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Tribology in MEMS

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SPIE Defense, Security, and Sensing
Emerging Technologies Track

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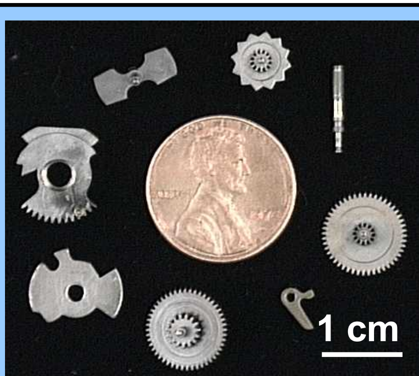
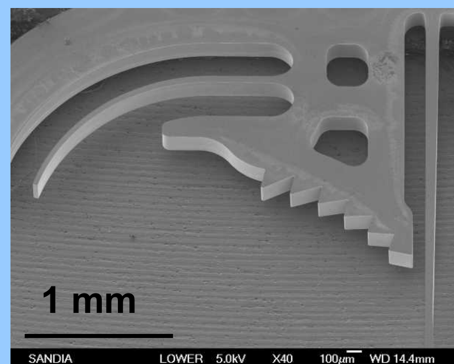
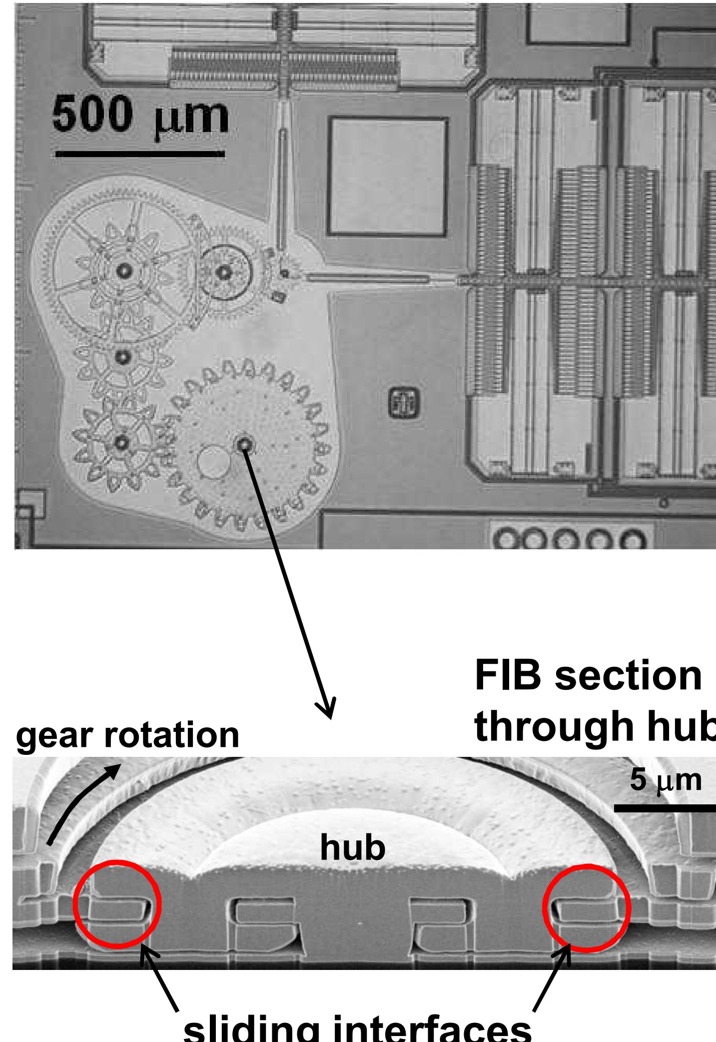
Solid Lubrication Becomes Increasingly Challenging As Component Dimensions Shrink



MoS_2-lubricated machine parts



new fabrication methods enable smaller metallic parts

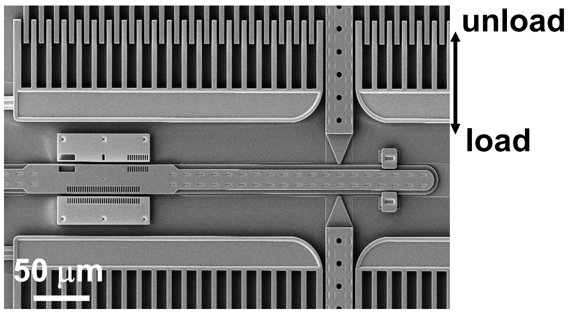


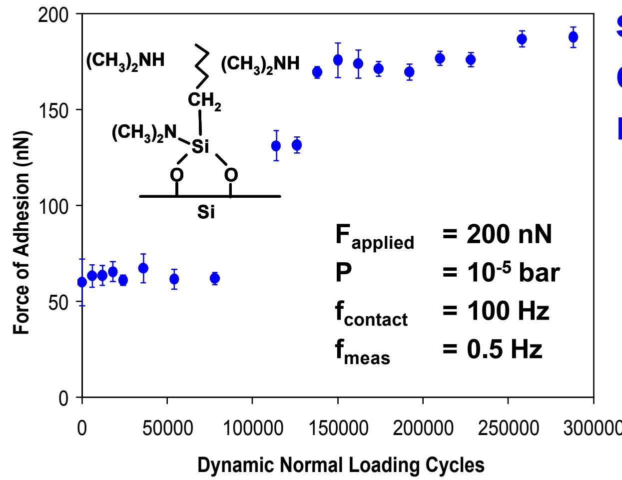
Lubricating small parts of complex shape is a challenge at present.

A size decreases, existing lubrication approaches are not feasible.

No successful lubrication approach exists for sliding contacts in microsystems.

