SAND2008-0053C

Materials Solutions for Robust Interfaces in Microsystems

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Materials Science and Engineering Center
Sandia National Laboratories

DARPA/MTO Workshop

Materials and Technologies

for 21st Century MEMS and NEMS

8 January 2008

Miami, FL

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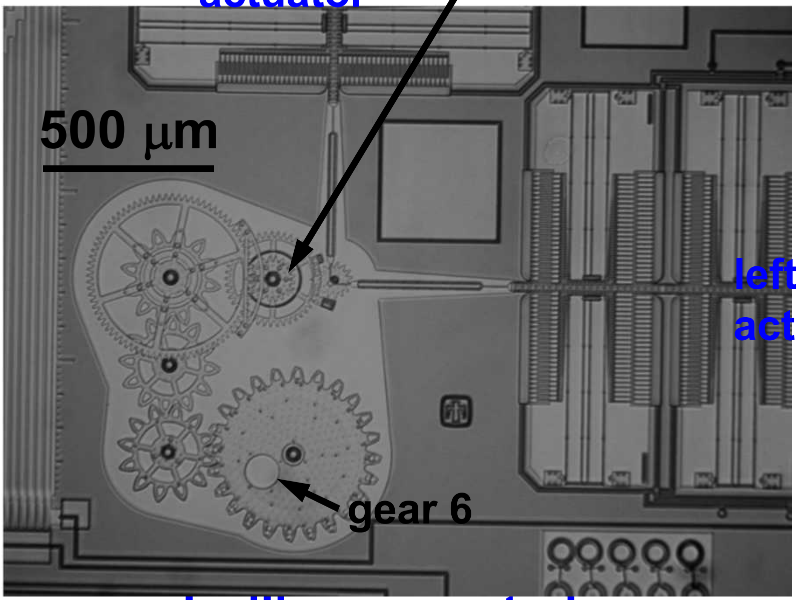
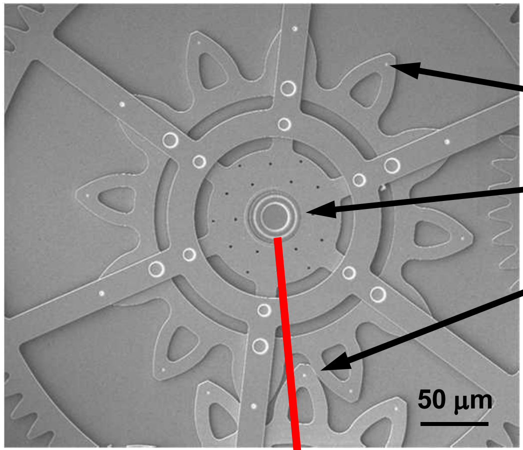
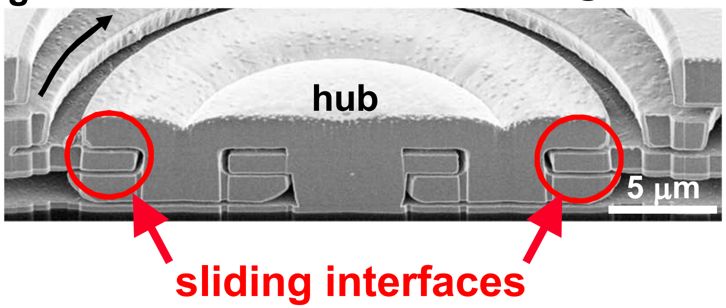
Fully-Assembled MEMS Limit Surface Treatment Options



polysilicon gear train



gear 3 assembly



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

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DARPA Group Summarized Main Issues in MEMS Reliability

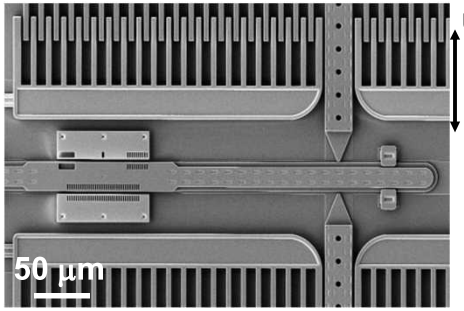
MEMS Technology Office, HERMIT Program

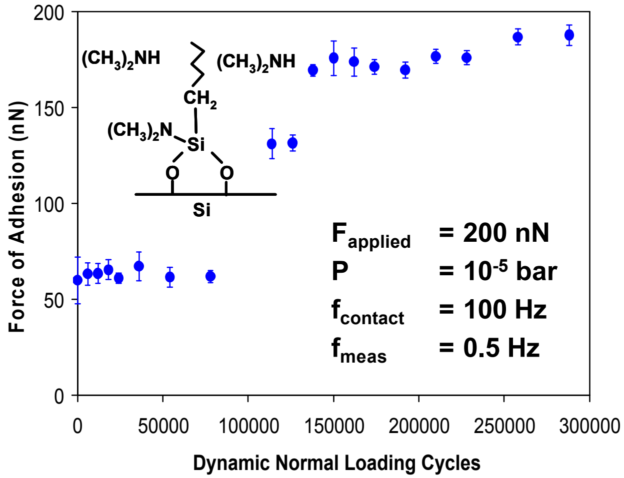
- **MEMS Industry Group (MIG) Report**
- **www.darpa.mil/mto/programs/hermit/summaries/mems.html**

Top Five Failure Modes by Device Type

Actuators	Sensors	Integrated Systems	Passive Elements
Stiction (Adhesion)	Electric Short/Open	Temperature	Contamination
Wear	Leakage	Contamination	Package Stress
Electric Short/Open	Package Stress	Clogging	Electric Short/Open
Package Stress	Contamination	Package Stress	Crack Propagation
Contamination	Crack Propagation	Leakage	Deformation

Failure Mode is a Function of MEMS Design

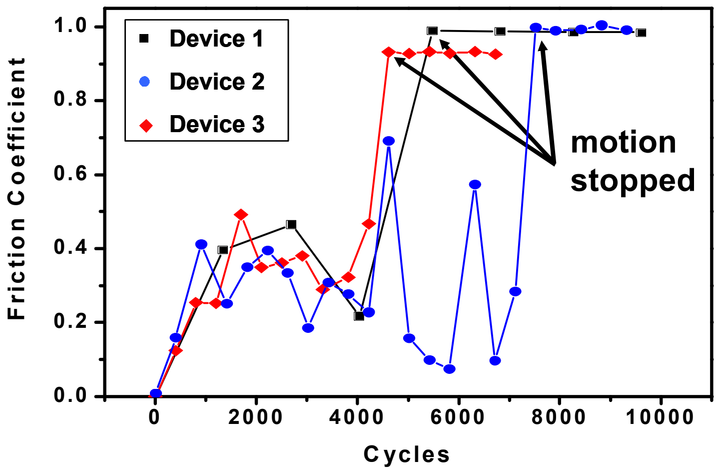




surface treatments are damaged easily, even for normal contact alone

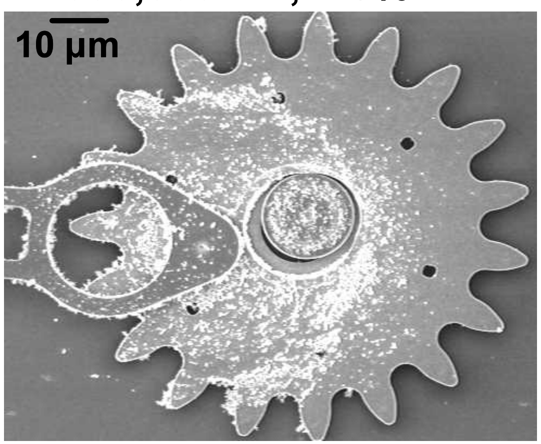
$F_{friction} > F_{actuation}$

$F_{actuation} > F_{friction}$



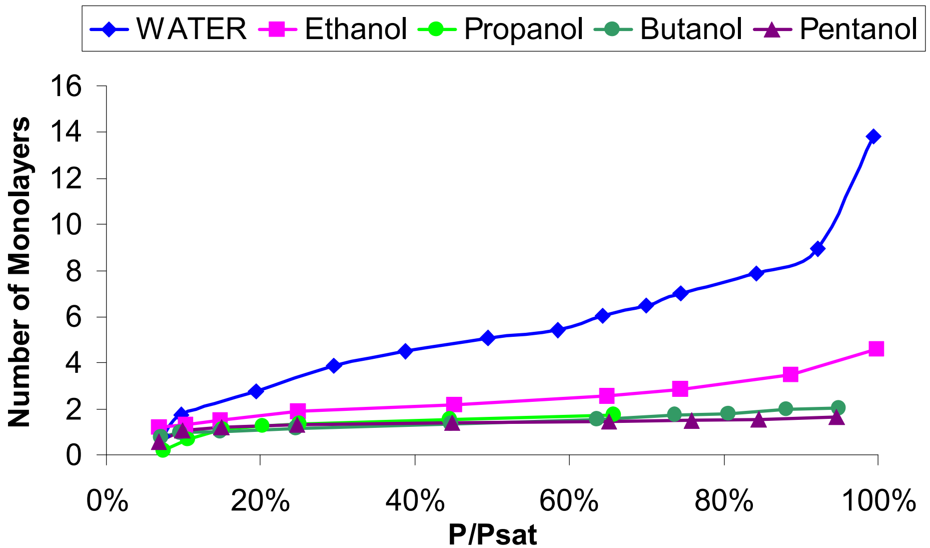
D. Tanner et. al, International Reliability Physics Symposium, 1998

