^2 \gamma_{LA}\cos(\theta)}{z}$$

- Pressure inside liquid is lower than pressure outside
- Analysis of collapse has to account for drying of liquid

(Tas, Sonnenberg, Jansen, Legtenberg & Elwenspoek)

## 3. Shock Loads




$a_0$ : 20g to 120,000g

τ : 50 μs to 5000 μs

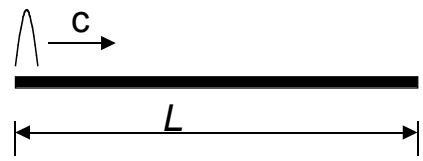
$$a(t) = a_0 \sin\left(\frac{\pi t}{\tau}\right) \qquad [0 \le t \le \tau]$$

$$a(t) = 0 \qquad [t \ge \tau]$$

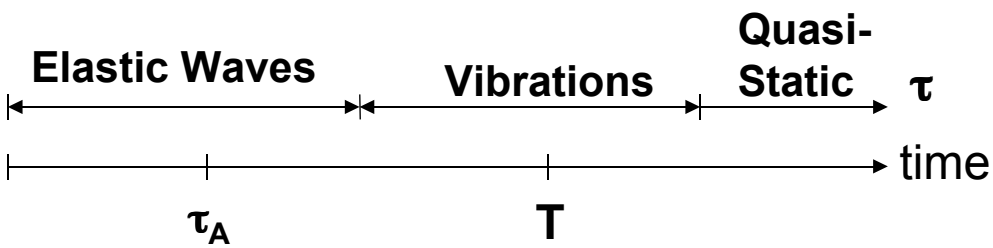
## 3. Shock Loads: Scaling Analysis

Mechanical response is governed by

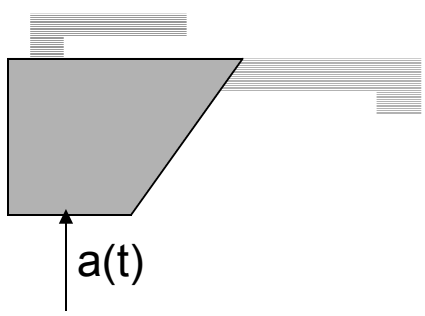
- Acoustic transit time ($\tau_A$)
- Time period of vibrations (**T**)
- Duration of shock load ($\tau$)



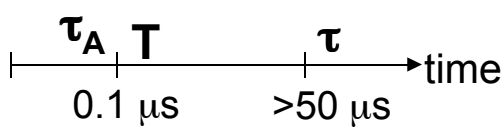

$$\tau_A = \frac{L}{c}$$




## 3. Shock Loads: Response of Substrate

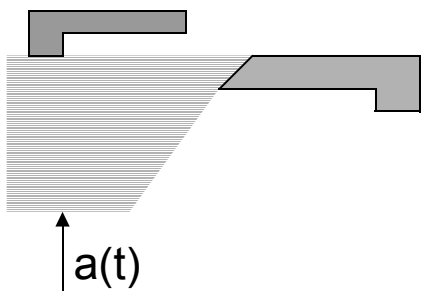


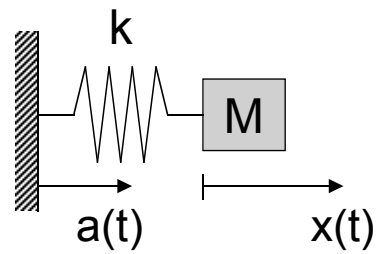

$c = 8000\ ms^{-1}$
$L < 1$ mm
$\tau_A < 0.1\ \mu s$




⇨ Substrate = rigid body motion

## 3. Shock Loads: Response of Microelements




•Resonators attached to accelerating support

$$\frac{M}{k}\frac{d^2}{dt^2}\left(\frac{d^2x}{dt^2}\right)+\frac{d^2x}{dt^2}=a(t)$$

## 3. Shock Loads: Response of Microelements

$\tau < 0.25$ T: **Impulse Response** $\frac{d^2x}{dt^2}=\omega\left(\int_0^{\tau}a(t)dt\right)\sin(\omega\ t)$

0.25 T < $\tau$ < 2.5 T: **Resonant Response**

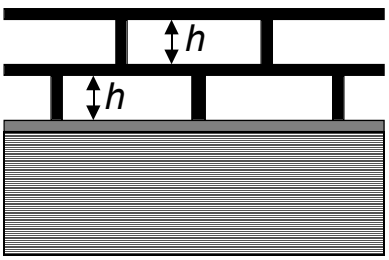
$$\frac{d^2x}{dt^2}=\frac{4\tau^2a_0}{4\tau^2-T^2}\left(\sin\left(\frac{\pi\ t}{\tau}\right)-\frac{T}{2\tau}\sin\left(\frac{2\pi t}{T}\right)\right) \qquad [0\le t\le\tau]$$

$$\frac{d^2x}{dt^2}=\frac{4\tau T a_0}{T^2-4\tau^2}\cos\left(\frac{\pi\tau}{T}\right)\sin\left(\frac{2\pi}{T}\left(t-\frac{\tau}{2}\right)\right) \qquad [\tau\le t]$$

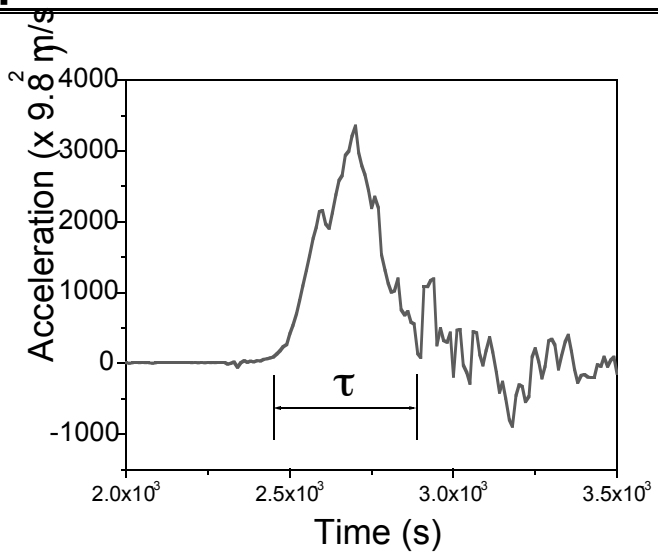
$\tau > 2.5$ T: **Quasi-static Response**

