SAND2007-2408C

Joint DoD/DOE Munitions Program (JMP)

Five Year Plan

MEMS Reliability Task under

Materials Reliability Project (TCG XIV)

Project '*Materials Reliability*' *Five Year Plan for FY08-12*

MEMS Reliability Task

Performing Organization: Sandia National Laboratories

Principal Investigator: Thomas Buchheit
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Sandia National Laboratories
Albuquerque, NM 87185

Key Customers:

Customer	**Collaboration**
Picatinny Arsenal (Army Corrosion Office) *Jim Zunino, Don Skelton, Robert Kuper, Frank Gagliardi*	***Develop MEMS Reliability Test Platform/Methods useful for the qualification of processing technologies for replacement SnA devices, IMU devices, and other MEMS-based RF devices.*** ***Post-Mortem characterization of prospective replacement MEMS devices.***
Redstone Arsenal (AMRDEC) *Abdul Kudiya* *Dave Locker*	
NSWC *Mike Bucher,* *Michael Deeds*	

MEMS Reliability - Key Personnel

Name	Org	Role
Thomas Buchheit (tebuchh@sandia.gov (505)-845-0298	*Dept. 1824 Sandia Labs*	*Task Leader*
Michael Dugger mtdugge@sandia.gov (505)-844-1091	*Dept. 1824 Sandia Labs*	*Tribology, (Friction, Wear)*
Brad Boyce blboyce@sandia.gov (505)-845-7525	*Dept. 1824 Sandia Labs*	*Mechanical Properties*
Danelle Tanner tannerdm@sandia.gov (505)-844-8973	*Dept. 1769-1 Sandia Labs*	*Reliability Physics*
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Predictive Materials Aging and Reliability

MEMS Reliability **GOTChA Chart 5yr. plan**

Goal

Understand and predict the aging and reliability of MEMS materials

Objectives

- Design, fabricate and characterize test structures to measure *process diagnostics*, strength, friction and fatigue response in various MEMS processing technologies
- Use test structures and post mortem characterizations to develop mechanism-properties relationships
- Design and perform series of experiments which isolate the effects of aging and environment on the performance of MEMS materials

Challenges

- Test structures have only been developed in surface micromachined polysilicon and LIGA
- To establish mechanism-properties relationships in any materials/device class requires careful science-based research
- Mechanism-properties relationships must be linked to design and reliability of MEMS devices
- No current program exists for translating results into DOD/DOE device design optimization

Approach

- Choose SOI as MEMS processing technology (relevant to DOD/DOE missions)
- Invest 1 ½ years to develop key mechanism-properties relationships in SOI, including submission of refined test geometry designs
- Fabricate test structures in 2nd, preferably metal-based, MEMS processing technology
- Develop key mechanism-properties relationships in 2nd processing technology.
- Use DOD input, previously developed test structures and fundamental knowledge gained from mechanism-properties studies to guide direction of aging and environment studies.

Predictive Materials Aging and Reliability

MEMS reliability- Funding- 5 yr. plan

Planned:

FY08	FY09	FY10	FY11	
$210K	$210K	$210K	$220K	

Historical:

FY03	FY04	FY05	FY06	FY07
$0K	$0K	$0K	$200K	$200K

Includes the total of both DoD and DOE $s

Task *'MEMS Reliability'* Four-Question Chart

What are you trying to do in this task? *Understand the reliability MEMS materials and devices*

- Provide semi-standard measurement techniques, materials and tribological properties data within a MEMS fabrication processes
- Apply results and analysis to lifetime/reliability issues in prospective MEMS devices across the DOD/DOE complex

What makes you think you can do it?

- Previously developed strength, friction and fatigue test designs for SMM polysilicon (one MEMS technology) will guide aging/lifetime/reliability diagnostic studies
- Experience with microsystems reliability physics

What difference will it make?

- Optimized design and reliability of MEMS-based components and systems
- Properties database of MEMS process materials
- Mechanism-based understanding of reliability and lifetime issues associated with MEMS devices

What / When Will You Deliver?

- SOI strength, friction, fatigue test structure fabrication and preliminary evaluation 10/06
- Demonstrated ability to drop-in to a second MEMS processing technology by 09/08
- Preliminary lifetime-reliability study using SOI diagnostic test structures 1/08

Predictive Materials Aging and Reliability
MEMS Reliability *FY07 specific activities*

- Finish 700 μm deflection experiments on mass-spring structures
- Begin Testing in-plane and out-of-plane fatigue diagnostic structures
- Characterize and begin baseline testing friction test structures
- (8 die – levitation forces range of friction forces, test with monolayer coatings)

Later FY2007 deliverables:
- Second SOI die design
- Accelerated aging study

Predictive Materials Aging & Reliability (MEMS)

MEMS	FY08 Q1 Q2 Q3 Q4	FY09 Q1 Q2 Q3 Q4	FY10 Q1 Q2 Q3 Q4	FY11 Q1 Q2 Q3 Q4	FY12 Q1 Q2 Q3
Strength, Friction, Fatigue studies on 1st generation MEMSCAP SOI design					
Strength, Friction, Fatigue studies on 2nd generation SOI design					
Identify second MEMS processing technology for diagnostic testing					
Strength, Friction, Fatigue studies for second technology					
Identify Accelerated Aging/Reliability testing protocol					
Aging and Reliability studies for predictive model development using diagnostic test structures					
Confidence in providing flexible test platforms for obtaining fundamental measurements of strength, friction, and fatigue in any MEMS technology					
Correlation between aging and reliability failures in prototype devices and predictions based on studies using diagnostic test structures					

Summary of Kickoff meeting MEMS Reliability Task subgroup

Two categories of Reliability issues:
I. Initial Design/Processing
II. Aging/Lifetime/Storage

Two categories Devices:
I. Homegrown
II. COTS-commericial

Fault Tree items:
-**Shock**- Pyroshock, High G shock
-**Outgassing** – Degradation of packaging seal and hermeticity issues
-**Storage environments** -Long term storage issues, e.g. temp. cycling
-**Interacting Surfaces**- Adhesion of devices (stiction), metal film delamination within devices

- Current project direction is a bottom-up approach, developing diagnostics to gain a fundamental understanding of the process dependent key characteristics of MEMS materials.

- Some funding will be redirected to a top-down approach, i.e device failure determination. Isolating primary causes of failure in prospective DOD MEMS devices will feed into the bottom-up approach, developing diagnostics to isolate key failure and reliability mechanisms

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

List of DOD MEMS Devices

Class I – no moving parts
Class II – moving parts with no contact
Class III – moving with impacting surfaces
Class IV – moving with rubbing surfaces

S&A for the XM29 Airburst Weapon. The technology here is a Ni on steel that is etched to make the structures (kind of LIGA-like). The device is not hermetically sealed but will be sealed in the overall fuze component.

IMU (Inertial Measurement Unit) for common guidance. This is SOI technology being developed by Honeywell.

ARL RF Switch. Manufactured by Harry Diamond Labs- it has undergone some environmental stress testing.

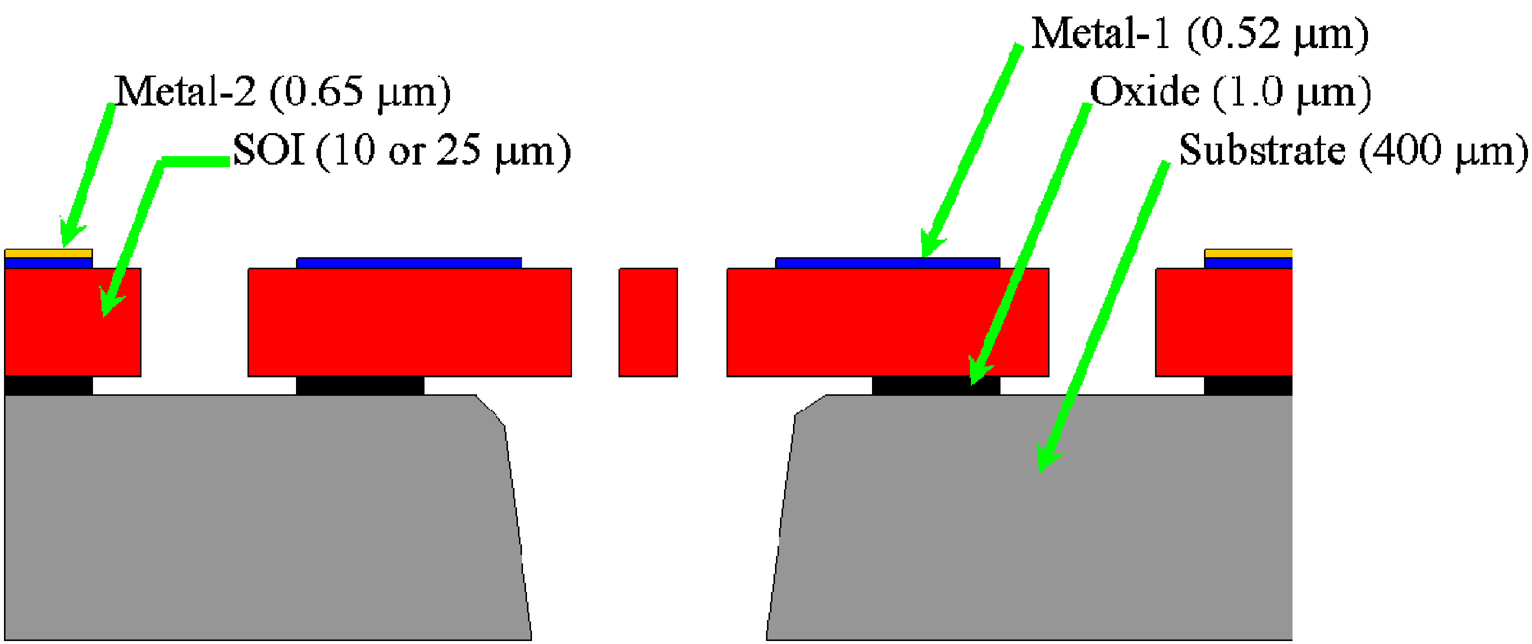
NSWC S&A. basic geometry platform for several systems

