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Vapor Phase Lubrication of Precision Electromechanical Mechanisms

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Collaborators

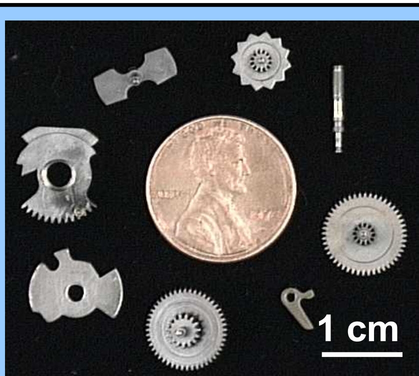
Former Students

- David Asay and Anna Barnette
  - 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)

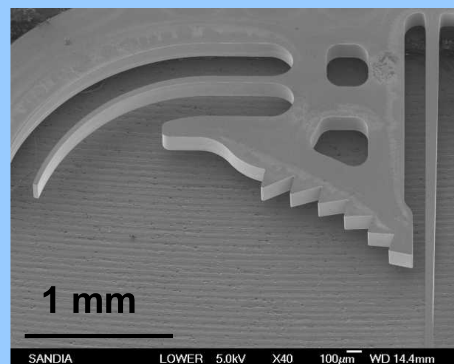
Sandia Coworkers

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

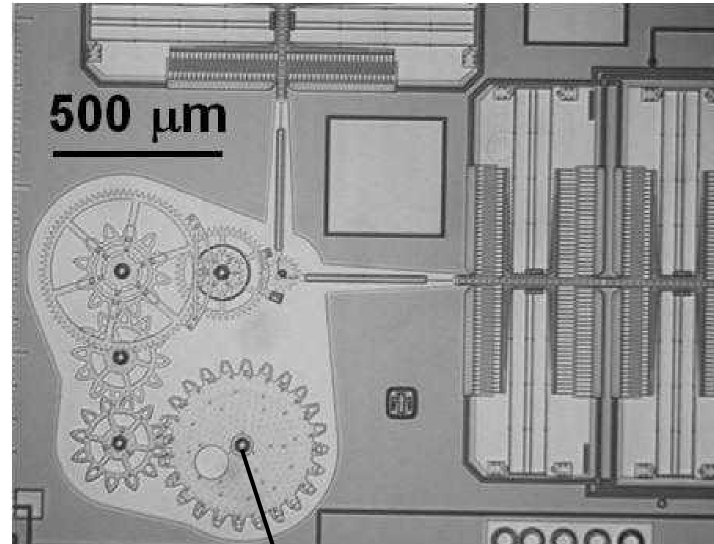
Solid Lubrication Becomes Increasingly Challenging As Component Dimensions Shrink

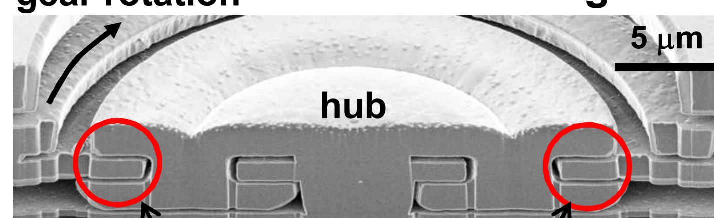


MoS_2-lubricated machine parts



new fabrication methods enable smaller metallic parts





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

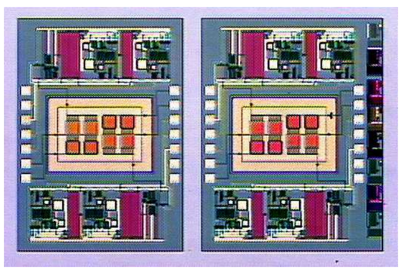
A size decreases, existing lubrication approaches are not feasible.

No robust lubrication approach exists for sliding contacts in microsystems.

