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Water Vapor Effects on the Lubrication of Silicon MEMS by Alcohol Vapor

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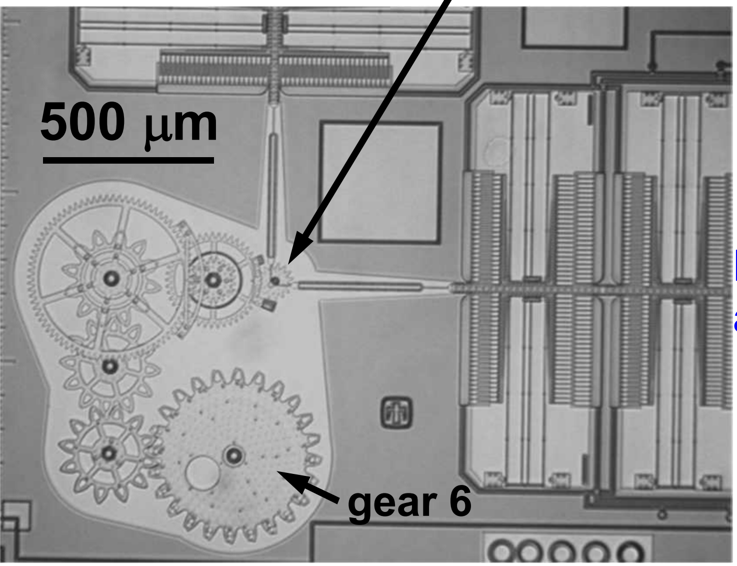
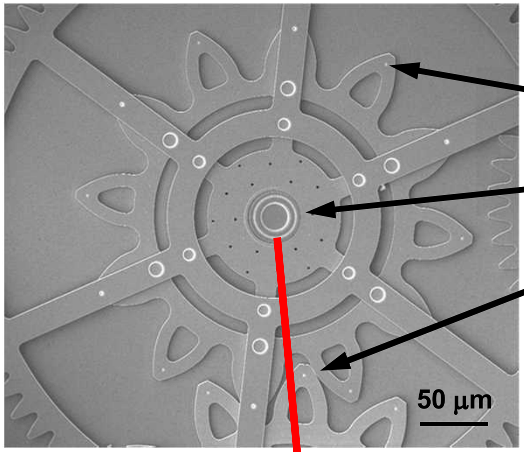
Fully-Assembled MEMS Limit Surface Treatment Options

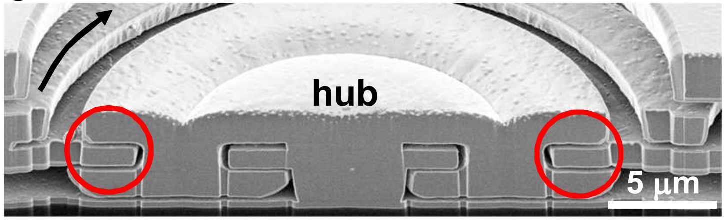


polysilicon gear train



gear 3 assembly

FIB section through hub



sliding interfaces

- limited actuation and restoring forces
  - 1 µN to ~ 10 mN
- complexity afforded by multiple layers
  - deeply buried sliding surface

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Friction and Wear Represent the Greatest Limitations to Microsystem Reliability

process

tribology

Silicon popular due to mature fabrication infrastructure

- processes well known to grow, pattern, and etch
- can control residual stress

~~**Particles**~~

- ~~more sensitive than microelectronics~~

~~**Fracture**~~

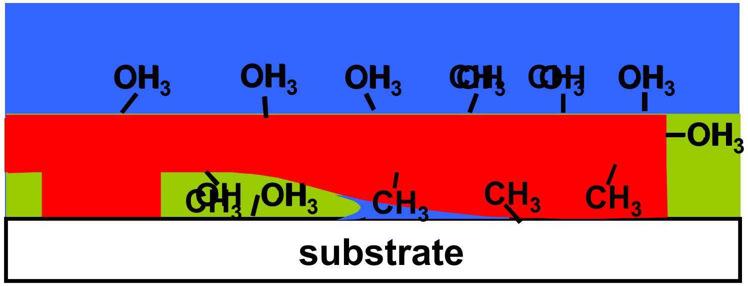
- ~~handling or overshock~~

~~**Adhere after fabrication**~~

- ~~"in-process adhesion"~~

~~**Adhere during use**~~

- ~~"in-use adhesion"~~

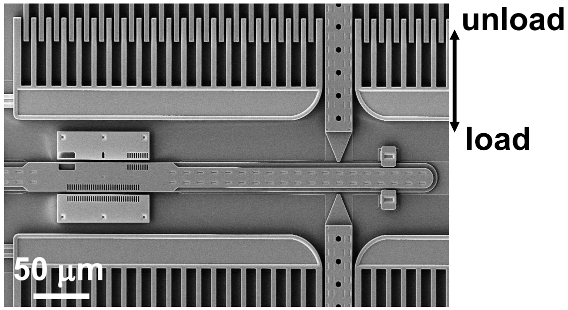


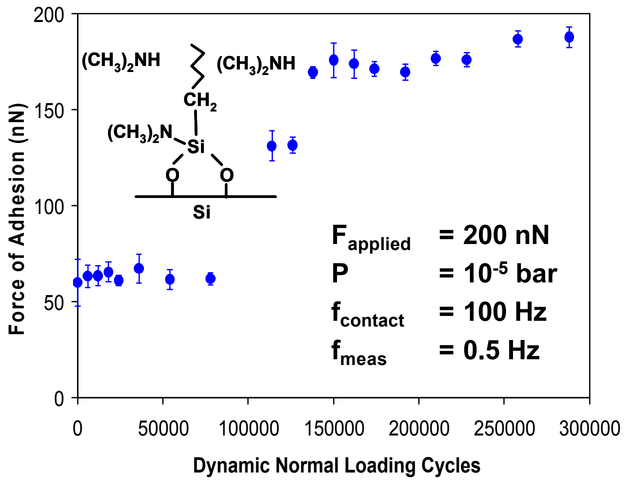
initial adhesion no longer an issue with monolayer surface treatments

Friction exceeds available actuation force (monolayer damage)

Wear (debris formation)

