Sandia National Laboratories

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Science-based MEMS reliability methodology

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Purpose

- **To demonstrate an approach that incorporates a solid science base of modeling, simulation, and material science into standard reliability practices.**

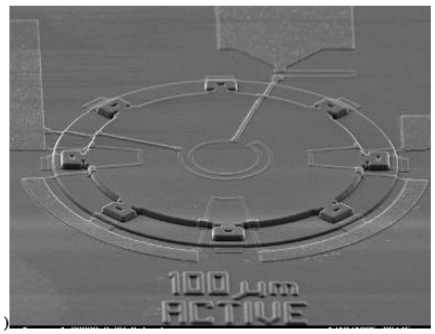
- **To relate this methodology to experiments performed on a 144-piston mirror array.**

Outline

- MEMS/Microsystem Taxonomy
- General MEMS Relaibility Method
- Reliability Method for a 12x12 Micromirror Array
  - Design, Model, Fabricate
  - Test Structures and Devices
  - Identify Failure Mechanism
  - Develop Predictive Reliability Models
- Summary & Conclusions

MEMS Taxonomy classifies reliability concerns – most commercial products (blue text) at lower classes

Class I
No Moving parts



Pressure Sensors
Inkjet Print Heads
Strain Gauge

Class II
Moving Parts, No Rubbing or Impacting Surfaces

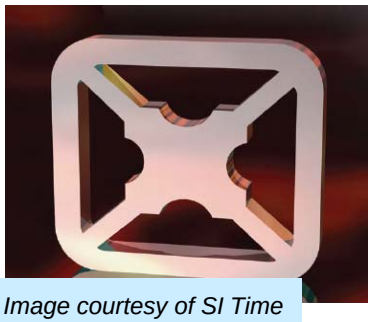


Image courtesy of SI Time

Gyros
Accelerometers
FBAR
(Film Bulk Acoustic Resonator)
RF Oscillators

Class III
Moving Parts, Impacting Surfaces

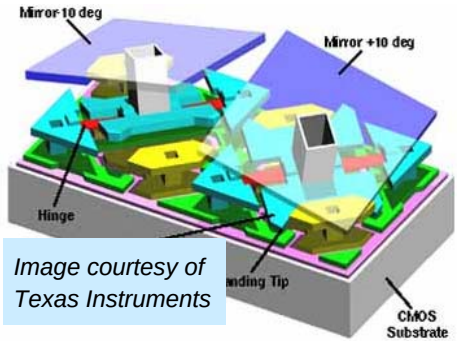
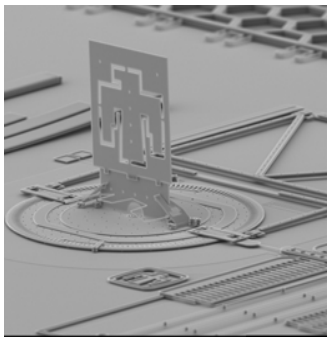


Image courtesy of Texas Instruments

Texas Inst. DLP
Accel. with stops
RF Switch
Adaptive Optics
Optical Switch

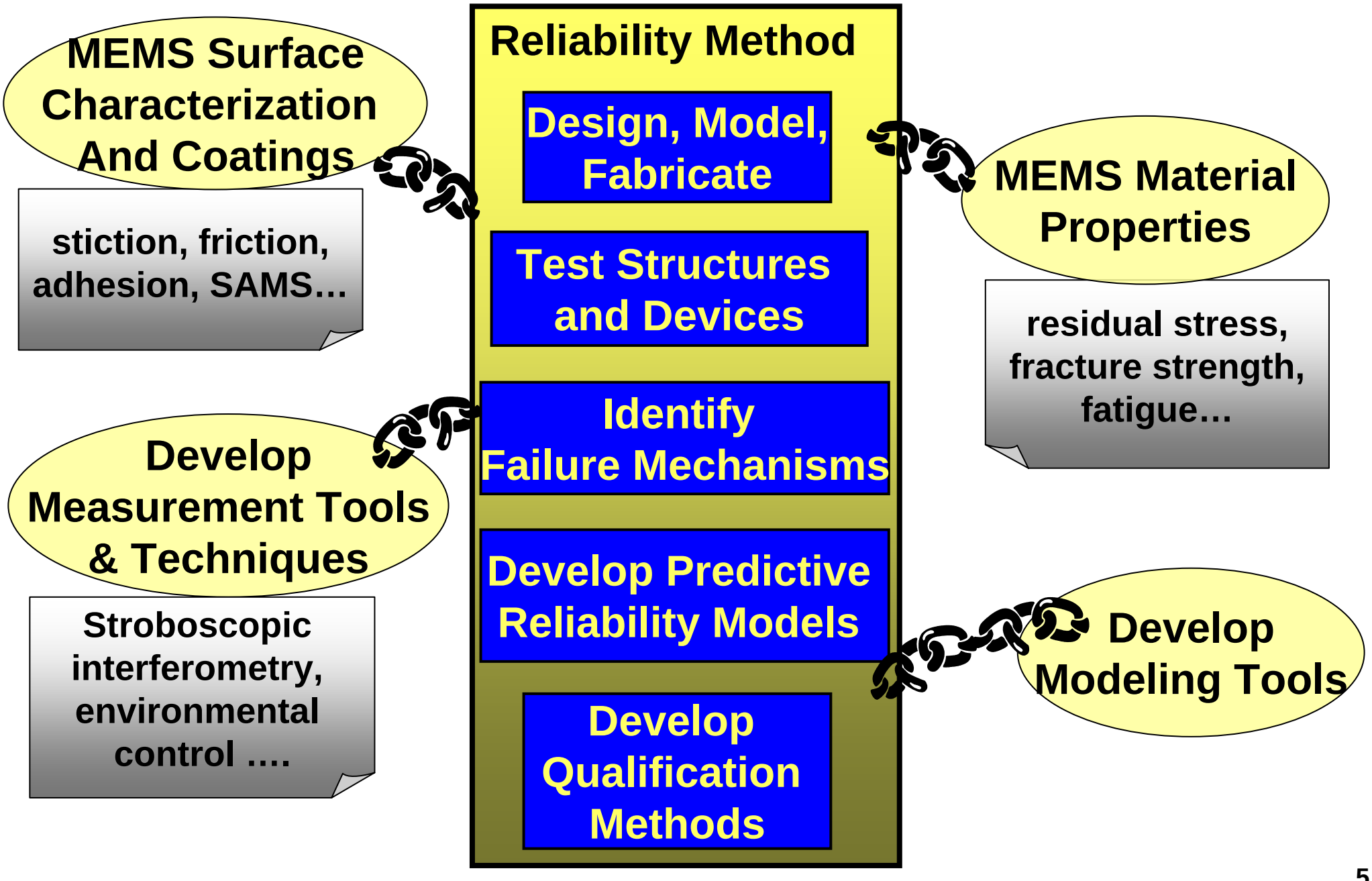
Class IV
Moving Parts, Impacting and Rubbing Surfaces



Optical Switches
Shutters
Scanners
Locks
Discriminators

Billions of inkjet print cartridges produced using HP technology!
Analog Devices ships 1 million MEMS accelerometers a week! - over 200 million
Texas Instruments has shipped over 10 million DLP subsystems!

