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Mitigation of Wear-Induced Failure of Microsystems by Vapor Phase Lubrication

Michael T. Dugger

Materials Science and Engineering
Sandia National Laboratories
mtdugge@sandia.gov

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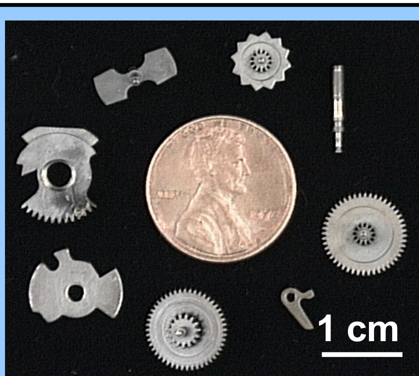
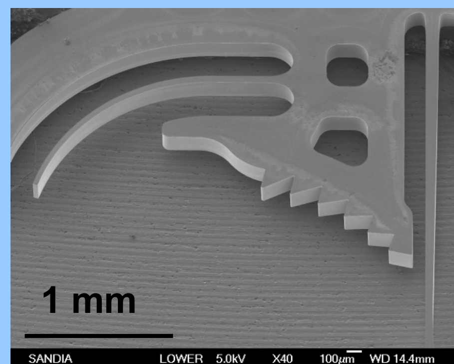
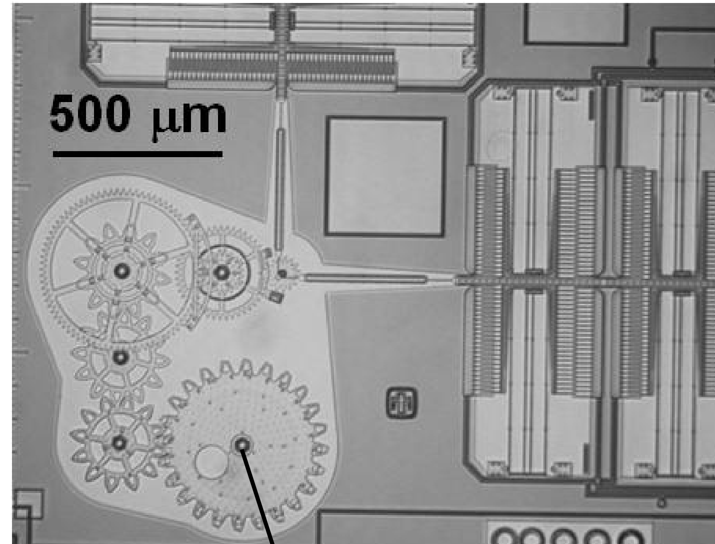
Solid Lubrication Becomes Increasingly Challenging As Component Dimensions Shrink

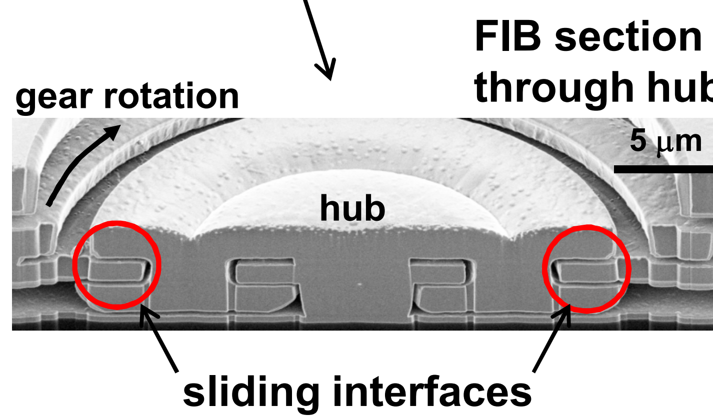


MoS_2-lubricated machine parts



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.

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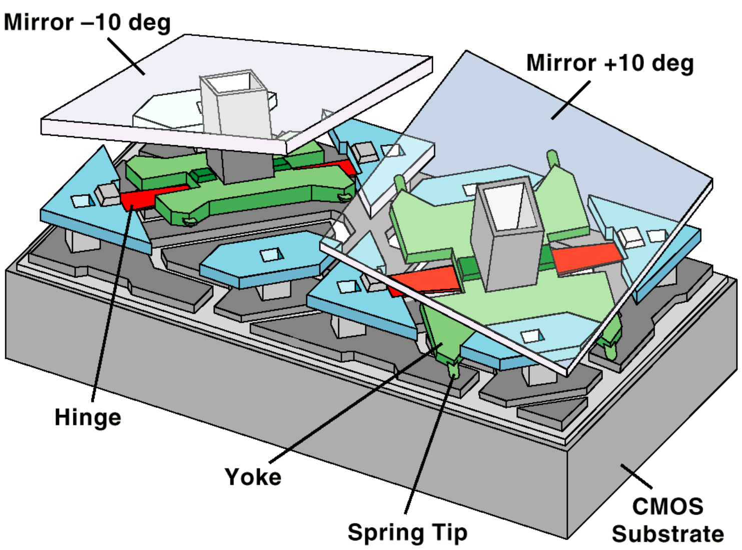
Texas Instruments' Digital Micromirror Array - A Dynamic Contact Success Story



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

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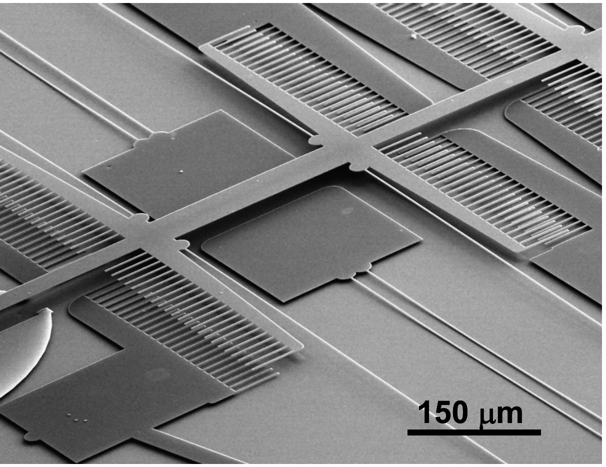
Material Changes to Mitigate Adhesion, Friction and Wear in MEMS Have Met With Limited Success

t:aC comb drive,
T.A. Friedmann, Sandia



Diamond-bonded Amorphous Carbon Films

- although net residual stress can be relaxed to zero, gradients remain
- upon release, compliant structures curl–not functional

Small Structures from Nanocrystalline Diamond

- resonators
- AFM tips

SiC Structural Layers

- high temperature CVD required
- etch in KOH > 600°C, or O_2/CHF_3 plasmas; selectivity only ~5:1

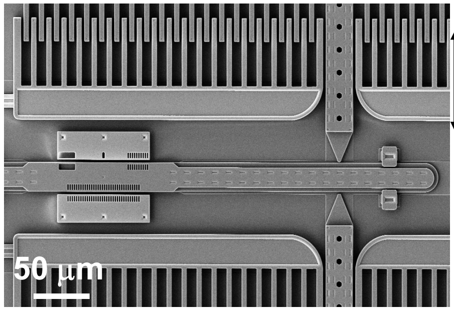
M. Mehregany et. al, Proc. IEEE 86 (1998) p. 1594