Taxonomy for MEMS Devices

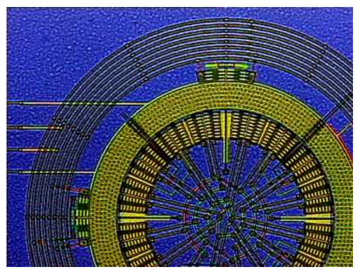
commercial success = reliability

Class I
No Moving parts



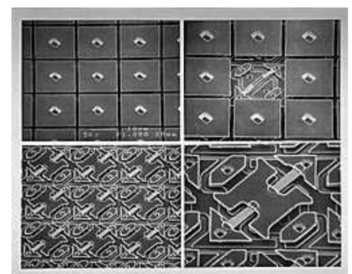
Accelerometer
Pressure Sensor
Ink Jet Print Head
Strain Gauge

Class II
Moving Parts, No Rubbing or Impacting Surfaces



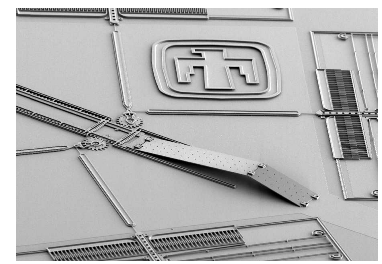
Gyro
Comb Drive
Resonator
Filter

Class III
Moving Parts, Impacting Surfaces



TI DMD
Relay
Valve
Pump

Class IV
Moving Parts, Impacting and Rubbing Surfaces



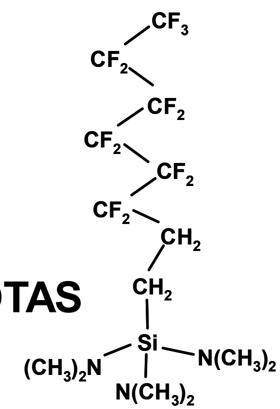
Optical Switch
Shutter
Scanner
Lock
Discriminator

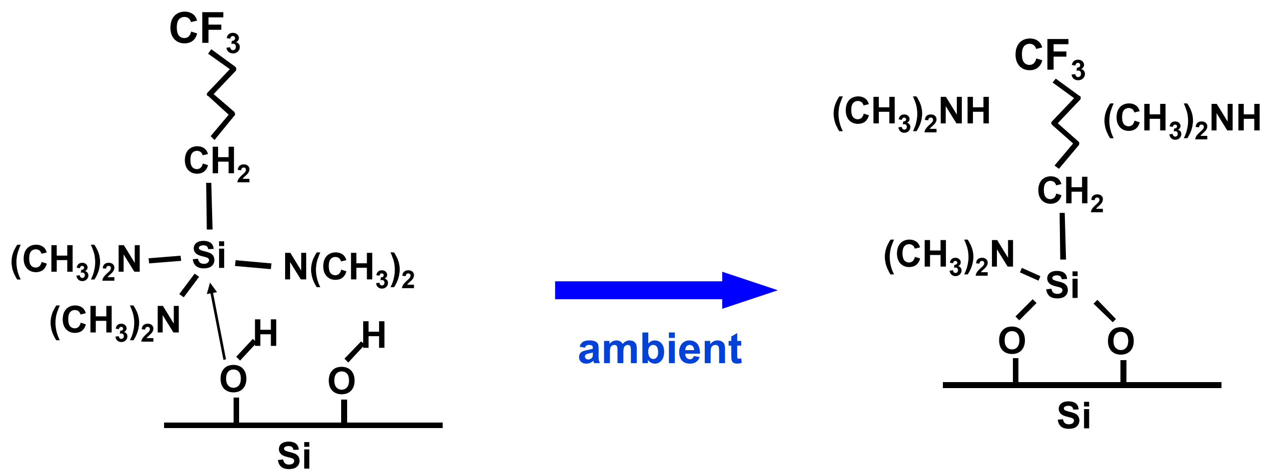
A.D. Romig, M.T. Dugger and P.J. McWhorter,
Acta Materialia ***51*** *(2003) p.5837-5866*

Chemisorbed Monolayers Reduce Adhesion and Friction in Silicon Microsystems

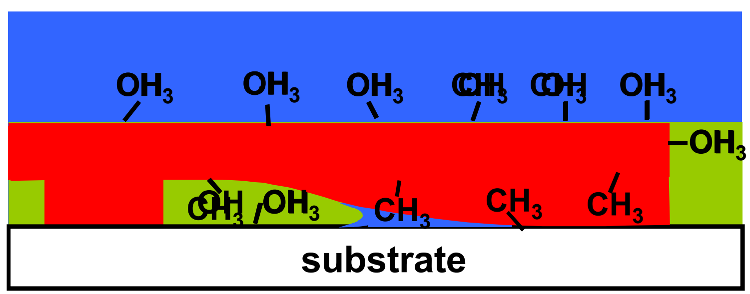
Hydrocarbon or fluorocarbon molecules attached via functional group to silicon surface