MEMS Failure Mode is a Function of the Device's Design

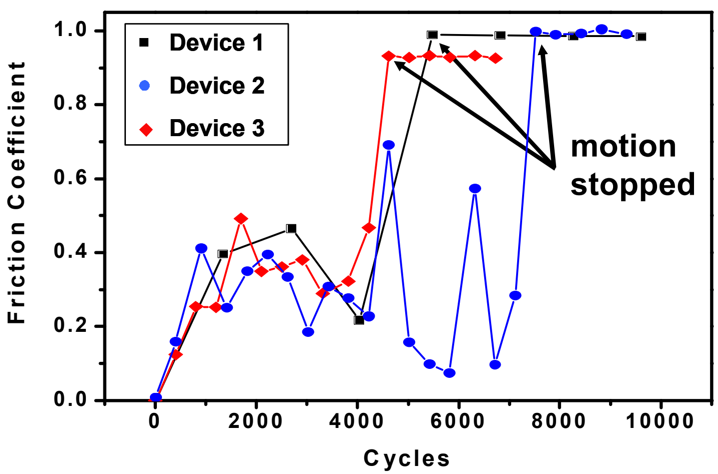




surface treatments are damaged easily, even for normal contact alone

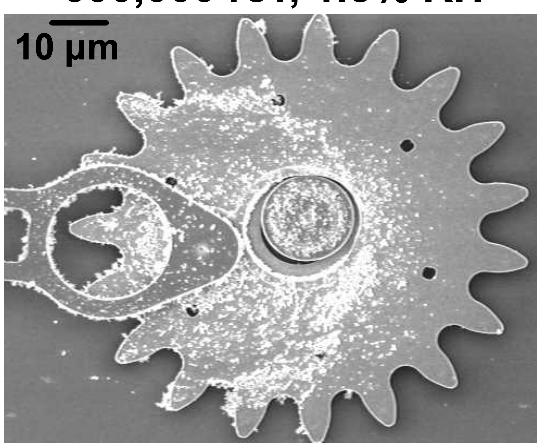
courtesy D.A. Hook, these proceedings

$F_{friction} > F_{actuation}$



$F_{actuation} > F_{friction}$

600,000 rev, 1.8% RH



D. Tanner et. al, International Reliability Physics Symposium, 1998

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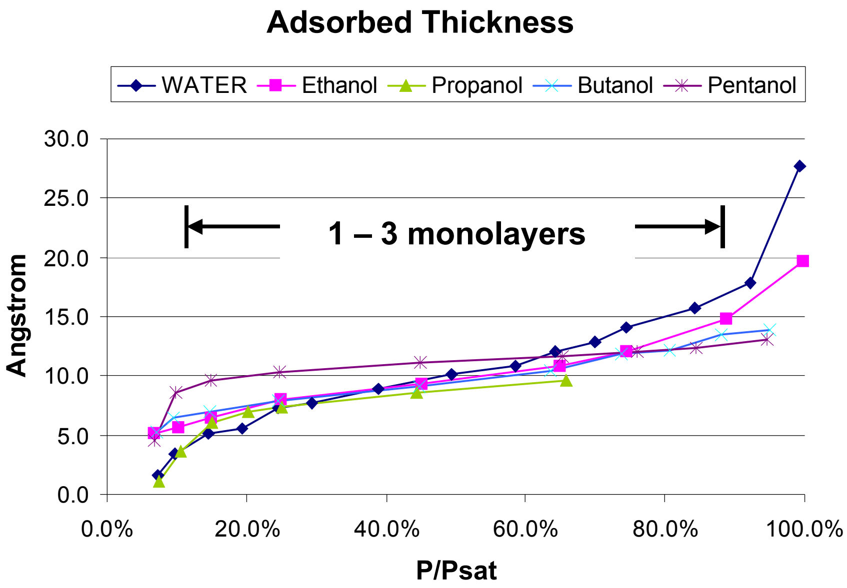
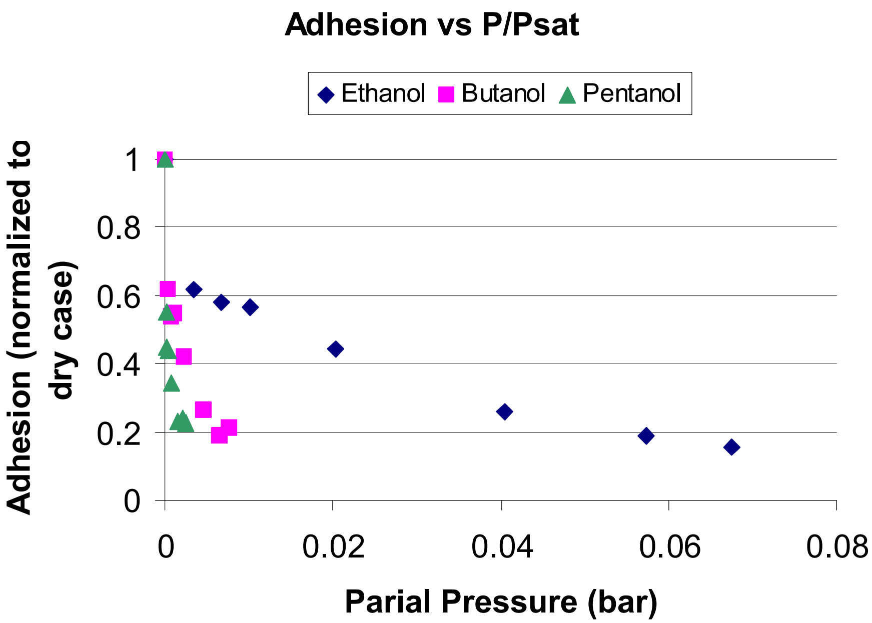
Alcohols Explored for Reducing Adhesion Between Silicon Surfaces

K. Strawhecker, D.B. Asay, J. McKinney and S.H. Kim, *Trib. Lett.* **19** (2005) 17-21.





ATR-FTIR measurement of adsorbed film thickness

- 1-3 monolayers at $0.1 < P/P_{sat} < 0.9$

AFM measurement of adhesion

- low concentrations significantly reduce adhesion

alcohol dissolves surface contaminants and water, creating a lower surface tension film

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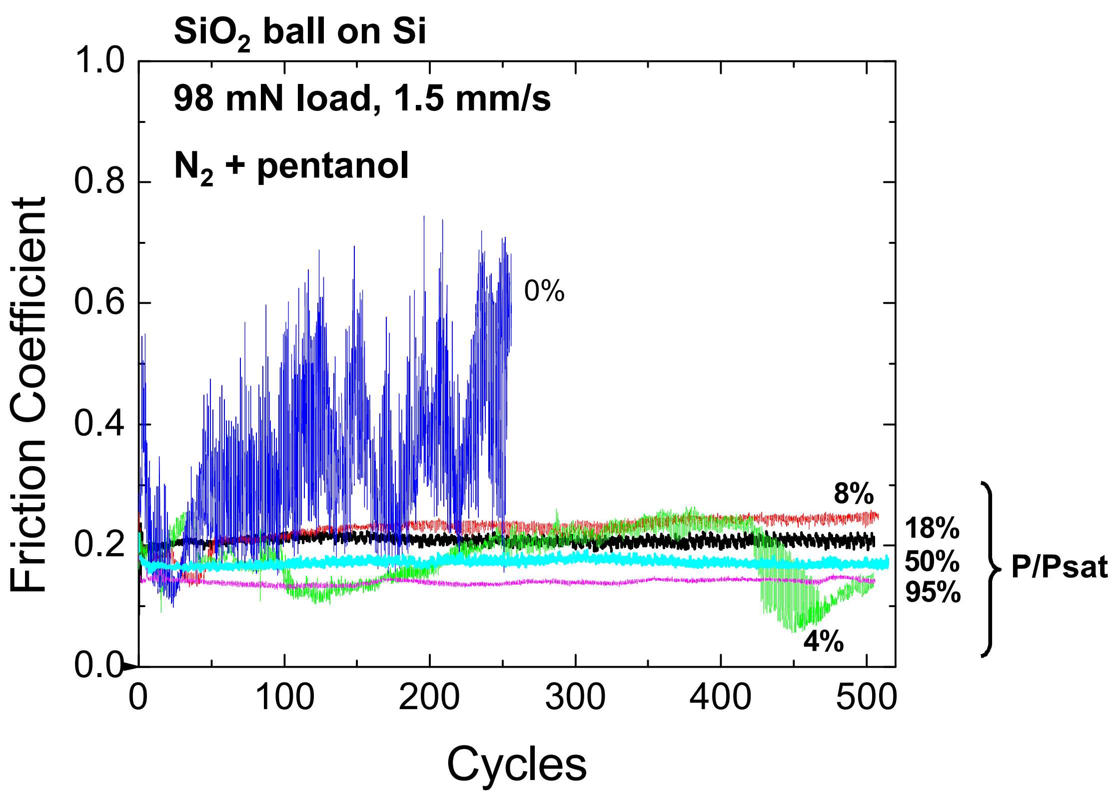
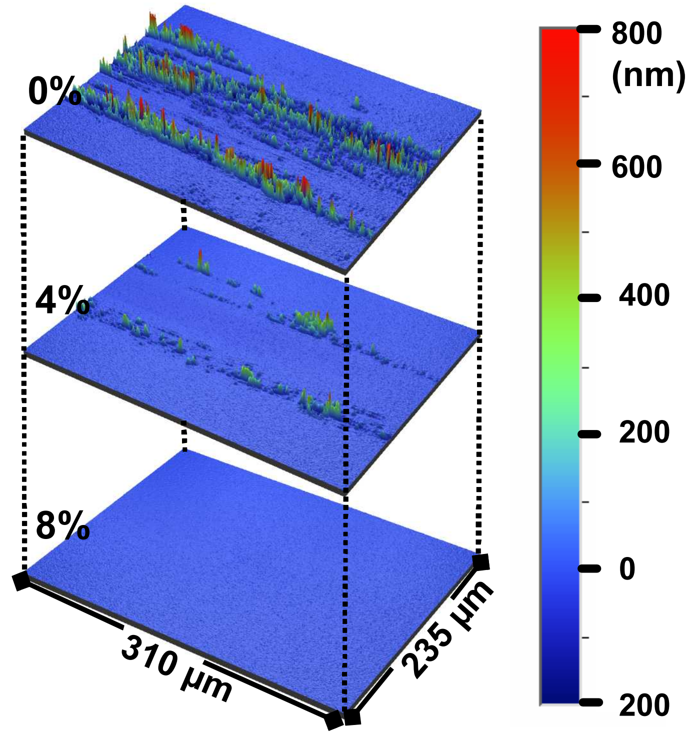
Vapor Phase Lubrication of Silicon Reduces Friction in Macroscale Sliding