MEMSCAP SOI-MUMPS fabrication process

process used for test structure fabrication under MEMS Reliability MOU

Online at: www.memsrus.com

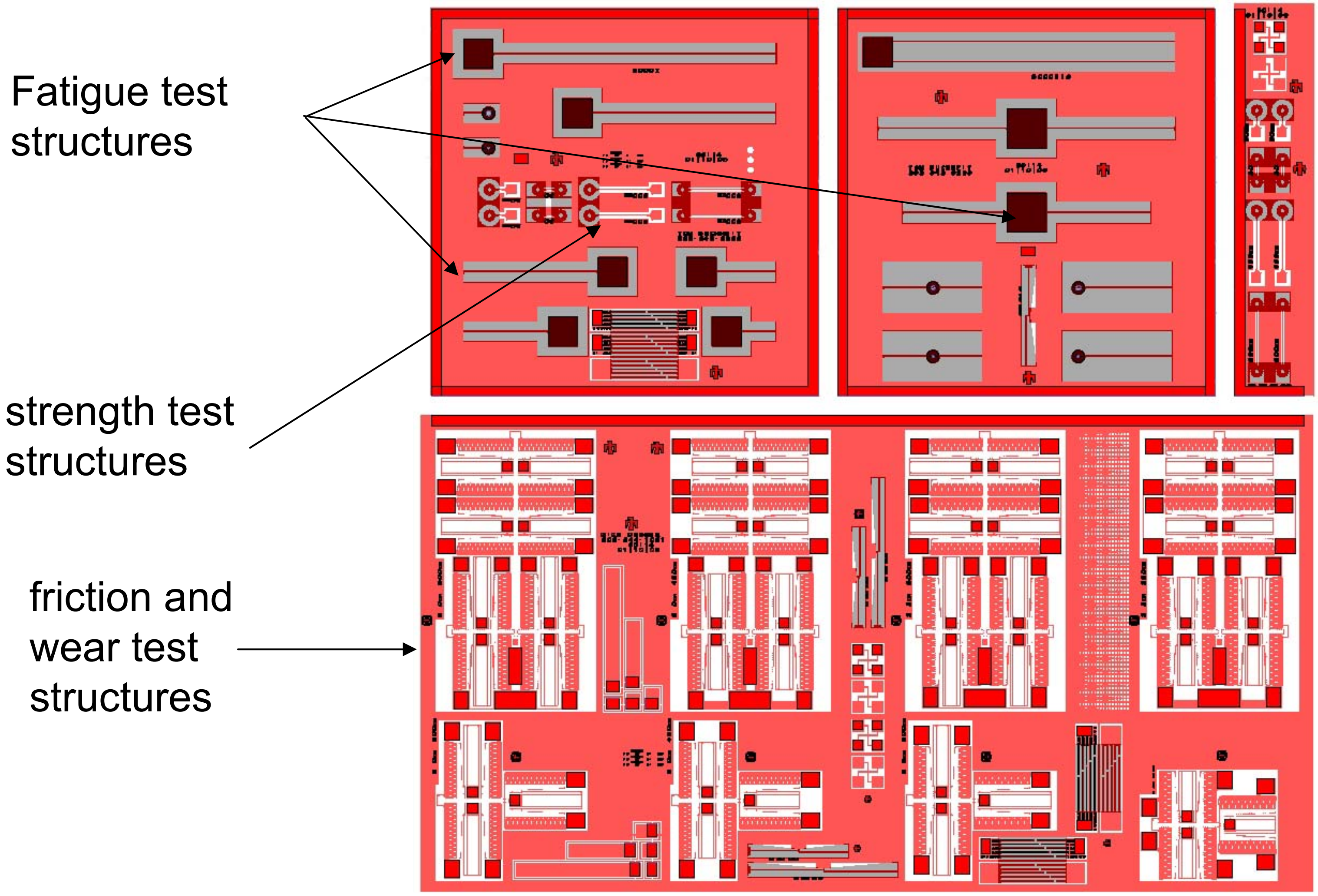
- 1 structural layer located on 1 handle wafer
- (15) dice, 9x9 mm
- Handle wafer: <001>, 400 μm thick, P-doped @ 1-10 Ohm-cm
- Oxide: thermal
- Structural layer: <110> along x- and y-axes. <001> is 45˚. P-doped at top surface.
- More info available in wafer data sheet, design rules document



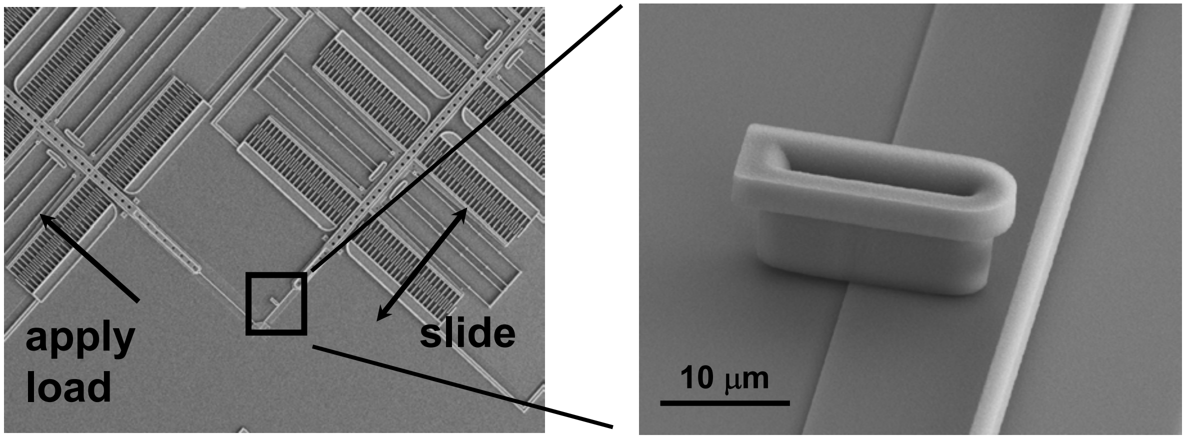
Metal-1 = "Padmetal"
Metal-2 = "Blanketmetal"

Cross-section, fabrication technology

1st generation SOI design containing strength, fatigue and friction test structures

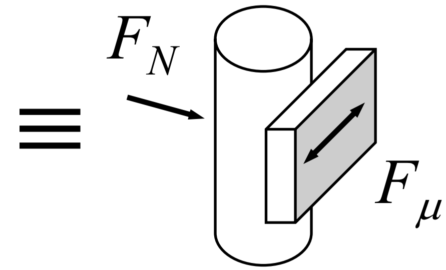


MEMS Tribometer used to measure friction

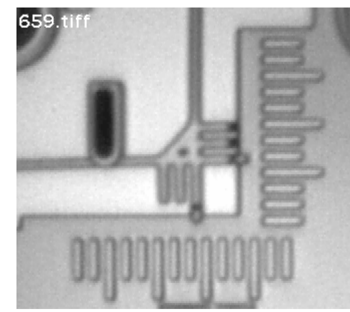


D.C. Senft and M.T. Dugger, Proc. SPIE, **3224** (1997) pp. 31-38.

