Probing Interfacial Contact via MEMS-based Microinstrumentation

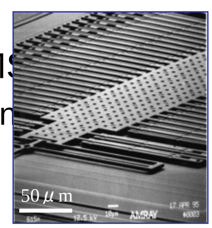
Roya Maboudian

Department of Chemical & Biomolecular Engineering
Berkeley Sensor and Actuator Center (BSAC)
Center of Integrated Nanomechanical Systems (COINS)
Center for Interfacial Engineering of MEMS (CIEMS)

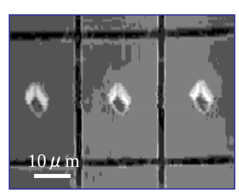
University of California at Berkeley

Outline of the Talk

- Surface-related reliability issues in MEMS
  - adhesion (stiction); friction; wear; corrosion
- Test structure development
- Surface modifications
  - self-assembled monolayer
  - hard inorganic coatings
- Environmental effects
  - fluidic; temperature; relative humidity

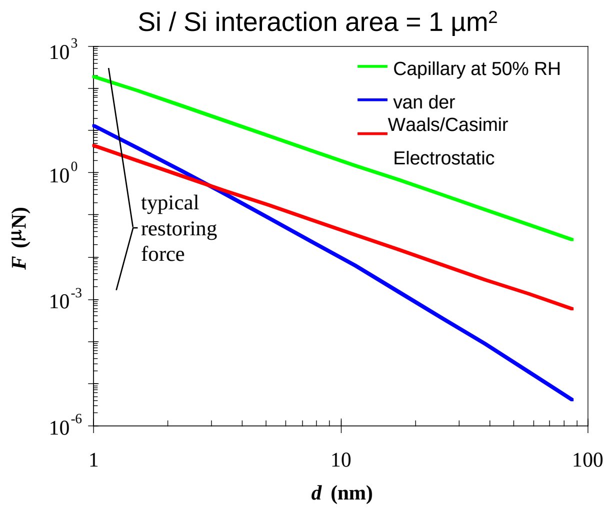


Accelerometer



Micromirror Display

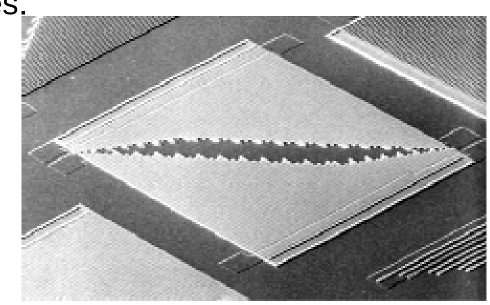
Interfacial Forces in MEMS



(R. Maboudian and C. Carraro, Ann. Rev. Phys. Chem. 2004; Surf. Sci. Reports 2007)

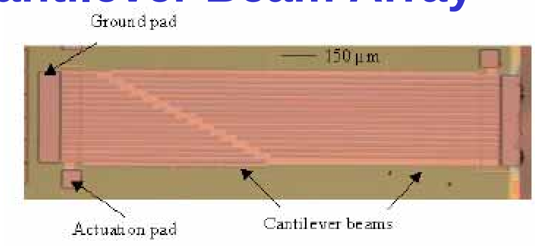
Instrumentation Needs

- MEMS-based instruments can provide information on:
  - material systems of interest to MEMS following the appropriate processing sequence;
  - length scales not easily accessible with other techniques.

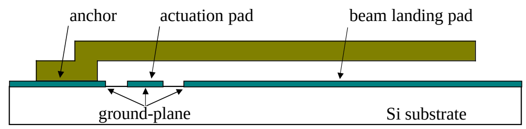


Adhesion Micro-instrument: Cantilever Beam Array

Top View



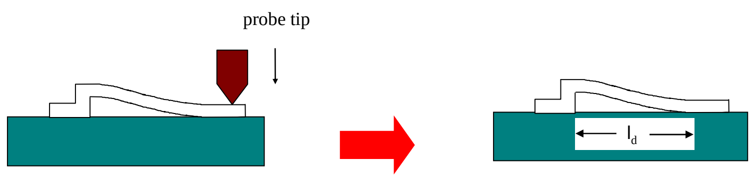
Side View



$$l_d \approx l_c + \sum_{i=min}^{i=max} [1-P(l_i)]\Delta l \qquad l_c = l_{min} - \Delta l$$

l_d = detachment length
$P(l_i)$=sticking probability

Adhesion Measurement



Beam analysis yields:

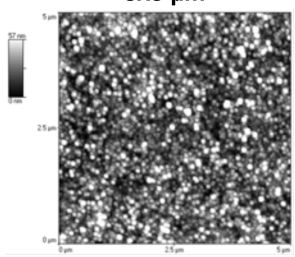
$$W = \frac{3}{8}\frac{Et^3h^2}{l_d^4}$$

W = work of adhesion
E = Young's modulus
t = thickness of the beam
h = height above the surface
l_d = detachment length

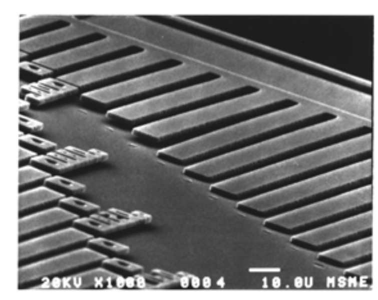
[C. H. Mastrangelo, *Tribology Letters* '98]

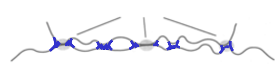
In-use Adhesion: SiO_2-coated Surfaces

5x5 μm²



RMS = 12 nm



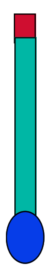


Increasing length

At 50% relative humidity:

l_d = 110 μm → W = 20 mJ/m²

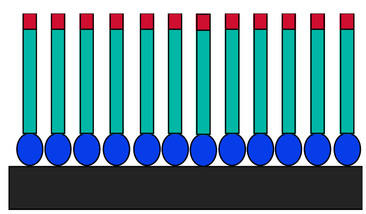
Self Assembled Monolayers (SAM)



End group

Alkyl chain

Surface active head group

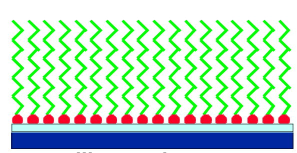


- **Form well-packed films**
- **Modify surface properties**

CH_3-$(CH_2)_{17}$-$SiCl_3$: OTS

SAM Formation

close-packed alkyl chains



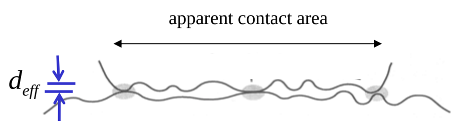
Silicon substrate

Θ_{H2O} on Si(100) ~ 110°

Characteristics of OTS-Coated MEMS

- Work of adhesion: W= 0.012 ± 0.004 mJ/m^2
  - cf., ~ 20 mJ/m^2 for oxide-coated surfaces
- W unchanged even in 99% relative humidity
  - cf., 140 mJ/m^2 for oxide-coated surfaces

$$W_{vdW} = \frac{A}{12\pi d_{eff}^2} \approx 0.01\, mJ/m^2$$



- Static friction coefficient: μ_s= 0.07 ± 0.005
  - cf., ~ 1 for oxide-coated surfaces

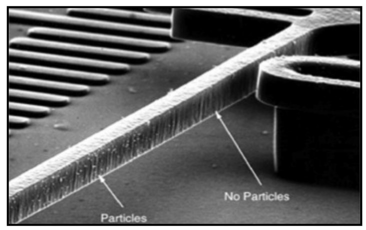
Effects of Repetitive Contact

Accelerated Life-time Testing

Motivation:

- MEMS devices designed for repeated contact often fail due to wear;
- It is desirable to understand and predict the failure mechanisms.

Sliding sidewall-contact microinstrument



(W.R.Ashurst et. al. *Tribology Letters* 2004)

Microinstrument Design

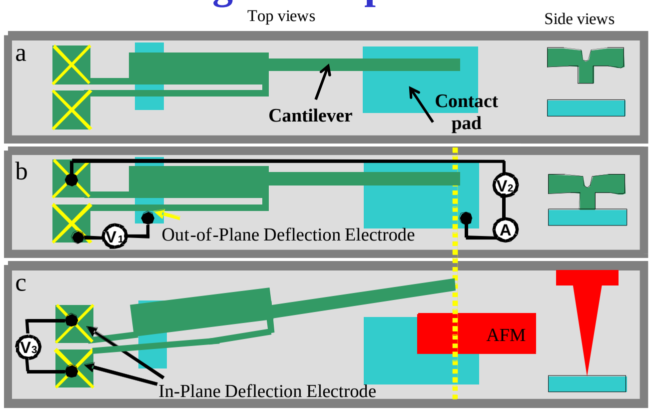
Planned Operation

1. Cyclic contact between two MEMS surfaces
2. Separation of the surfaces
3. **In situ** Analysis of surfaces
4. **Repeat** steps 1-3