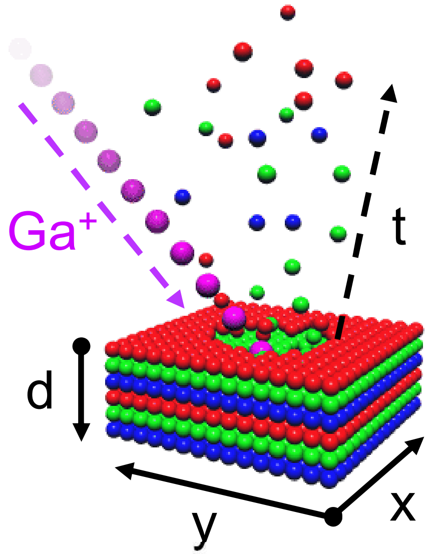
No measurable wear for P/Psat ≥ 8%

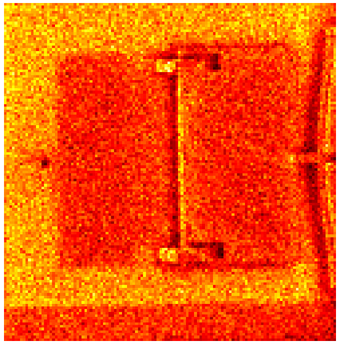
- corresponds to ~ monolayer coverage from ATR-FTIR data

Multivariate Analysis Of SIMS Data Allows Detection of Subtle Changes In Chemistry

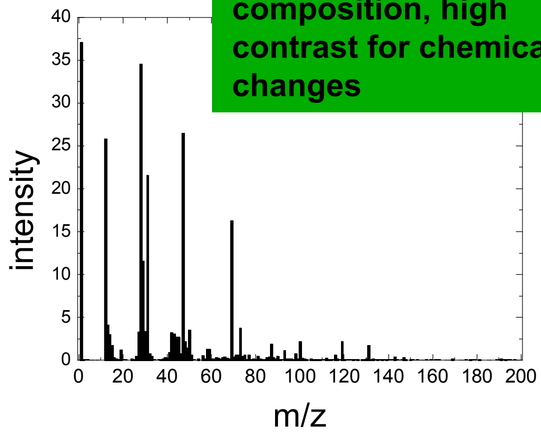
Time-of-Flight Secondary Ion Mass Spectroscopy (TOF-SIMS)

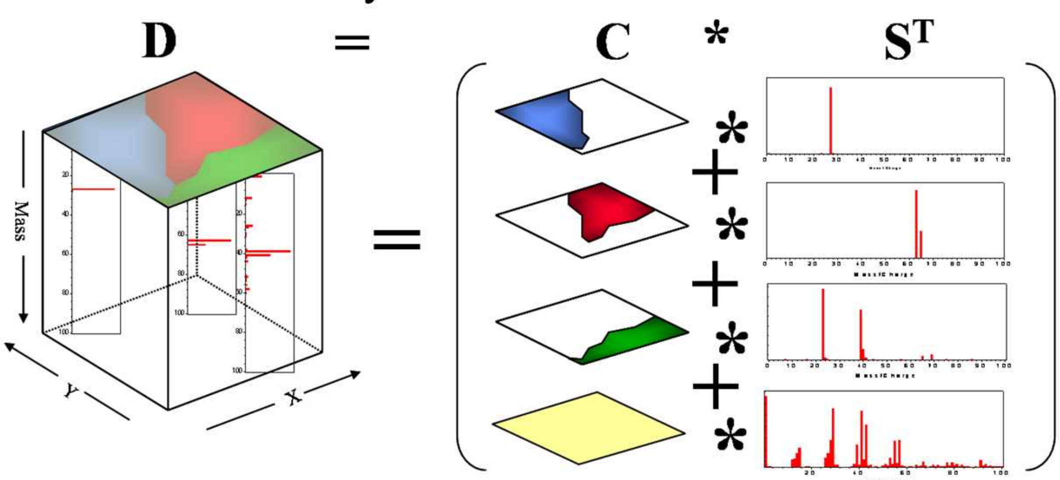
+ Automated eXpert Spectral Image Analysis (AXSIA)





Unbiased analysis of composition, high contrast for chemical changes

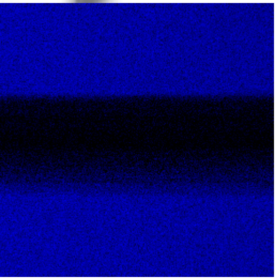


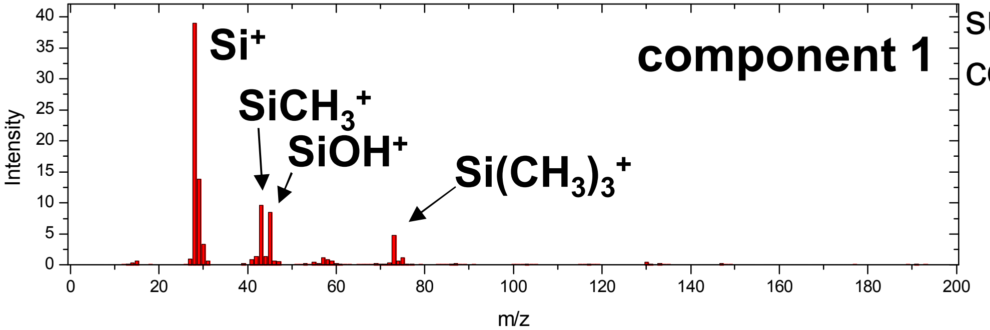


- solve $D=C*S^T$ using constrained alternating least squares
- constrain to physically realistic solutions
- number of components C is the minimum needed to reconstruct the original data, minus noise
- no bias or assumptions; rapidly identifies subtle changes

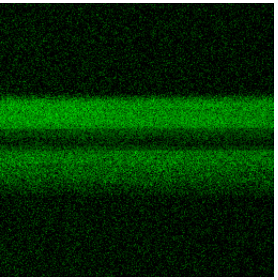
M. Keenan and P. Kotula, *Surf. Interface Anal.* ***36*** (2004) 2433.

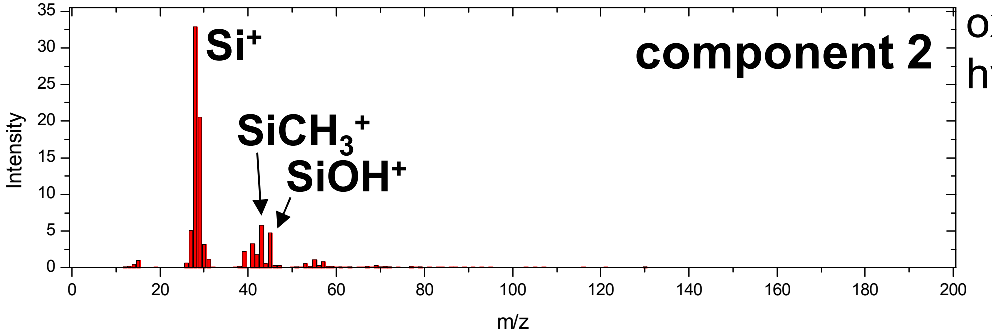
ToF-SIMS With Multivariate Analysis Shows Formation of High MW Product



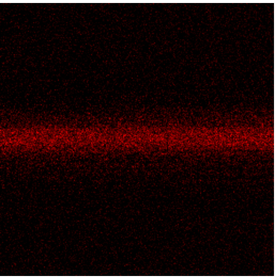


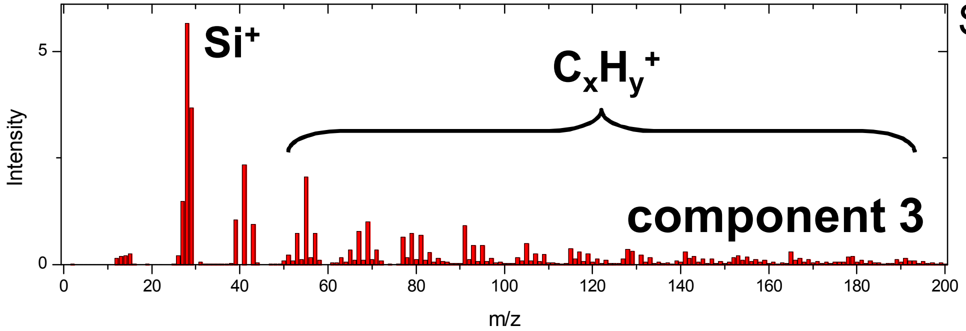
surface oxides and contaminants (silicones)