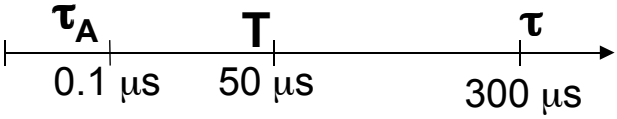
$$\frac{d^2x}{dt^2}=\begin{cases}a_0\sin\left(\frac{\pi t}{\tau}\right) & [0\le t\le\tau]\\ 0 & [t\ge\tau]\end{cases}$$

## 3. Shock Loads: Example



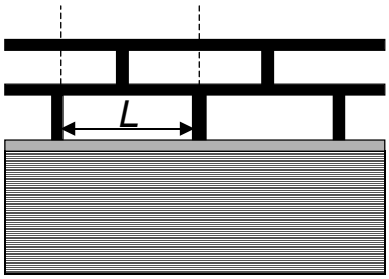

*The Polychromator*

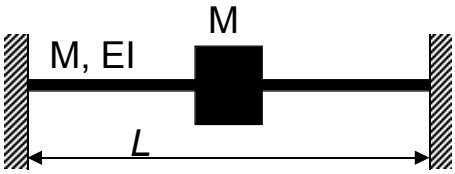


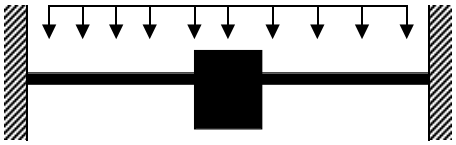




➡ Quasi-Static Response

## 3. Shock Loads: Example



L = 500 μm
h = 2μm
E = 160 GPa
a = 3000g

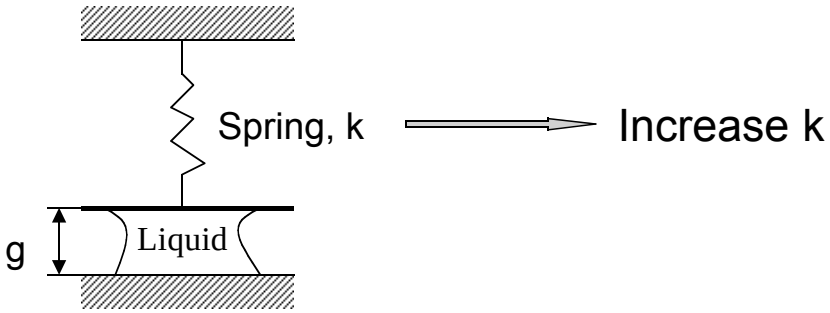
$$\delta = \frac{3M\,L^3 a}{384\,E\,I} = 0.6\,\mu m$$

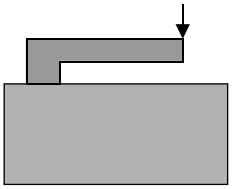
Q-static, therefore use F=Ma

$\delta < h$ ⇨ No collapse during shock loading!

## Elimination of Collapsing Force

- **Change Design**: Increase stiffness of structures



$$k = \frac{E\,b\,h^3}{4L^3}$$

- Hard to increase k of surface-micromachined beams

## Elimination of Collapsing Force

- **Change Processing**

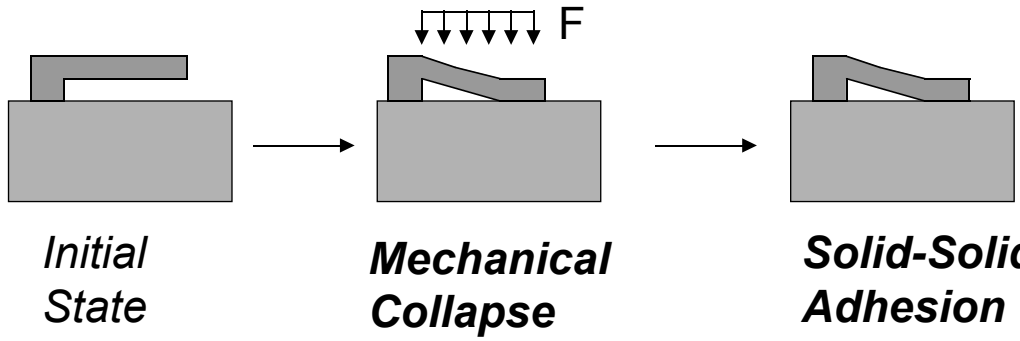
Wet release ✗

Sublimation:
- Freeze drying ✓
- Supercritical drying ✓

Dry etching ✓

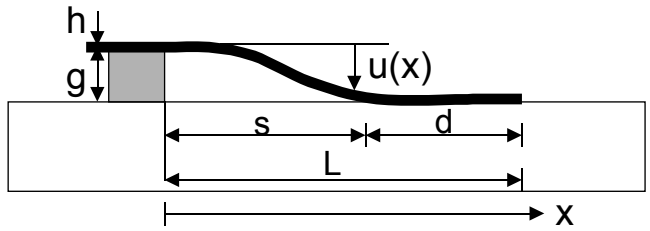
## Necessary Ingredients for Stiction

•*Collapsing force and Solid-solid adhesion*




•Electrostatic forces
•Capillary forces
•Shock loads
•Van der Waal's forces

## Solid-Solid Adhesion

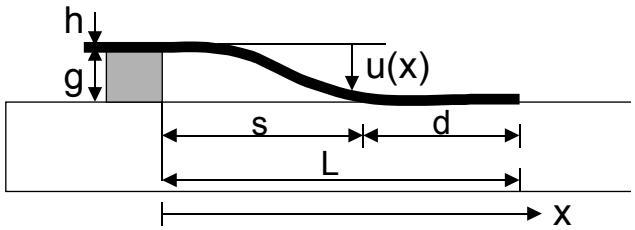



$$\left.\begin{aligned} & EI\frac{d^4u}{dx^4}=0, \qquad I=\frac{b\,h^3}{12} \\ & \left.\frac{du}{dx}\right|_{x=0}=\left.\frac{du}{dx}\right|_{x=s}=0, \quad u(0)=0,\ u(s)=g \end{aligned}\right\} \quad u=g\left(\frac{x}{s}\right)^2\left(3-2\frac{x}{s}\right)$$

$$U_T=U_E+U_S=\frac{6\,E\,I\,g^2}{s^3}-\gamma\,b(L-s)$$

(Mastrangelo)

