SAND2007-7623C

Vapor Phase Lubrication of Silicon MEMS

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Materials Research Society, Fall 2007

26 November 2007

Boston, MA

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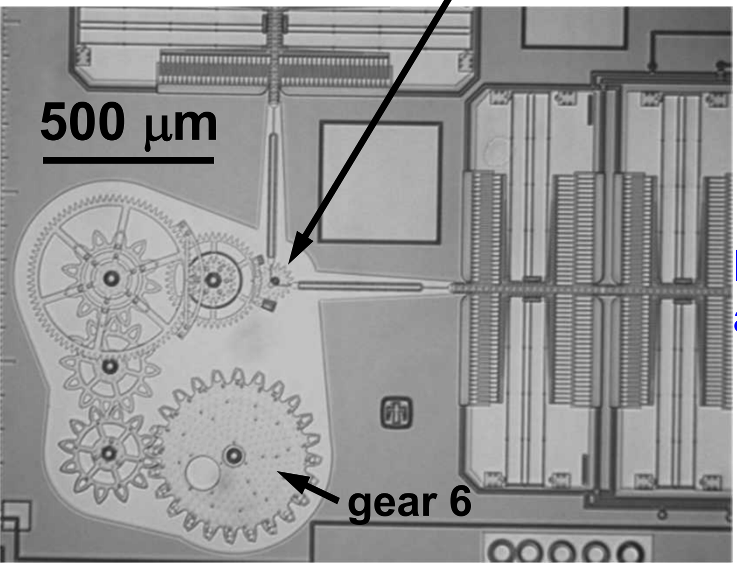
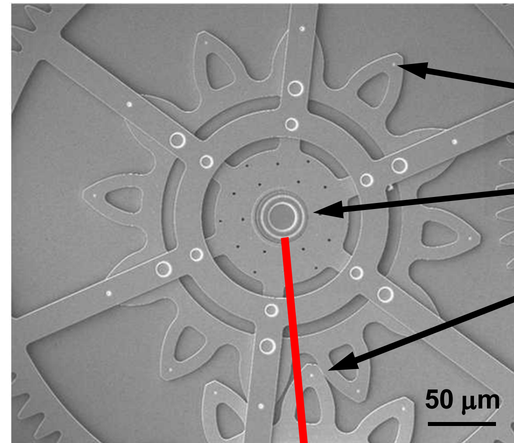
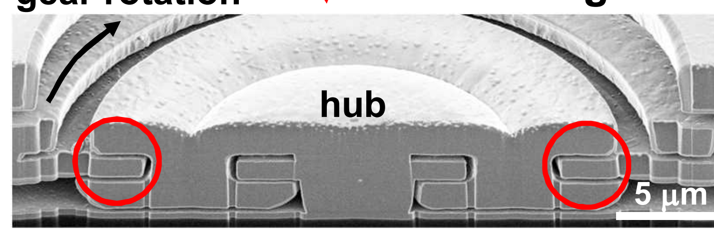
Fully-Assembled MEMS Limit Surface Treatment Options



polysilicon gear train





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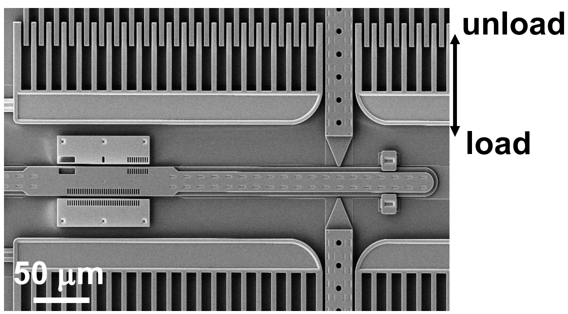
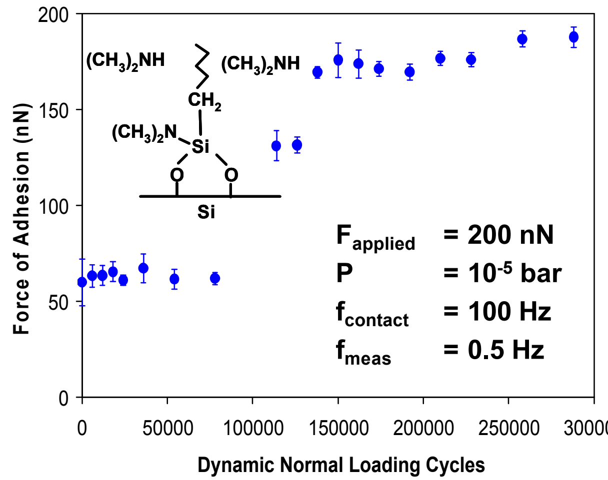
MEMS Failure Mode is a Function of the Device's Design