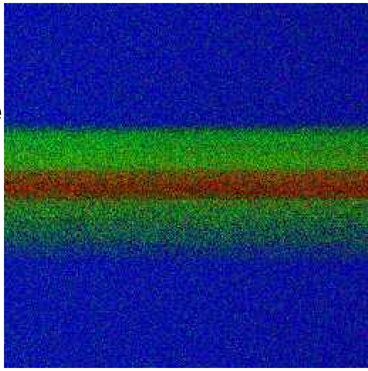
oxidized Si + short chain hydrocarbons





Si + long chain hydrocarbons

composite image



Reaction product forms *when, and where,* it is needed

Potential Show-Stoppers with VPL using Alcohols

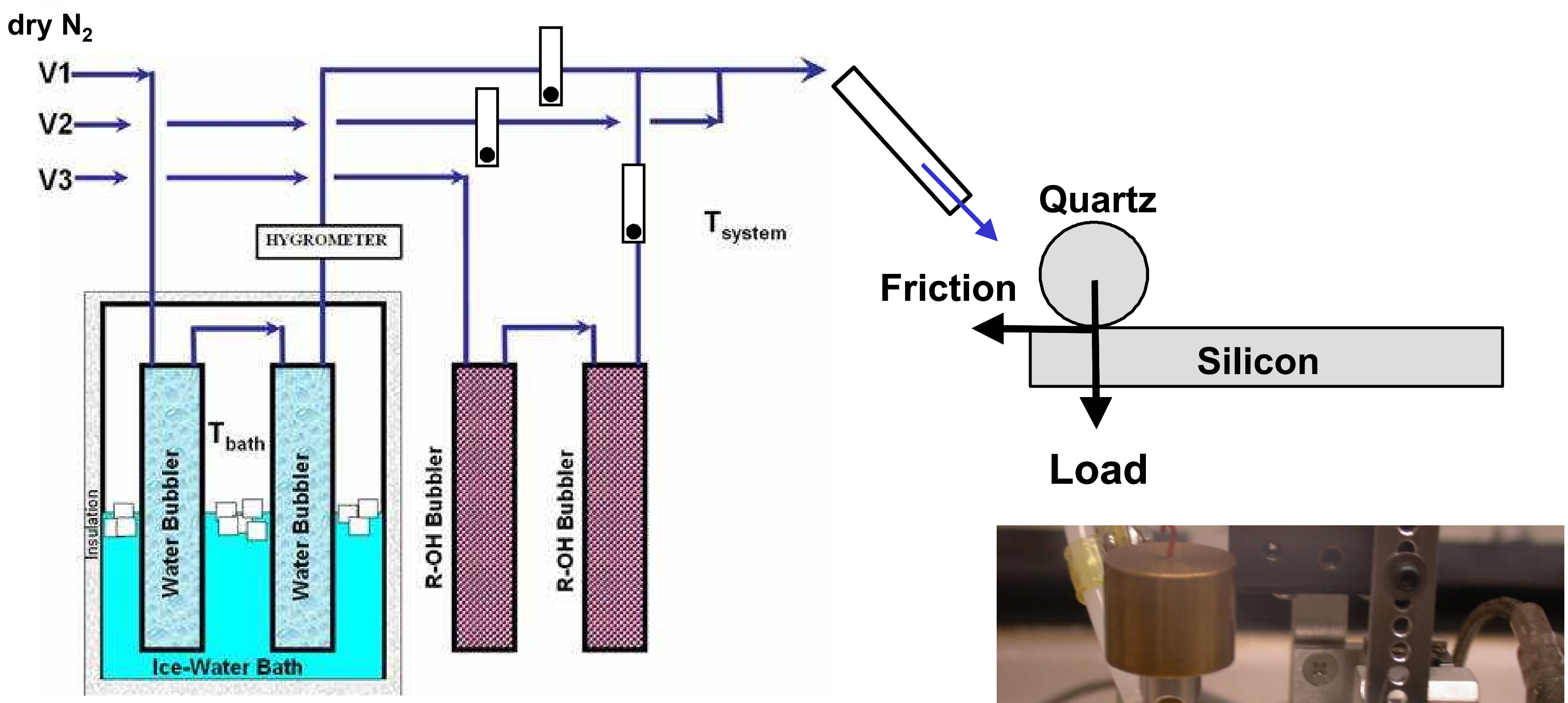
Competitive adsorption of water vapor

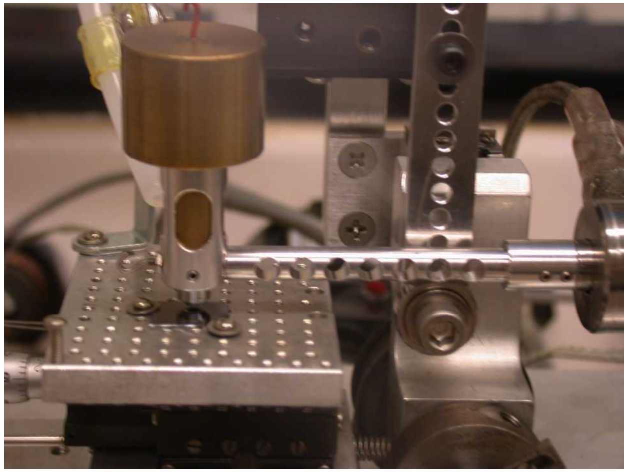
- will water vapor in the environment inhibit high MW film formation?

Complex devices

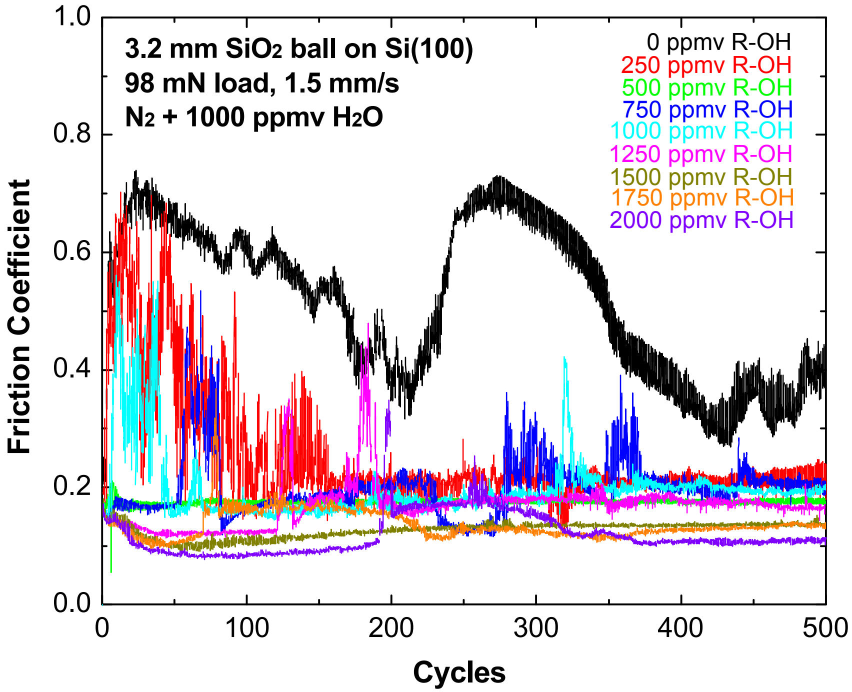
- demonstrate lubrication of deeply-buried interfaces in real MEMS devics with alcohol vapor