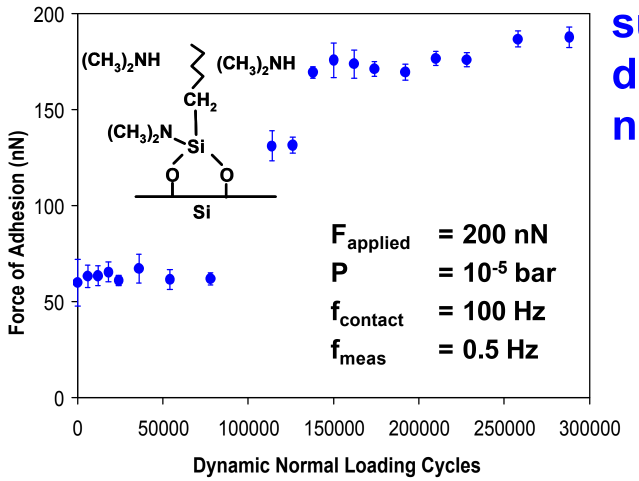
Conformal SiC Thin Films on Si

- CVD deposition using 1,3-disilabutane
- growth at 650º to 800ºC
- adhesion still a potential issue

W.R. Ashurst et. al, Tribology Letters 17 (2004) p. 195-198

Our Best Chemisorbed SAM Films Do Not Survive Mechanical Contact

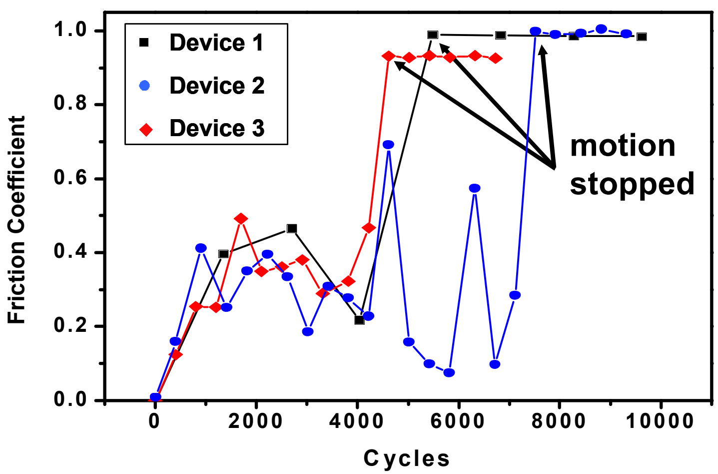




surface treatments are damaged easily, in normal contact alone

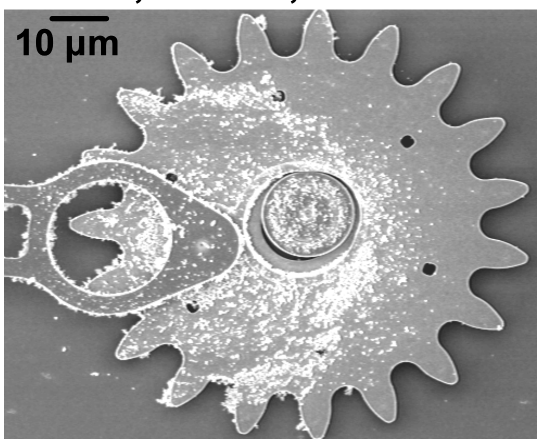
D.A. Hook, S.J. Timpe, M.T. Dugger and J. Krim, *J. Appl. Phys.*, **104** (2008) p. 034303

$F_{friction} > F_{actuation}$



$F_{actuation} > F_{friction}$

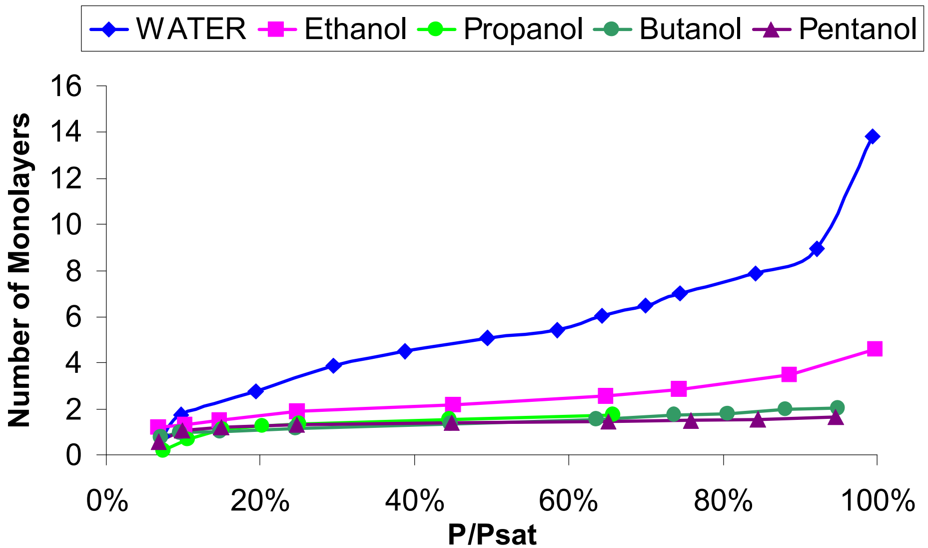
600,000 rev, 1.8% RH



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

Alcohols Reduce Adhesion Between Silicon Surfaces

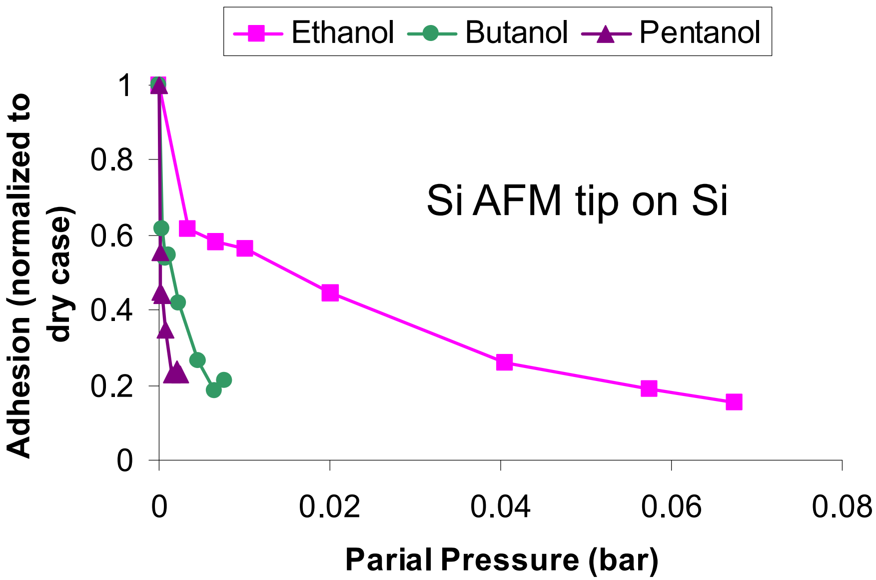
K. Strawhecker, D.B. Asay, J. McKinney and S.H. Kim, *Trib. Lett.* **19** (2005) p.17-21



