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Durability of Materials for Nanoelectromechanical Switches Studied by Scanning Probe Microscopy

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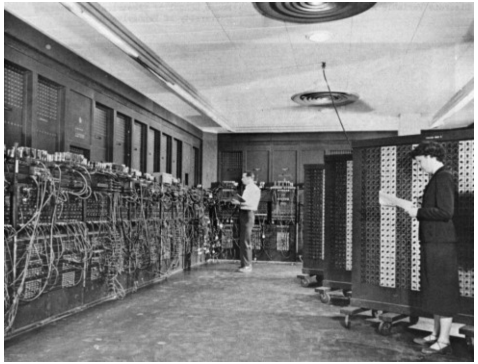
University of Pennsylvania

Overview

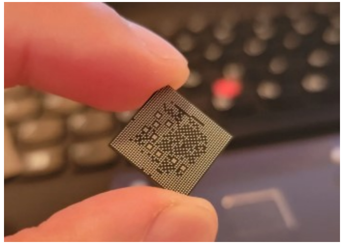
- Background
- Controlling tribopolymer formation:
  - contact stress and bias voltage
- Exploring contact materials
- Summary

Background



EINIAC, the world's first general-purpose computer (1945)

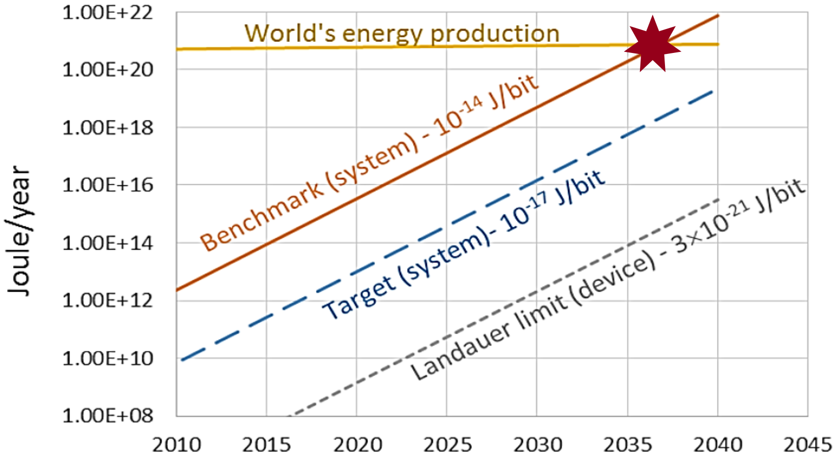
Moore's Law



Processor of a modern smart phone

Power crisis:

- Information and communication technology accounts for **5-9% of world's electricity consumption**, **2% of all emissions**.



Trend for world's computing energy consumption
(2015 report, Semiconductor Industry Association & Semiconductor Research Corporation)

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Solid-State Transistors & NEMS switches

- Solid-state transistors

  Facing scaling limits:

  – Leaking current even at OFF state

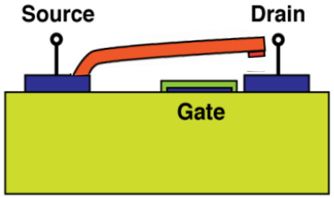
  – Requires large voltage to turn on

- NEMS switches

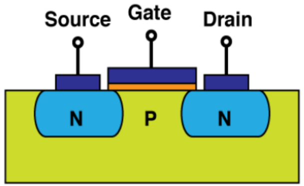
  10~100 times lower power consumption:

  – Negligible OFF-state leakage

  – Low operating voltage/power



NEM Contact Switch



Field Effect Transistor

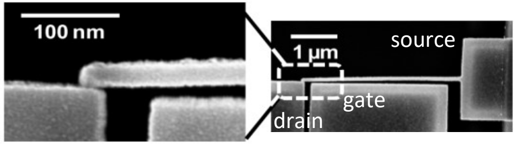


Image: S. Chong et al. (2011)

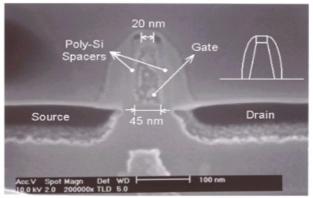
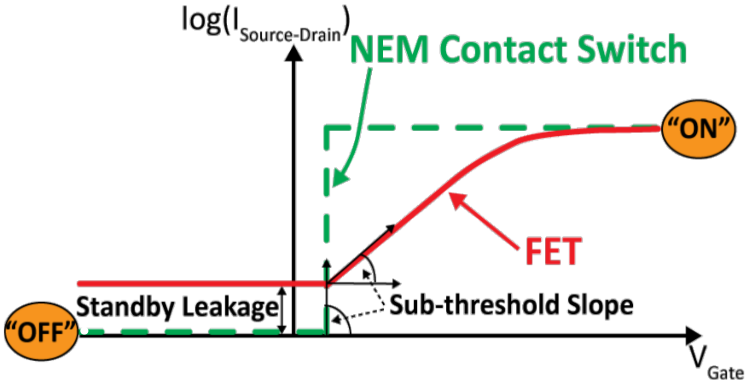


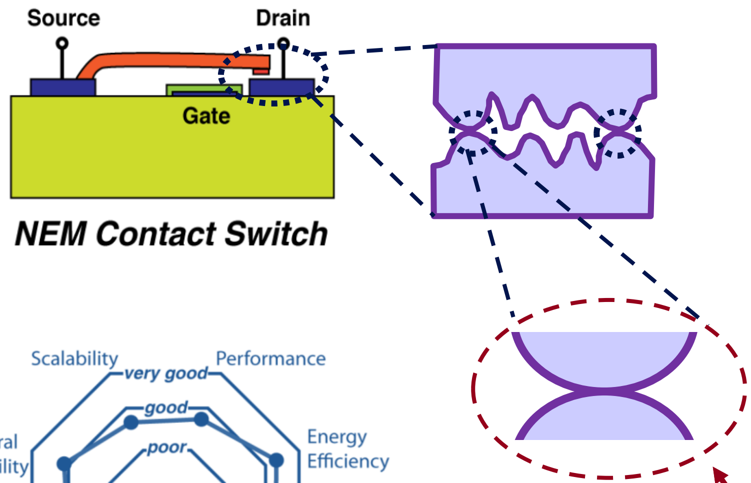
Image: J. Kim et al. (2004)

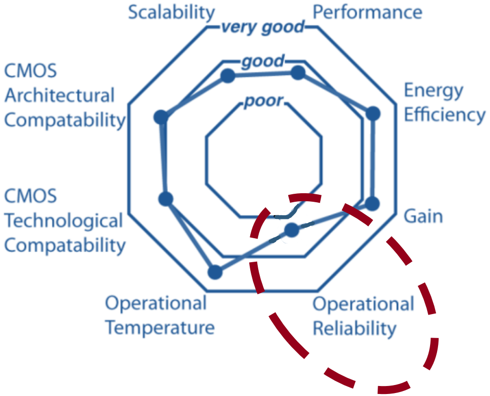


- F. Streller, et al. Novel materials solutions and simulations for nanoelectromechanical switches. IEEE Nanotechnol. Mag. 9, 18 (2015).