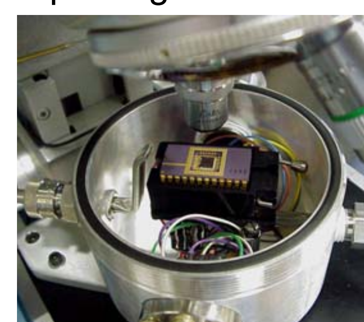
"Surface Micromachined Sidewall Tribometer"



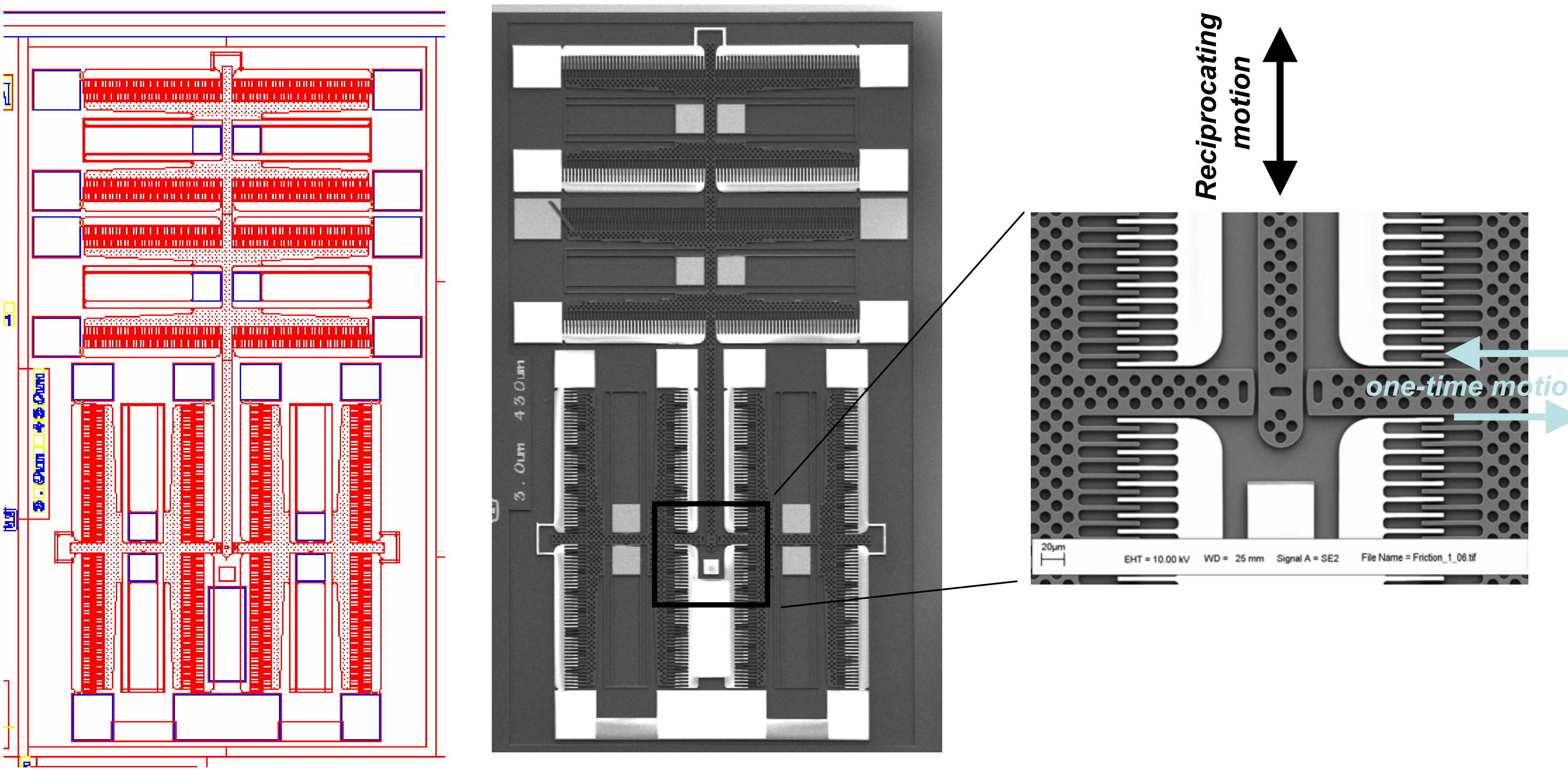
- **Static Friction**
  - **beam is pulled into contact with post**
  - **lateral voltage (force) is ramped up until beam slips laterally**
- **Dynamic Friction**
  - **beam is pulled into contact with post**
  - **beam is oscillated laterally against post**
- **Pull-Off Force**
  - **beam is pulled into contact with post**
  - **normal voltage (force) decreased until beam pulls off of post**



