MEMS Reliability

Materials Reliability TCG XIV

SAND2010-7703P

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Brad Boyce	***MEMS Reliability and Properties***
Mike Dugger	***MEMS Tribology and Wear***
Leslie Phinney	***Microscale S&T / Device Reliablity***
Dave Reedy	***Fracture of MEMS***
John Lopez	***Reliability of COTS MEMS Devices***

Customer	Collaboration
Mike Deeds, NSWC, Indian Head,	**SOI Test Structures MEMS Reliability Test Platform**
Abdul Kudiya, Judy Potter-Shields ***AMRDEC Redstone***	**Reliability Testing of COTS MEMS Devices**
James Zunino, ARDEC	**Reliability of MEMS Devices**
Dan Rader, *SNL* **Ernie Garcia, *SNL*** **Randy Shul, *SNL***	**Manager- Microscale Science and Technology** **SOI Micro-optical Switch Project Lead** **Reliability and Process Test Structures associated with Sandia SOI fabrication process**

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Task *'MEMS Reliability'* Four-Question Chart

What are you trying to do in this task?

- Develop diagnostic test structures to gain an understanding of the process dependent reliability characteristics of MEMS materials
- Realize the common failure modes in MEMS components

What makes you think you can do it?

- Experimental platforms for microscale characterization, environmental aging and reliability.
- Staff members with expertise bridging, materials, mechanics and device reliability.
- Collaboration with DOD personnel focused on MEMS development and reliability.

What difference will it make?

- Necessary information will be provided to develop qualification specs. for MEMS devices used in military applications
- Current qualification procedures follow microelectronics specifications.

What / When / To Whom Will You Deliver?

- Accelerated Aging protocol leading to a specification for the qualification of MEMS devices for military applications

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Task: MEMS Reliability – A Few Major Results To Date

- Characterization of measurable properties that govern reliability on SOI-MUMPS fabrication process (Miller, D.C., et al. Sensors and Actuators A, 2007)

- Steering group meetings began in 2008
  -Bottom-up/Top Down approaches
  -focus on obtaining results useful for reliability specifications

- SOI Reliability Test Platform

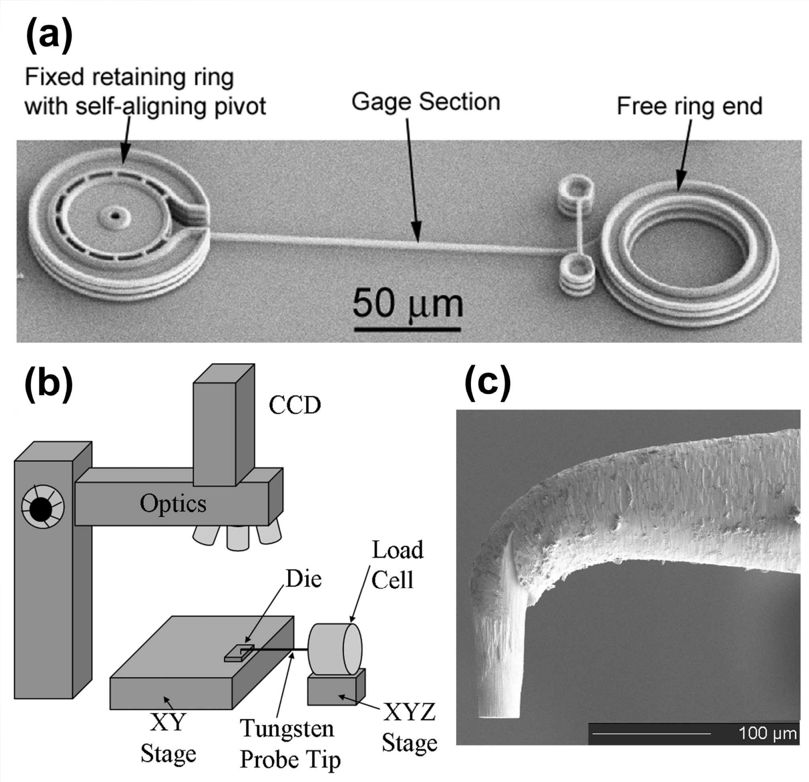
- Shock Margin Testing of ADXL-80 Accelerometer
  (SAND2009-3909)

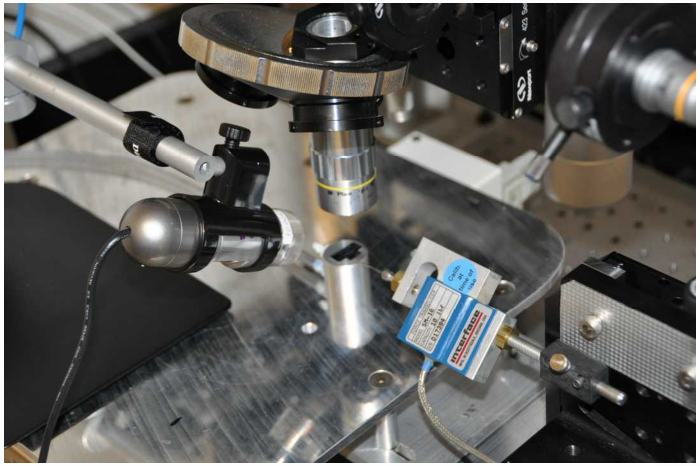
- A method for rapid measurement of fracture strength of MEMS structural silicon (Boyce B.L., Experimental Mechanics 2010)

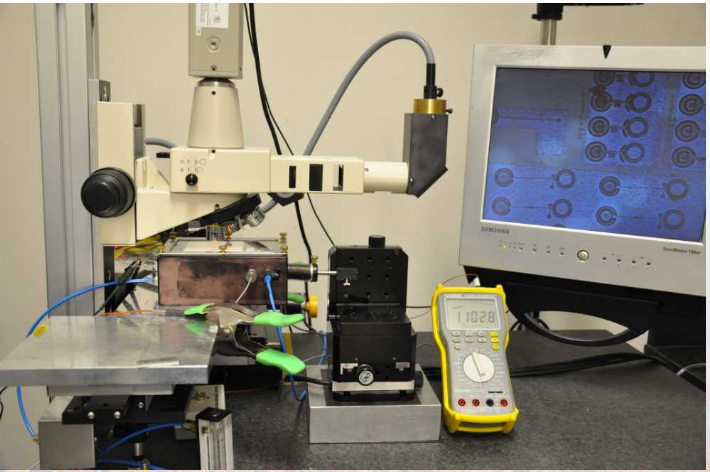
Task MEMS Reliability- FY11 Activities

- Characterization of High Temp. degradation of Silicon used in MEMS fabrication (WSEAT+JMP)
- Predicting/Understanding Fracture in micron scale silicon structures (ASC+WSEAT)
- Characterization and measurement of SOI reliability test structures (WSEAT+JMP)
- MEMS/COTS Device Reliability (WFO+JMP)

Platform for testing the Mechanical Response of MEMS Devices





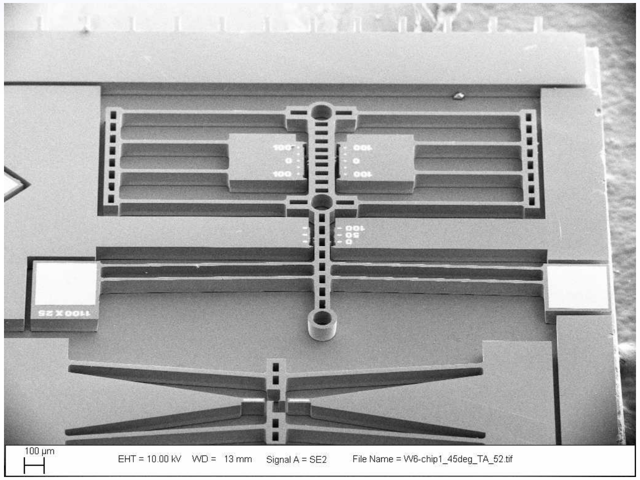


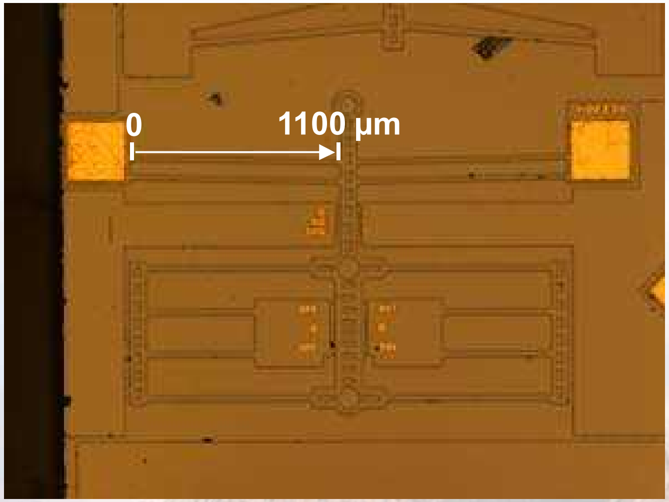
High Temp. test set-up

- Passive load cell – 25 µN resolution
- mechanical testing
- mechanical characterization of devices
- high temperature testing