Design Constraints

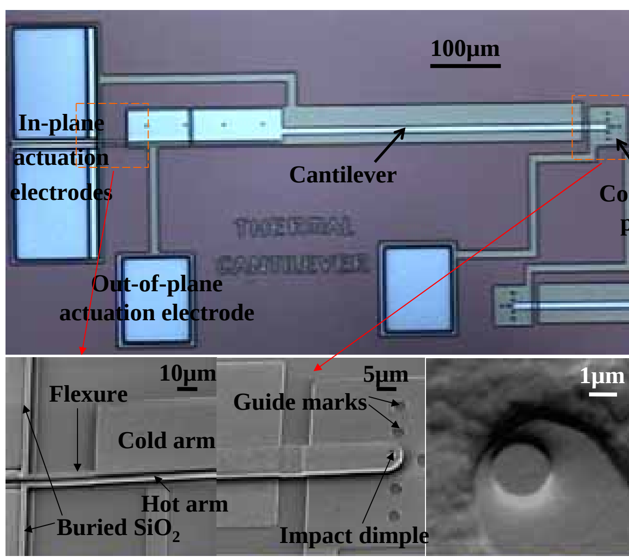
1. Surfaces must be capable of repeated contact (**out-of-plane**)
2. Surfaces must be capable of *temporary* separation at large enough distances to permit analysis (**in-plane**)

2-Axis MEMS Deflecting Cantilever (2AM-DC): design and operation



- Out-of-plane electrode is biased with respect to cantilever (V_1) to induce cantilever-substrate contact at distal end of cantilever
- Voltage V_2 applied between contact pad and cantilever and current measured.
- Cantilever is displaced in-plane with bias V_3, allowing interrogation of contact region.

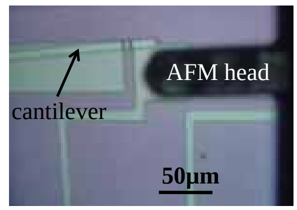
2AM-DC Microinstrument



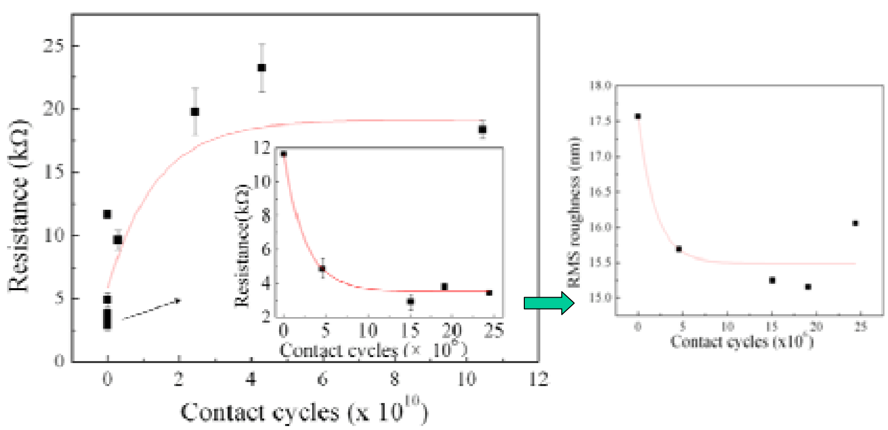
Interrogation Methodologies

Evolution in contact region probed via:

- I-V measurements: Contact resistance
- AFM/KPFM: Surface topography, surface potential
- Scanning Auger electron spectroscopy: Chemical composition map