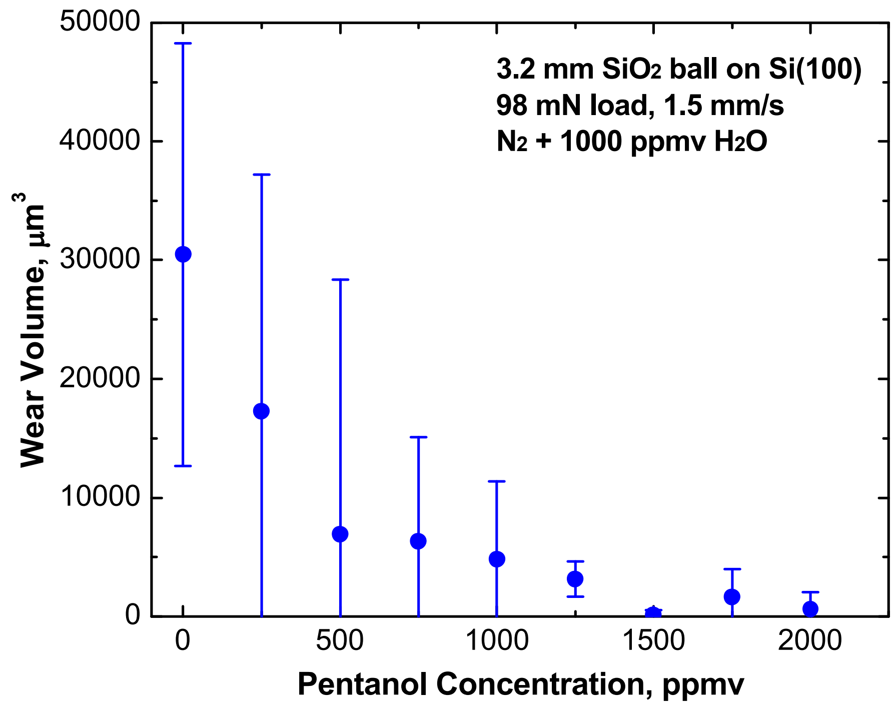
Linear Wear Testing in Mixed Alcohol/Water Environments





Water Vapor Inhibits VPL with Alcohol Above a Critical Concentration Ratio





1000 ppmv H_2O observed in non-gettered MEMS packages

- ~3.5% RH at room temperature
- MIL spec for microelectronics is 5000 ppmv

Friction coefficient reduced above 1000 ppmv pentanol, but results in measurable wear

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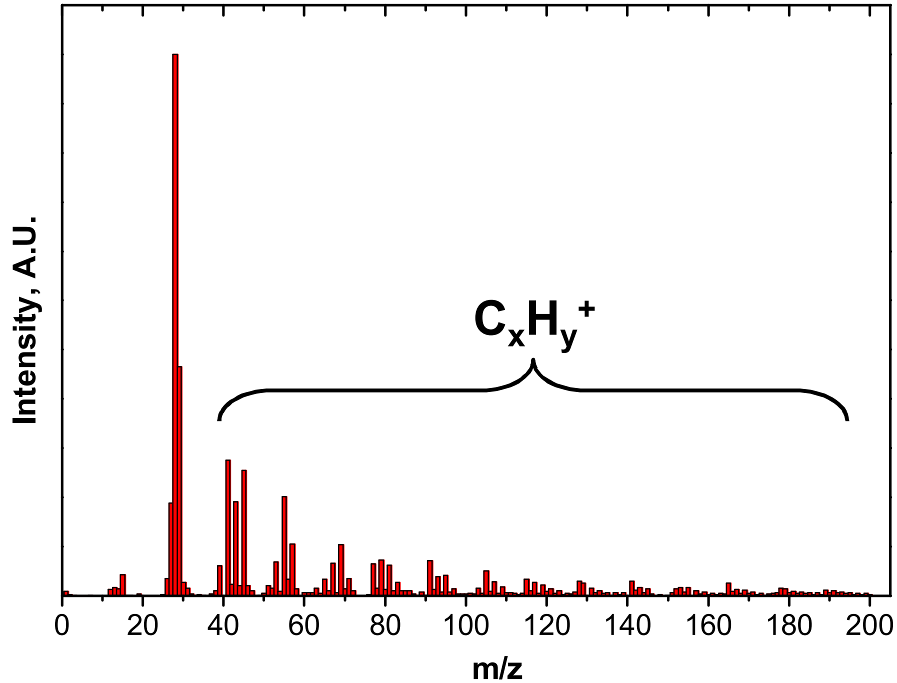
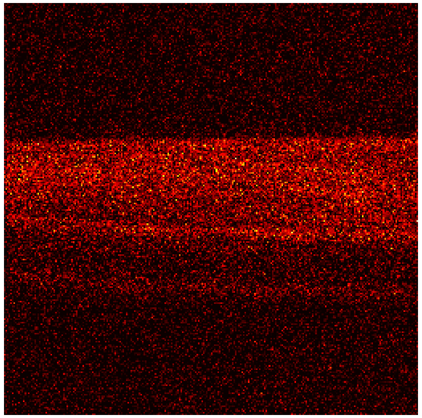
ToF-SIMS Multivariate Analysis Shows Oligomer Formation in the Presence of H_2O Vapor



N_2 + 1000 ppmv pentanol



High MW product is observed in the wear track, but at lower concentration than with pentanol vapor alone

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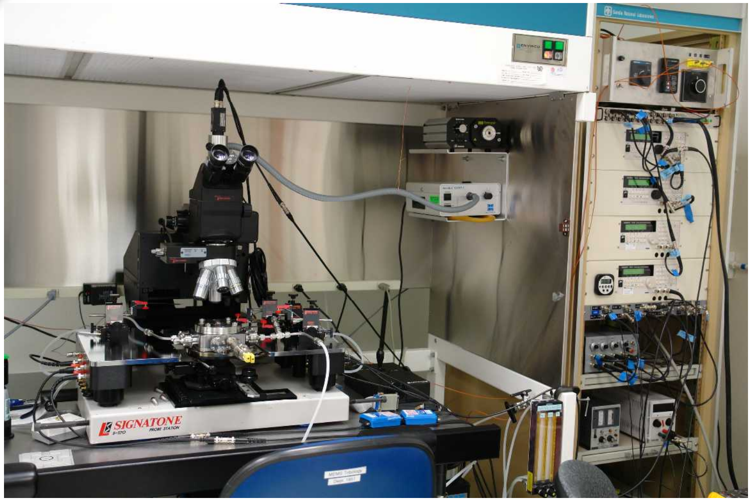
MEMS Device Testing in Mixed Alcohol/Water Environments

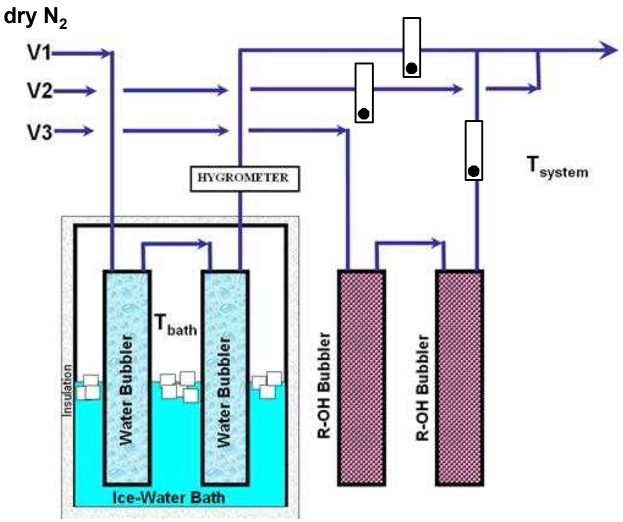


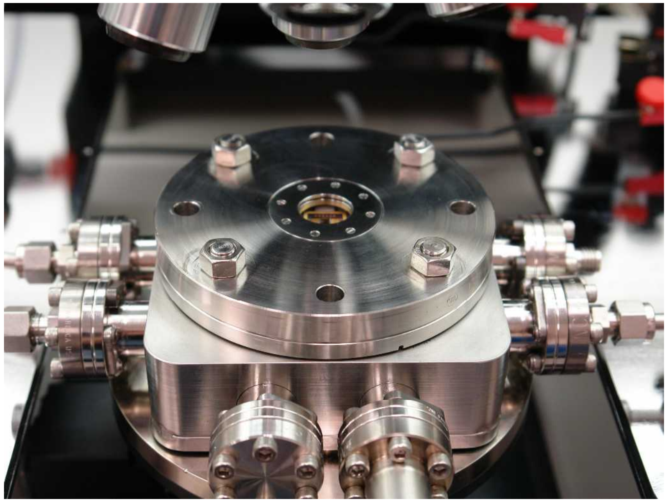
Probe Station and Drive Electronics

Device packaged in 24-pin DIP

Process image data to give displacements

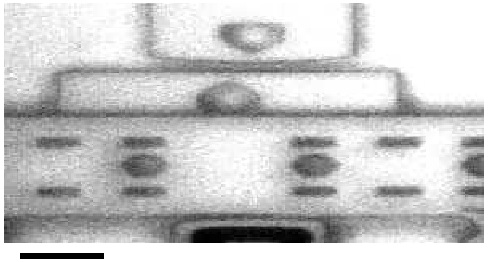
- adhesion $F_{ad} = F_{unload} - F_{load} + F_r$
  $= a(V_c^2 - V_p^2) + kx$
- static friction $F_{fr} = F_{push} - F_{pull} - F_r$
  $= a(V_{slip}^2)$
- dynamic friction $F_d = k\Delta x$