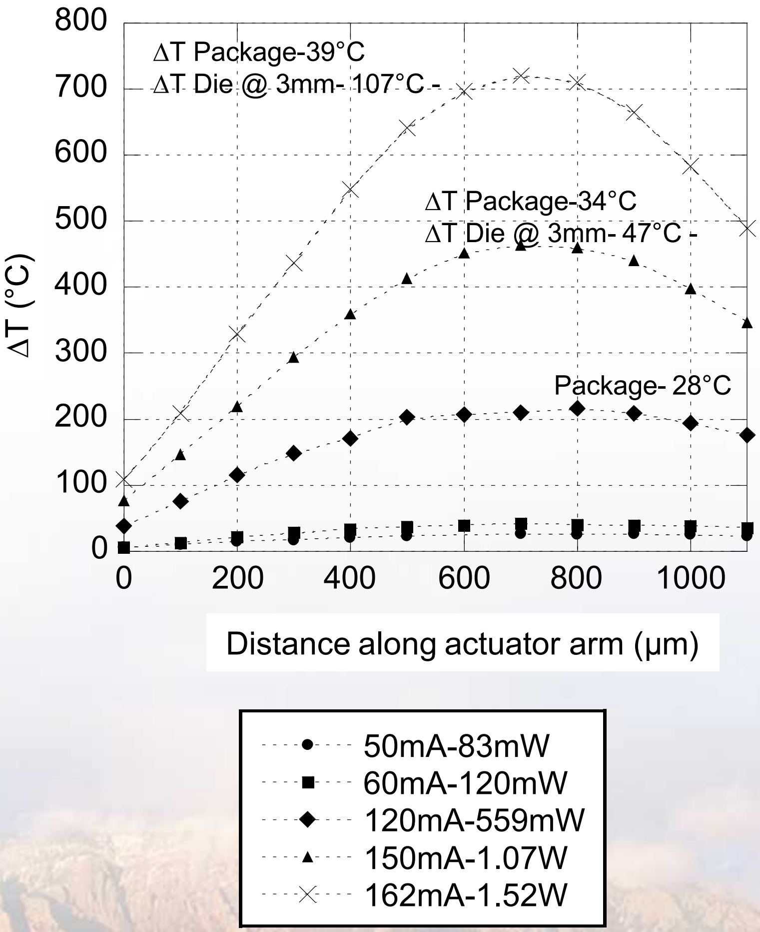
Boyce, *Experimental Mechanics,* 2010

Temperature profile within a thermal actuator





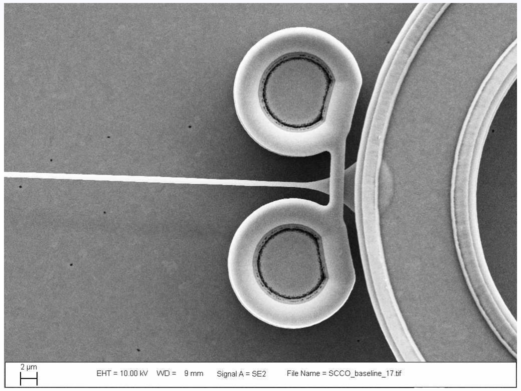
Temperature profile at several power inputs on a 1100 μm Thermal Actuator



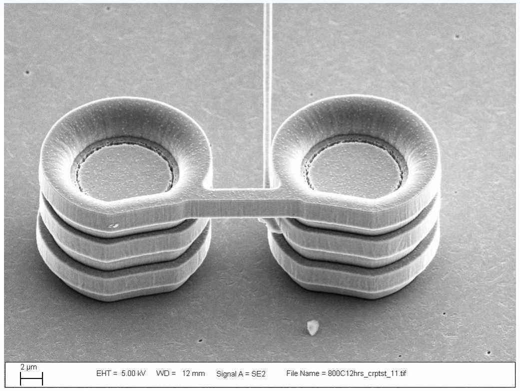
Machiraju, H., Infantolino. B., Sammakia B., and Deeds M., "Thermal Analysis of MEMS Actuator Performance", Proceedings IMECE 2007,

Preliminary results from Thermal Exposure on SMM polysilicon raised concerns

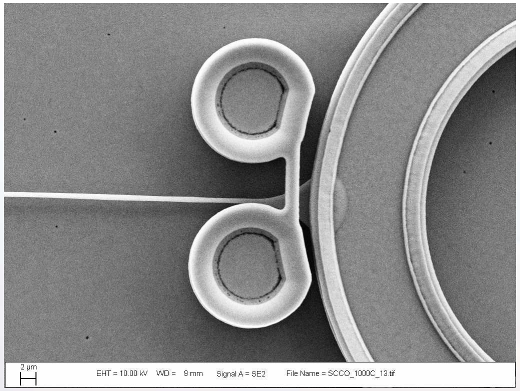
(Environment – Ar with ~5-7ppm oxygen)



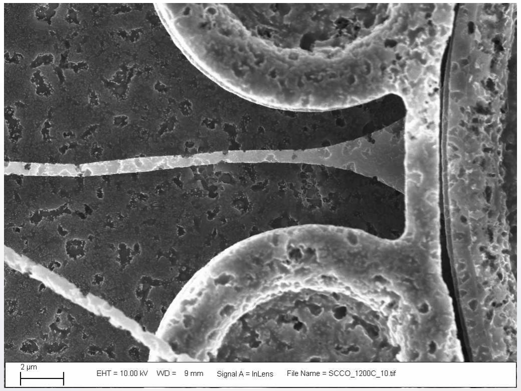
Baseline Sample



800C (~12 hr) SCCO2 release

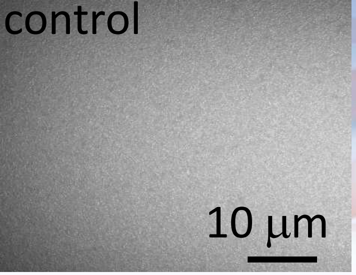


1000C (~1hr) SCCO2 release

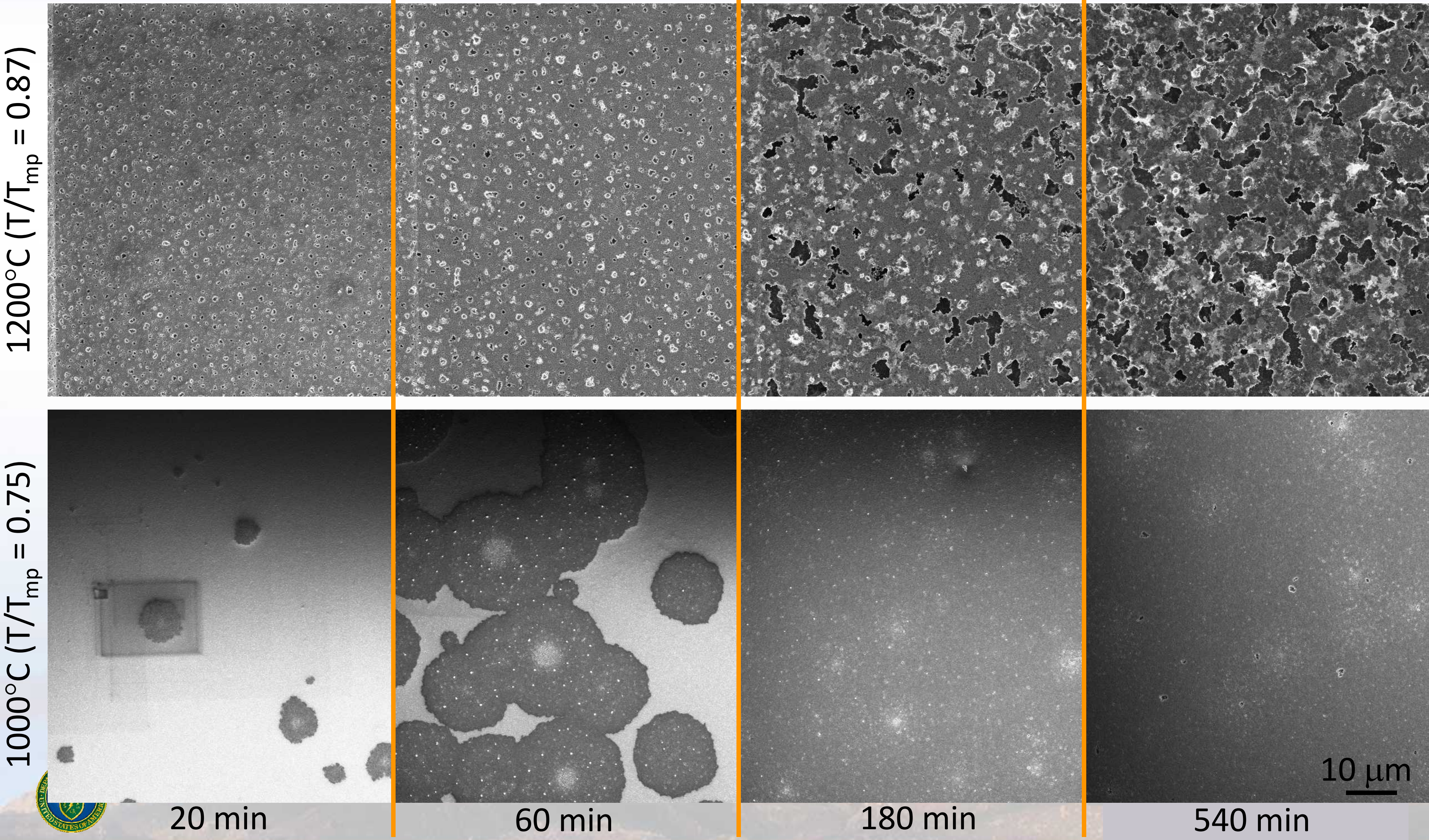


1200C (~1hr) SCCO2 release

	20 min	60 min	180 min	540 min
1200°C	**Argon & Air**	**Argon & Air**	**Argon & Air**	**Argon & Air**
1000°C	**Argon & Air**	**Argon & Air**	**Argon & Air**	**Argon & Air**