## Solid-Solid Adhesion




$$s^* = \sqrt[4]{\frac{3\,E\,h^3 g^2}{2\gamma}}$$

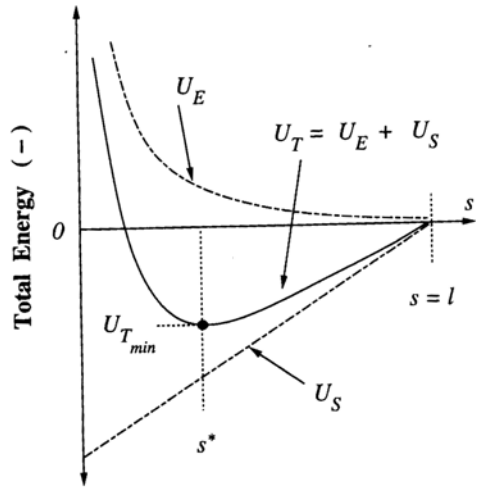
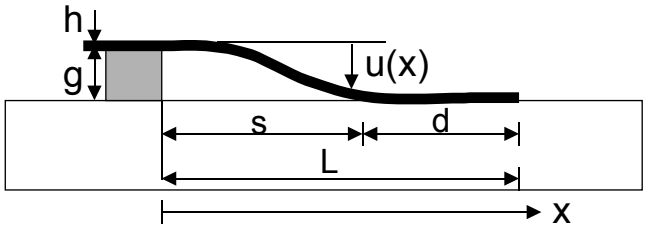



Fig. 8. Typical total energy curve for cantilever beam adhering to the substrate.

If L > s*, permanent adhesion
If L < s*, no permanent adhesion

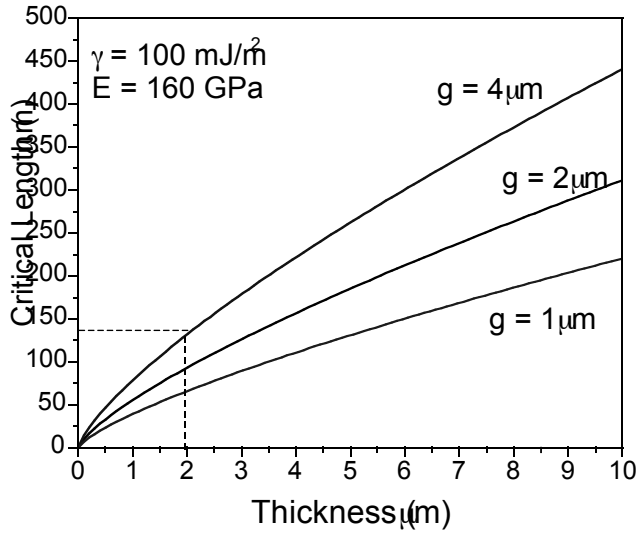
(Mastrangelo)

## Solid-Solid Adhesion: Critical Lengths




$$s^* = \sqrt[4]{\frac{3\,E\,h^3 g^2}{2\gamma}}$$

E = 160 GPa
$\gamma$ = 100 mJ/m$^2$

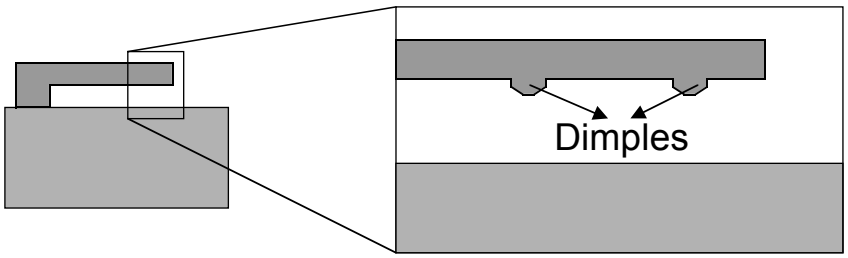



•Need longer beams

(Mastrangelo)

## Elimination of Adhesion: Dimples

- Textured surfaces and posts (dimples)



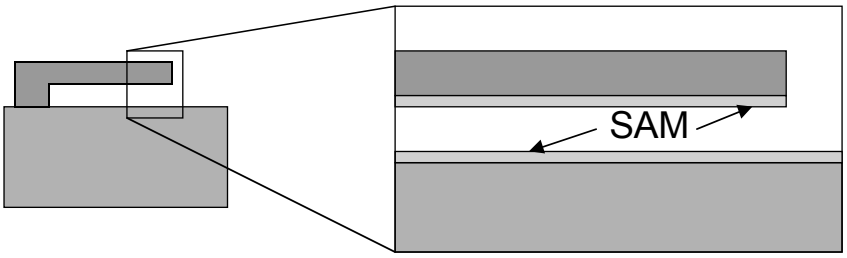

$$F = \frac{3}{2}\pi\gamma R \quad \Rightarrow \quad F \to 0 \;\; as\, R \to 0$$

F: Force required to detach dimple
R: Radius of dimple

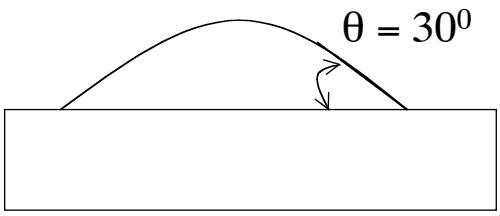
(Mastrangelo)