environmental cell for packaged devices

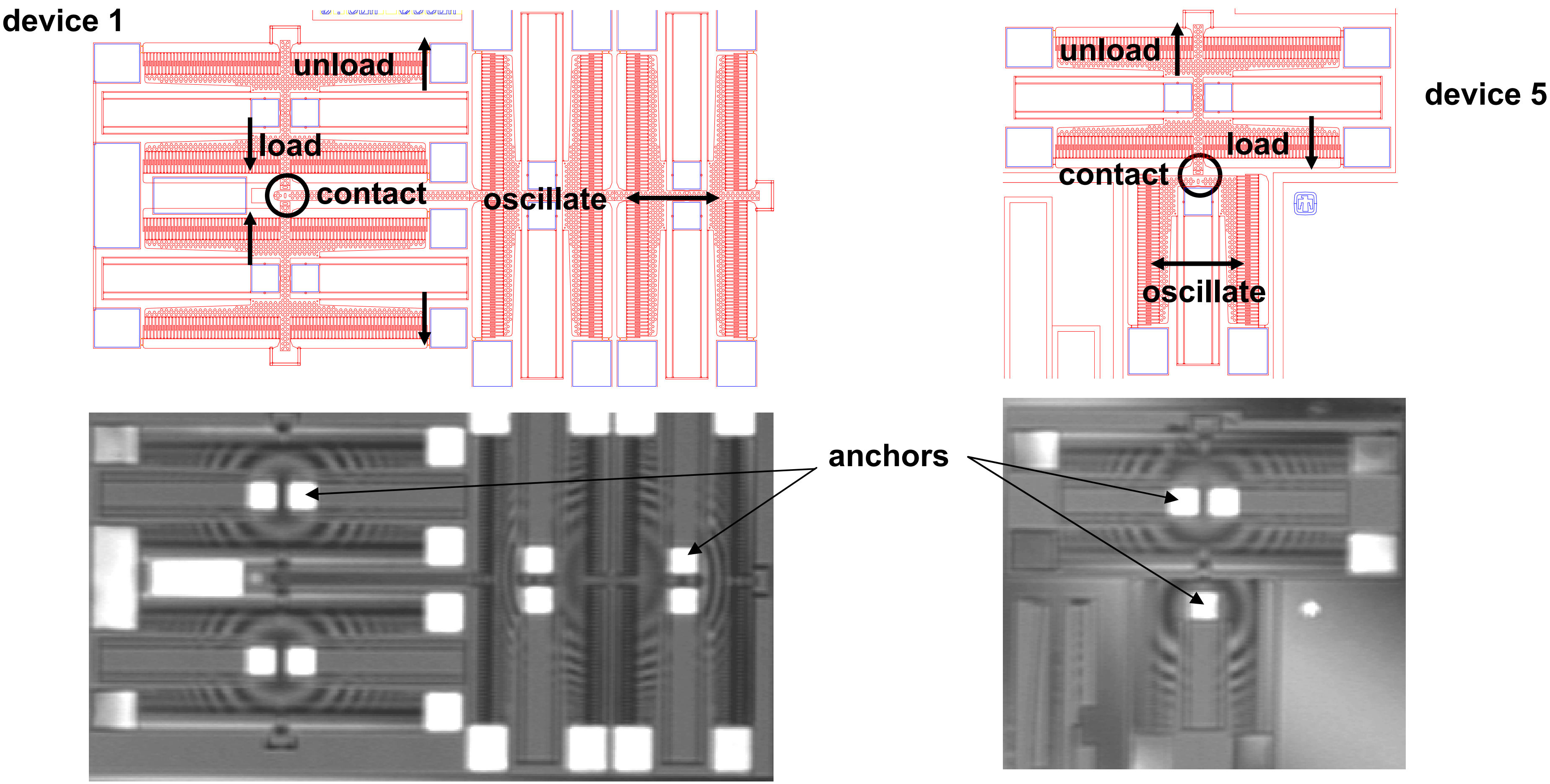


A SOI fabricated Friction and Wear device



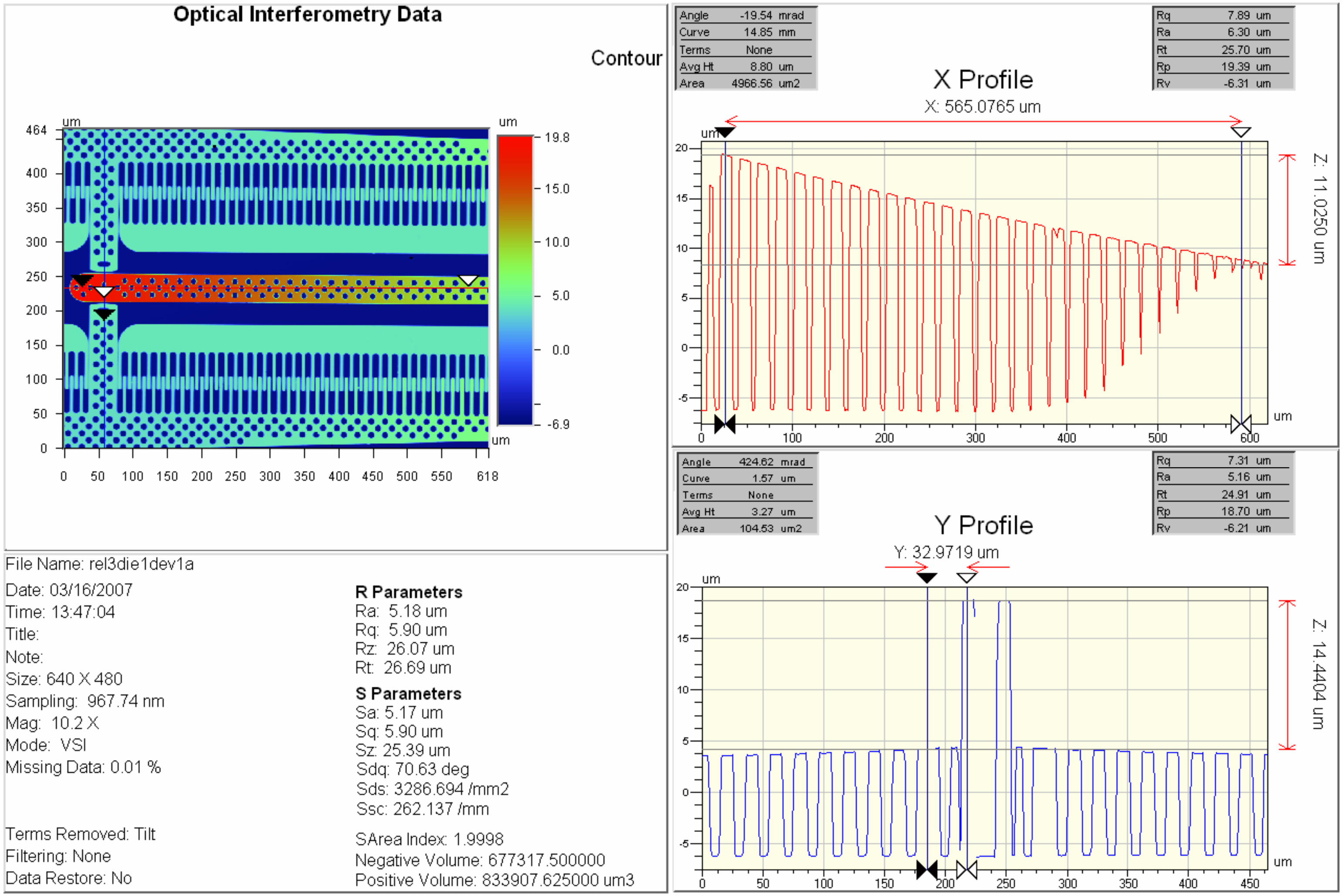
Stress observed in 1st generation SOI tribometer

“pinch” device | “compact” device



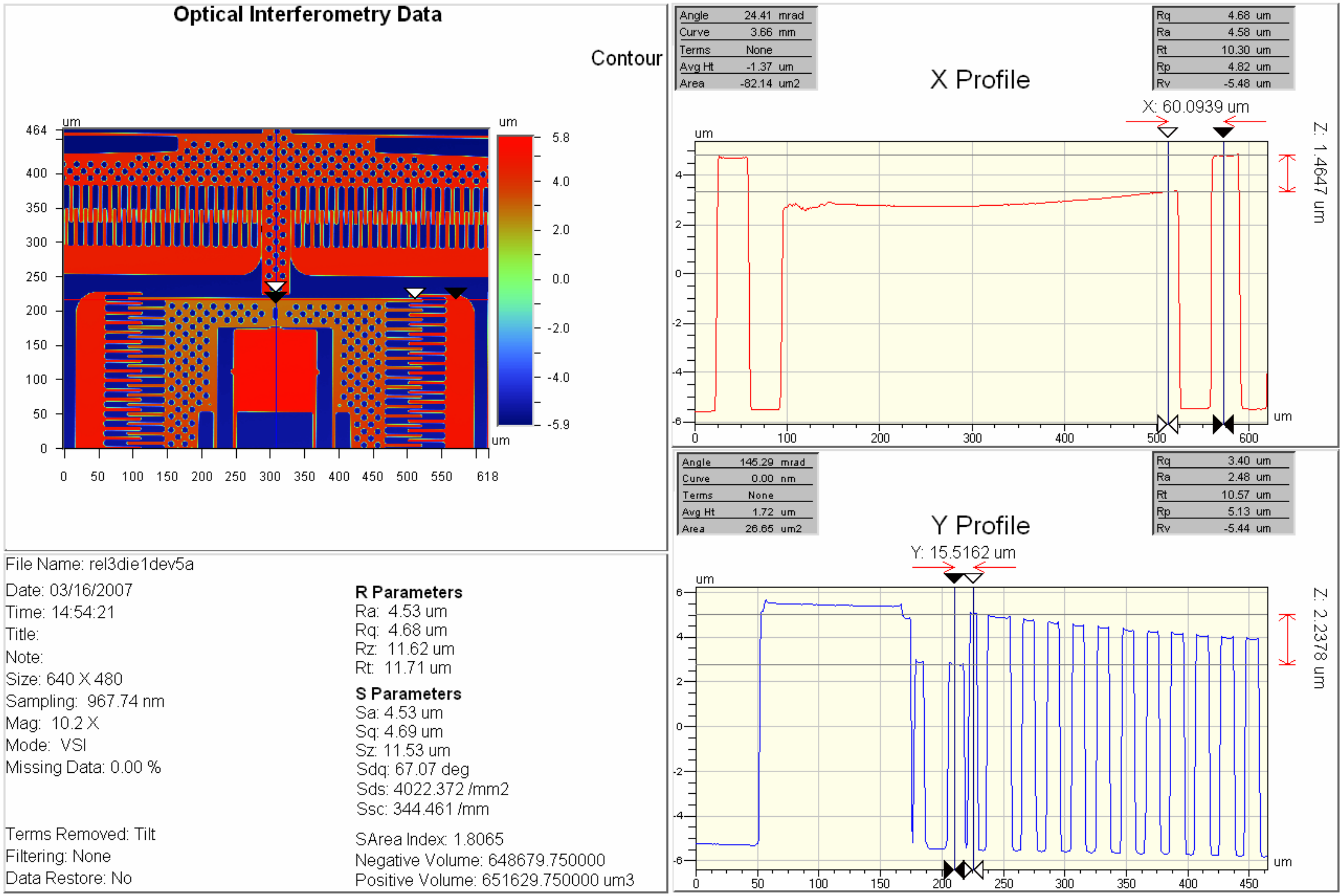
- **Suspended structures curled out of plane away from anchors**

Misalignment of mechanical contact



- **Pinch actuators do not contact oscillating beam**

Compact device exhibits less misalignment of mechanical contacts



- **Contacts will still touch over > 7.5 μm of their height**

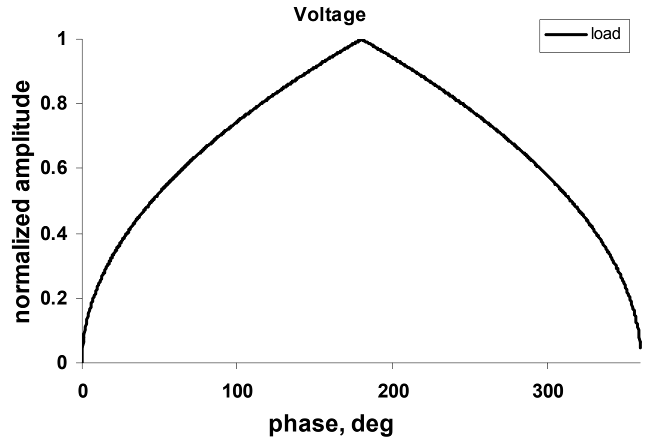
Lessons learned in SOI friction devices

- Stress in structural layer higher than observed in (SUMMiT) polysilicon process
  - keep suspended structures as small as possible to ensure alignment
- Adhesion effects compounded by lack of dimples
  - smooth bottom surface of structural layer easily sticks down, even with hydrophobic coatings
  - DRIE under large structures, or use thicker sacox layer
- Small gold fields undercut during release
  - omit lettering to avoid “alphabet soup”

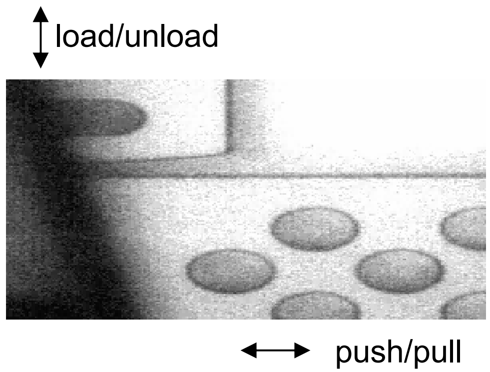
Adhesion tests monitor changes in intrinsic force that adds to normal load