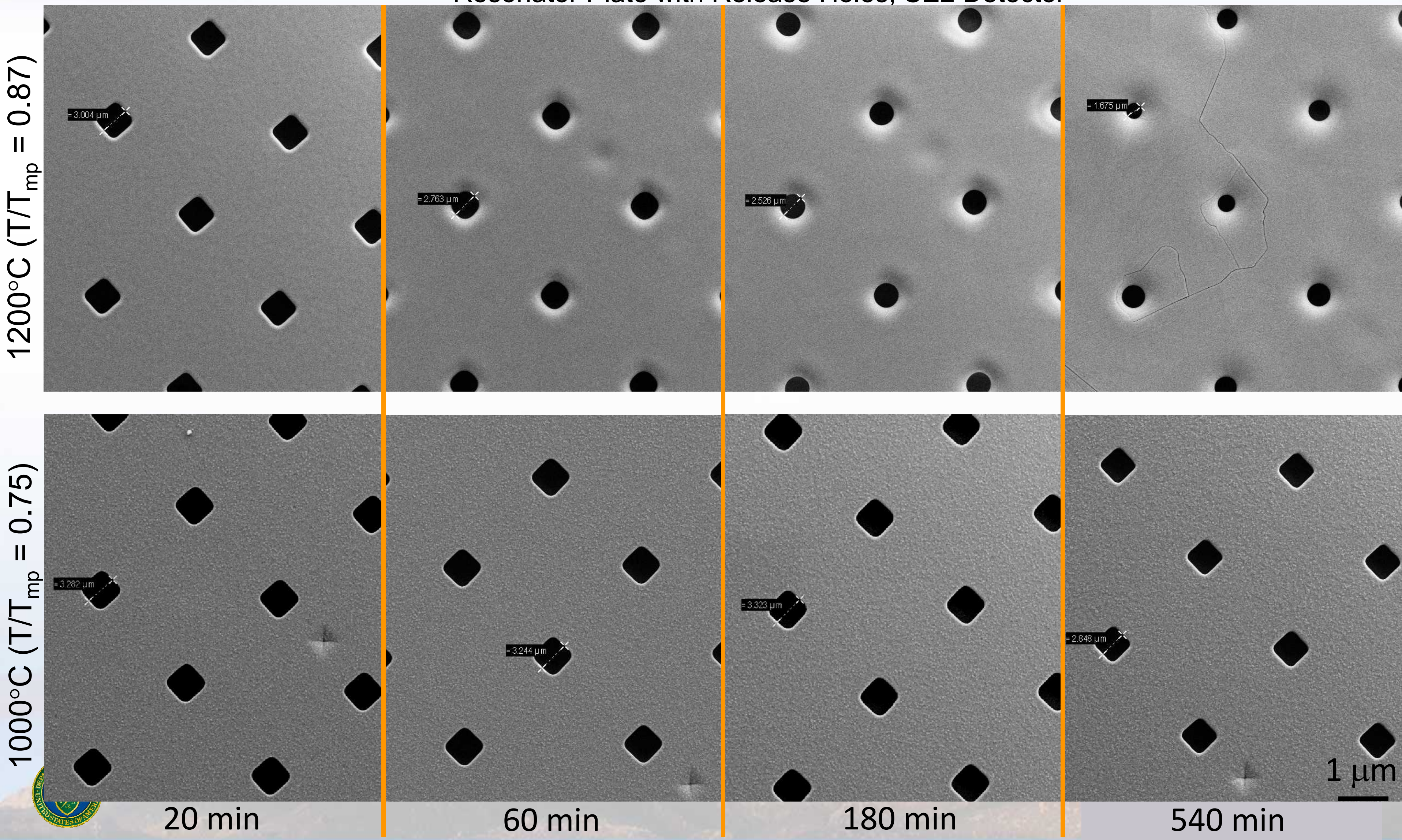
SUMMiT V Polysilicon: Annealing in Argon revealed an evolution of degradation



RS484 SCCO2 Release Poly3 or Poly4 layer Resonator Bondpad

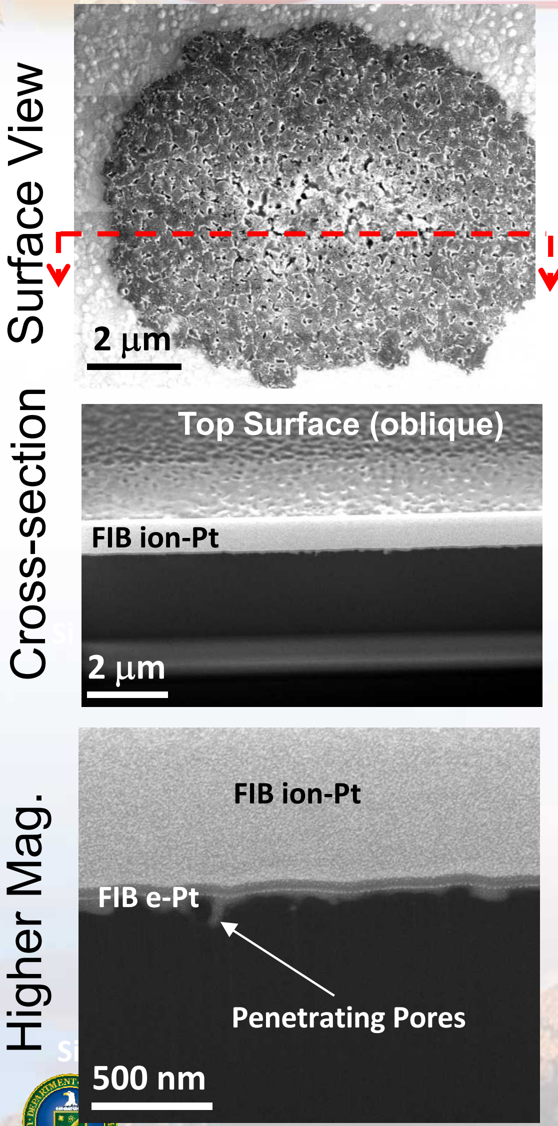
Degradation mechanism is suppressed when samples are annealed in an ambient (air) environment

Resonator Plate with Release Holes, SE2 Detector

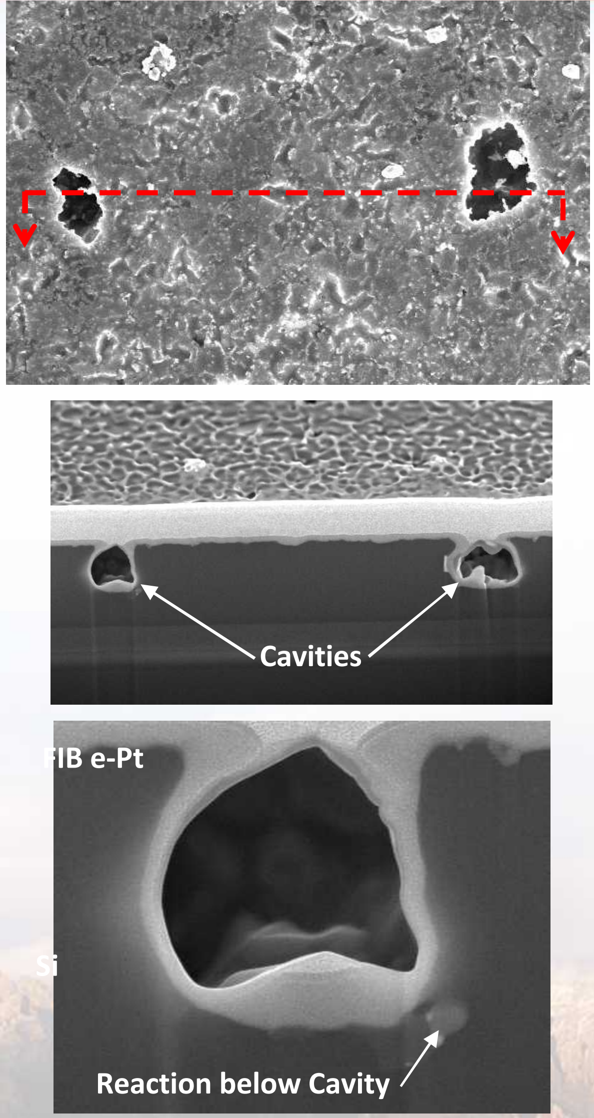


RS484, SCCO2 Release, Poly3 or Poly4 layer, Resonator Bondpad

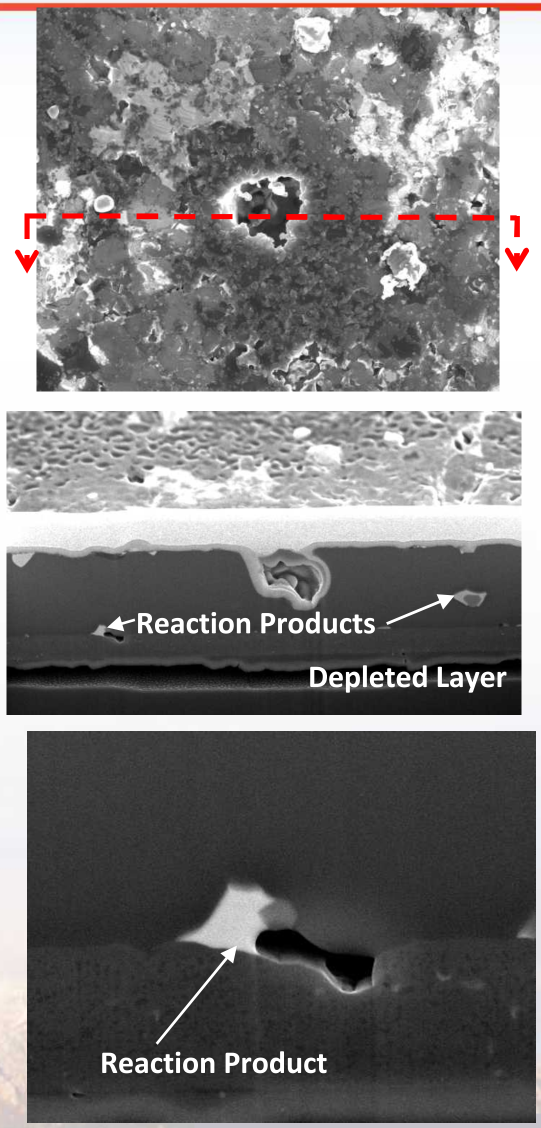
FIB cross-sectioning reveals a complex degradation process