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/cm^2)	V (cm^3/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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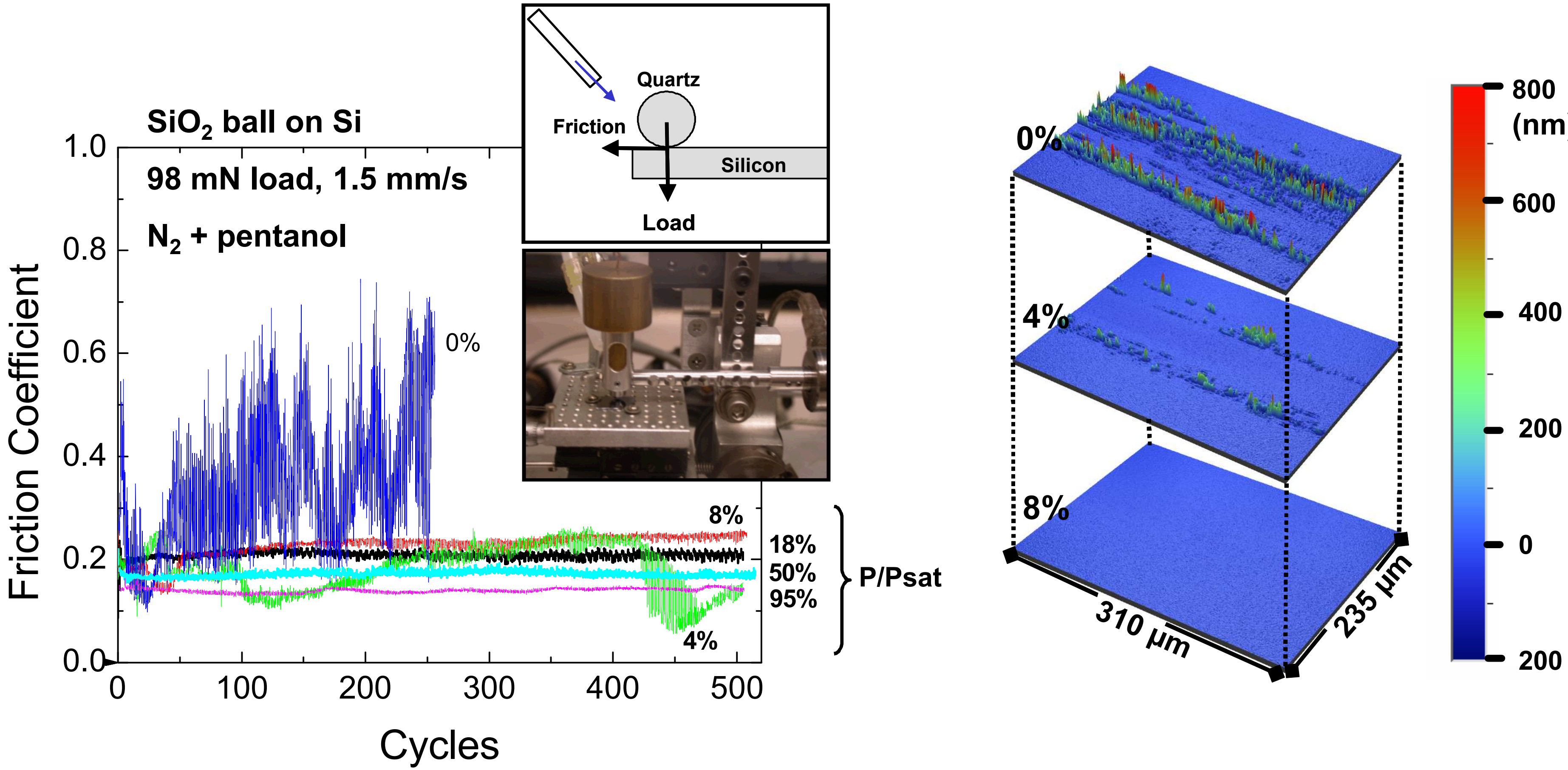
Vapor Phase Lubrication of Silicon Reduces Friction in Macroscale Sliding

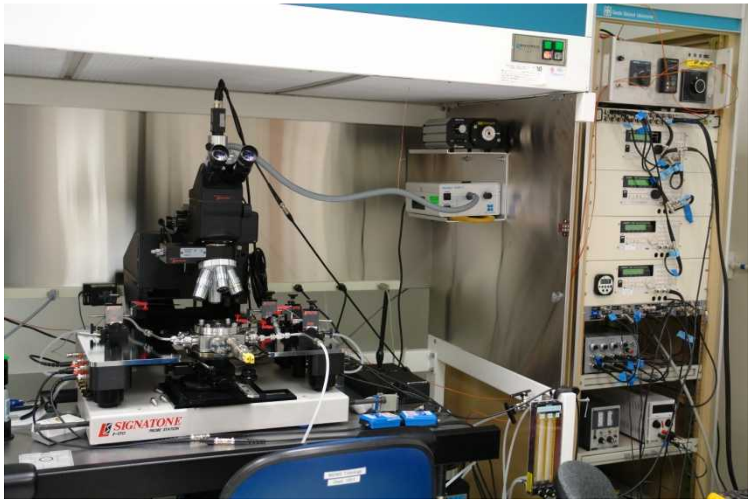


No measurable wear for $P/P_{sat} \geq 8\%$

- **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.

MEMS Device Testing in Controlled Environments

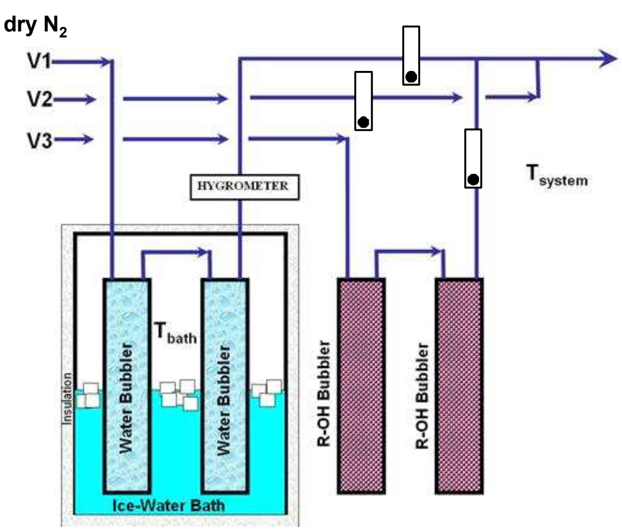


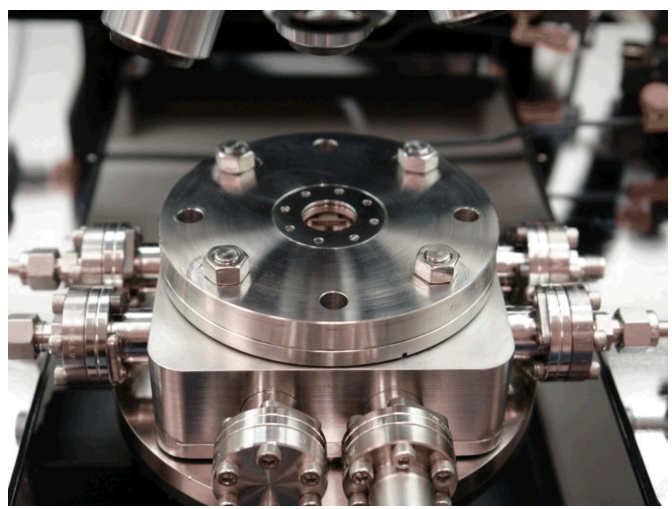
Probe Station and Drive Electronics

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 $F_d = k\Delta x$

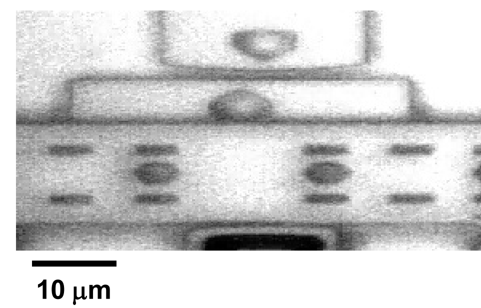




MEMS Environmental Test Chamber

Timed Image Capture

Displacement vs Input (V)