600,000 rev, 1.8% RH

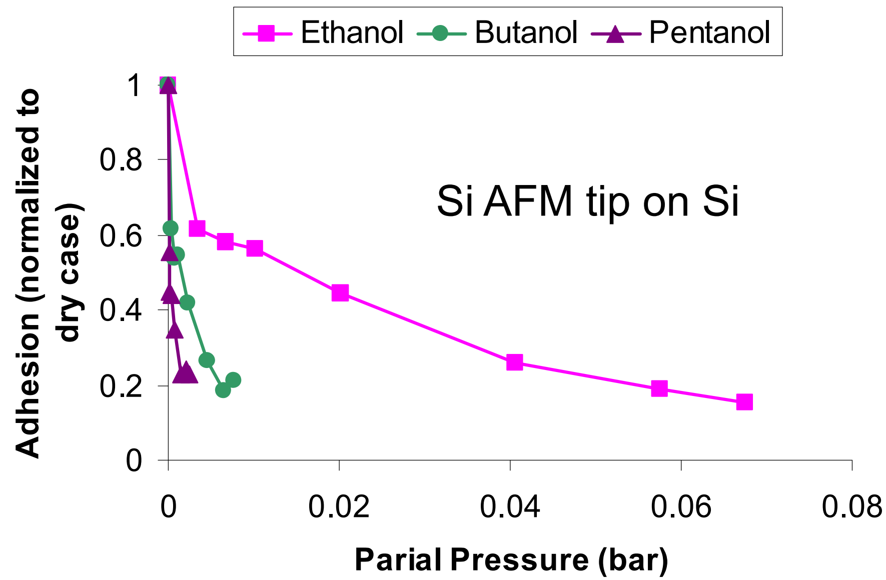


Alcohols Reduce Adhesion Between Silicon Surfaces

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



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



ATR-FTIR measurement of adsorbed film thickness

- 1-3 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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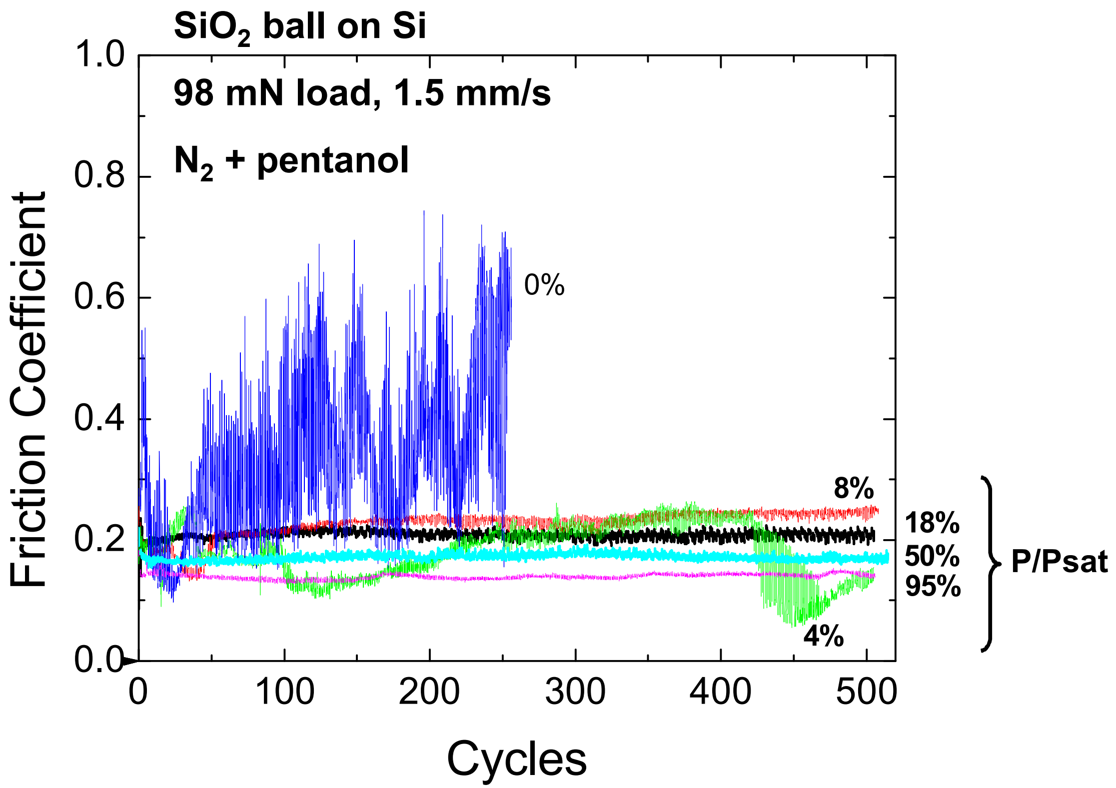
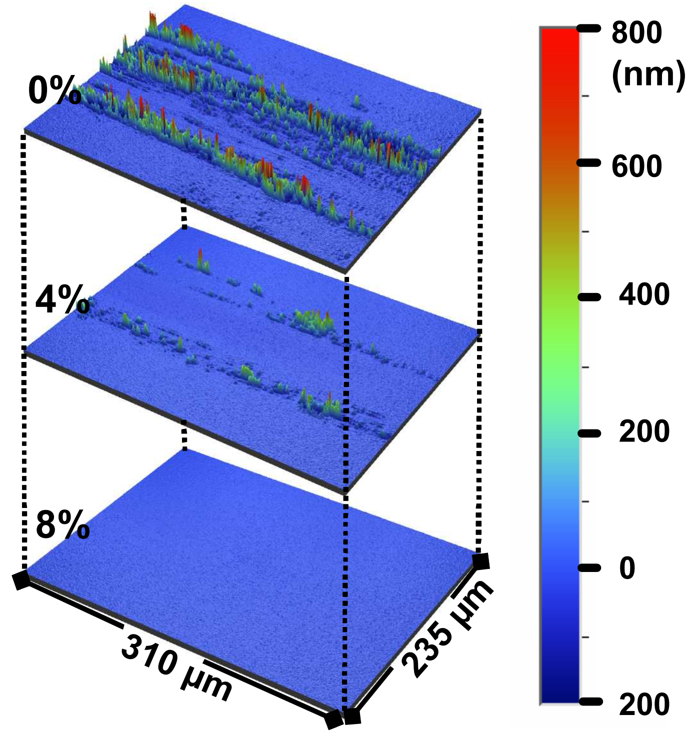
Vapor Phase Lubrication of Silicon Reduces Friction in Macroscale Sliding





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* (in press)

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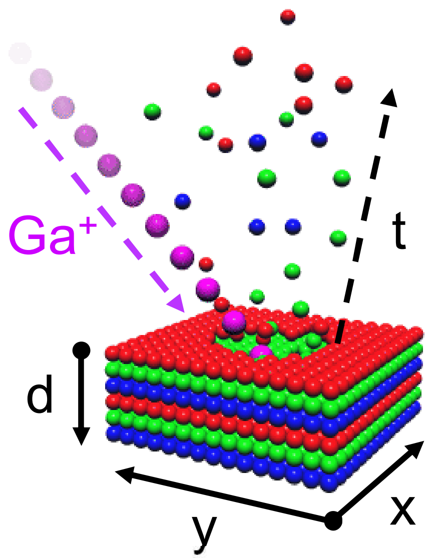
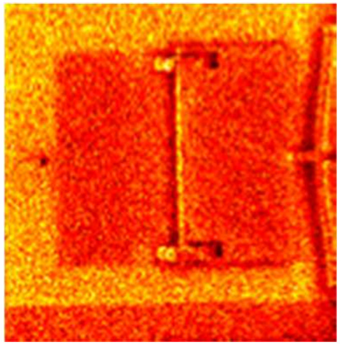
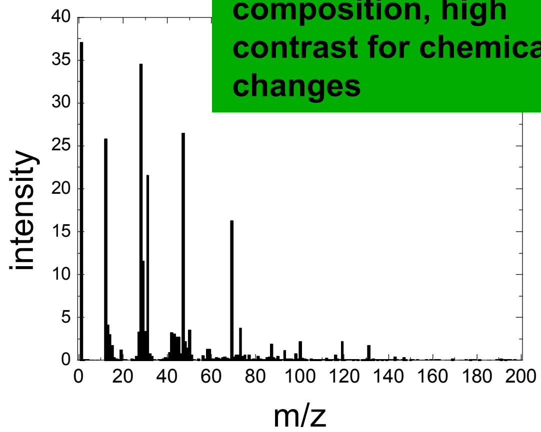
Multivariate Analysis Of SIMS Data Allows Detection of Subtle Changes In Chemistry

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

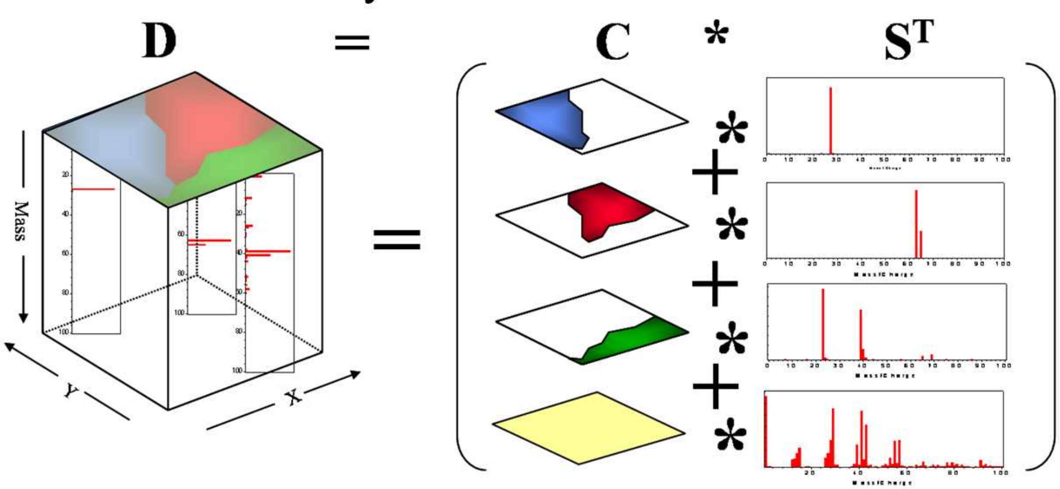
+ Automated eXpert Spectral Image Analysis (AXSIA)







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) p.2433

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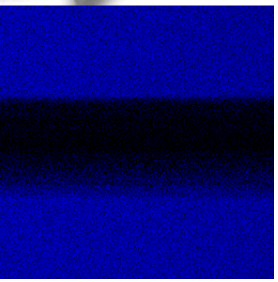
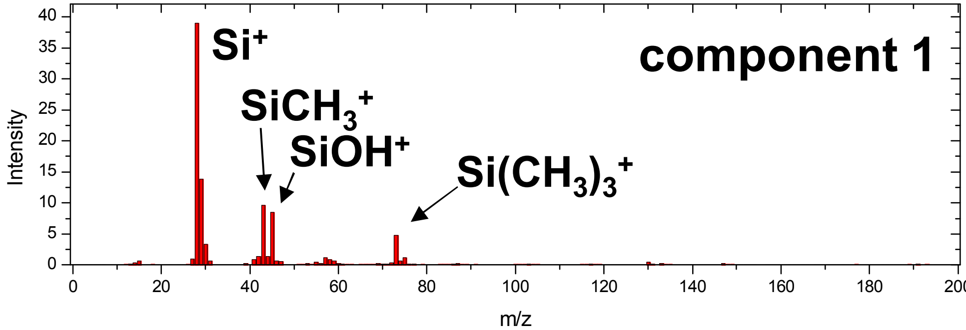
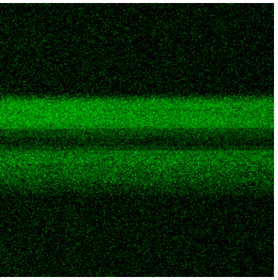
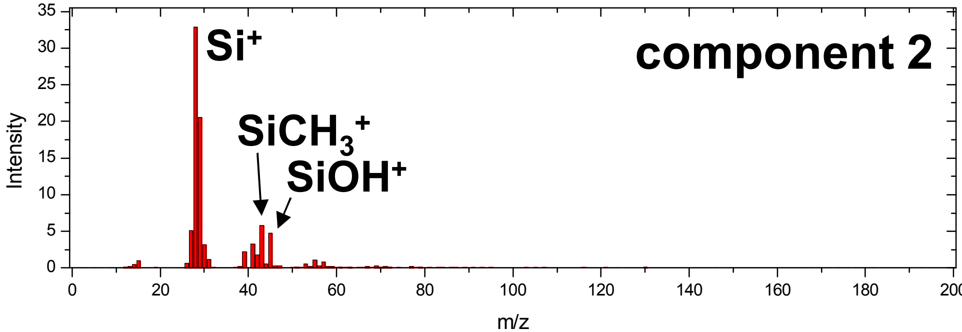
ToF-SIMS With Multivariate Analysis Shows Formation of High MW Product