C8 FOTAS



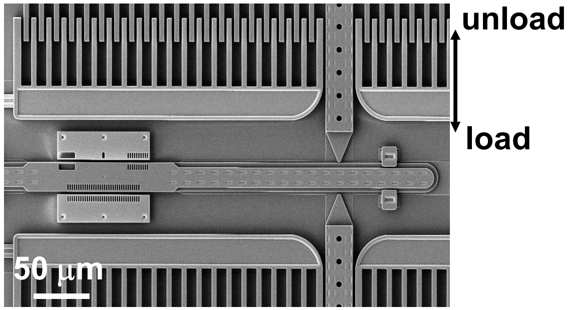


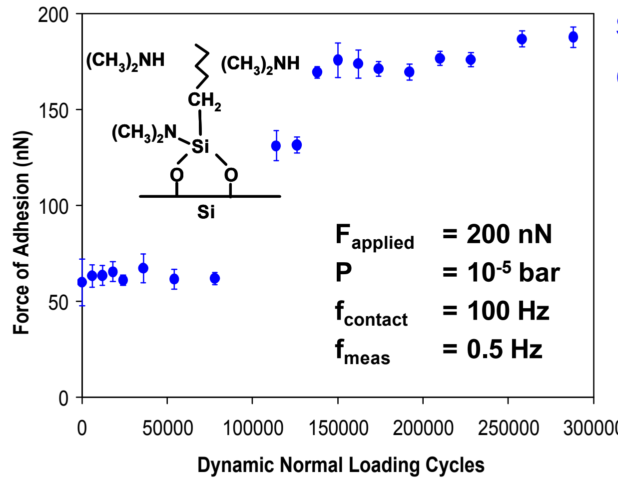
Prevent capillary formation and adhesion of compliant structures during release, or during in-use contact



initial adhesion no longer an issue with monolayer surface treatments

Our Best Chemisorbed SAM Films Do Not Survive Mechanical Contact



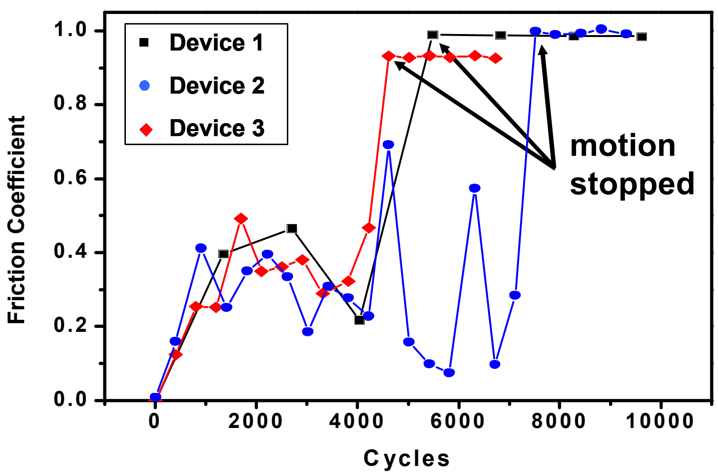


surface treatments are damaged easily, in normal contact alone

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

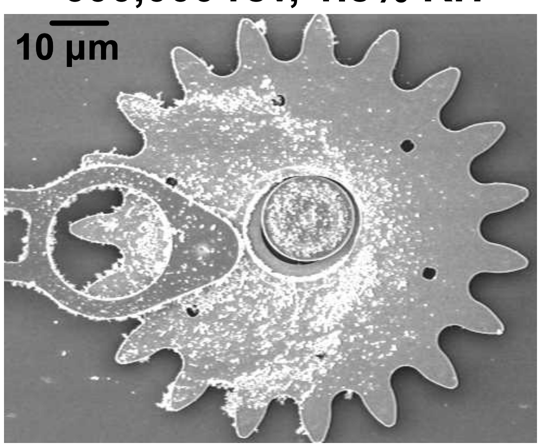
$F_{friction} > F_{actuation}$

$F_{actuation} > F_{friction}$



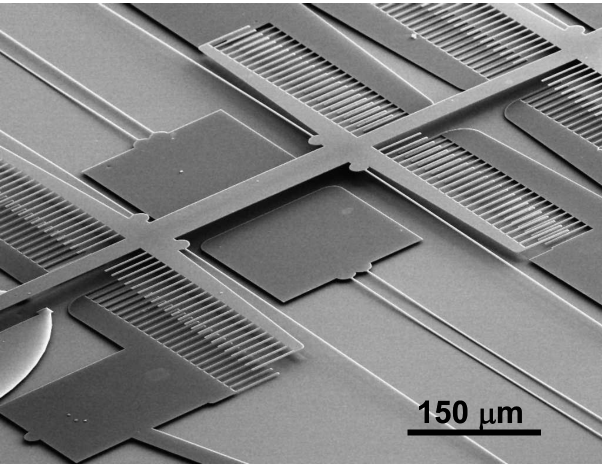
D. Tanner et. al, International Reliability Physics Symposium, 1998