Reliability Challenge in NEMS switches

- **Reliability** issue
  - **Required: 10^9 to 10^{15} cycles**
- Degradation mechanisms:
  - Tribomechanical
    - Adhesion, plasticity, wear, …
  - Mechanochemical
    - Tribopolymer, oxidation, …
  - Electromechanical
    - Arcing, electromigration, …

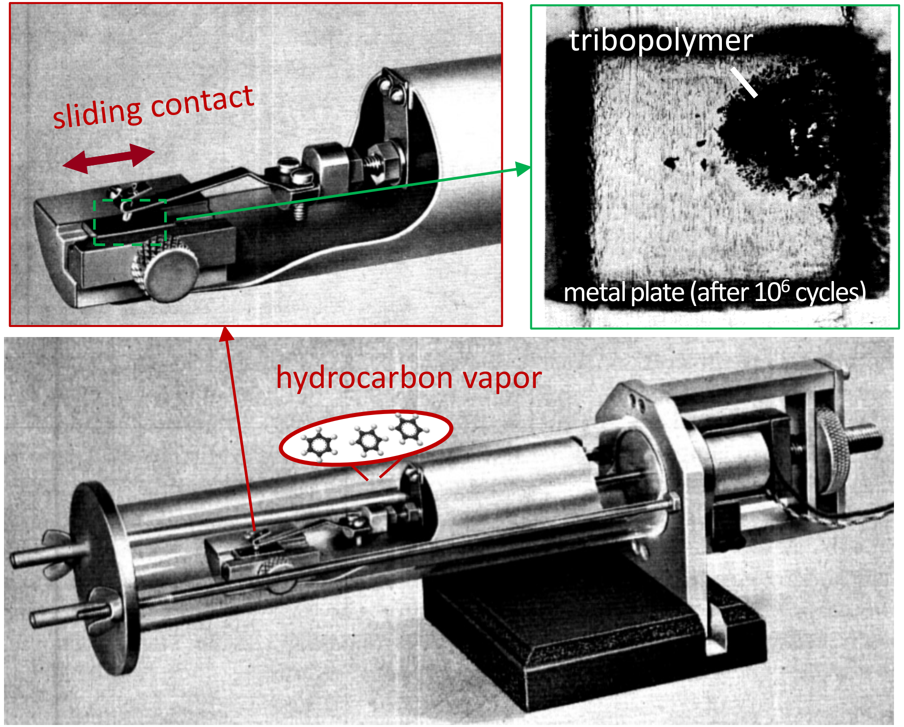




where tribology matters…

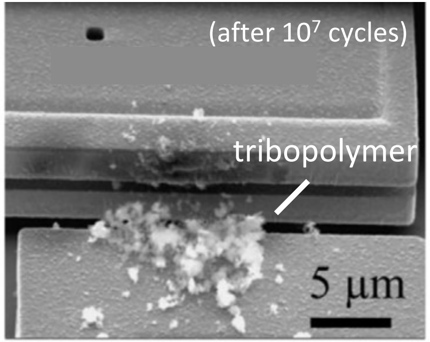
- International Technology Roadmap for Semiconductors (2009 report) – Emerging Research Devices.
- F. Streller, et al. Novel materials solutions and simulations for nanoelectromechanical switches. IEEE Nanotechnol. Mag. 9, 18 (2015).

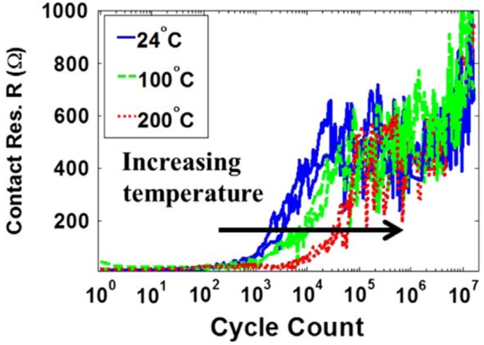
Tribopolymers in Electrical Contacts



Macroscale contacts

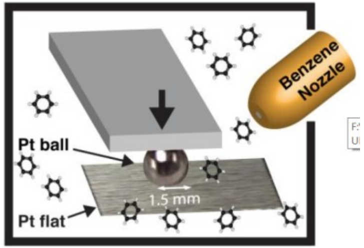
MEMS switch

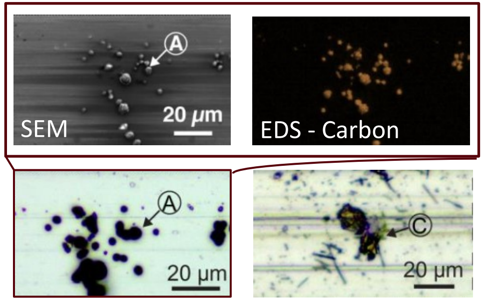


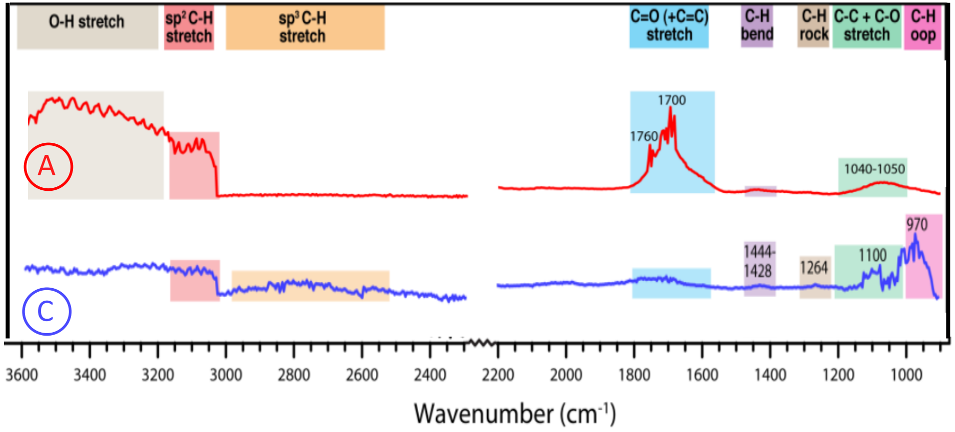


- H. W. Hermance and T. F. Egan, Organic Deposits on Precious Metal Contacts. Bell Syst. Tech. J. 37, 739 (1958).
- V. Brand, et al. Effects of electrical current and temperature on contamination-induced degradation in ohmic switch contacts. Tribol. Int. 85, 48 (2015).