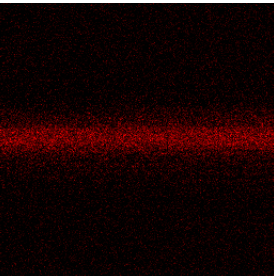


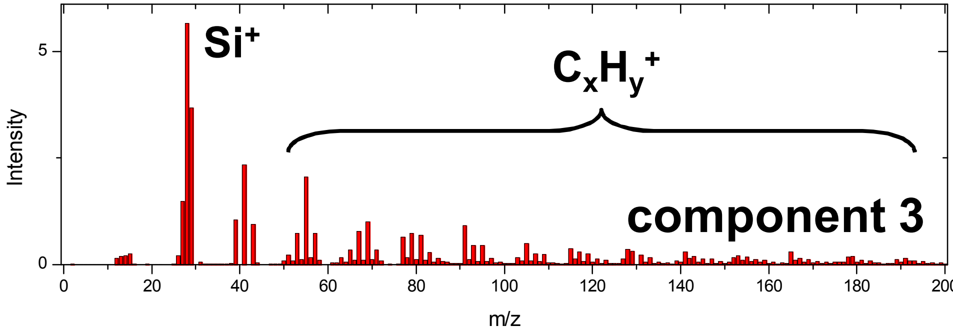
surface oxides and contaminants (silicones)





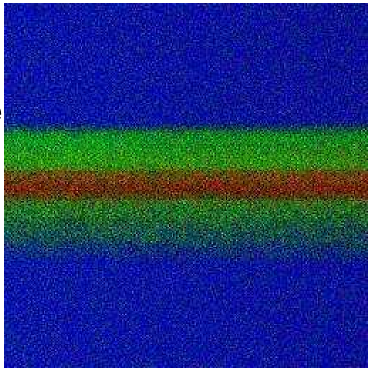
oxidized Si + short chain hydrocarbons





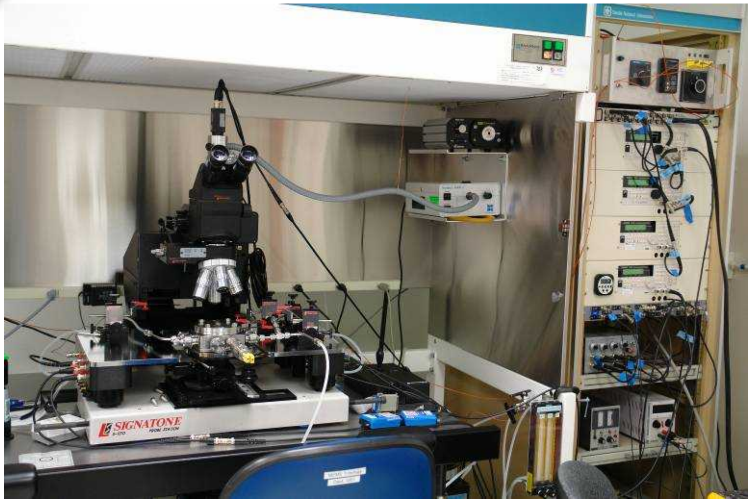
Si + long chain hydrocarbons

composite image



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

MEMS Device Testing in Controlled Environments

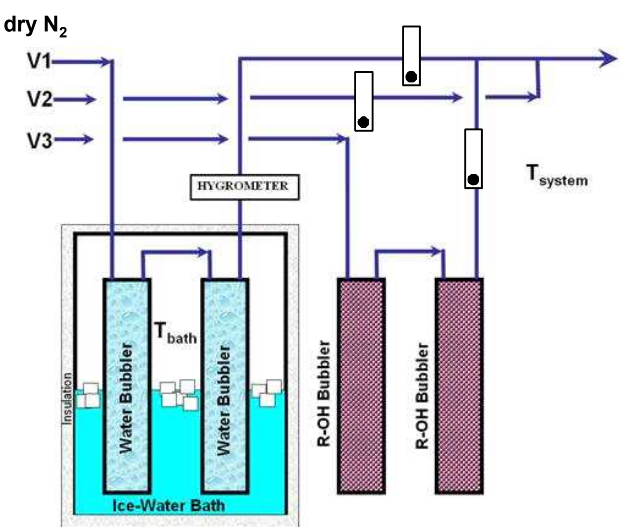


Probe Station and
Drive Electronics

Device packaged in 24-pin DIP

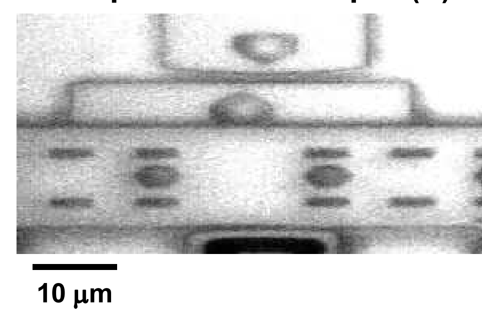
Process image data to give forces

- 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 $F_d = k\Delta x$



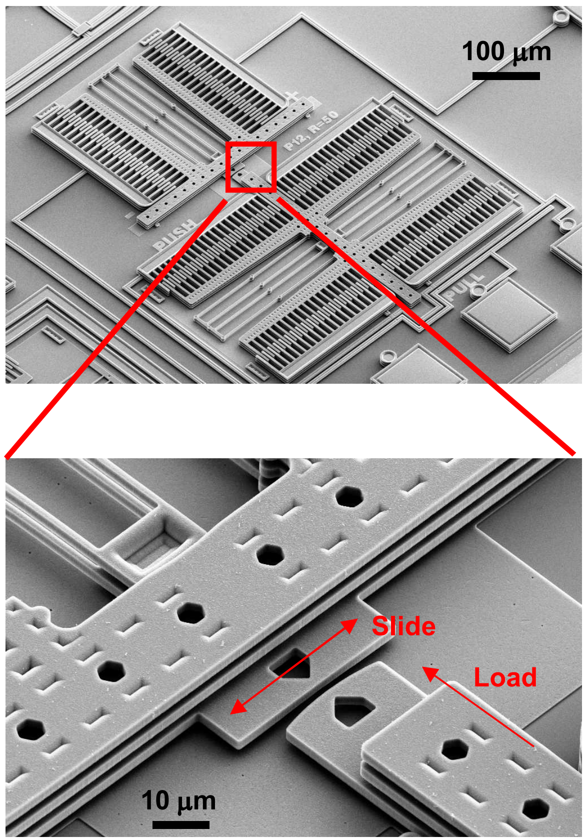
MEMS Environmental
Test Chamber

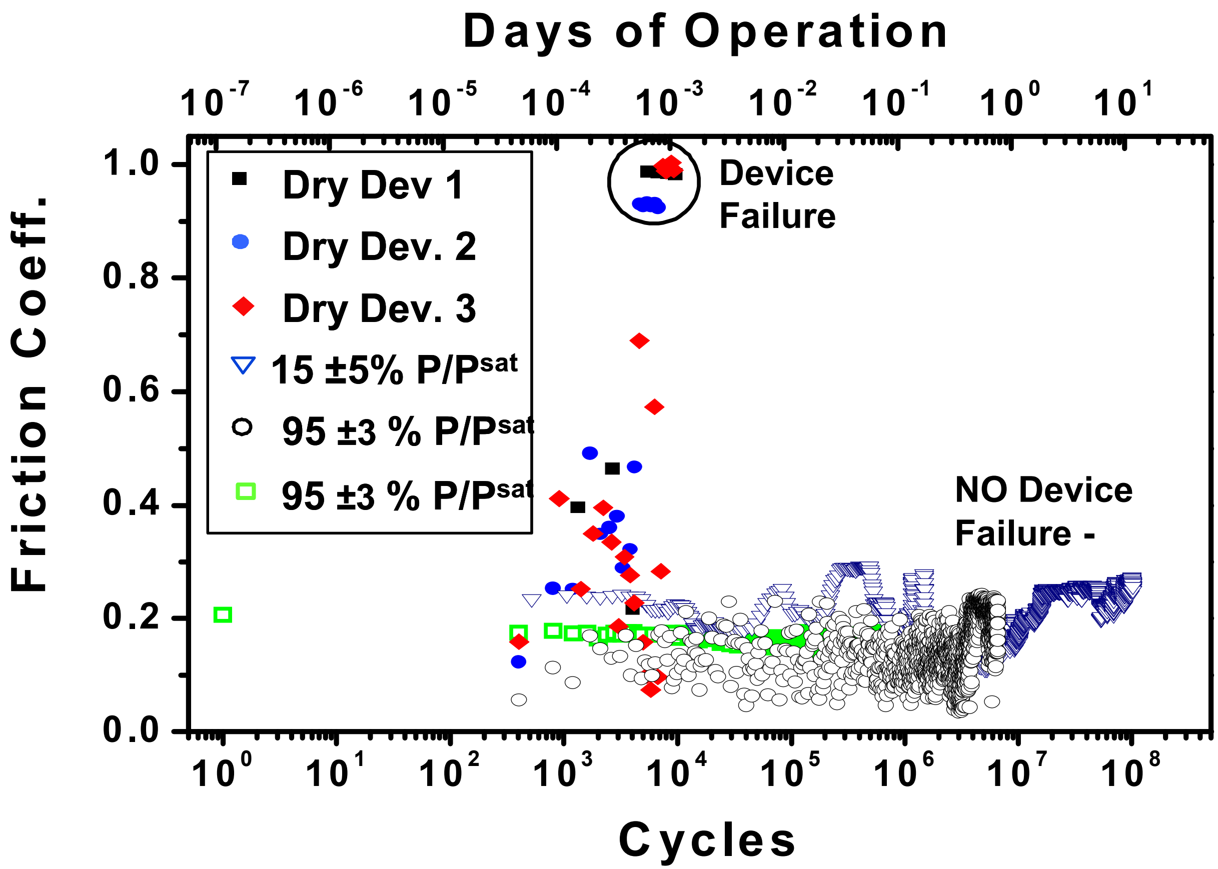
Timed Image Capture
Displacement vs Input (V)



