State of the Art in MEMS Deformable Mirrors

Mirror Technology Days
November 12, 2015

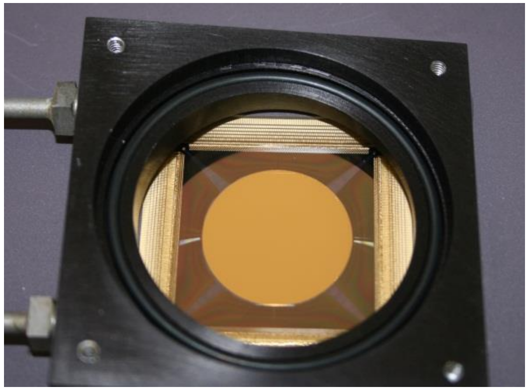
Peter Ryan(1), Steven Cornelissen(1), Charlie Lam(1), Paul Bierden(1) and Thomas Bifano(1,2)

(1) Boston Micromachines Corporation, Cambridge, MA 02138

(2) Boston University, Boston, MA 02215

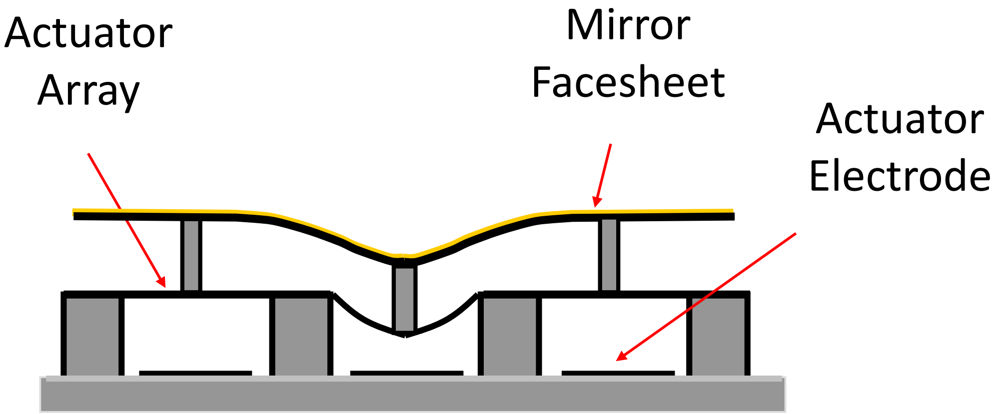
Outline

- NASA SBIRS
  - Topography Improvements
  - Enhanced Reliability
  - TITLE OF PHASE I
- TDEM
- Commercialization of BMC DMs
- BMC mirrors in the field
- 10K+ actuator DM exploratory work

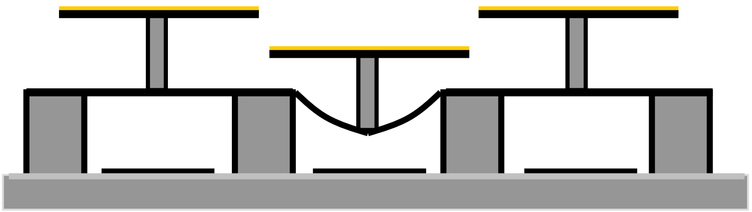


2040 Actuator (2K) Continuous Facesheet DM

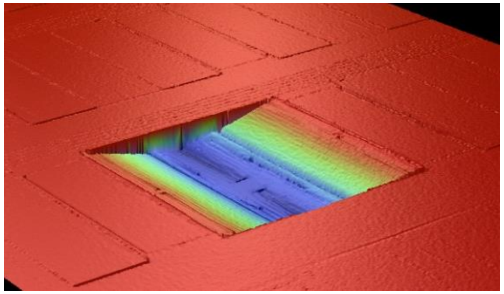
MEMS DM Architecture



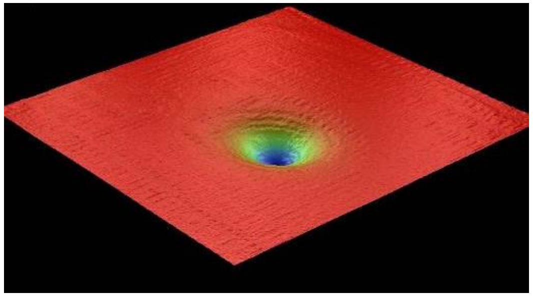
Continuous mirror (smooth phase control)



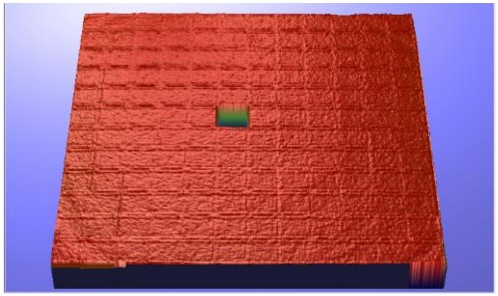
Segmented mirror (uncoupled control)



Deflected Actuator



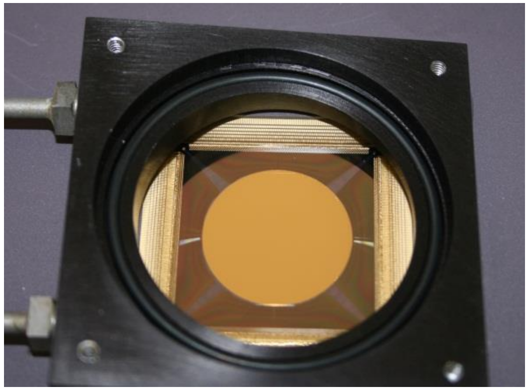
Deformed Mirror Membrane



Deformed Segmented Mirror

Outline

- NASA SBIRS
  - Topography Improvements (Phase II)
  - Enhanced Reliability (Phase II)
  - Improved yield, performance, and reliability of high-actuator-count deformable mirrors (Phase I)
- TDEM
- Commercialization of BMC DMs
- BMC mirrors in the field
- 10K+ actuator DM exploratory work



