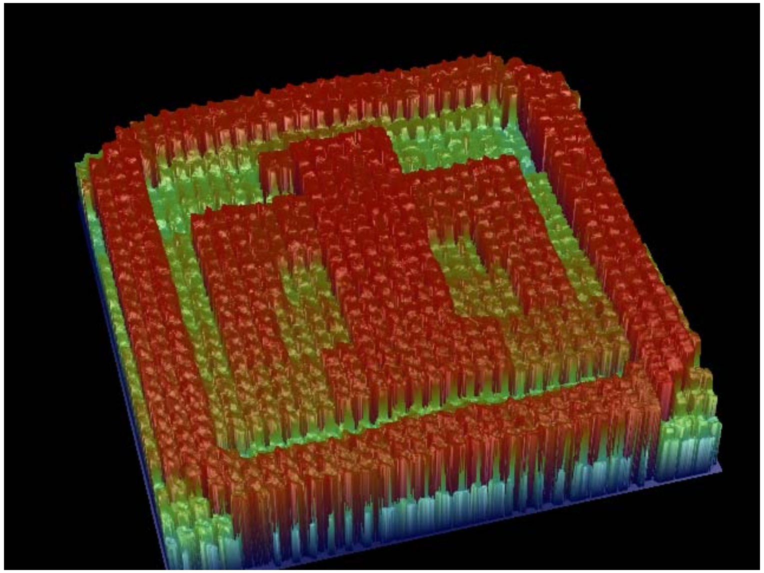
SAND2008-0387C



MEMS Active Optics Update

William D. Cowan, Olga B. Spahn,

Brett E. Bagwell, David V. Wick

and Grant D. Grossetete*

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

*L&M Technologies

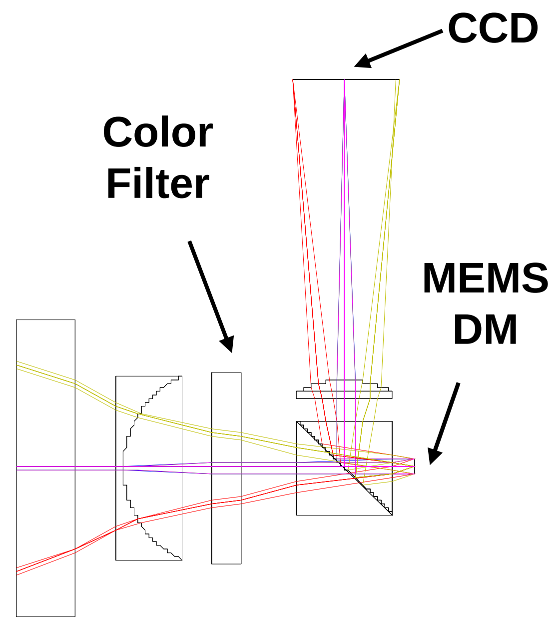
Overview

- Applications and 2007 Focus
- SUMMiT™ Technology
- Beam Steering Mirrors
- High Stroke Mirror Arrays & Results
- SFET - SUMMiT™ with Co-fabricated FETs
- Latest SFET OMEMS Results
- Summary

Applications

- Agile Imaging Systems
  - Non-mechanical Zoom
  - Foveated imaging
- Beam Steering and Beam Switching
  - Novel imaging approaches
  - Fast scanning/tracking
- Gimbal Replacement
  - MEMS steering speed can overcome angle limitations for some applications
  - Potentially large cost reduction

Foveated Imaging



- **Increase resolution in a selected area of FOV**
  - Extremely wide FOV and low f/#
  - Smaller, more compact than conventional imaging systems
  - Eliminates gimbals (cost, weight, speed limitations, etc.)
  - Multiple threat detection enabled by fast (msec), high resolution tracking of area of interest within the wide FOV
  - Single MEM-DM reduces system aberration

Sandia National Laboratories

Non-mechanical Zoom

- **Decrease FOV and increase resolution**
  - **Optical magnification**
  - **NO macroscopic moving parts**
  - **Very fast (20 Hz – 1 kHz)**
  - **Broadband – Visible to LWIR (if MEMS are used)**
  - **Two moving optical elements**
    - **2 MEM-DMs or macroscopic mirror & MEM-DM**

2007 Focus Across Several Efforts

- Improve
  - Position repeatability
  - Uniformity and yield
  - Mirror flatness
  - Mirror dynamic behavior
  - Optical power handling
- Larger aperture DMs
  - W/o addressing scale-up issues
  - Speed less important
- Demonstrate scale-up using SFET

Sandia National Laboratories

SUMMiT V™ MEMS Technology

Process Features

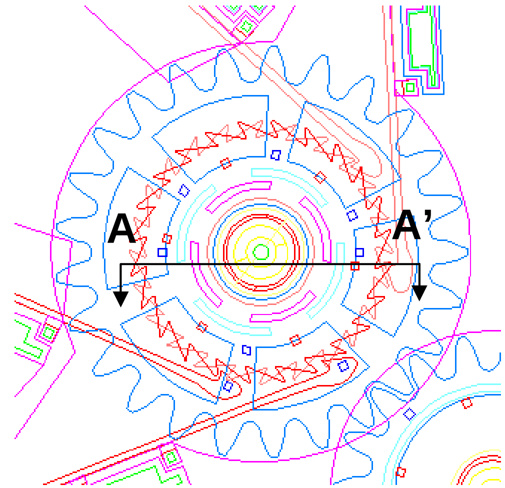
- Polycrystalline silicon (Poly)
- Low stress (< 5 MPa)
- Conformal depositions
- High fracture strength (~ 3 GPa)

- Ground plane layer (Poly 0)
- 4 structural levels (Poly 1- 4)

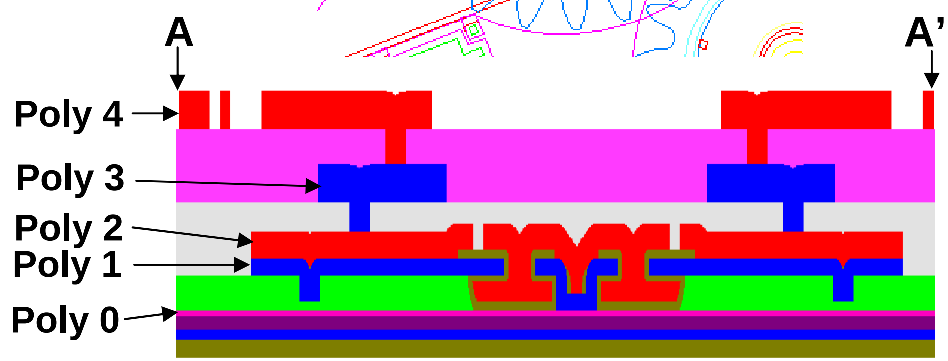
- Chemical Mechanical Planarization (CMP)
- 1 µm design rules

- Technology accessible through SUMMiT foundry (SAMPLES)

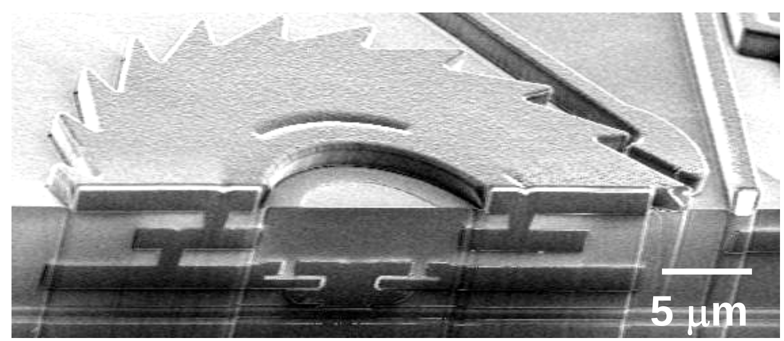
- OMEMS specific BEOL processes
    - Metallization
    - Packaging



Design layout



Cross-section drawing

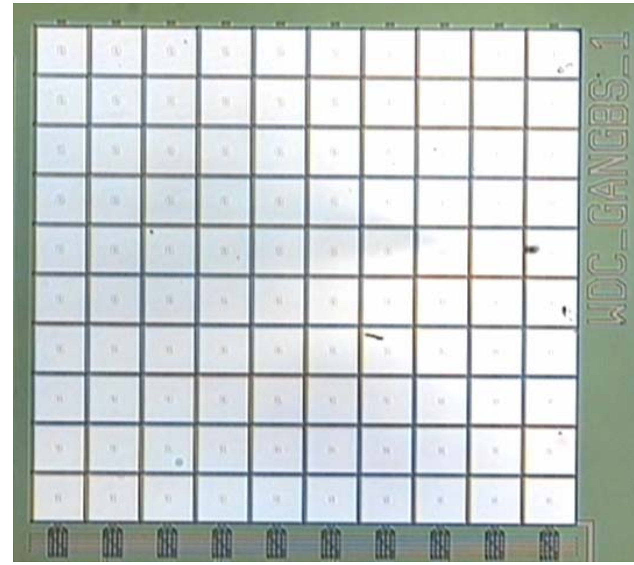


FIB cross-section

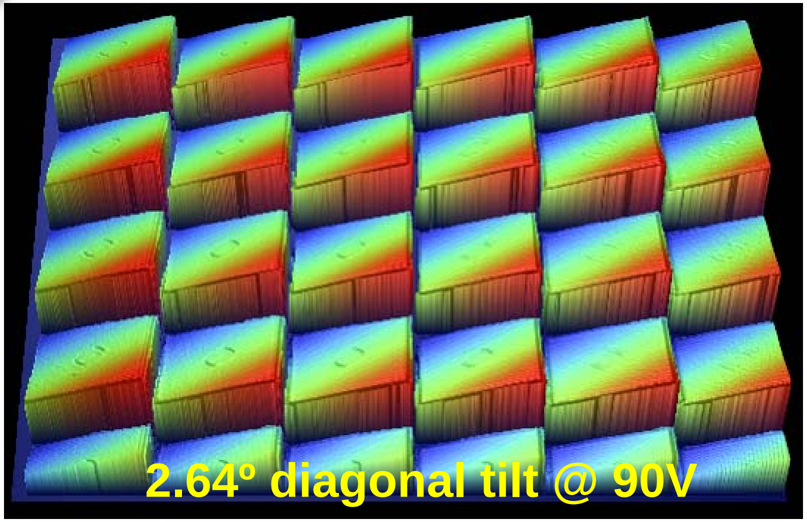
Sandia National Laboratories

Beam Steering Mirrors

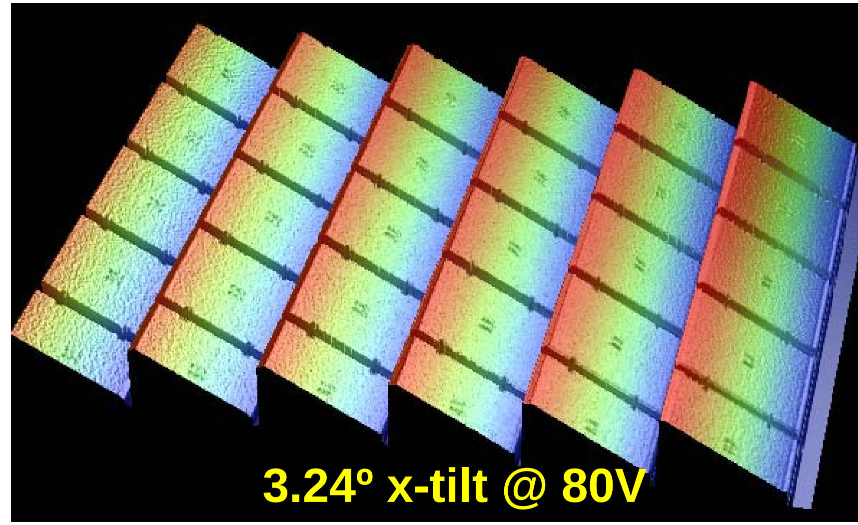
- **100μm mirrors**
  - **4 electrodes per mirror with analog position control**
  - **All like electrodes in arrays are tied together – “ganged” – by surface wiring**
  - **10x10 array prototypes=1mm**
- **Pros**
  - **Small size allows large steering angle, speed, easy to keep flat**
  - **No scale-up problem due to wiring or pin out**
- **Cons**
  - **Incoherent steering only**
  - **No calibration, so deflection uniformity is critical**



Ganged Arrays



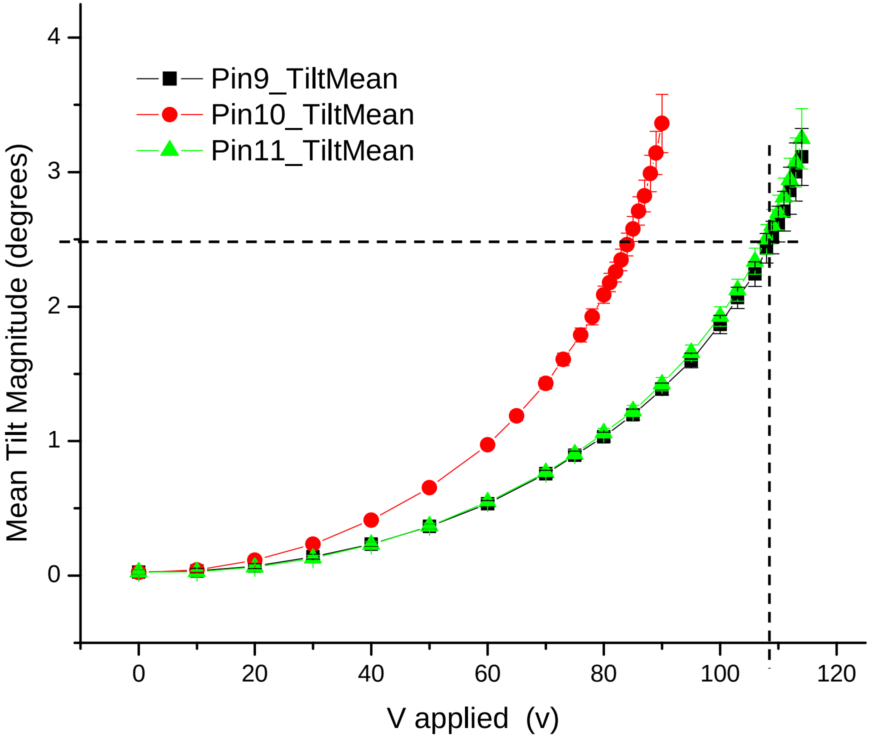
- **Ganged Beam Steering**
  - **Four electrodes per mirror**
- **Currently in a bench top beam steering demo w/ ~10° FOR**

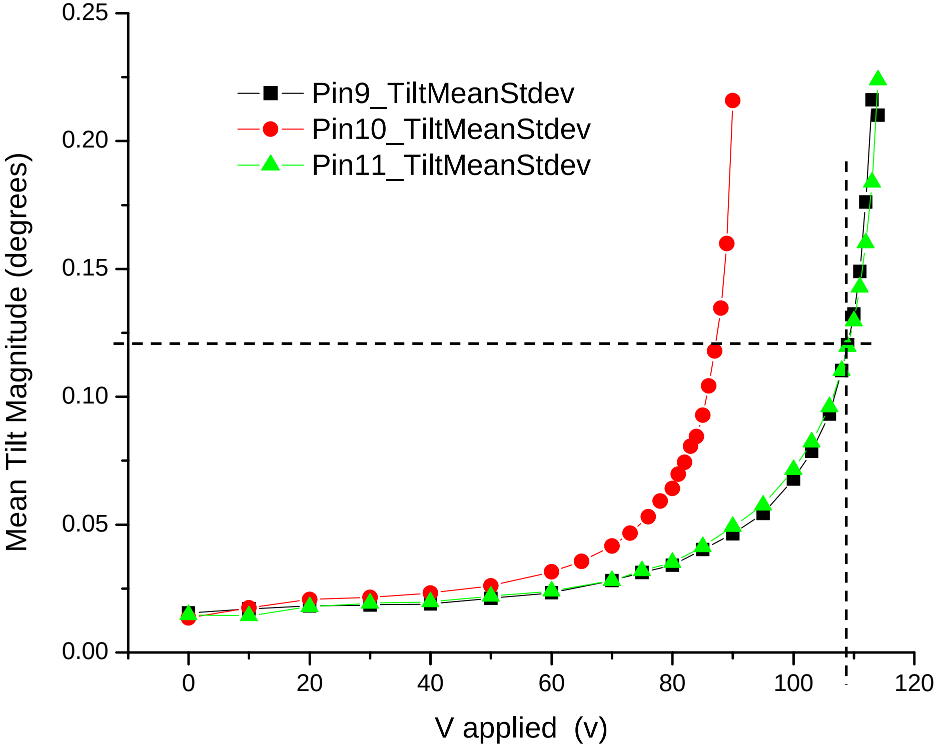


- **Slat Mirror Arrays**
  - **Two electrodes per mirror**
  - **Two arrays and auxiliary mirror required for 2-D steering**

- Fast – switching speeds <10μsec, analog position control
- Applications: scanning sensors, missile seekers (gimbal replacement), novel imaging