Tribopolymers in Electrical Contacts





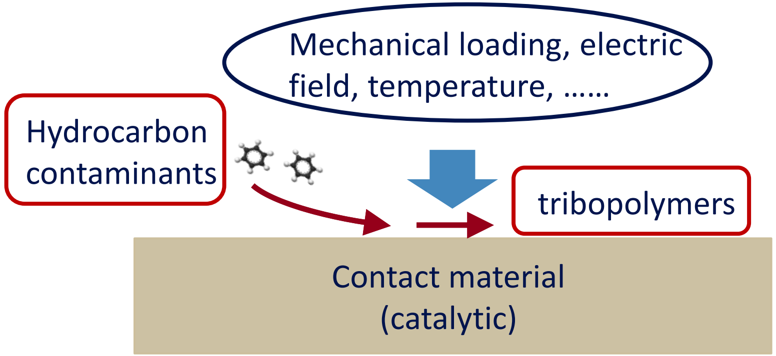


Chemical composition (nano IR): C=C, -OH, C=O, CH=CH, etc.

Tribopolymer

– Insulating organic deposits, resulting from **airborne hydrocarbon** contaminants.

– **Tribo-electro-chemical** reaction **catalyzed** by contact material.



- Streller, Frank, Development and Characterization of Next-Generation Contact Materials for Nanoelectromechanical Switches, (2016). Publicly Accessible Penn Dissertations. http://repository.upenn.edu/edissertations/2043.

Overview

- Background
- Controlling tribopolymer formation:
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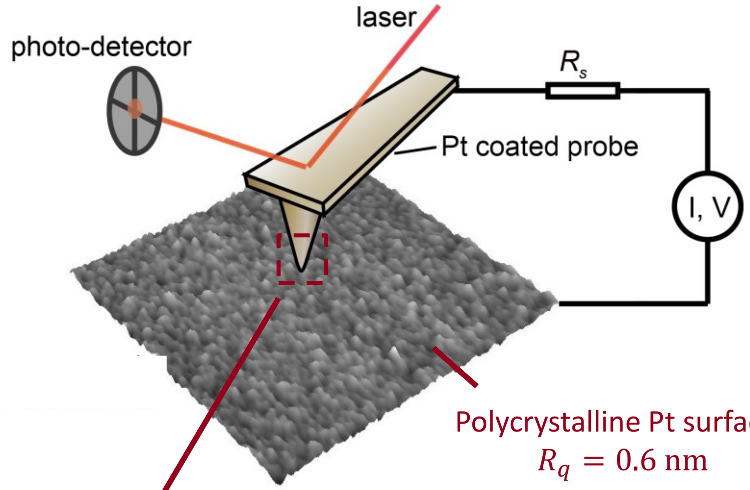
- Summary

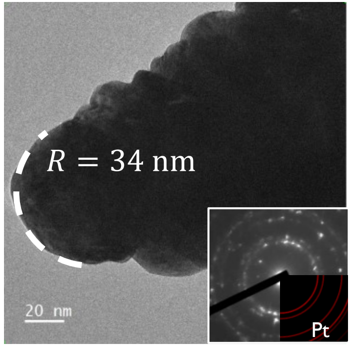
Experimental Setup

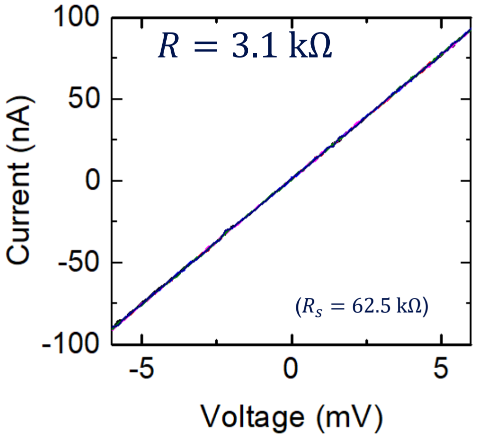
- Testing conditions
  - Ambient air, room temperature
- Pt electrical contact
  - 10~100 nm thick Pt coating, by magnetron sputtering (for both tip and sample)
  - Single asperity nano-contact
- Conductive AFM
  - Simulating NEMS switch contact
  - Capable of both **mechanical** and **electrical** measurements



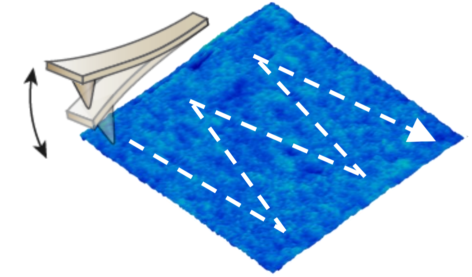
Polycrystalline Pt surface
$R_q = 0.6$ nm

Polycrystalline Pt tip

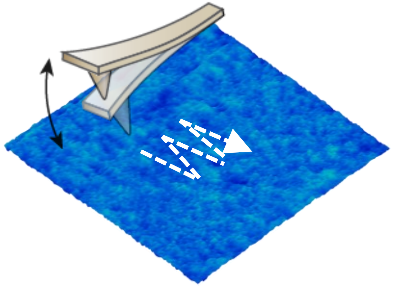




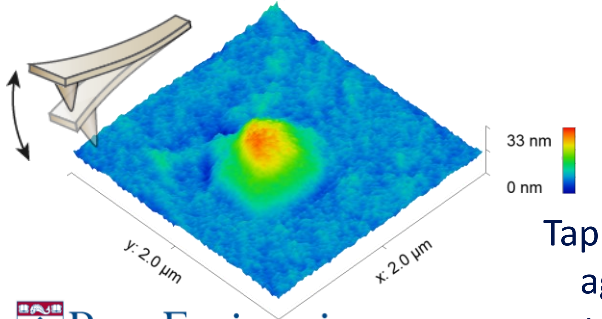
Visualizing Tribopolymers: AFM Imaging



Initial height image
- tapping mode



Tapping mode scan in central region x *N* (tribopolymer growth)



Tapping mode scan again to image tribopolymers

Cyclic testing (typical parameters & values)

	Imaging cycles	Reaction cycles
Mode	Tapping	Tapping
Scan size	2x2 µm^2	500x500 nm^2
Scan speed	5 µm/s	15 µm/s
Tapping frequency	70 kHz	
Signals measured	surface height	\
N	1:50	