Our Best Chemisorbed SAM Films Do Not Survive Mechanical Contact



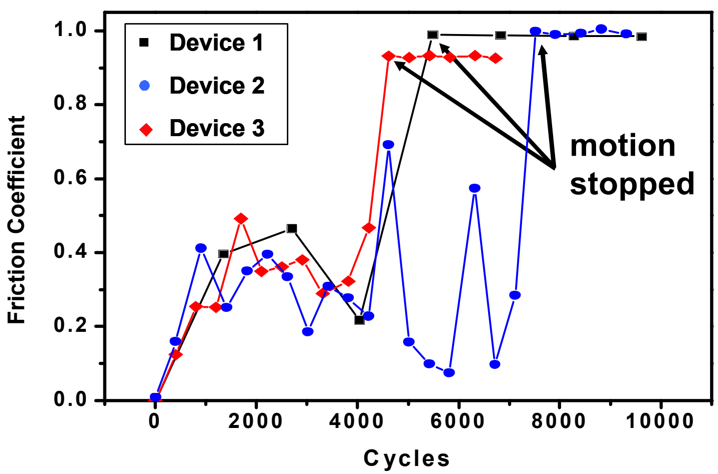


surface treatments are damaged easily, in normal contact alone

D.A. Hook, S.J. Timpe, M.T. Dugger and J. Krim, *J. Appl. Phys.*, **104** (2008) p. 034303

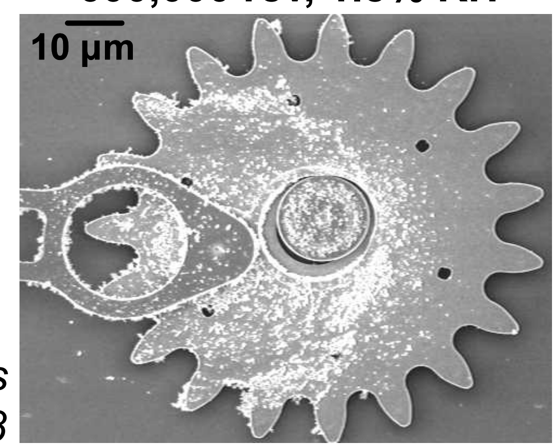
$F_{friction} > F_{actuation}$

$F_{actuation} > F_{friction}$



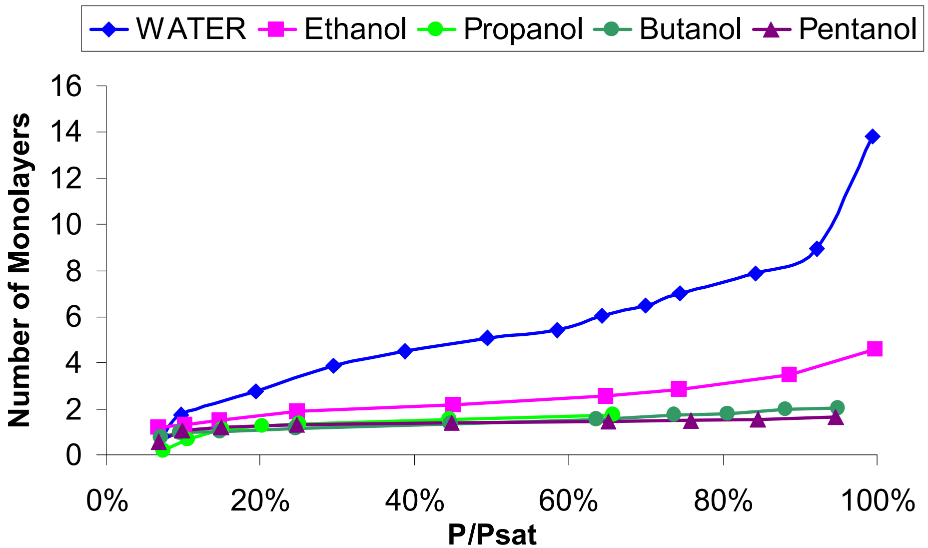
D. Tanner et. al, International Reliability Physics Symposium, 1998

600,000 rev, 1.8% RH



Alcohols Reduce Adhesion Between Silicon Surfaces

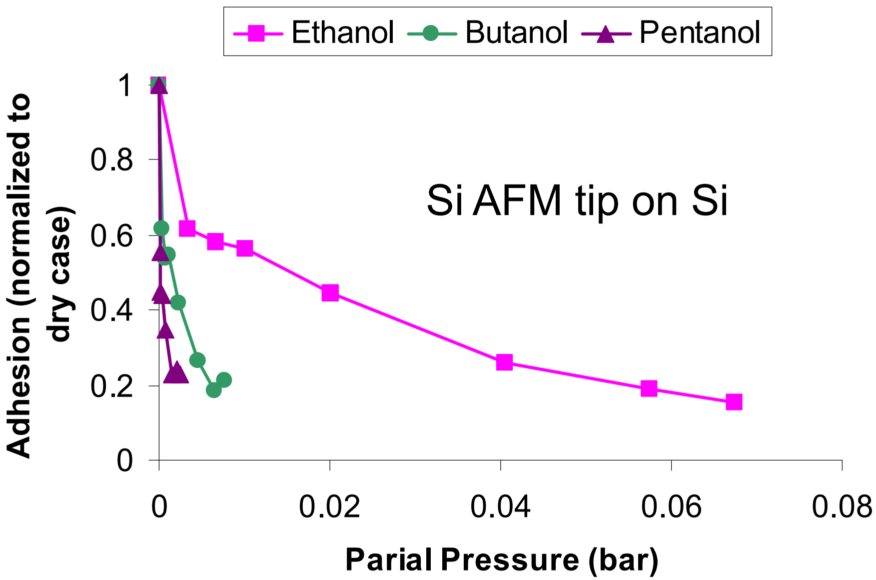
K. Strawhecker, D.B. Asay, J. McKinney and S.H. Kim, *Trib. Lett.* **19** (2005) p.17-21



Adsorbed film thickness by ATR-FTIR

- ***for C ≥ 2, adsorb 1-2 monolayers at $0.1 < P/P_{sat} < 0.9$***

D.B. Asay and S.H. Kim, *Langmuir* **23** (2007) pp. 12174 - 12178



	γ (erg/cm²)	V (cm³/mol)
water	72.8	18.1
ethanol	21.8	58.7
1-butanol	24.6	91.2
1-pentanol	24.9	108.7