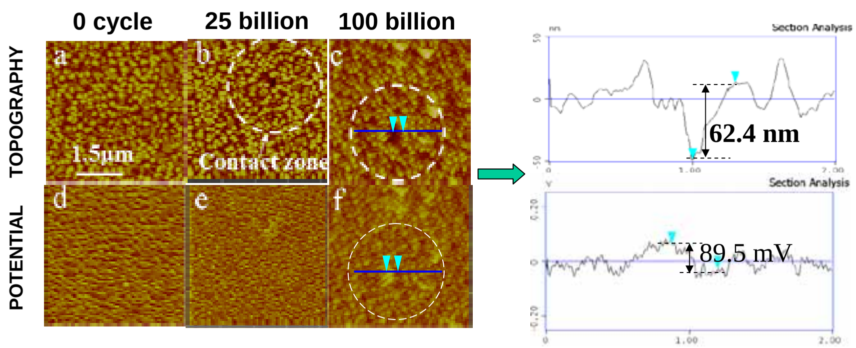


Contact Resistance Evolution



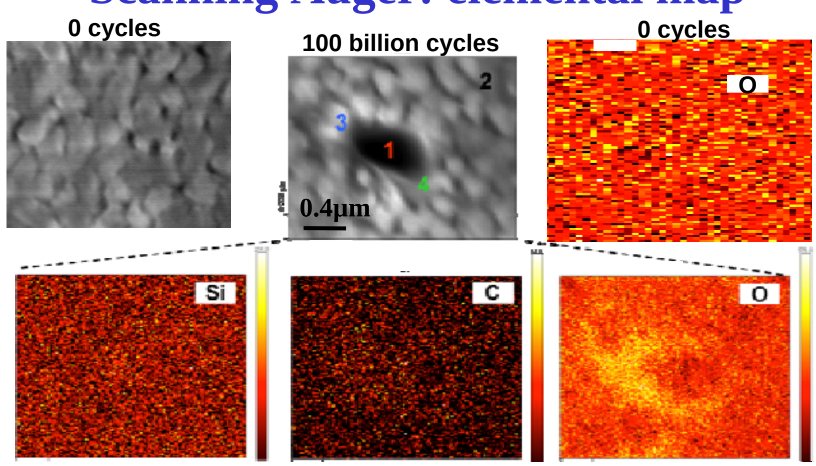
- Contact resistance ↓ during first tens of millions of impacts; then ↑ with increased contact cycles.

Contact Area Evolution: topography and surface potential vs. contact cycles



- ➢ **Crater-like surface feature develops and grows after ~25 billion of contacts;**
- ➢ **KPFM shows a potential rise around the contact zone.**

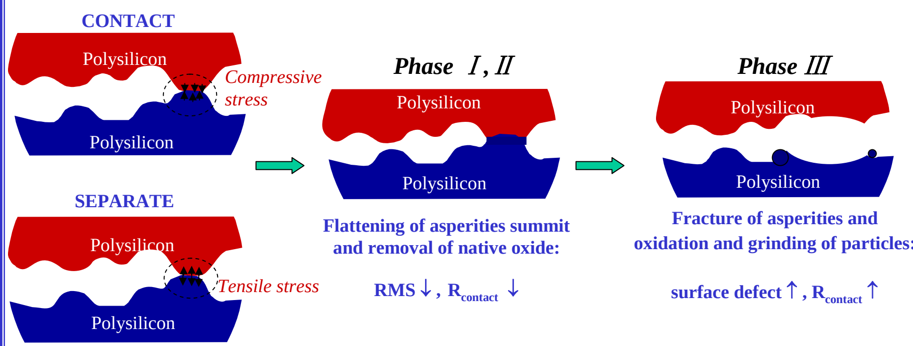
Scanning Auger: elemental map



- **(Top) SEM micrograph of contact region and specific spots (numerals) selected for Auger analysis;**
- **(Bottom) corresponding Auger maps for Si, C and O:**
  - ➢ **Homogeneous concentrations of Si and C; higher oxygen concentration around the crater.**