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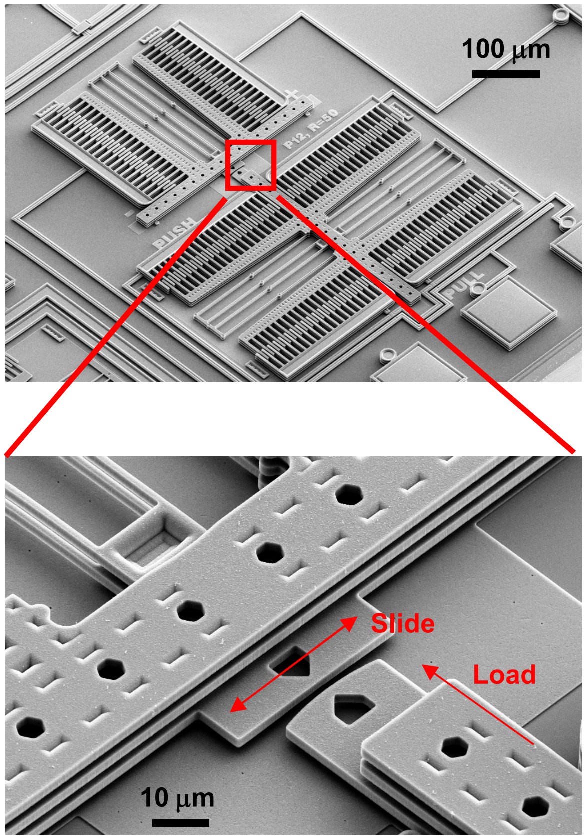
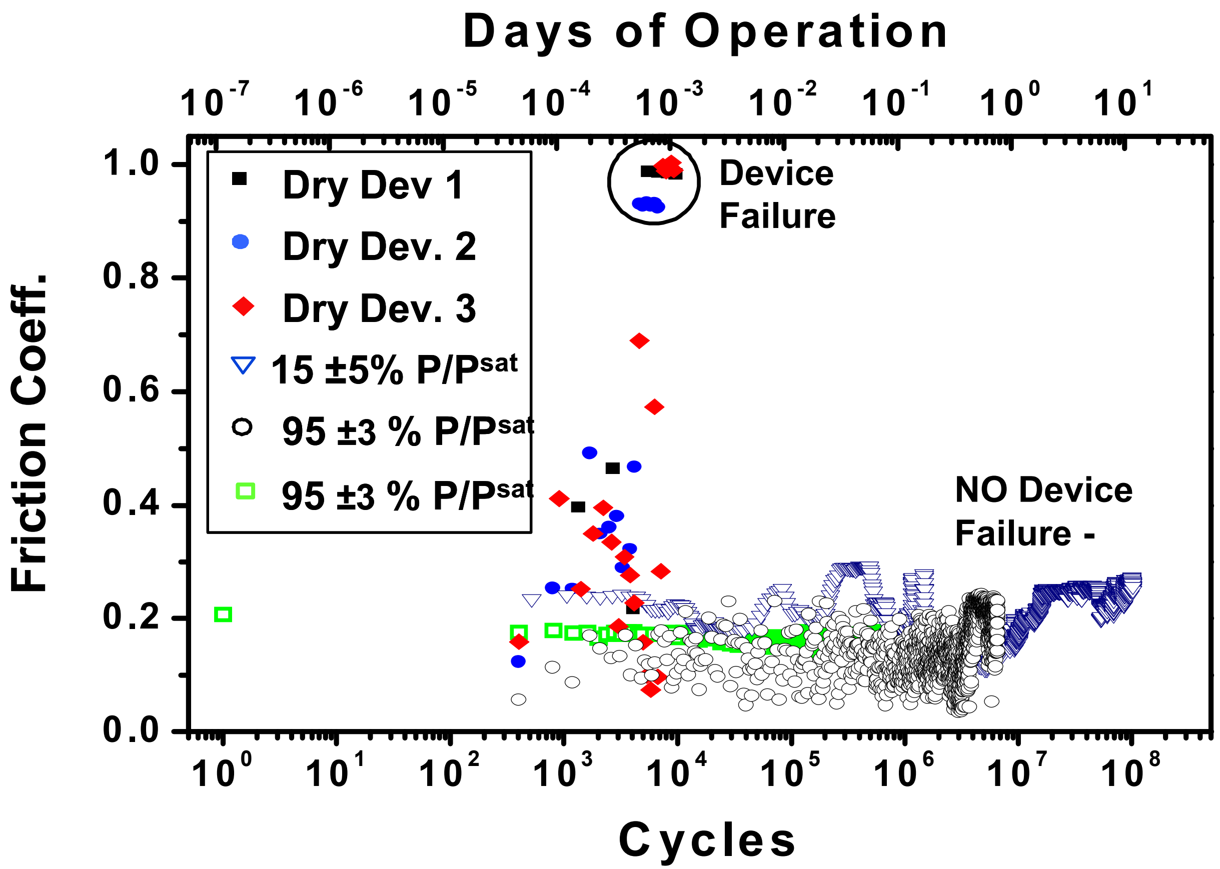
Unprecedented Operating Life of MEMS Tribometers is Observed with VPL

MEMS tribometer

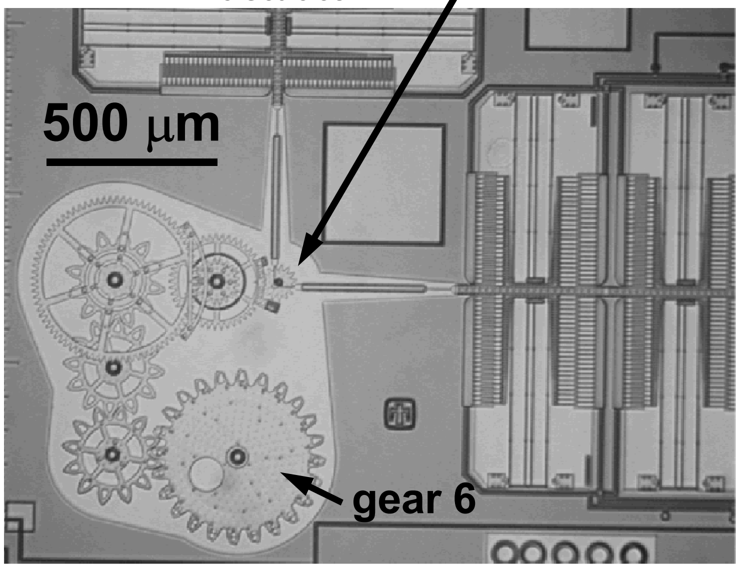




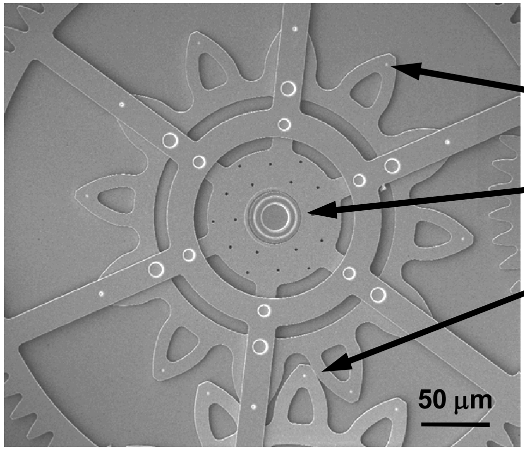
- operate < 10^4 cycles with CF_3 monolayers
- <u>***no failure***</u> in > 10^8 cycles with alcohol vapor