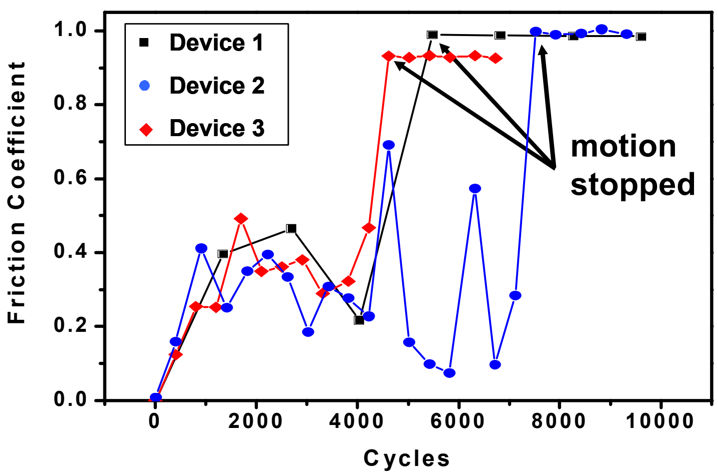


surface treatments are damaged easily, even for normal contact alone

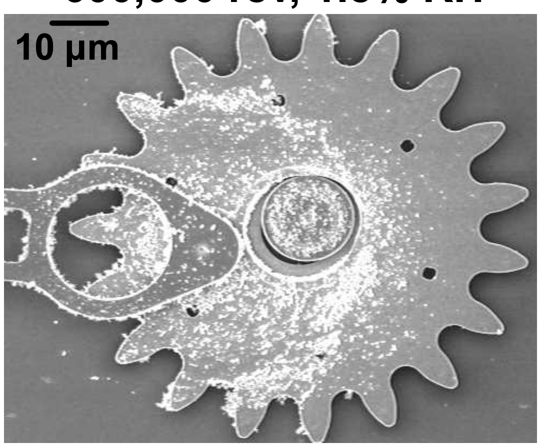
D.A. Hook, in preparation

$F_{friction} > F_{actuation}$

$F_{actuation} > F_{friction}$



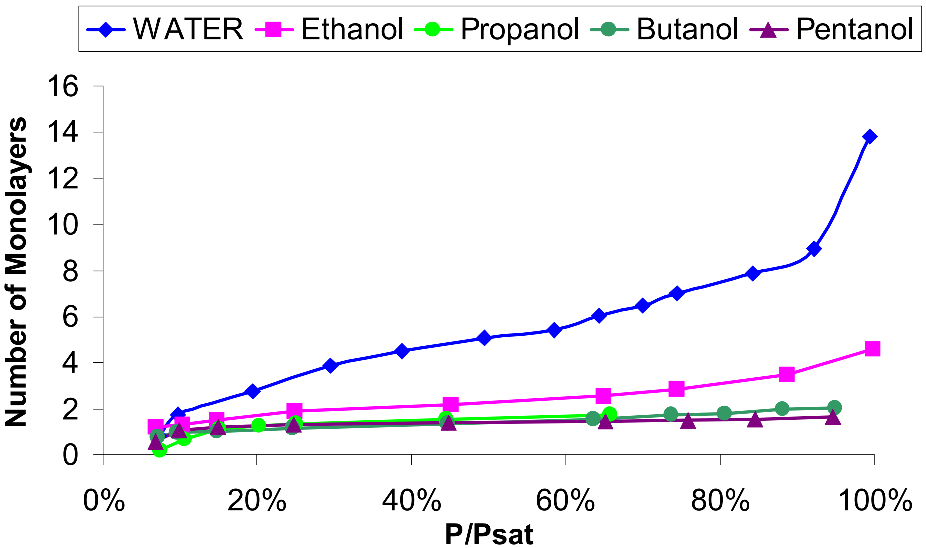
600,000 rev, 1.8% RH

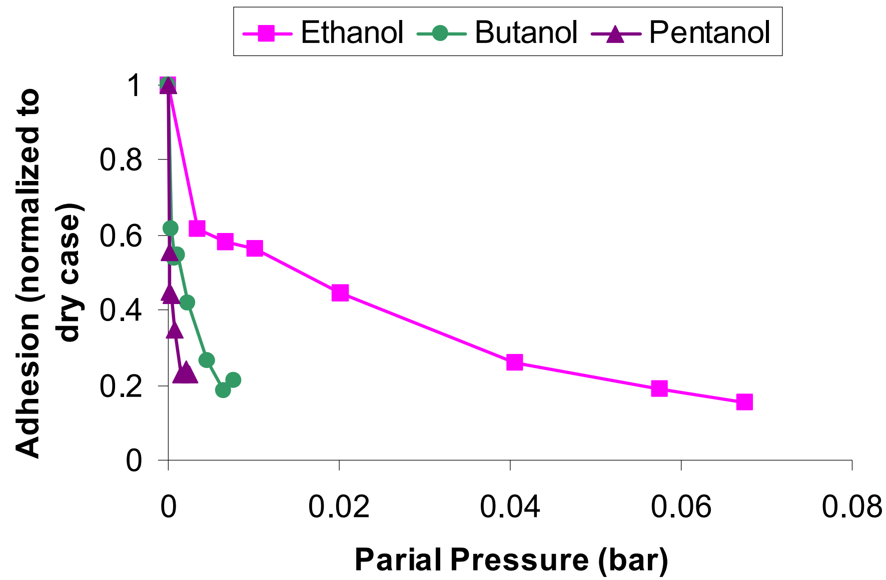


D. Tanner et. al, International Reliability Physics Symposium, 1998

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

Lower surface tension, limited adsorbed film thickness, and high molar volume of alcohols limit capillary adhesion