Ganged mirror array - Tilt magnitude and standard deviation vs. applied voltage

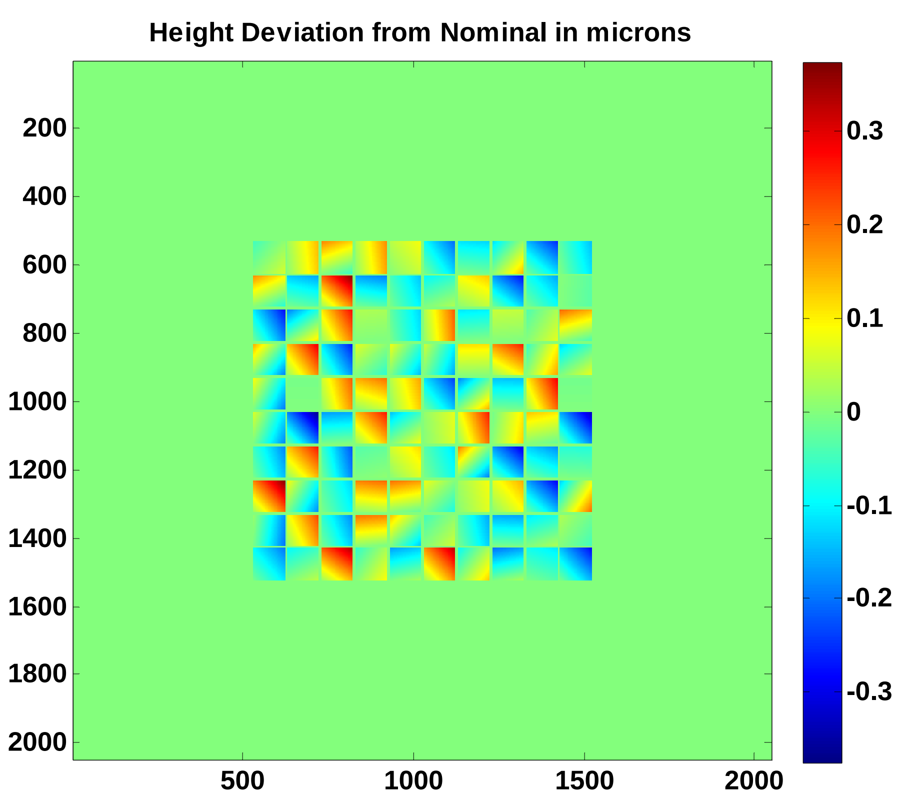


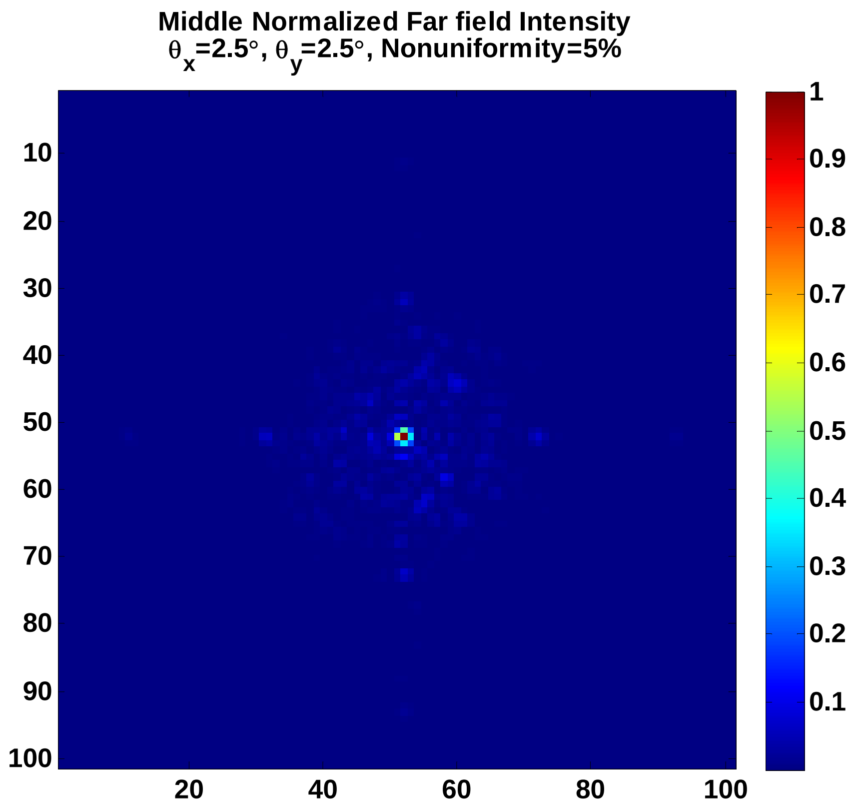


Deviation ~0.125° at 2.5 ° deflection => ~5%

Impact of Angle Non-uniformity

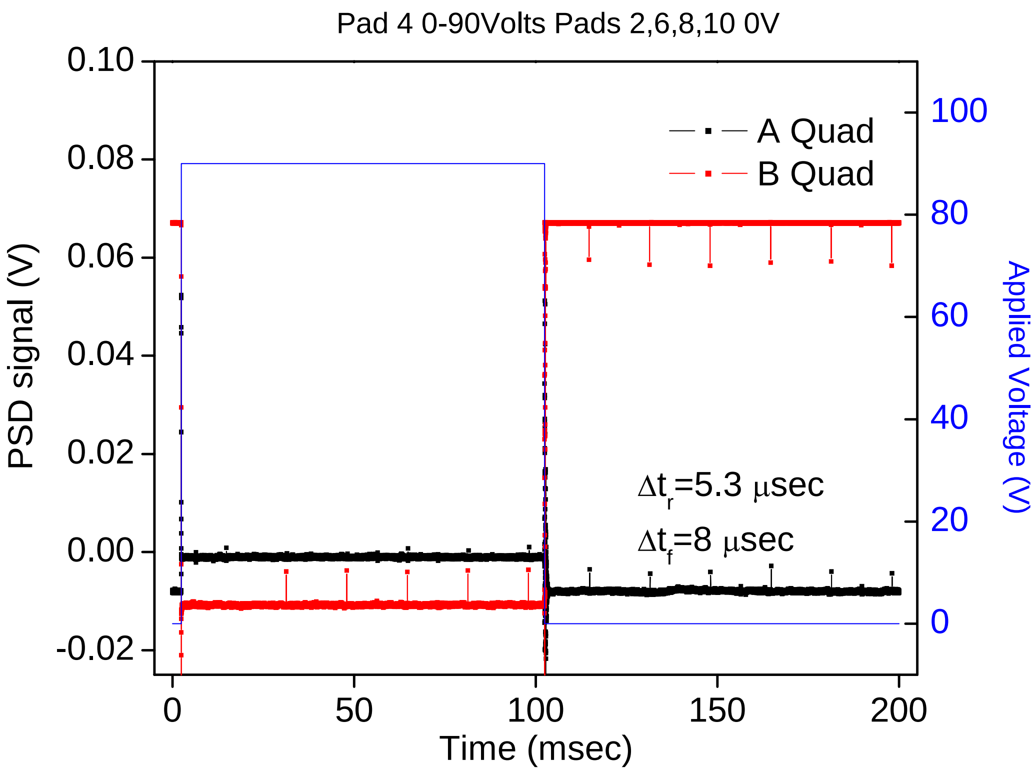
Matlab Model, $\theta_x = \theta_y = 2.5°$, Nonuniformity=5%, λ=532nm

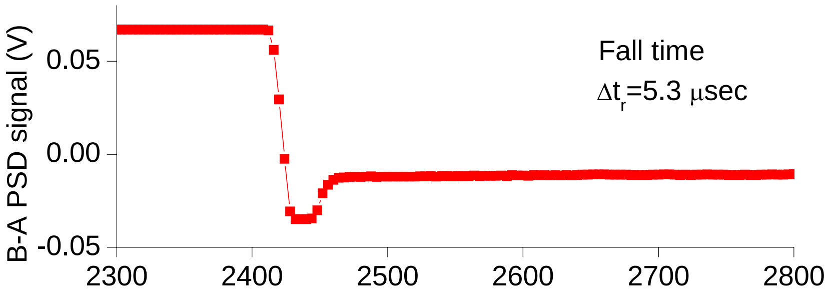


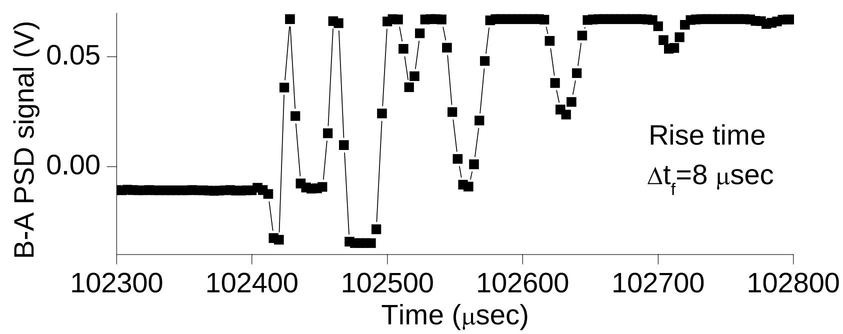


Sandia National Laboratories

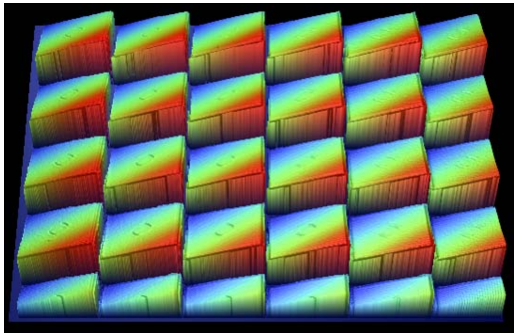
Dynamic Behavior of Ganged Arrays





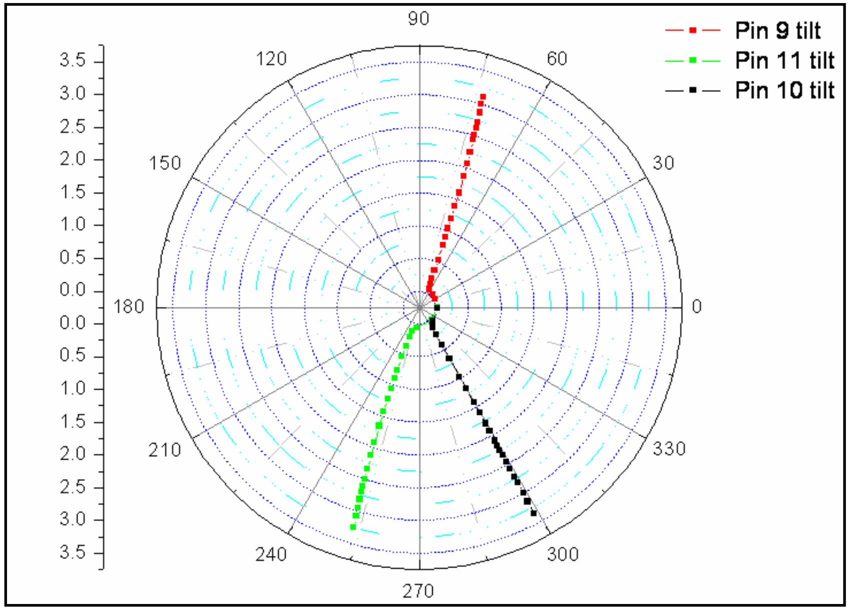


GANGBS_1A 90V, 2.64º diagonal tilt

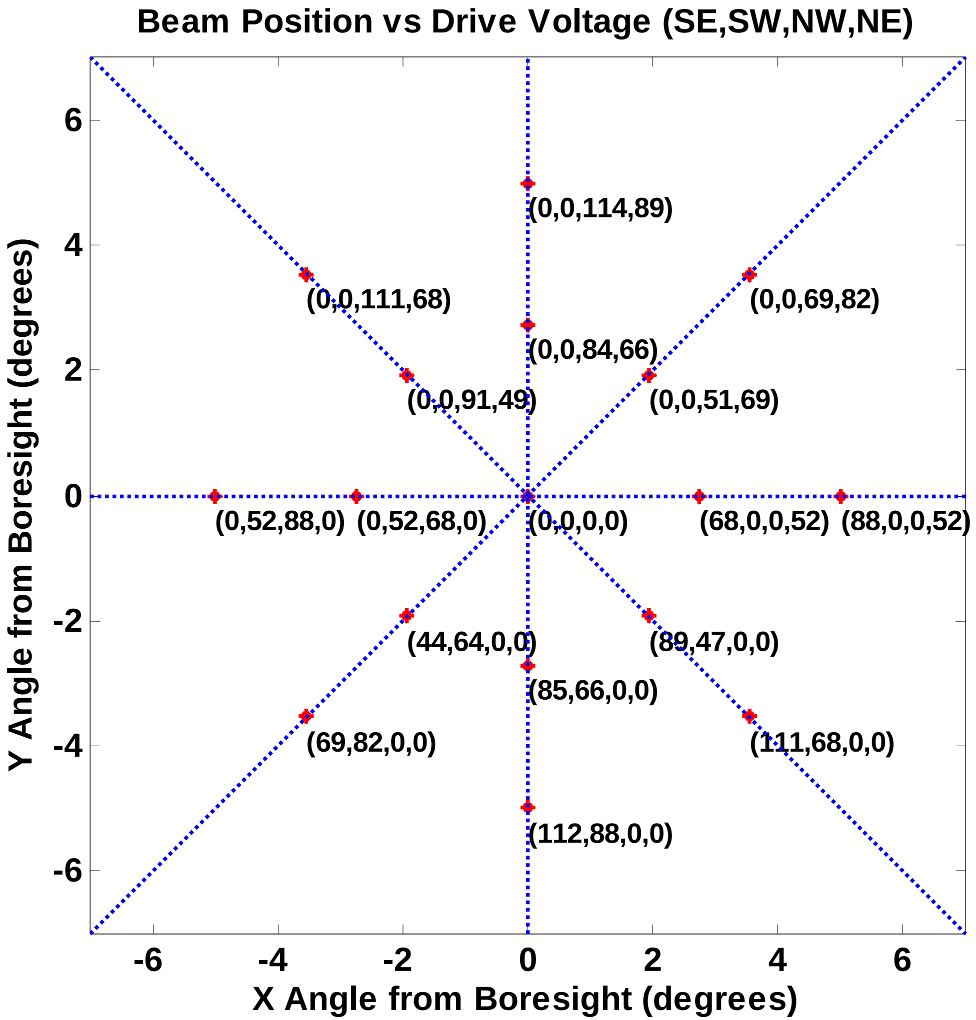


Sandia National Laboratories

Beam Steering Demo



Mechanical Angle, Single Electrode Drive



Sandia National Laboratories

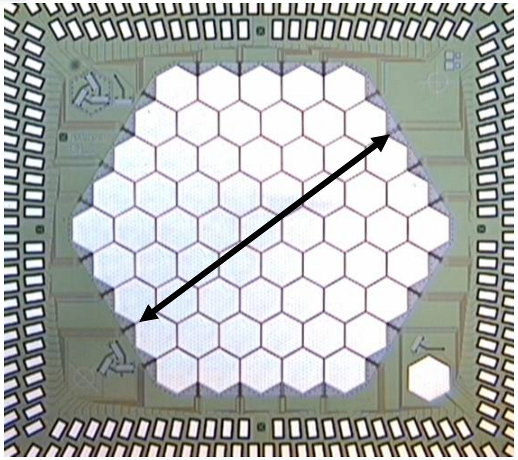
MEM-DM Requirements

- In addition to the usual requirements of mirror quality, high fill-factor, good reflectivity, etc.
- Large stroke
  - Foveated imaging
    - Greater stroke allows greater degree of uncompensated aberration
    - Greater aberration = greater steering angle
  - Non-mechanical zoom
    - More stroke = more optical magnification
- Larger apertures required for practical systems
  - Larger pixels or more actuators
  - Larger pixels conducive to larger stroke BUT…
    - Speed and mirror flatness get more difficult
  - More actuators requires addressing the pin-out problem
- Currently working all the angles

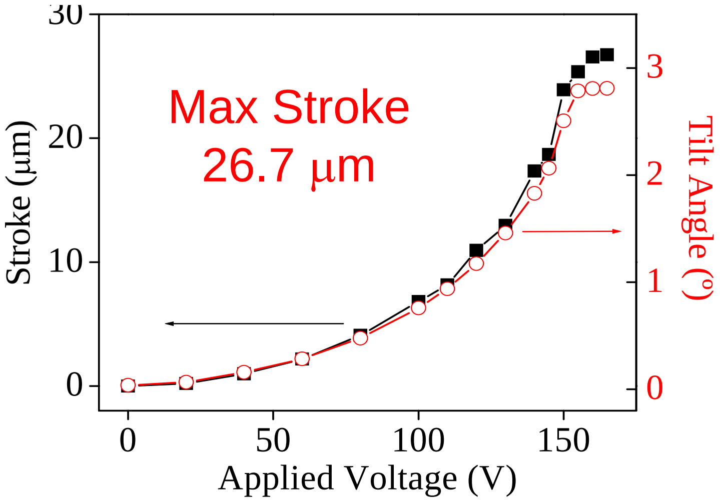
2007 DM focus was on increasing aperture… …without losing functionality…(and improving uniformity/repeatability)

Sandia National Laboratories

New 500μm Piston/Tip/Tilt Mirror Arrays

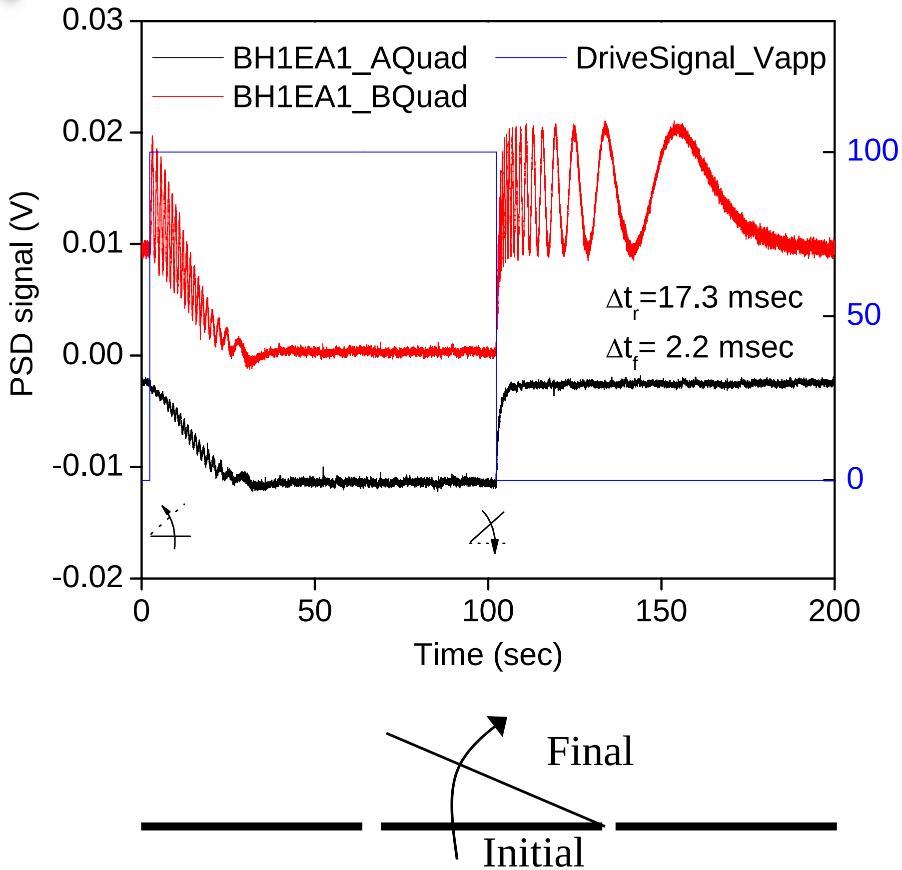


- 61 hex mirrors in hex array
- Mirrors 0.5 mm edge-to edge
- 3.9 mm array aperture
- 208 pin PGA package