2040 Actuator (2K) Continuous Facesheet DM

Topography Improvements

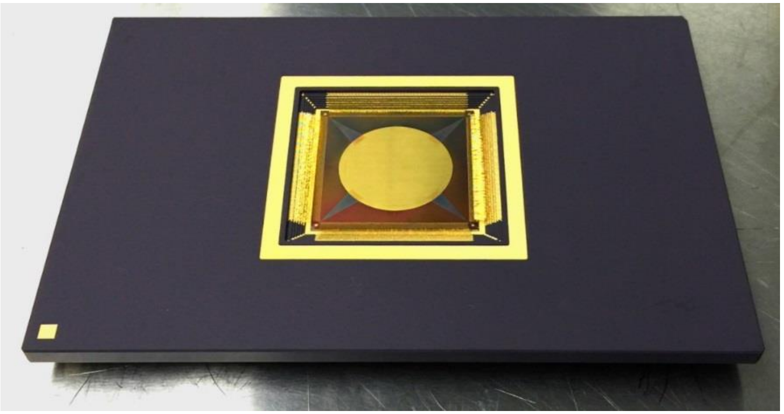
Topography Improvements in MEMS DMs for High-contrast, High-resolution Imaging

Contract#: NNX13CP03C (closed 2015)

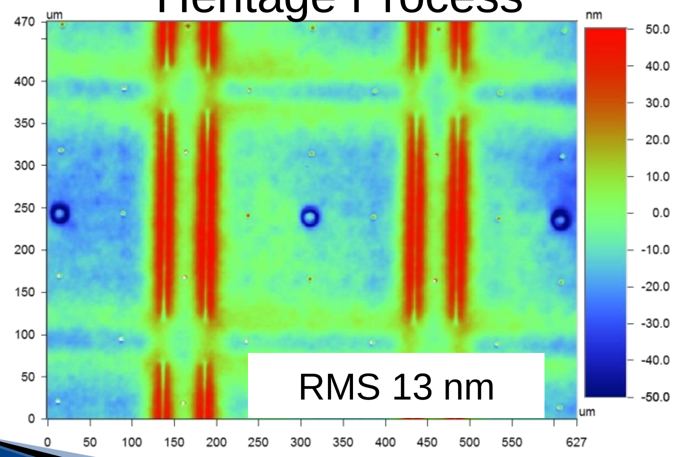
SBIR Phase II

Objective: To develop a MEMS deformable mirror with reduce surface figure errors resulting from actuator "print-through" topography and stress-induced mirror scallop topography.