600,000 rev, 1.8% RH



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

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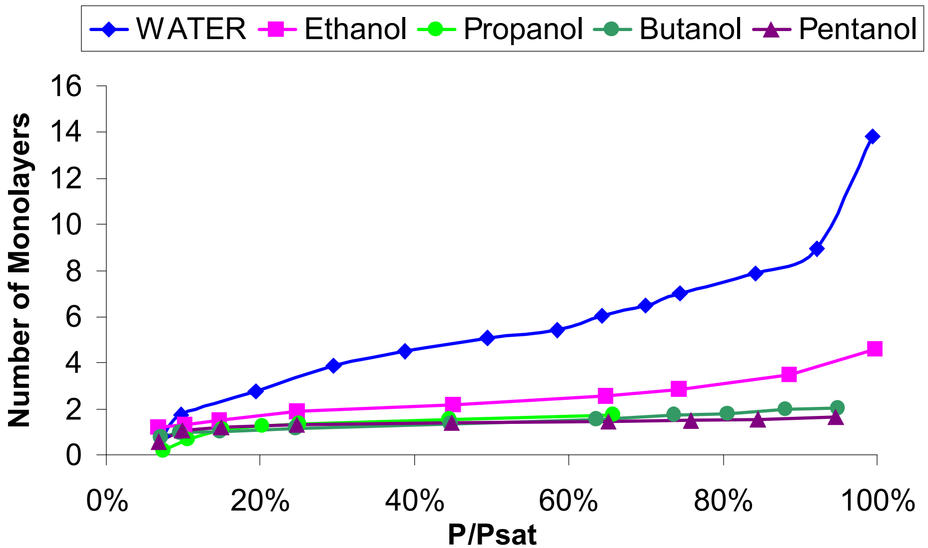
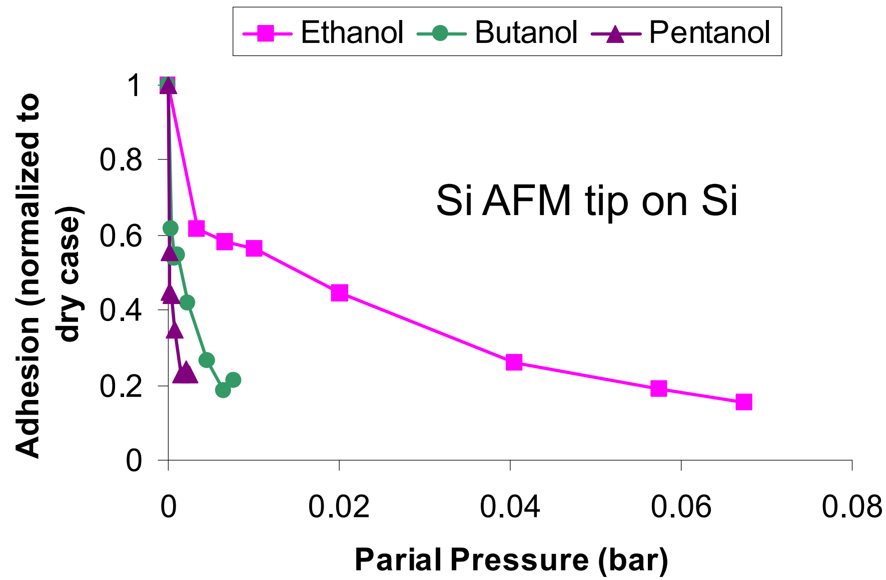
Alcohols Reduce Adhesion Between Silicon Surfaces