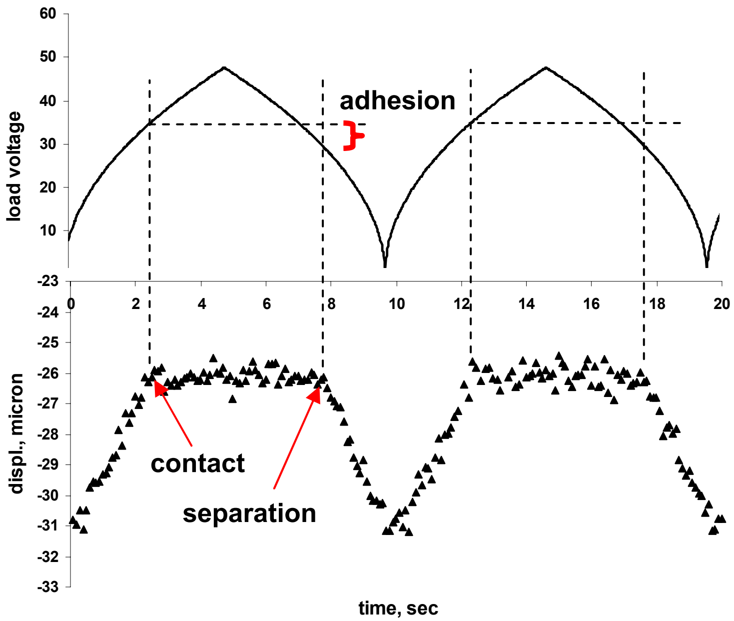
desired displacement

required input



resulting motion



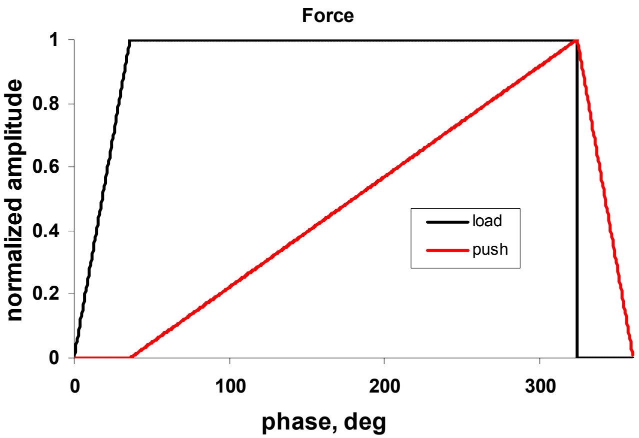


(contact - separation) voltage permits quantification of adhesion force

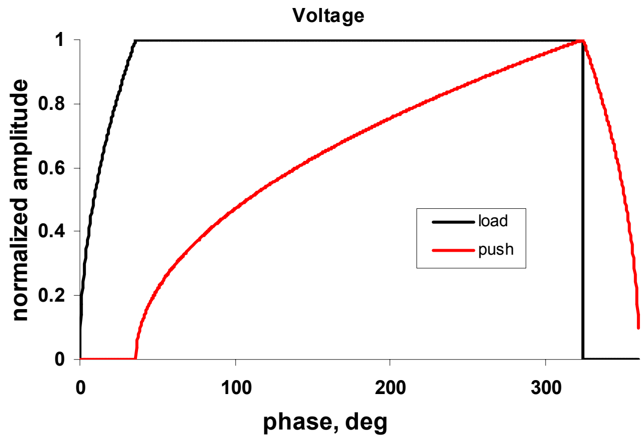
- **measure after operation, environment exposure, aging, etc.**
- **examine changes in contact surfaces due to degradation**

Static friction test is used to determine changes in start-up force for sliding surfaces

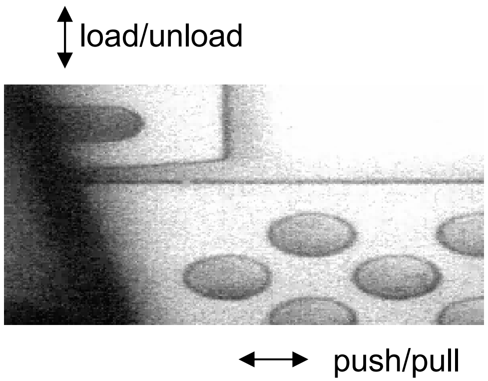
desired displacement

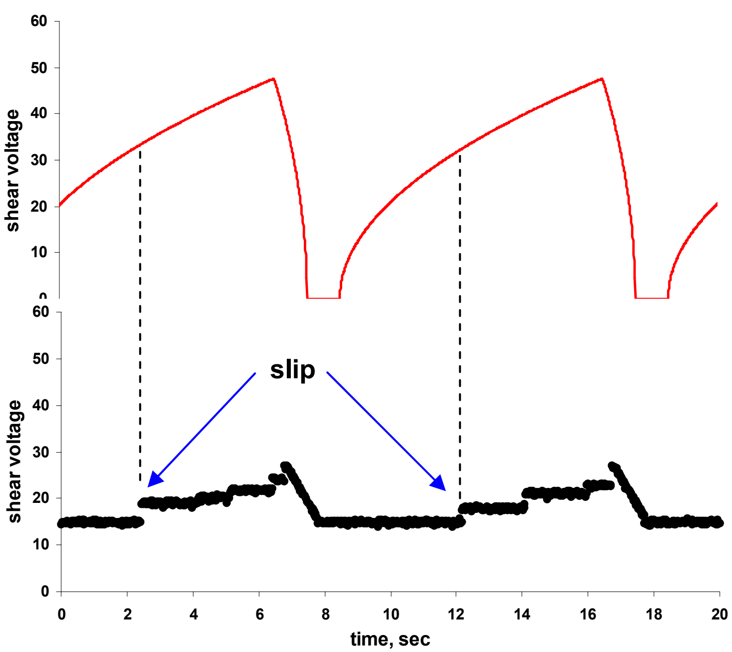


required input



resulting motion



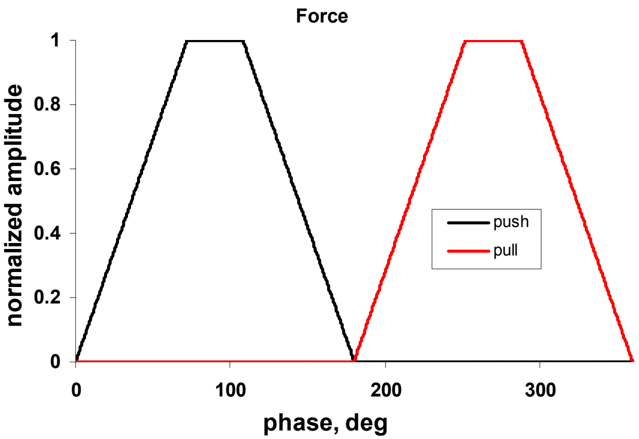


voltage at slip permits quantification of static friction force

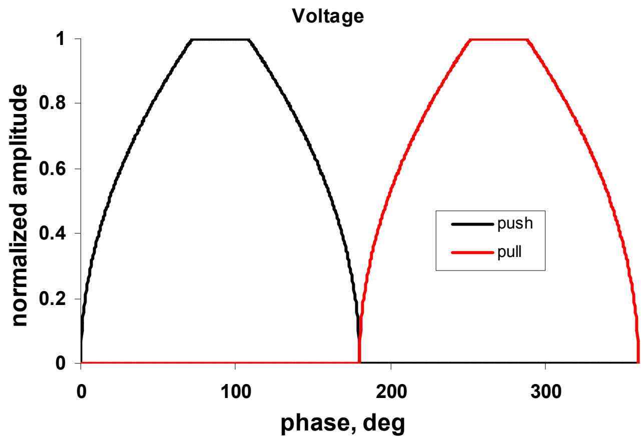
- **measure after operation, environment exposure, aging, etc.**
- **examine changes in contact surfaces due to degradation**