MEMS Environmental Test Chamber

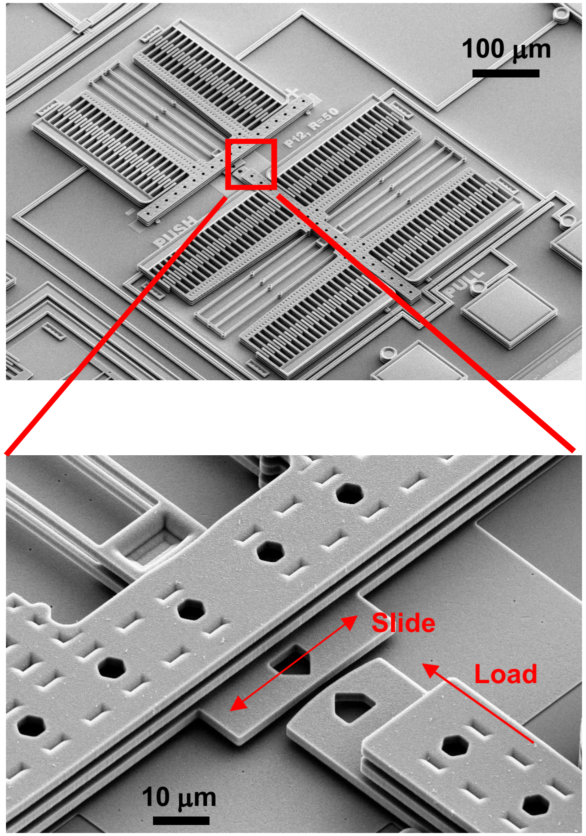
Timed Image Capture
Displacement vs Input (V)



10 μm

Effects of Competitive Water Adsorption on MEMS Tribometer Operation

MEMS tribometer



typical of packages without desiccant

ppmv	WATER 0	250	500	750	1000
1-Pentanol 0	1E+4				1E+4
500	1E+6				
1000			1E+6		
1500					
2000	1E+6		1E+6		5E+5

devices run for 10^6 cycles or until failure (no motion with applied drive signals)

MEMS tribometers operate in mixed pentanol-water vapors

Evidence of surface degradation at 2000 ppmv pentanol - 1000 ppmv water

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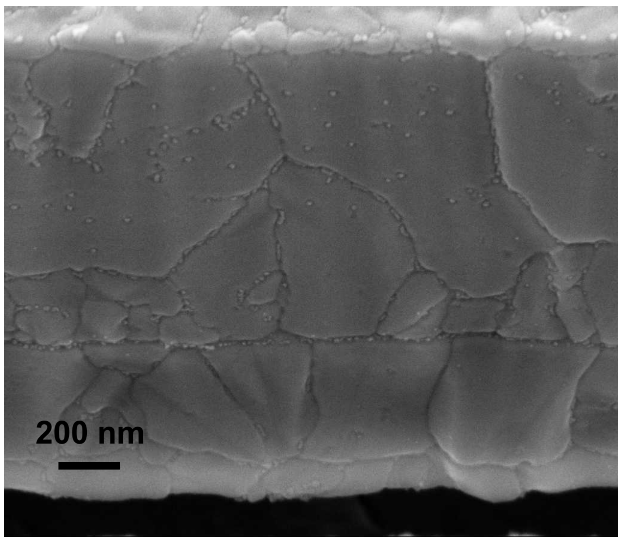
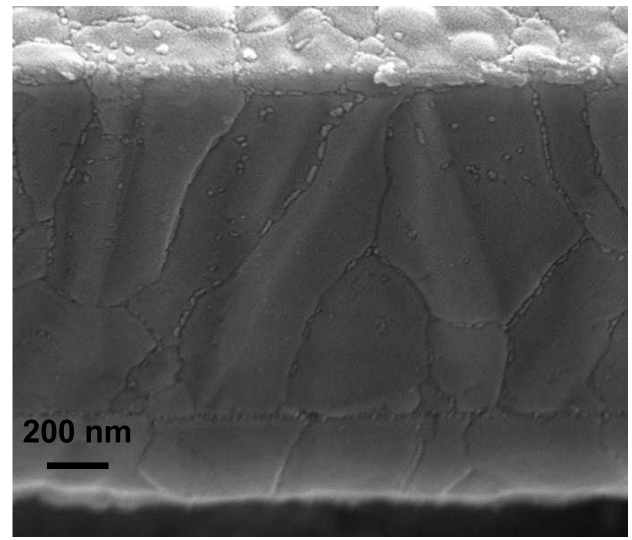
Wear is Minimized with In Situ Vapor Phase Lubrication

1-Pentanol (ppmv) \ WATER (ppmv)	0	250	500	750	1000
0	1E+4				1E+4
500	1E+6				
1000			1E+6		
1500					
2000	1E+6		1E+6		5E+5

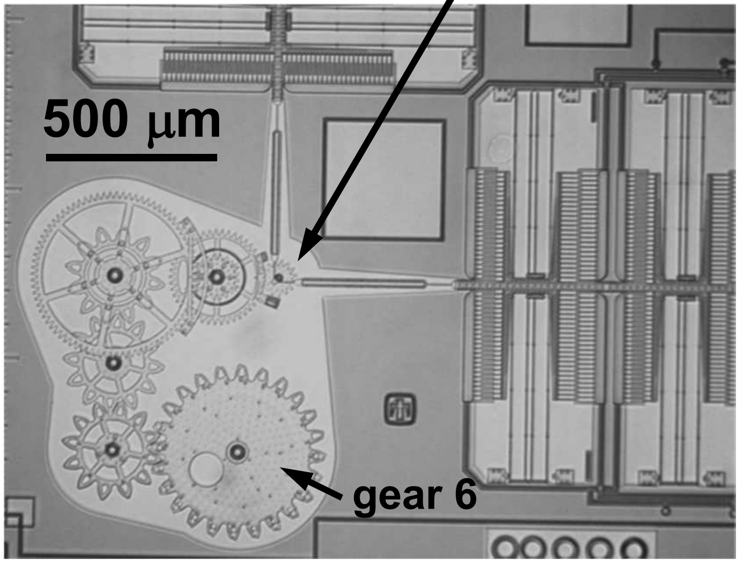
100 Hz
500 nN applied load



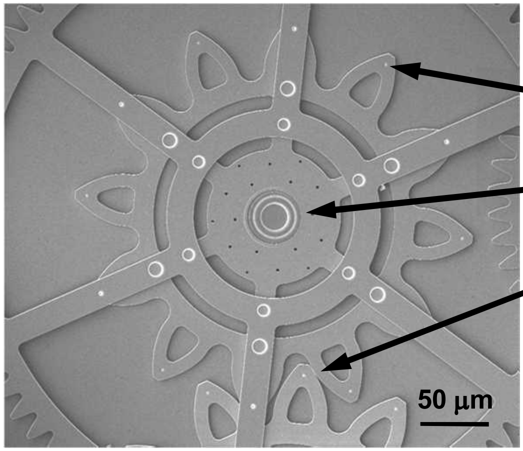


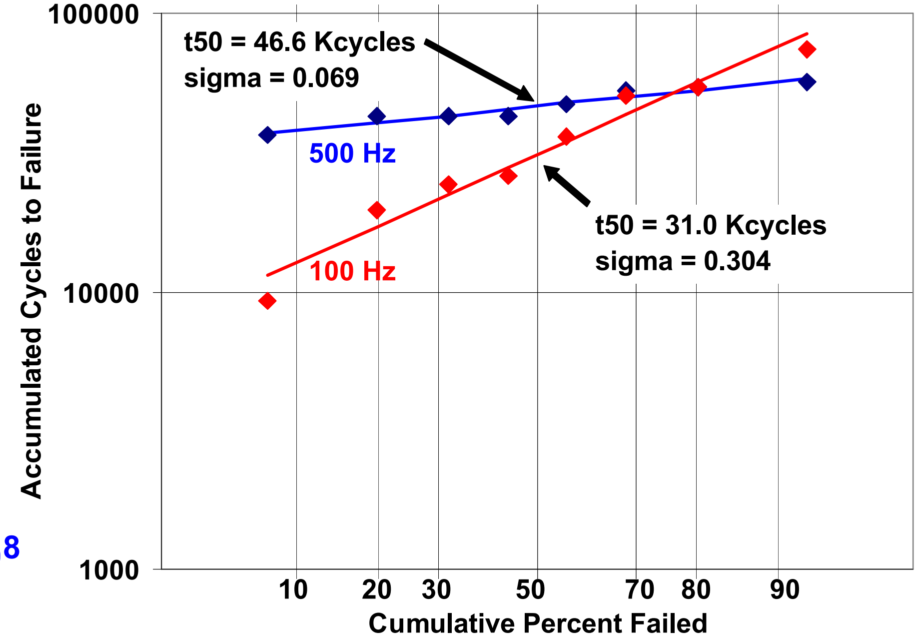
Deposit collected adjacent to asperity locations (real contact) on sidewall of MEMS tribometer