1000°C/20 min/Argon



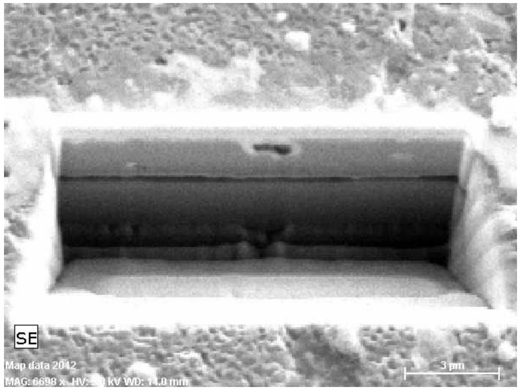
1200°C/20 min/Argon

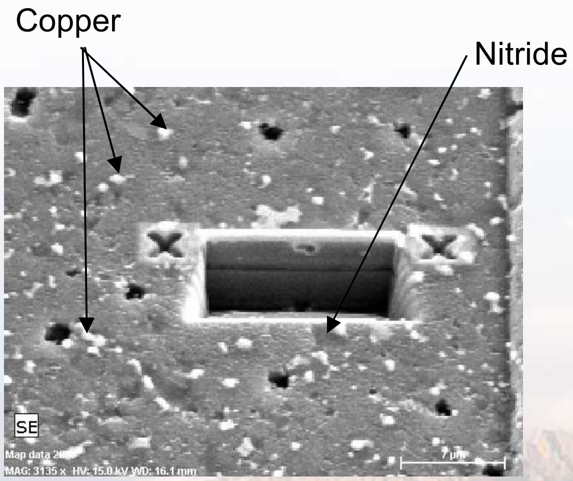


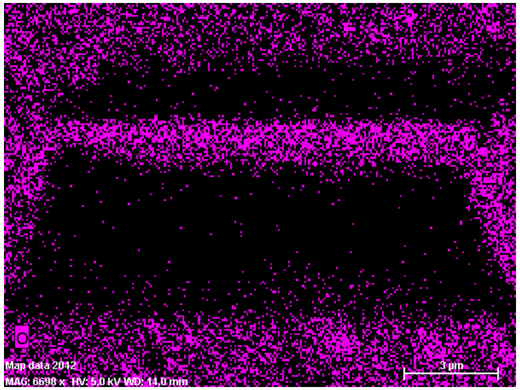
1200°C/3 hr/Argon

Energy Dispersive Spectroscopy revealed contamination during the annealing treatments

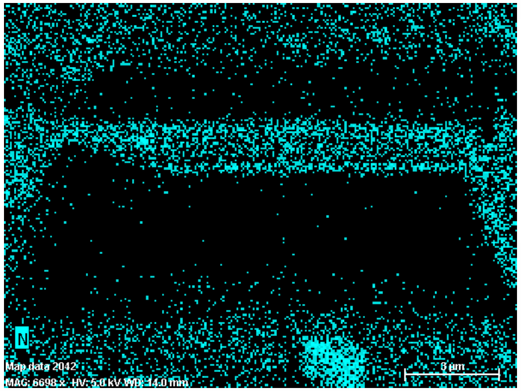
Sample: 1200C/3hr in Ar



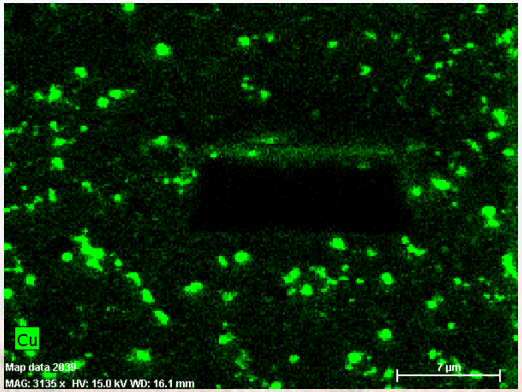




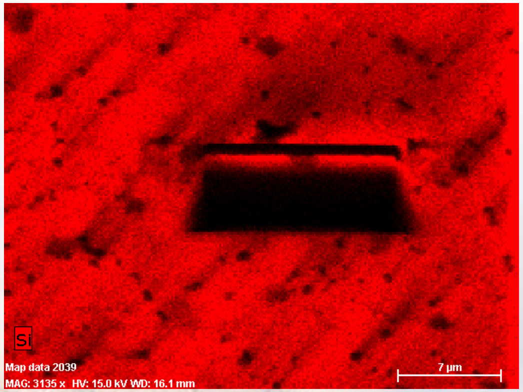
Oxygen



Nitrogen



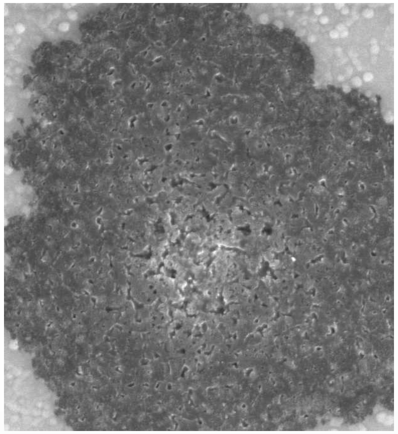
Copper



Silicon

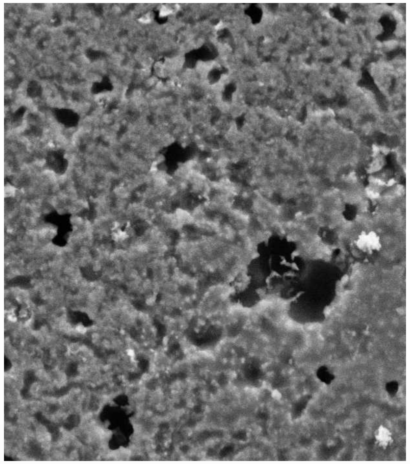
Four Degradation Processes have been Hypothesized

Nucleation of generalized surface nanoporosity and propagation away from nucleation sites.



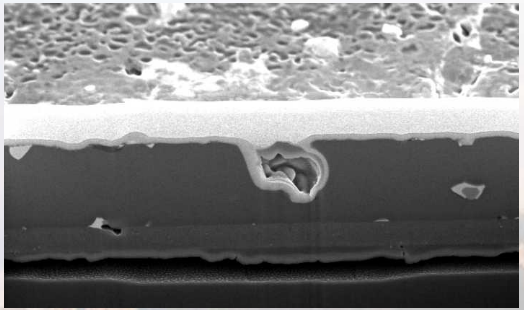
< 1000°C / 20 min

Formation of Penetrating Microcavities



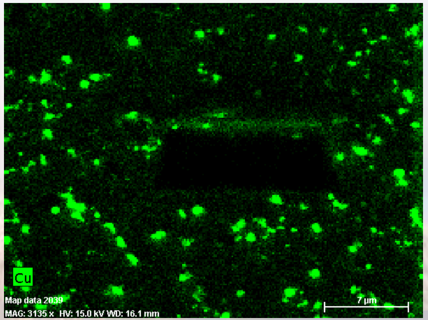
<1000°C / 9 hrs

Depletion/consumption of wafer thermal oxide layer below nitride



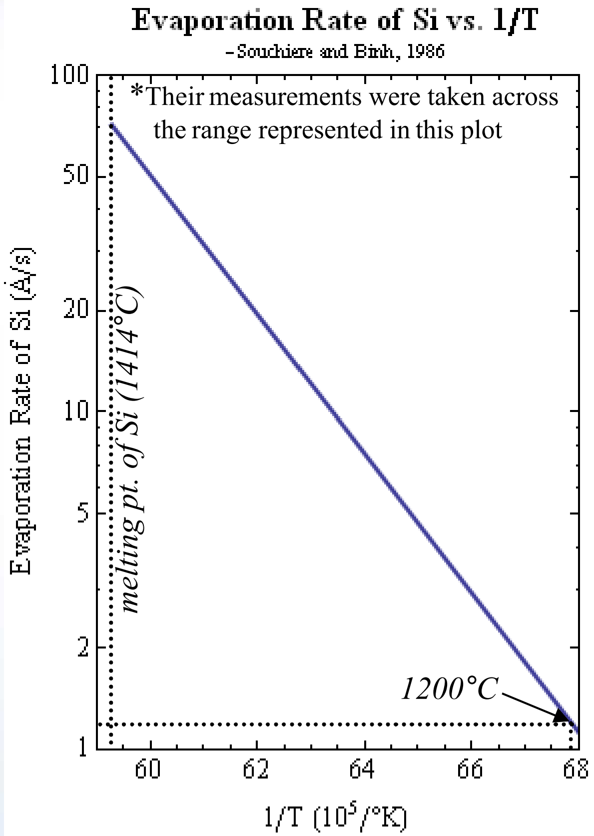
<1200°C / 3 hrs

Copper-containing particles on surface and in tunneling pores



< 1200°C / 3 hrs

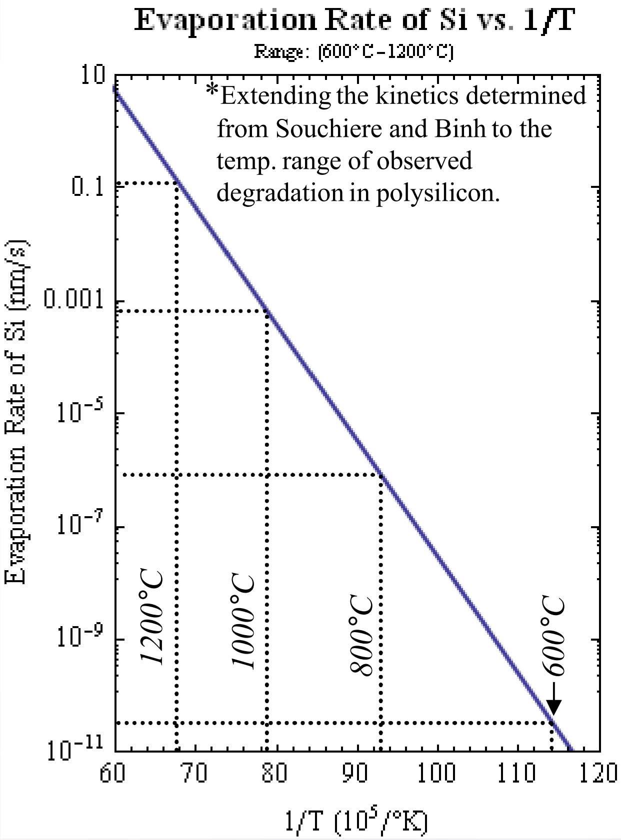
Evaporation as a primary degradation mechanism is expected to shut down near 800°C



Evaporation Rate of Si vs. 1/T

–Souchiere and Binh, 1986

*Their measurements were taken across the range represented in this plot



Evaporation Rate of Si vs. 1/T

Range: (600°C–1200°C)

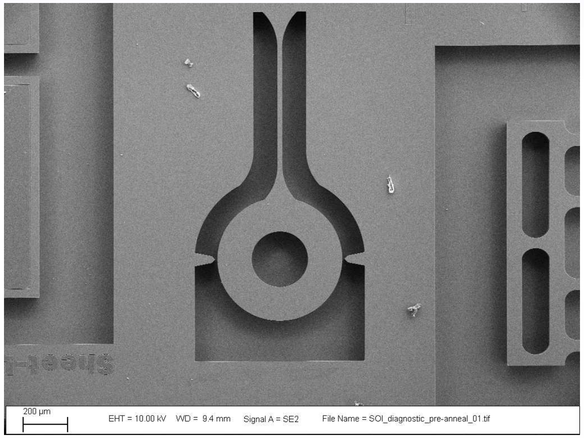
*Extending the kinetics determined from Souchiere and Binh to the temp. range of observed degradation in polysilicon.