Unprecedented Improvements in Operating Life are Observed with MEMS Tribometers

MEMS tribometer





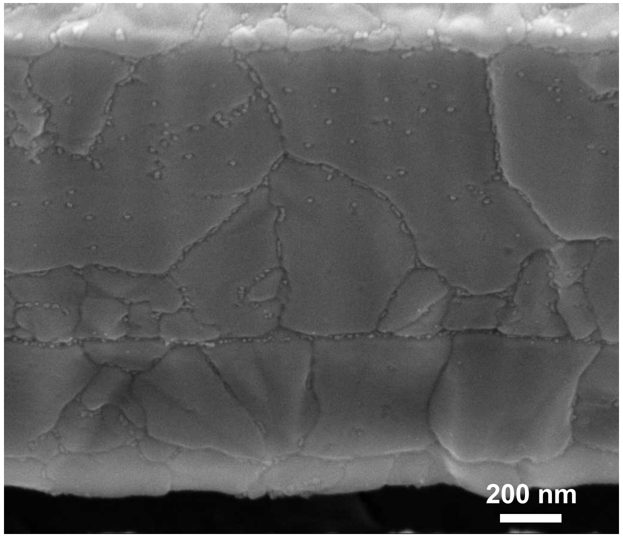
D.B. Asay, M.T. Dugger, J.A. Ohlhausen and S.H. Kim, *Trib. Lett.* (in press)

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

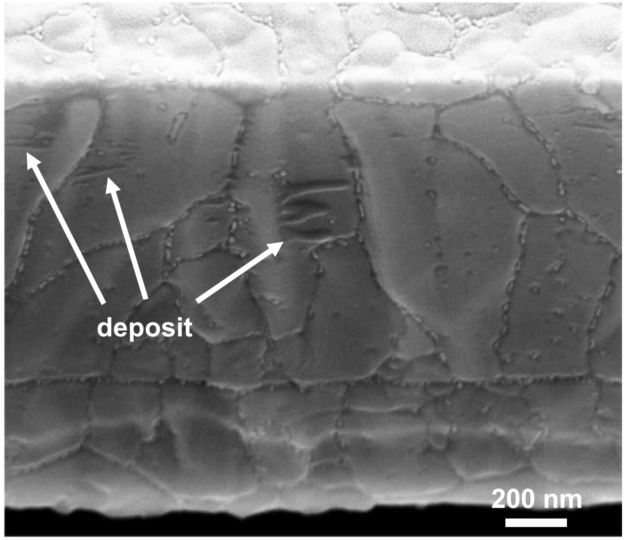
Wear is Minimized with In Situ Vapor Phase Lubrication

100 Hz
500 nN normal load
N_2 + pentanol, P/Psat = 0.2

not tested

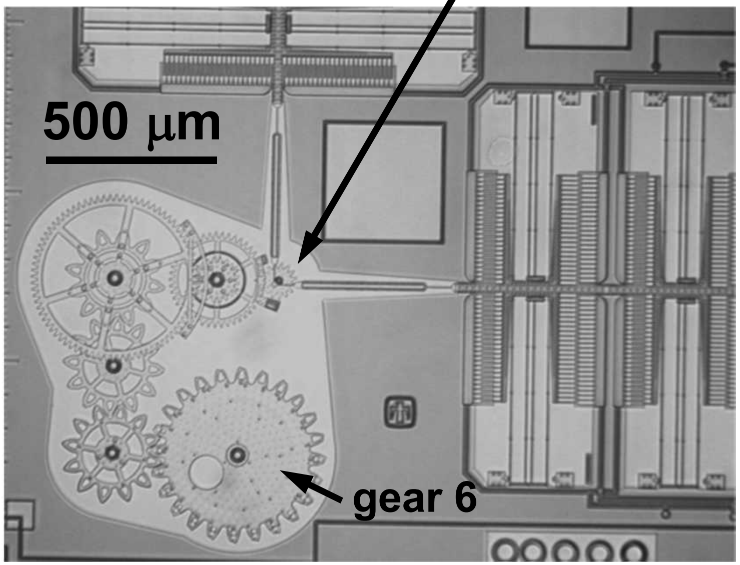


10^8 cycles without failure

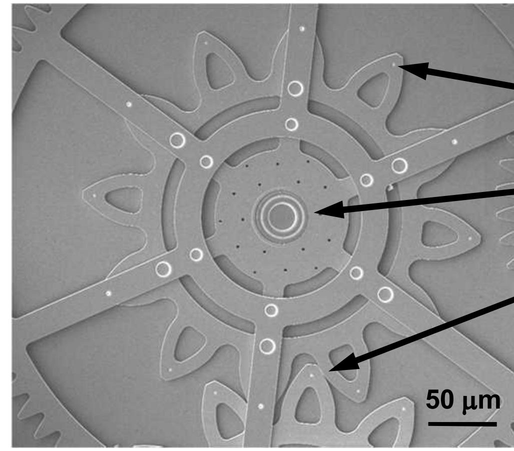


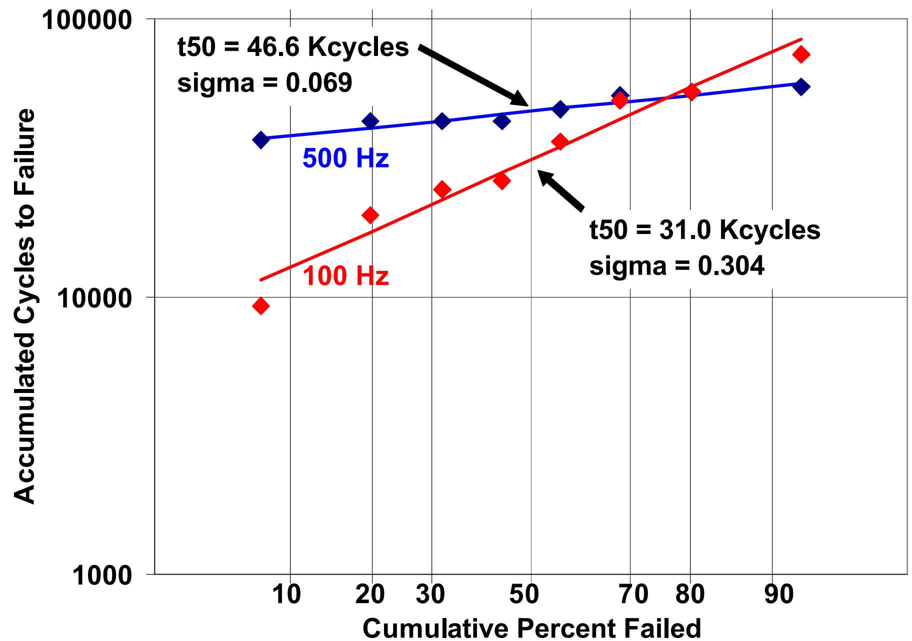
Deposit observed adjacent to real contact locations on sidewall of MEMS tribometer

Increased Operating Life of Gear Train with Vapor Phase Lubrication



gear train on aging module





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

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

- **1000 ppmv pentanol, 0 H_2O**

D. Tanner, Sandia

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Vapor Phase Lubrication of Silicon by Tribochemical Reaction

Alcohol lubrication observed in machining of bulk ceramics

S.M. Wiederhorn and D.E. Roberts, *Wear* **32** (1975) p.51-72

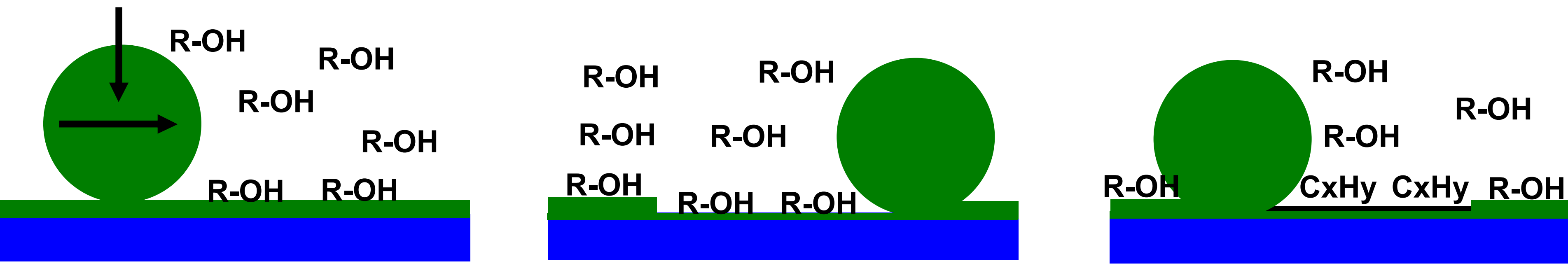
- reduced friction when abrading silicate glass in alcohols

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



Si or oxidized surface adsorbs alcohol

if damaged, alcohol re-adsorbs

adsorbed species react to form high MW product

Key for MEMS lubrication is the ability of the film to be replenished from the vapor

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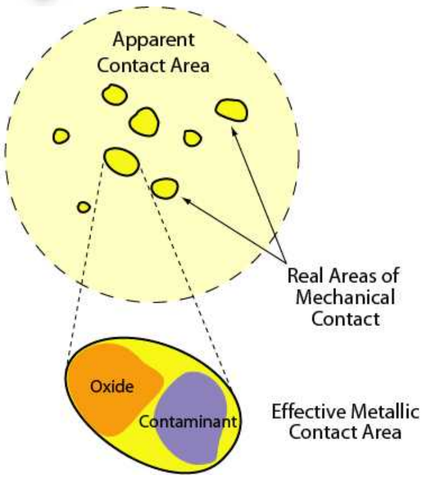
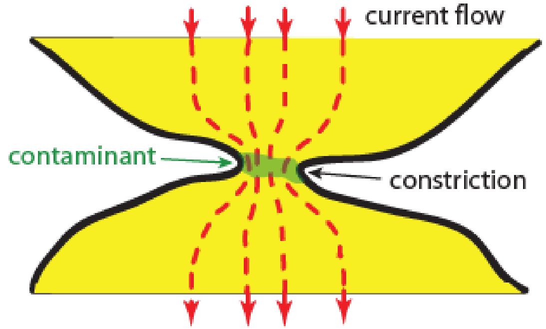
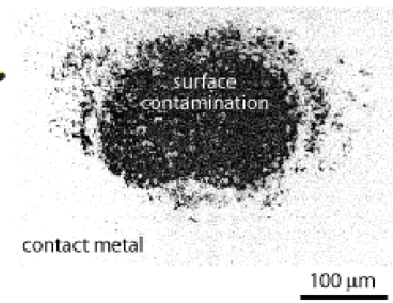
Dynamic Low Force Electrical Contacts



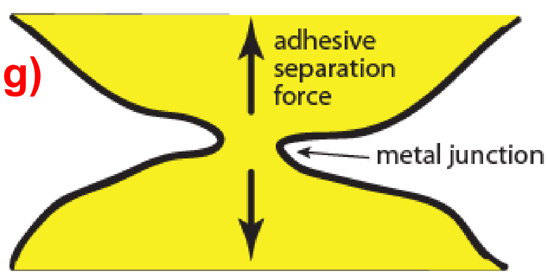
Reduced Conductivity

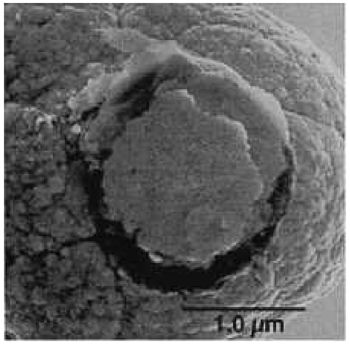




Tamai, T., 1995, "Effect of Silicone Vapour and Humidity on Contact Reliability of Micro Relay Contacts," IEEE Transactions on Components, Packaging, and Manufacturing Technology – Part A, 19(3), pp. 329-338.