Dynamic friction test is used to investigate surface degradation during shear

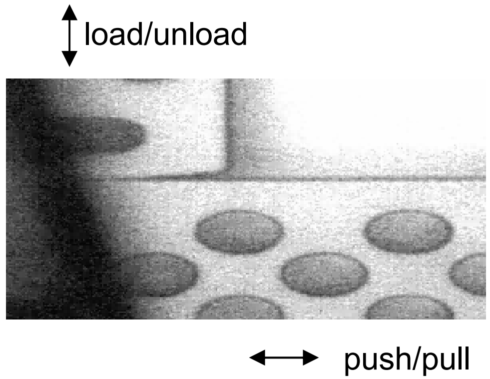
desired displacement



required input



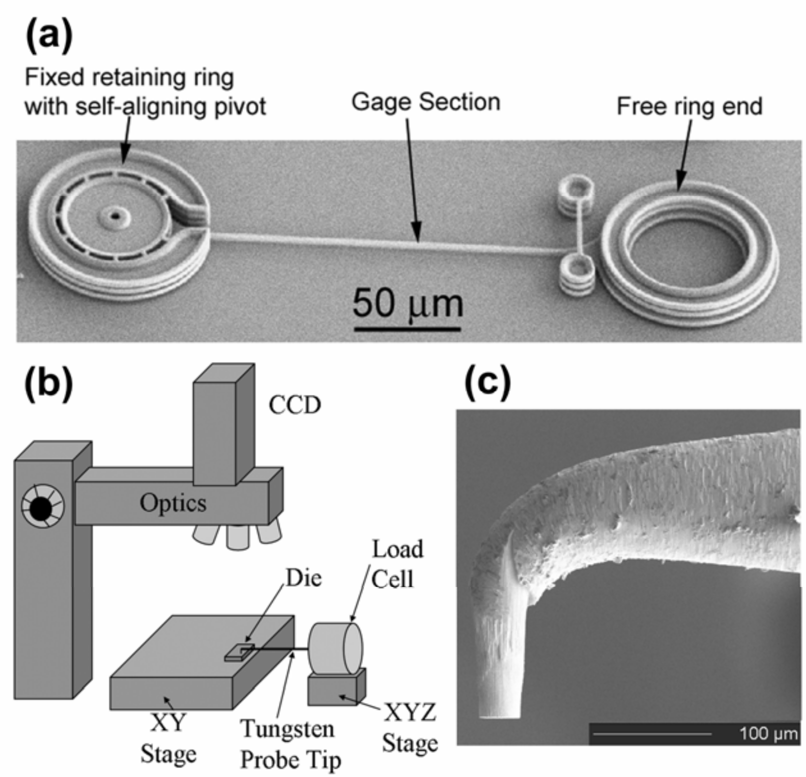
resulting motion

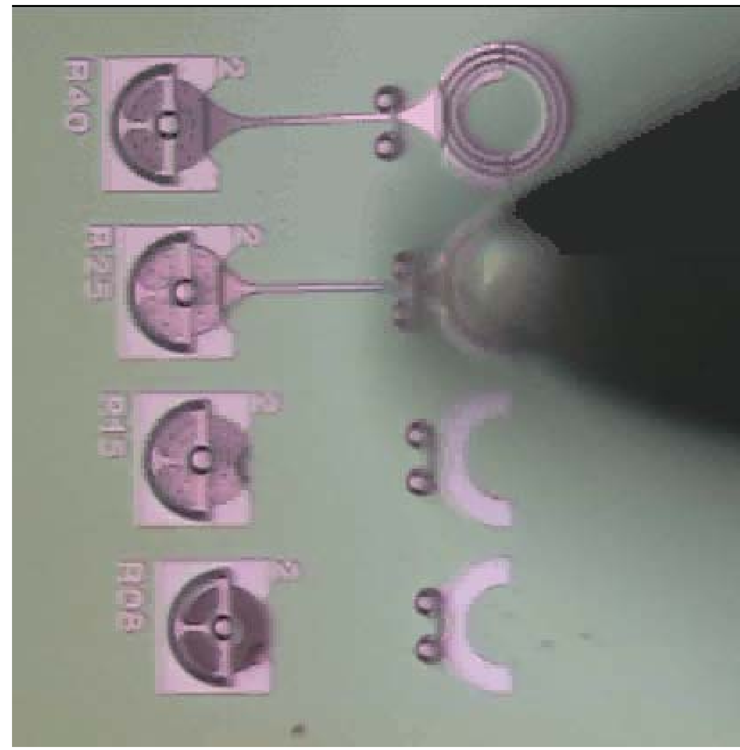


displacement amplitude is related to dynamic friction force

- **$F_d = k\Delta x$, where k = suspension stiffness and Δx is reduction in device amplitude from non-contact**
- **examine changes in contact surfaces due to degradation**

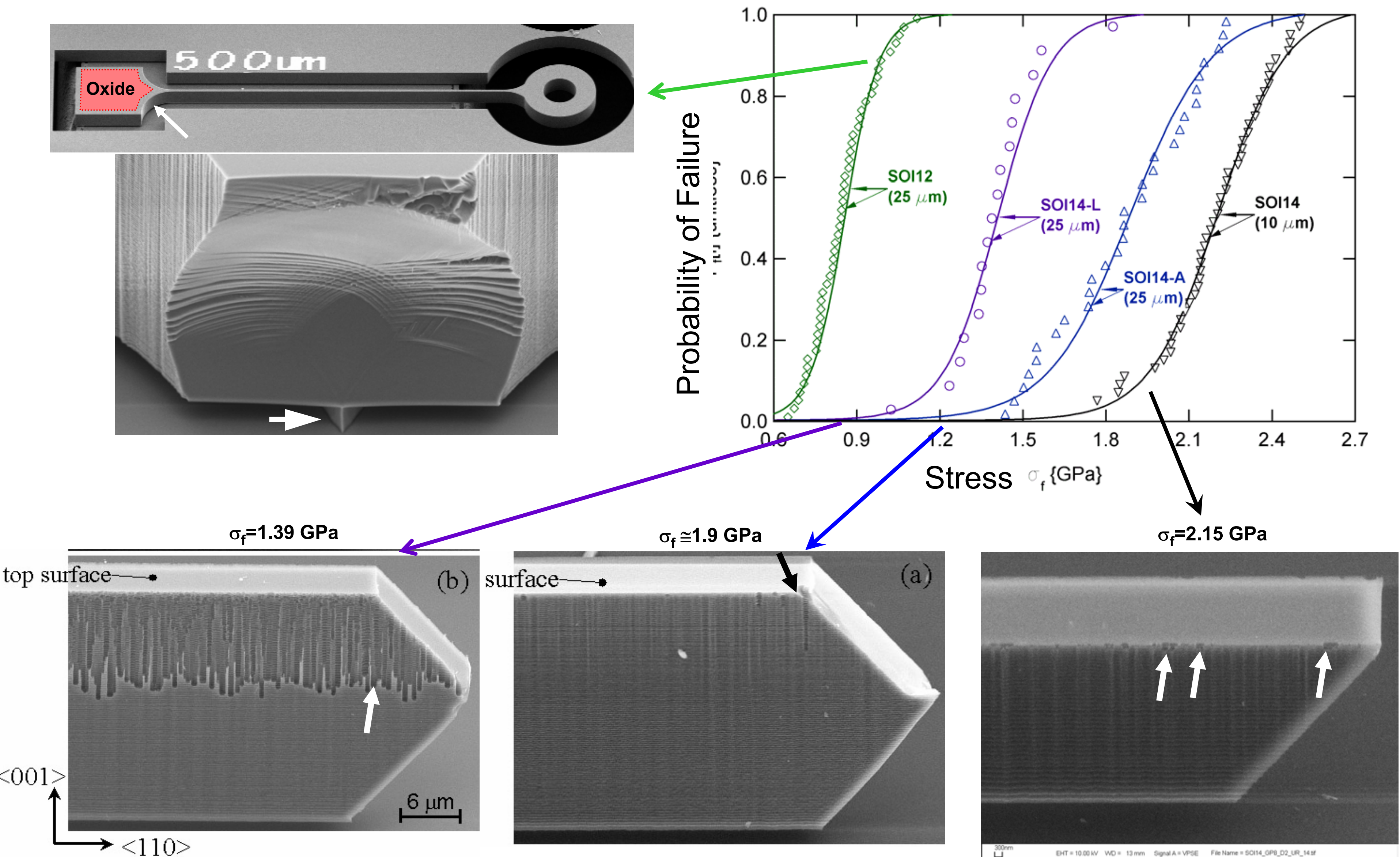
Fundamental Strength Measurements On Microfabricated Silicon



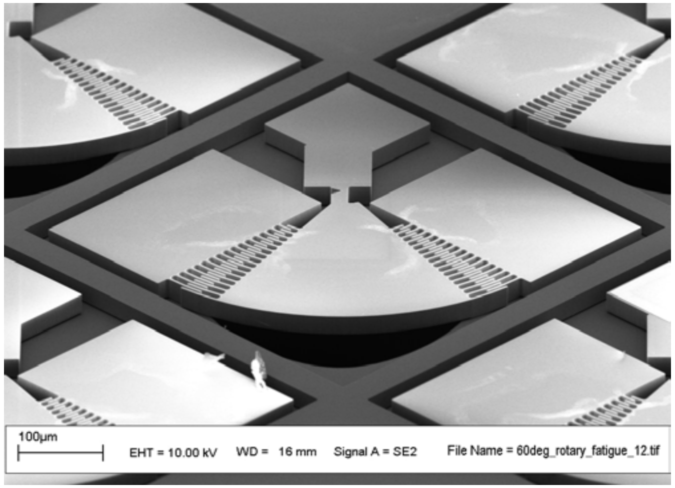


B.L. Boyce et al., J. MEMS, In Press, 2007

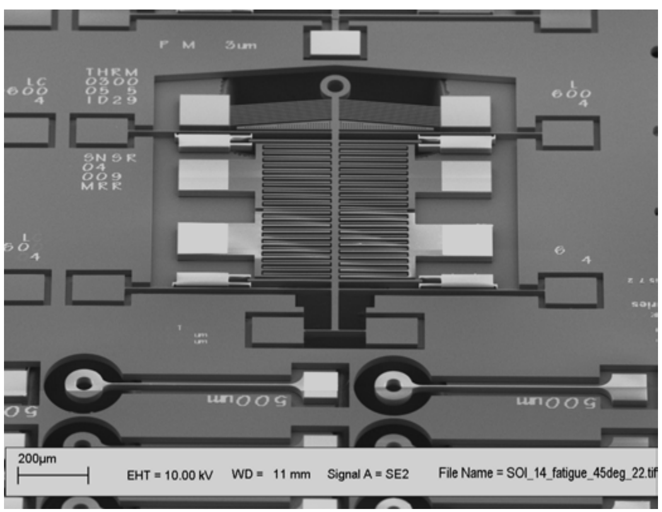
Surface Roughness and Processing induced flaws govern fracture behavior in SOI