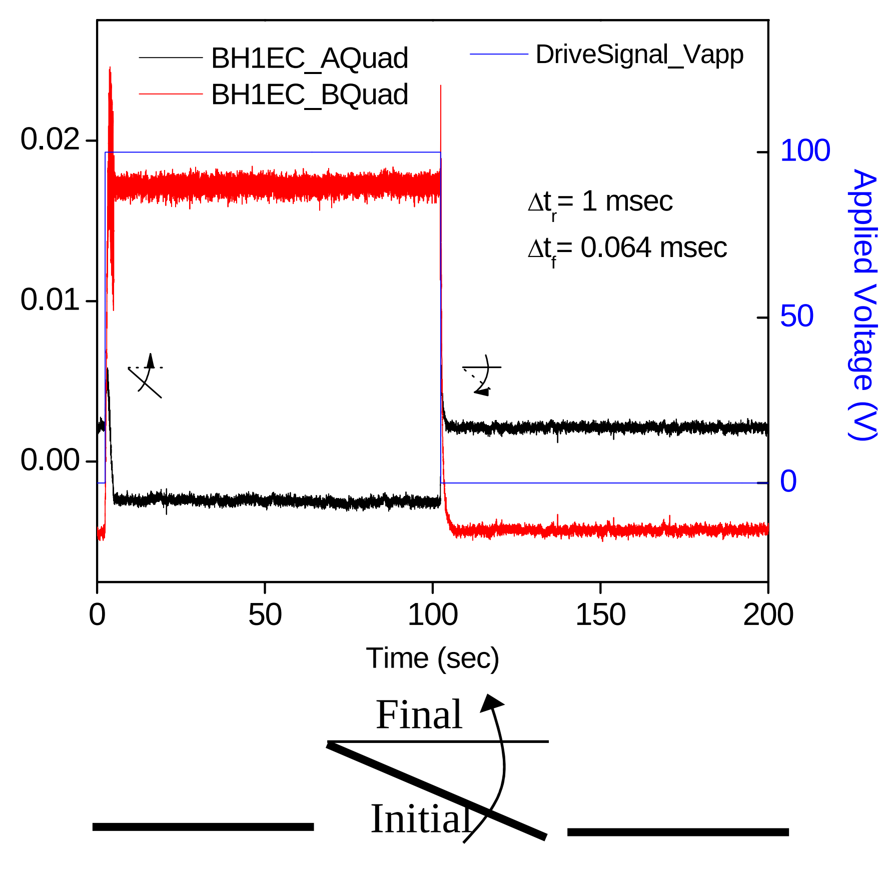


- Original employed mechanical pivot in actuators
  - Ensured full stroke but bad for uniformity, position repeatability and dynamics
- Revised (BH1_E & _F)
  - No mechanical contact in actuators (except at full deflection)
  - Optimized torsion springs and actuator to mirror plate springs using beam element models
  - BH1_F has slightly longer lever for >stroke

500μm Mirror Dynamics (in air)



Profile of mirror position



Profile of mirror position

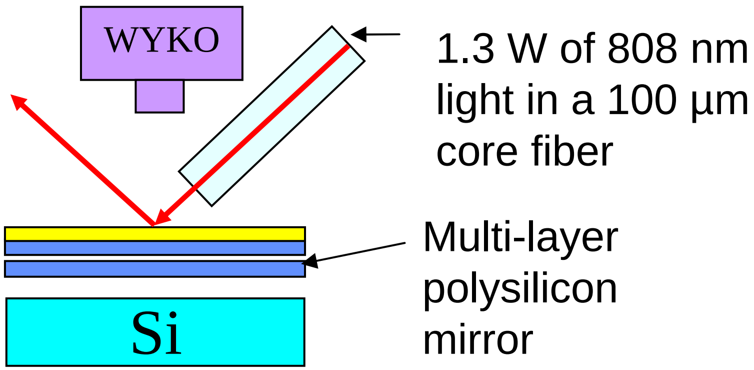
Air damping and mechanical contact of mirror edge

Minimal damping, NO mechanical contact

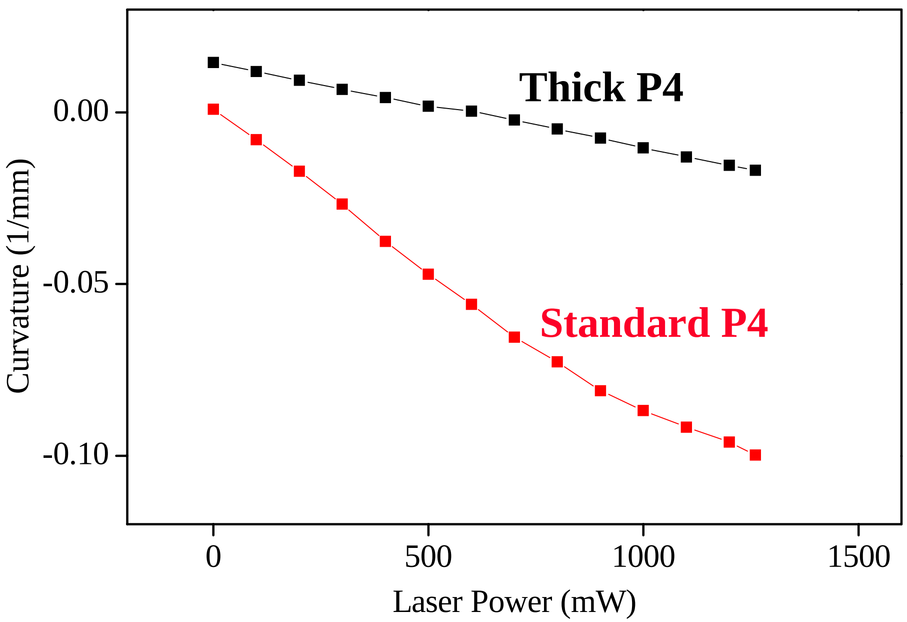
Sandia National Laboratories

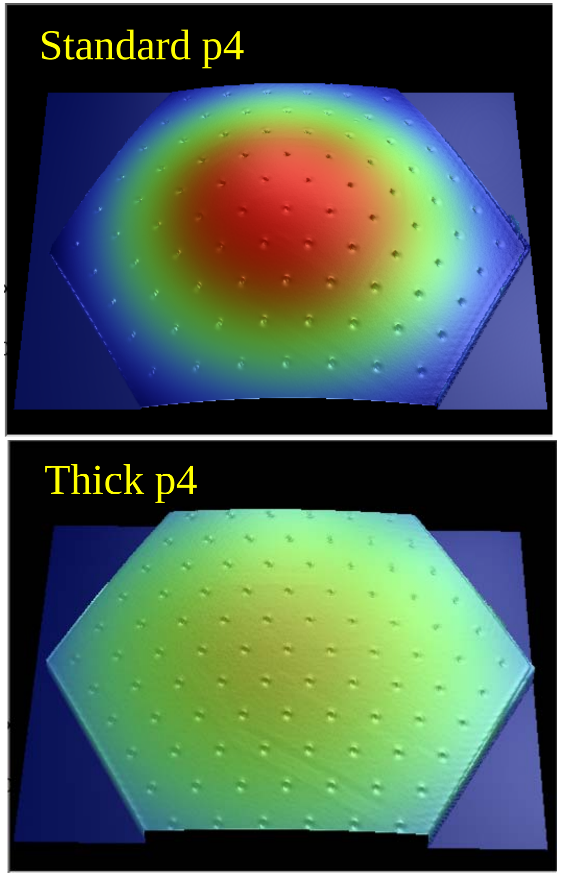
Improved Optical Power Handling Using Thicker Poly4

Laser Heating Setup



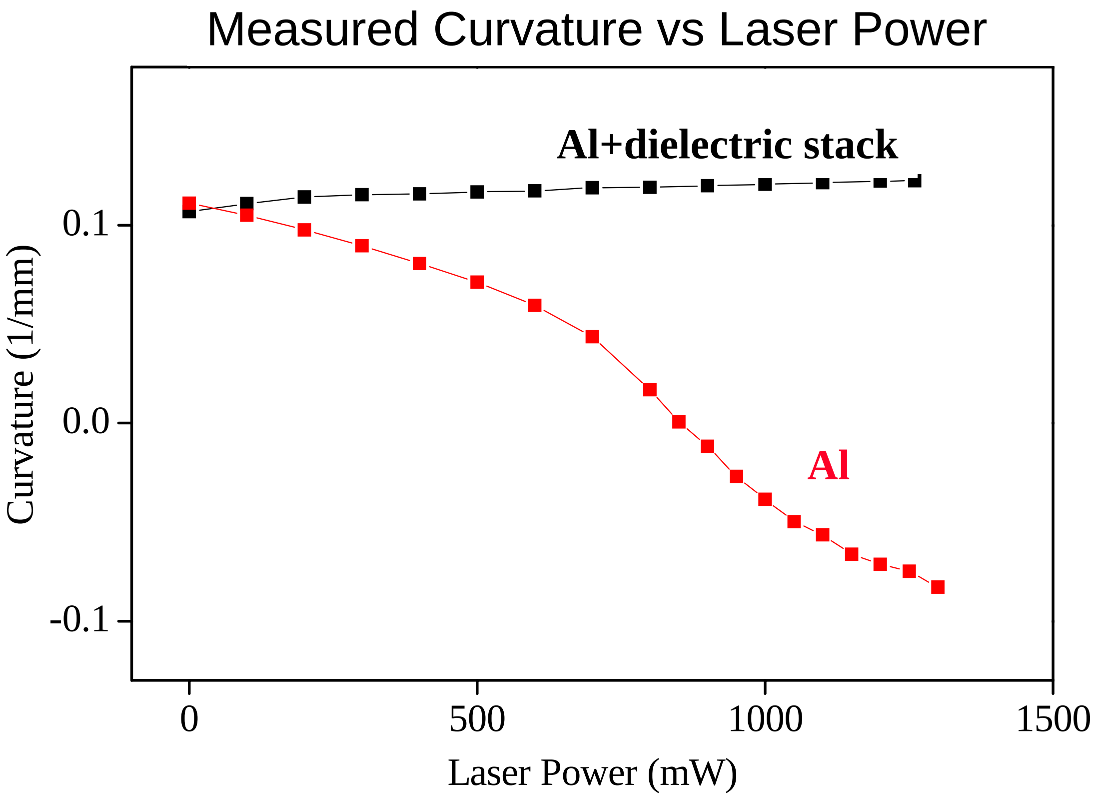
Measured Curvature vs Laser Power

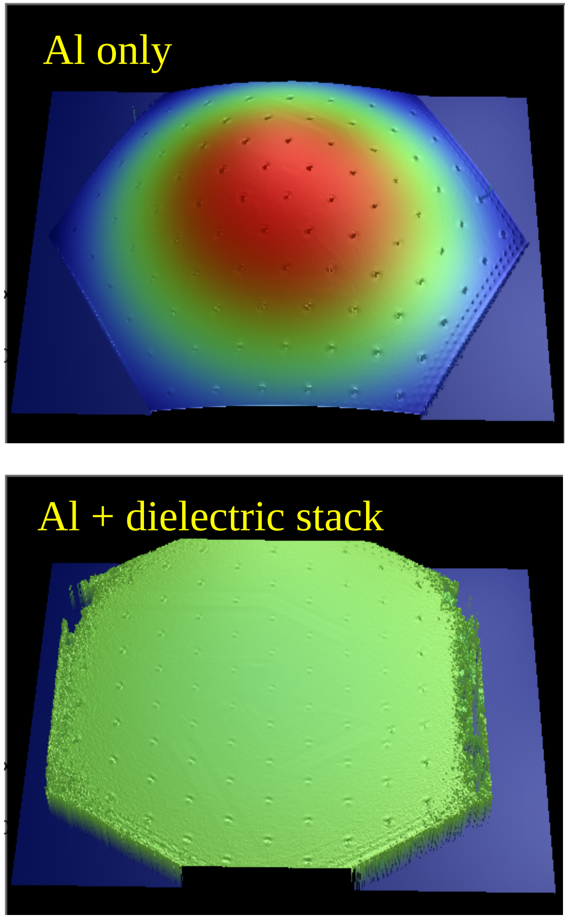




Difference Surfaces (1.25W – 0W)

Improved Optical Power Handling Using Dielectric "helper" Stack on Metal



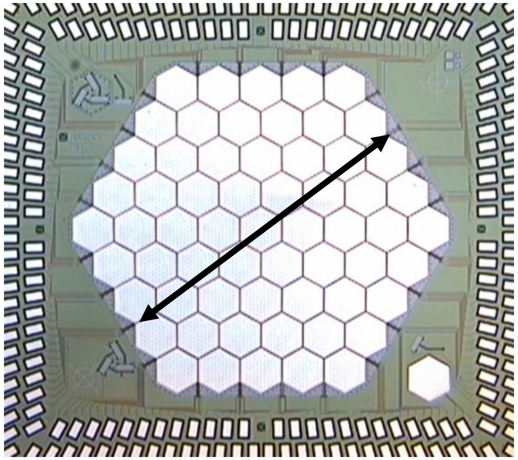


Difference Surfaces
(1.25W – 0W)

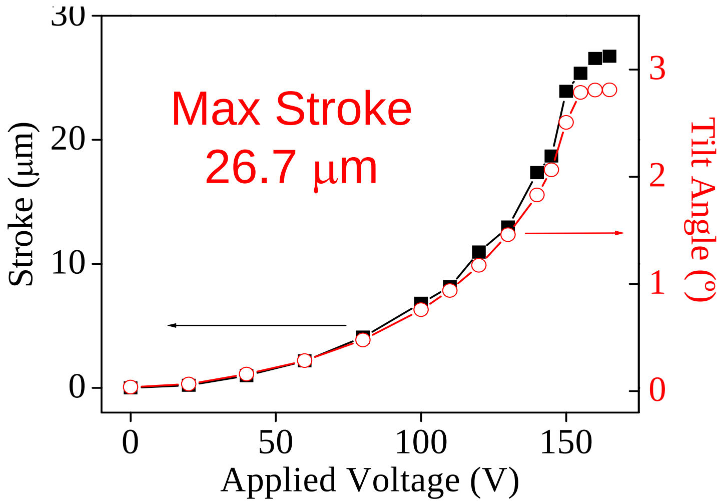
Helper stack=4 pairs SiO_2/HfO_2
Absorbance at 808 nm = 2.3% for dielectric+Al
(vs. 15.8 % for Al only coated mirrors)
Mirror mechanical functionality not tested