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

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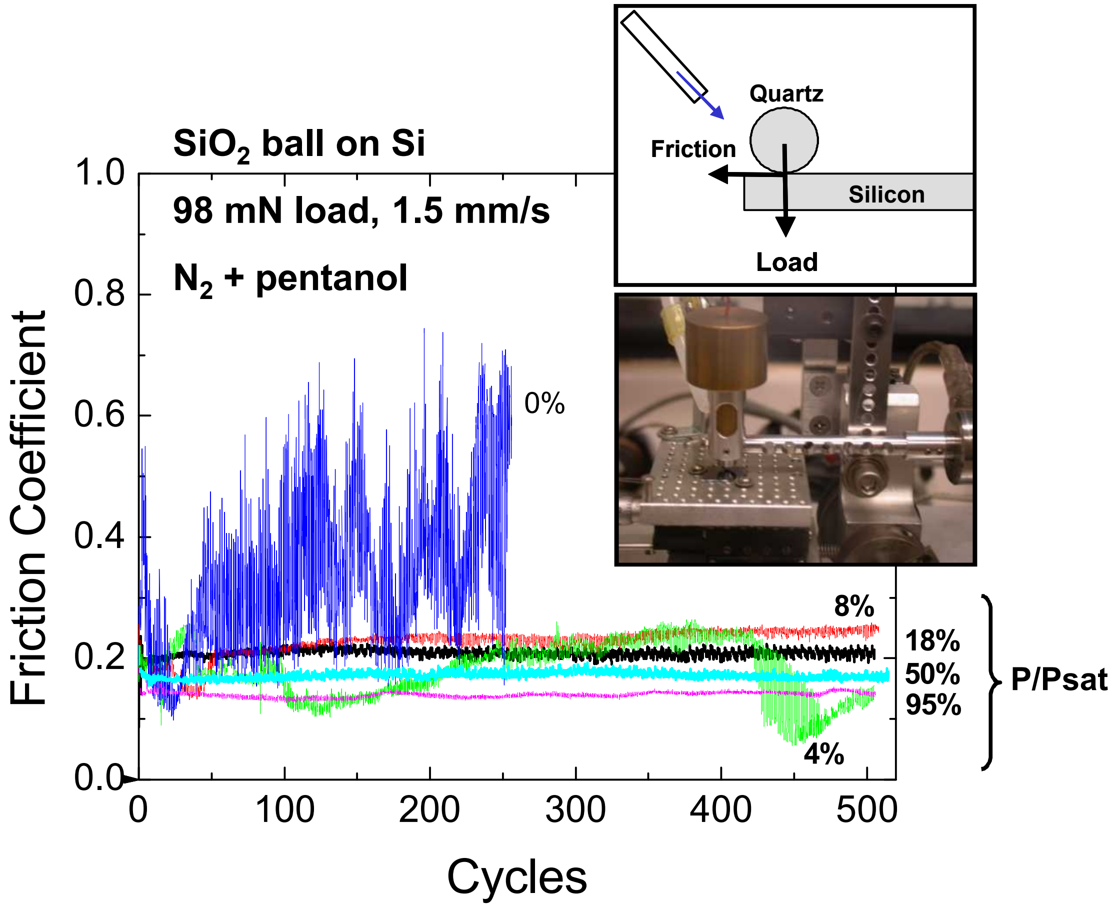
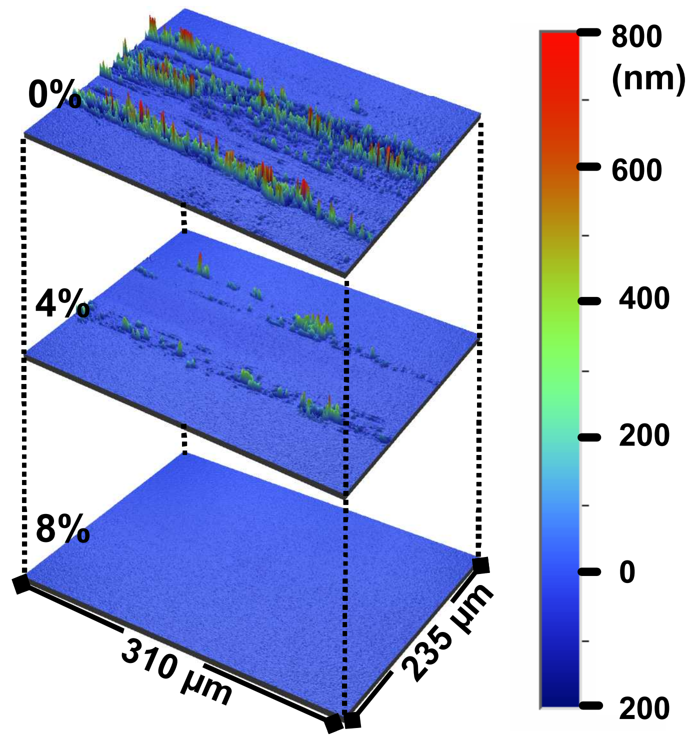
Vapor Phase Lubrication of Silicon Reduces Friction in Macroscale Sliding



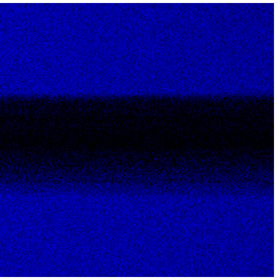


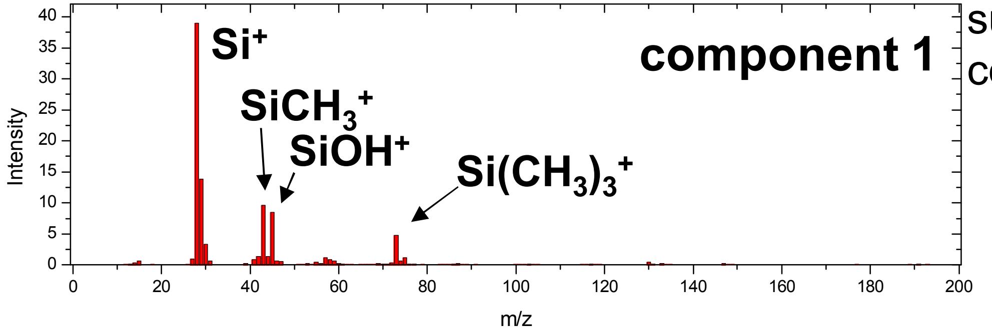
No measurable wear for $P/P_{sat} \geq 8\%$

- corresponds to monolayer coverage from ATR-FTIR data

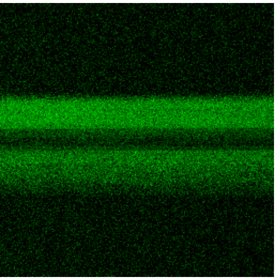
D.B. Asay, M.T. Dugger, J.A. Ohlhausen and S.H. Kim, *Langmuir* **24** (2008) p. 155-159.