Excess Adhesion





Hyman, D., and Mehregany, M., 1999, "Contact Physics of Gold Microcontacts for MEMS Switches," IEEE Transactions on Components and Packaging Technology, 22(3), pp. 357-364.

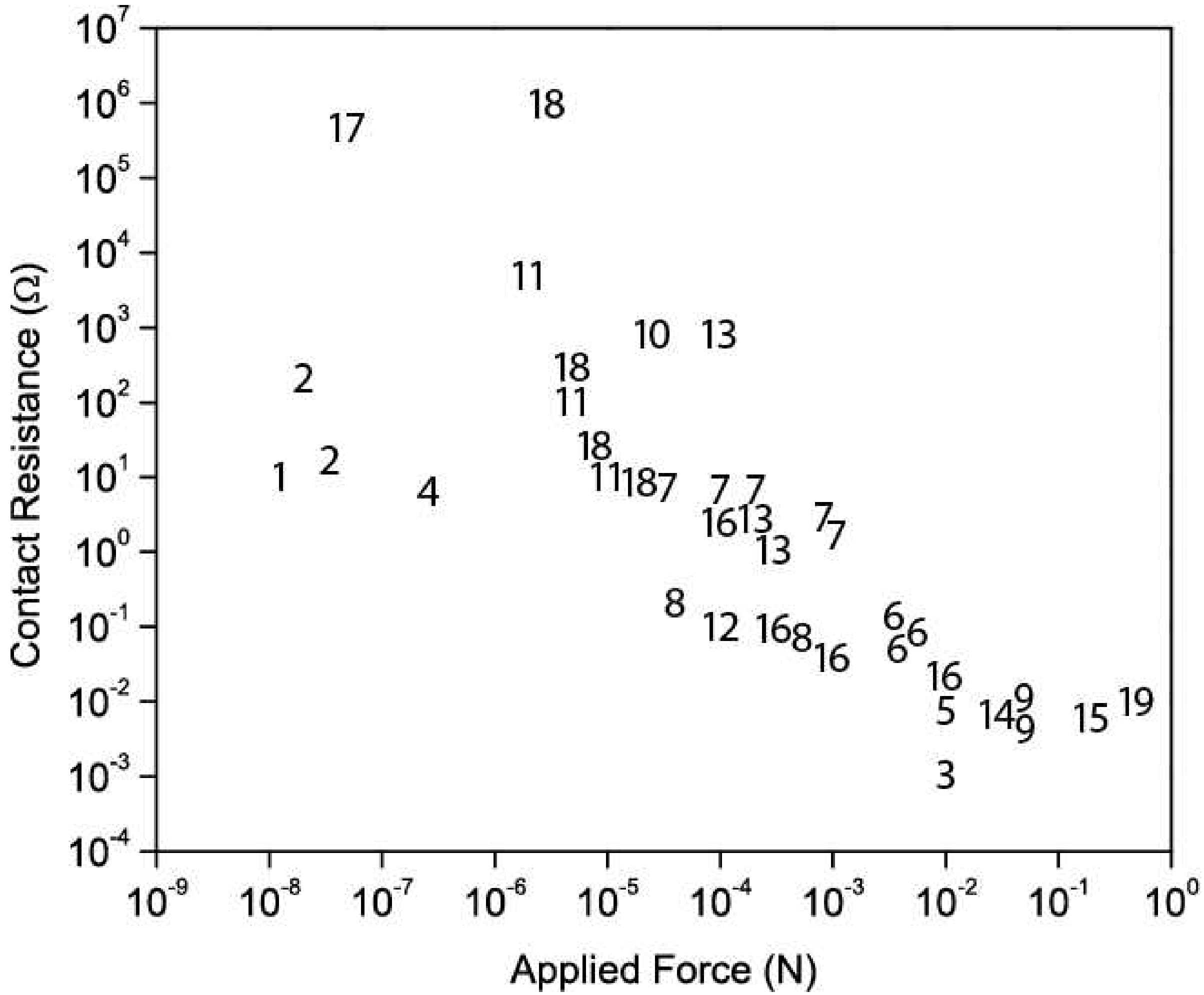
Degradation mechanisms:

- **thermal (melting, arcing)**
- **physical damage (adhesion, delamination)**
- **contamination (oxidation, segregation)**

D.J. Dickrell III, U. Florida

Long term operation of MEMS electrical contacts depends on the balance between *conductivity* and *separability*

Electrical Contact Resistance Increases with Decreased Contact Force



references available upon request

- **MEMS contact forces ~ μN – 100 mN**

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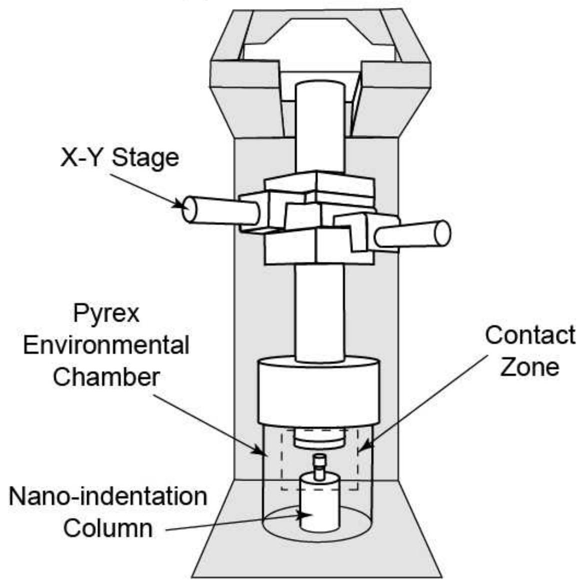
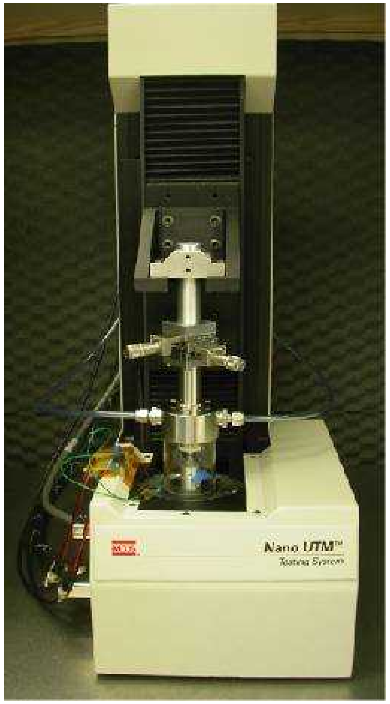
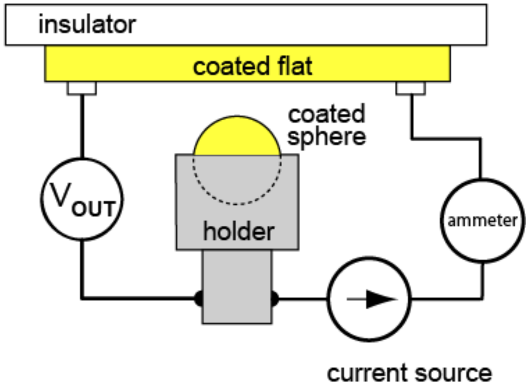
Low-Force Electrical Contact Apparatus

Apparatus Schematic

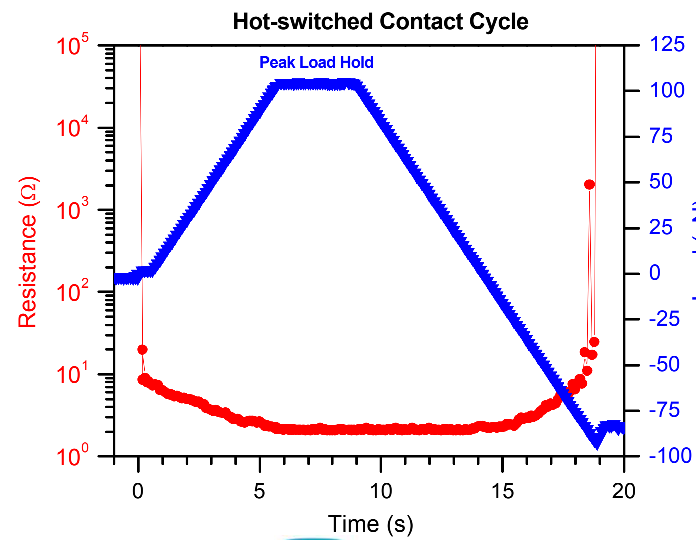


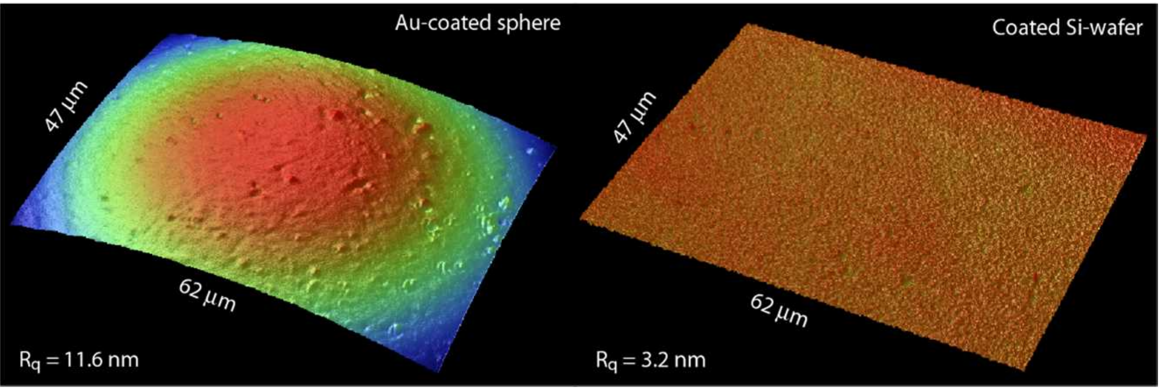


Contact Zone Schematic



F_n = 10 μN – 60 mN
V_{open} = 0 – 20V
I_{source} = 0 – 1 A
Accepts all deposited materials