Amt. of Si evaporated (or sublimated) per Hr.

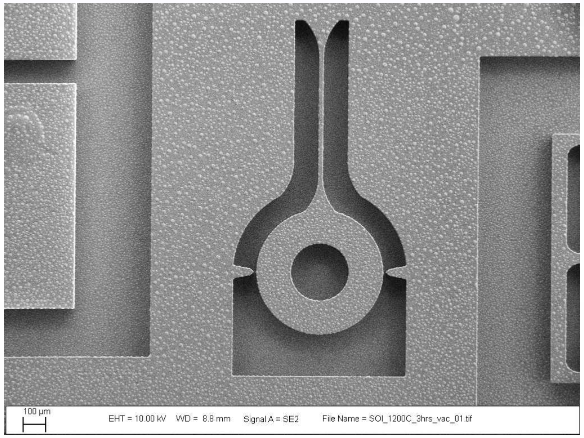
1200°C = 360 nm
1000°C = 3.5 nm
800°C = .004 nm

- Seems to be a good qualitative correlation between this model and observed results.
- Predicted Evaporation rates are 10 times slower at 1000C vs. 1200C
- Evaporation, as a degradation mechanism, is predicted to shut down by 800C

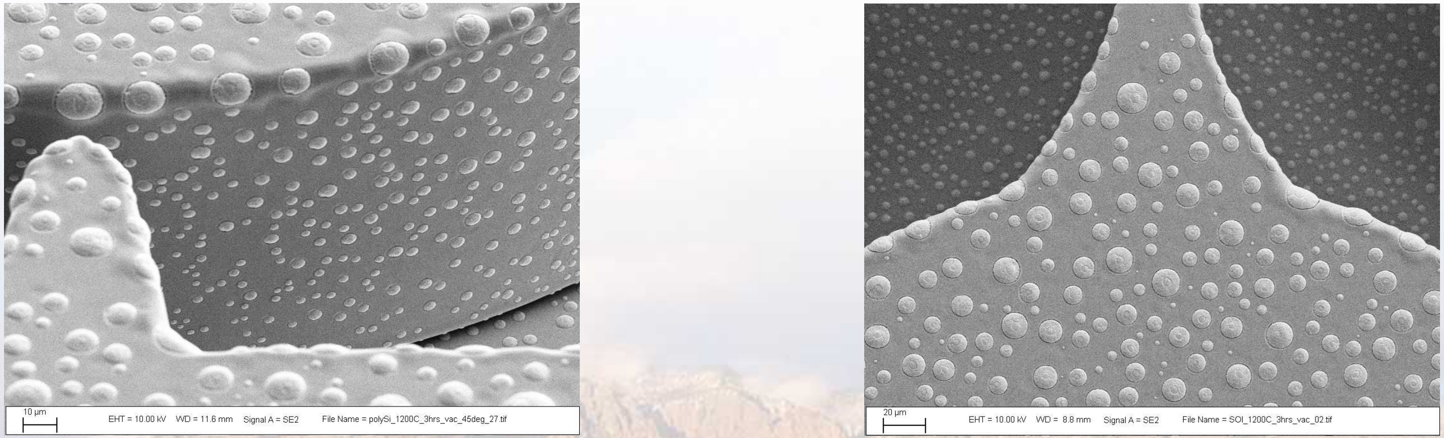
What happens to SOI MEMS during thermal exposure at high temperatures?



Baseline – before exposure

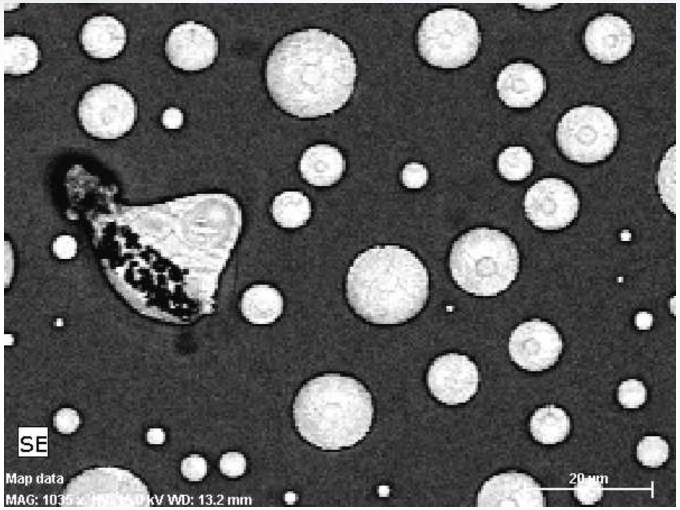


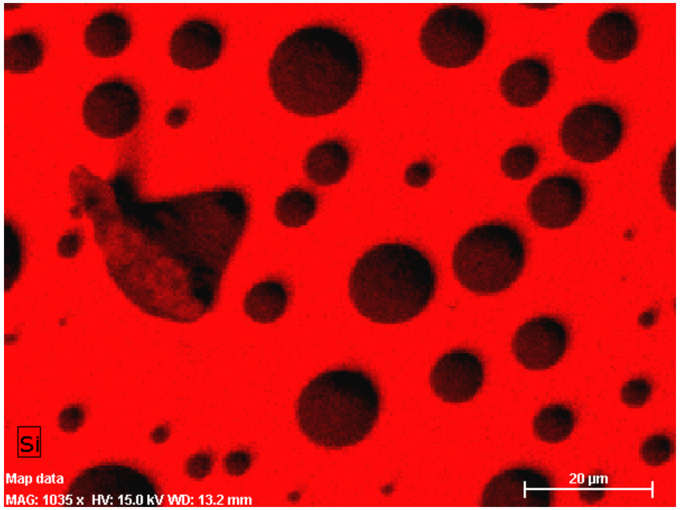
after 3 hrs/1200°C in vacuum

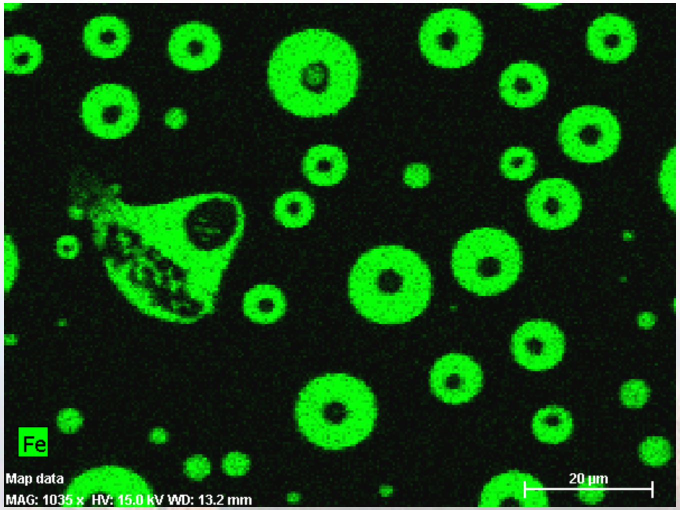


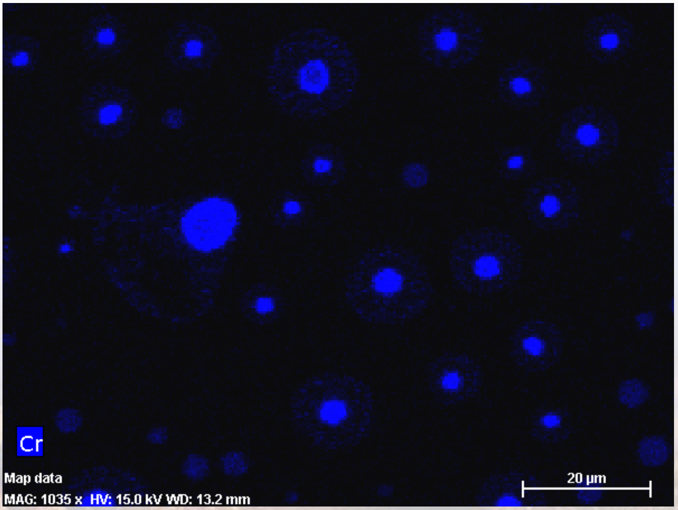
High magnification images – after thermal exposure