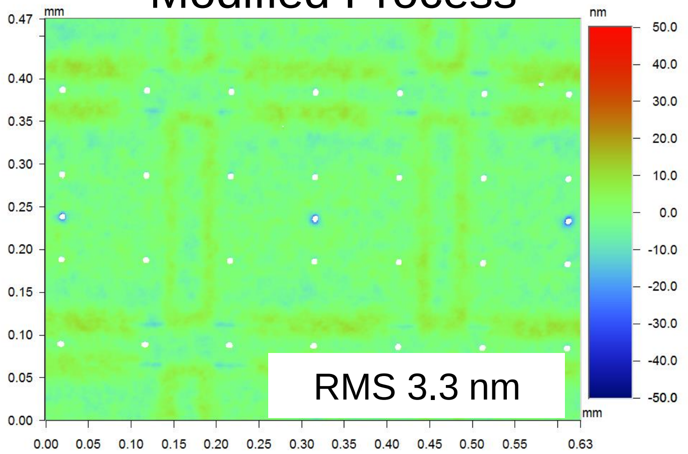
Delivered 3064 actuator device



Heritage Process

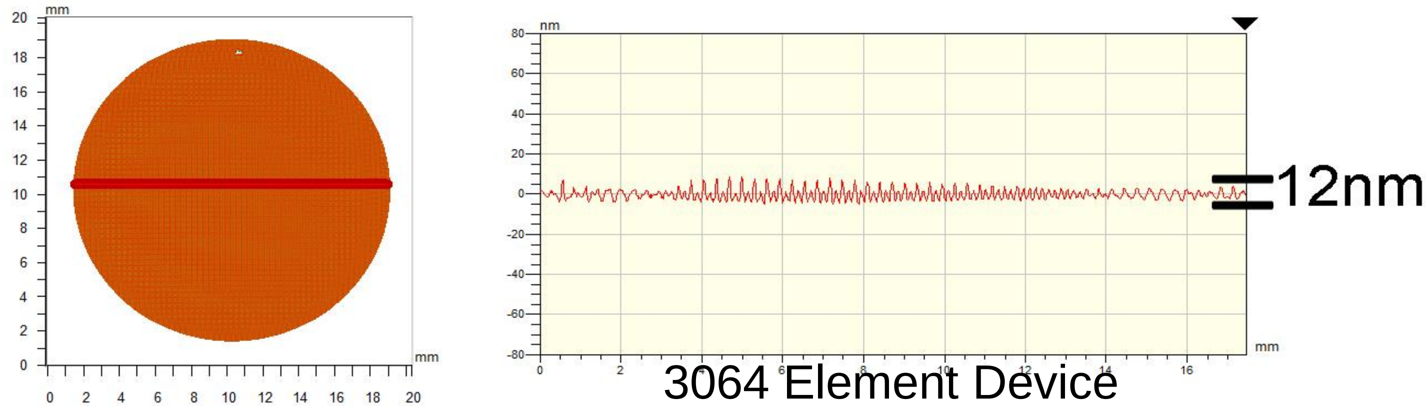


Modified Process

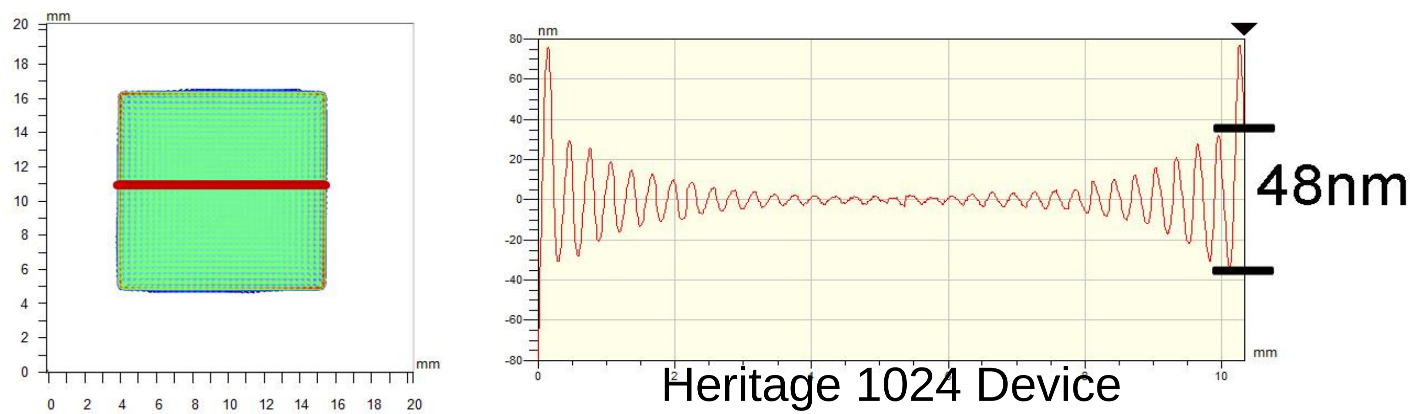


Topography Improvements

Scalloping across mirror compared to heritage devices



3064 Element Device



Heritage 1024 Device

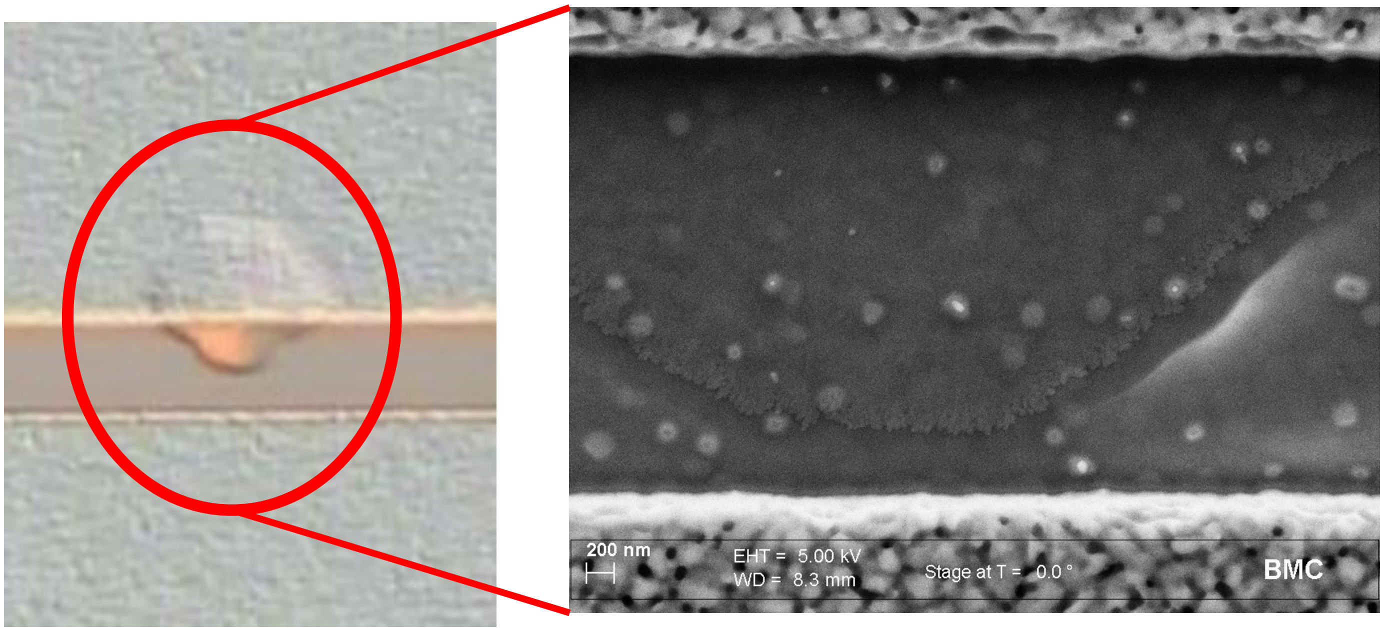
Note 3064 aperture is 17mm while heritage is 10mm

Topography Improvements

Things we learned

- Order of operation is critical when considering the thermal budget in microfabrication.
- Surface figure error in BMC DMs is dominated by reflow of the sacrificial material under the mirror layer.
- Phosphorus segregation, where polysilicon seeps out dopant materials, occurs non linearly with temperature.

Phosphorus Segregation

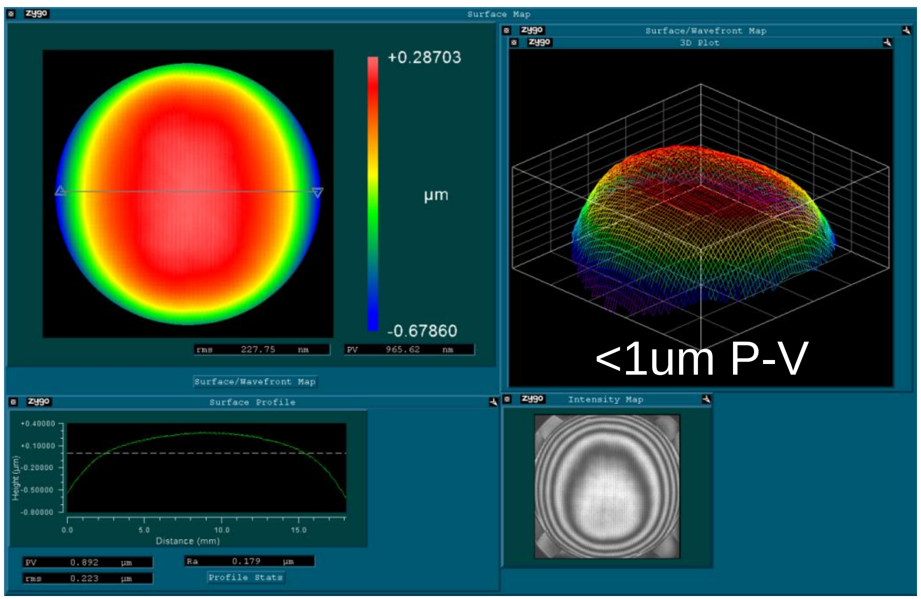


Optical Image and SEM of foreign material seen in the 3um electrode cuts of fabrication material leading to the reduced yield.