D.B. Asay and S.H. Kim, Langmuir, in press

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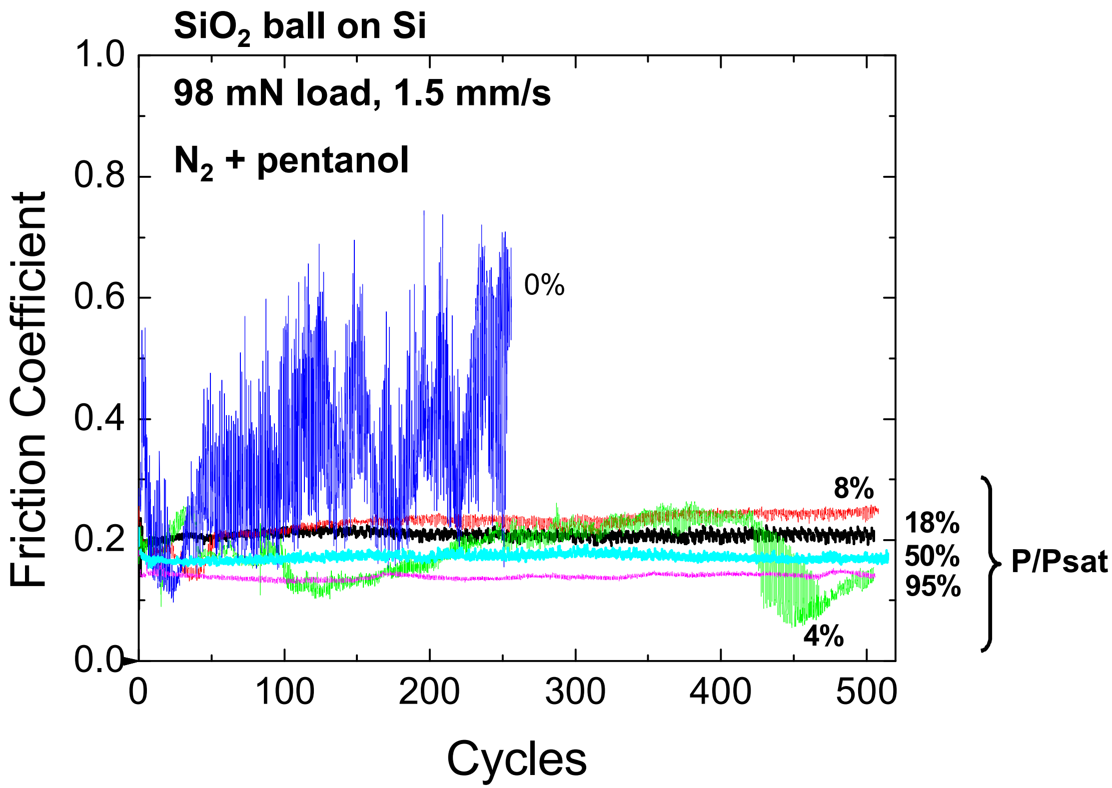
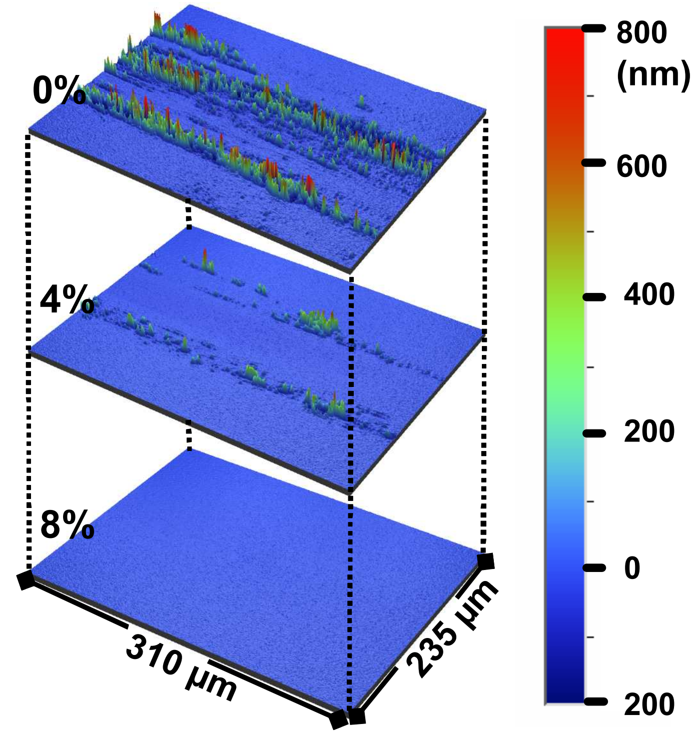
Vapor Phase Lubrication of Silicon Reduces Friction in Macroscale Sliding





No measurable wear for $P/P_{sat} \geq 8\%$

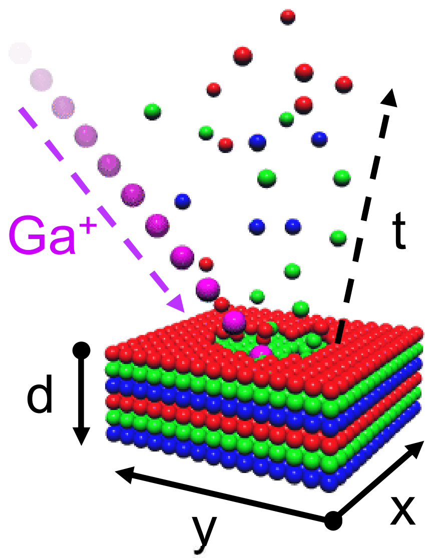
- **corresponds to ~ monolayer coverage from ATR-FTIR data**