## Reduction of Adhesion: Self-Assembling Monolayers

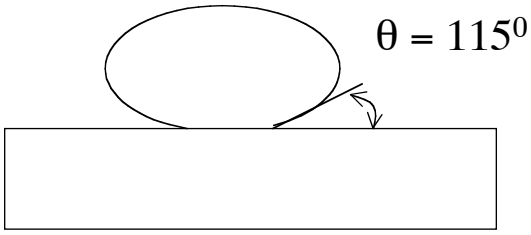
- Low energy coatings (SAM) (also diamond like carbon, DLC)




Strategy: Make surfaces hydrophobic




Oxide-coated Si




Fluorinated SAM-coated Si

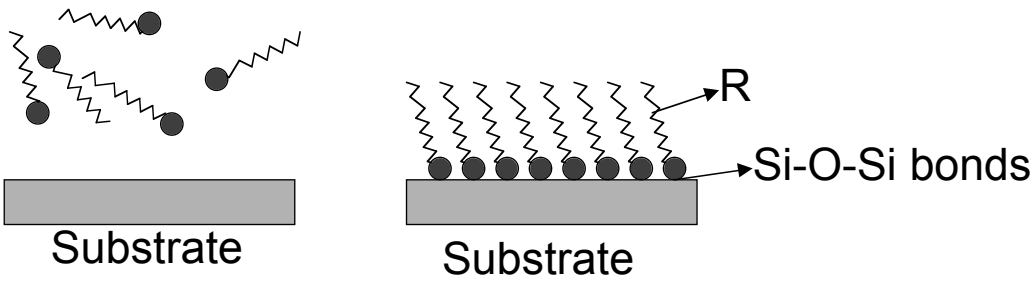
## Elimination of Adhesion: SAM

Typical Precursor Molecules:

octadecyltrichlorosilane (OTS): $CH_3\ (CH_2)_{17}SiCl_3$

Perfluorodecyltrichlorosilane (FDTS): $CF_3(CF_2)_7(CH_2)_2SiCl_3$

i.e., R- $SiCl_3$




(Maboudian, Ashurt, Carraro)

## Elimination of Adhesion: SAM Formation Process

Typical thickness: 1 – 3 nm

Coat at ambient; Bake at ~100 $^{o}$C for 2 –3 hours

<u>Manufacturability Concerns:</u>

- Reproducibility (Many process parameters)
- Scaling from die-level to wafer-level
- Aging characteristics
- Damage during contact (wear)

(Maboudian, Ashurt, Carraro)

## Recovery after Stiction

•Apply External Forces:

Mechanical (Probe tip)

Magnetic (Lorentz)

Dynamic (Stress waves)

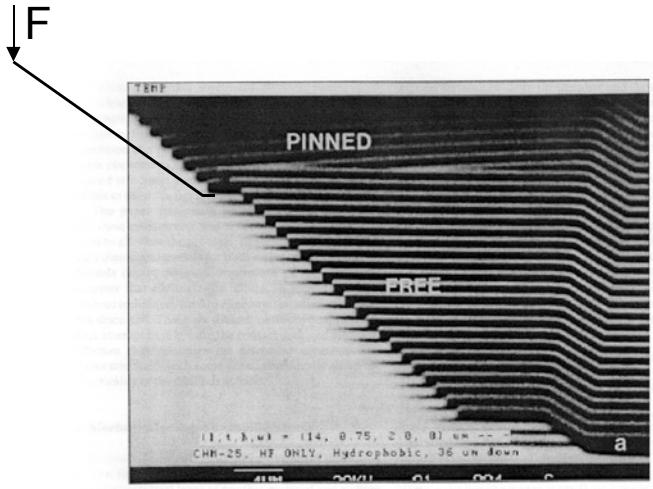
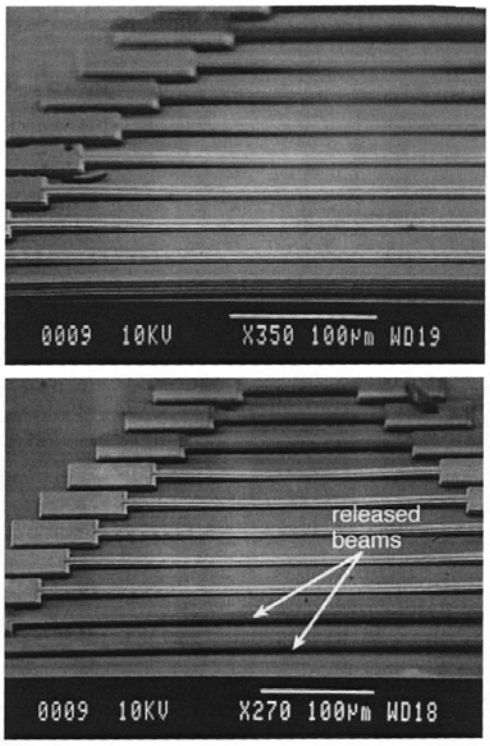
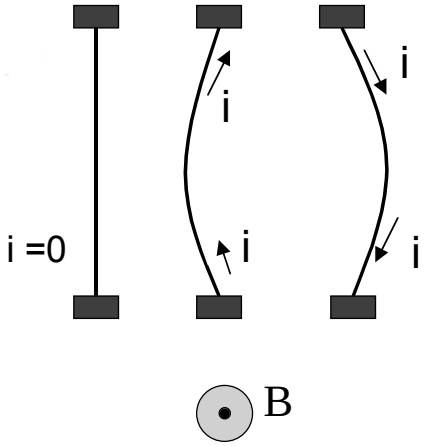



Fig. 1. SEM of micromachined polysilicon cantilever beams of increasing length. The photograph shows clearly the onset of the pinning state for beams longer than 34 μm.