MEMS Reliability method identical to microelectronics, but failure mechanisms are not as well quantified



Specific MEMS reliability for a 12x12 mirror array

- Verify functionality at operating conditions
  - Characterize the array via voltage versus diaplacement measurements
- Perform cycling experiment
  - Inspect for failures
  - Establish operational margin

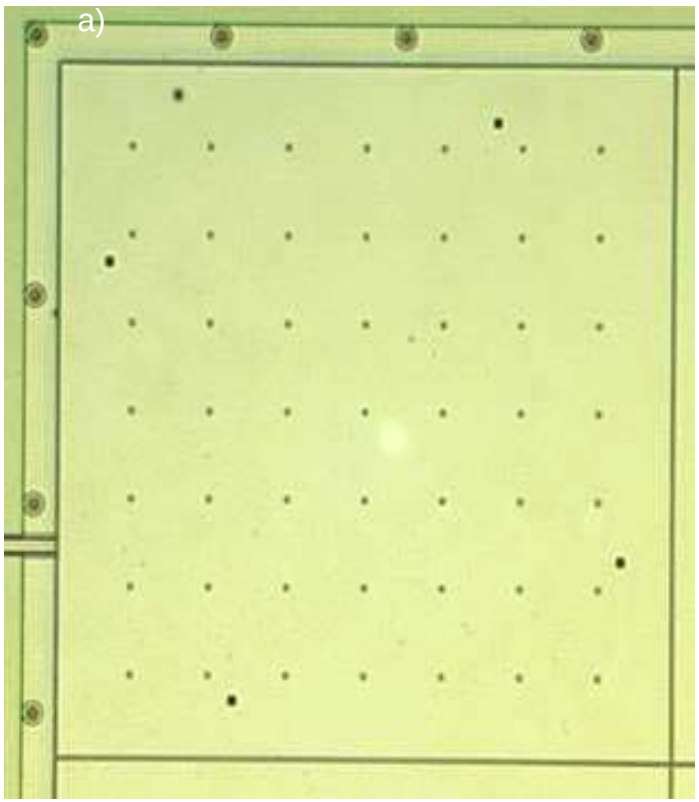
Design, Model, Fabricate

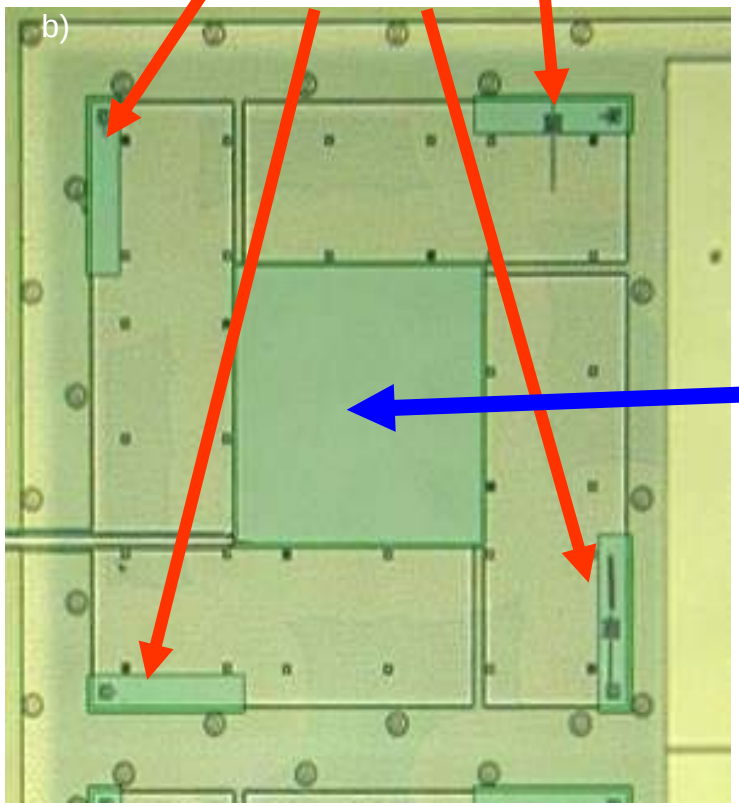
The electrostatic mirror pixel has 2.5 μm of stroke