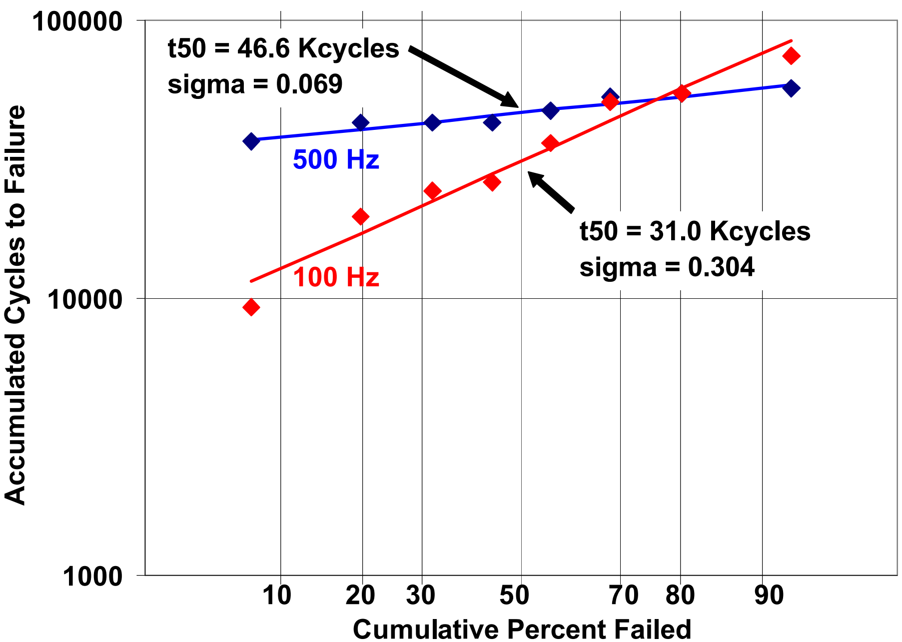
D.B. Asay, M.T. Dugger, J.A. Ohlhausen and S.H. Kim, *Trib. Lett.* **29** (2008) p. 67-74.

Increased Operating Life of Gear Train with Vapor Phase Lubrication



gear train on aging module





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

With VPL, device was stopped at $4.8\text{x}10^8$ cycles *without failure*

- 1000 ppm pentanol, <100 ppm H_2O

D. Tanner, Sandia

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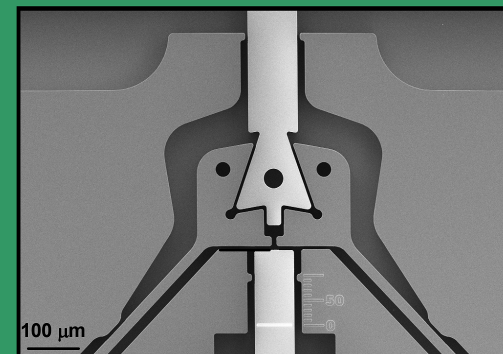
VPL is Effective on MEMS Devices with Thermal Actuators

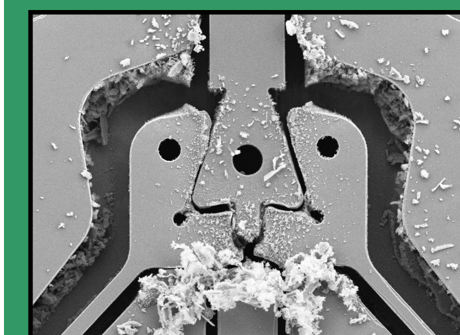
latch-unlatch motion

air

20% Psat pentanol

single crystal silicon Fiber Switch



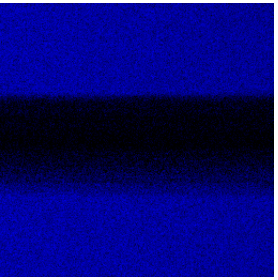


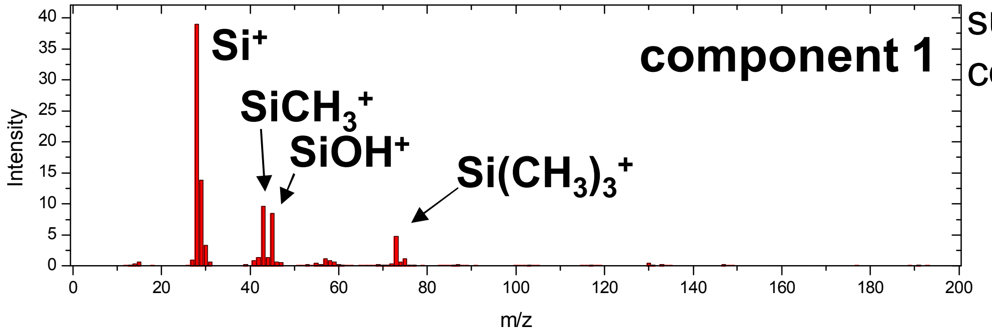
5x10^6 cycles in air

5x10^6 cycles in 20% Psat pentanol

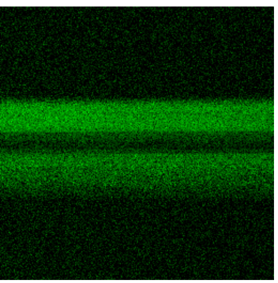
VPL with pentanol produces extraordinary operating life in a variety of MEMS devices

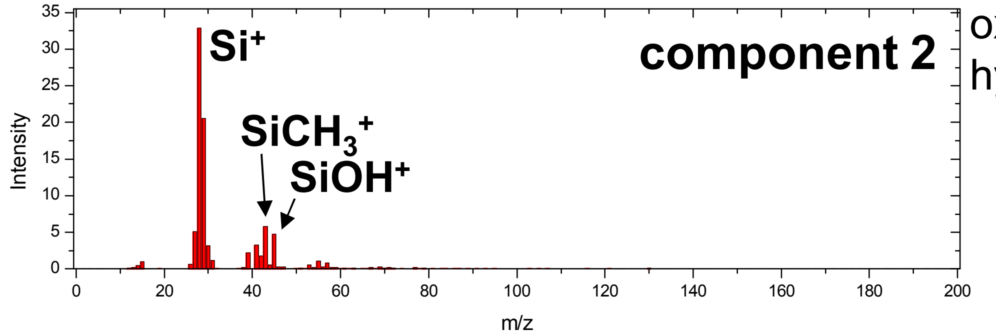
High MW Product Forms in the Contact



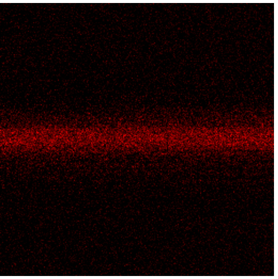


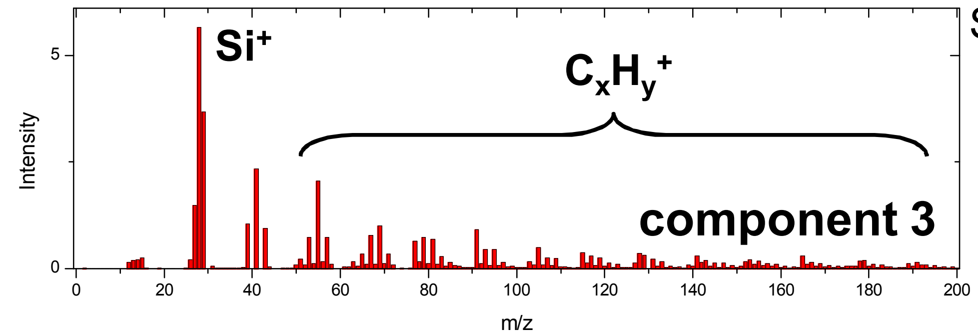
surface oxides and contaminants (silicones)