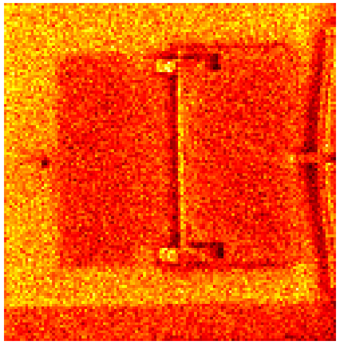
D.B. Asay, M.T. Dugger, J.A. Ohlhausen and S.H. Kim, Langmuir, in press

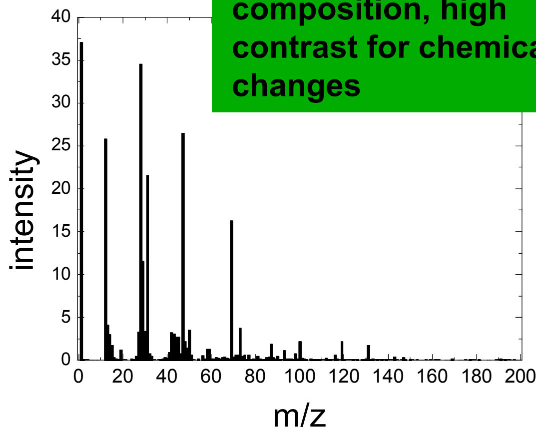
Multivariate Analysis Of SIMS Data Allows Detection of Subtle Changes In Chemistry

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

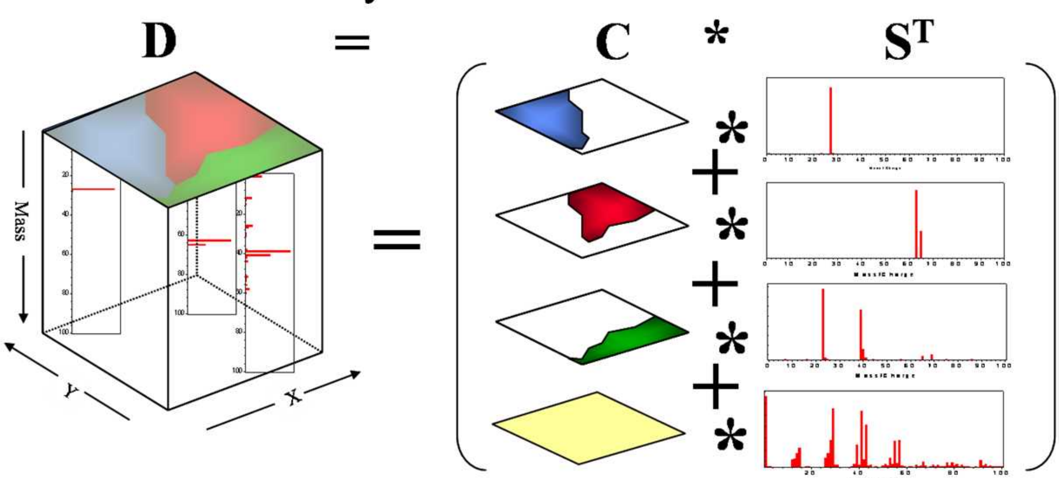
+ Automated eXpert Spectral Image Analysis (AXSIA)







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.

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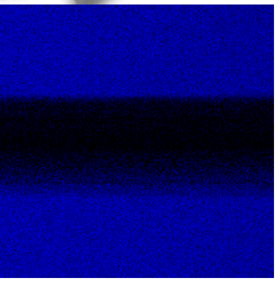
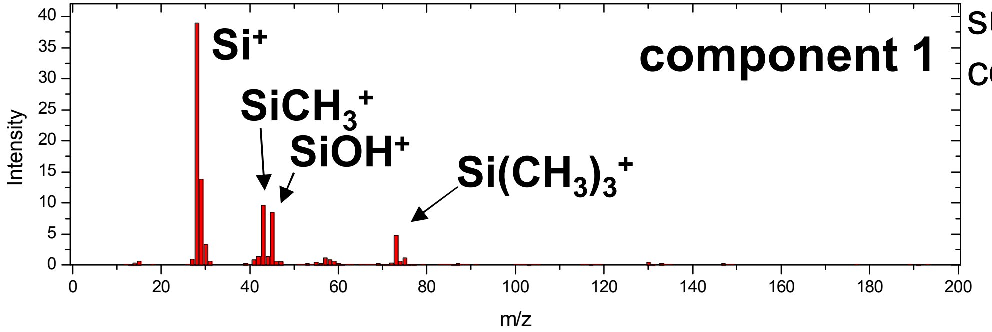
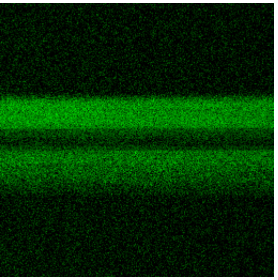
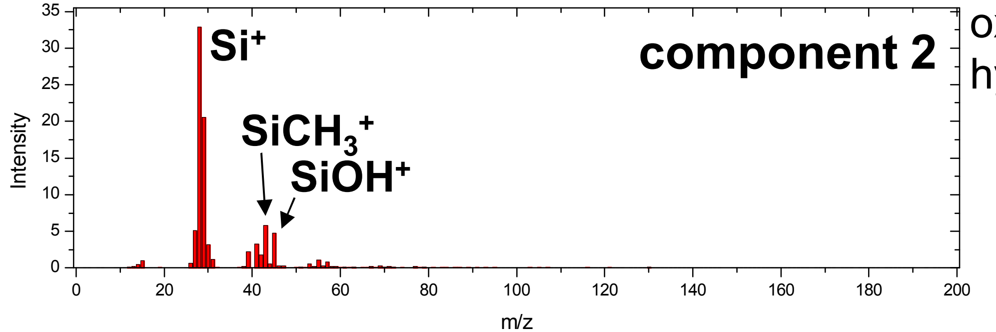
ToF-SIMS With Multivariate Analysis Shows Formation of High MW Product