Micro-mirror pixel

300 μm x 300 μm Mirror

Spring Locations





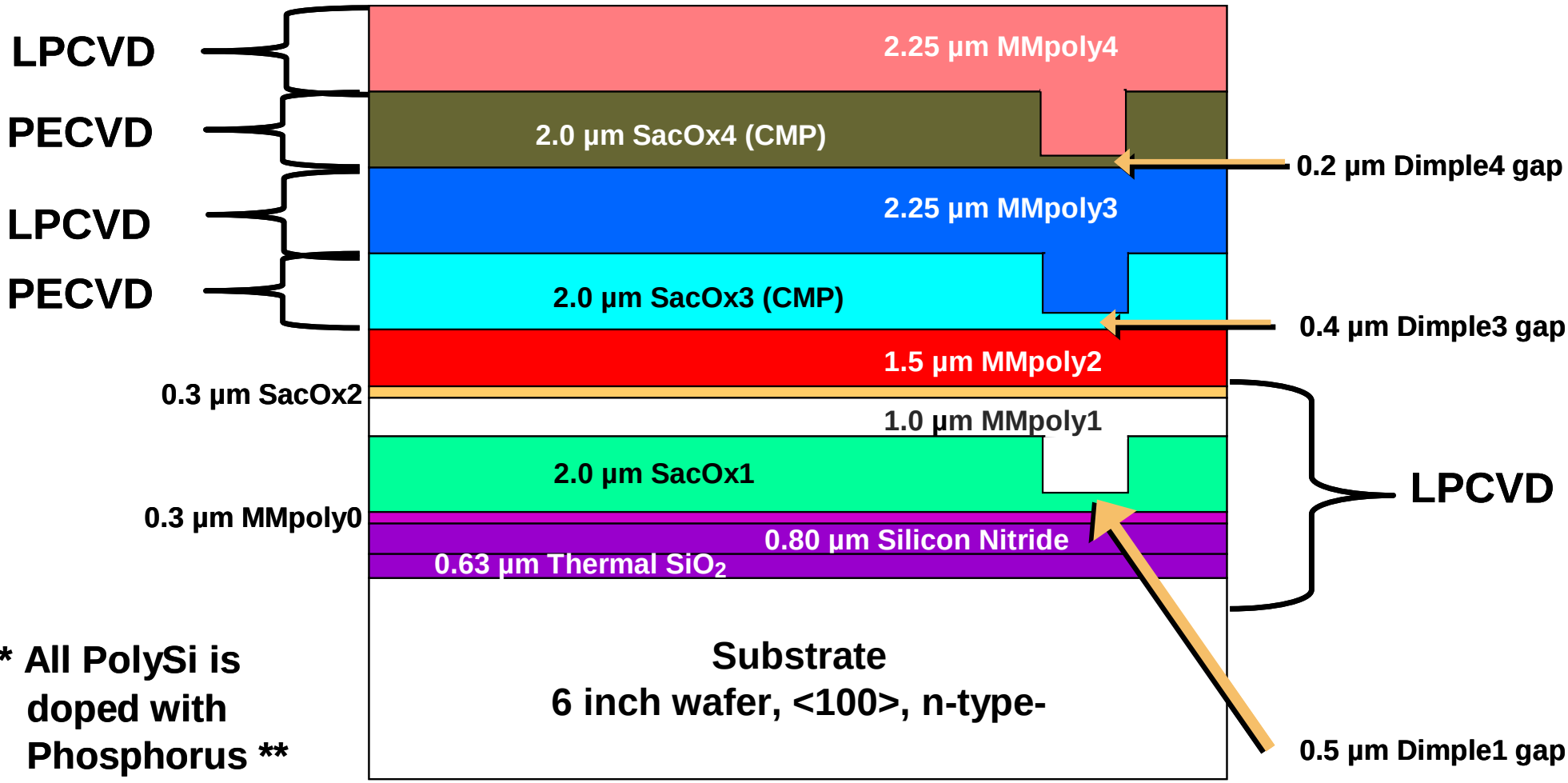
Actuator Pad

Underlying Structure

Design, Model, Fabricate

The spring structure utilizes many SUMMiT V layers

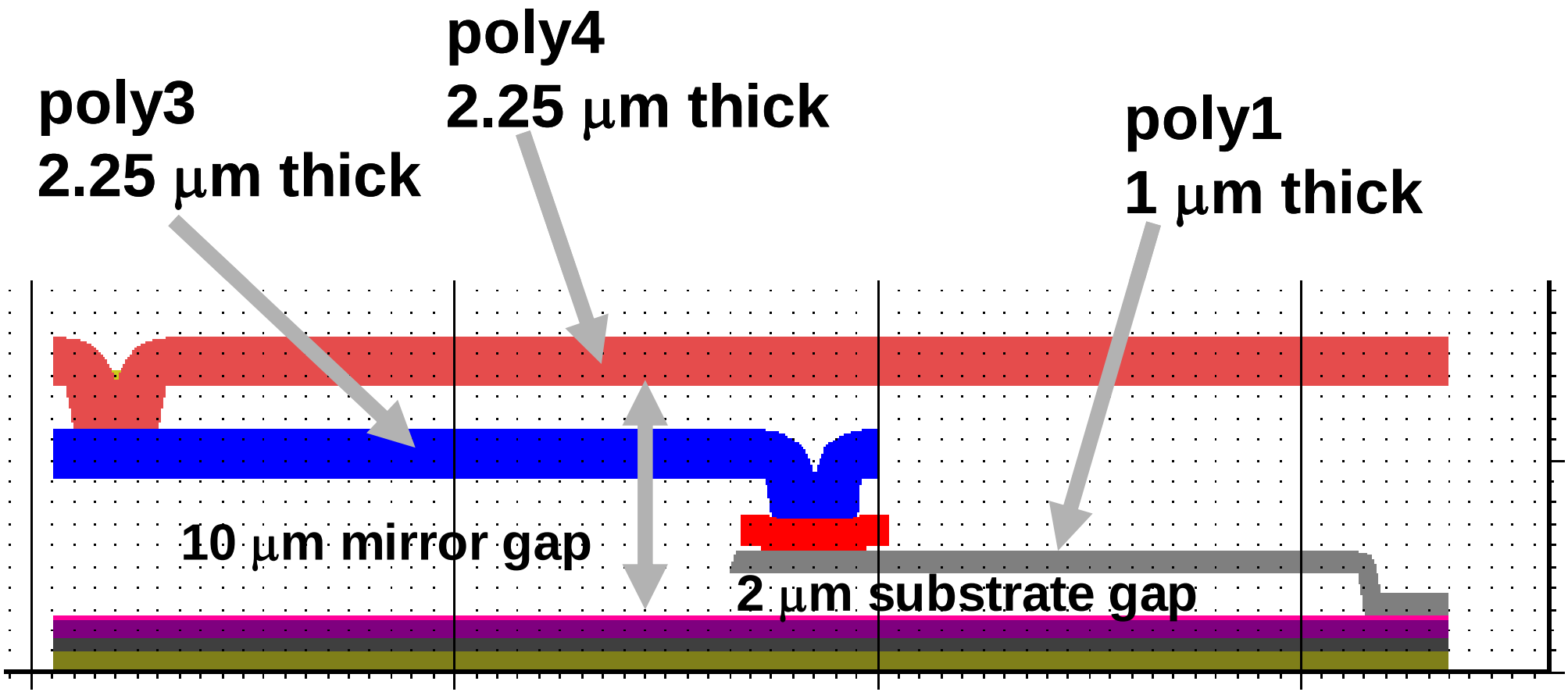
SUMMiT™ Layer Descriptions



** All PolySi is doped with Phosphorus **

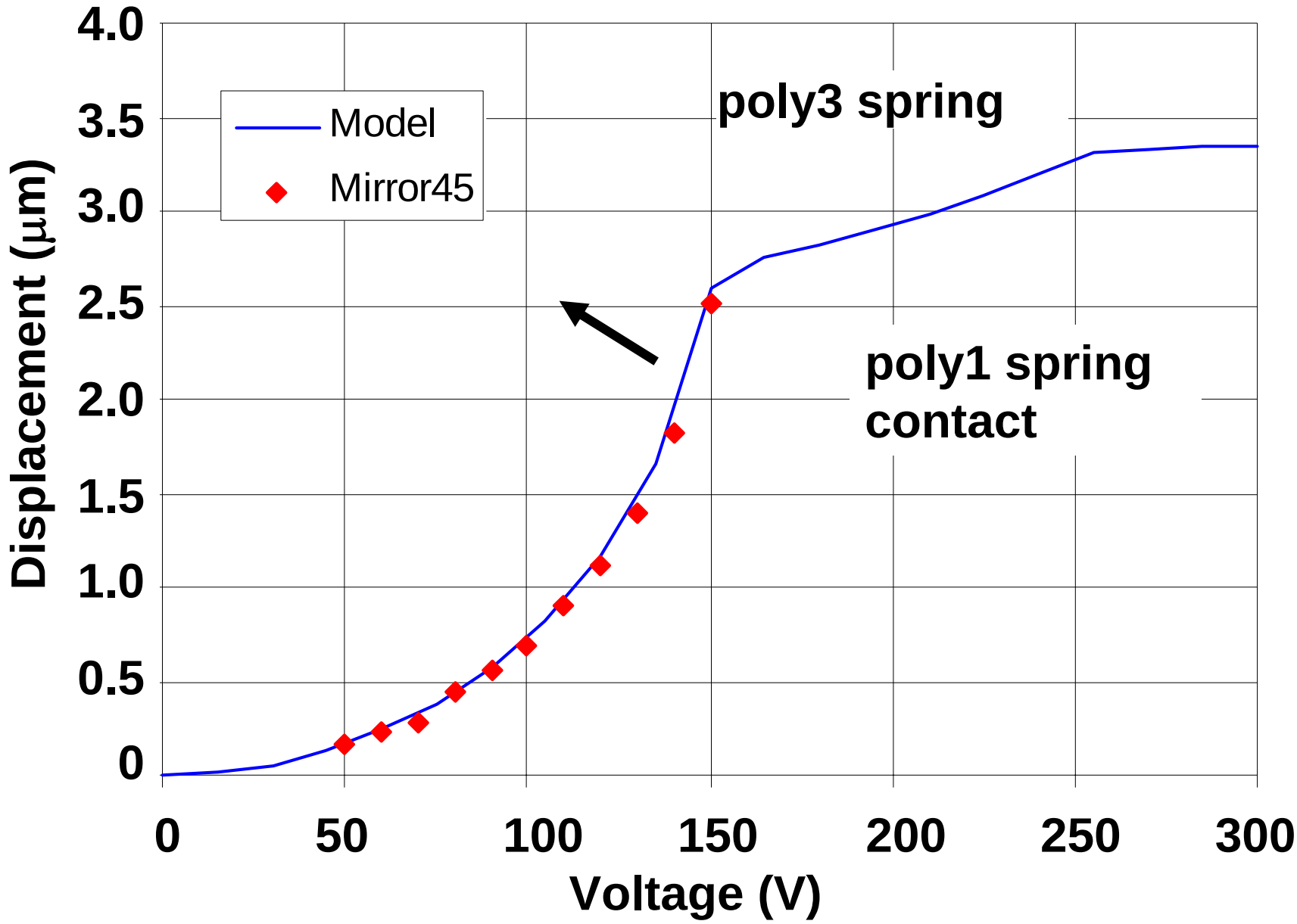
Design, Model, Fabricate

Spring cross section shows layer choices



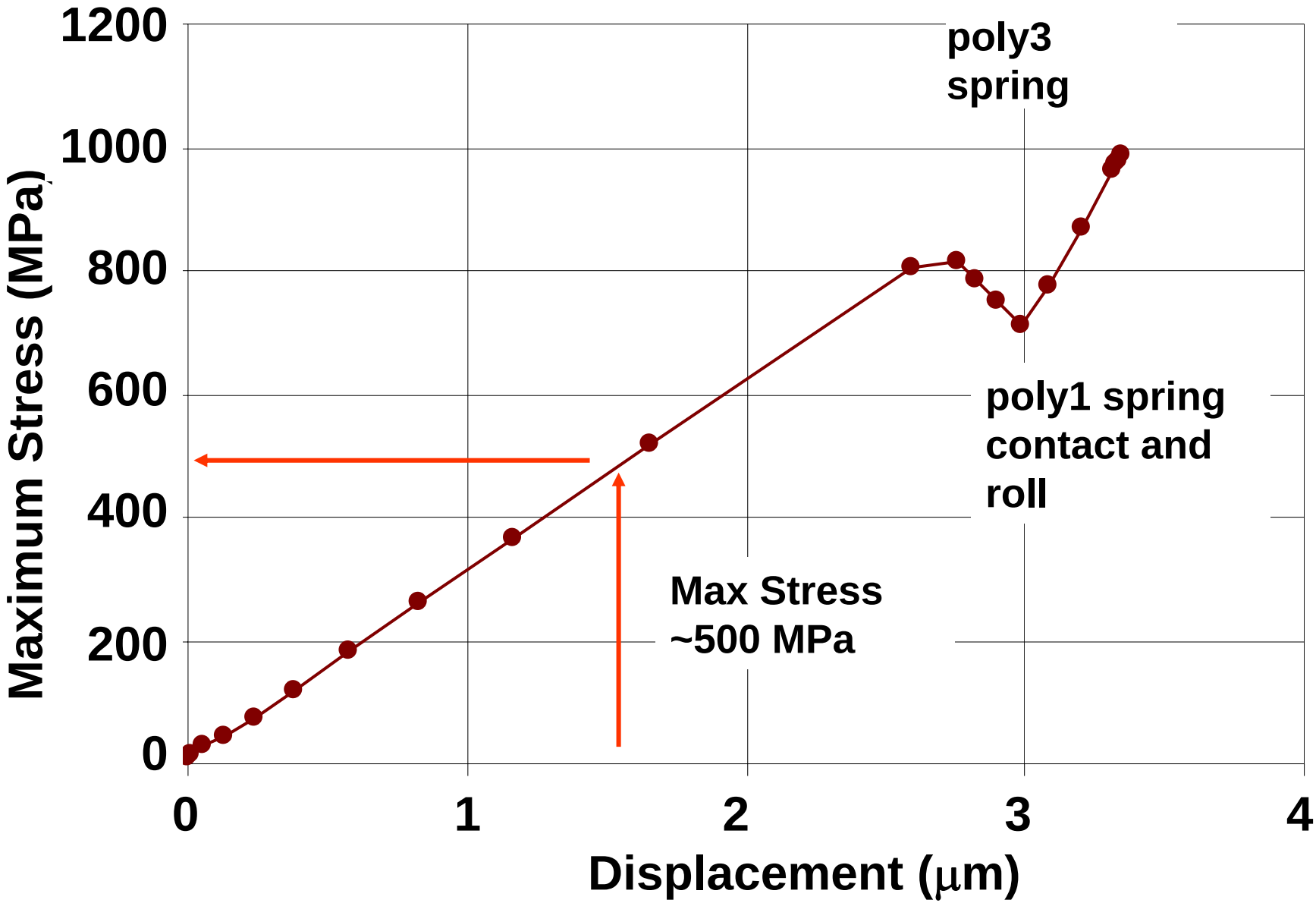
Design, Model, Fabricate

Model was validated



Design, Model, Fabricate

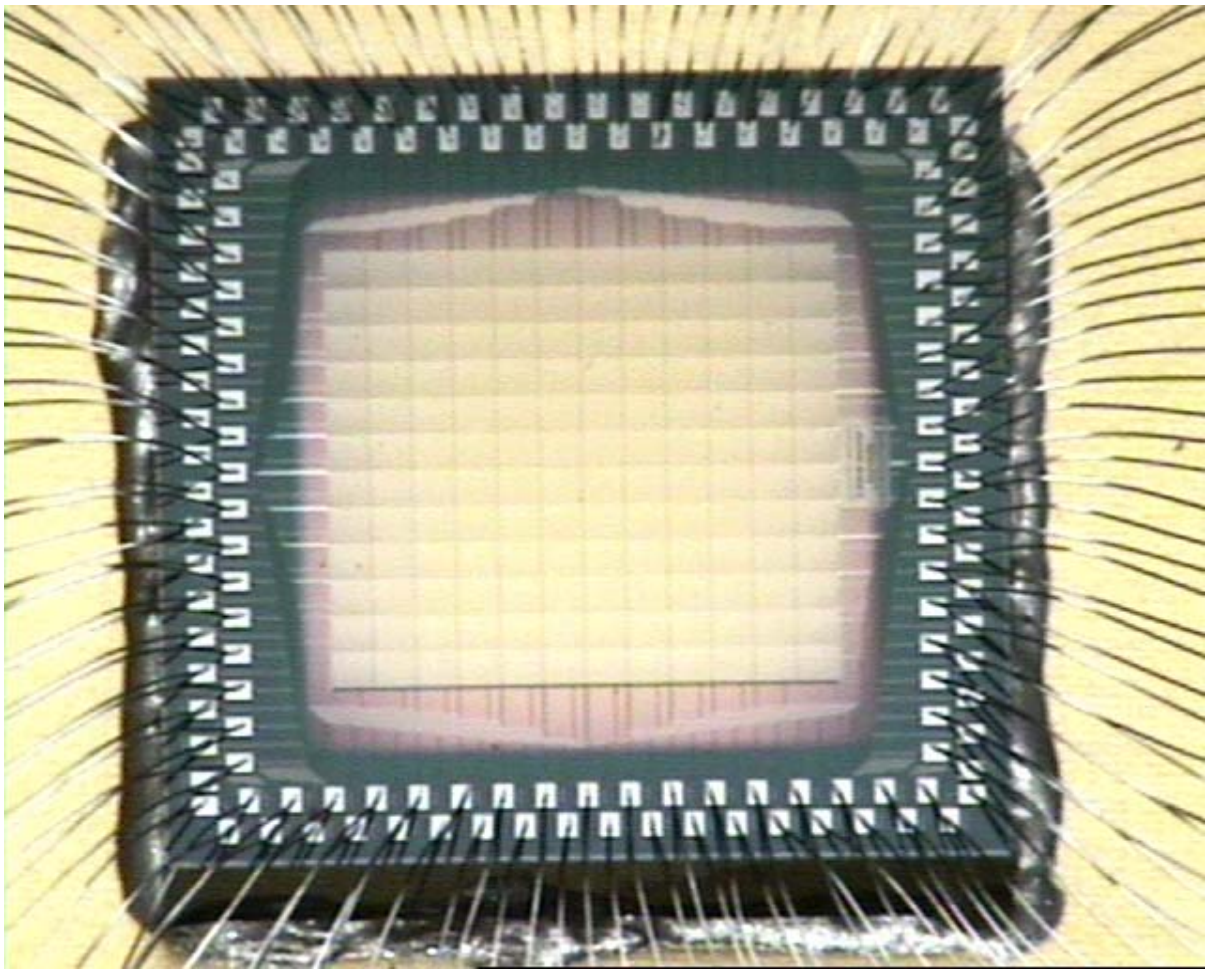
Spring stress was predicted



Design, Model, Fabricate

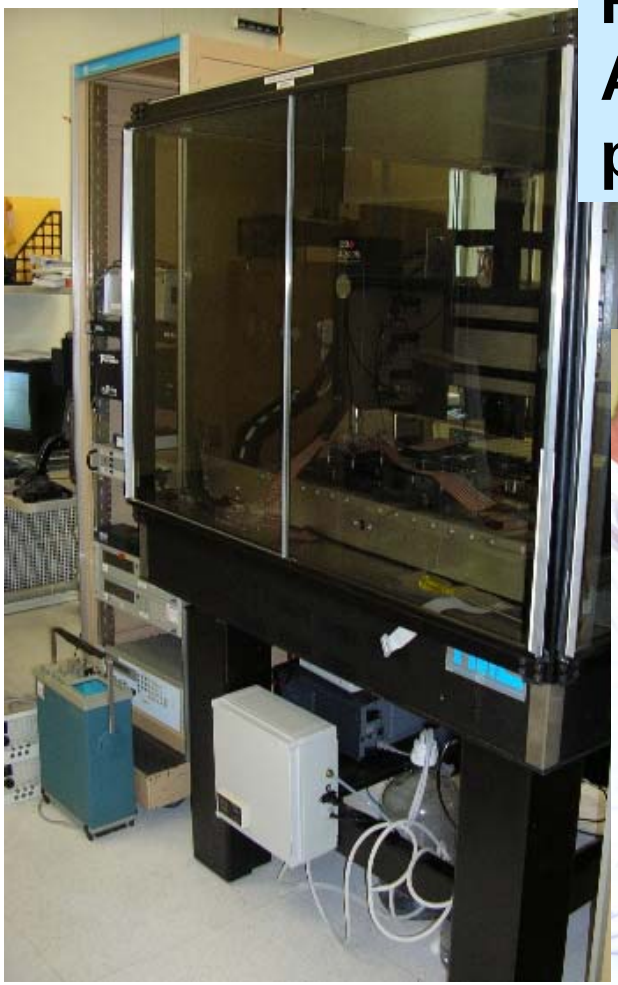
Back-End-of-Line processing yielded packaged die

- Die attach
- Wire bond
- Shadow mask inside the package well
- Sputter metal on poly4 layer – TiAu (7.5 nm/50nm)



Active Cycle Lifetime Experiment Set-Up

Develop Measurement Tools & Techniques



SHiMMeR 1 - Sandia High-volume Measurement of Micromachine Reliability

Humidity controlled, Ambient temperature, parallel test system

Gantry-Mounted Microscope, Automated positioning and control for inspection

Independent control of each mirror, ability to zero voltage on failed mirror using switch matrix

Develop Measurement Tools & Techniques

Experiment Test Plan

- Actuate in checkerboard pattern (135V) in controlled 2000 ppm nitrogen environment
- At specified times, stop cycling and inspect
  - Catastrophic failure
  - Mirror displacement
- Maintain one Control array – no cycling, stored in dry nitrogen, ambient temperature