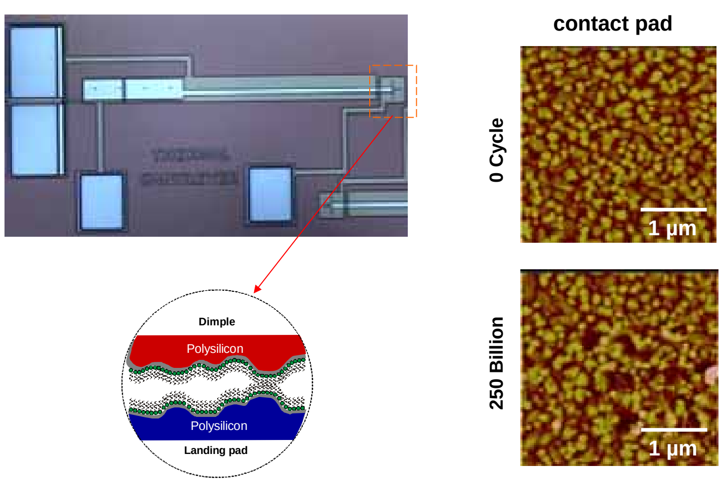
Proposed PolySi Wear Mechanism

- High local pressure generated across a few asperities



(F. Liu, et. al., *Appl. Phys. Lett.* 2010)

Effect of SAM on Cyclic Contact



➢ SAM effective in reducing wear and enhancing device lifetime

[I. Laboriante et. al., *Tribology Letters* 2011]

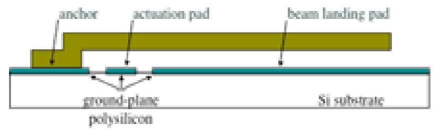
Effects of Relative Humidity in Presence of High Electric Field

Effect of Relative Humidity

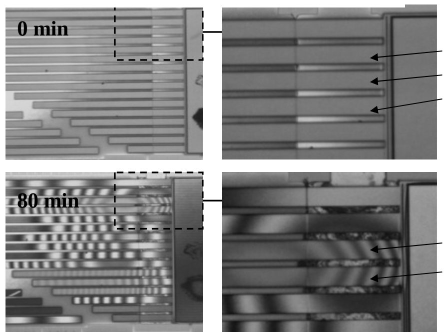
- Ubiquitous presence of water vapor makes the study of relative humidity (RH) effects on the performance and reliability of M/NEMS devices crucial.
- Due to reduced dimensions, M/NEMS devices operate under high fields (> 10^6 V/m).
- Combination of relative humidity and electric field during device operation results in electrochemical reactions affecting the life time of M/NEMS devices.

Life-time Testing

- Effect of Positive Actuation Voltage
  - beams begin to deflect upwards;
  - observed for relative humidity > 55 %



$V_{actuation}$ = +100 V; RH = 97%

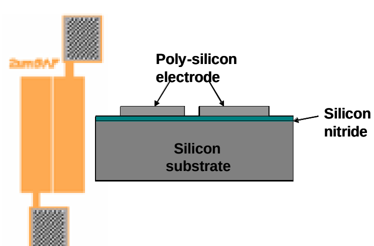


No interference pattern. All beams in flat position (normal).

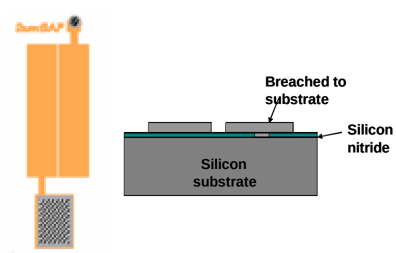
Interference pattern. Beams are deflected away from ground plane due to the corrosion and delamination of the underlying actuation pad.

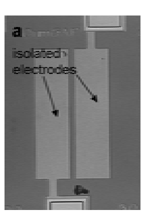
Corrosion Test Structures

Isolated: Symmetric

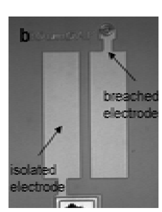


Breached: Asymmetric



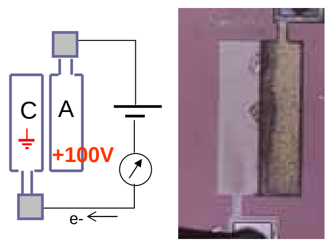


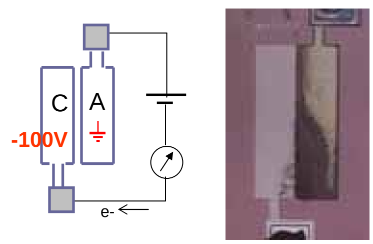
Electrode Size
Width: 80 µm
Length: 300 µm
(Thick: 0.5 µ m)
Gap: 2-10 µm



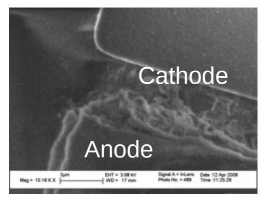
Symmetric Electrodes under High Humidity and Applied Voltage