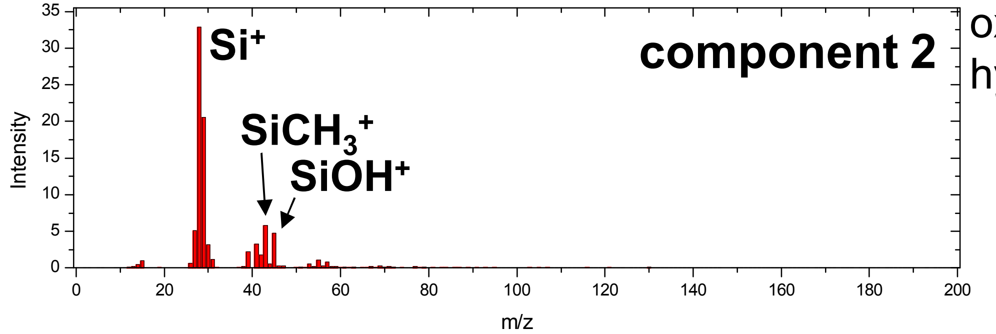
High MW Product Forms in the Contact



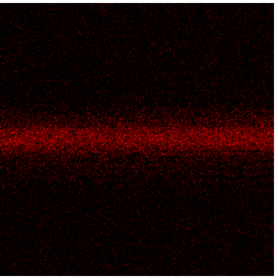


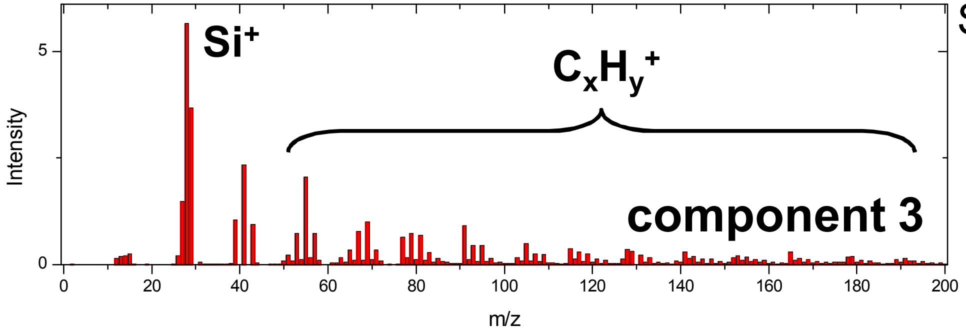
surface oxides and contaminants (silicones)