Actuation pattern

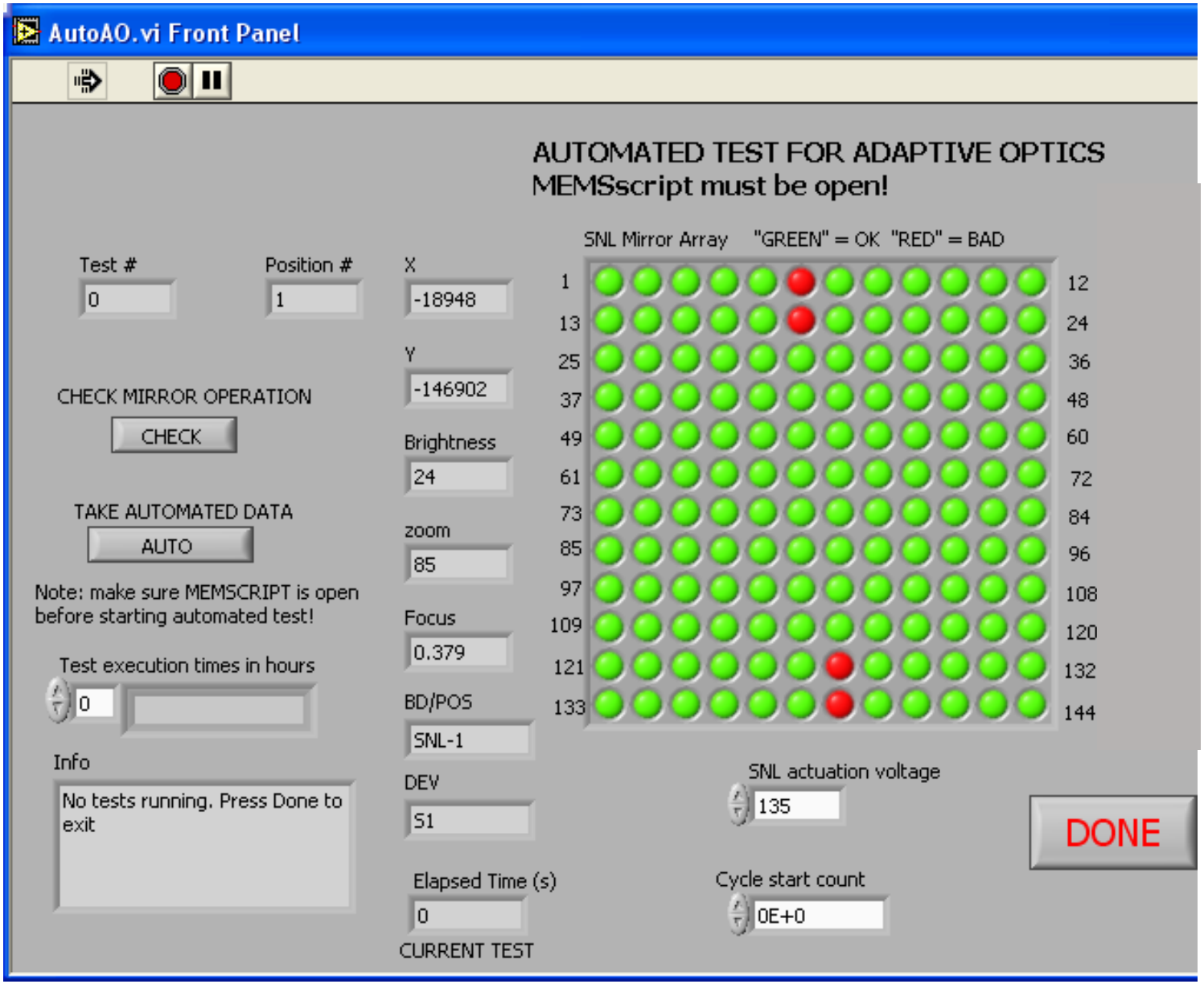
Set voltage to get 1.55 μm stroke**

1	2	3	4	5	6	7	8	9	10	11	12
13	14	15	16	17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70	71	72
73	74	75	76	77	78	79	80	81	82	83	84
85	86	87	88	89	90	91	92	93	94	95	96
97	98	99	100	101	102	103	104	105	106	107	108
109	110	111	112	113	114	115	116	117	118	119	120
121	122	123	124	125	126	127	128	129	130	131	132
133	134	135	136	137	138	139	140	141	142	143	144

○ Voltage-Displacement curves

Develop Measurement Tools & Techniques

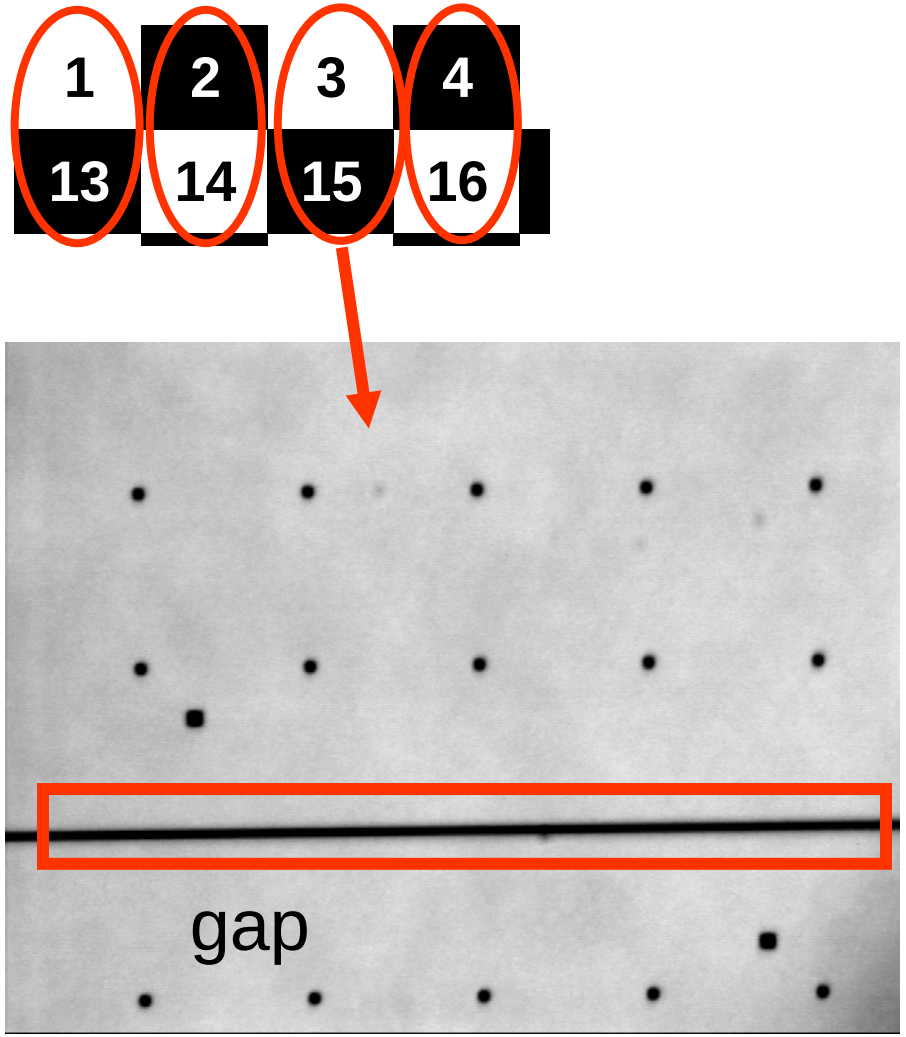
Developed a testing interface to cycle and check the mirror functionality