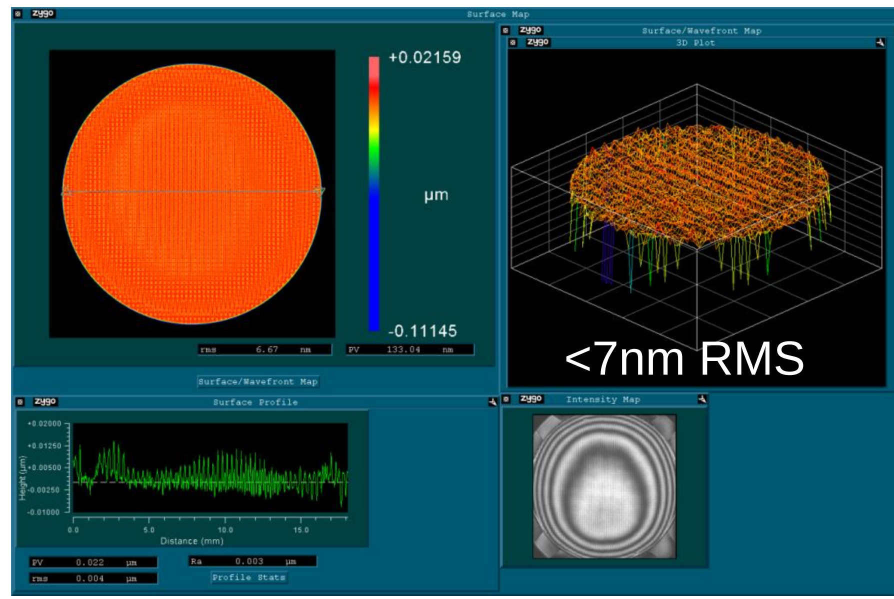
Topography Improvements

Technological Achievements

- Delivered a 3064 element continuous facesheet DM with figure error better than a factor of 3 than what has been made thus far.



Unpowered Surface



With low order filtered

Enhanced Reliability

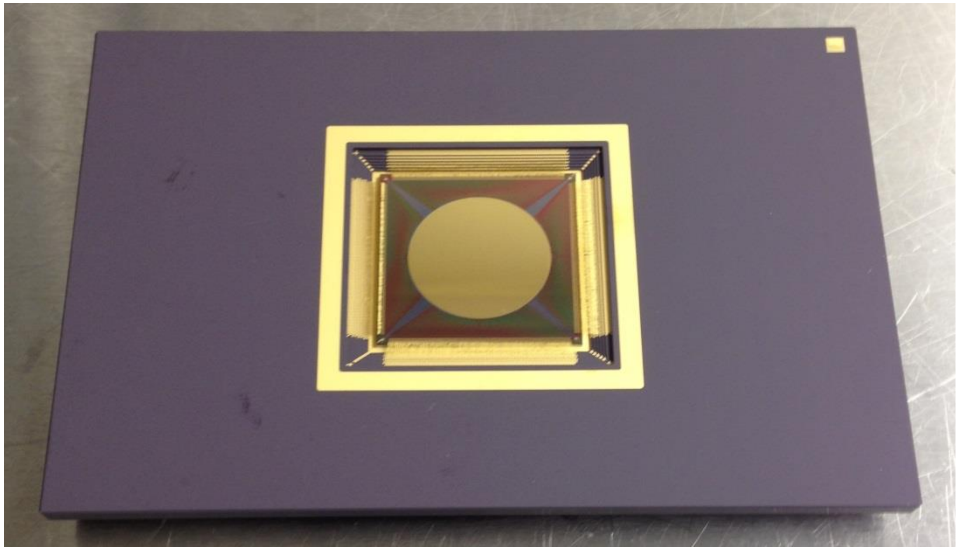
Enhanced Reliability MEMS Deformable Mirrors for Space Imaging Applications

Contract #: NNX12CA50C (closed 2015)

NASA Phase II SBIR

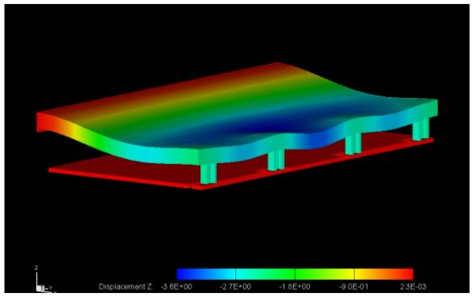
Objective: Demonstrate the ability to prevent single point failures resulting from electrical overstress caused by electronic or software faults that may occur during ground test or space-based operation