(Mastrangelo)

## Release using Lorentz Forces




•Requires conductors

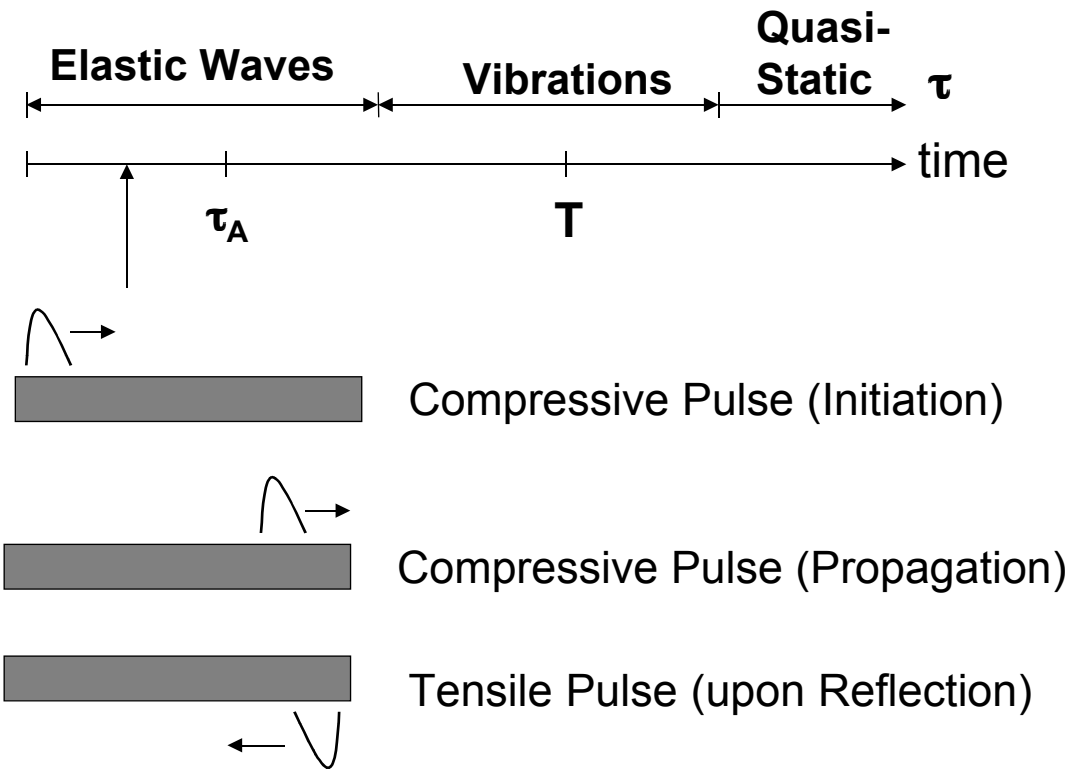
•Requires B

Fig. 17. Array of doubly-supported beams (top) before and (bottom) after the application of the discharge. The last two beams were released by the Lorentz force. The longest beam is 270 μm long.

(Mastrangelo)

## Release using Stress Waves

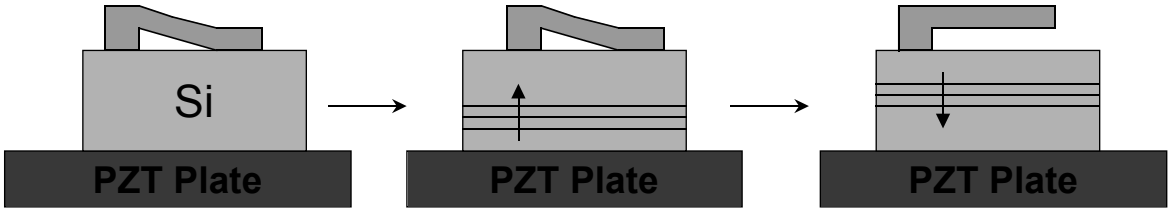
•Recall:




## Release using Stress Waves: Spalling


Spalling if $\sigma > \sigma_{IF}$

•Key Requirement: Pulse with $\tau < 10$ ns




•Potentially Wafer-level technique

(Kaajakari & Lal, U. Wisconsin)

## Summary of Stiction

•Failure = Mechanical Collapse + Solid-Solid Adhesion

•Forces causing collapse: Electrostatic; Capillary; Mechanical..

(Quantitative understanding of many mechanisms)

•Qualitative understanding of solid-solid adhesion

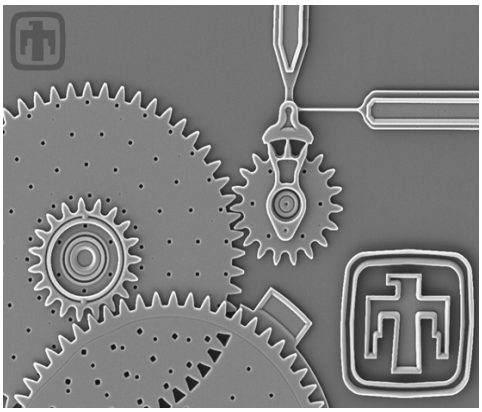
•Stiction can be reduced by

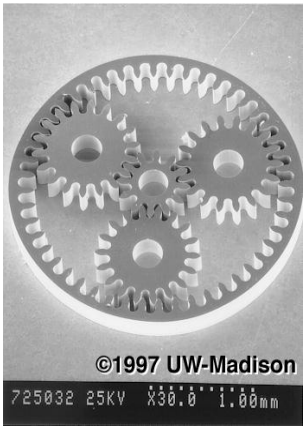
-- Avoiding wet release processes

-- Reducing surface energies (DLC, SAM; texturing)

-- Applying external release forces (Magnetic; Mechanical)