Develop Measurement Tools & Techniques

Inspection – Failure Scan

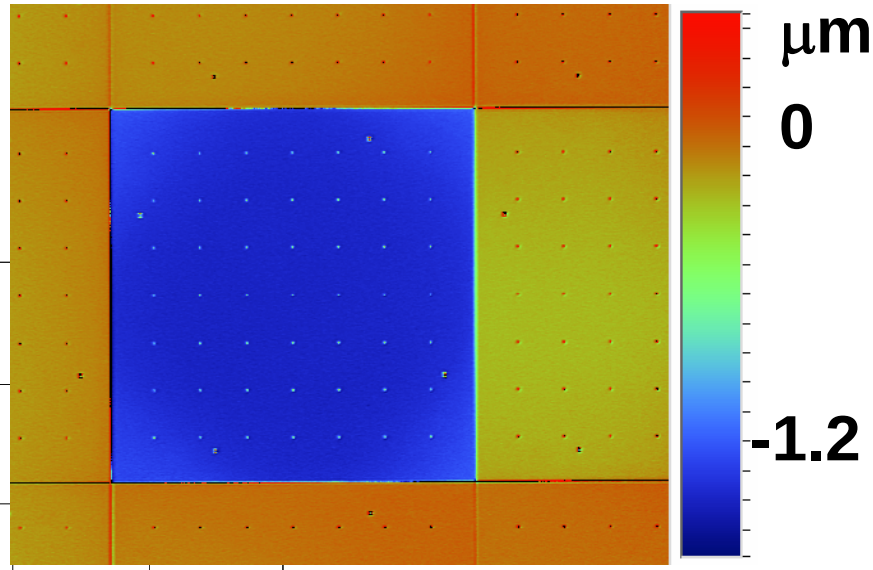
- **Inspect a pair of mirrors**
  - **Hold lower stationary, move upper**
  - **Monitor image contrast focusing on gap between mirrors - Contrast change with voltage change implies functionality**
  - **Reverse pair role and repeat**
- **Flag failures (record total number of cycles) and remove voltage signal to that mirror for future cycling**
- **Move to the next mirror set until all mirrors have been checked**