97%RH
20 hrs

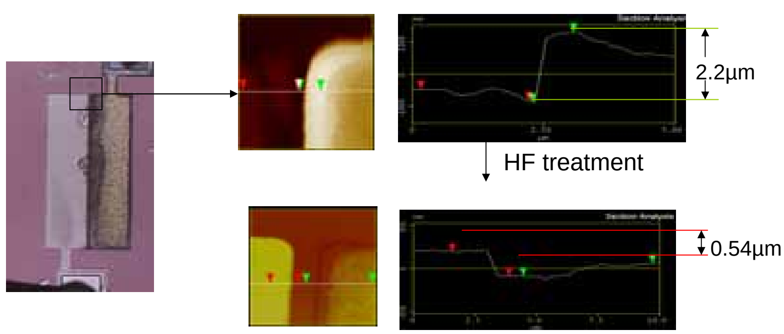




→ Anodic Oxidation



Morphology of the Corroded Electrode



Regardless of positive or negative bias, the anode is corroded:

- Oxidation and volume expansion
- Surface film crack

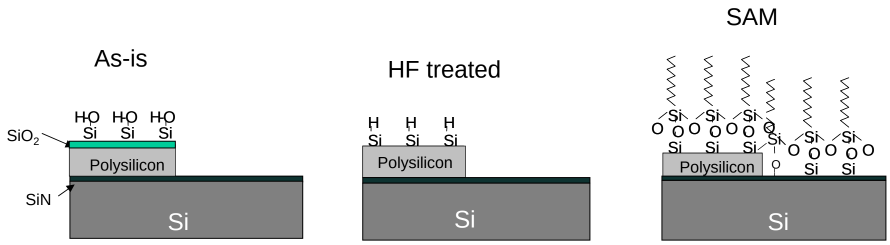
rate ↑ as gap distance↓
rate ↑ as voltage ↑
rate ↑ as RH ↑

Possible reactions at the anode:

$$H_2O \longrightarrow H^+ + OH^-$$

$$Si + 2OH^- + 2h^+ \longrightarrow SiO_2 + H_2$$

Effect of Surface Modification on Corrosion



Surface treatment	θ_{H_2O}
Polysilicon SiO_2/OH termination	0-20
Polysilicon H termination	75
FDTS coated polysilicon	115
Silicon nitride	0-25
FDTS coated silicon nitride	87

Effect of Surface Termination on Corrosion

89% RH,+100V, 20 hours

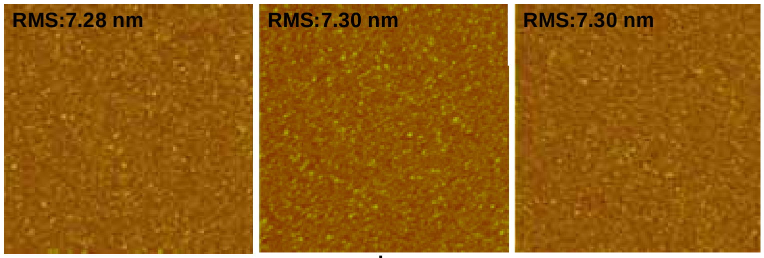
SiO_2/OH terminated   H terminated   FDTS coated

Surface treatment	Oxide terminated	H terminated	FDTS coated
Total charge (mC)	643. 8	31. 9	5. 4

(M. Hon et. al., *Sensor & Actuator A* 2011)

Corrosion Inhibition via SAM

Surface topography of anode



a — Uncoated anode

b — FDTS coated anode

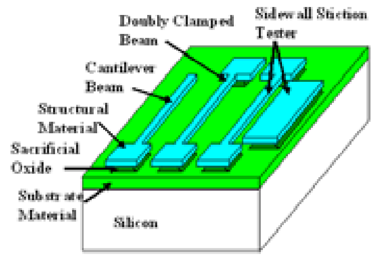
c — FDTS coated anode after testing at 89% for 20 hrs