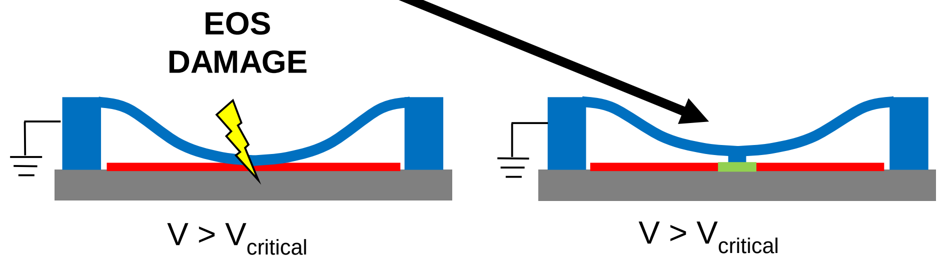
Delivered 2040 actuator device

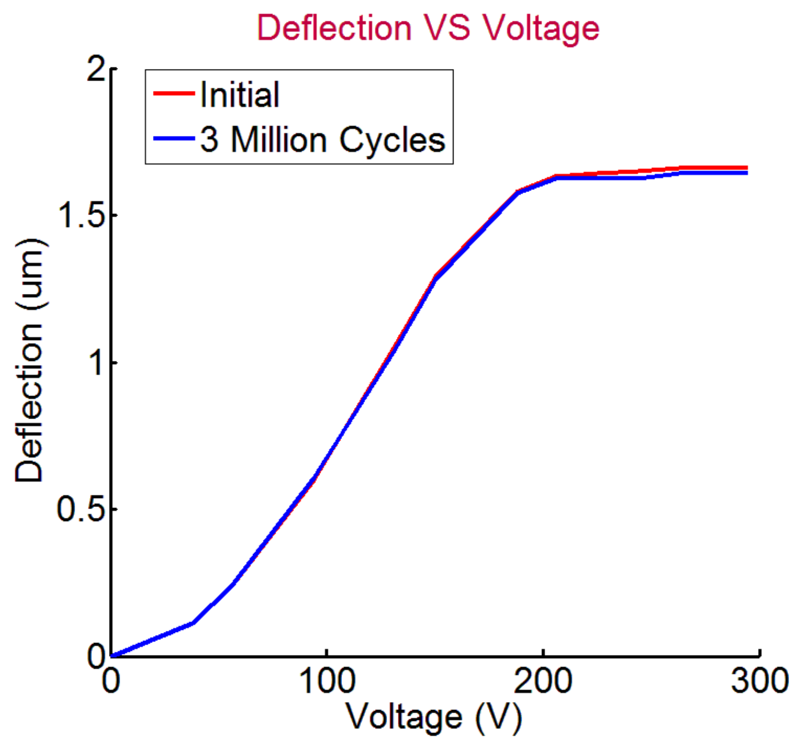


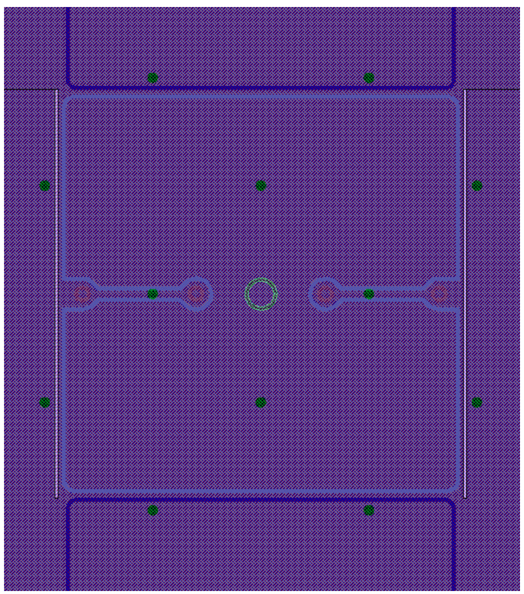
Enhanced Reliability Concept

"Hard Stops"









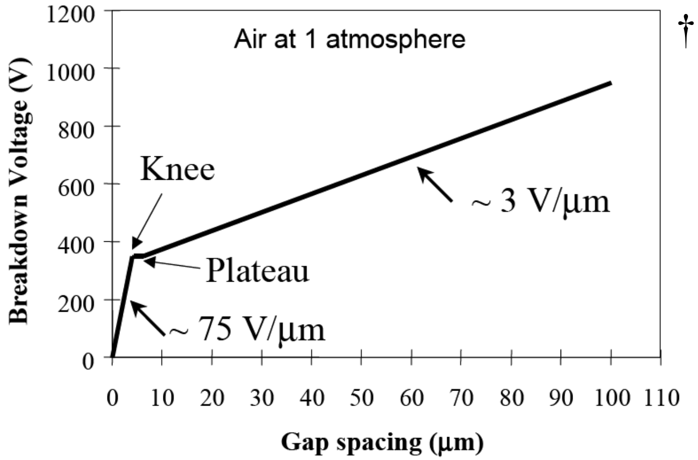
Enhanced Reliability Actuator Design

Deflection versus voltage. Initial, after cycling 3 million times above critical voltage (295V).

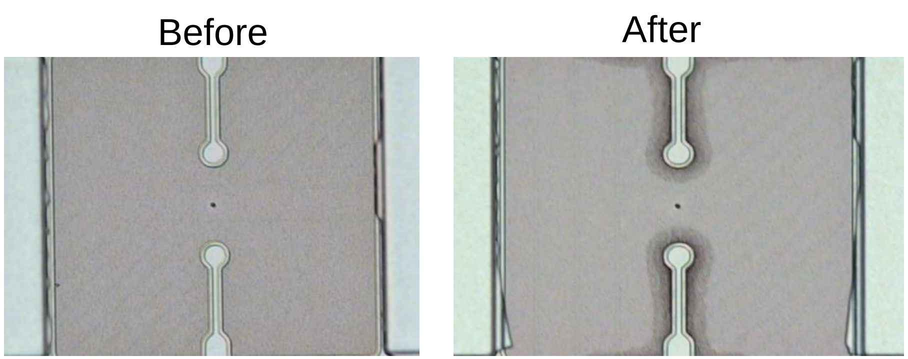
Enhanced Reliability

Things we learned

- The hardstops are good at preventing one-off failures due to a number of over voltage events.
- Damage can occur to electrodes if the voltage is higher than some threshold and applied for long enough.
- Modified Pachens curve predicts this electrical breakdown



Electrode Damage



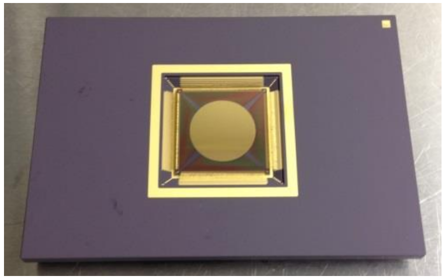
Damage seen after 11 million flexure cycles to 295V

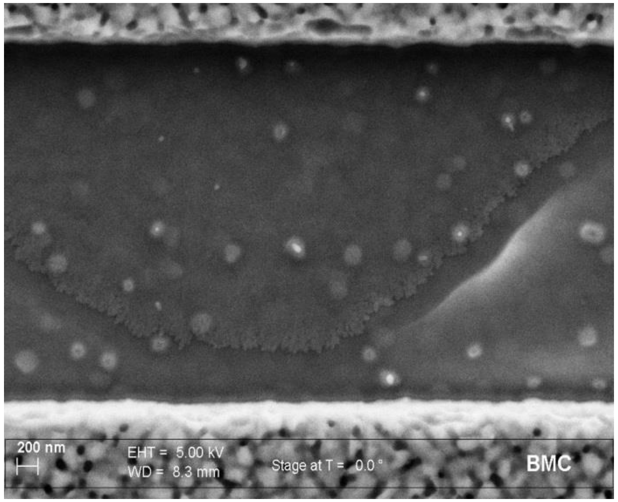
†. Wallash AJ, Levit L, editors. Electrical breakdown and ESD phenomena for devices with nanometer-to-micron gaps. Micromachining and Microfabrication; 2003: International Society for Optics and Photonics.