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



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



Adsorbed film thickness by ATR-FTIR

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

	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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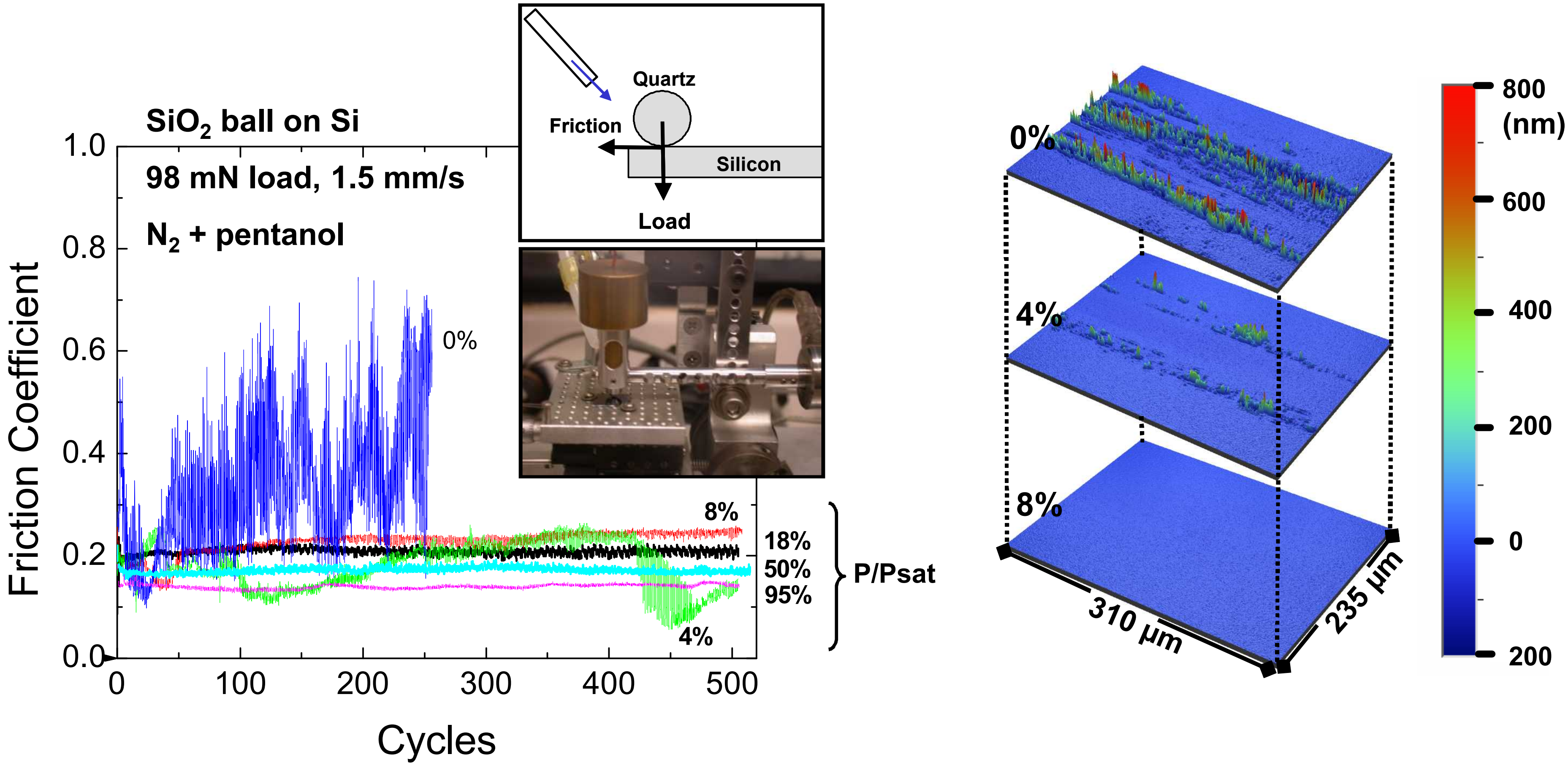
Vapor Phase Lubrication of Silicon Reduces Friction in Macroscale Sliding



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.