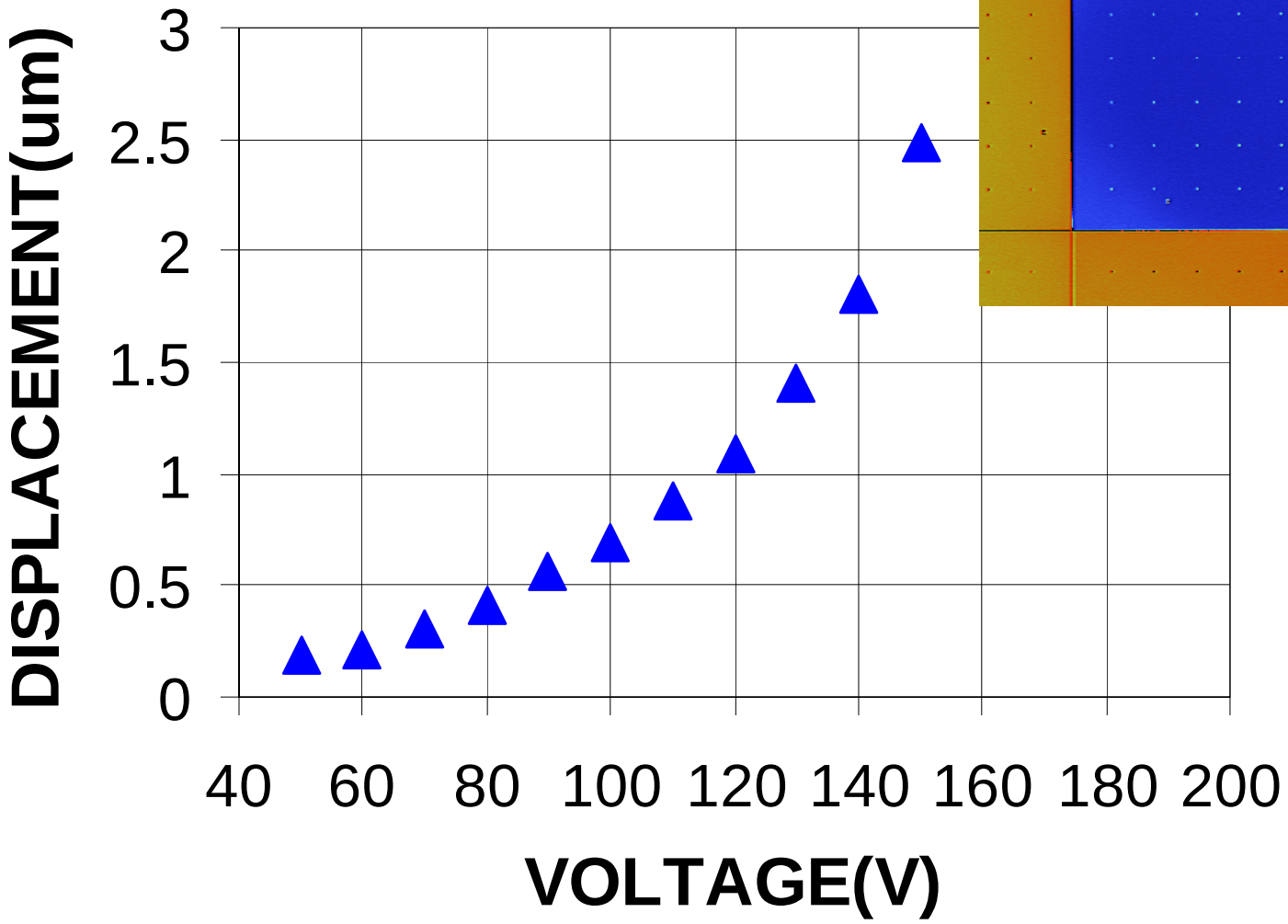


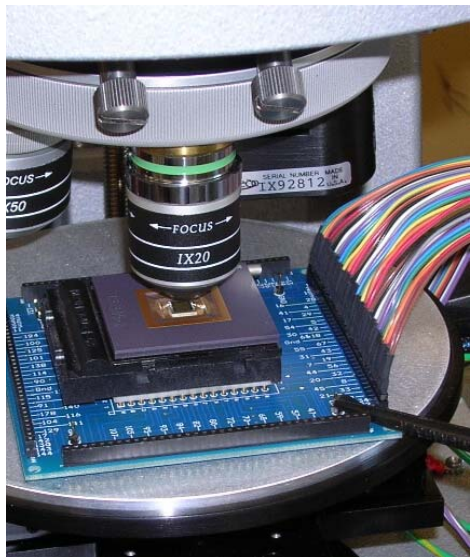
Develop Measurement Tools & Techniques

Inspection – Voltage Displacement

WYKO Measurement







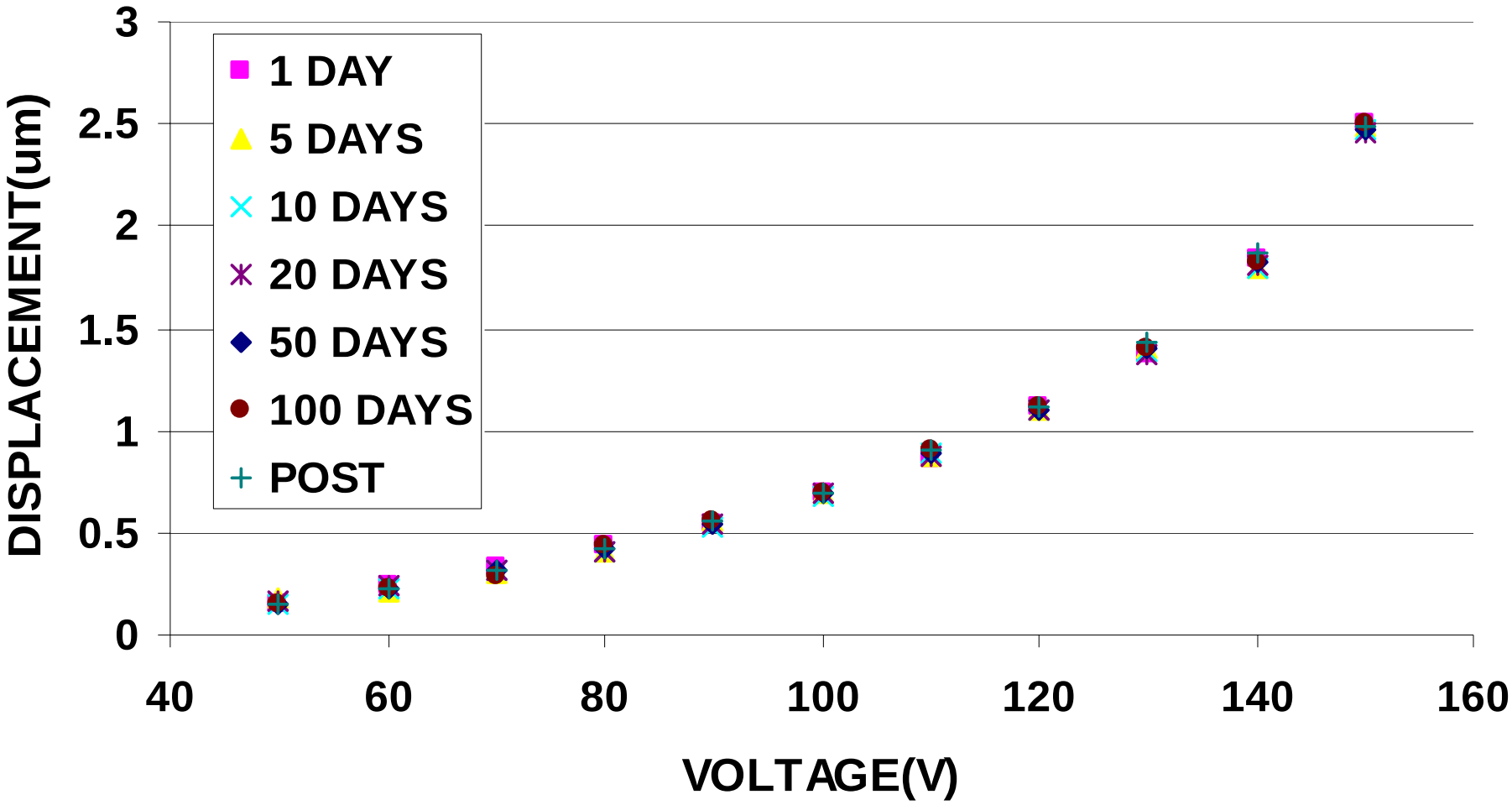
Identify Failure Mechanisms

No failure or degradation was observed!

- **Over 26 billion cycles on 140 mirrors with NO catastrophic failures using stroke of 1.5 microns stressing at 3 KHz (180V) in an nitrogen environment with 2000 ppmv humidity**

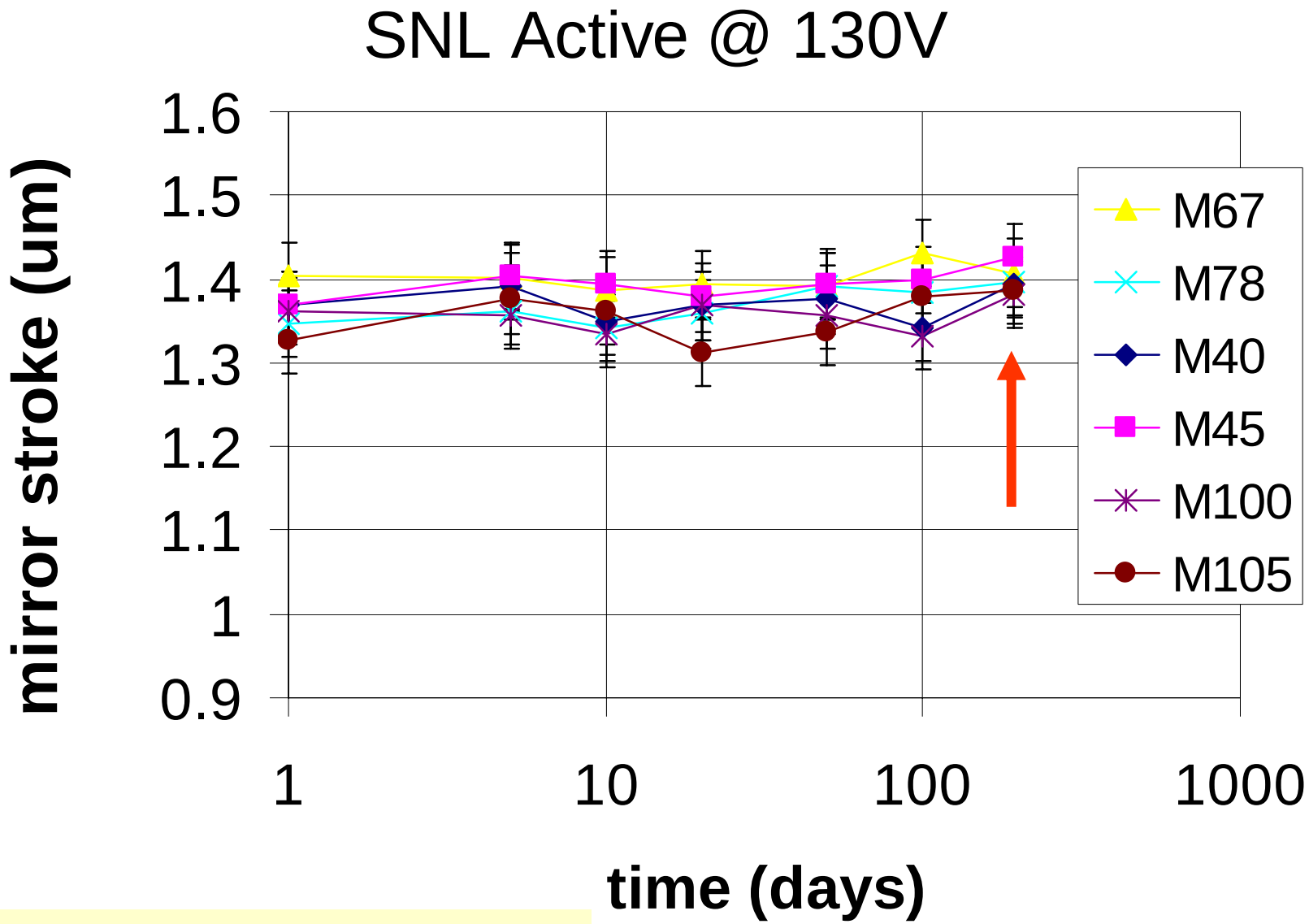
Test Structures and Devices

NO observed change in displacement – voltage profile



Test Structures and Devices

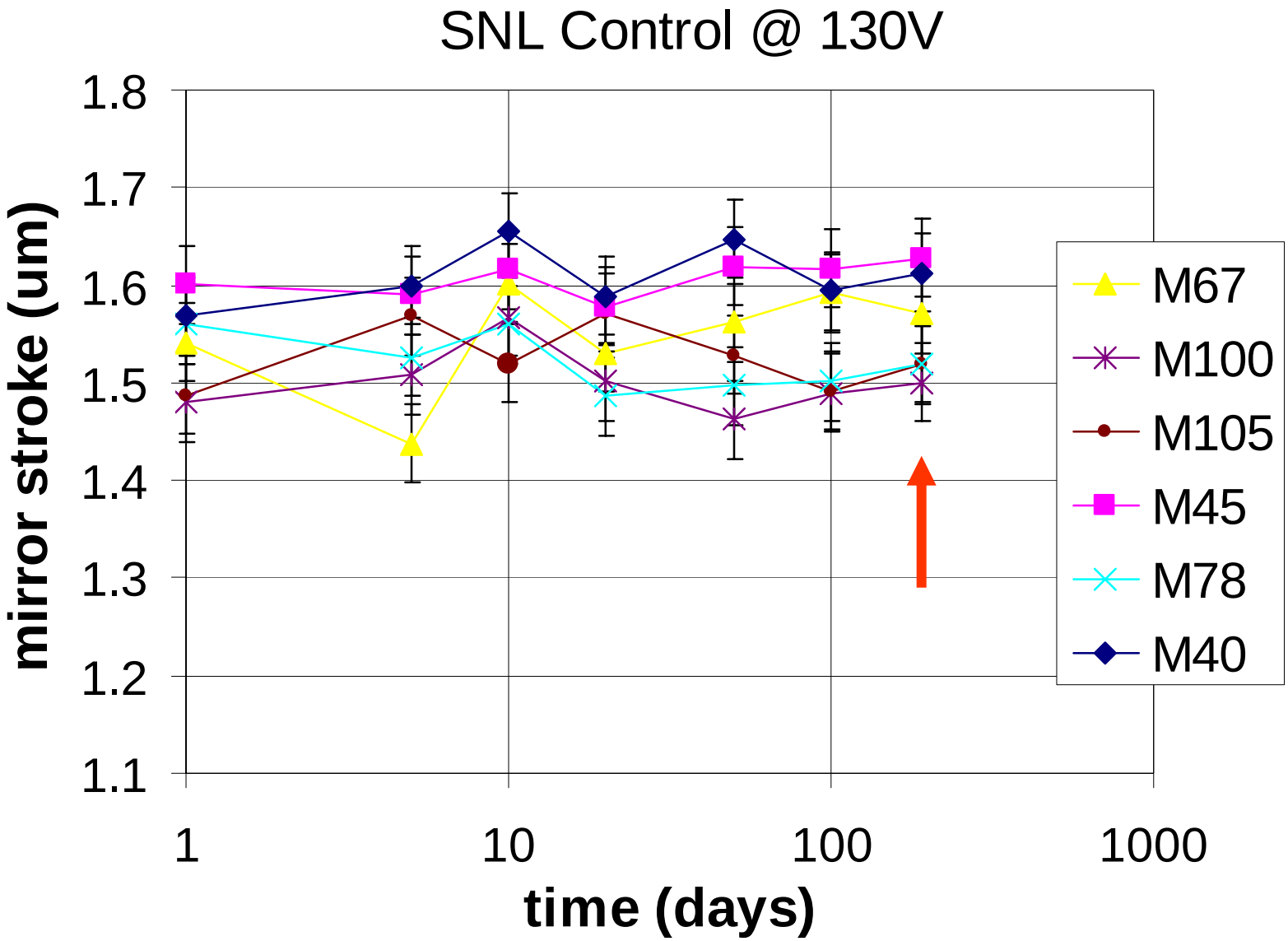
Observe NO change in mirror stroke over time