Enhanced Reliability

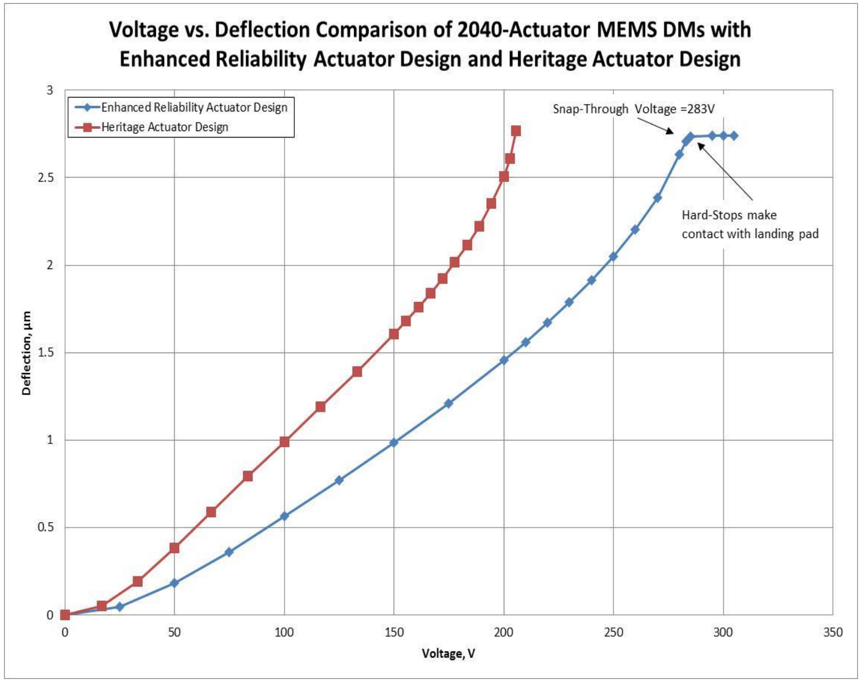
Technological Achievements

- Delivered 2040 element high reliability device with 96% yield.
- Reduced yield was a result of phosphorus segregation which has since been mitigated.
- Hard stops are shown to prevent actuator failures.
- We are further studying electrical breakdown





SEM of foreign material seen in the 3um electrode cuts of fabrication material leading to the reduced yield.



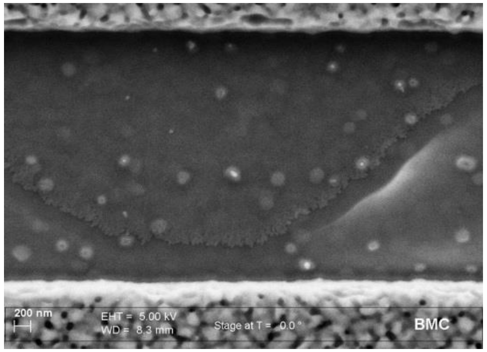
Improved DMs

Improved Yield, Performance and Reliability of High-Actuator-Count Deformable Mirrors

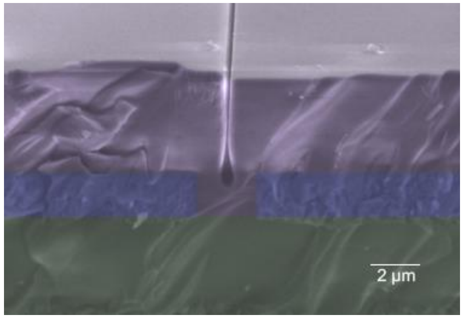
Contract#: NNX15CP39P (Ongoing)
Phase I SBIR

Objective: Address known fabrication issues for high actuator count deformable mirrors

Phosphorus Segregation

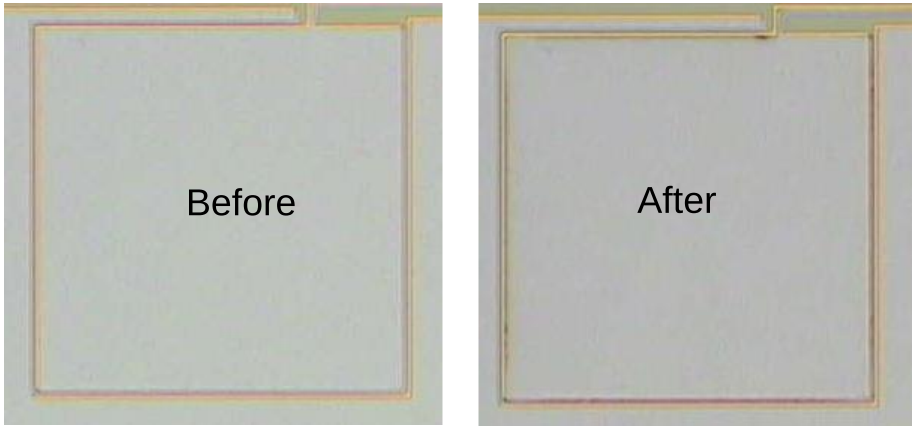


Keyhole Voids



Address these issues and integrate with the process for the best surface figure.