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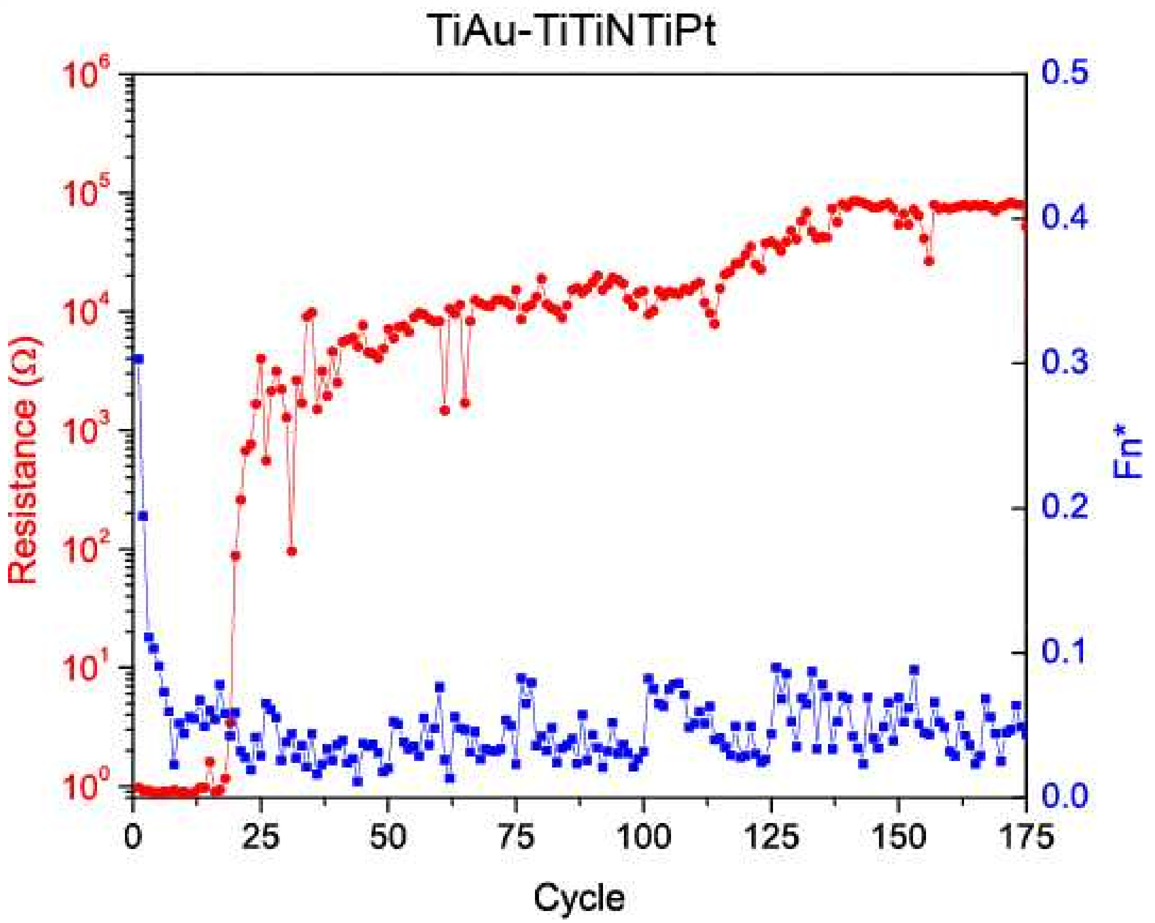
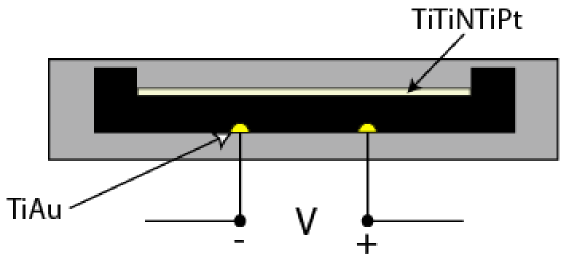
Cyclic Degradation of Electrical Contact Resistance





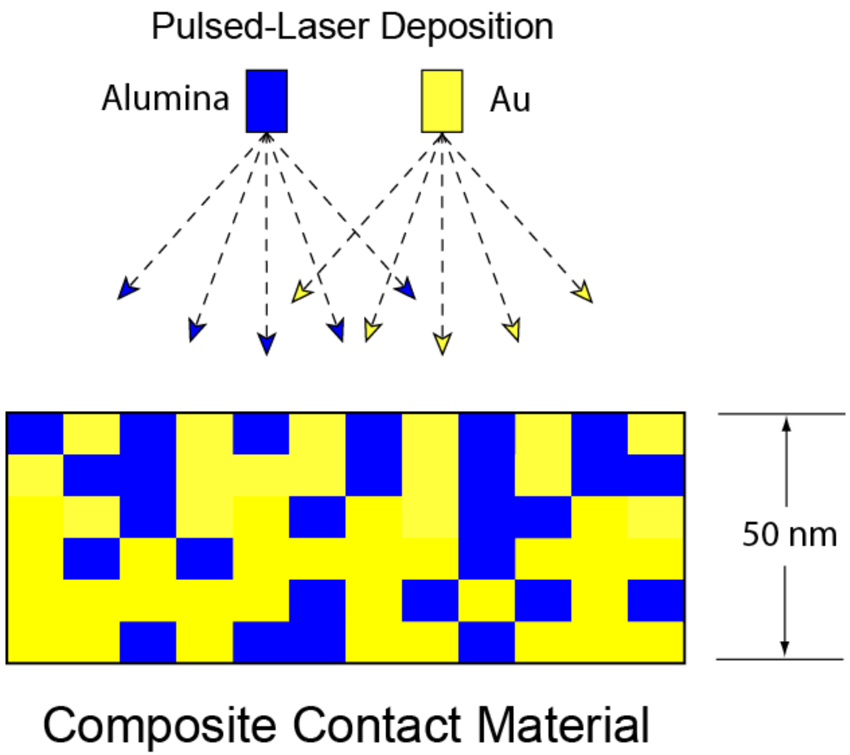
Resistance degrades in relatively few (<75) repeated contact cycles

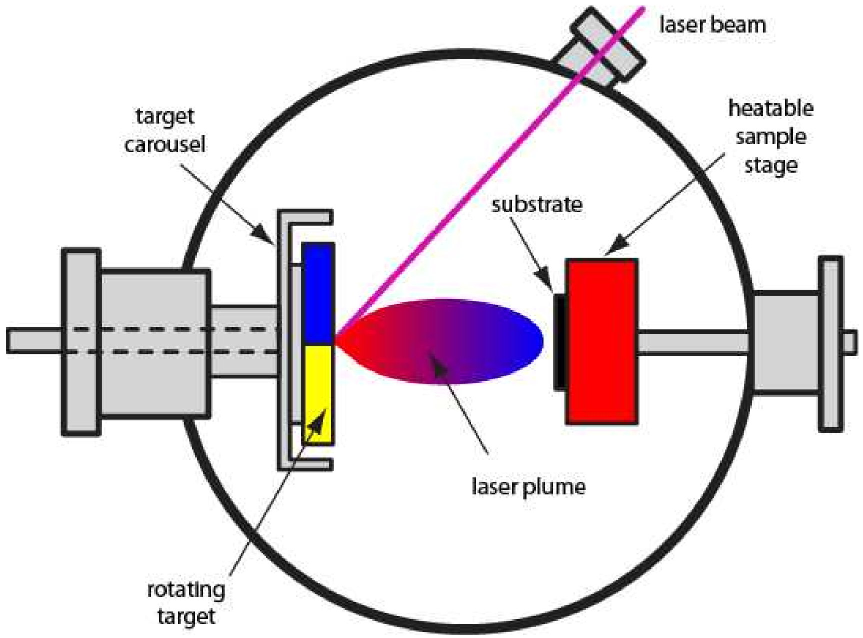
- **Build-up of nonconductive, carbonaceous material at contacts causes resistance increase**
- **Occurs during cold switching, but more slowly**

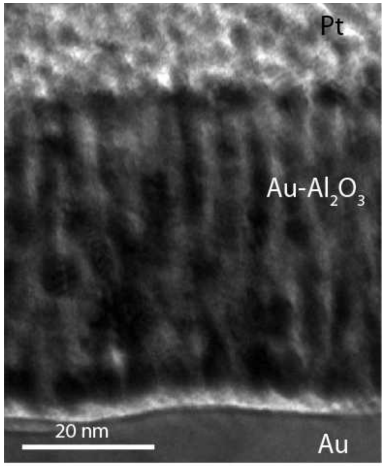
$$F_n^* = \frac{F_{pull-off}}{F_n}$$

Air
F_n = 150 μN
V_s = 3.3 V
I = 3 mA

Pulsed Laser Deposition (PLD) Was Used to Create Au/Al_2O_3 Composite Films







20% Au

- **nanocomposite formed by PLD or sputtering**
- **H = 5 GPa (2 GPa for electroplated Au)**
- **reduced plastic junction growth**