SEM Energy Dispersive Spectroscopy revealed contamination

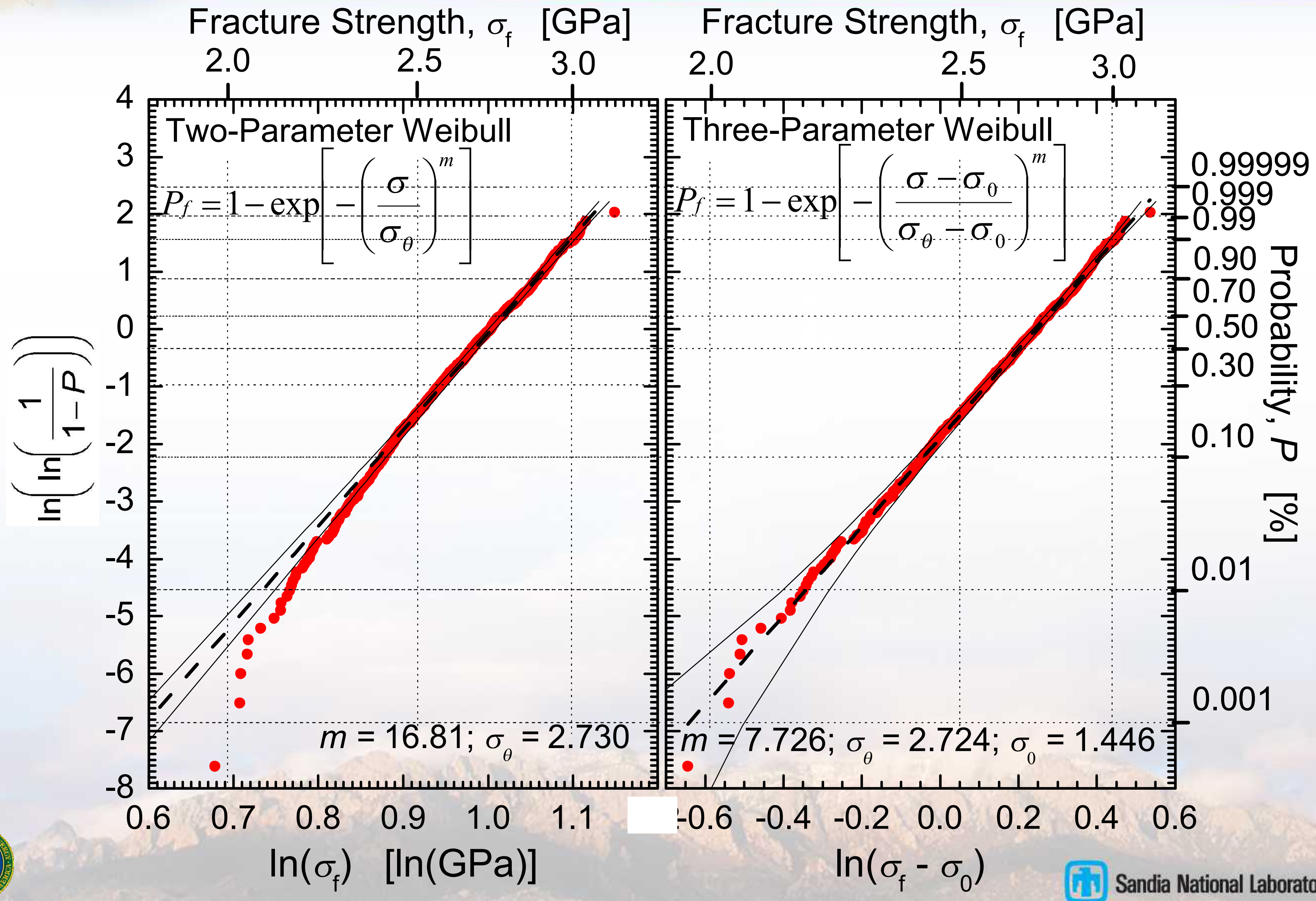








The Strength of MEMS polysilicon: Stastical fits to 1,008 Nominally Identical Tests



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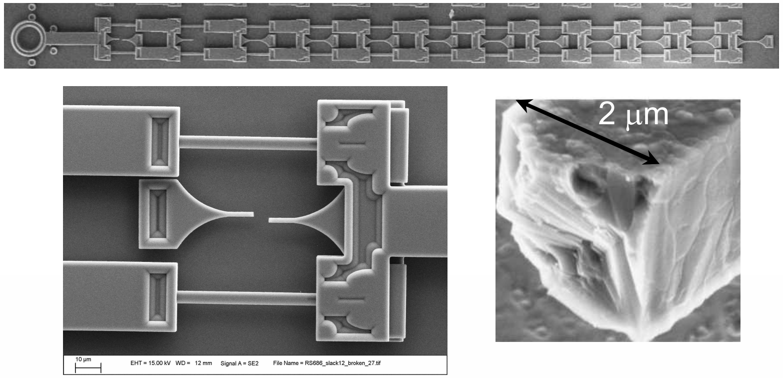
Boyce, *Experimental Mechanics*, 2010

There is evidence linking tensile strength distribution to processing and sidewall roughness

slack chain method



on-chip method

thermal actuator

displacement gauge

tensile bar

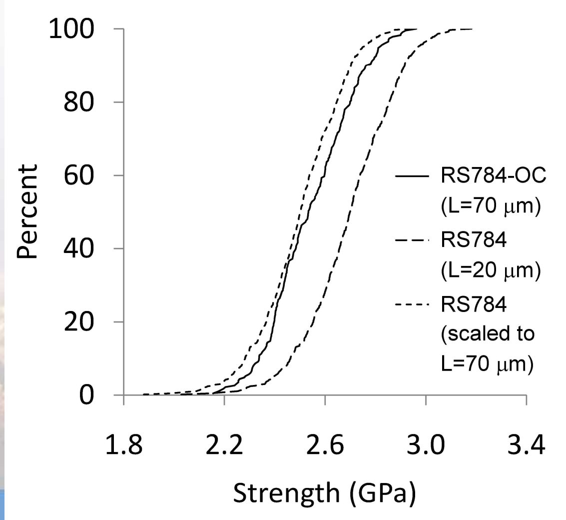
grips

20-mm gage length
Measure breaking force.
(Boyce, Exp. Mech., 2010).

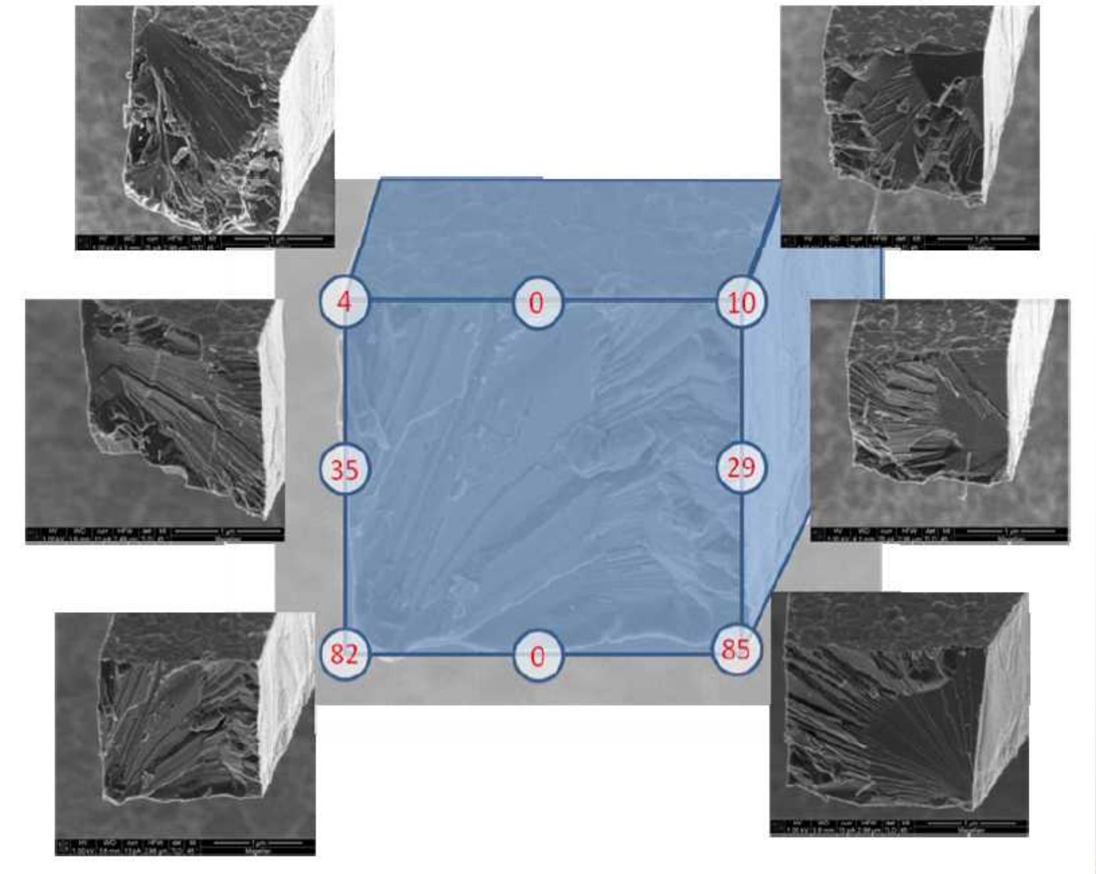
- Measure breaking end displacement.
- 70-mm gage length

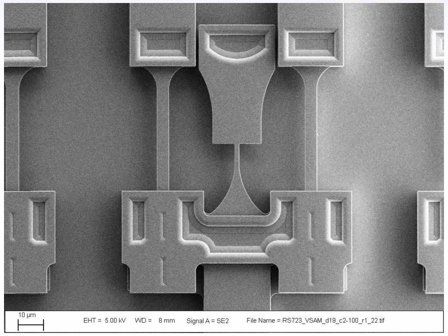
(Hazra, Baker, Beuth, and deBoer, J. Micromech. Microeng, 19, 2009

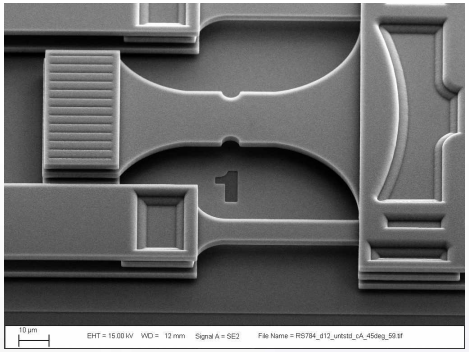
$$\frac{\sigma_2}{\sigma_1}=\left(\frac{A_1}{A_2}\right)^{1/m}$$

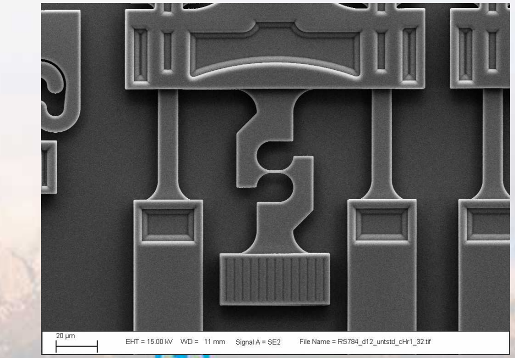


Fracture analysis of specimens with stress concentrations









Question: How to use measured tensile strength data to predict the strength of MEMS structures with stress-concentrating features?