Increased Operating Life of Gear Train with Vapor Phase Lubrication



gear train on aging module





FOTAS monolayer alone, $t_{50} = 4.7 \times 10^4$

With VPL, device was stopped at 4.8×10^8 *without failure*

Summary

Vapor Phase Lubrication of silicon at room temperature has been demonstrated

- **linear alcohol (pentanol) results in reduced wear**
- **ability to replenish lubricant film from the vapor phase**

Reduced wear is accompanied by oligomer formation

- **reaction product forms at real contact locations**
- **suggests that thermionic emission or a catalytic surface are critical**

Water vapor reduces oligomer formation and limits film replenishment

- **measurable wear in macroscopic sliding with alcohol + water vapor**
- **limited operating life of MEMS in alcohol + water vapor**

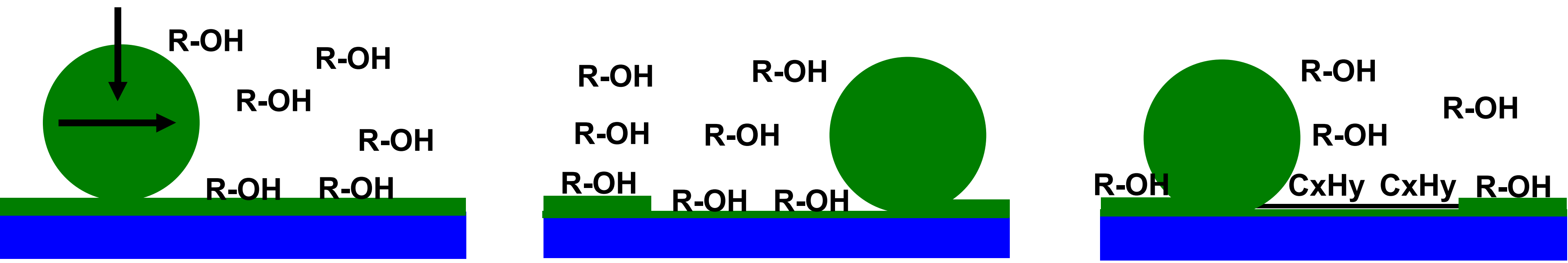
Recent paradigms about the reliability of MEMS devices with contacting surfaces must be revisited

Vapor Phase Lubrication of Silicon by Tribochemical Reaction

S.M. Wiederhorn and D.E. Roberts, *Wear* **32** (1975) p.51-72
- reduced friction when abrading silicate glass in alcohols

Y. Hibi and Y. Enomoto, *Wear* **231** (1999) p.185-194
- alcohols reduce friction when cutting Si_3N_4
- very low wear rate in “higher” alcohols (4<n<11)

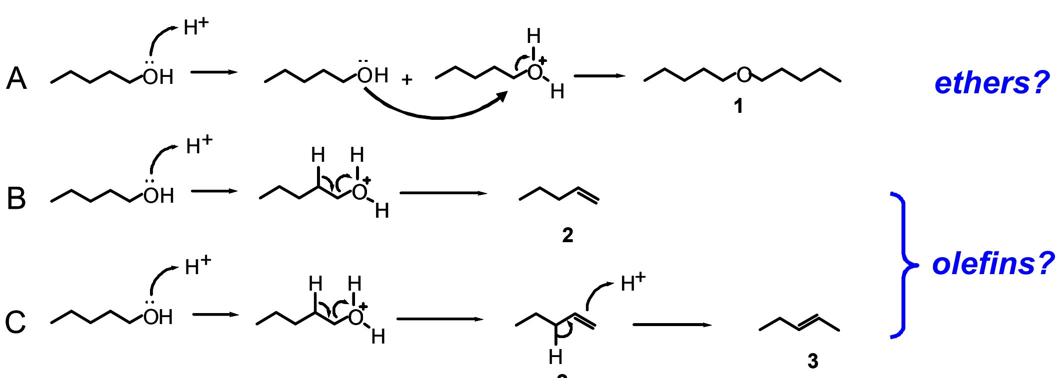
Y. Hibi, Y. Enomoto and A. Tanaka, *J. Mat. Sci. Lett.* **19** (2000) p.1809-1812
- postulate metal alkoxides condense to polymer and act as lubricant