In 7 hr lab runtime:
3500 reaction scans≈ 1.6×10^9 ON/OFF events

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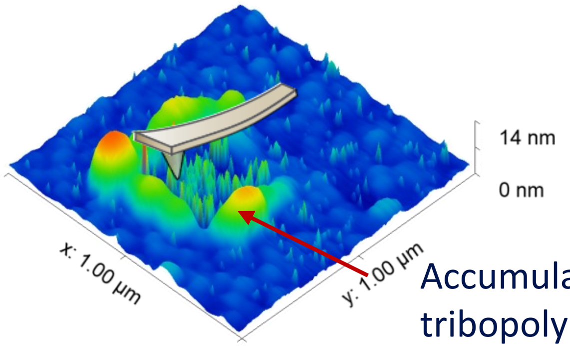
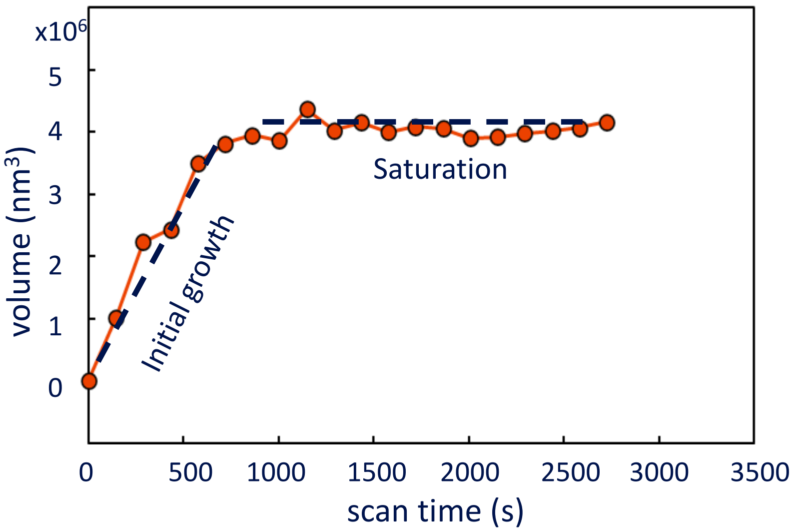
Controlling Stress for Tribopolymer Growth





Cyclic testing (typical parameters & values)

	Imaging cycles	Reaction cycles
Mode	Tapping	Contact
Scan size	1x1 μm^2	300x300 nm^2
Contact force	7 nN (peak value)	64 nN (constant)
Scan speed	5 µm/s	15 µm/s
Tapping frequency	70 kHz	\
Signals measured	surface height	(apply) normal force, bias voltage
N	1:10	

Volume of tribopolymers

Stress-assisted Tribopolymer Growth

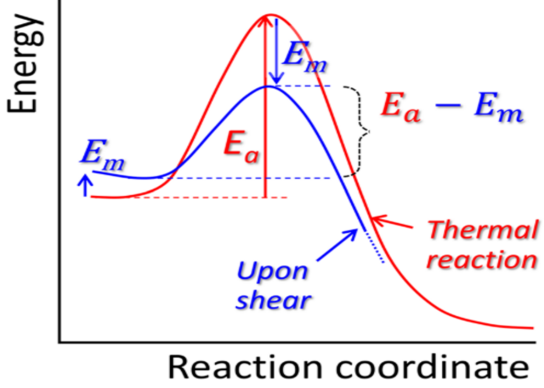
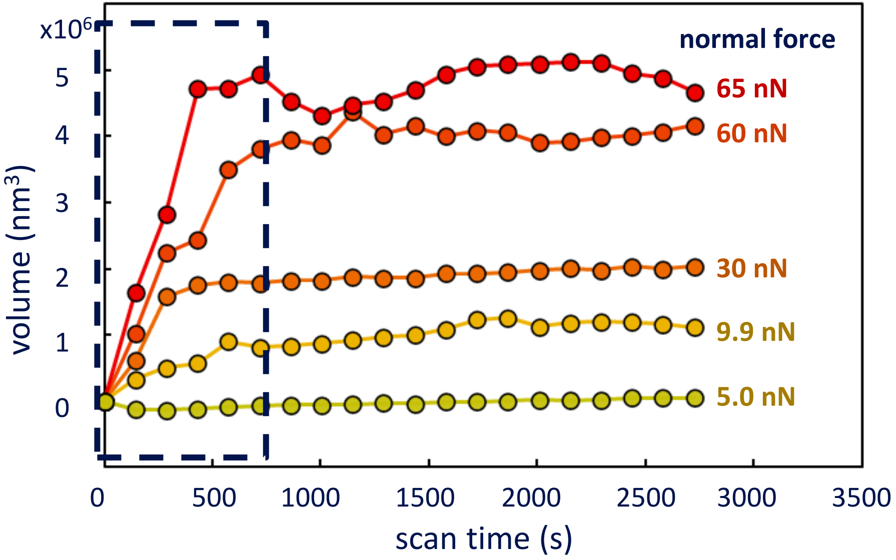
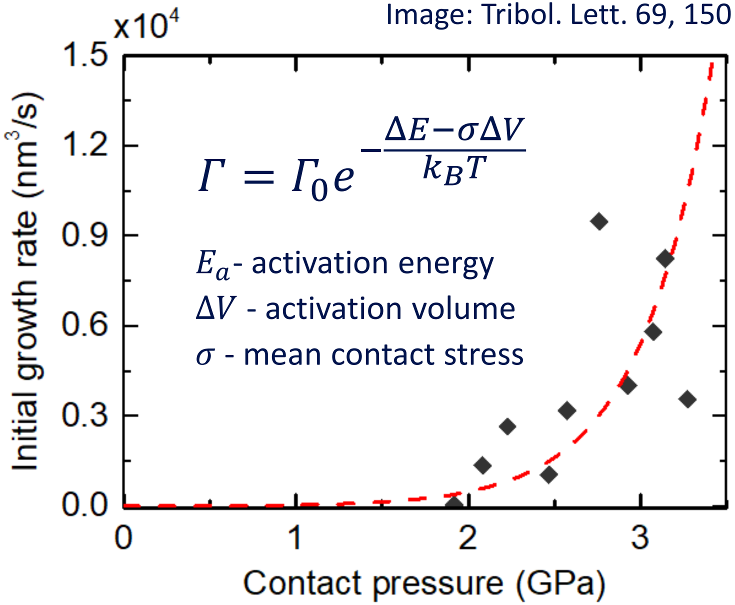


Image: Tribol. Lett. 69, 150 (2021)

- Tribopolymer growth under **various contact force/stress**
  - Stress calculated from normal force and (initial) tip radius
  - Stress-dependent growth rate: **stress-assisted thermal activation model**