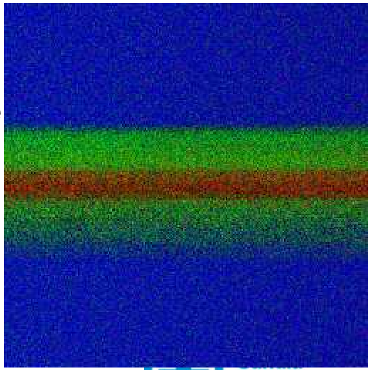
oxidized Si + short chain hydrocarbons



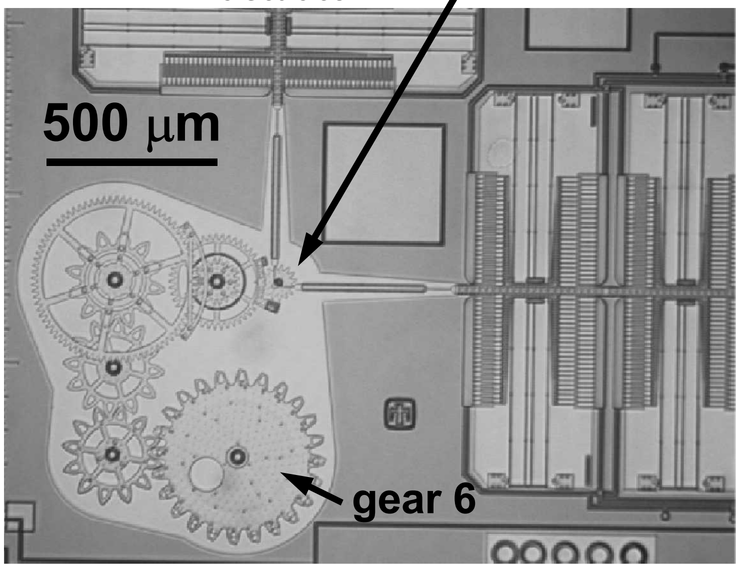


Si + long chain hydrocarbons

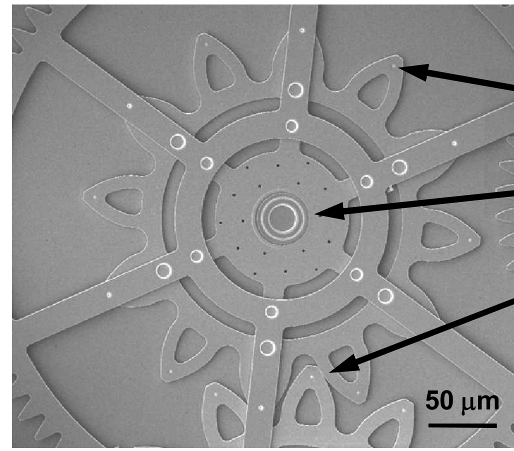
composite image

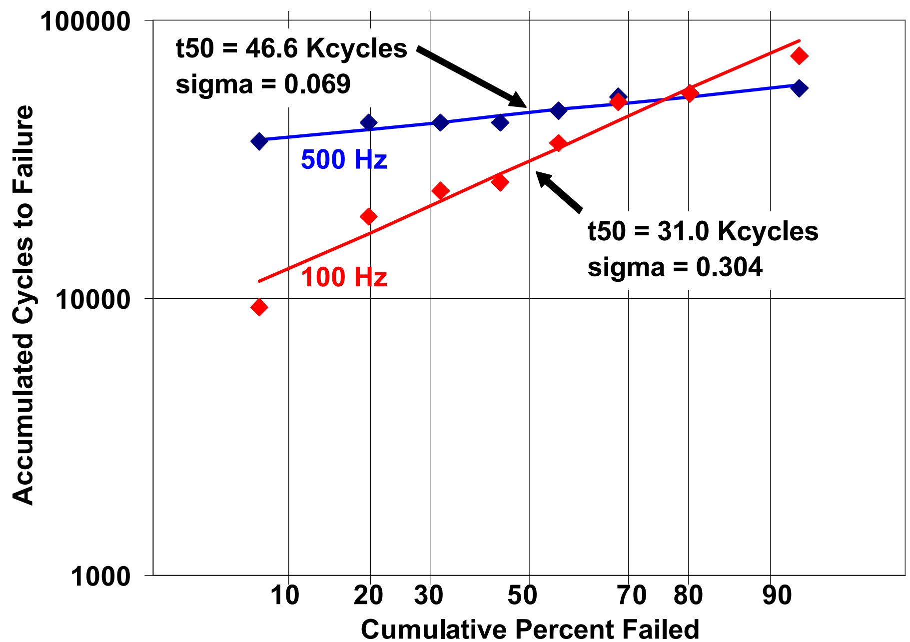


Increased Operating Life of Gear Train with Vapor Phase Lubrication



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 cycles *without failure*

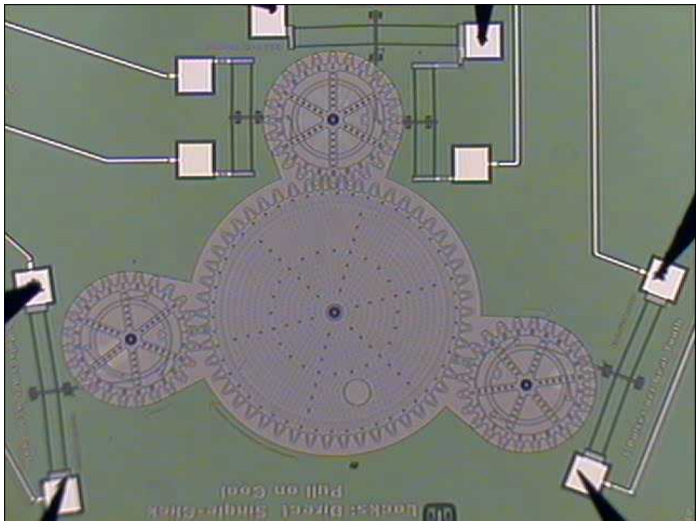
- **1000 ppm pentanol, <100 ppm H_2O**

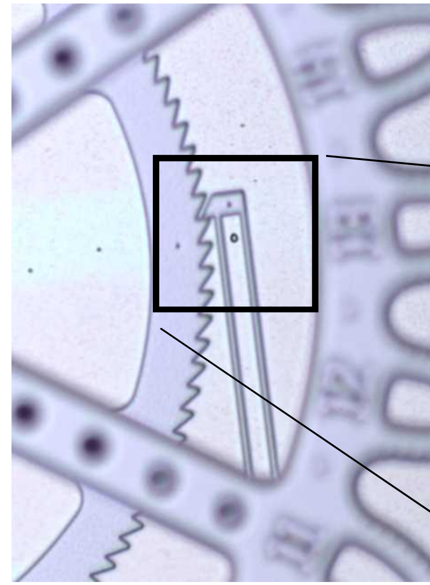
D. Tanner, Sandia

National Laboratories

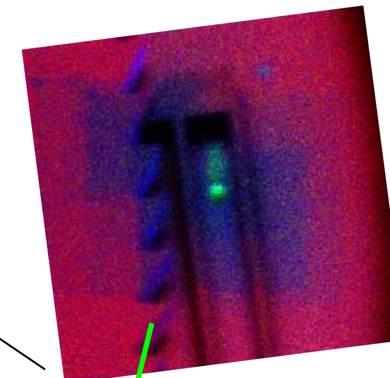
High MW Reaction Product Observed on MEMS Device

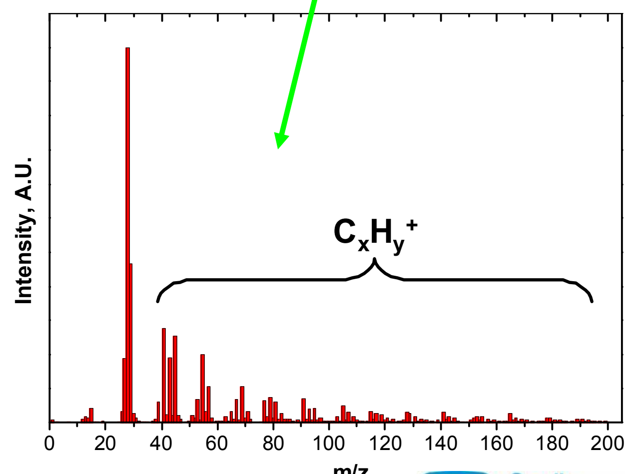
Thermally-actuated device, 5×10^8 cycles in pentanol at $P/P_{sat}=0.2$, *<u>without failure</u>* (fails at 5×10^5 in air)