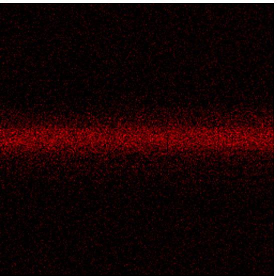


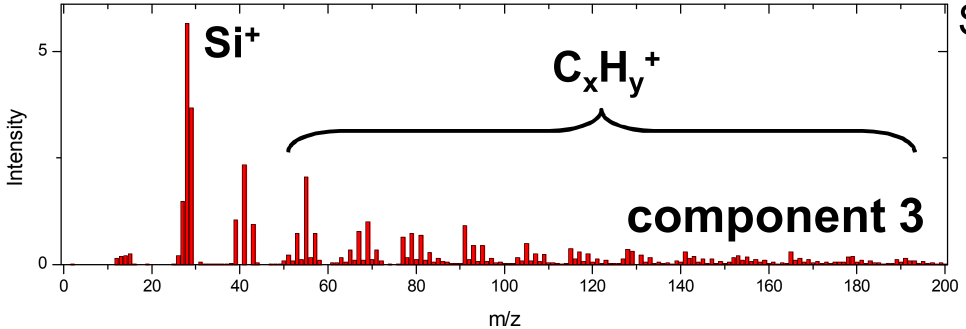
surface oxides and contaminants (silicones)