* Tip radius 34 nm, pressure calculated from initial geometry

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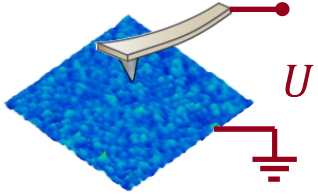
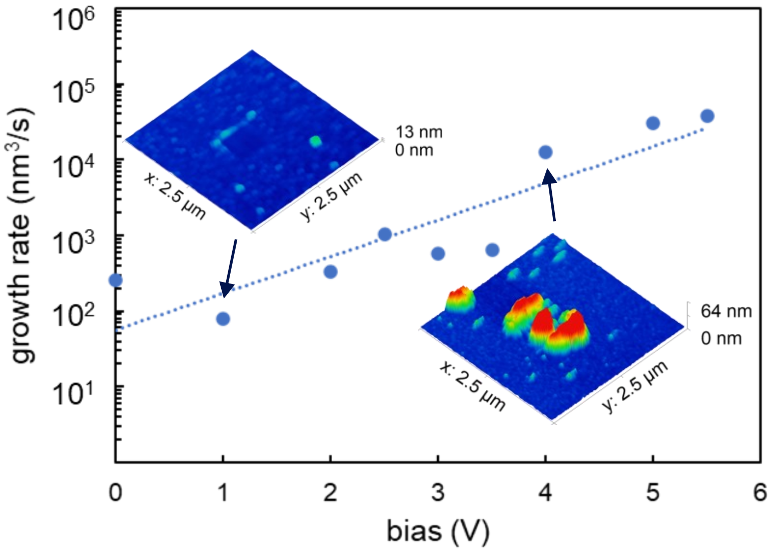
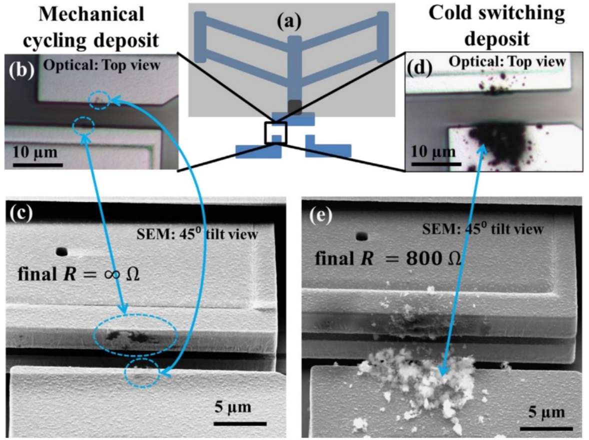
Voltage-assisted Tribopolymer Growth

Voltage-assisted tribopolymer growth

- Similar exponential dependence: $\ln \Gamma \sim aU + b$
- 5 V ≈ 2 GPa ≈ 260 times increase in growth rate





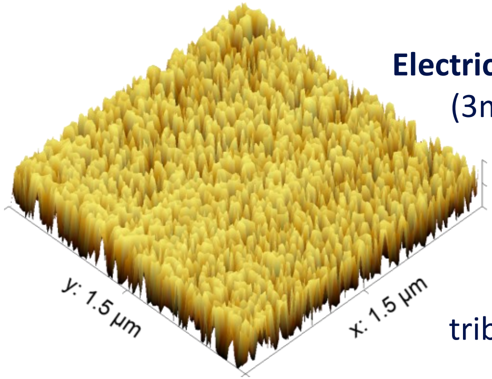


Consistent with MEMS observations:
Passing through current produces more tribopolymers

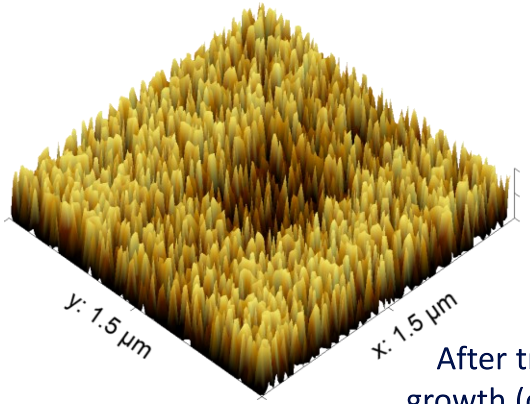
- V. Brand, et al. Effects of electrical current and temperature on contamination-induced degradation in ohmic switch contacts. Tribol. Int. 85, 48 (2015).

Monitoring Conductivity Evolution with AFM

Electric current image
(3mV voltage)



Before tribopolymer growth

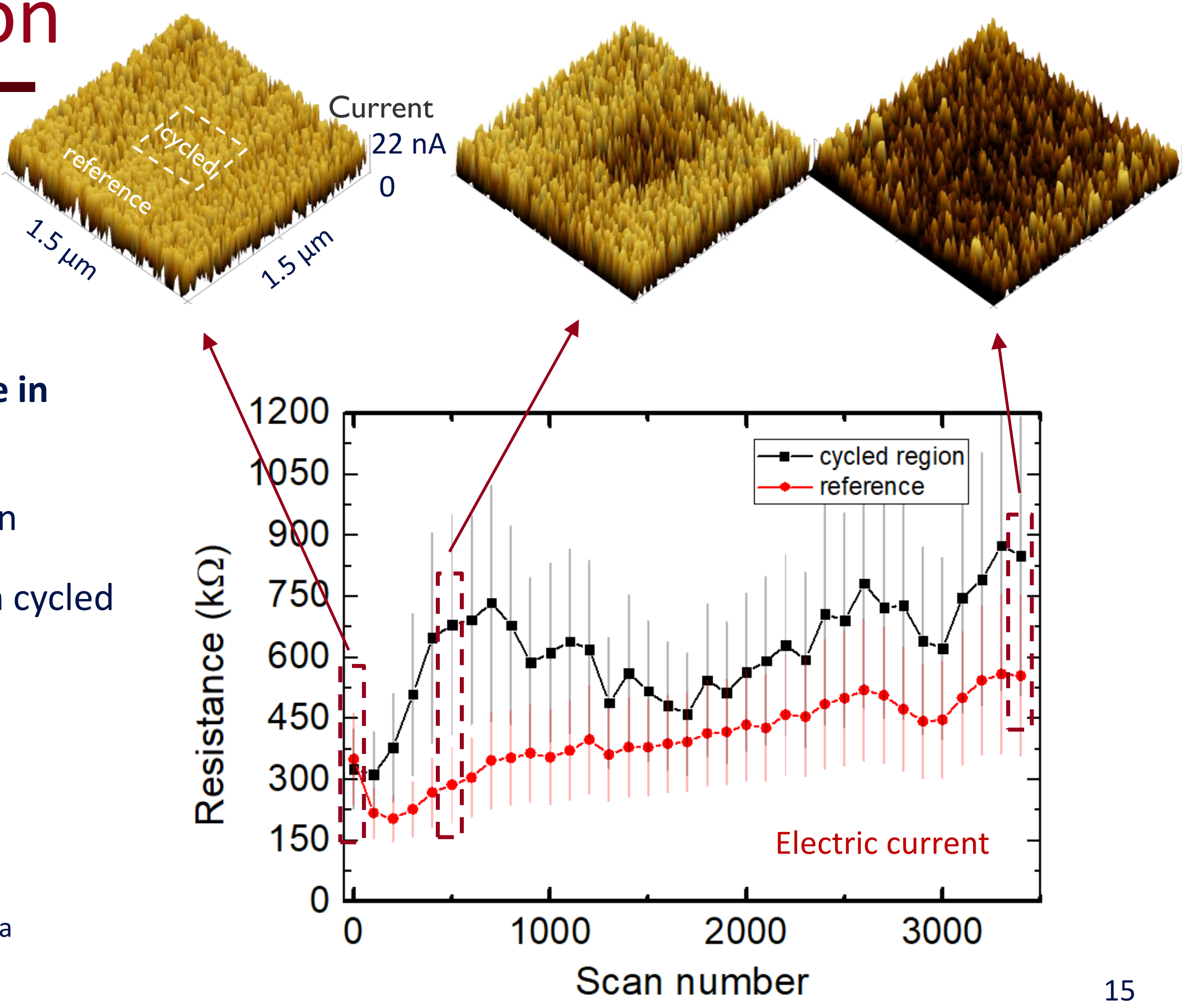


After tribopolymer growth (central region)