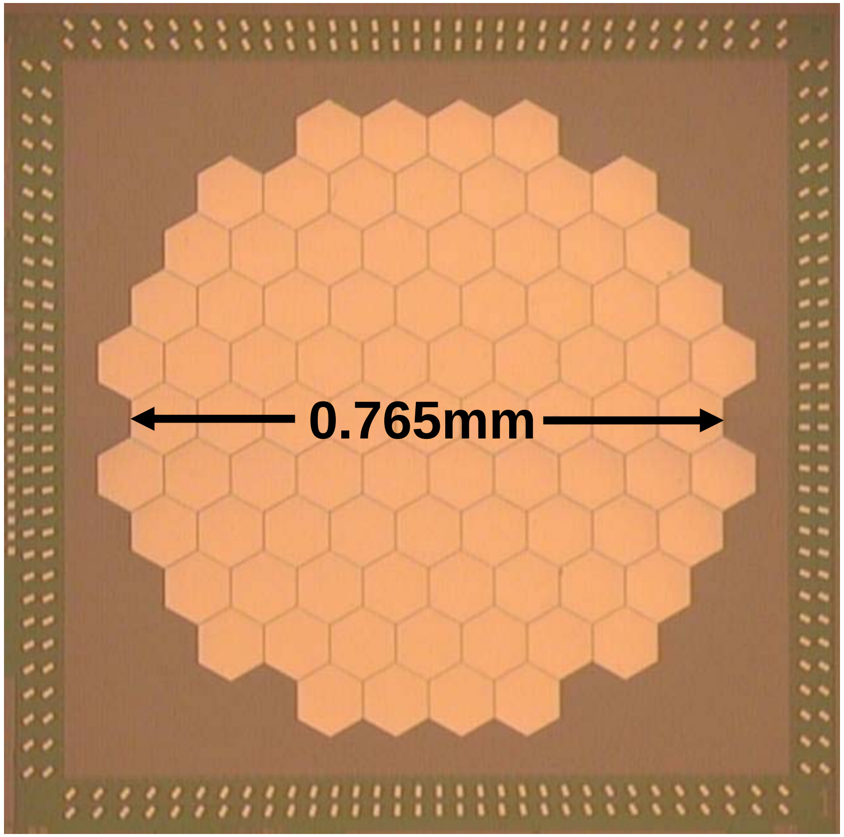
Sandia National Laboratories

~8mm Piston/Tip/Tilt Mirror Arrays



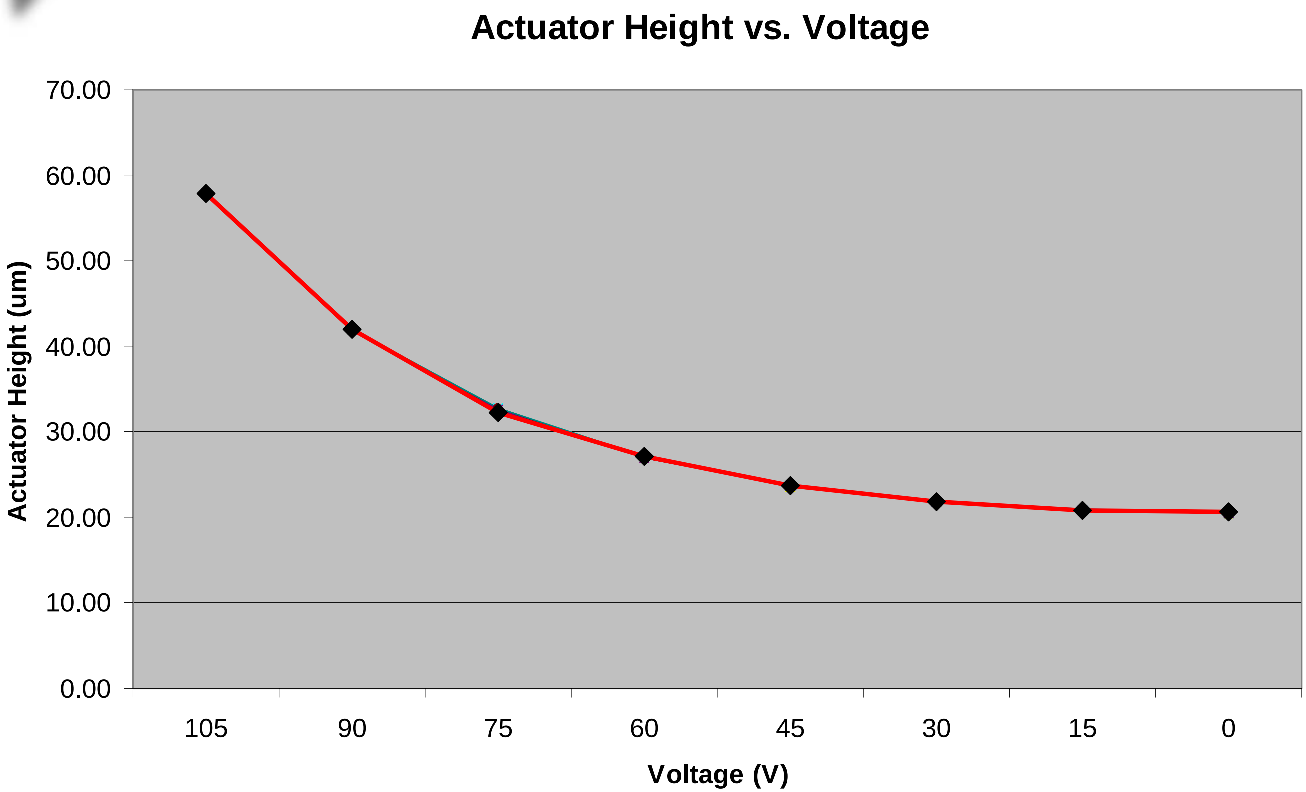
- 61 hex mirrors in hex array
- Mirrors 0.5 mm edge-to edge
- 3.9 mm array aperture
- 208 pin PGA package





- 85 hex mirrors in hex array
- Mirrors 0.85 mm edge-to-edge
- ~8 mm array aperture
- 256 pin PGA package
- 3 actuator variations

850um Mirror Position Repeatability
Lever 1 Design with 2 Up, 1 Down

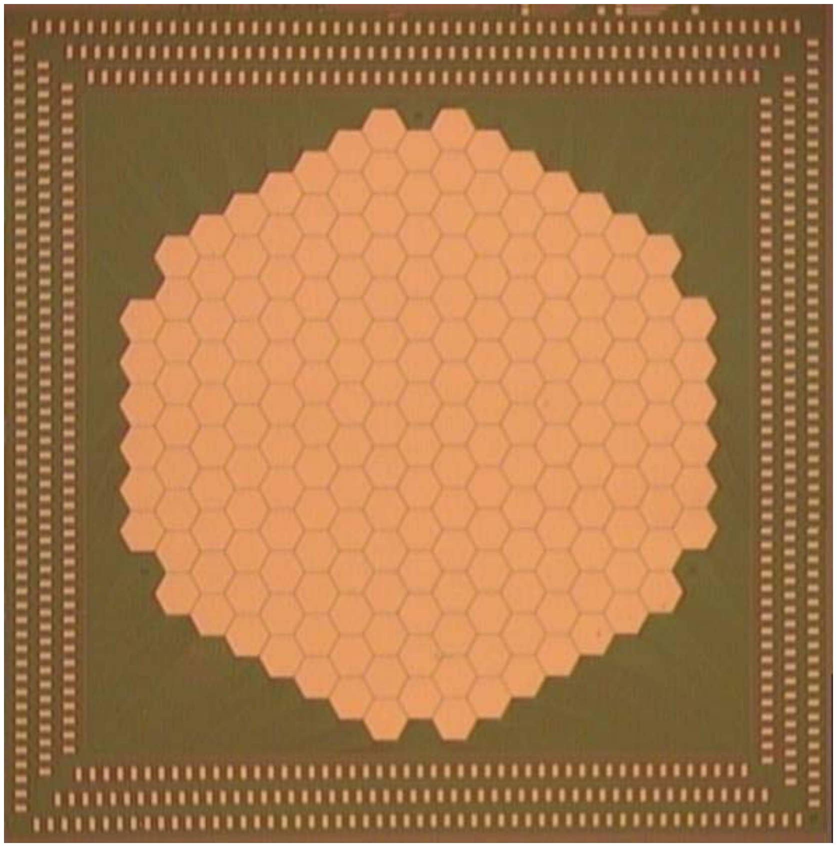


V	Height (um)	σ (um)
105	**57.80**	**3.16E-02**
90	**41.99**	**7.97E-02**
75	**32.54**	**2.22E-01**
60	**27.09**	**5.45E-02**
45	**23.67**	**3.14E-02**
30	**21.84**	**3.79E-02**
15	**20.89**	**3.37E-02**
0	**20.54**	**4.22E-02**
Avg		**6.66E-02**

- 10 Iterations
- 2 up → 1 down
- 8 samples across 0-105V
- Average Template Fit = 995/1000

Radius of curvature of 850 L1
(Standard poly4, 50 nm AlCu, wafer center)

~8mm Aperture, 211-Mirror Array

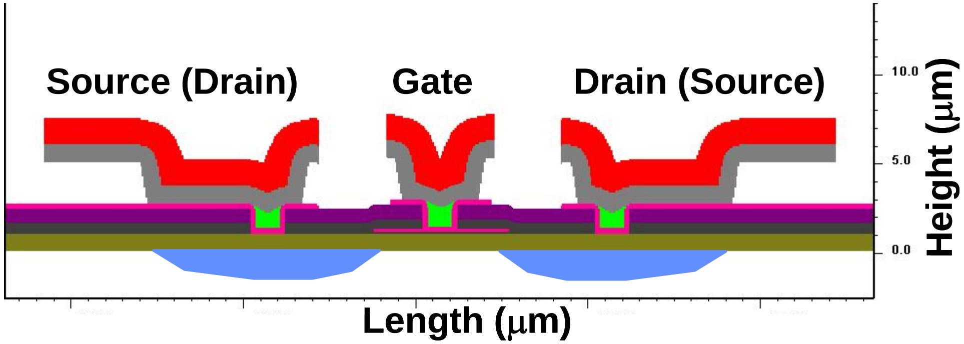


10.5 mm

- 211-hex mirrors in hex array
- ~8 mm array aperture
- Mirrors 0.5 mm edge-to-edge
- BH1_F design, >25μm stroke

- Status – largely untested
  - BGA packages on hand but no parts packaged yet
  - Mirror flatness OK
  - Visual yield OK (quarter wafer inspection)

SUMMiT™ Field Effect Transistor (SFET) Fabrication



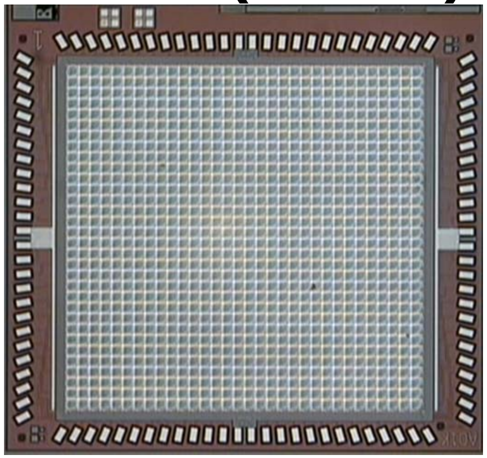
- **SUMMiT™ flow with added gate level for SFET**
  - Gate oxide, 1000Å steam, grown on bare Si p-type substrate
  - Polysilicon gate uses same film *type* as Poly0; deposited immediately after gate is grown
  - Poly12 source/drain contacts doped in-situ with phosphorus
  - Subsequent high temperature anneals (for stress control) diffuse dopant into substrate to form source and drain
- **Remaining fabrication steps identical to SUMMiT™ V**
  - Building on a mature and robust MEMS process
- **Back end processes: 100nm Al metal, release & packaging**

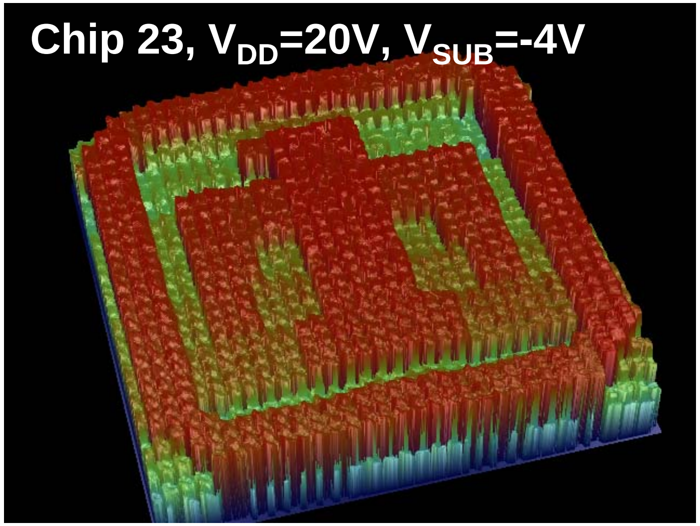
B. L. Draper, M. Okandan, S. S. Mani, and R. S. Bennett, "A Novel Method of Fabricating Integrated FETs for MEMS Applications," *IEEE JMEMS*, Vol. 13, No. 3, pp. 500-504, June 2004.

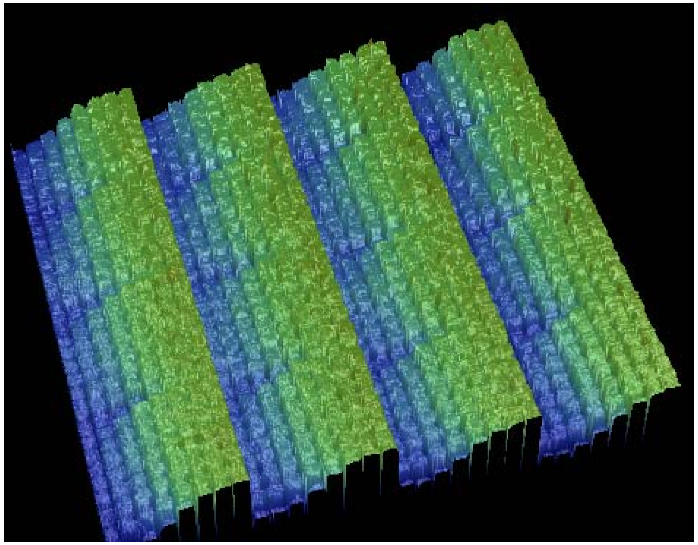
Sandia National Laboratories

Piston Mirror Array (PW2007)

AO1K (RS562)





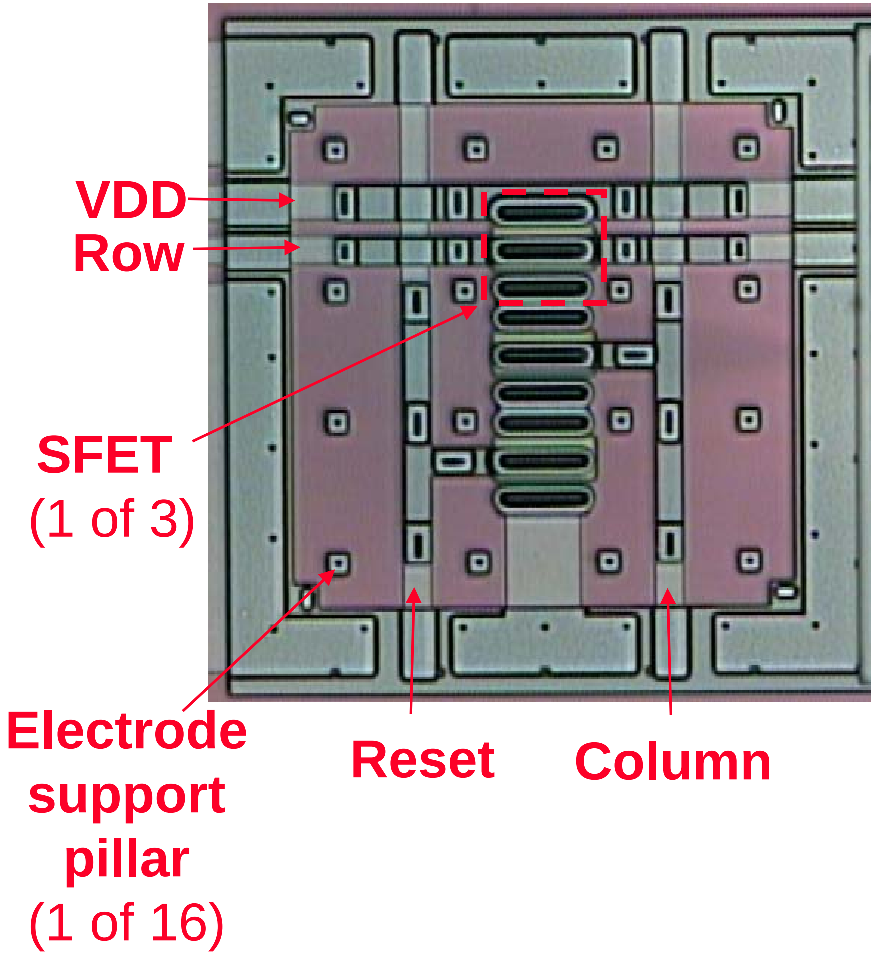


- 1024 Piston-only mirrors
- Mirrors 0.15 mm square
- Maximum stroke: 2 μm
- 4.8 mm array aperture
- 132 pin PGA package
- Applications: laser communications, narrowband/high-speed aberration correction

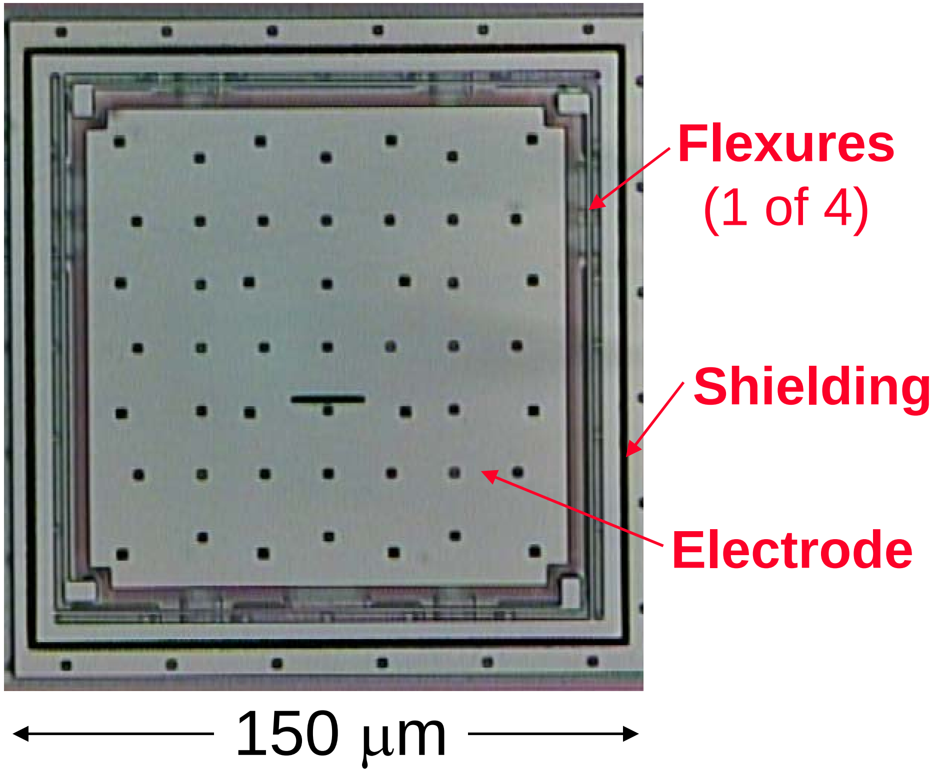
Sandia National Laboratories

AO1K Construction Details

Through Poly2
(No Poly3 or Poly4)

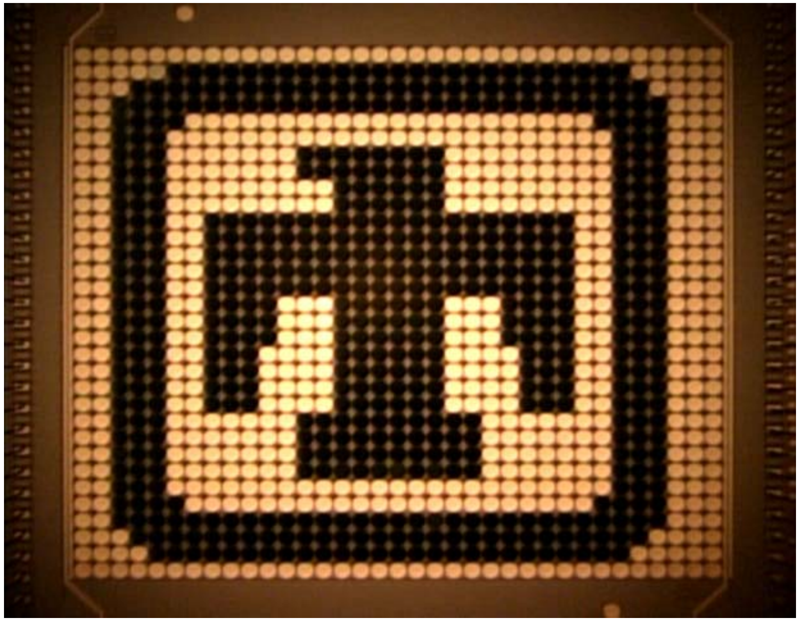


Through Poly3
(No Poly4)