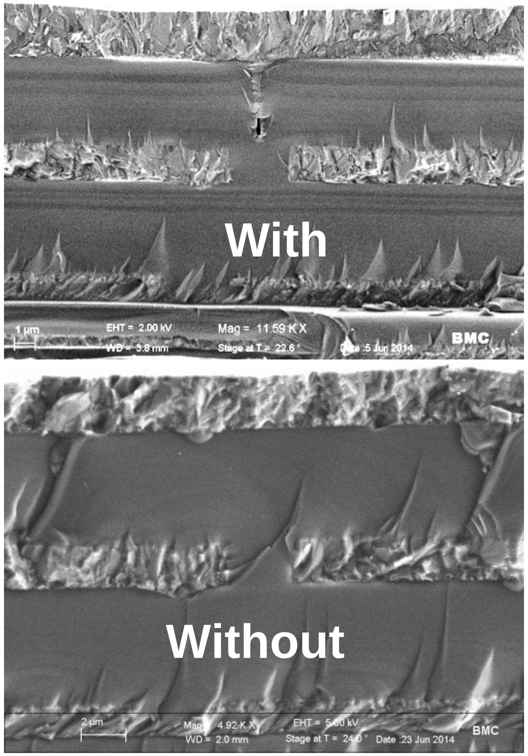
Electric Breakdown



Damage seen on 3um spaced electrode held for 1 hour at 275V

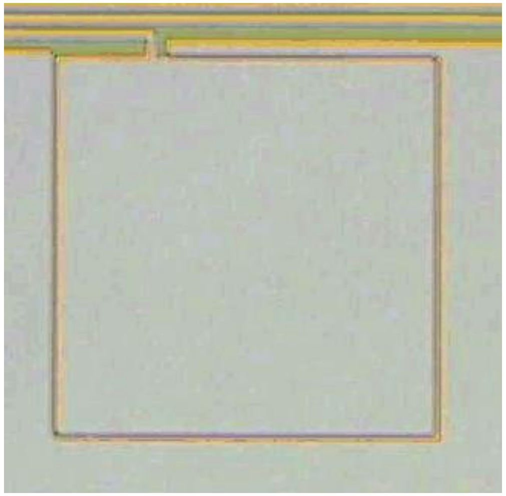
Improved DMs

Keyhole Voids: the cause of the keyholes was determined and checks are done at this point in the process to ensure they will not occur.



Phosphorus Segregation: has been eliminated by implementing two process changes.

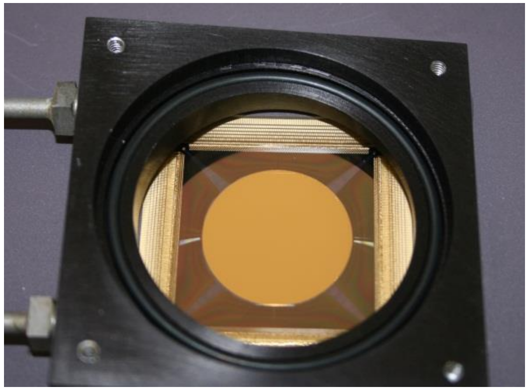
Electric Breakdown: Work is ongoing.



2um spaced electrode optical images 10 minutes apart with 275V applied

Outline

- NASA SBIRS
  - Topography Improvements (Phase II)
  - Enhanced Reliability (Phase II)
  - Improved yield, performance, and reliability of high-actuator-count deformable mirrors (Phase I)
- TDEM
- Commercialization of BMC DMs
- BMC mirrors in the field
- 10K+ actuator DM exploratory work



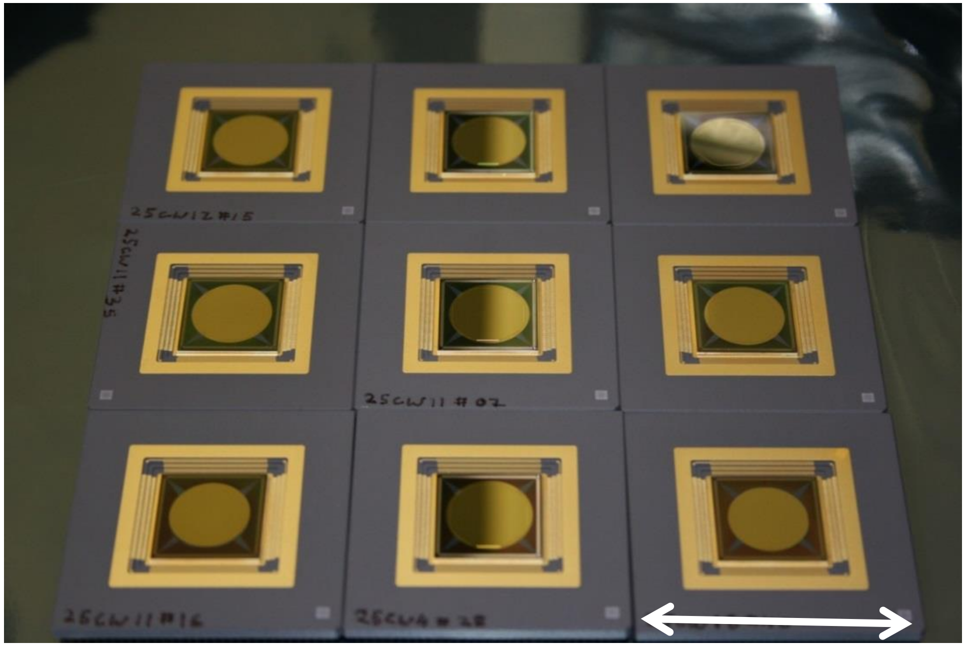
2040 Actuator (2K) Continuous Facesheet DM

TDEM Program

Ongoing Contract#: NNH12CQ27C
TDEM/ROSES
MEMS Deformable Mirror Technology Development for Space-Based Exoplanet Detection

Objective: Demonstrate survivability of the BMC MEMS Deformable Mirror after exposure to dynamic mechanical environments close to those expected in space based coronagraph launch.