26 billion cycles in 100 days

Test Structures and Devices

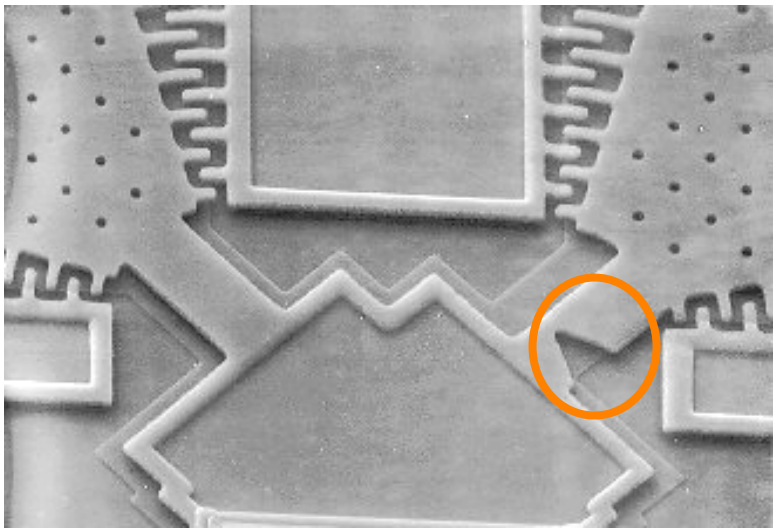
Control package measurements were steady over time



26 billion cycles in 100 days

MEMS Material Properties

Is Fatigue of polysilicon a mechanism of concern?



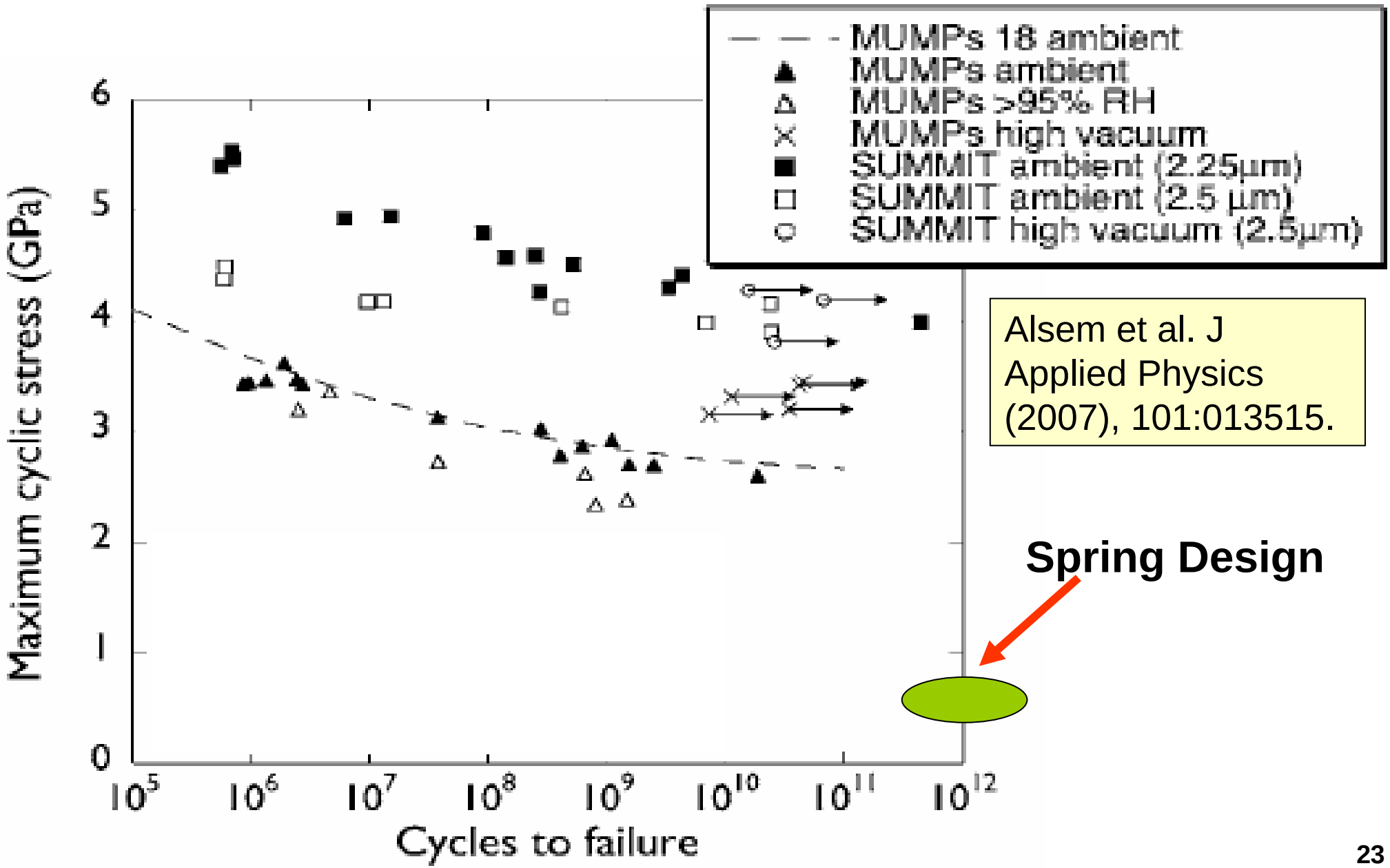
Experiments performed using fatigue test structure

Muhlstein et al./ Acta Materialia 50(2002), 3579-3595

- **Native oxide thickening, crack nucleation mechanism found as possible fatigue failure mode in MEMS polysilicon**
- **SAMS coatings mitigate oxide thickening and delay this fatigue-fracture mechanism**
- **High stress concentrations needed to observe effect**

MEMS Material Properties

Modeling and experiment results rule out fatigue as a mechanism



Alsem et al. J Applied Physics (2007), 101:013515.

Spring Design

Develop Predictive Reliability Models

No wear out mechanism – analyze with exponential distribution

$$\lambda_{100(1-\alpha)} = \frac{\ln(\alpha)}{nT}$$

Failure rate prediction

"ASSUMES NO WEAROUT"

nT = 140 mirrors * 100 days = 38.3 mirror years

- **Operating frequency is 3 KHz, unit operates continuously 24/7**
- **PRODUCT: 1000 mirror system with 5 year lifetime**

Develop Predictive Reliability Models

Estimate defects using "No-Fail" Statistics

Confidence Level	Lambda (%/yr)	Predicted Defects
50%	1.8%	90
90%	6.0%	300
95%	7.8%	391

Predicted maximum number of defects for product with 1000 mirrors and 5 year lifetime

Must test more mirrors or cycle longer to improve defect estimate

Summary and Conclusions

- **Demonstrated a step by step method of assessing the reliability of a micro-mirror array**
- **Showed that the science base of modeling, test structure evaluation, and materials properties characterization lead to elimination of fatigue of polysilicon as a mechanism of concern**
- **Can confidently use the exponential distribution to describe the data (NO wearout mechanism)**

Acknowledgments

We thank:

- **Ernie Garcia for use of the packaged micro-mirror arrays**
- **Laura Halbleib for statistical analysis**
- **Dave Czaplewski and Tom Buchheit for careful review and discussion**