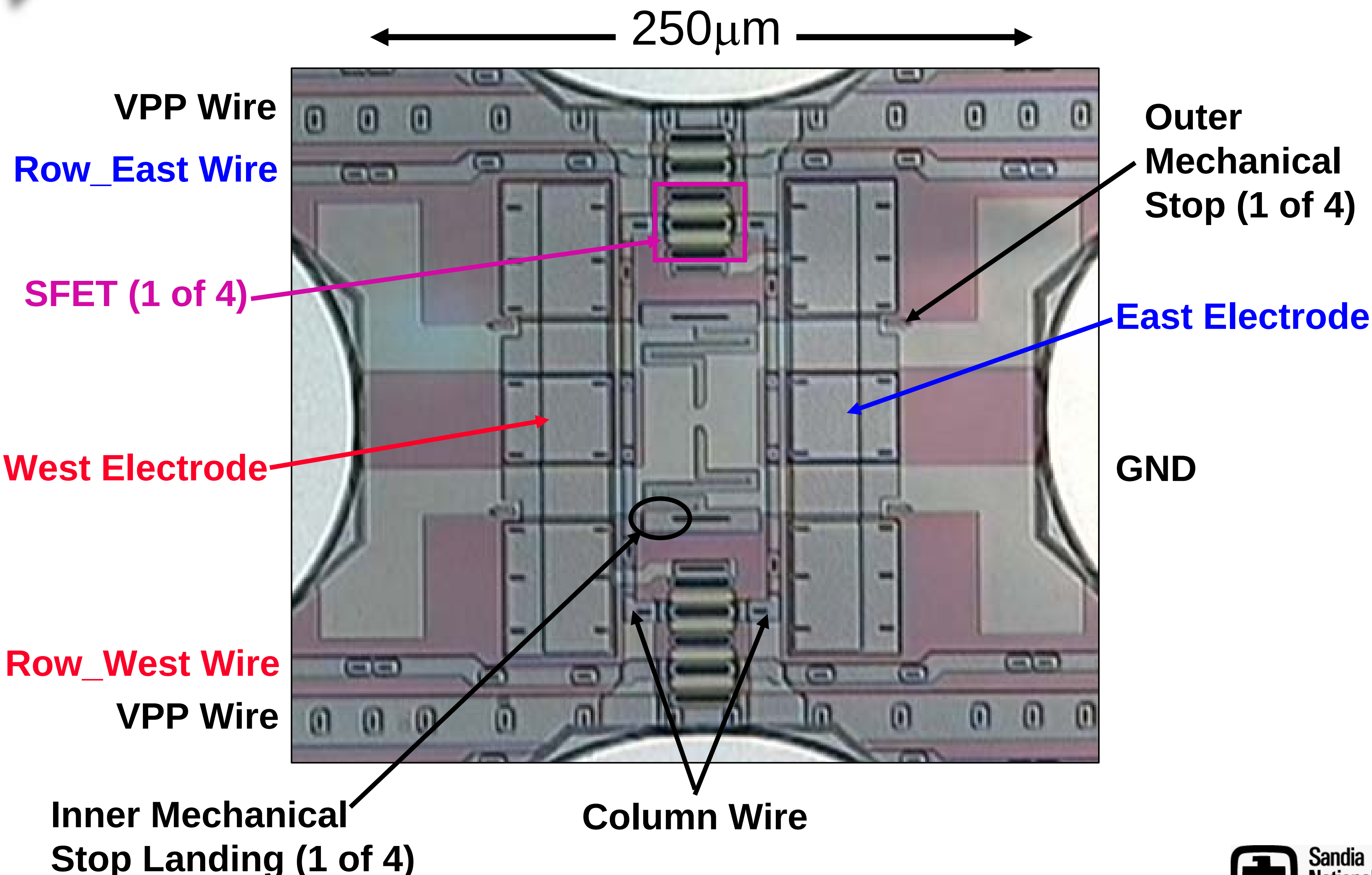


SFET Beam Switching Mirror Array

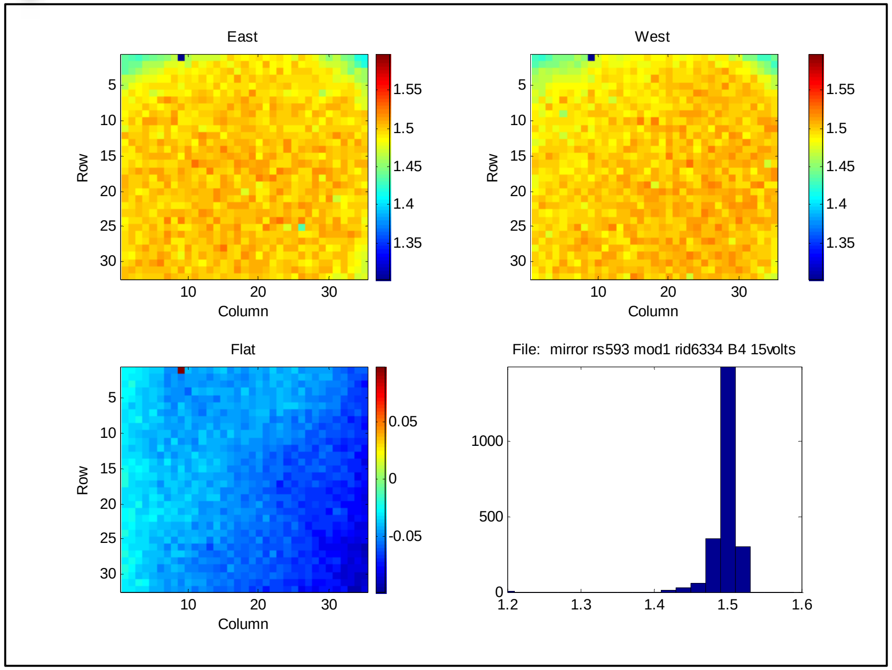
- **Largest SFET-OMEMS devices to date**
  - **1120 mirrors (32-rows x 35-columns)**
  - **240 μm diameter mirrors, 250 μm pitch**
- **Integrated row/column address electronics**
  - **2240 electrodes (2 per mirror)**
  - ***4* or 6 transistors per mirror cell**
  - **Packaged in 120 pin PGA**
- **Tri-stable mirrors: ±1.4^o, 0^o (flat)**
  - **Angle deviation <0.1^o**
- **Mirror flatness: <30nm peak-to valley**
- **Switching speed:**
  - **Mechanical:** <150 μsec in air
  - **Circuit/transistors:** >20MHz (current version of electronics support ~45 μsec array update)
- **Functional Mirror Yield:** 99-100%

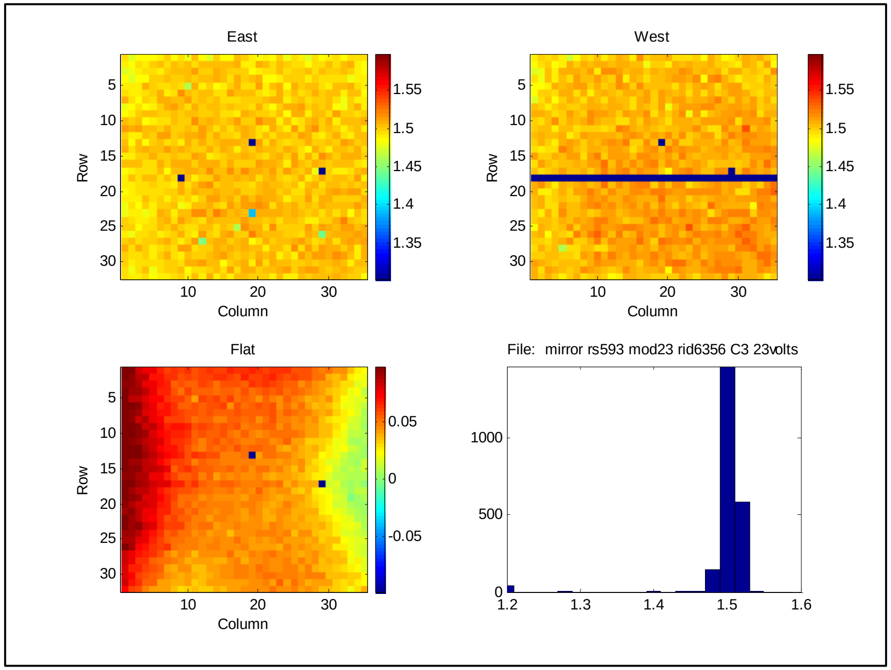


SFET Switching Mirror Detail



Etched vs Backfilled DIMPLE3



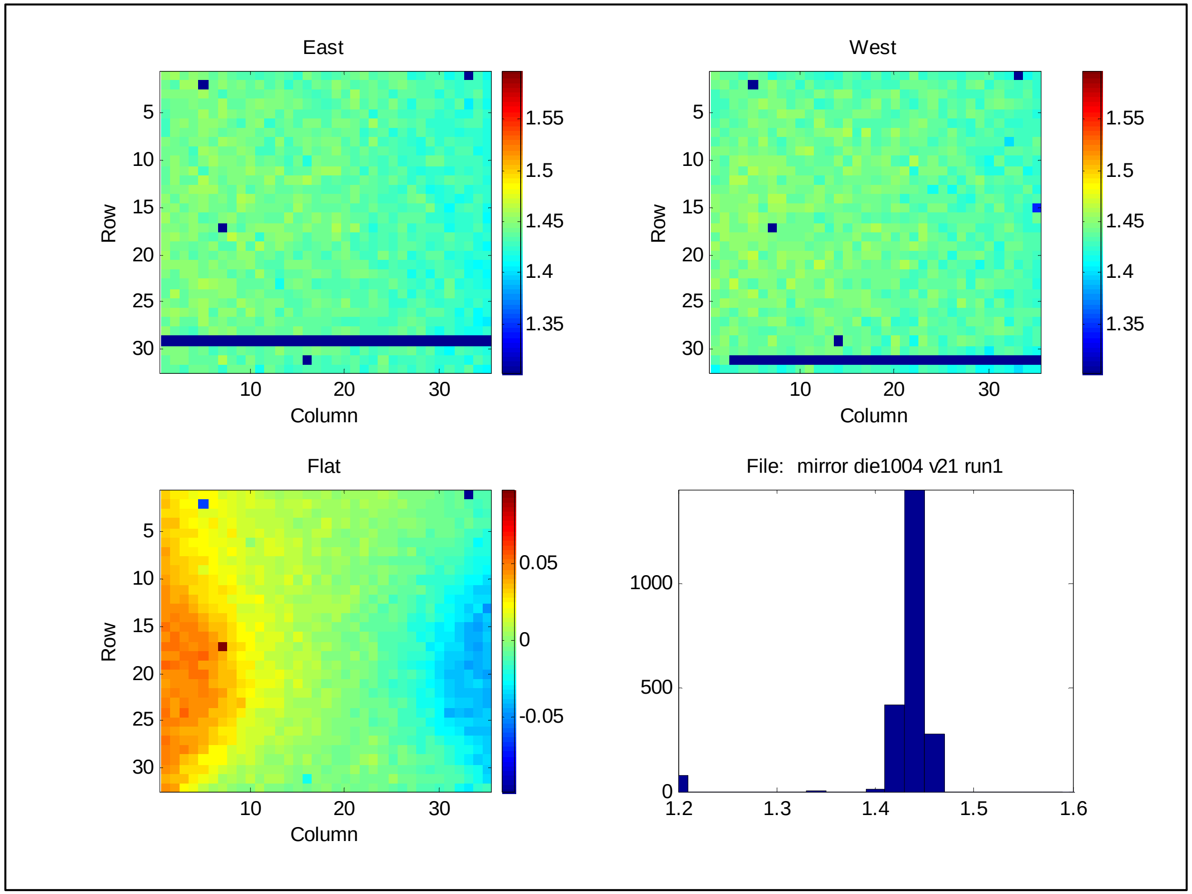


East mean= 1.497 std dev=**0.014** with 1119 points
West mean= 1.498 std dev=**0.014** with 1119 points
Combined East/West mean= 1.498
Flat mean= -0.051 std dev=0.014 with 1119 points

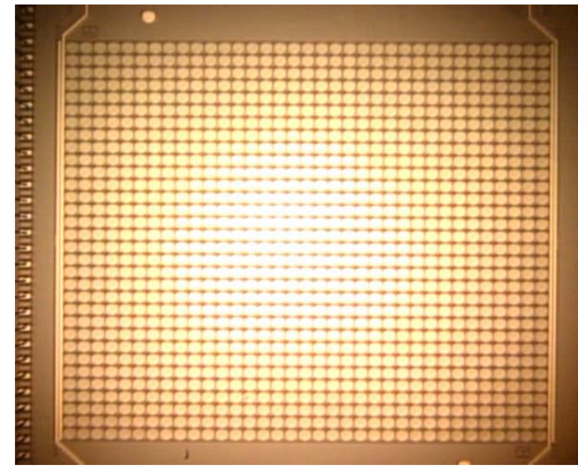
East mean= 1.500 std dev=**0.008** with 1116 points
West mean= 1.508 std dev=**0.009** with 1083 points
Combined East/West mean= 1.504
Flat mean= 0.049 std dev=0.020 with 1103 points

Sandia National Laboratories

Angle Uniformity



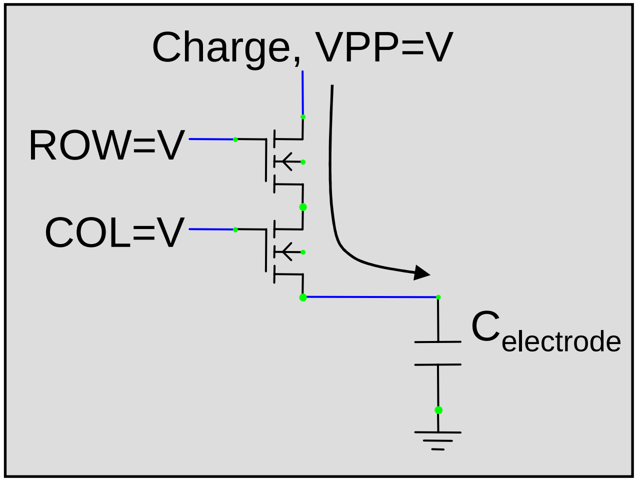
East mean= 1.438, std dev=0.010 with 1081 points
West mean= 1.439, std dev=0.010 with 1082 points
Flat mean= 0.005, std dev=0.022 with 1118 points

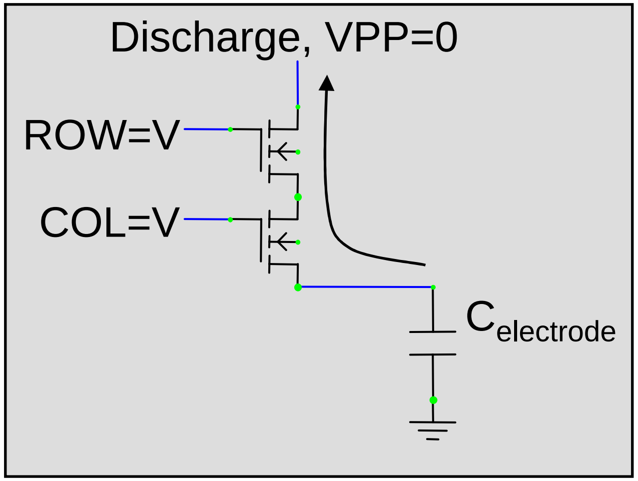


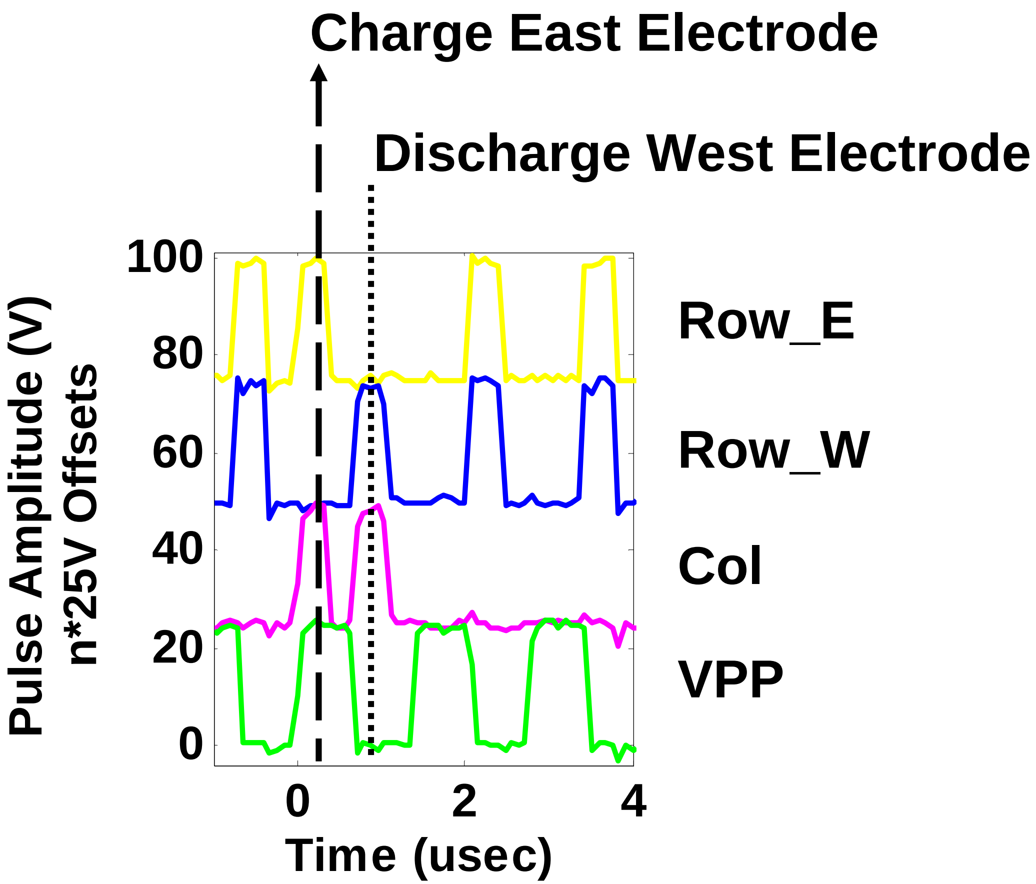
- **Video capture of mirrors operating at 8ms/cycle (E-F-W-F)**
- **Stuck mirrors released by mechanical shock**
- **Vdd=25V, Vsub-4V**