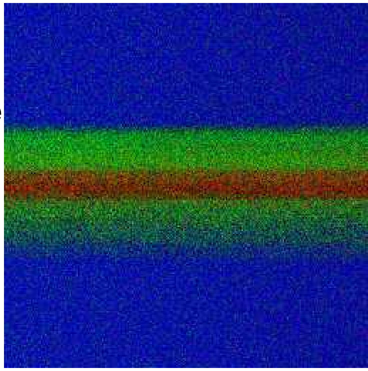
oxidized Si + short chain hydrocarbons





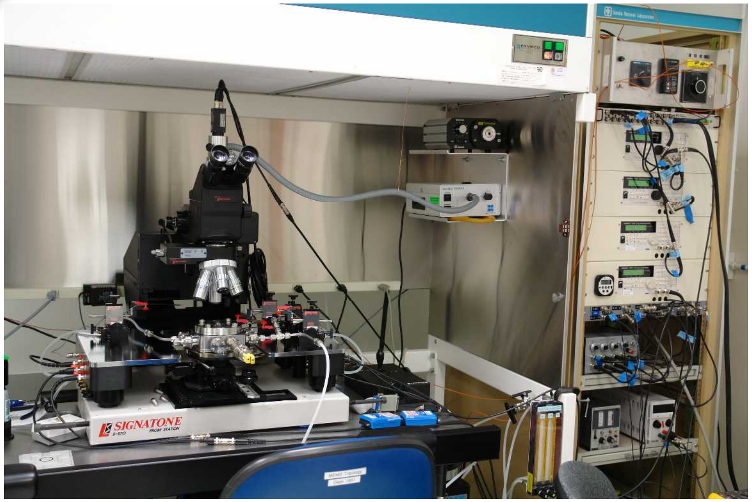
Si + long chain hydrocarbons

composite image



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

MEMS Device Testing in Controlled Environments

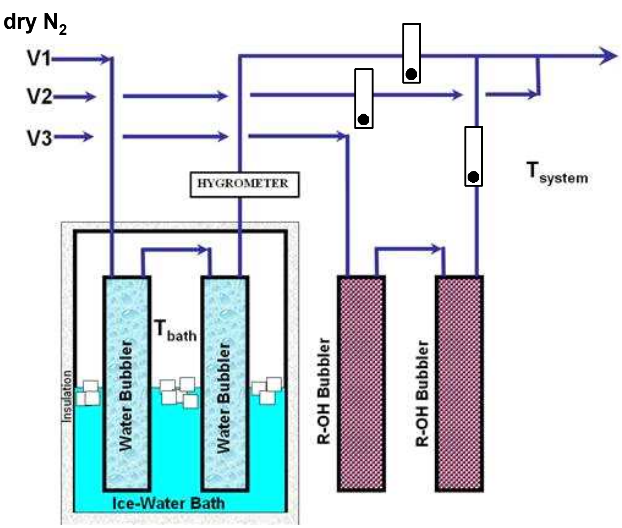


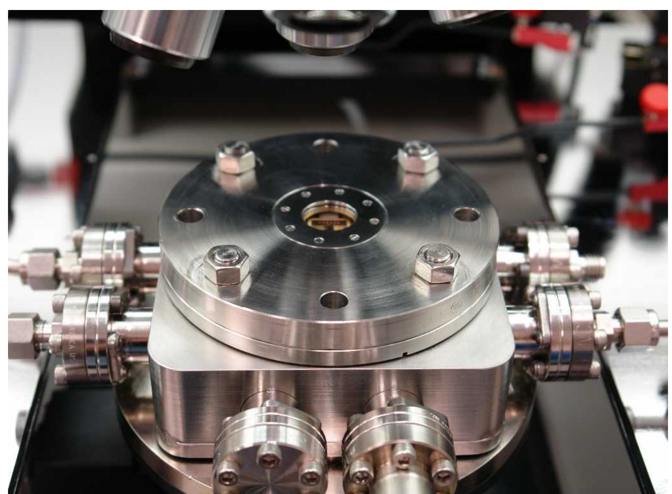