Cyclic testing (typical parameters & values)

	Imaging cycles	Reaction cycles
Mode	Contact	Tapping
Contact force	31 nN (constant)	72 nN (peak value)
Scan size	1.5x1.5 µm^2	500x500 nm^2
Scan speed	5 µm/s	15 µm/s
Tapping frequency	\	70 kHz
Signals measured	surface height, electric current (@3mV voltage)	\
N	1:100	

Conductivity Evolution



Electric current images:

- Evolution of contact resistance
  - Cycled region shows a 2 times **increase in resistance**, but…
  - It partially recovers as scanning goes on
  - Overall: increase of resistance for **both** cycled and reference regions
  - suggests **formation** and **spreading** of tribopolymers …

*errorbars represent standard deviation of current

*maximum tapping force 72 nN, estimated pressure 2.7 GPa

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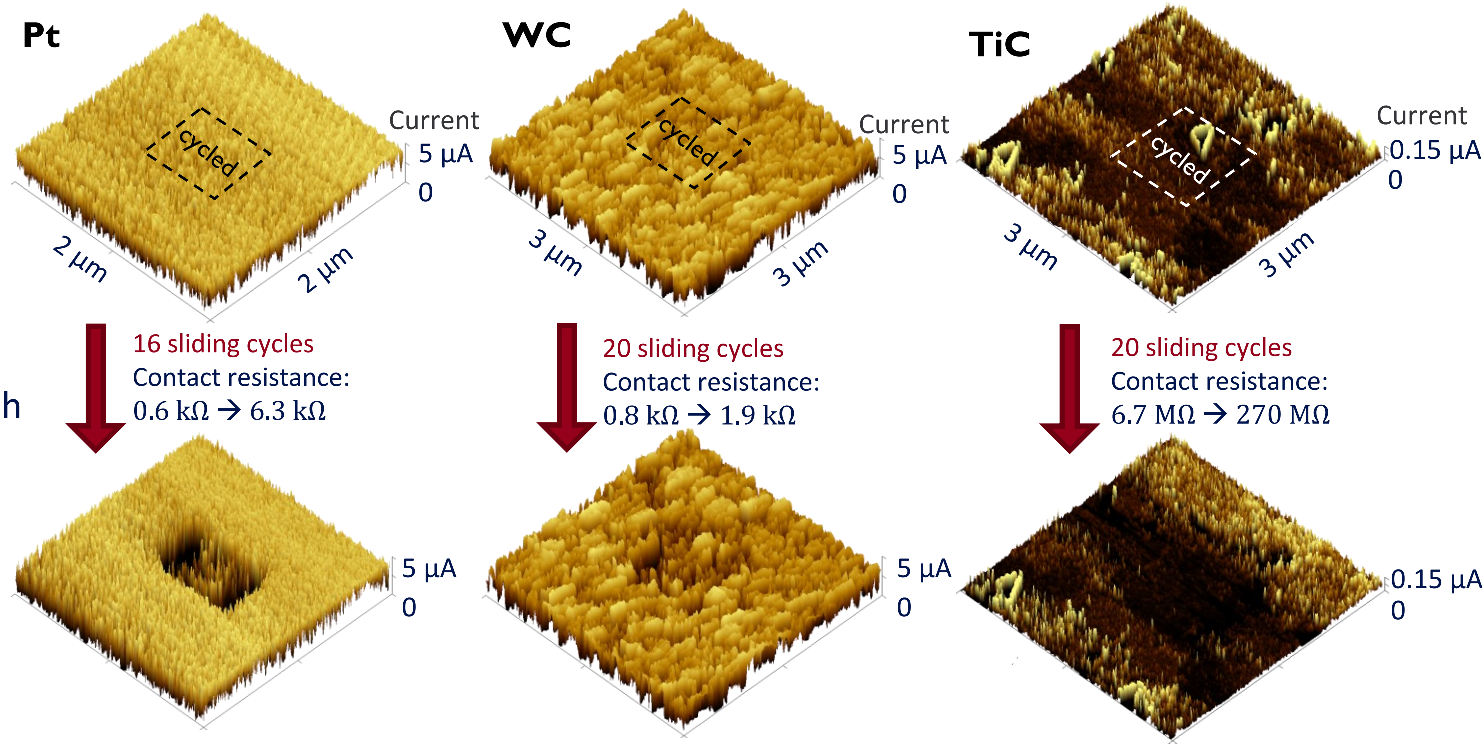
Contact Material and Tribopolymer Growth

WC, TiC, and Pt:

cyclic sliding

- Comparing conductivity loss after cyclic sliding
- WC and TiC build much less tribopolymers compared to Pt



***Electric current images**: before & after cyclic sliding*

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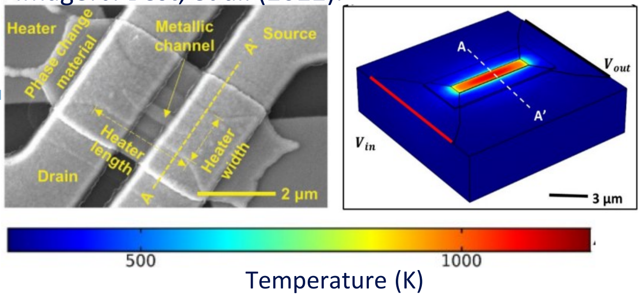
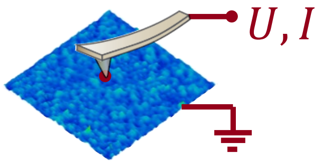
Conductivity & Thermal Stability

Image: J. Best, et al. (2022).