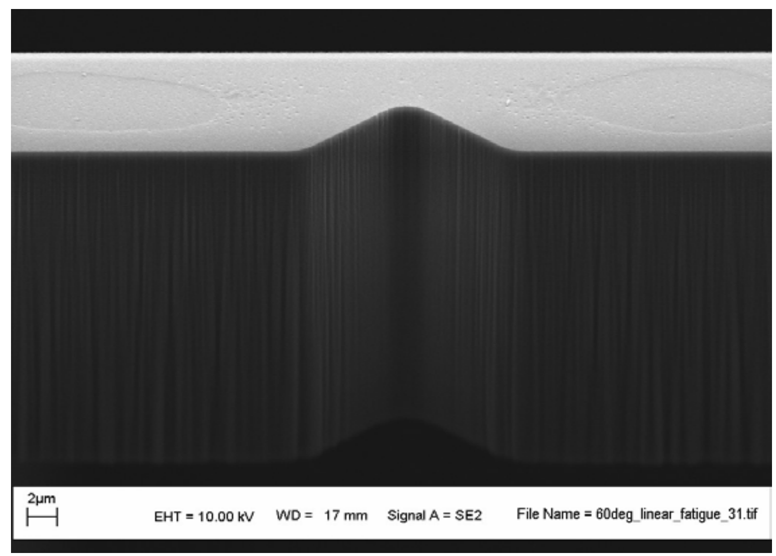


In-Plane fatigue test structures



- **Devices actuated at 100 Hz (thermal "resonance" at 200 Hz)**
- **Test rate: 8.6 million cycles/day**

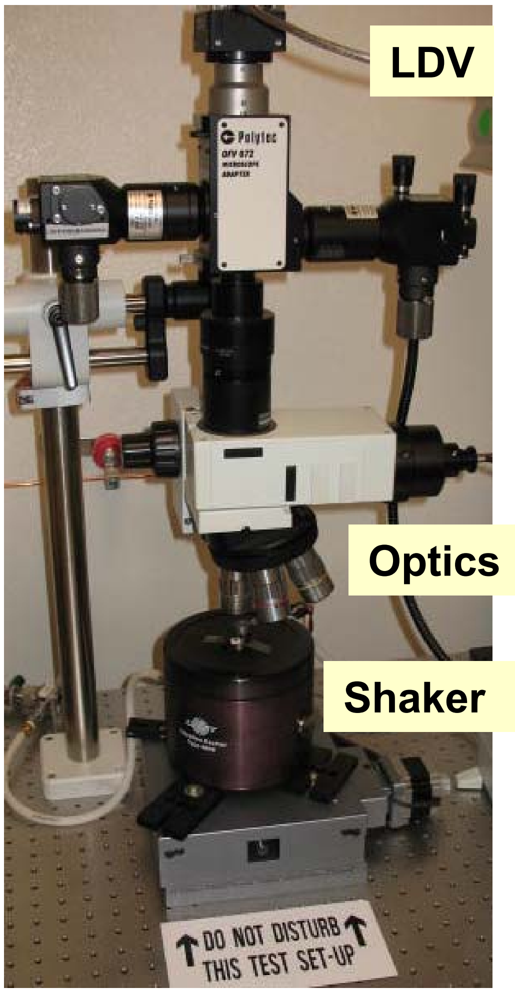




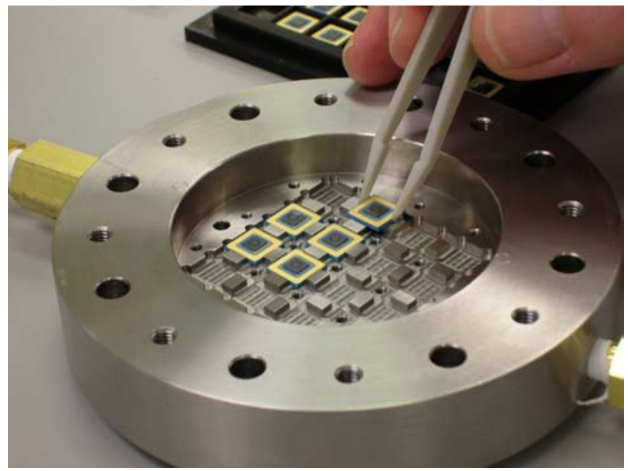
Long Term Reliability MEMS test-bed

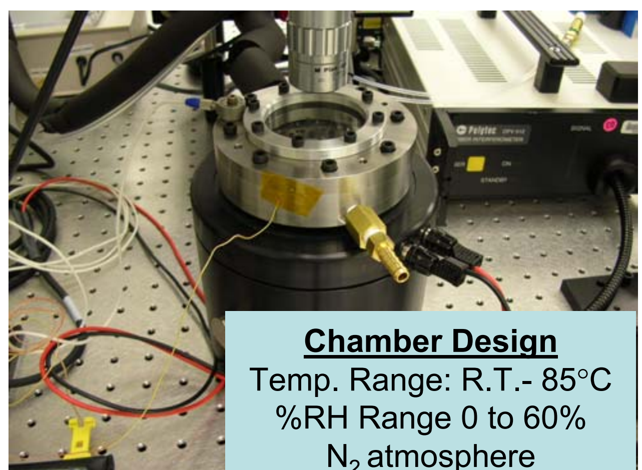
used to performed ±80 μm and ±700 μm fatigue experiments on mass-spring test structure

Experimental set-up



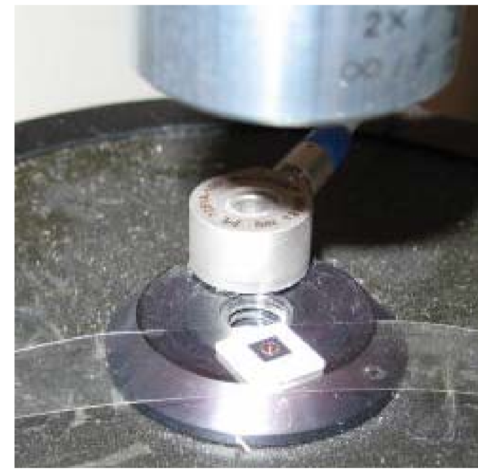
Environmental Control Chamber





Chamber Design
Temp. Range: R.T.- 85°C
%RH Range 0 to 60%
N_2 atmosphere

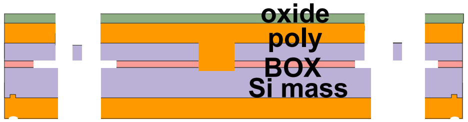
Accelerometer for additional sensing



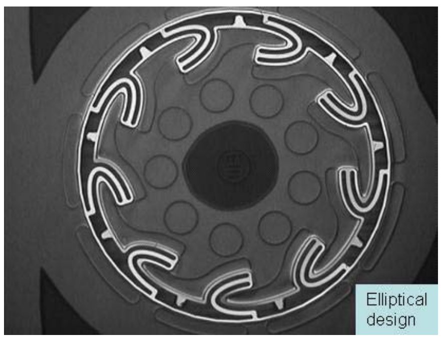
- **Environmental control chamber used for ±*80 μm experiments***
- ***Accelerometer used for ±700 μm experiments***

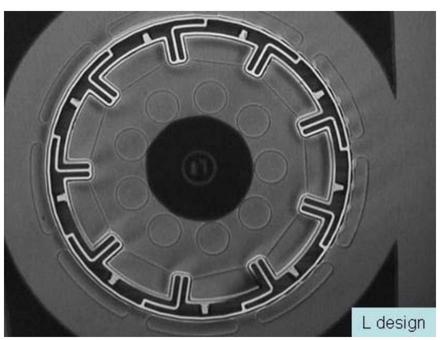
A long-term fatigue reliability study on the spring-mass test structure

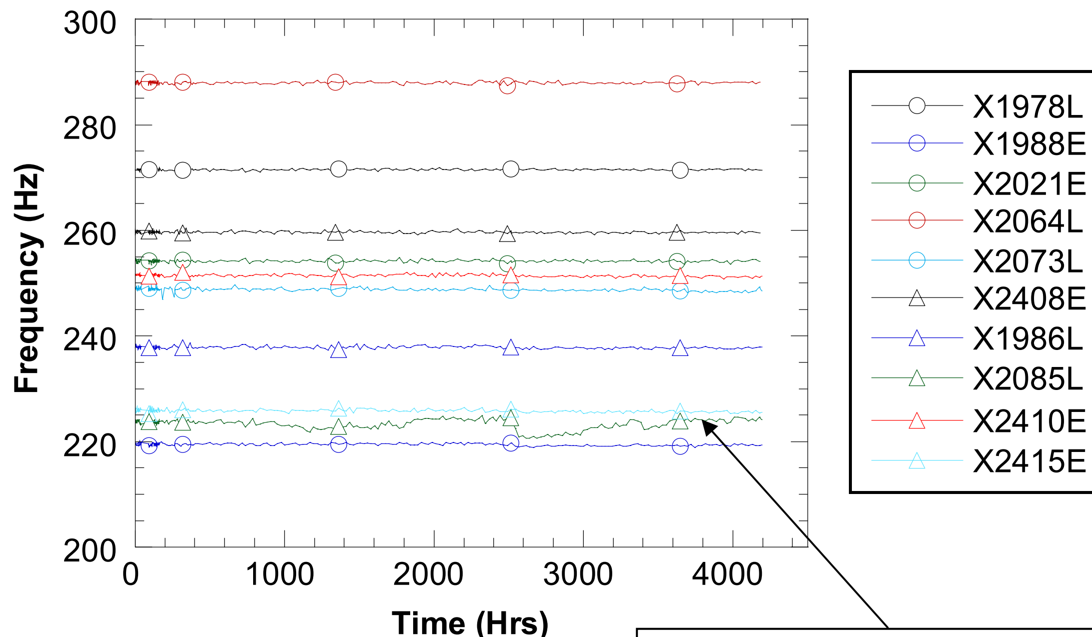
Resonant Frequency Tracking of 10 SOI-spring-mass structures