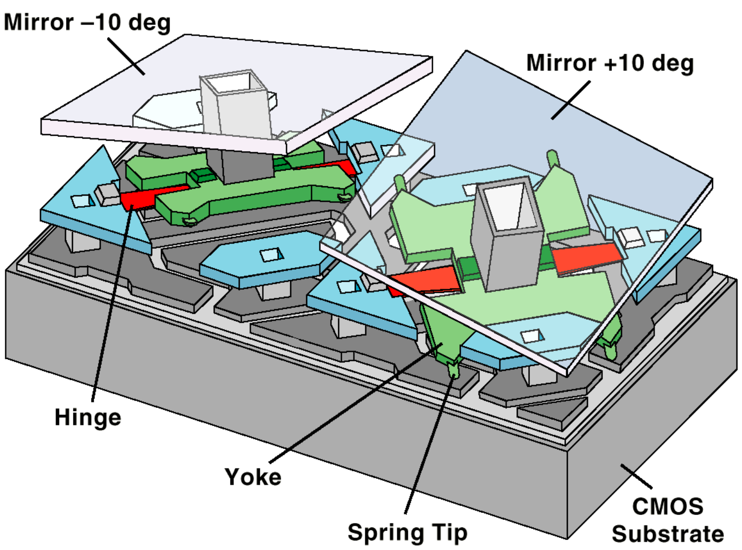
oxidized surface adsorbs alcohol

oxide wears, alcohol re-adsorbs

adsorbed species react to form high MW product



Texas Instruments' Digital Micromirror Array - A Dynamic Contact Success Story



S. Henck, *Tribol. Letters* 1997

Array of ~10^6 Al-alloy mirrors modulate reflected light

- ***limited sliding (~10nm)***

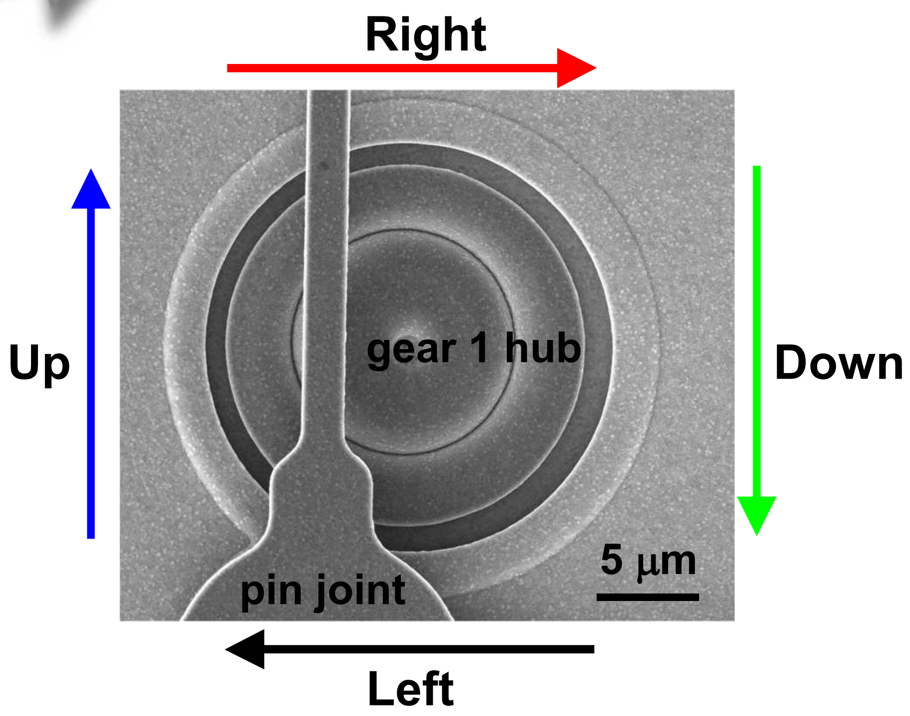
Surface Treatments Investigated

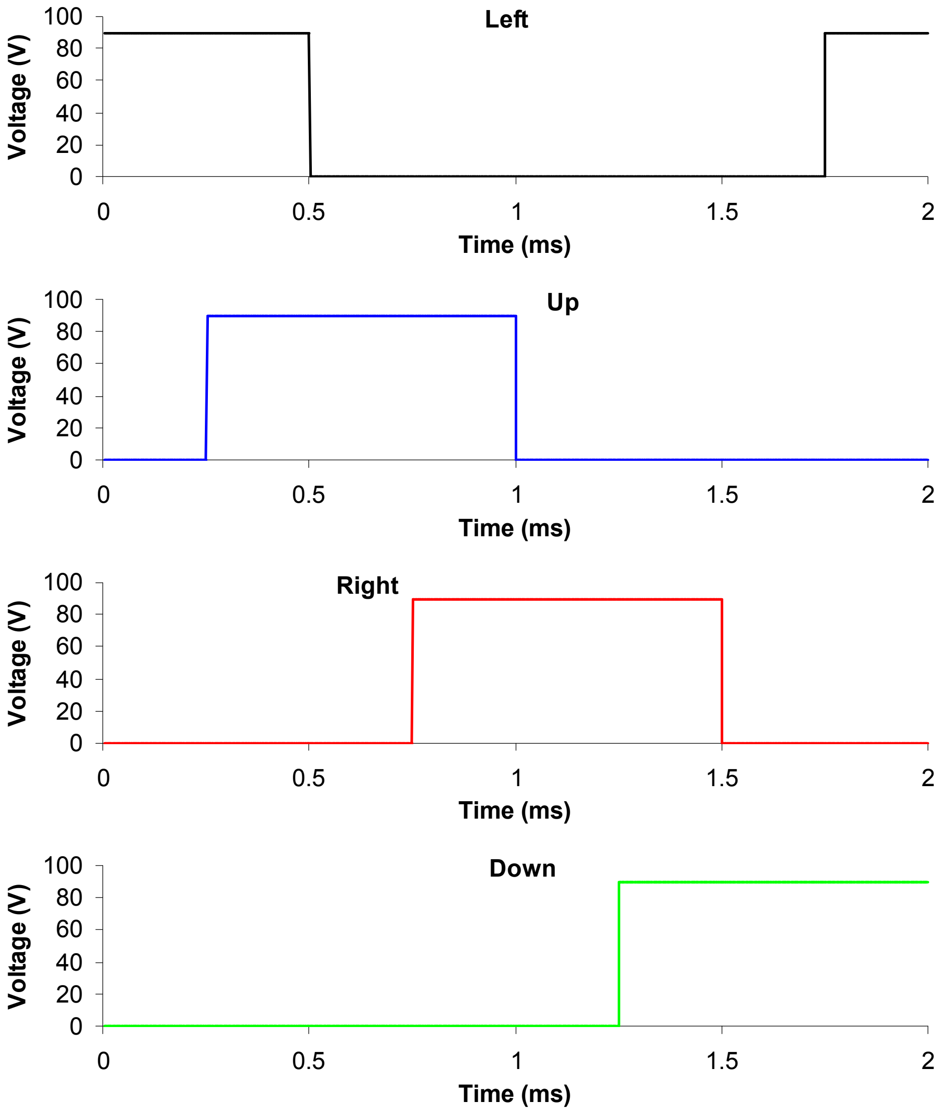
- **chlorosilane monolayers**
- **fluorinated ethers and other boundary lubricants**
- **solid films (diamond-like carbon, nitrides)**
- ***perfluoroalkanoic acids (PFDA,* $C_{10}F_{19}O_2H$*) gave high reliability***

- **device operates at 60-80°C in a hermetic package**
- **PFDA vapor pressure allows re-deposition of passivation layer**
- **also use reset voltage pulse to snap spring tip off of substrate**

Keys to success: limited sliding, special actuation signals, repassivation, and not stored in contact

Device Driven with 90 V Square Waves





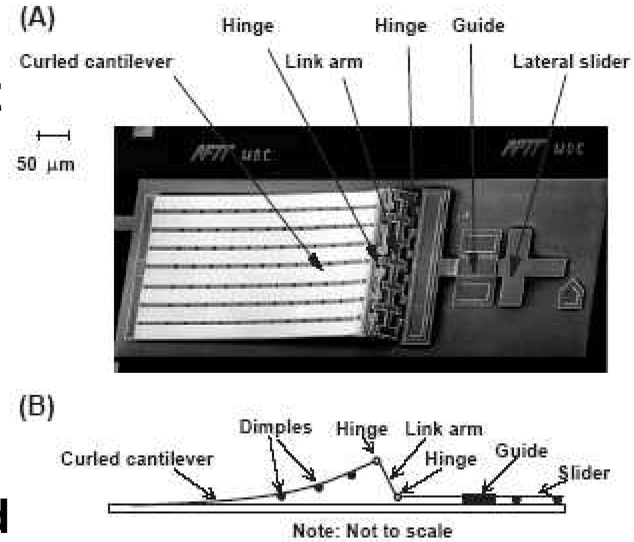
Pin joint constrained to travel a circular path around gear

- large radial forces at hub and pin joint of gear 1
- 500 Hz rotation rate of gear 1
- 16 forward revs, then 16 in reverse

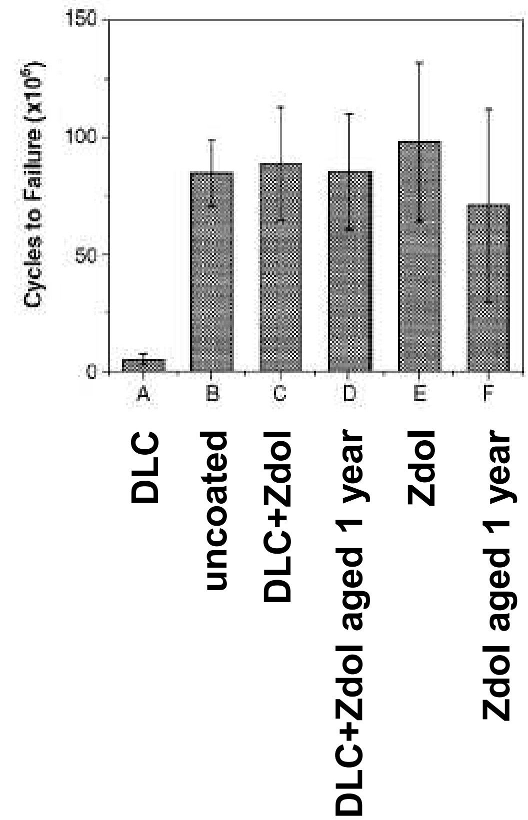
A Mobile Phase Needed to Impart a “Self Healing” Capability to Lubricant Films

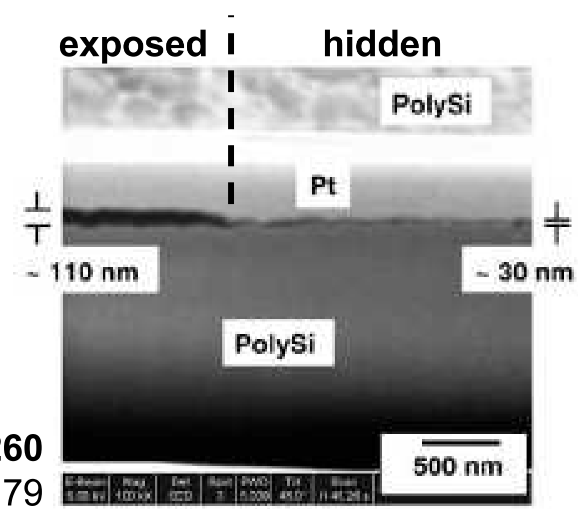
Perfluoropolyether lubricant dramatically improved the operating life of a lateral actuator

- **successful in magnetic recording tribology**
- **carbon film needed to prevent decomposition and silicon roughening**
- **carbon film present in hidden areas**



Eapen et. al *Surf. and Coating Tech.* **197** (2005) p. 270





Smallwood et. al *Wear* **260** (2006) p. 1179

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