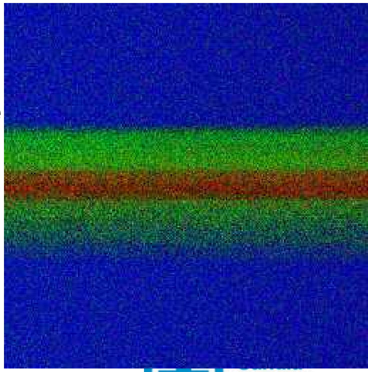
oxidized Si + short chain hydrocarbons





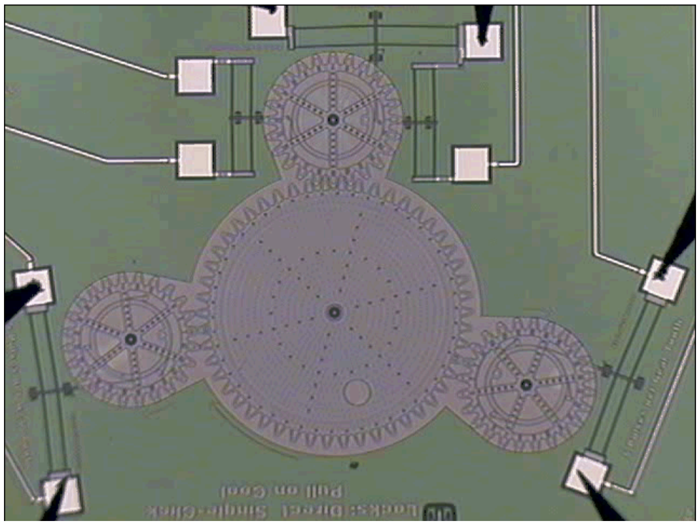
Si + long chain hydrocarbons

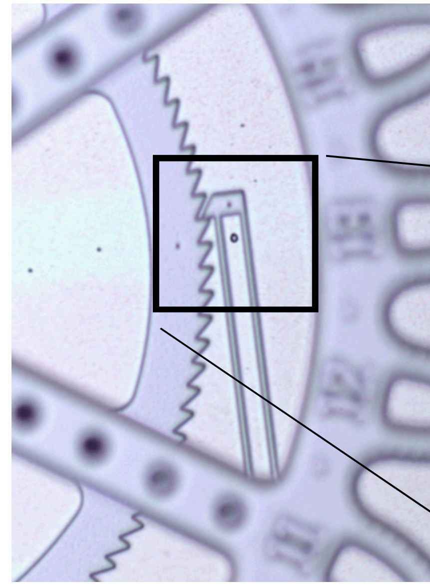
composite image



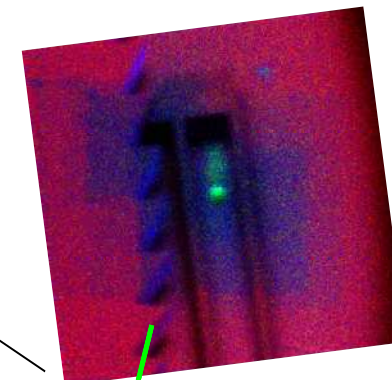
High MW Reaction Product Observed on MEMS Device

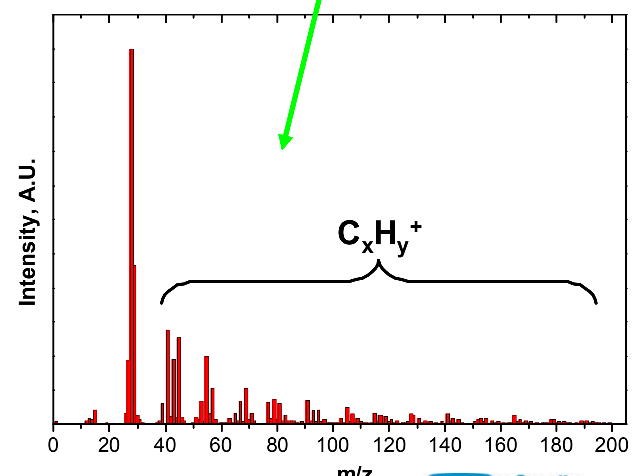
Thermally-actuated device, $5x10^8$ cycles in pentanol at P/P_{sat}=0.2, *without failure* (fails at $5x10^5$ in air)