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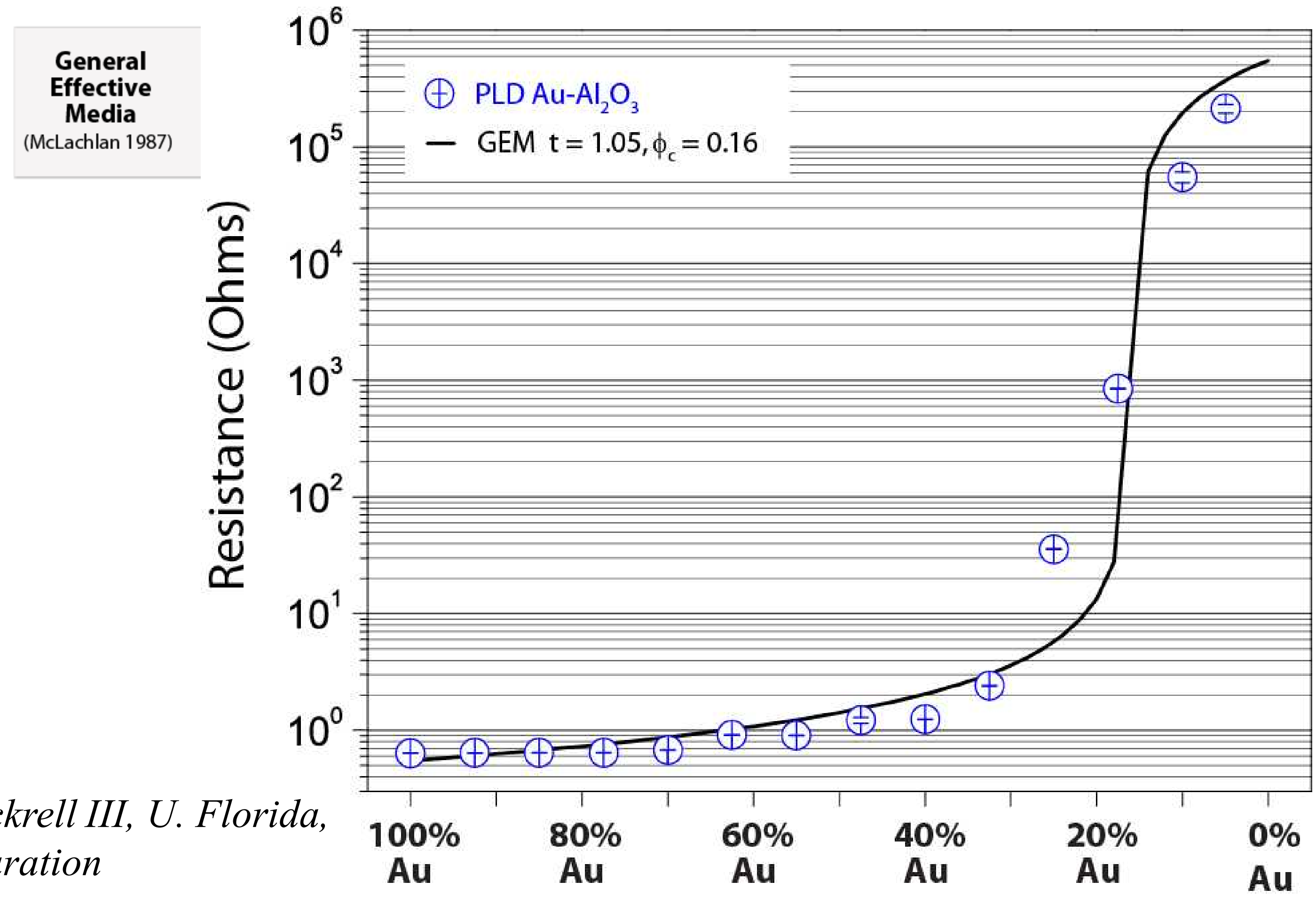
Percolation Threshold Describes Behavior of Au/Al_2O_3 Composites

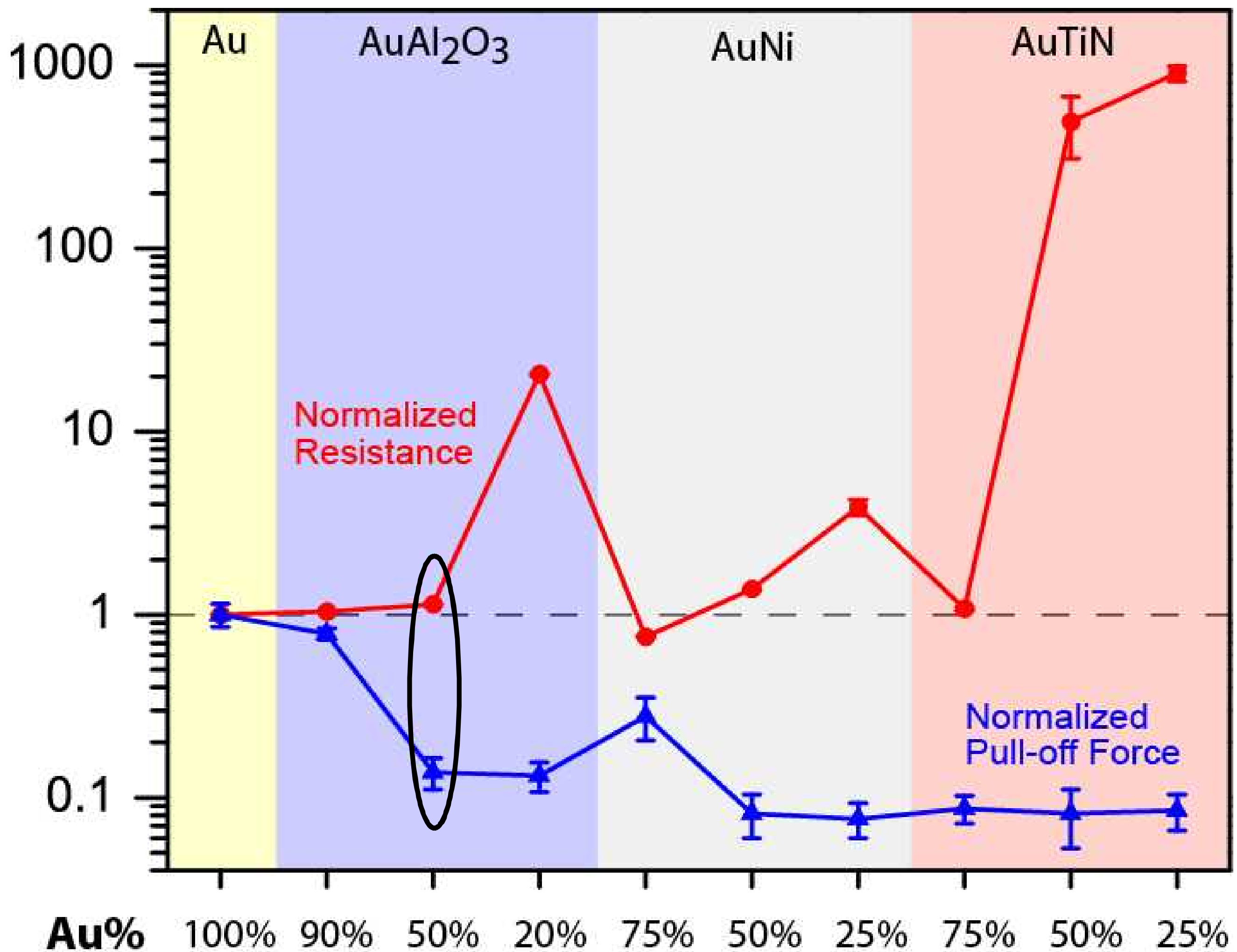


D.J. Dickrell III, U. Florida, in preparation

Au – ceramic nanocomposites maintain low resistance for ceramic concentrations > 50% by volume

- **reduce contact welding without segregating species**

Experimental Results



Normalization Values

$R_{AuAu} = 533 \pm 7\ m\Omega$

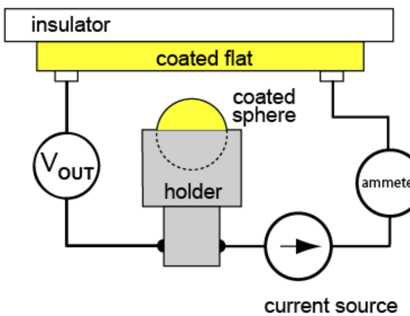
$F_{po_{AuAu}} = 253 \pm 36\ \mu N$

$F_n = 100\ \mu N$

$I_{src} = 3\ mA$

N_2 ambient

10 cycle average



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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**

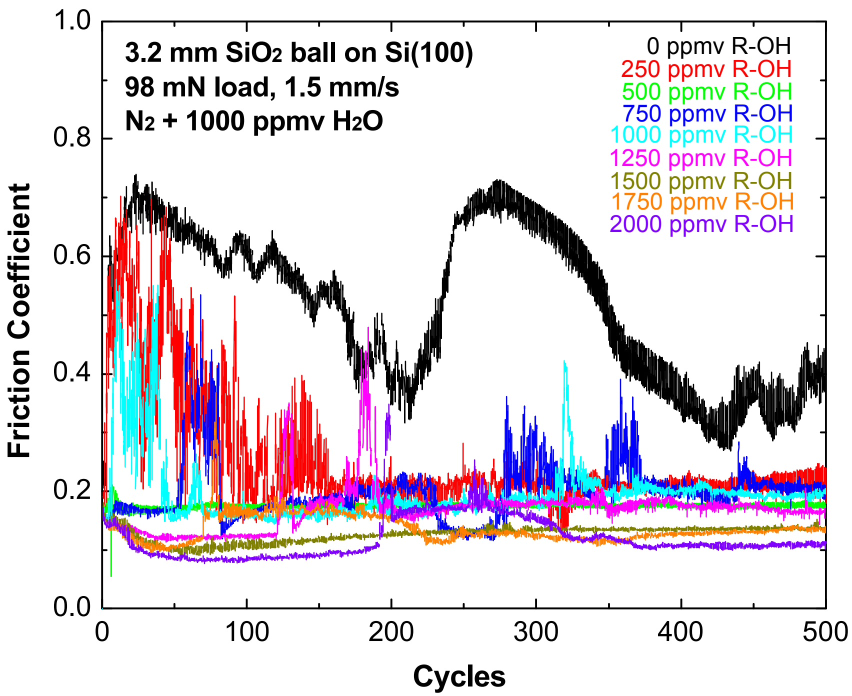
MEMS electrical contacts require balance between low resistance (high contact stress) and low adhesion (low contact stress)