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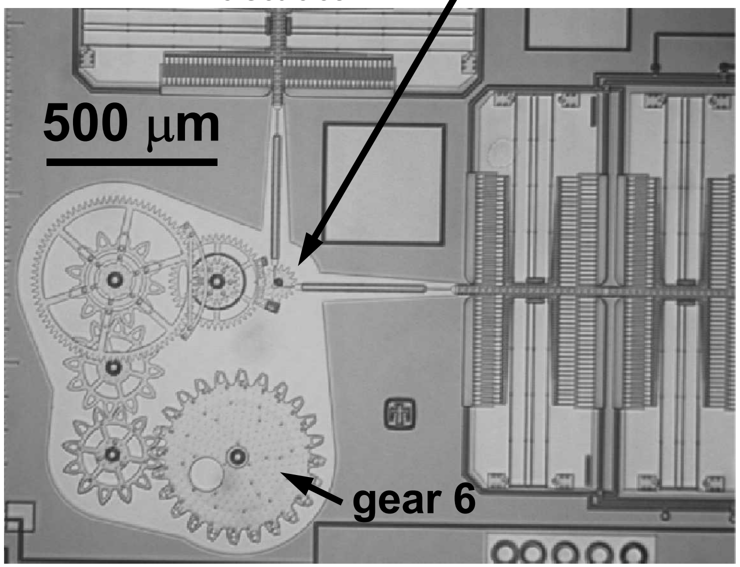
Increased Operating Life of Gear Train with Vapor Phase Lubrication

up/down actuator

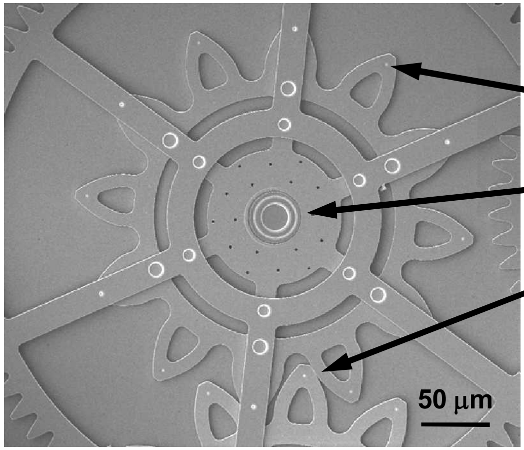
gear 1 (output gear)



left/right actuator

gear train on aging module

contacts:

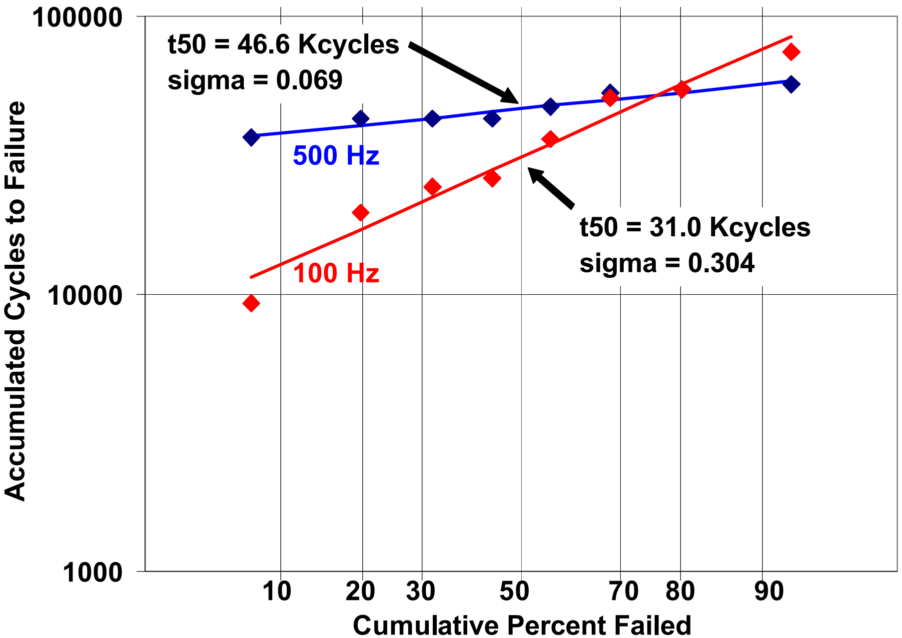


dimples

hubs

teeth

gear 3 assembly



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

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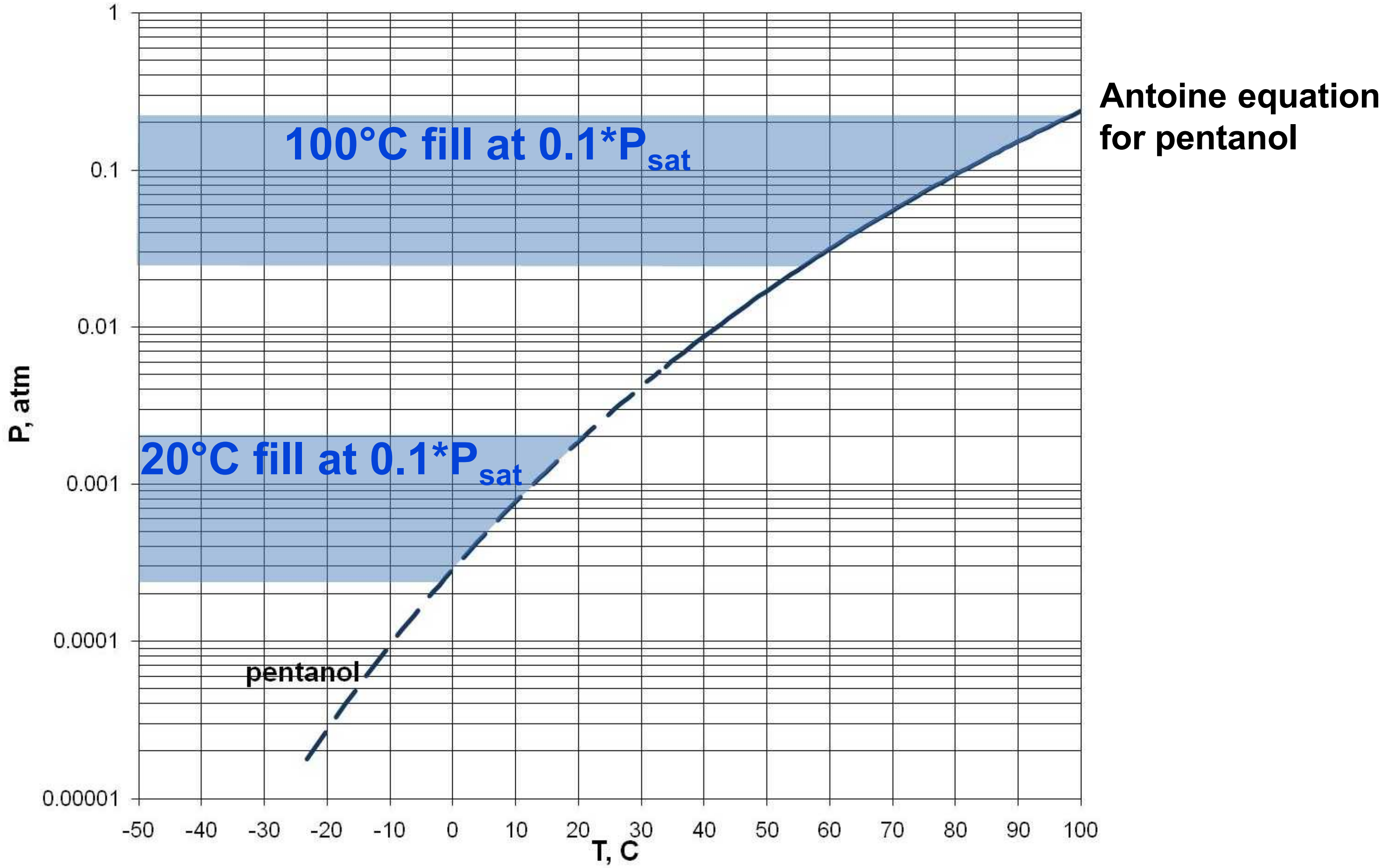
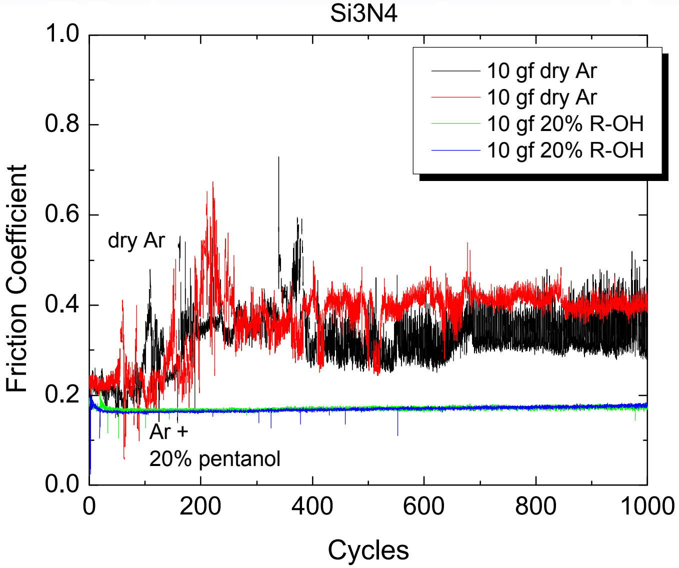
Packaging Solution Required to Enable VPL over Large Temperature Range