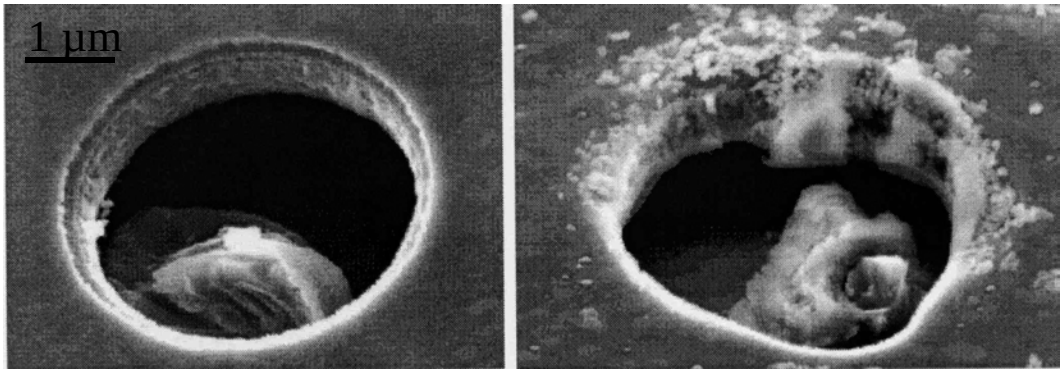
# TRIBOLOGY IN MEMS






John Williams, Cambridge University Engineering Dept

# Wear of a MEMS journal bearing

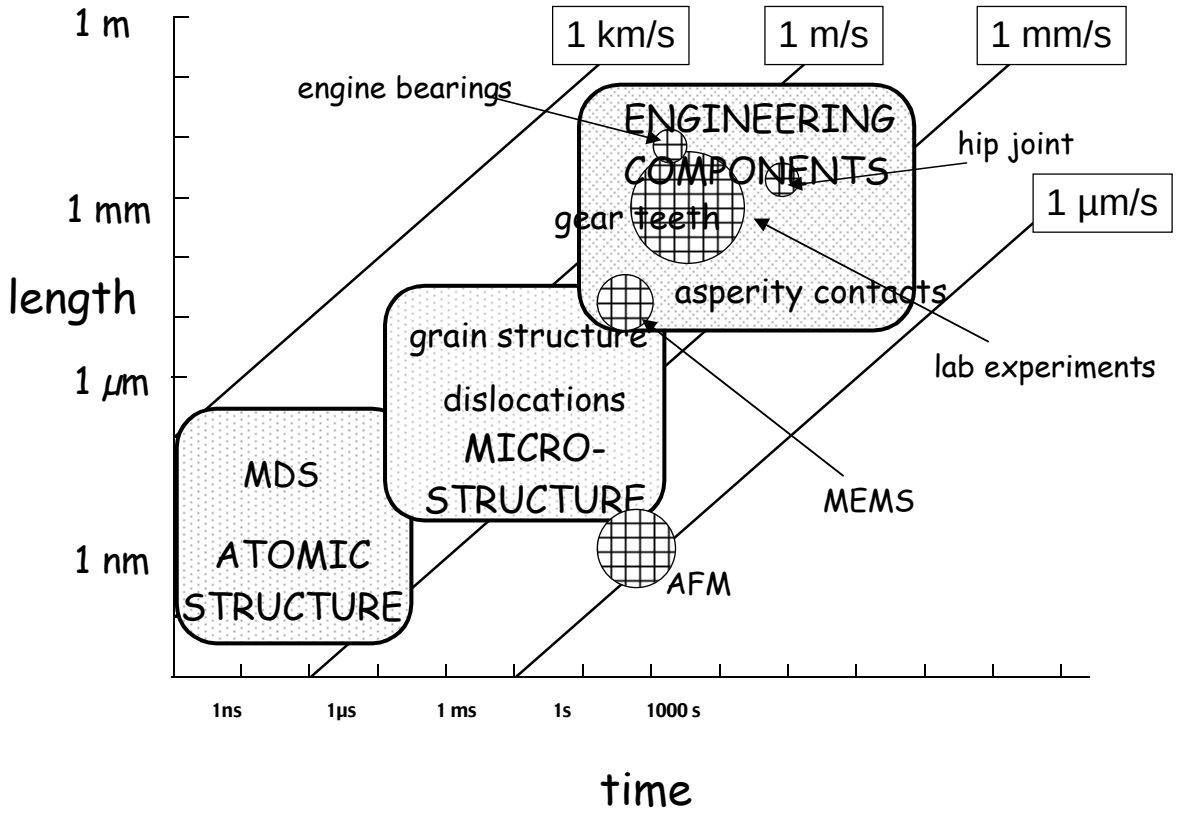



Run to failure at 1720 Hz for 158000 cycles, i.e. 91 s

After: Tanner, D., Miller, W. et al 'The effect of Frequency on the Lifetime of a Surface Micromachined Microengine Driving a Load' Sandia National Labs, Albuquerque.

# THE MEMS OPERATING REGIME

- Macroscopic machines often limited by inertia stresses: MEMS usually limited by surface forces – stiction/friction – and wear
- Conventional liquid lubrication impossible because of meniscus force effects – MEMS invariably run dry
- Linear dimensions in MEMS typically x1/100 those of macro-machines
- Rotational speeds in MEMS typically x30 those of macro-machines
- Sliding speeds are (by macro standards) lowish: 10 – 100 mm $s^{-1}$
- Sliding distances, in rotating bearings, of order of hundreds of km (100 km typical for a month of continuous use)




# CONSEQUENCES FOR WEAR LIFE

- For 'reasonable' mechanical performance, nominal bearing pressures $p$ in MEMS must be ~ 1 MPa or more
- For 'reasonable' mechanical life, wear coefficients $K$ must be ~ $10^{-8}$ $mm^3$ $N^{-1}$ $m^{-1}$ or less
- Many MEMS devices based on semiconductor fabrication techniques: silicon is a poor tribo-material – needs surface engineering SiC, DLC...?
- Aim to reduce both static adhesion – stiction – and running friction
- Both stiction and μ can be influenced by surface topography
- Relevant surface features will be of 10 nm - 1μm, influenced by microstructure, processing

# ARCHARD WEAR LAW

- Local wear rate = $K_w$ x pressure x sliding velocity
- $K_w$ is the 'dimensional wear coefficient' or 'specific wear rate'
- $K_w$ conventionally expressed in: $mm^3\ N^{-1}\ m^{-1}$
- For 'reasonable' mechanical life, wear coefficients *K* must be ~ $10^{-8}\ mm^3\ N^{-1}\ m^{-1}$ or less
- Si on Si has $K_w$ of $10^{-6}$ or more

## NORMALIZED WEAR LAW

•Wear = Volume of material removed per unit length of contact

$$\frac{\Delta V}{\Delta l} \propto \frac{P_n}{H} \approx \frac{K P_n}{9\sigma_f}$$

$P_n$: Normal load (< 1μN)
$\sigma_f$: Fracture strength (< 1 GPa)
K: $3 \times 10^{-7}$
n: $10^5$cycles/sec
$\Delta l$: $10^5 \times 10^{-6}$ m/s

⇨ $\Delta V \sim 0.3 \times 10^{-4}\ \mu m^3/s$

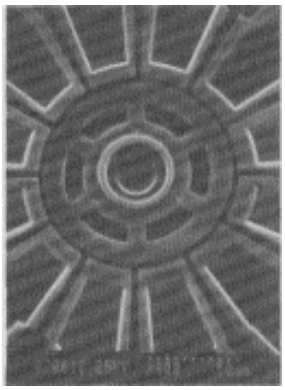
~ 1 $\mu m^3$ every 10 hours!