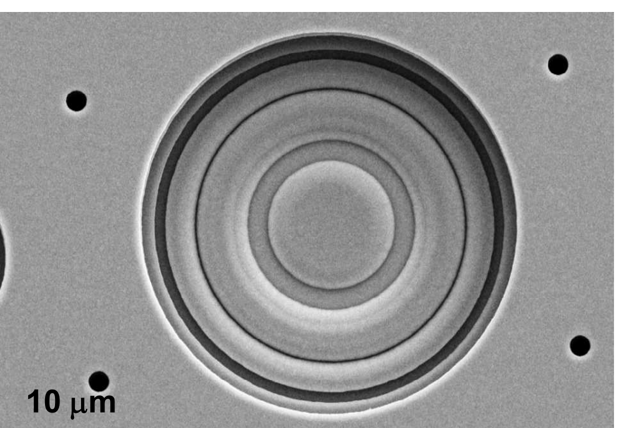


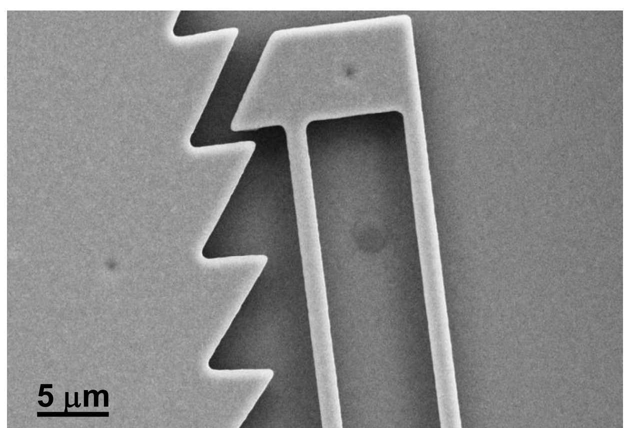


ToF-SIMS spectral imaging









no evidence of wear, but deposit at dimple contact

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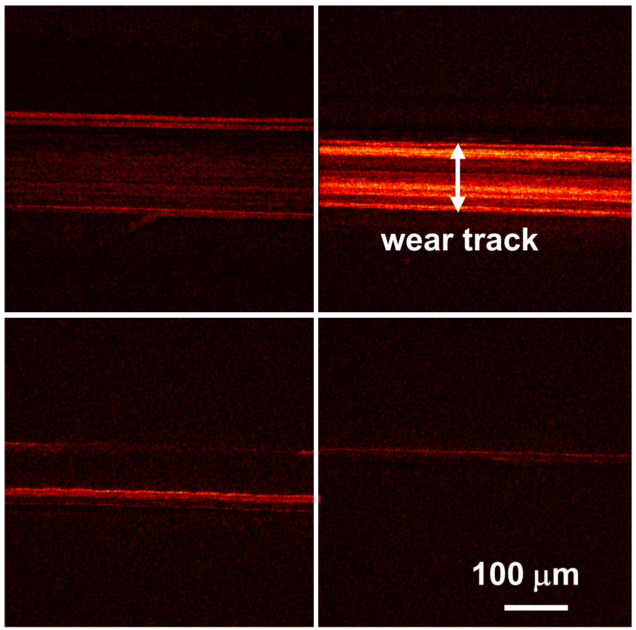
Polymerization Not Required for Wear Prevention

Ar + | 10% pentanol | 50% pentanol

730 MPa wear

480 MPa no wear

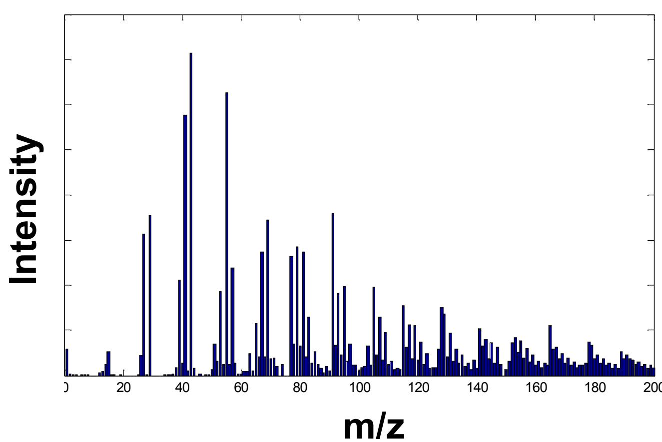


ToF-SIMS with AXIA reaction product spatial maps

Reaction product accompanies surface damage

- previously, no wear for P/P_{sat} > monolayer
- higher contact pressure requires higher lubricant vapor pressure to avoid wear

Wearless sliding is achievable without reaction product formation



reaction product fragmentation spectrum

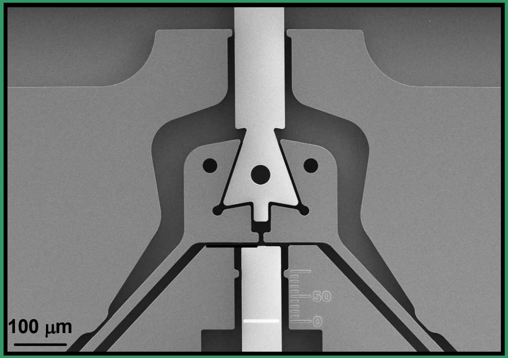
VPL is Effective on MEMS Devices with Thermal Actuators