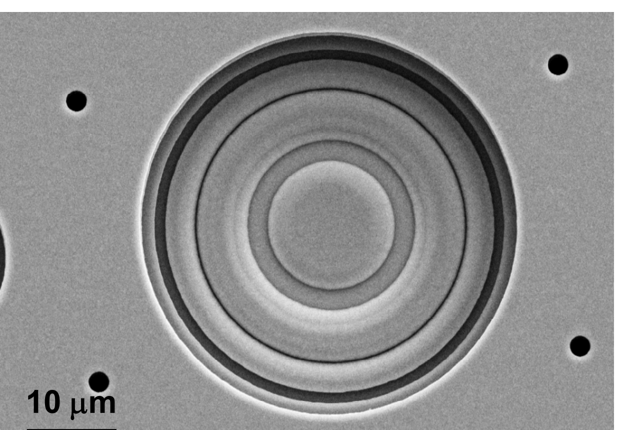


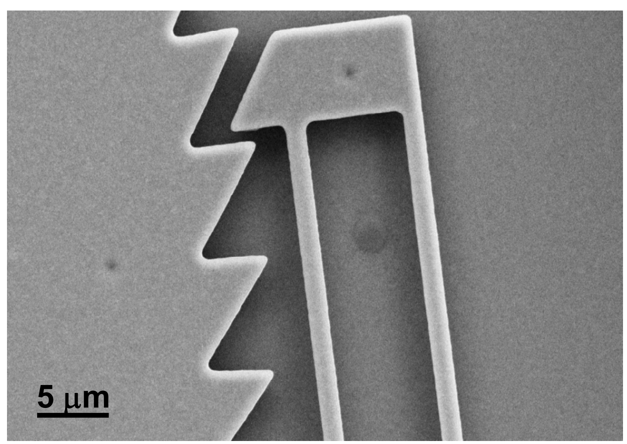


ToF-SIMS spectral imaging



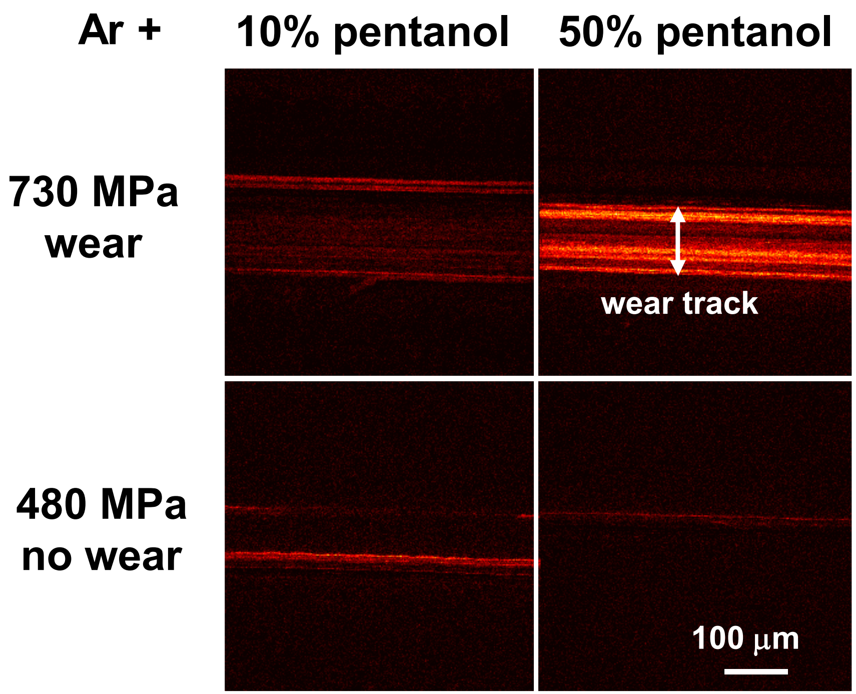






no evidence of wear, but deposit at dimple contact

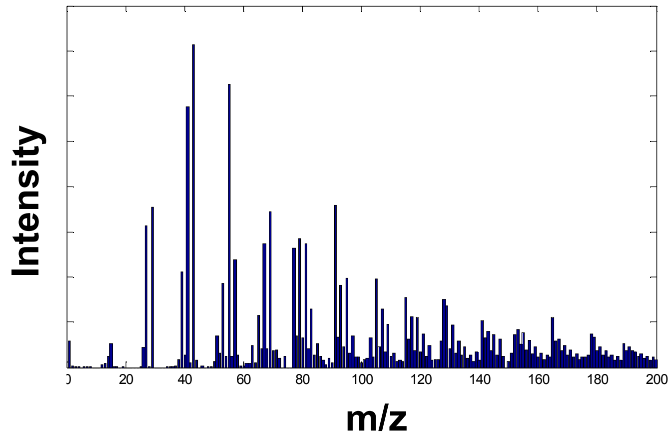
Polymerization Not Required for Wear Prevention



ToF-SIMS with AXIA reaction product spatial maps

Reaction product accompanies surface damage

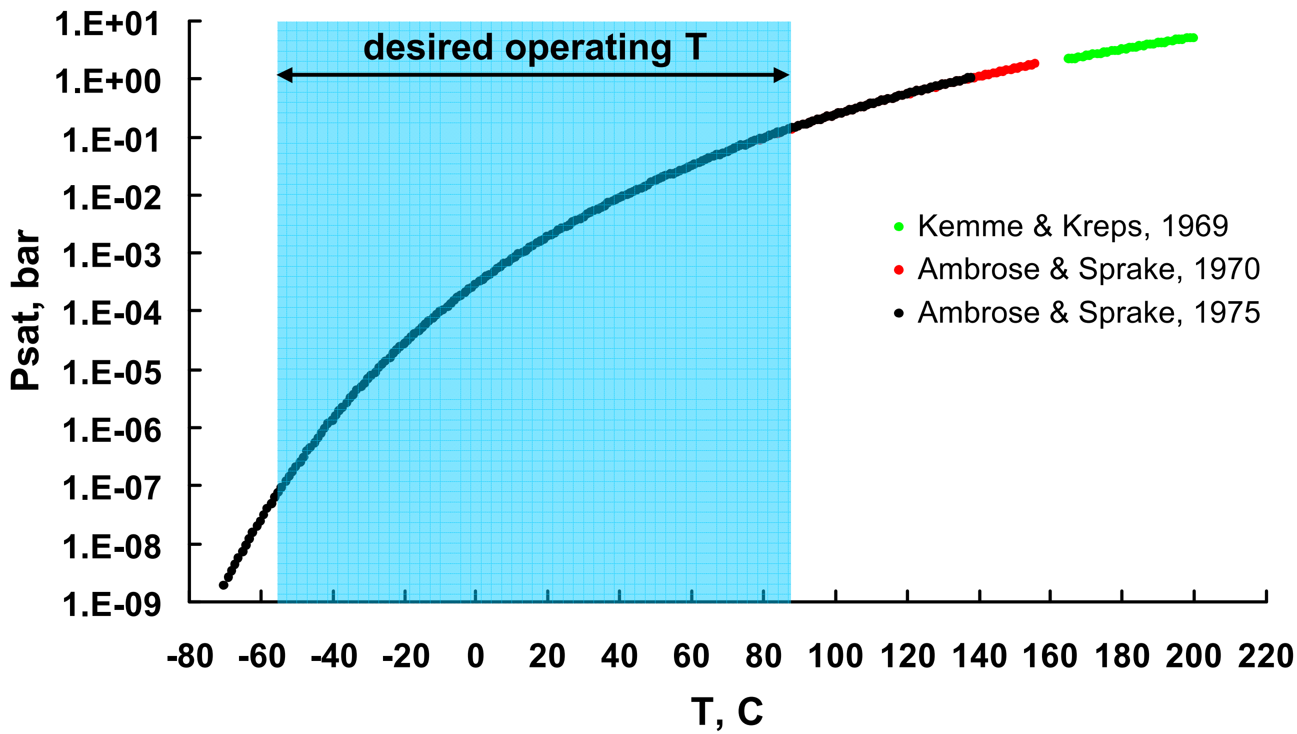
- previously, no wear for P/P_{sat} > monolayer
- higher contact pressure requires higher lubricant vapor pressure to avoid wear