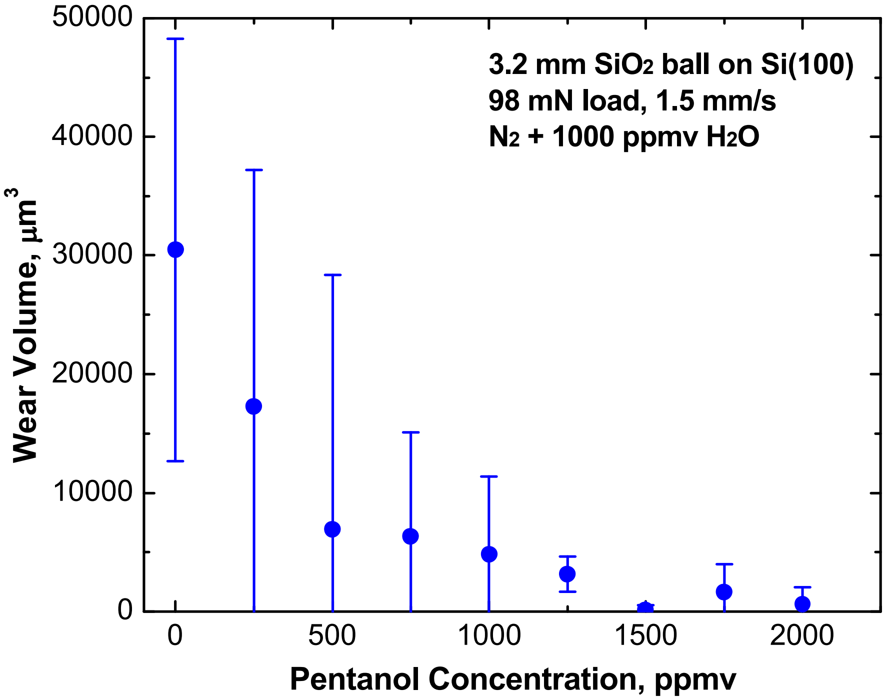
- **adsorption and decomposition of hydrocarbons leads to increased contact resistance**
- **optimized film structure (hard yet conductive) could lead to mechanically robust electrical contacts for MEMS**

Materials solutions to address major reliability issues will increase application opportunities for MEMS – and their viability for future defense systems

Backups

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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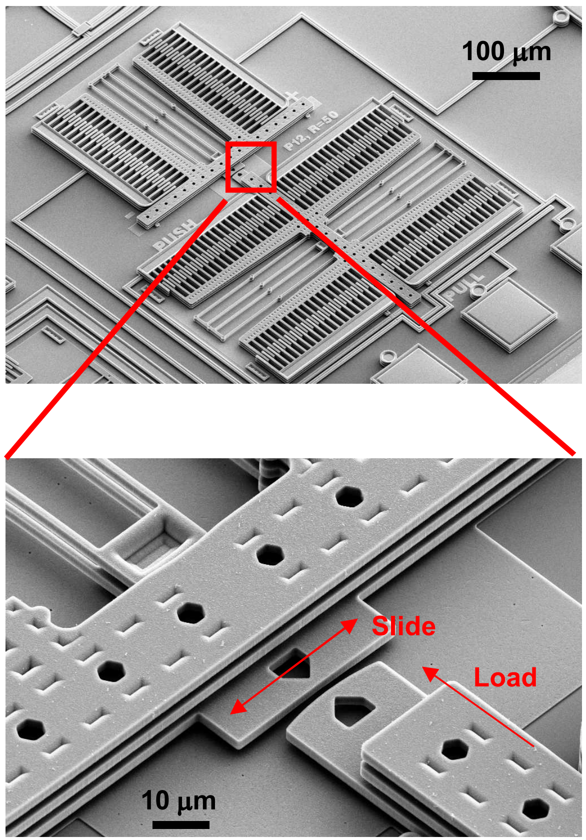
Effects of Competitive Water Adsorption on MEMS Tribometer Operation

MEMS tribometer

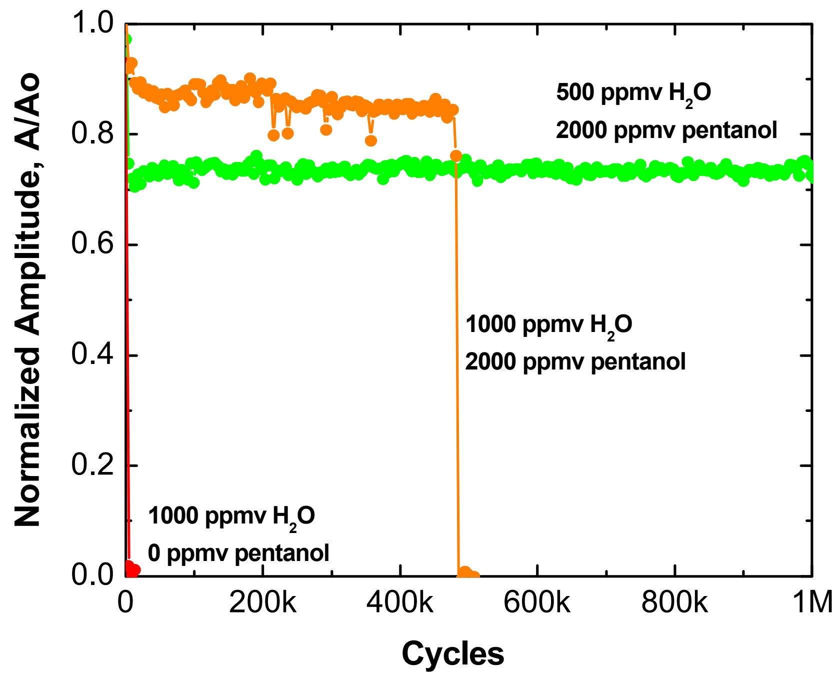


WATER

1-Pentanol ppmv	0	250	500	750	1000
0	$5x10^3$				$4x10^3$
500	$1x10^6$				
1000			$1x10^6$		
1500					
2000	$1x10^6$		$1x10^6$		$5x10^5$

← typical of packages without desiccant (water = 1000 ppmv)

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

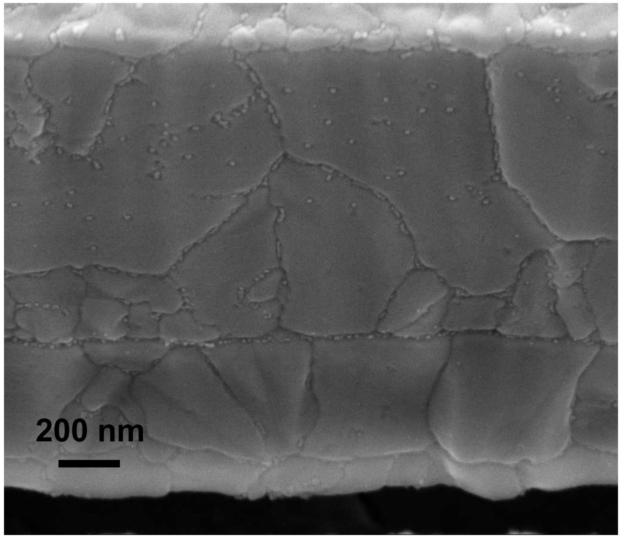


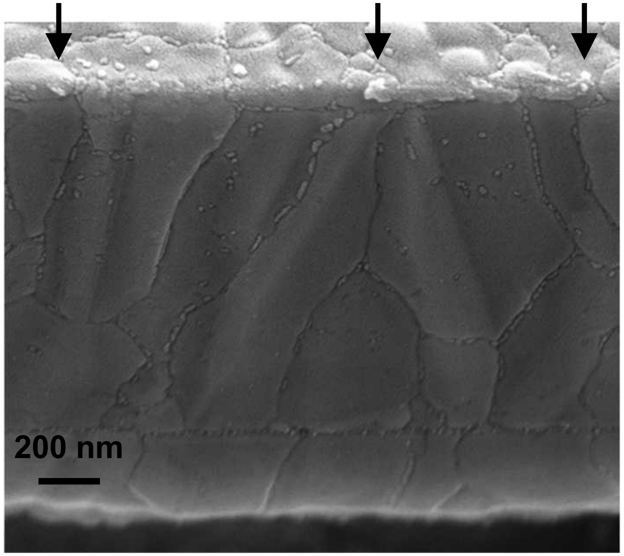
- **MEMS tribometers operate in mixed pentanol-water vapors**
- **Evidence of surface degradation at 2000 ppmv pentanol + 1000 ppmv H_2O**

Wear is Minimized with In Situ Vapor Phase Lubrication

1-Pentanol (ppmv) \ WATER (ppmv)	0	250	500	750	1000
0	$5x10^3$				$4x10^3$
500	$1x10^6$				
1000			$1x10^6$		
1500					
2000	$1x10^6$		$1x10^6$		$5x10^5$

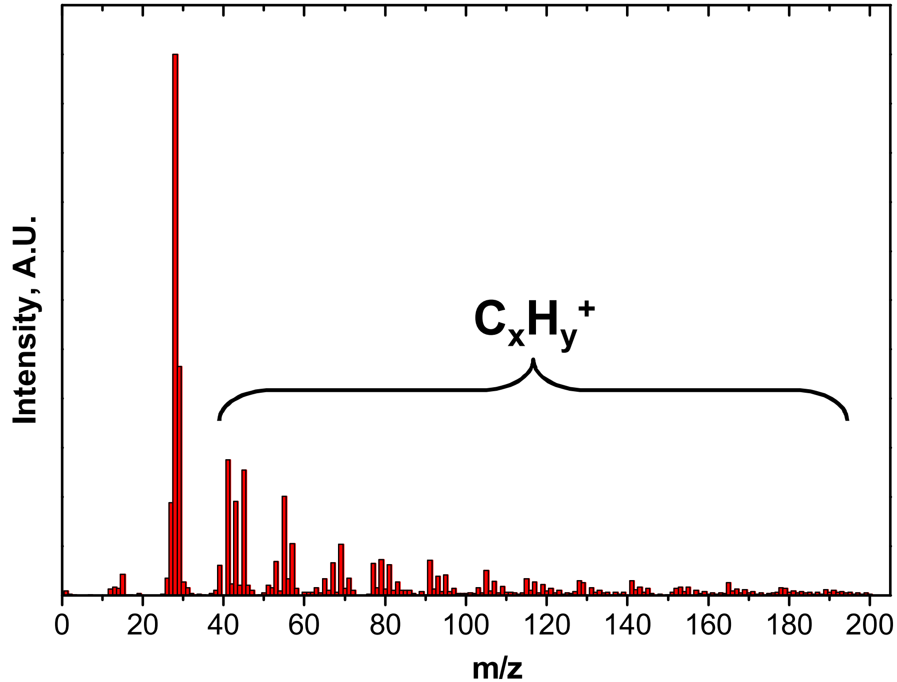
100 Hz
500 nN applied load



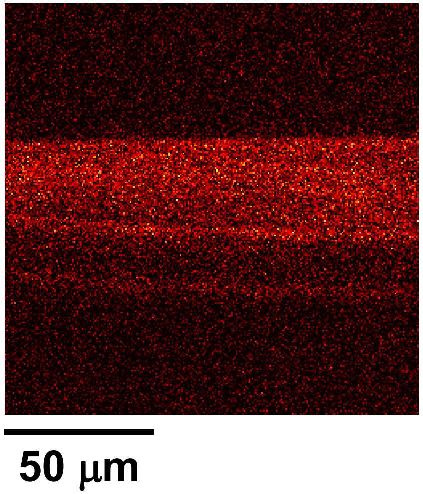


- Without pentanol, devices adhere before significant surface damage accumulates
- A few particles observed at 1000 ppmv H_2O + 2000 ppmv pentanol

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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