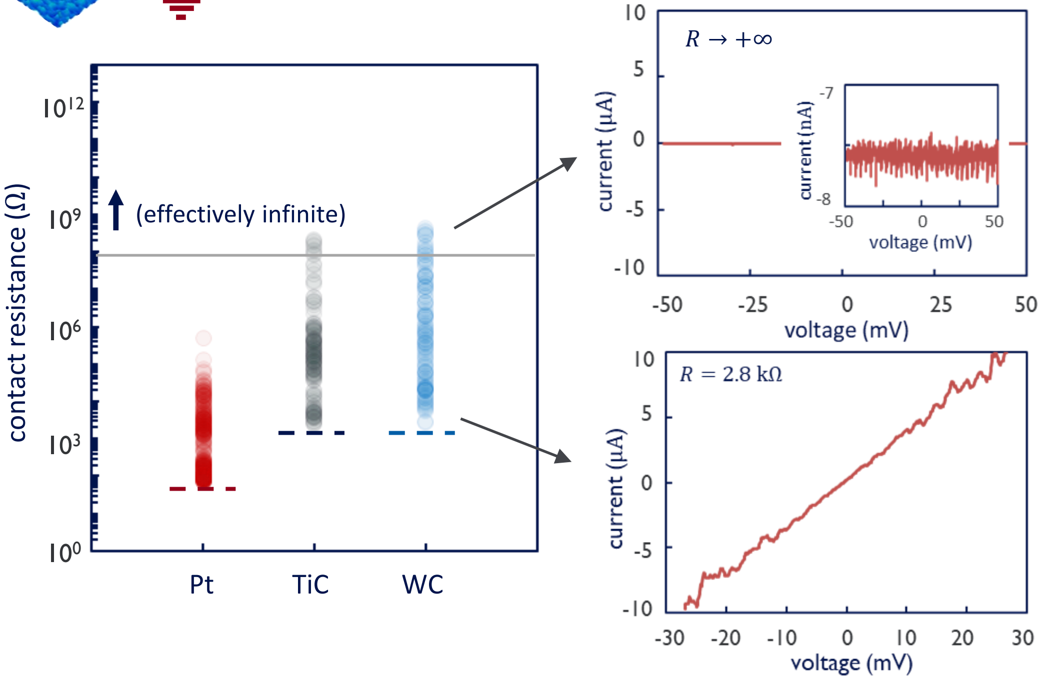




WC, TiC, and Pt:

Conductivity & thermal stability

- Pt:
  - no change (small decrease) in contact resistance
- WC and TiC:
  - Contact resistance **increase** in after heated in air…



Conductivity & Thermal Stability

WC, TiC, and Pt:

Conductivity & thermal stability

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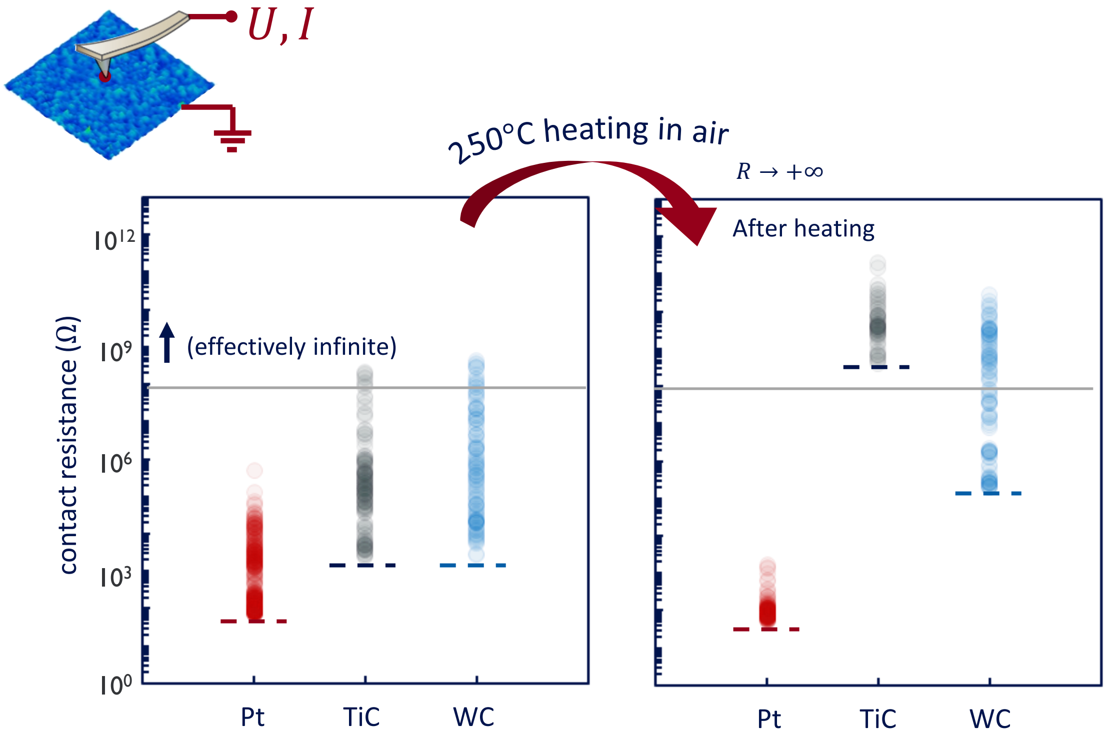


Conductivity Loss due to Oxidation

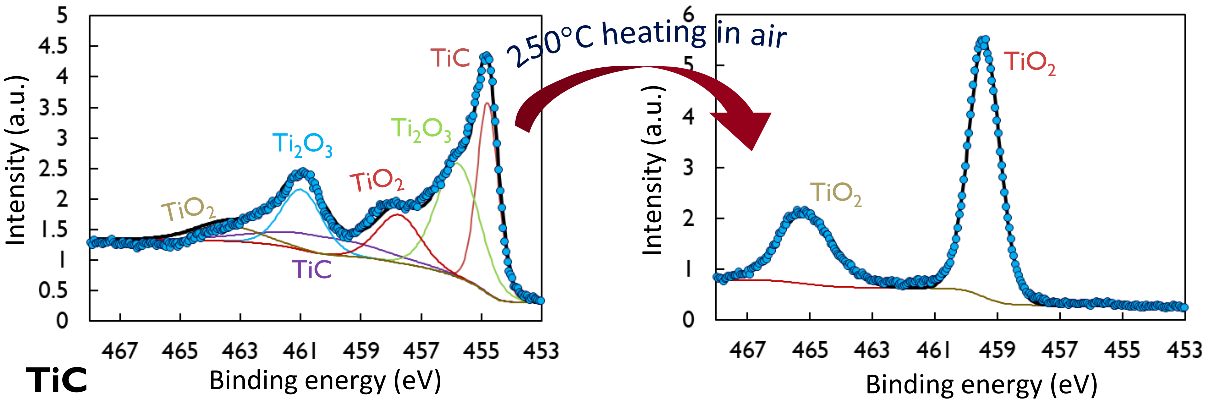
WC, TiC, and Pt:

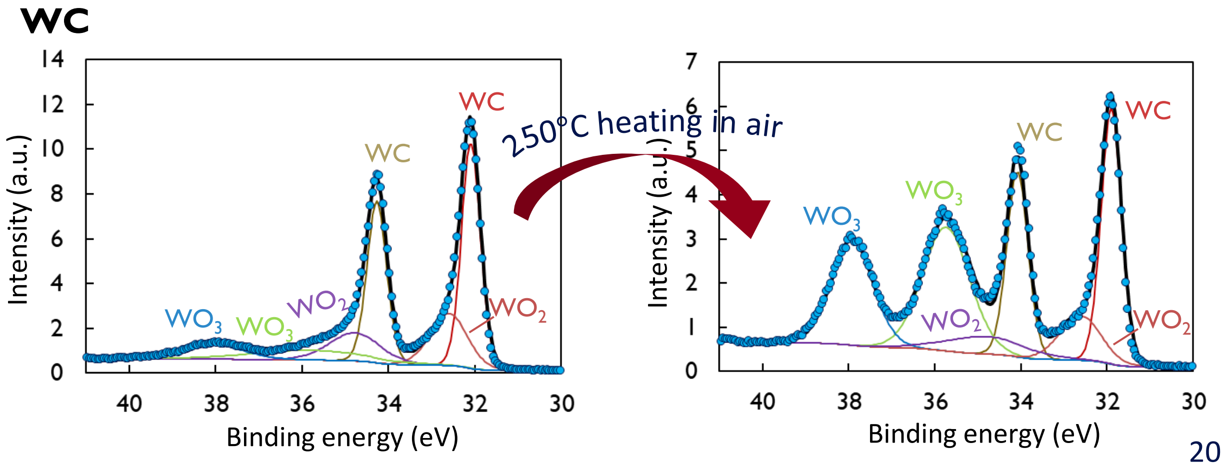
Thermal stability - oxidation

- XPS results: conductivity loss is due to oxidation

Ti atomic%	Ti^{2+} (TiC)	Ti^{3+} (Ti_2O_3)	Ti^{4+} (TiO_2)
Before heating	37%	44%	19%
After heating	\	\	100%

W atomic%	WC	WO_2	WO_3
Before heating	58%	26%	15%
After heating	40%	14%	45%





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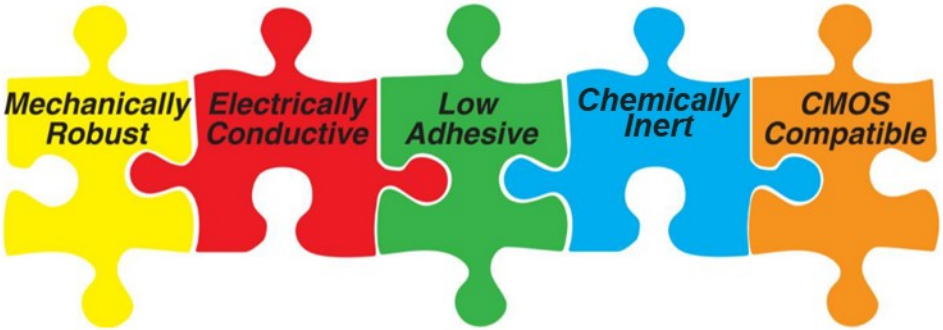
Exploring Contact Materials

WC, TiC, and Pt:

- Thermal stability/oxidation resistance: Pt > WC >TiC
- Tribopolymer-free: TiC≈ WC > Pt

Searching for ideal contact materials …



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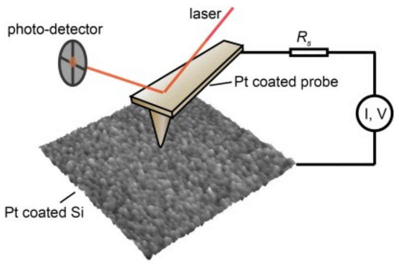
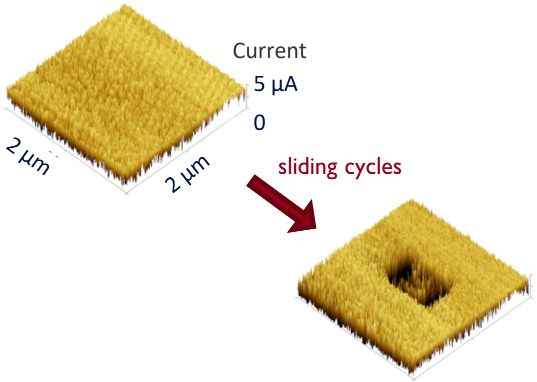
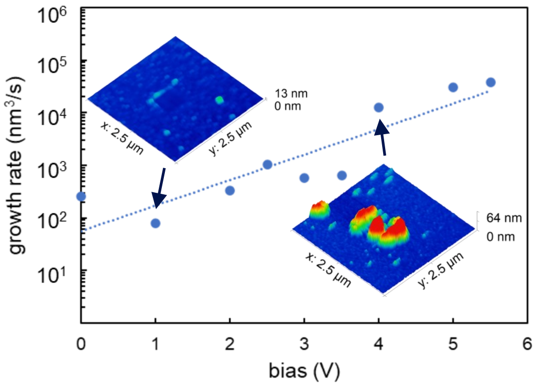
Summary

- Using AFM to study electrical contacts under NEMS switch-like conditions:
  - Monitoring conductivity evolution or tribopolymer growth, depending on imaging mode
- Stress and voltage dependence of tribopolymer growth
- Evaluating and searching for ideal contact materials…..







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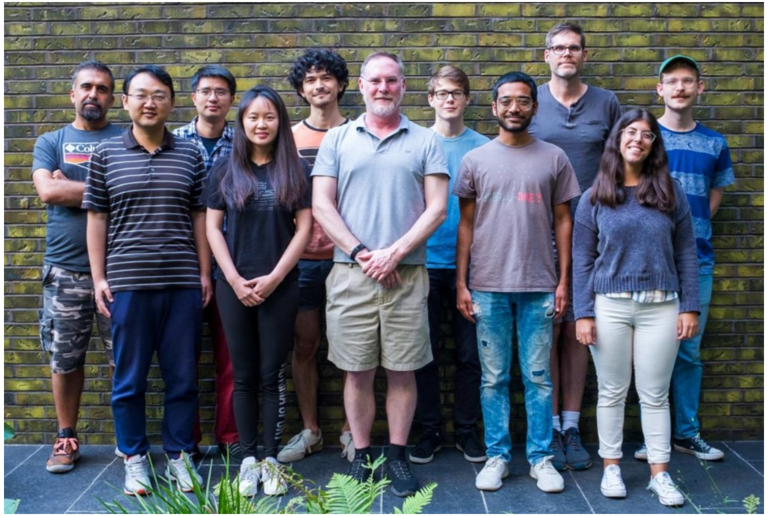
Acknowledgements

Carpick group



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Penn-CMU collaboration

Prof. Maarten de Boer

Prof. Gianluca Piazza

Carnegie Mellon University
College of Engineering

Penn Engineering

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