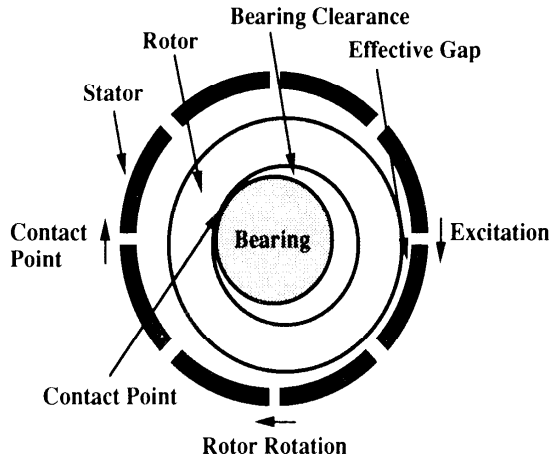
But, bulk wear equations may not completely apply - adhesion processes occur at small scales

(McClintock & Argon)

# WOBBLE MOTOR EXAMPLE

## Mehregany & Senturia, MIT






- *p* approximately 0.007 MPa
- sliding distances up to km, measure wear by observing slip
- $K_w$ ca. $10^{-6}$ mm $^3$ $N^{-1}$ m $^{-1}$ for poly Si on poly Si

# Pivot bearings – comparison of MEMS and watch

Watch - balance wheel bearing, steel on ceramic

$P = 0.1$ MPa, $\omega \approx 0.5\ s^{-1}$ , $K_w = 2 \times 10^{-7}\ mm^3\ N^{-1}\ m^{-1}$

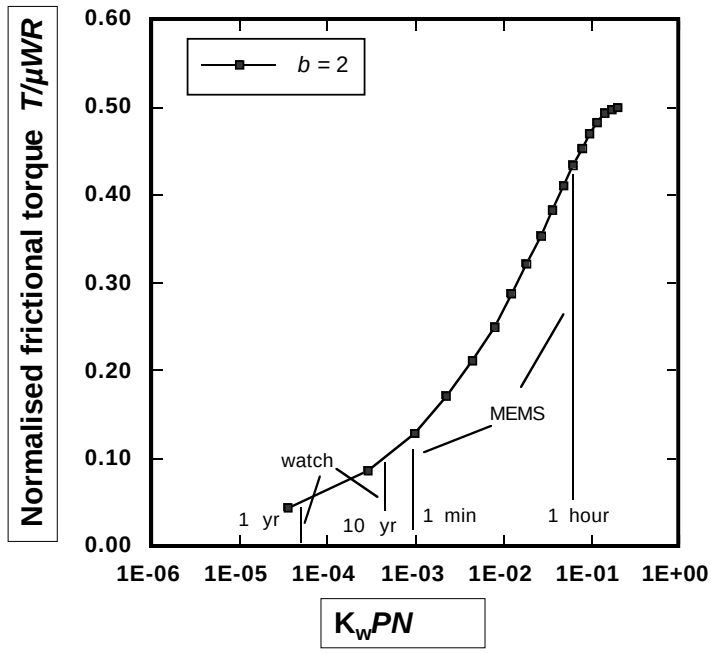
$K_w PN$ for one year $= 5 \times 10^{-5}$, ten years $= 5 \times 10^{-4}$

MEMS - silicon on silicon

$P = 0.1$ MPa, $\omega \approx 0.5\ s^{-1}$ (10,000 rpm) , $K_w = 1 \times 10^{-3}\ mm^3\ N^{-1}\ m^{-1}$

$K_w PN$ for one minute $= 1 \times 10^{-3}$, one hour $= 6 \times 10^{-2}$

# Frictional torque development in watch and MEMS pivot bearings

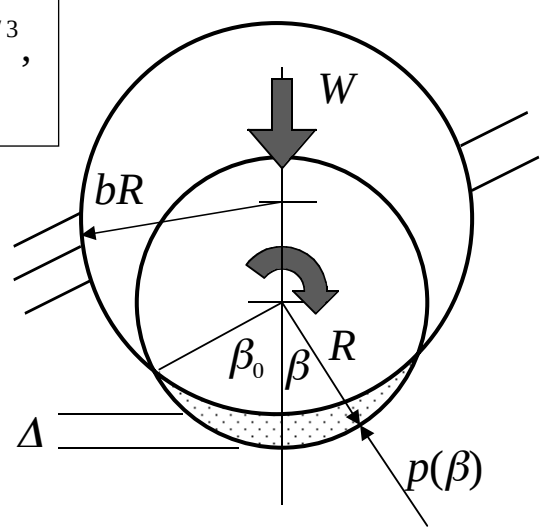



# Journal bearing

If, at every point Archard wear eqn applies, then

$$\frac{\Delta}{R} \approx \left(9\pi^2/2\right)^{1/3} \times (1-1/b)^{1/3} \times \left(\mathrm{K_w} PN\right)^{2/3},$$

$$\frac{V}{BR^2} \approx 4\pi \times \mathrm{K}_w PN$$




where $P = W/2RB$ , $N$ is no of revs.