Sandia National Laboratories

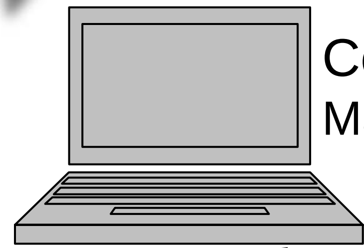
2-Transistor per Electrode
Single-ended Drive





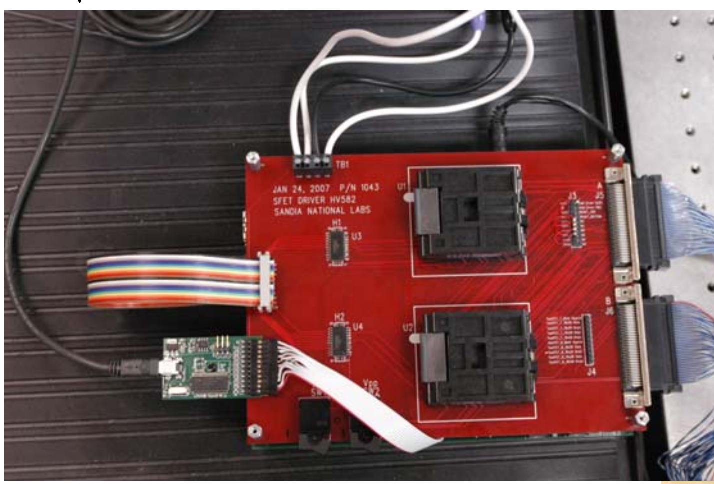


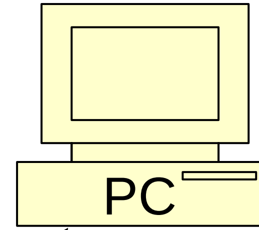
Beam Switching Mirror Demo



Control PC
Matlab w/USBee Interface

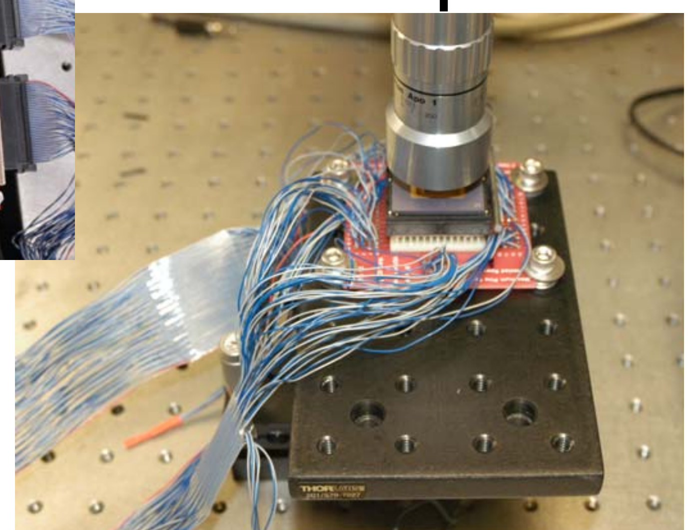
Power Supplies





Video Capture

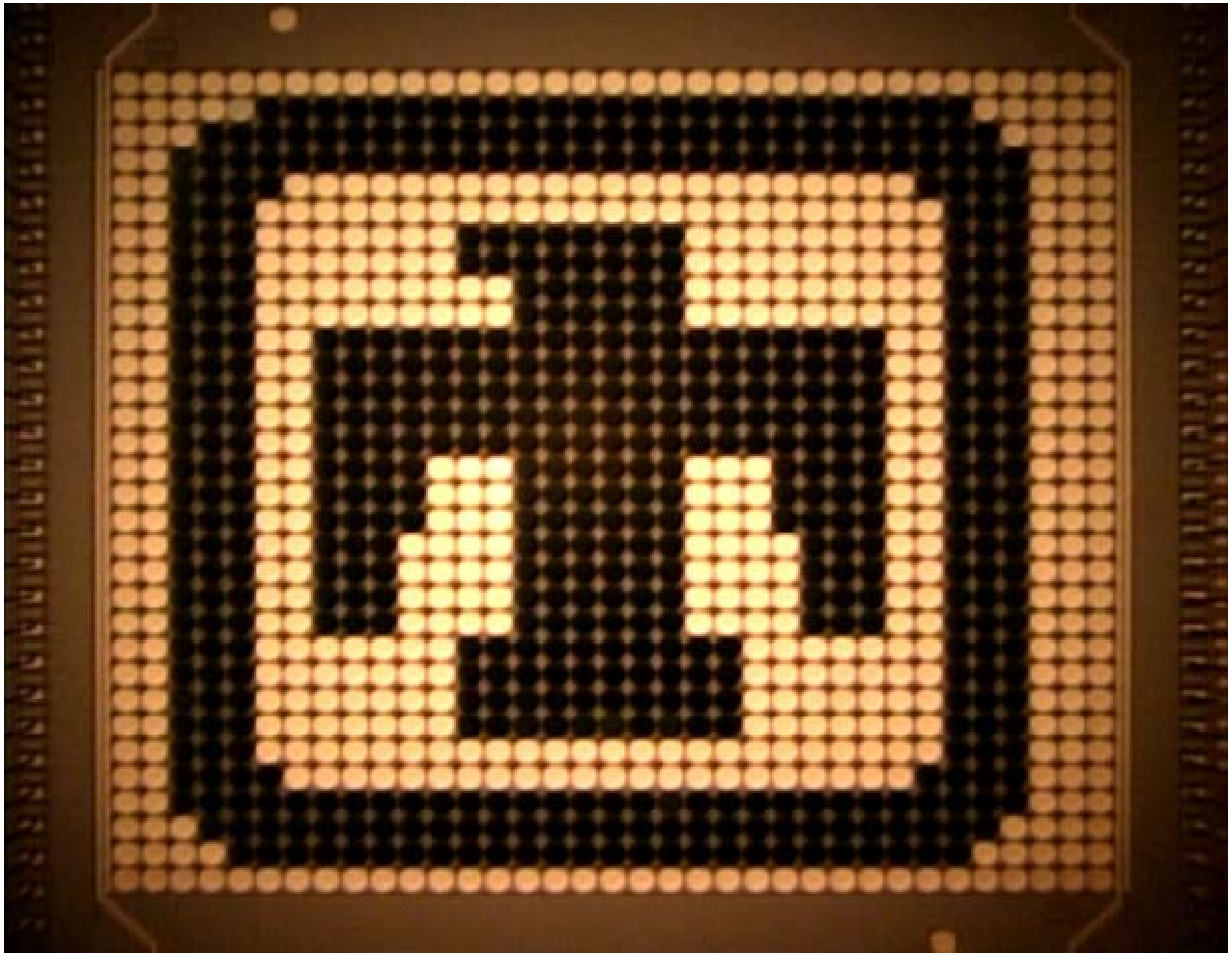
Microscope Camera



FPGA Demo Board (not visible) and Level shift cicuitry

Sandia National Laboratories

SFET Mirror Video



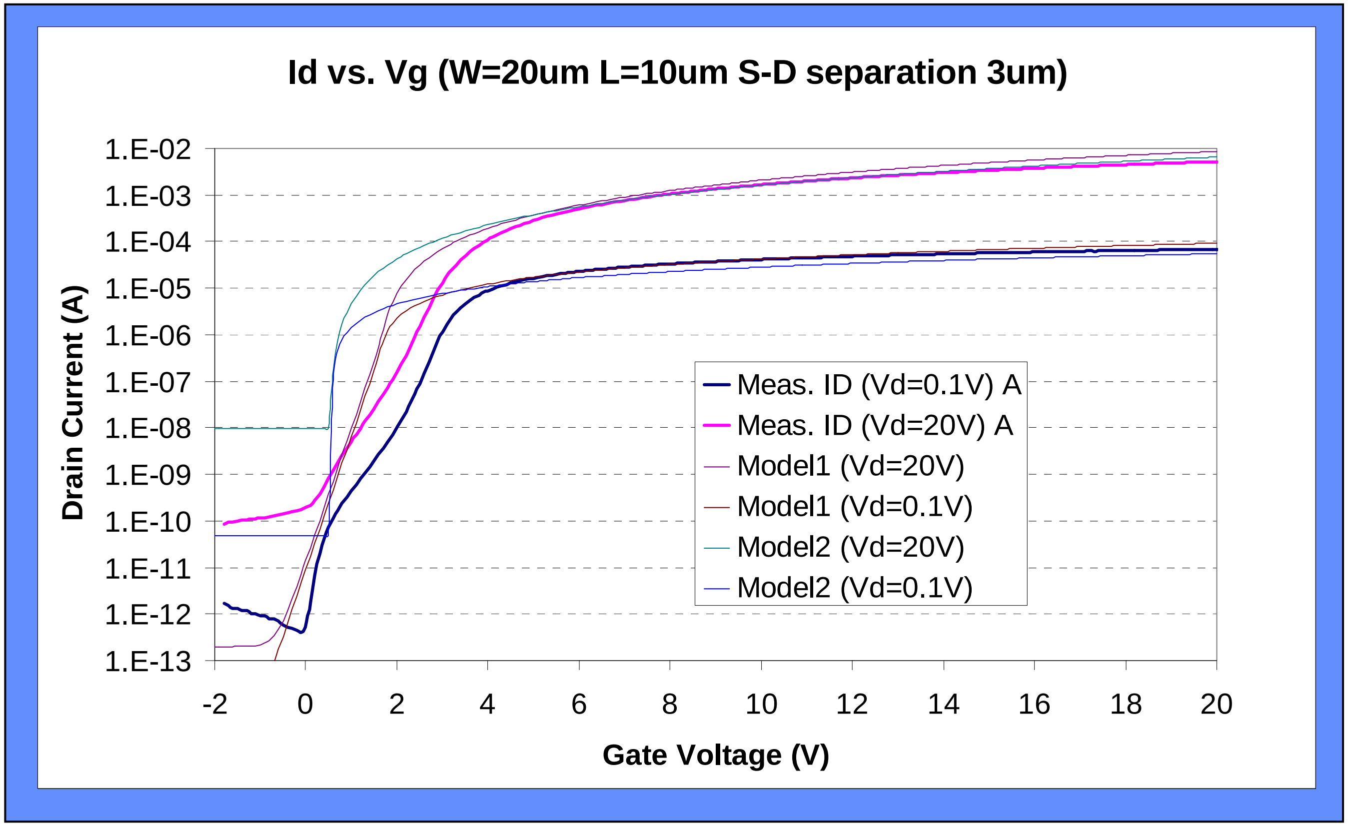
Summary

- Ganged beam steering mirrors show promise for fast, incoherent beam steering
  - Initial angle uniformity not bad
  - Improvement expected through device modeling and designs to minimize process-induced variations
- Position repeatability of lever mirrors improved by eliminating actuator mechanical contact
- Improved understanding of large mirror dynamics
- Large mirrors w/ acceptable flatness achievable
  - 850μm mirrors across ~8mm aperture demonstrated
- SFET solves pin-out problem for large scale arrays

wdcowan@sandia.gov

Backup Slides

SFET Characteristics and Model



- **Both models OK when transistors are "ON" (Vg >~5V)**
- **"OFF" transistor leakage current is under-predicted by Model1**
- **"OFF" transistor leakage current is over-predicted by Model2**
  - ***Used for all SPICE circuit simulations to date***

Sandia National Laboratories

SFET Design Considerations

- **Transistors consume layers up through Poly12**
- **Transistor size and spacing rules limit the circuit functionality that can be implemented in a given unit cell size**
  - **Nominal 10μm x 20 μm gate SFET area ~576 μm^2**
- **MEMS electrode and actuator structures must accommodate transistor footprint**
- **Two approaches for densely packed mirror arrays**
  - **Transistors under electrodes or beside electrodes**
  - **Minimum array mirror size ~ 100μm x 100 μm**
- **SFETs are photosensitive – must shield from light in operation**
- **Only NMOS transistors available limiting circuit configurations**
  - ***Think 70s era NMOS-only circuitry***
- **Despite limitations SFET offers tremendous potential for micromirror array scale up, localized sensing/amplification & novel detectors**

Sandia National Laboratories

Addressing Schemes

Use pulse-width modulation or charge control for pseudo-analog positioning

- Piston mirror examples demonstrate this approach
- Number of mirror positions, array size & switching speed dictate off-chip signal requirements
  - Limited by on-chip switching speed

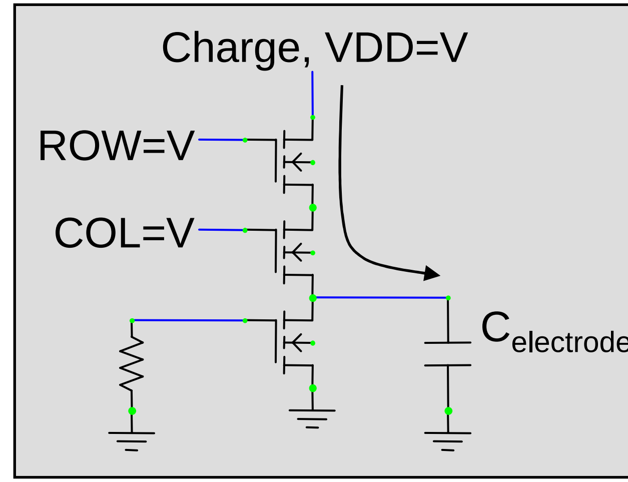
Single-ended drive of On-Off electrodes

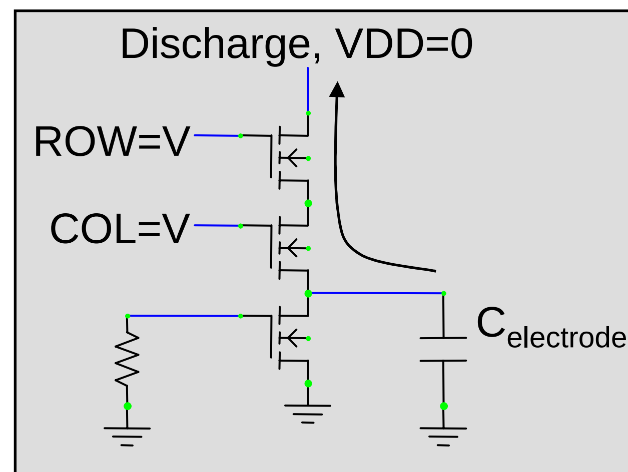
- Fill and empty the bucket through the same hose
- VDD a control signal rather than a DC source
  - When VDD=V & ROW & COL electrode charged
  - When VDD=0 & ROW & COL electrode discharged
- Demonstrated on 4x5 tri-stable mirror arrays
- SPICE simulation for 35x64 electrodes
- Allows reset transistors to be eliminated

Analog control of ROW (COL) gate signals

- Allows faster update and slower refresh cycle
- Requires sufficient transistor uniformity
- Works in SPICE simulations but untested

Single-ended Drive

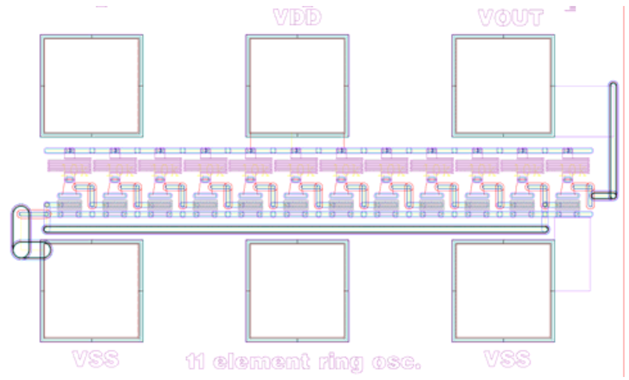


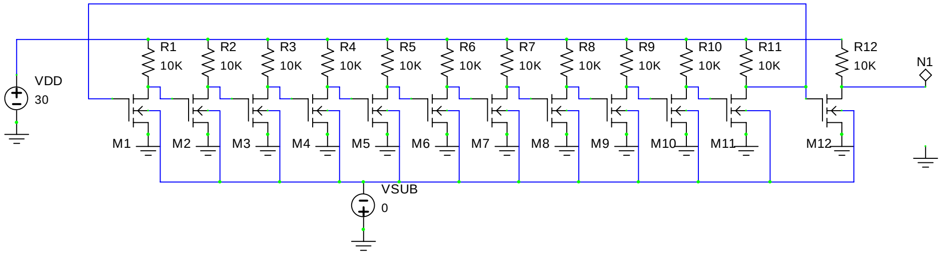


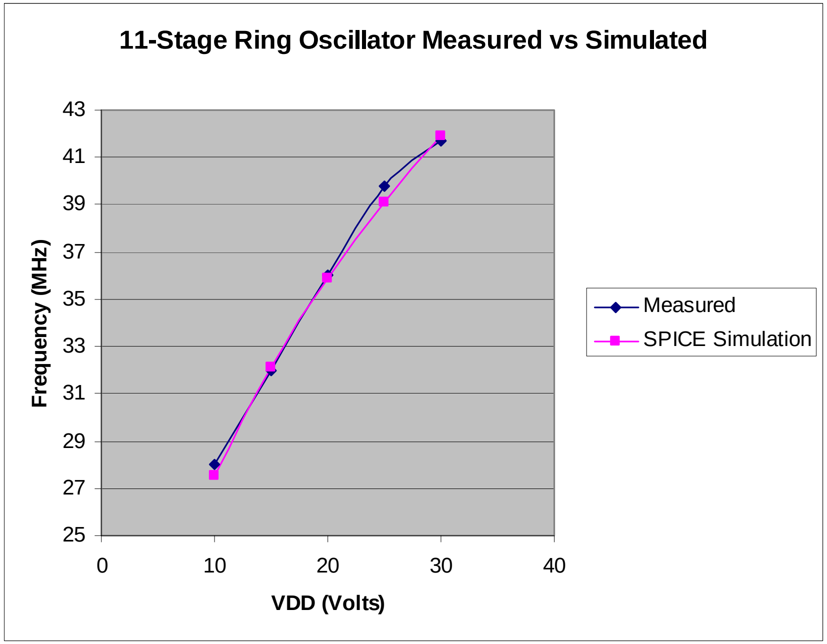
Sandia National Laboratories

SFET Ring Oscillator

- **11 stage ring oscillator**
  - **Nominal 10x20 SFETs**
  - **10KOhm pull-up resistors**
- **Measured data shows >40MHz switching at 30V**
- **Results used to tweak SFET model**
  - **Increasing Cgdo and Cgso from 700pf to 1600pf provided good simulation match to data**