Summary of SOI MEMS Reliability Test Structures

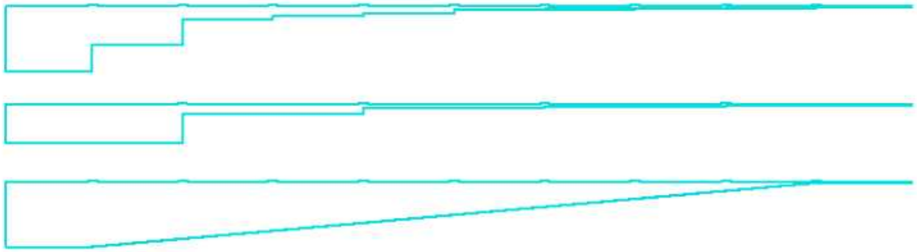
NSWC run

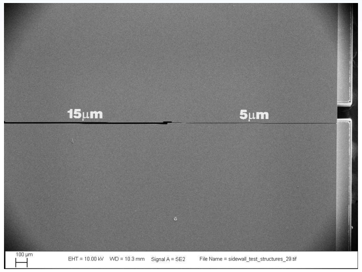
- **Load cell**
  <100> orientation
  <110> orientation
- **1100 um Thermal Actuator**
  <100> orientation
  <110> orientation
  attached
- **1750 um actuator**
- **2750 um four beam actuator**
- **3000 um actuator**
- **Cantilever beam arrays**
  wide beams
  narrow beams
- **In-Plane Residual Test structures (IPS gages)**
  Sandia Design
  Berkeley Design <100>
- **Adhesion test structures**
- **Van Der Pauw test structure**
- **Beam-In-Well test structure**
- **Series of Pull Tab strength test structures**

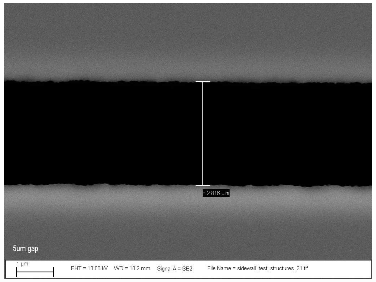
Sandia run

- **Friction Comb drives**
- **Vander Pauw Structures**
- **Thermal Actuators**
- **Thermal Actuators with Load Cells**
- **Cross Structures for Young Modulus and Poisson's Ration**
- **Straight Fixed-Fixed Beams**
- **U-Shaped Fixed-Fixed Beams**
- **Cantilevered beams with and without metal**
- **Residual Stress Bowtie**
- **Residual Stress Beams**
- **Individual Pull tabs**
- **Pull tab Chain**
- **Sidewall Test Structures**

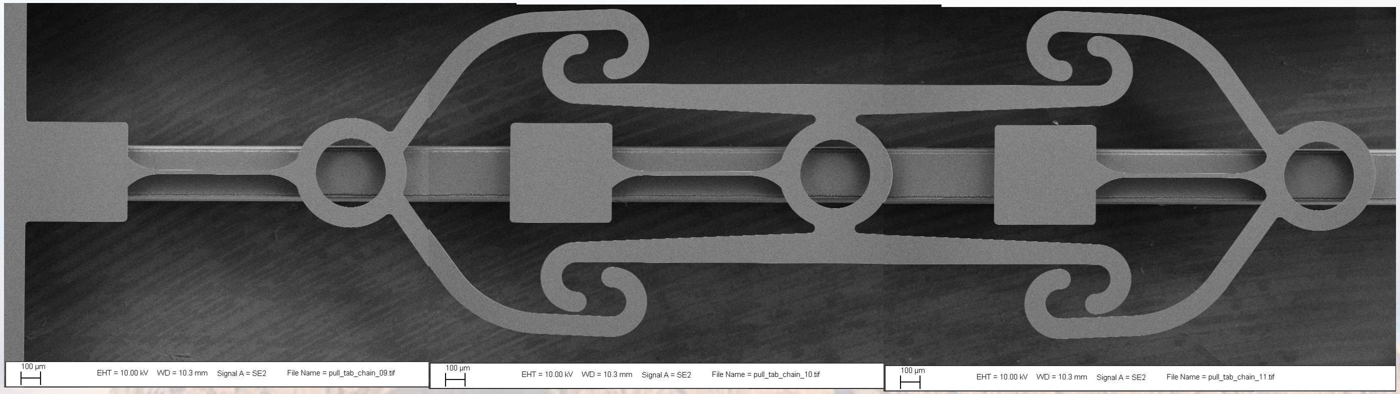
Initial Characterization from the Sandia fabrication run will be on the sidewall, pull-tab and friction test structures