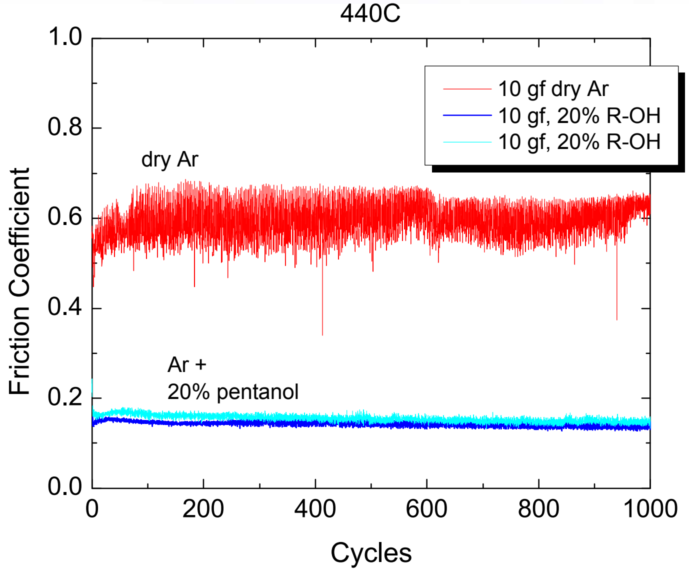


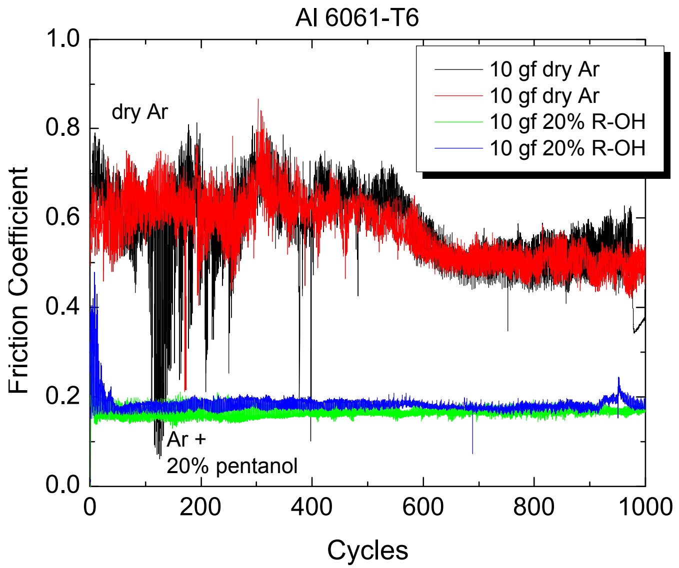
- high T: need monolayer coverage (P/P_{sat}~0.10)
- low T: prevent condensation (P/P_{sat}~0.95)

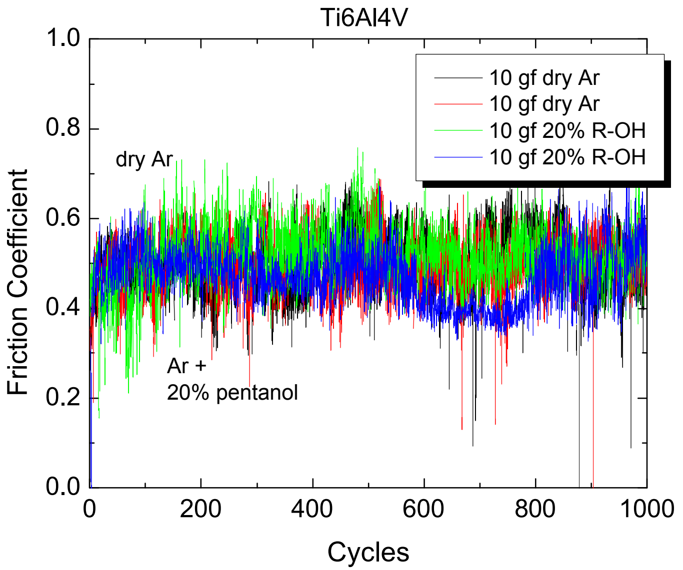
Ideal source would supply constant P/P_{sat} over desired operating temperature range

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***