Probe Station and Drive Electronics

Device packaged in 24-pin DIP

Process image data to give forces

- 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 $F_d = k\Delta x$

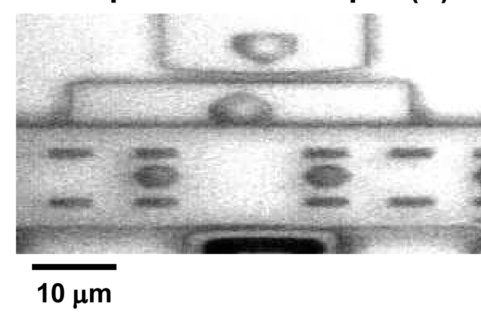




MEMS Environmental Test Chamber

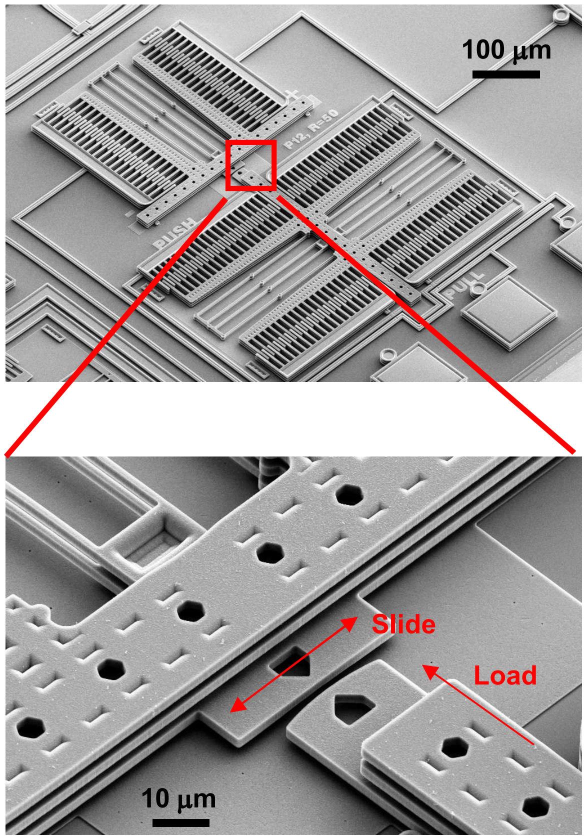
Timed Image Capture

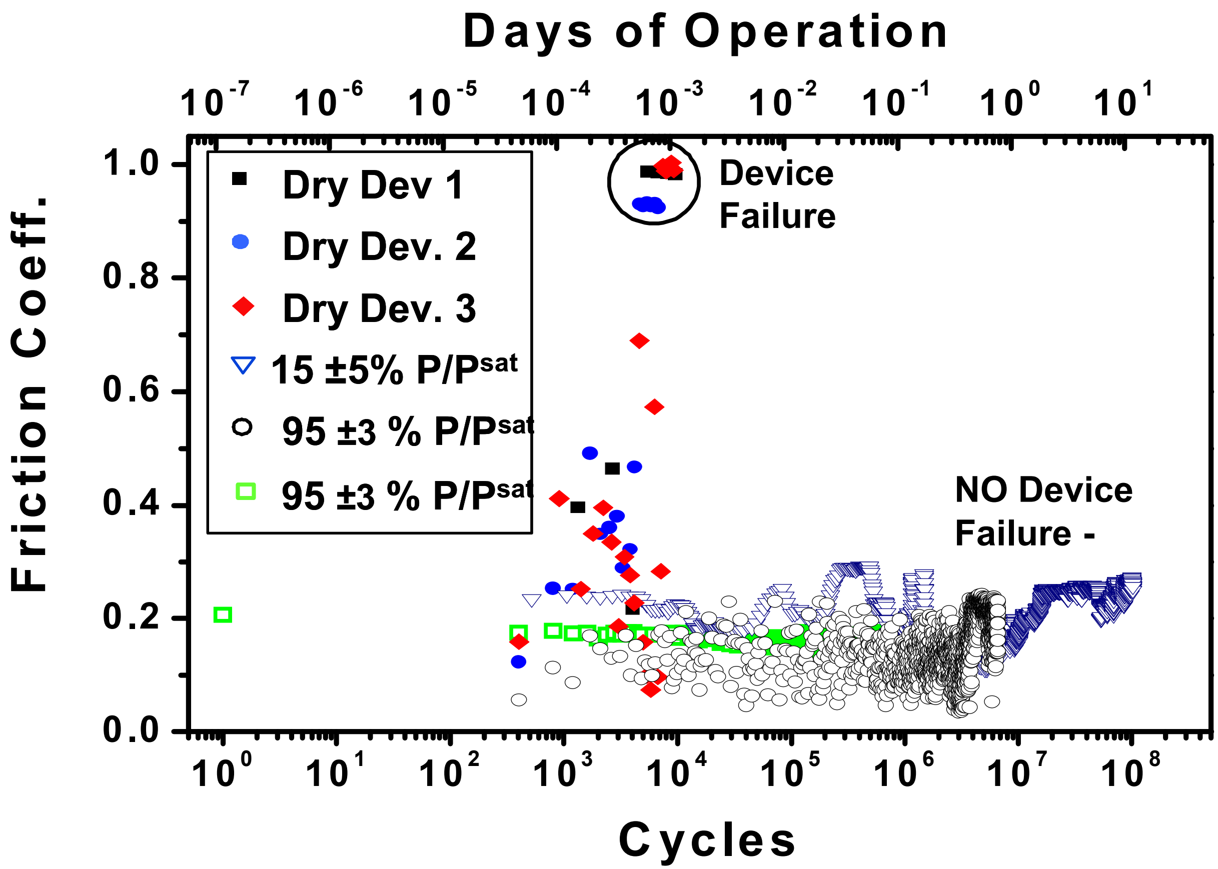
Displacement vs Input (V)