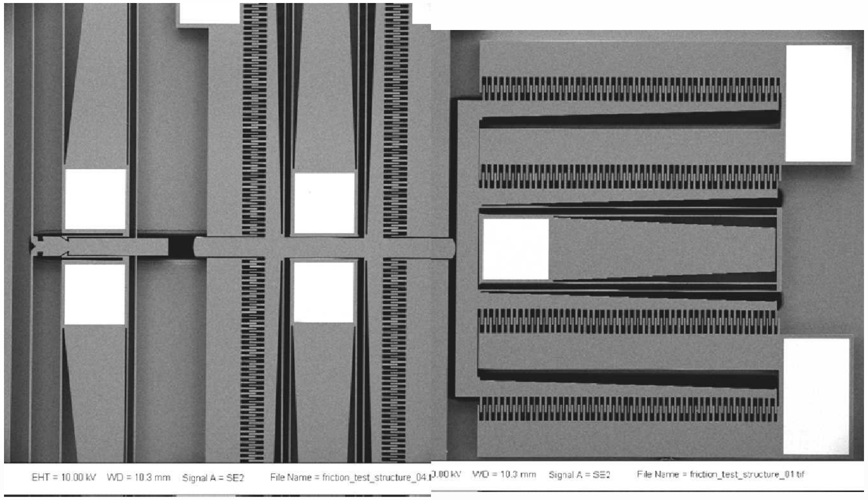


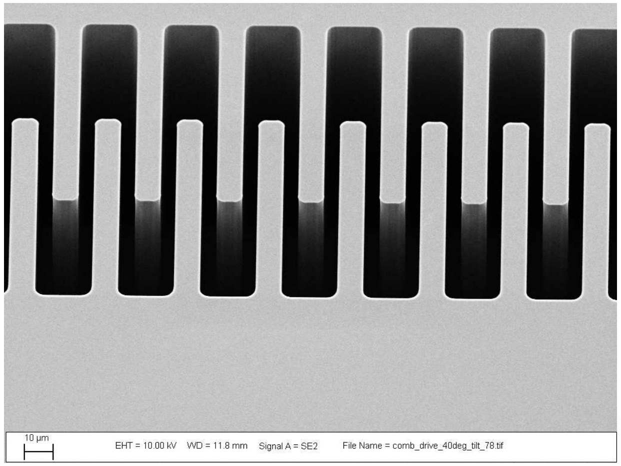
Sidewall Test Structures

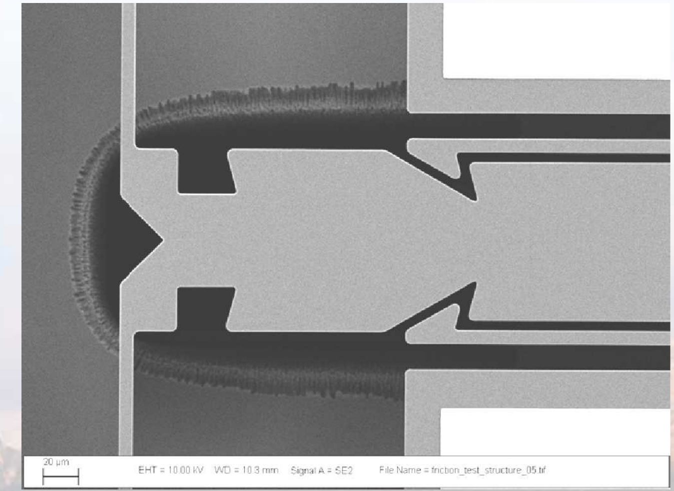


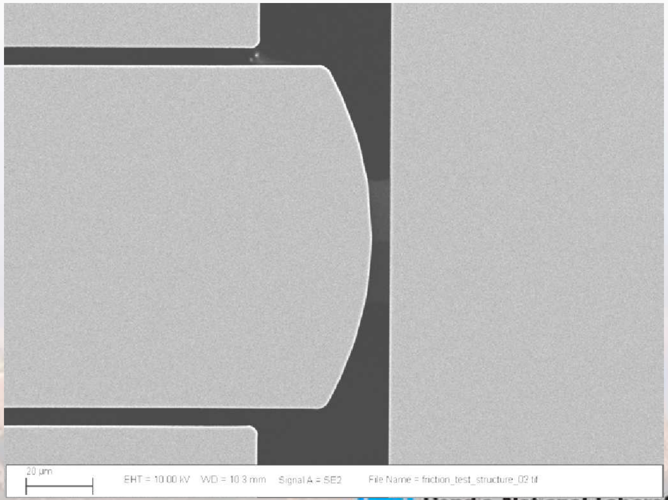
Pull-tab chain

Fabrication of the Friction Test Structure

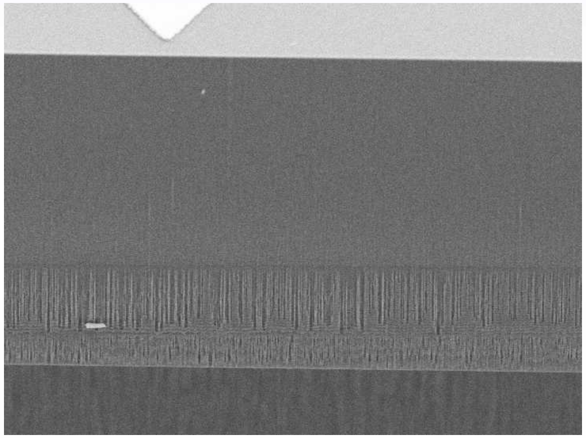




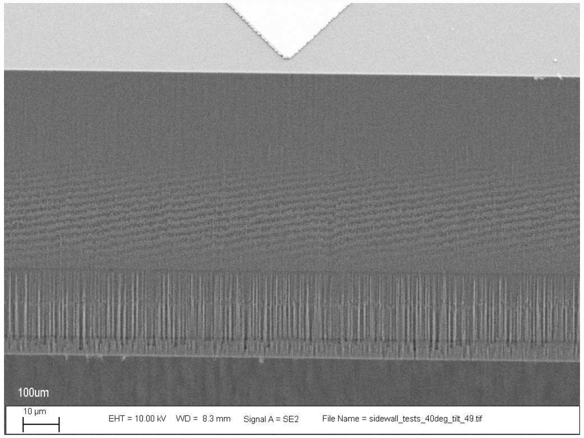




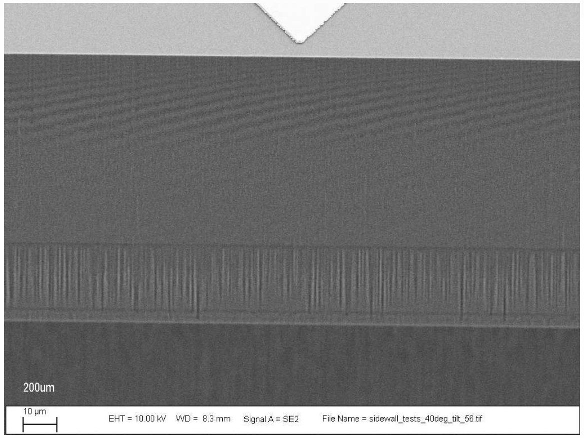
Preliminary results reveal the influence of spacing on sidewall morphology



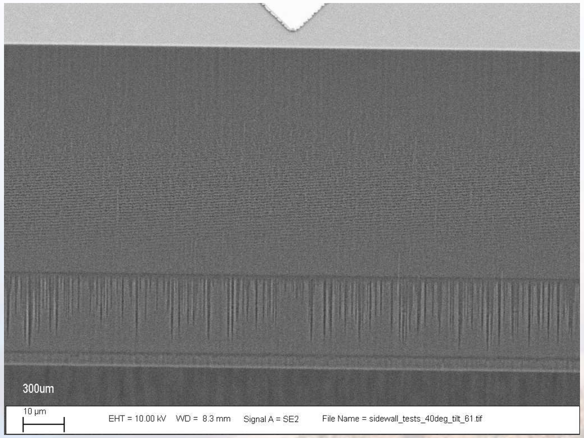
Gap: 50 µm



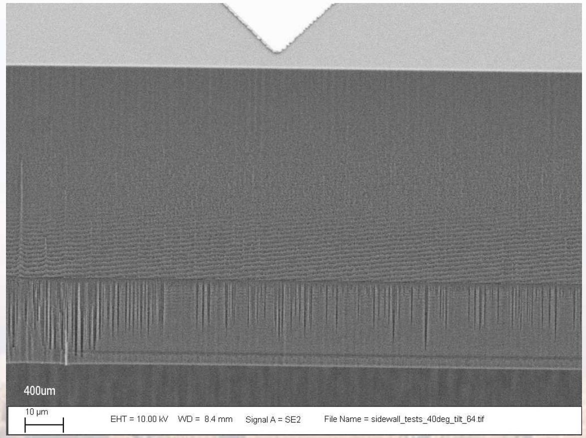
Gap: 100 µm



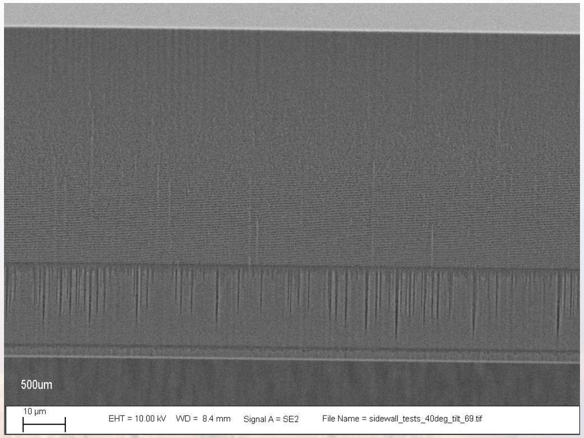
Gap: 200 µm



Gap: 300 µm

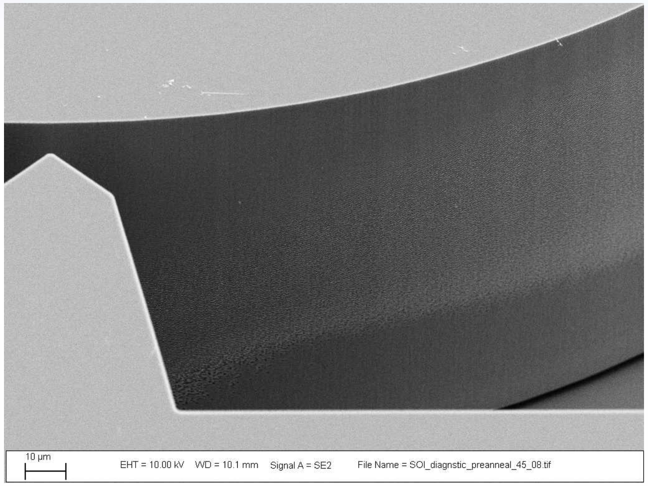


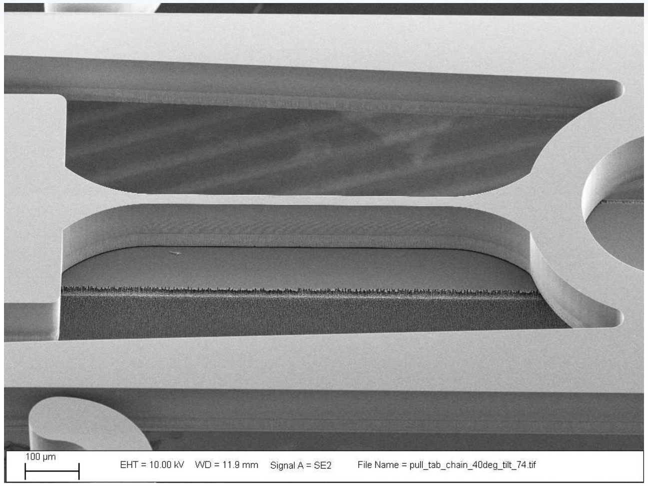
Gap: 400 µm

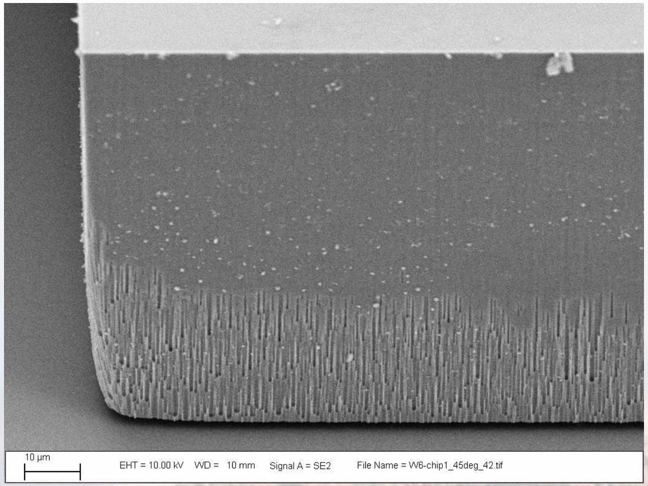


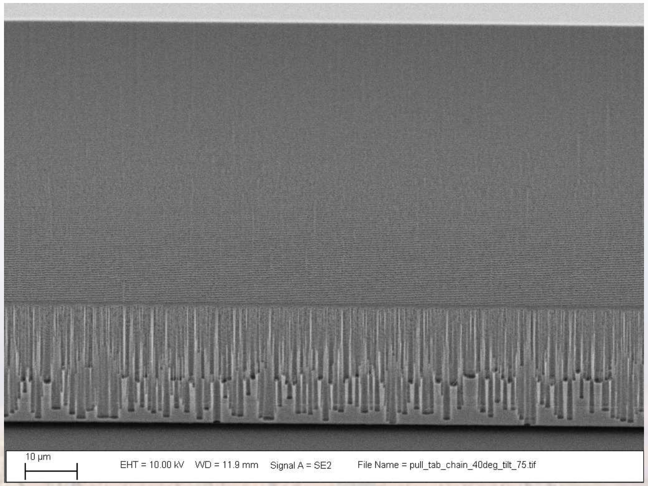
Gap: 500 µm

How do the structural layer sidewalls compare between two SOI device fabrication processes?









Task MEMS Reliability- FY11 Activities

- Characterization of High Temp. degradation of Silicon used in MEMS fabrication (WSEAT+JMP)
- Predicting/Understanding Fracture in micron scale silicon structures (ASC+WSEAT)
- Characterization and measurement of SOI reliability test structures (WSEAT+JMP)
- MEMS/COTS Device Reliability (WFO+JMP)

Task '*MEMS Reliability*' - Issues

- **Broad scope of problem. Challenging to meet the diverse set of interests involved in setting direction of project.**
- **A MEMS reliability model is likely to be device and process dependent**

These are big issues!