reaction product fragmentation spectrum

Wearless sliding is achievable without reaction product formation

Packaging Solution Required to Enable VPL over Large Temperature Range



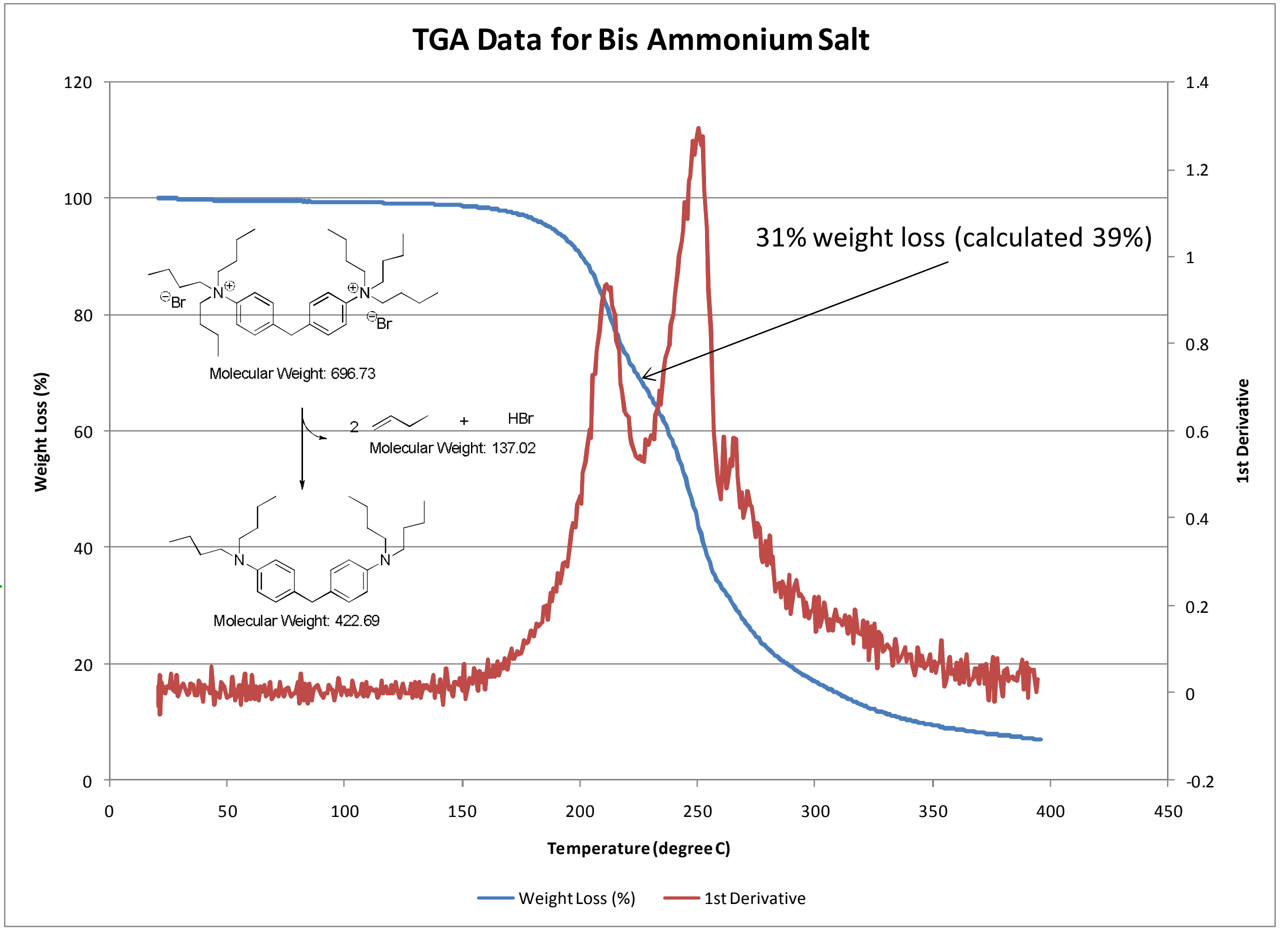
- **bound at high T by need to have monolayer coverage (P/P_{sat}~0.10)**
- **bound at low T by preventing multilayer adsorption and condensation (P/P_{sat}~0.95)**

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

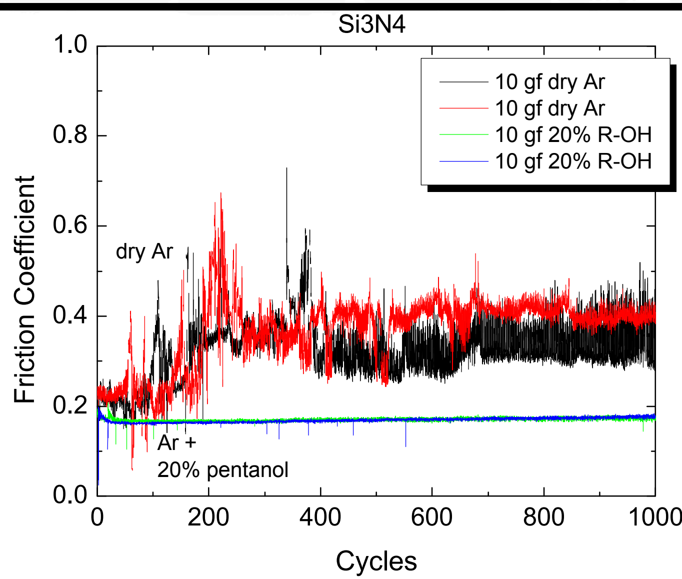


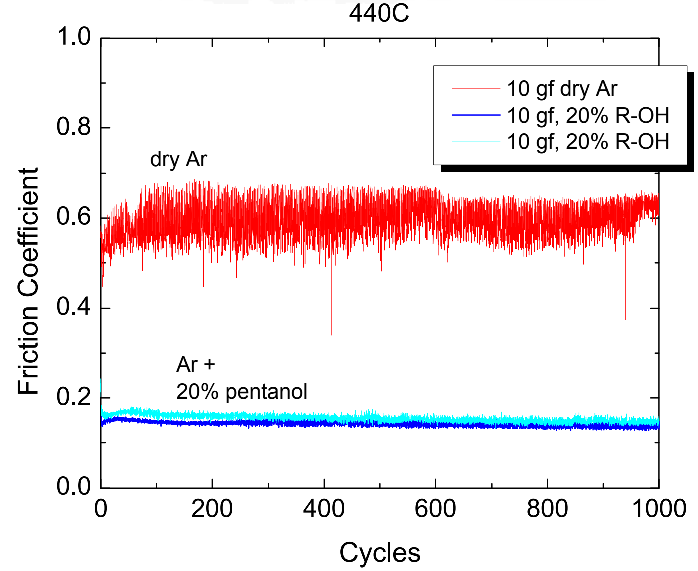
TGA data shows the decomposition of a diammonium salt to produce 1-butene

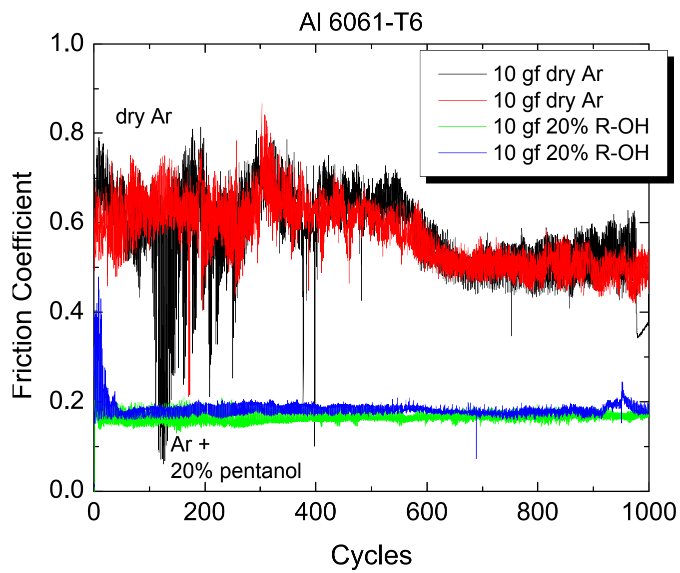
Shawn Dirk, SNL

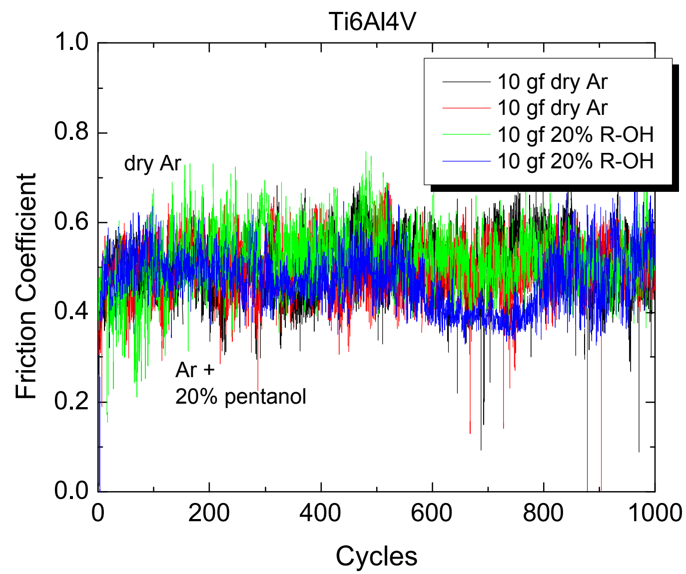
Sandia National Laboratories

Alcohol VPL on Other Materials









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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***