A different SOI process was used to fabricate these structures







250 Hz for 4000hrs = 3.6 billion cycles

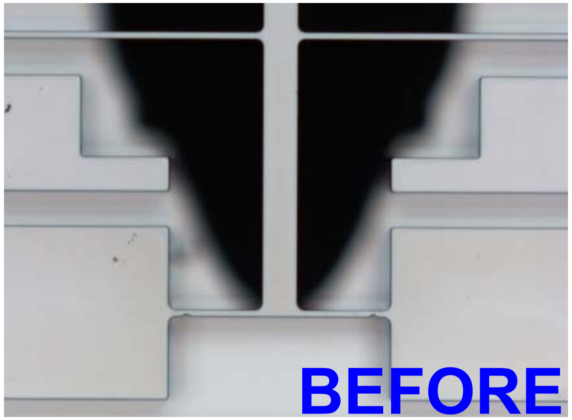
Broken spring noted on X2085L before fatigue testing experiment

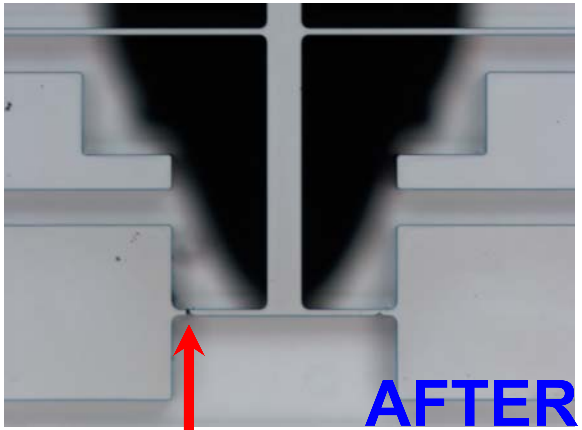
- **Spring-mass devices exhibited no evidence of fatigue when cycled at its designed operational range of ± 80 μm.**
- **Device-to-device variation of resonant frequency was observed.**

Phillip L. Reu, Danelle M. Tanner, David S. Epp, Ted B. Parson and Brad L. Boyce, Proceedings of SPIE, vol. 6111, 2006

In-Plane Fatigue Response of MEMSCAP SOI

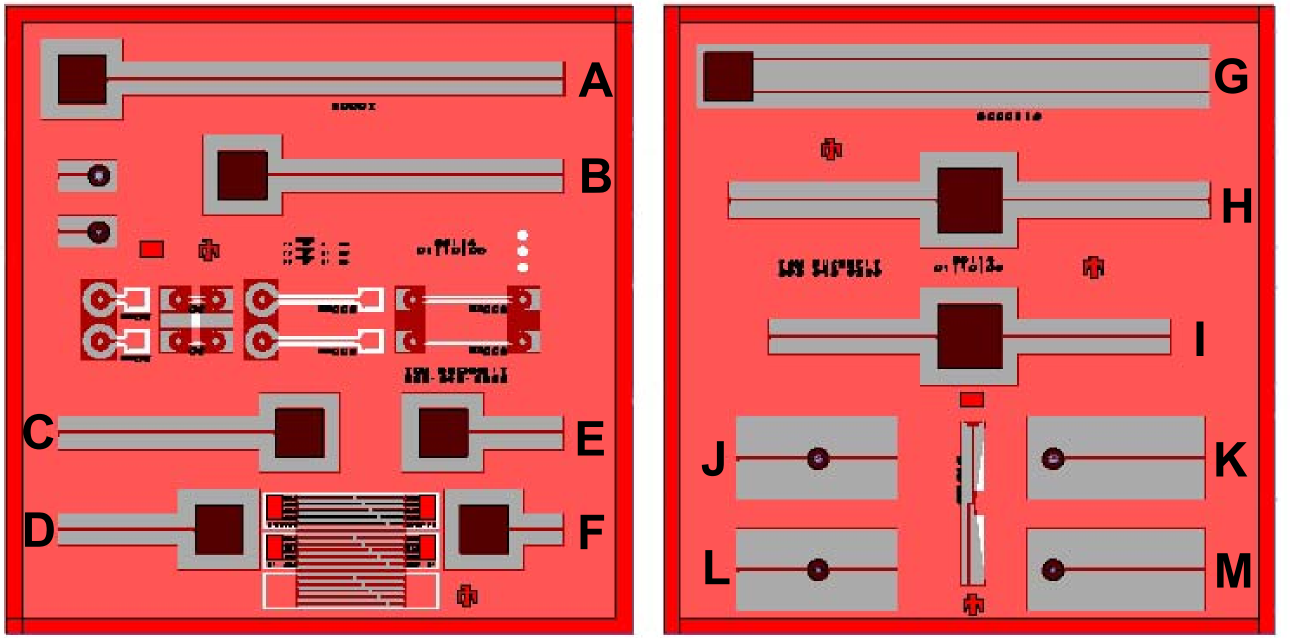
DIE	Specimen ID	Applied Voltage	Cycles to Failure (x10^6)	
SOI 14 GP5 D1	ID 18	9	37.89	
SOI 14 GP3 D3	ID 28	10	25.47	
SOI 14 GP4 D2	ID 16	10	32.4	
SOI 14 GP4 D2	ID 18	10.5	32.4	
SOI 14 GP4 D1	ID 28	12	27	
SOI 14 GP5 D1	ID 28	12.5	25.92	
SOI 14 GP5 D2	ID 16	10	23.4	
SOI 14 GP5 D2	ID 28	10.5	3.24	
SOI 14 GP5 D5	ID 20	13	32.4	
SOI 14 GP5 D5	ID 28	12.5	3.06	





Fracture at notch

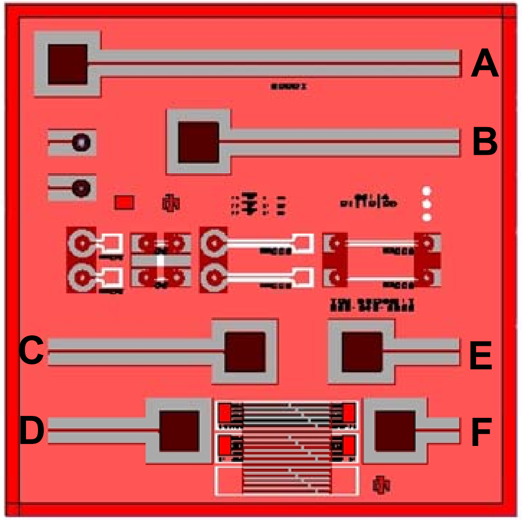
Out-of-plane fatigue response in MEMSCAP SOI



Label	Length (µm)	Label	Length (µm)	Label	Length (µm)
A	3000	D	1000	G	3000
B	2000	E	750	H	3000
C	1500	F	500	I	2500

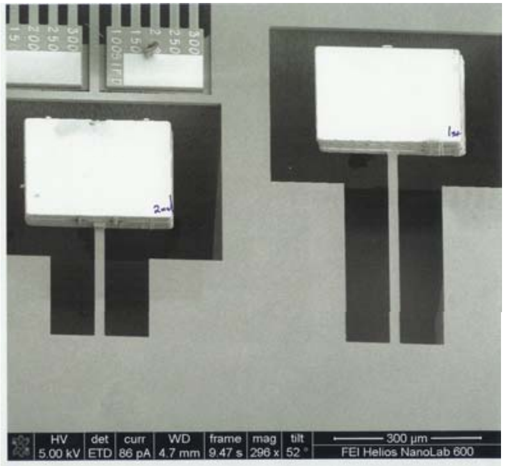
Out-of-plane fatigue response in MEMSCAP SOI

- **Failure of test structures did not occur during the initial stage of testing**



Beam	f_n (hz)	10g Accel.	max. stress	20g Accel.	max. stress
A	*did not fabricate*				
B	695	180 µm		380 µm	371 MPa
C	1050	93 µm		180 µm	312 MPa
D	1910	52 µm		104 µm	406 MPa
E	3000	36 µm		67 µm	465 MPa
F	5460	19 µm		36 µm	562 MPa

- **Adding weight to out-of-plane fatigue structures increases the maximum stress at resonance**



Beam	f_n (hz)	f_n (hz) FIB	f_n (hz) Au-pre	20g Accel.	
B	695				
C	1050		323	800 µm	1.39 GPa
D	1910		570		
E	3000	1840		160 um	1.11 GPa
F	5460				

MEMS Reliability Task Outcomes/Accomplishments for FY07

- Finish 700 μm deflection experiments on mass-spring structures

- Begin Testing in-plane and out-of-plane fatigue diagnostic structures

- Characterize and begin baseline testing friction test structures
- (8 die – levitation forces range of friction forces, test with monolayer coatings)

Later FY2007 deliverables:

- Second SOI die design

- Accelerated aging study