Unprecedented Improvements in Operating Life are Observed with MEMS Tribometers

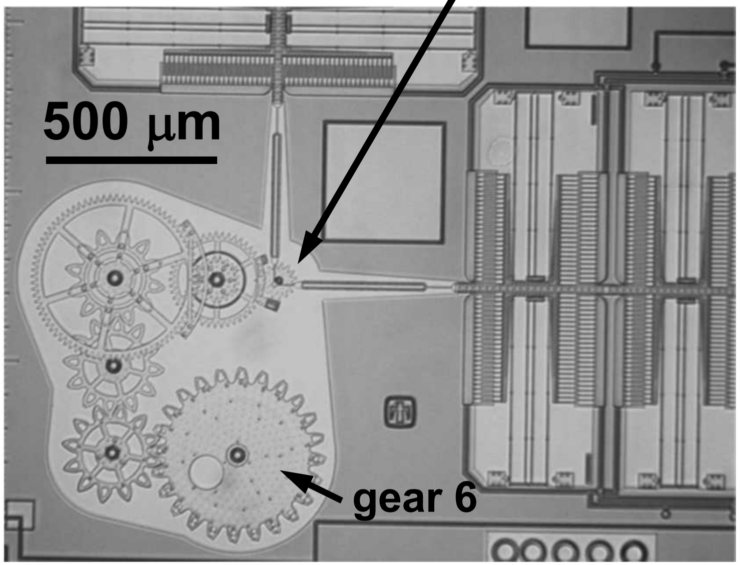
MEMS tribometer



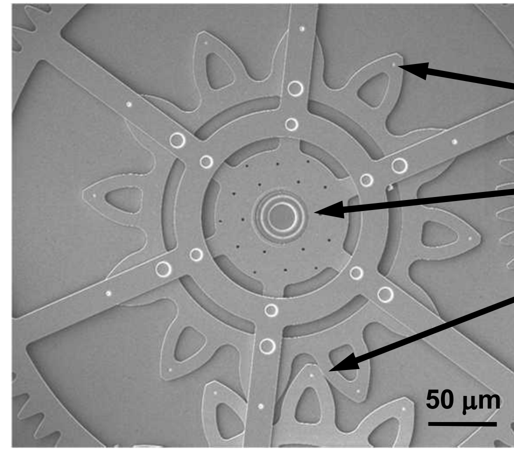


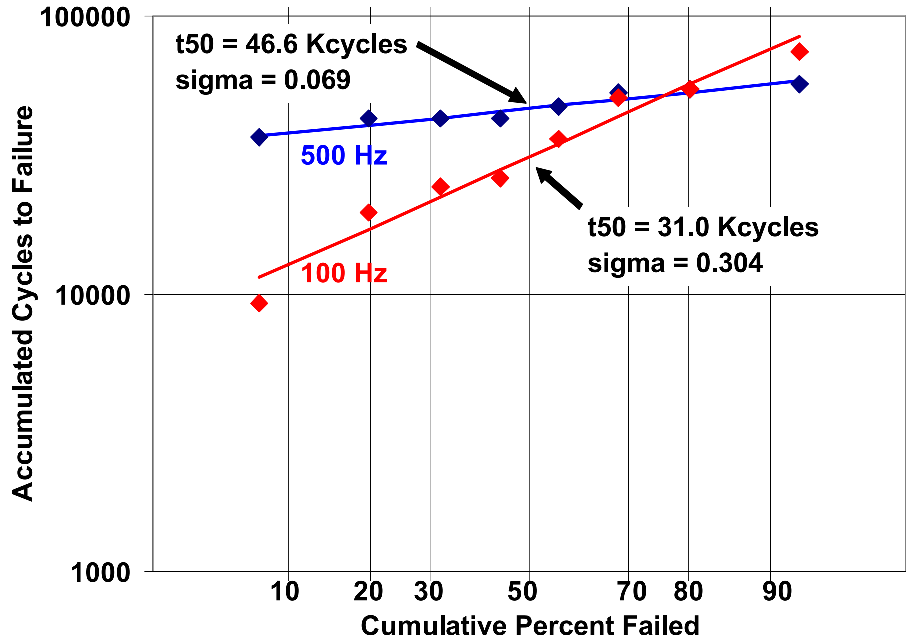
- **devices operated for 1-2 minutes at 100 Hz with CF_3-terminated monolayers alone**
- **no failure observed in > 10^8 cycles with alcohol vapor present**

Increased Operating Life of Gear Train with Vapor Phase Lubrication



gear train on aging module





FOTAS monolayer alone, t_{50} = 4.7x10^4

With VPL, device was stopped at 4.8x10^8 cycles *without failure*

- **1000 ppmv pentanol, 0 H_2O**

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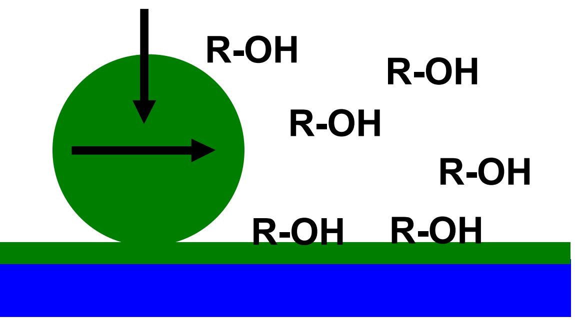
Vapor Phase Lubrication of Silicon by Tribochemical Reaction

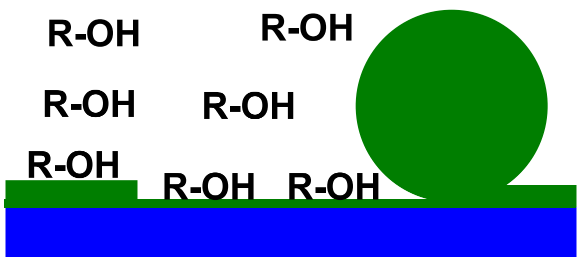
S.M. Wiederhorn and D.E. Roberts, *Wear* **32** (1975) p.51-72
- reduced friction when abrading silicate glass in alcohols

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)

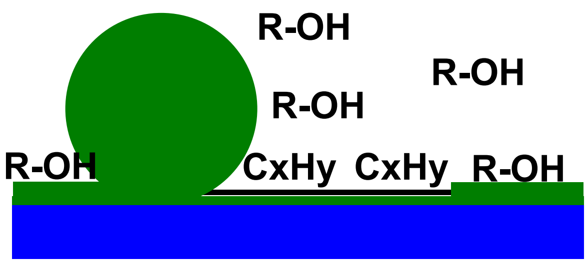
Y. Hibi, Y. Enomoto and A. Tanaka, *J. Mat. Sci. Lett.* **19** (2000) p.1809-1812
- postulate metal alkoxides condense to polymer and act as lubricant



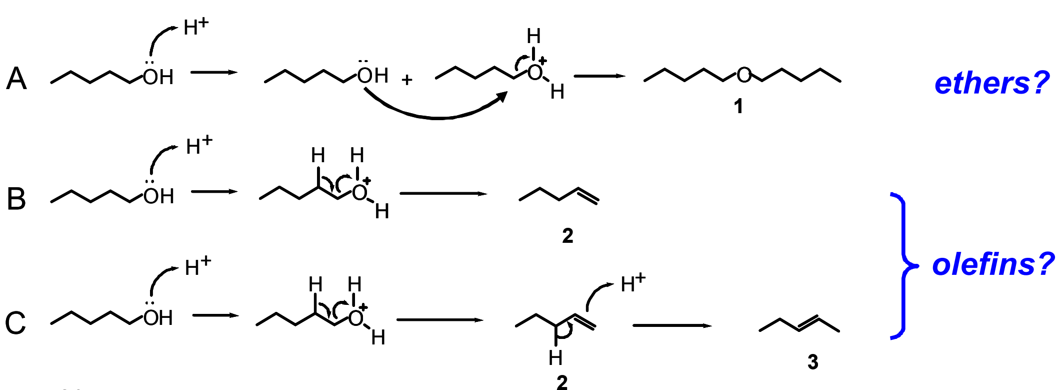
oxidized surface adsorbs alcohol



oxide wears, alcohol re-adsorbs



adsorbed species react to form high MW product



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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

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

Our paradigm about the reliability of MEMS devices with contacting surfaces must be revisited