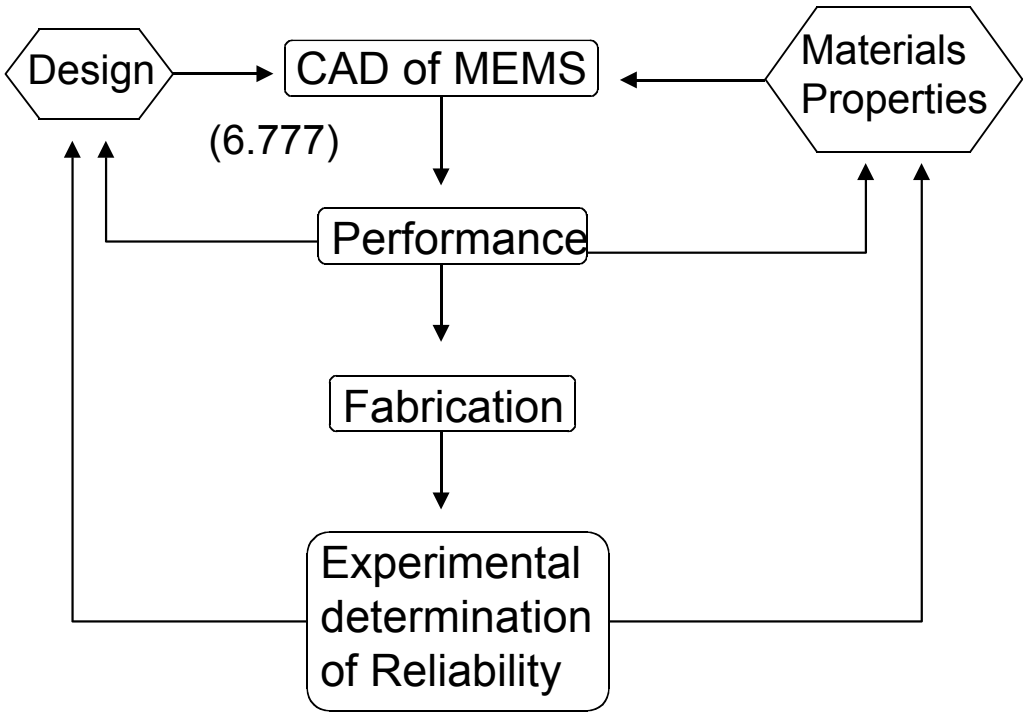
and $\beta_0$ is small.

# TRIBOLOGICAL CONCLUSIONS FOR MEMS

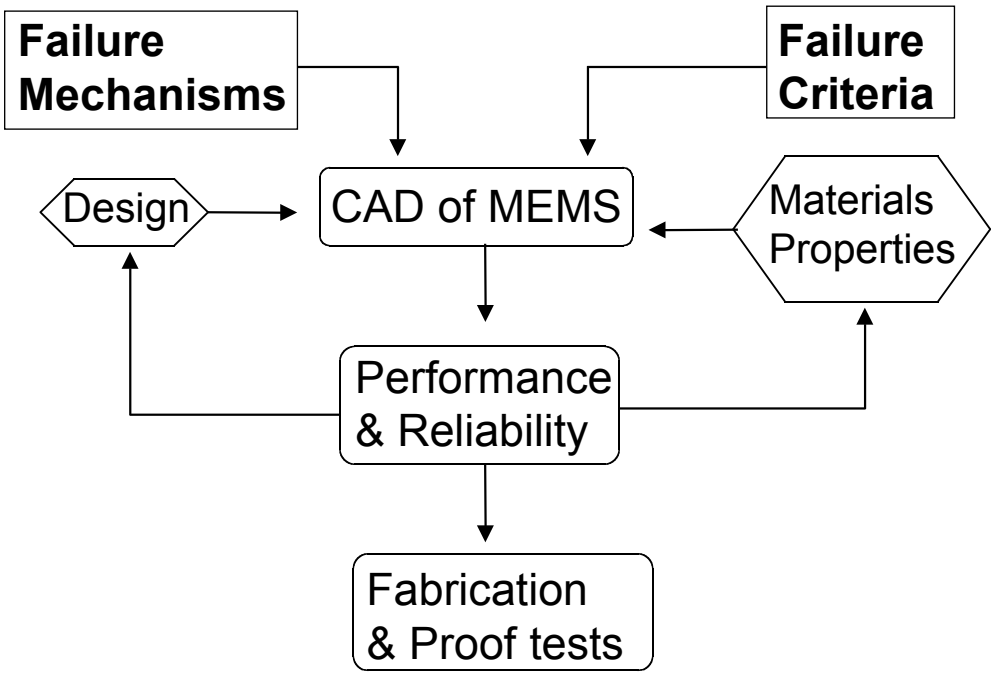
- Si on Si is a poor bearing combination
- Hard materials, surface modification may provide solutions
- Air bearings may allow for high speed operation
  - Cube - square scaling
- At the moment no successful commercial MEMS use sliding contacts or rotating elements
  - Due to power density and wear considerations

## Concluding thoughts: The Big Picture

Current Methodology



## The Goal: Design for Reliability




## References


1. C. H. Mastrangelo, *Adhesion-related failure mechanisms in microelectromechanical devices*, Tribology Letters, vol. 3, pp. 223 – 238 (1997)

2. C. H. Mastrangelo and C. H. Hsu, *Mechanical stability and adhesion of microstructures under capillary forces*, Parts I & II, J. Microelectromechanical Systems, vol. 2, pp. 33 –55 (1993)

3. R. Maboudian, W. R. Ashurt, & C. Carraro, *Self-assembled monolayers as anti-stiction coatings for MEMS: characteristics and recent developments*, Sensors and Actuators, vol. A82, pp. 219-223 (2000)

4. N. Tas, T. Sonnenberg, H. Jensen, R. Legtenberg, & M. Elwenspoek, *Stiction in surface micromachining*, J. Micromech. Microeng., vol. 6, pp. 385 – 397 (1996)

5. V. T. Srikar & S. D. Senturia, *The reliability of MEMS in shock environments*, J. Microelectromechanical Systems (June 2002)

6. F. A. McClintock & A. S. Argon, *Mechanical Behavior of Materials*, Addison-Wesley (1965)