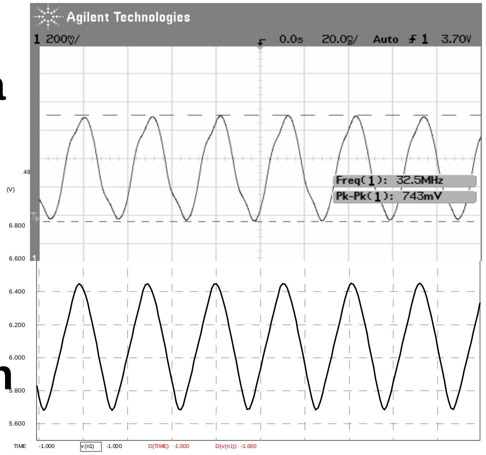






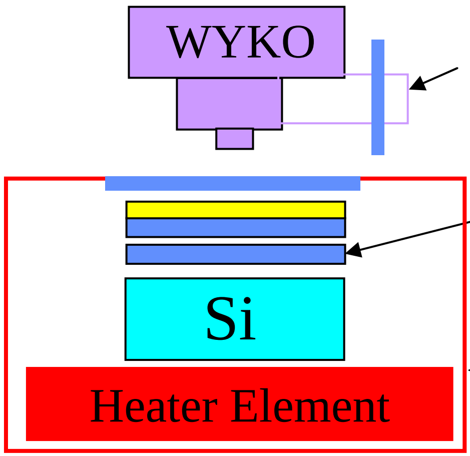
Data

SPICE Simulation

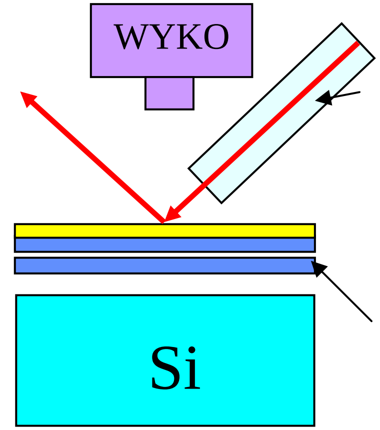


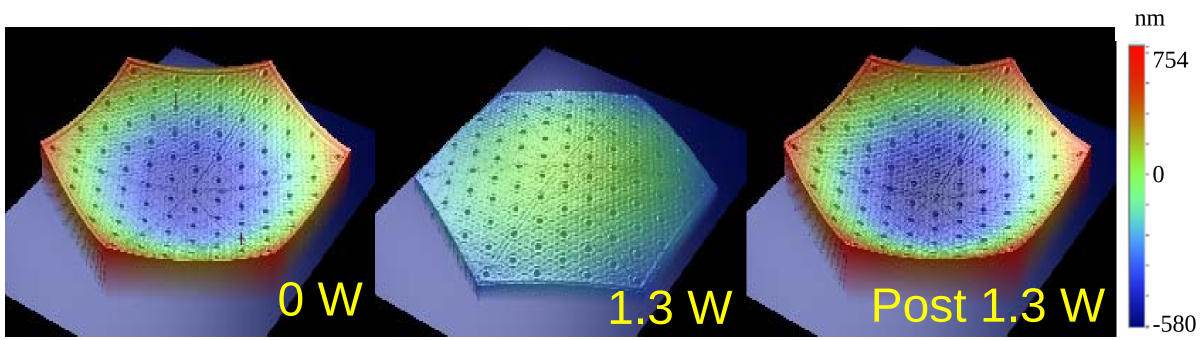
Temperature & High Optical Power Effects

Ambient



Laser Heating

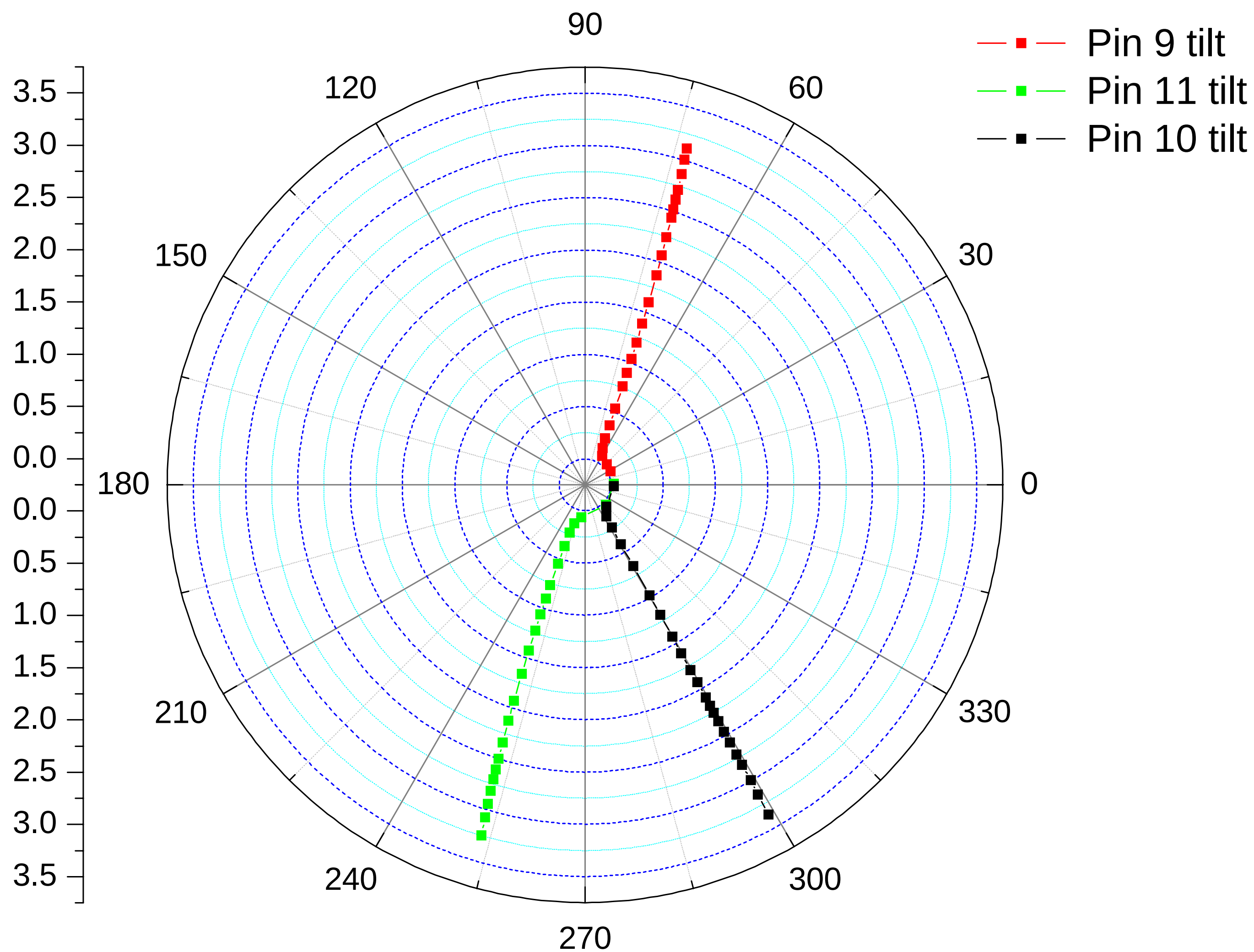




Laser heating results for 1.3 W (2.8 kW/cm²)

Permanent deformations have been observed for both gold and aluminum mirrors

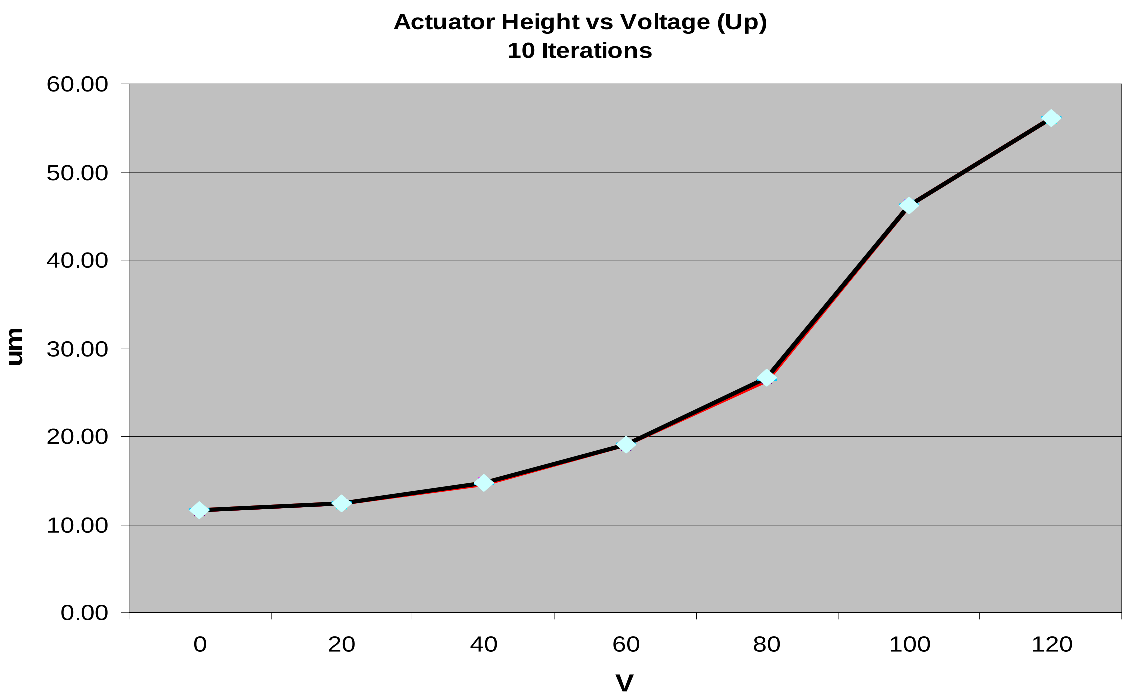
Diagonal tilt of ganged mirror array – polar representation



Sandia National Laboratories

Repeatability: 1 Up

L1



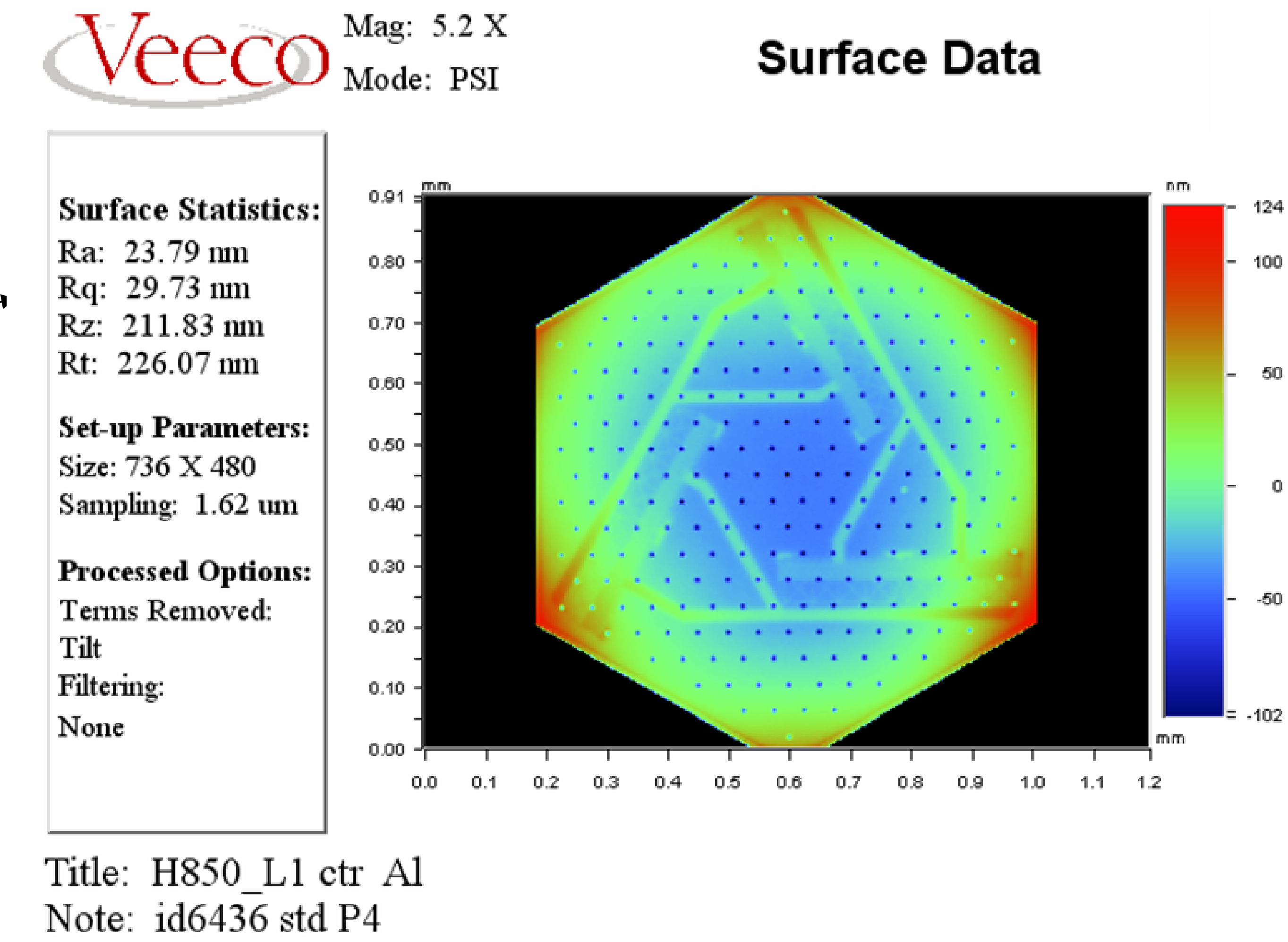
Voltage	σ	
0	**6.77E-02**	
20	**6.30E-02**	
40	**8.06E-02**	
60	**5.36E-02**	
80	**6.13E-02**	
100	**6.26E-02**	
120	**7.69E-02**	
Avg =	6.65E-02	um

- 10 Iterations
- 2 down → 1 up
- 6 samples across 0-120V

Sandia National Laboratories

RMS roughness (w/curvature)

rms roughness (includes ROC)



RMS roughness (w/o curvature)

rms roughness (curvature removed) Remaining major contributor is print through (~23 nm peak-to-valley)