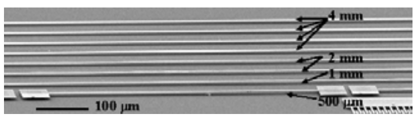
Scan size 8 × 8 µm, z scale 200 nm

Long Term Reliability

Adhesion Characteristics of Silicon Carbide

- Significant reduction in adhesion
- 1.5 mm long beam experience no adhesion to SiC substrate whereas 200 μm beams adhere to Si substrate
- 4 mm long doubly clamped SiC beams experience no adhesion

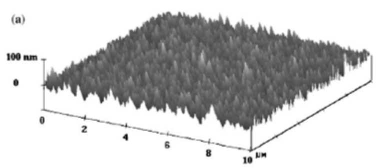




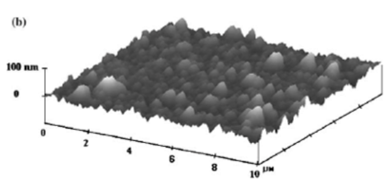
Structural Material	Substrate Material	Treatment	Cantilever Beams: Detachment Length (μm)	Cantilever Beams: Apparent Work of Adhesion (mJ/m^2)
poly-Si	poly-Si	After release	200	20
poly-Si	SiC	After release	>1500	<0.006
		After exposed to room air for 1 week	>1500	<0.006
		After exposed to room air for 2 weeks	1000	0.034

(D. Gao, *et al*., Tribo. Lett. 2006)

Adhesion Characteristics of Silicon Carbide

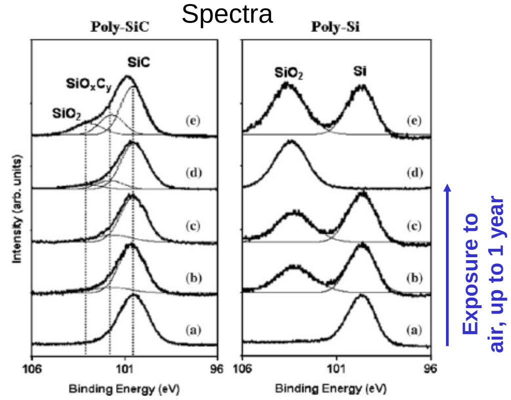


Si: rms ≈ 12 nm



SiC: rms ≈ 11 nm

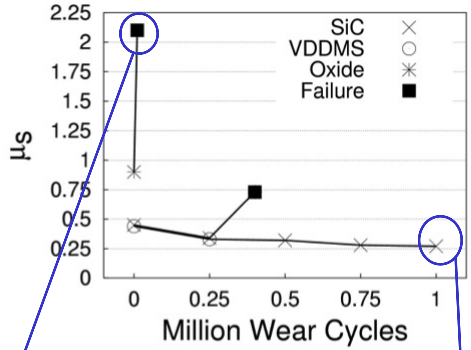
X-ray Photoelectron Spectra

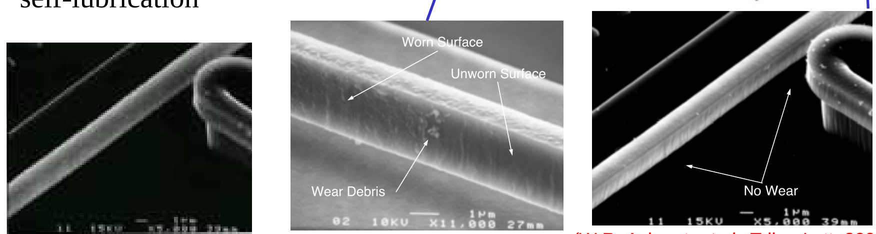


- **Few points of contacts**
- **High SiC hardness**
- **Slow rate of SiC oxidation**

Wear Characteristics of SiC Coating

- significant reduction in friction and wear with 40 nm SiC coating
- smooth operation for contact cycles exceeding 1 M cycles vs. failure for uncoated devices after 100k cycles
- friction coefficient decreases w/ contact cycles, indicating self-lubrication





33

(W.R. Ashurst, *et al.*, Tribo. Lett. 2004)

Conclusions

- MEMS-based microinstruments allow for tribological studies under conditions and materials systems of direct technological interest, and over a fundamentally interesting length scale.
- CBA analyses highlight the intriguing effect of surface chemistry and roughness on adhesion between polysilicon surfaces.
- 2AM-DC analyses suggest that the wear processes involving polysilicon surfaces may be differentiated into three phases.
- SAMs and SiC are effective in reducing the tribological challenges in MEMS technology.