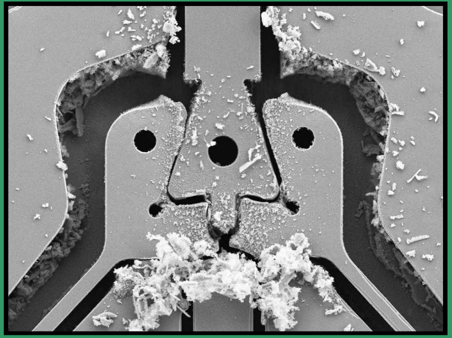
latch-unlatch motion

air

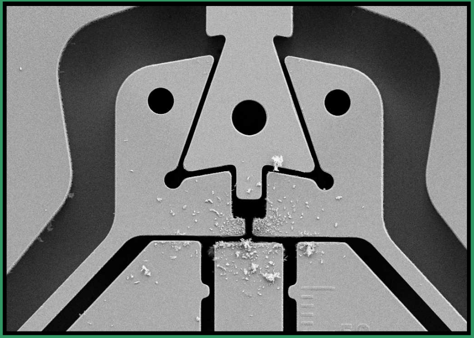
20% Psat pentanol

single crystal silicon Fiber Switch





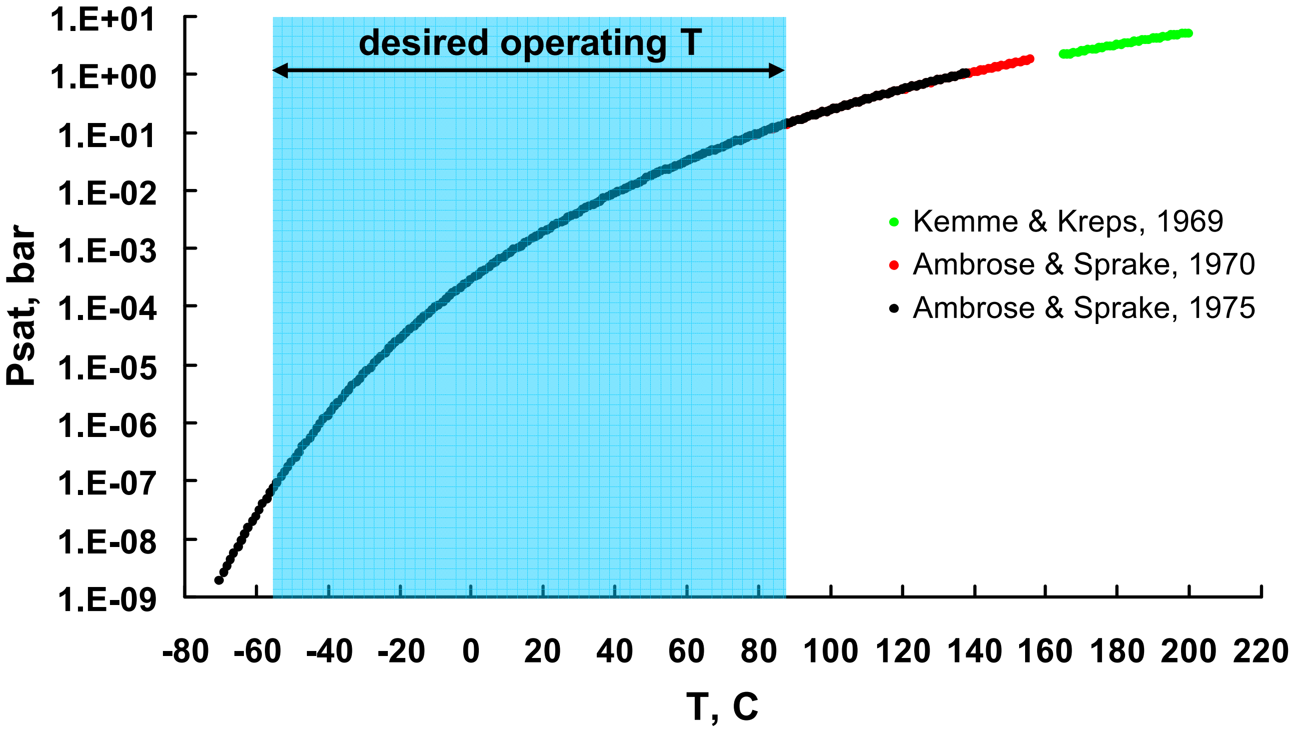
5x10⁶ cycles in air



5x10⁶ cycles in 20% Psat pentanol

VPL with pentanol produces extraordinary operating life in a variety of MEMS devices

Packaging Solution Required to Enable VPL over Large Temperature Range



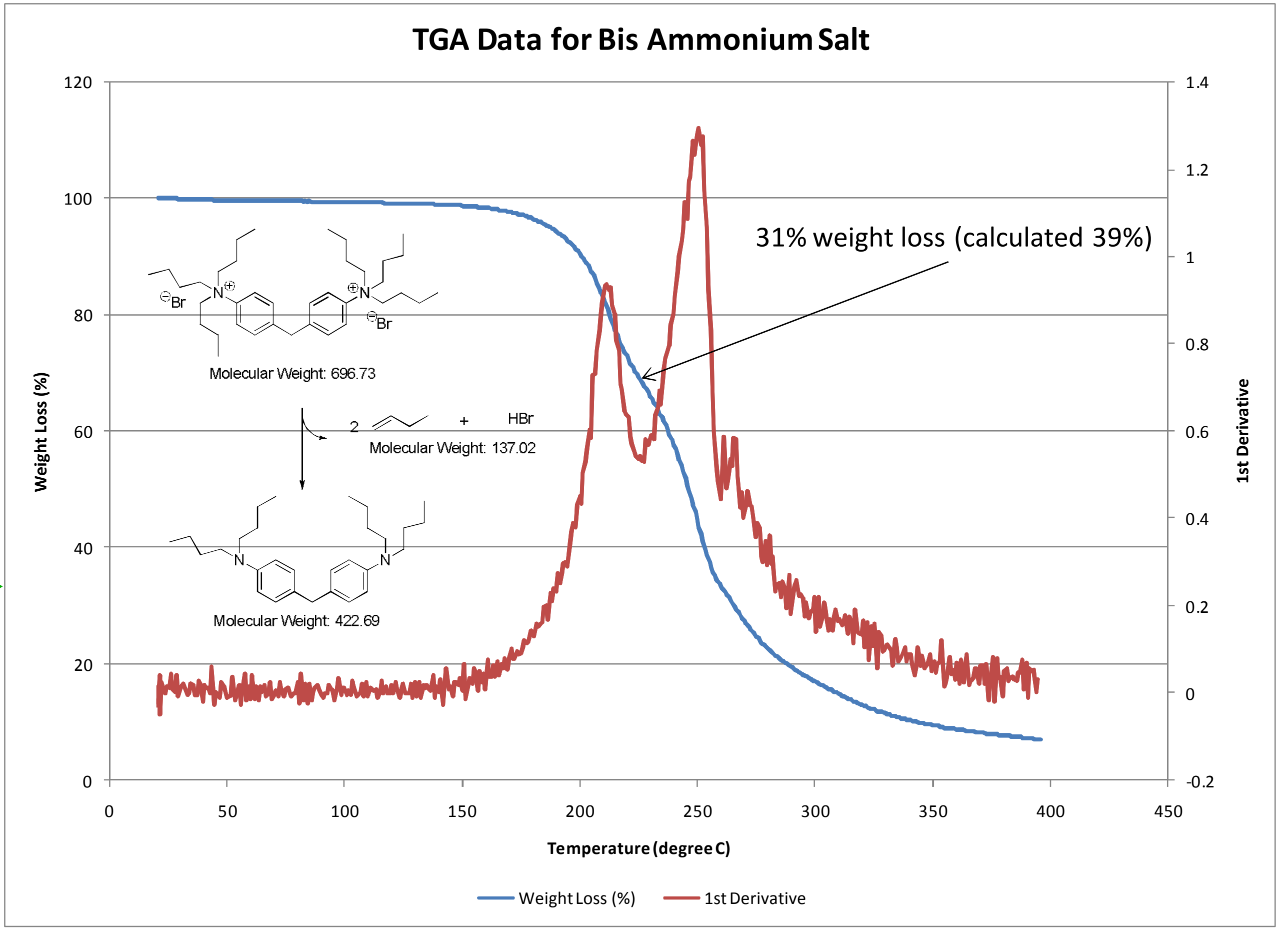
- **bound at high T by need to have monolayer coverage (P/P_{sat}~0.10)**
- **bound at low T by preventing multilayer adsorption and condensation (P/P_{sat}~0.95)**

Ideal source would supply constant P/P_{sat} over desired operating temperature range

Vapor Delivery Approach: In-Situ Generation

Explored thermally driven reactions to deliver a vapor as needed:

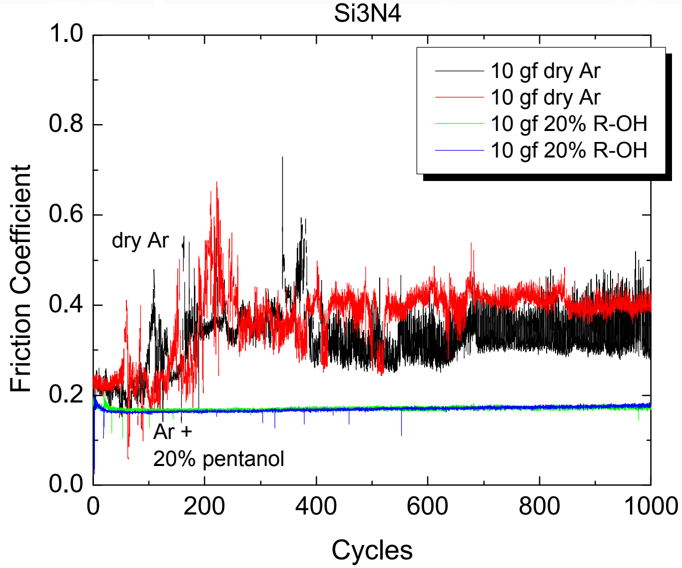
1) Retro-ene reaction
    - Deliver alcohols or thiols
2) Hoffman elimination reaction
    - Deliver olefins
3) Thermally removable protecting group chemistry
    - Deliver olefins

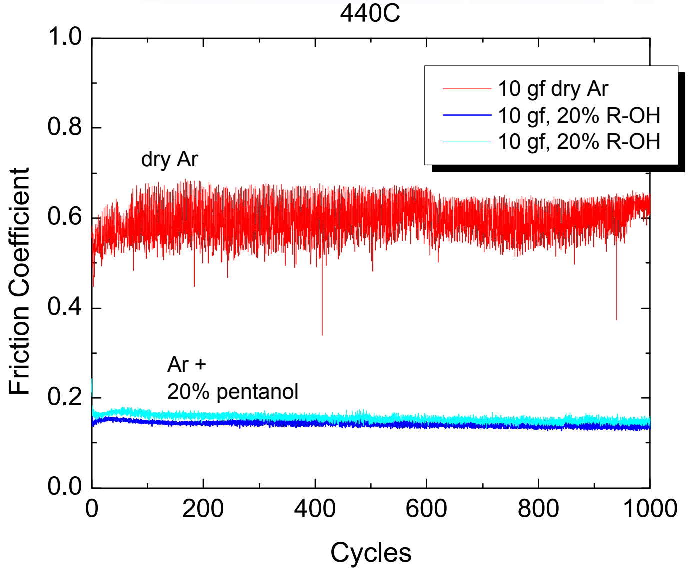


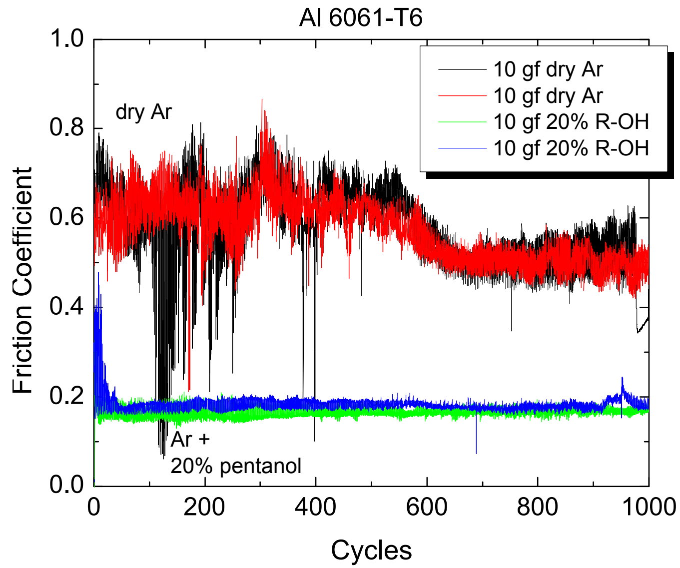
TGA data shows the decomposition of a diammonium salt to produce 1-butene

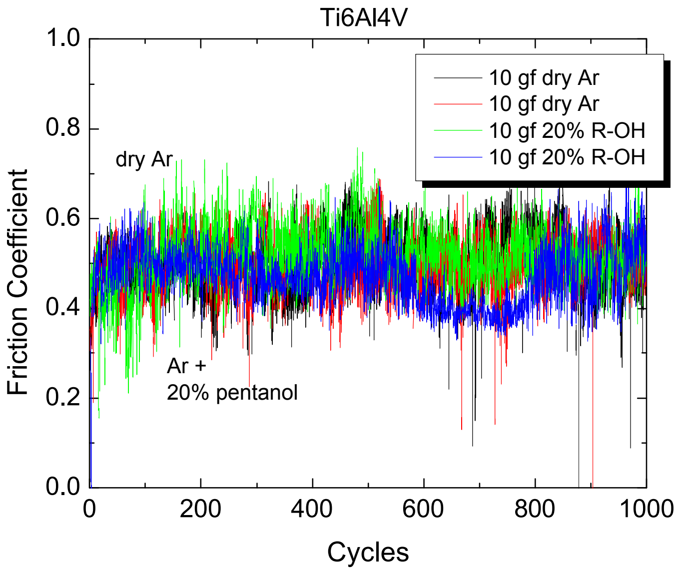
Shawn Dirk, SNL

Alcohol VPL on Other Materials









Summary

- ***Chemisorbed monolayer lubricants do not survive repeated mechanical contact in MEMS***
- ***Vapor phase lubrication can eliminate wear in MEMS contacts via continuous surface passivation***
  - **pentanol vapor reduces friction and results in non-measurable wear**
  - **ability to replenish lubricant film from the vapor phase**
- ***Vapor Phase Lubrication is applicable to a wide range of materials, dependent upon adsorption isotherm and surface chemistry***
- ***In-situ generation and multi-component vapors can increase allowable operating temperature range***
- ***Reliable MEMS devices with rubbing surfaces are now feasible***

Collaborators

Former Students

- David Asay
  - S. Kim at Pennsylvania State U. (Chem. E.)
- D. Adam Hook
  - J. Krim at North Carolina State U. (Physics)
- Dan Dickrell
  - W.G. Sawyer at U. of Florida (Mech. E.)
- Shannon Timpe
  - K. Komvopoulos at U. of California, Berkeley (Mech. E.)
- Daan Hein Alsem
  - R. Ritchie, U. of California, Berkeley (Materials)

Sandia Coworkers

- Tony Ohlhausen (Materials Science)
- Danelle Tanner and David Luck (Reliability Physics)
- Ernie Garcia and Marc Polosky (Electromechanical Component Design)