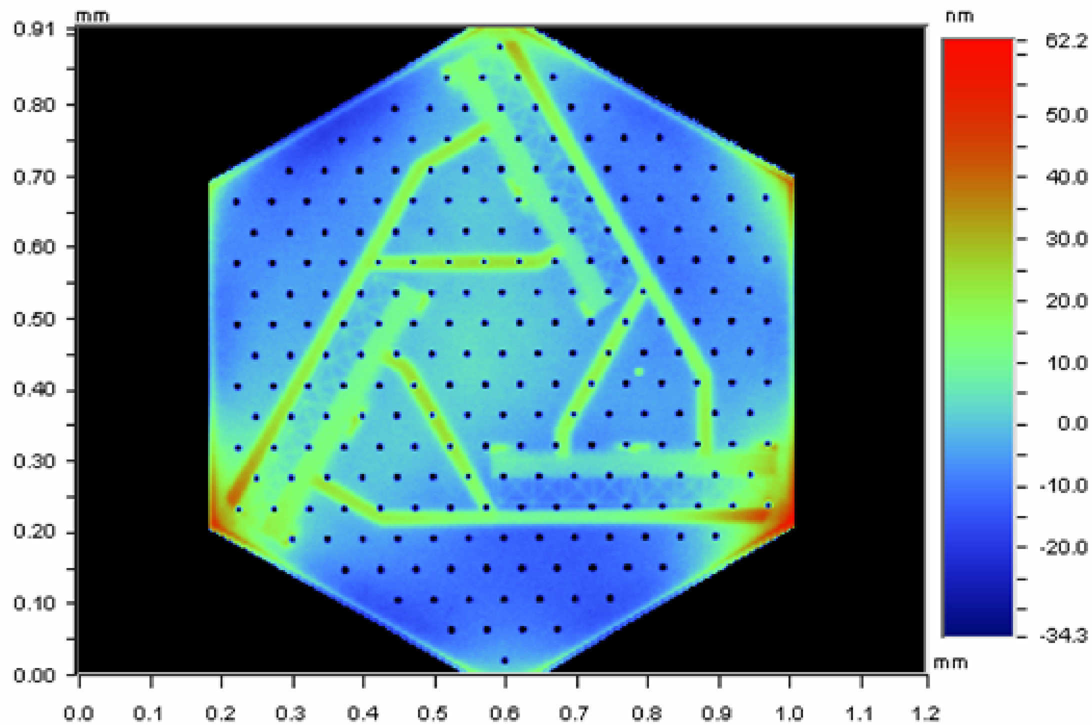
Mag: 5.2 X
Mode: PSI

Surface Data

Surface Statistics:
Ra: 7.96 nm
Rq: 10.55 nm
Rz: 86.13 nm
Rt: 96.49 nm

Set-up Parameters:
Size: 736 X 480
Sampling: 1.62 um

Processed Options:
Terms Removed:
Curvature & Tilt
Filtering:
None

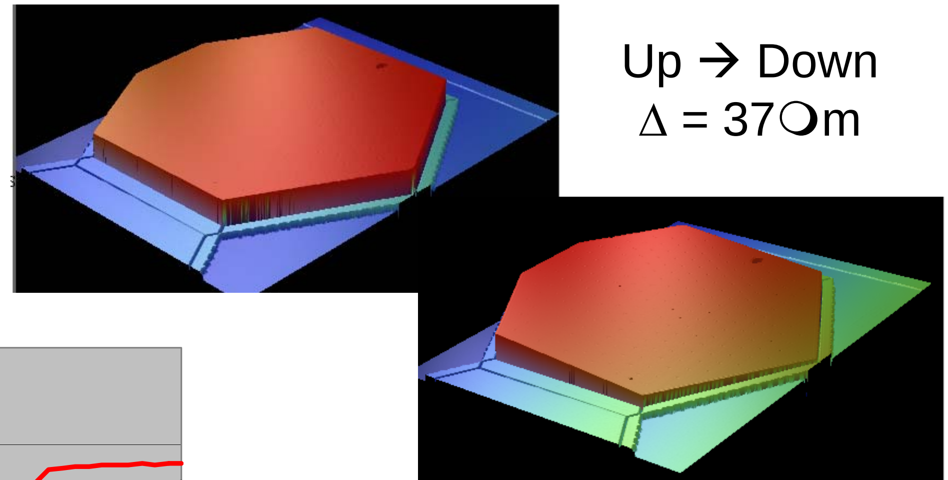


Title: H850_L1 ctr Al
Note: id6436 std P4

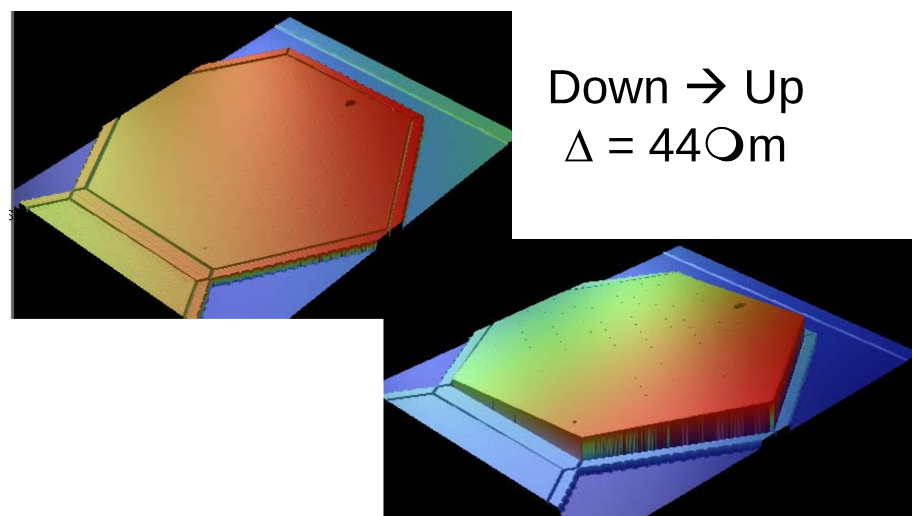
Voltage vs Deflection

L1

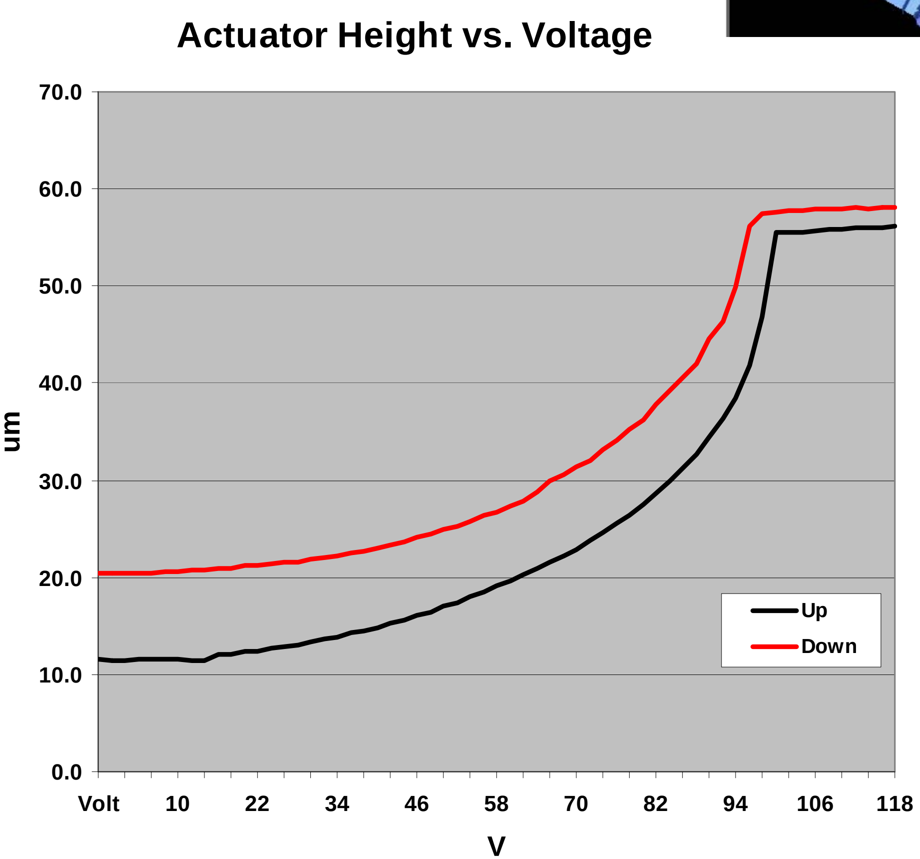
Single (varying) actuator. ∆is indicative of mech. Interference.



Up → Down
∆ = 37❍m

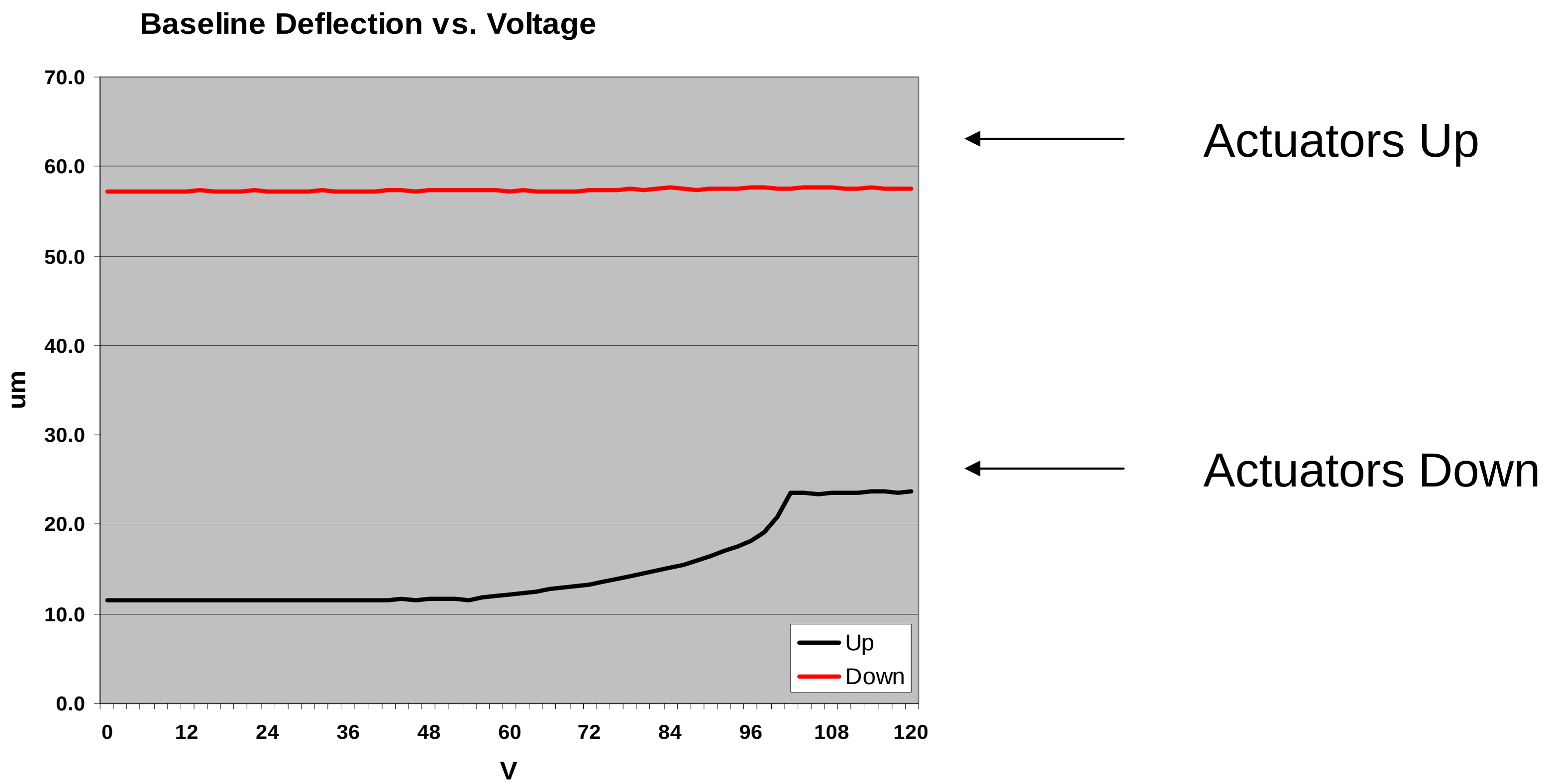


Down → Up
∆ = 44❍m



Mechanical Interference

L1



L1

Repeatability: Static

- **N = 10 measurements. Manual (lateral) displacement between measurements.**
- **Results are a quantitative measurement of our ability to infer height over an array. → Not good, but not a problem for right now…**

Max

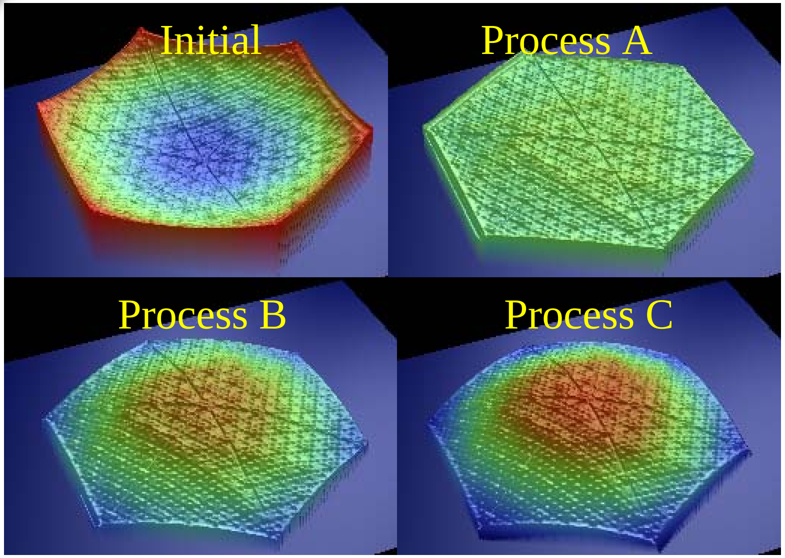
Act #	R01	R02	R03
Avg (um)	14.09	24.82	25.39
σ (nm)	12.2	186	160

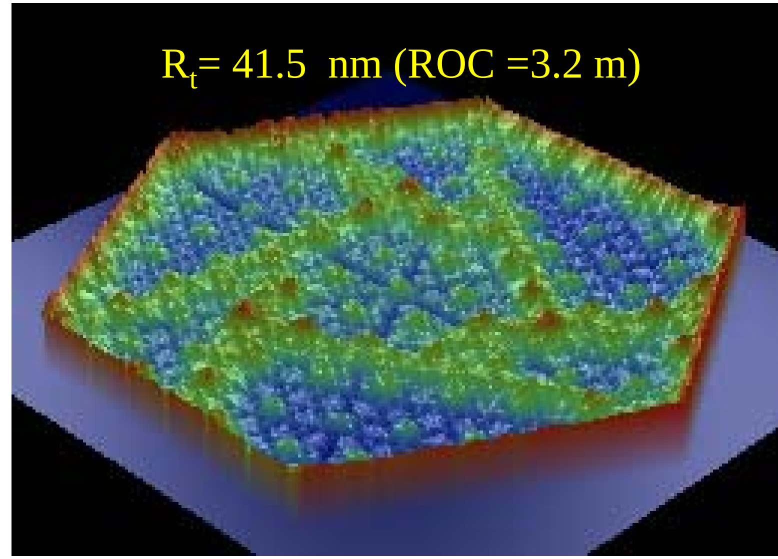
Min

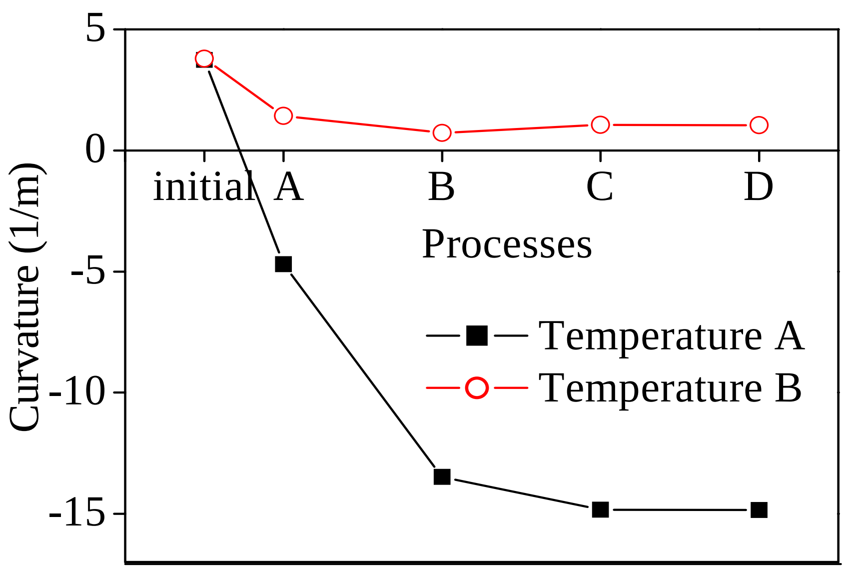
Act #	R01	R02	R03
Avg (um)	13.2	12.31	12.53
σ (nm)	470	470	480

Sandia National Laboratories

RTA Improves Mirror Surface Quality





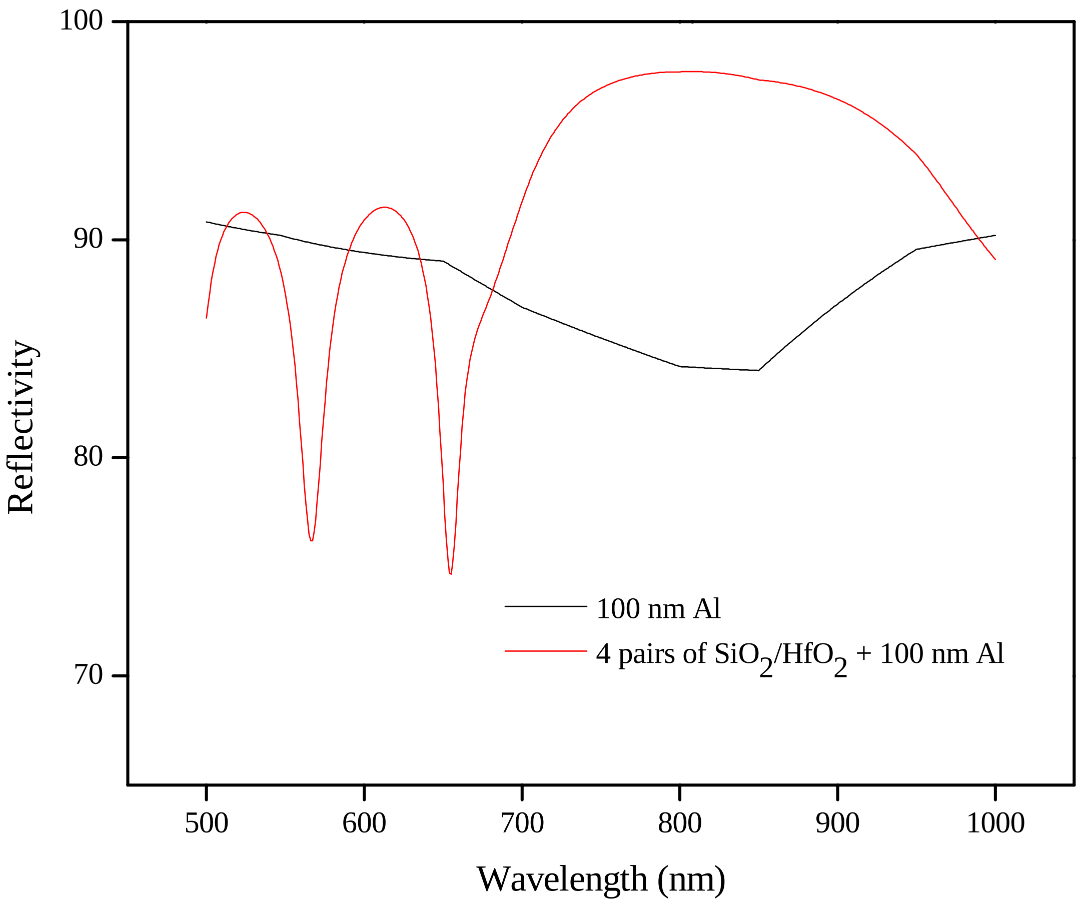


Reinforced Mirror, Flattened by Process A

- Process A
  - Pre-release RTA
  - Five 30-sec cycles @ 1100C
- Results shown w/o metal
  - Drive convex with RTA
  - Allow tensile metal to flatten
- Transfer to fab pending

Sandia National Laboratories

Reflectivity of metallized (Al) MEMS mirror with and without dielectric layers



Absorbance at 808 nm = 2.3 % for dielectric + Al coated mirrors vs. 15.8 % for Al only coated mirrors