9 Mirrors ready for testing



5cm

Project Flow

- Issues with initial MEMS Fabrication
- Problems resolved, but delayed

Coronagraph Test Bed Component Insertion and Baseline Null Testing

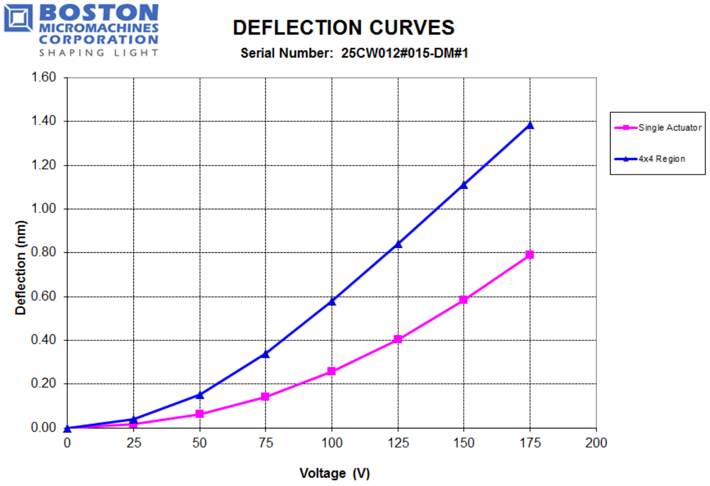
Environmental Testing

BMC Characterization

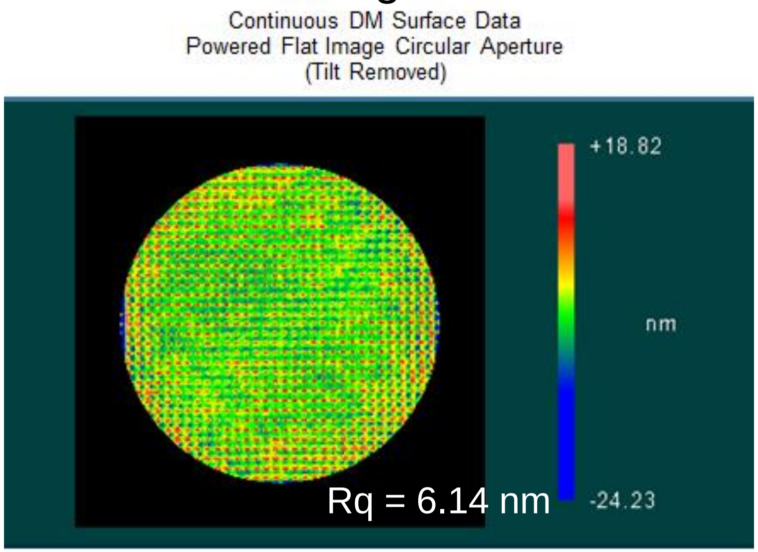
Coronagraph Test Bed Component Insertion and Baseline Null Testing

DMs Fabricated and Characterized Delivered to JPL and Princeton

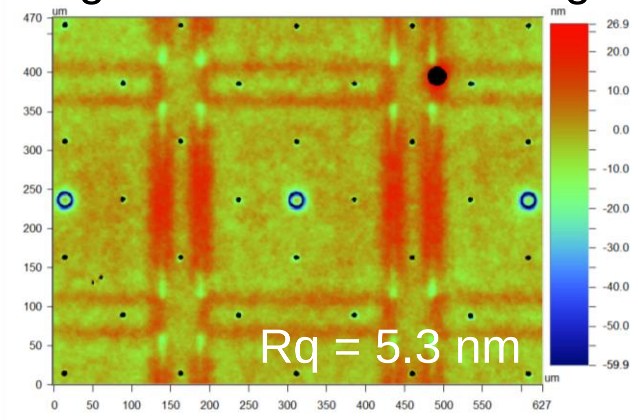
Voltage v. Deflection



Active Flattening of DM Surface

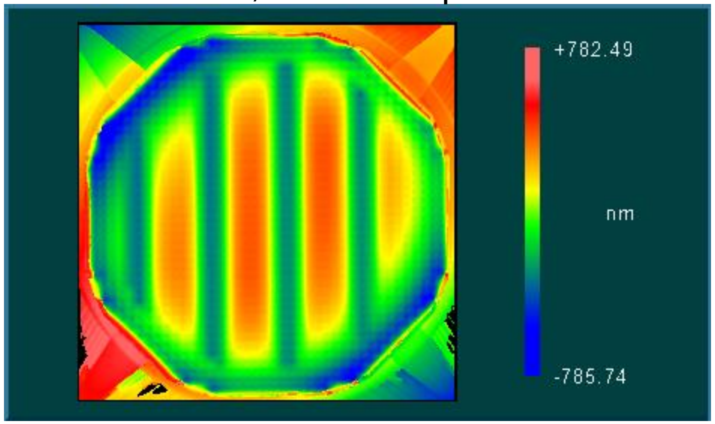


Single Actuator Surface Figure

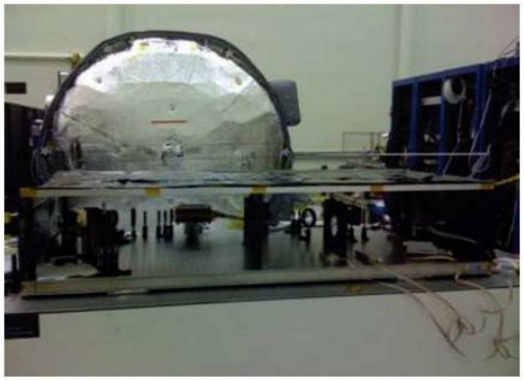


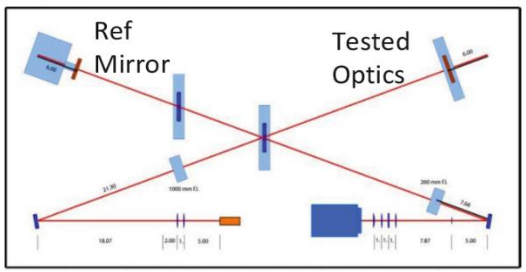
Sinusoid Shape

4 Period, 400nm Amplitude



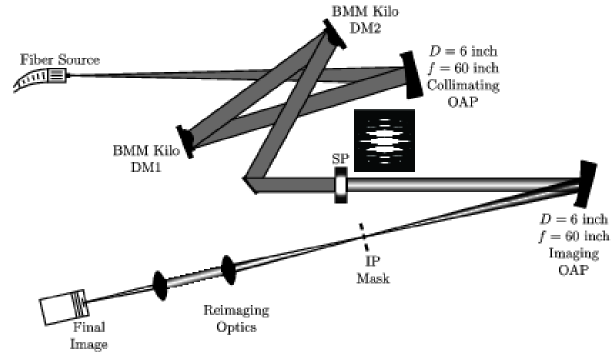
Test Bed Measurements/Characterization





JPL/VSG

- Influence function
- Repeatability
- Position stability
- Surface Shape

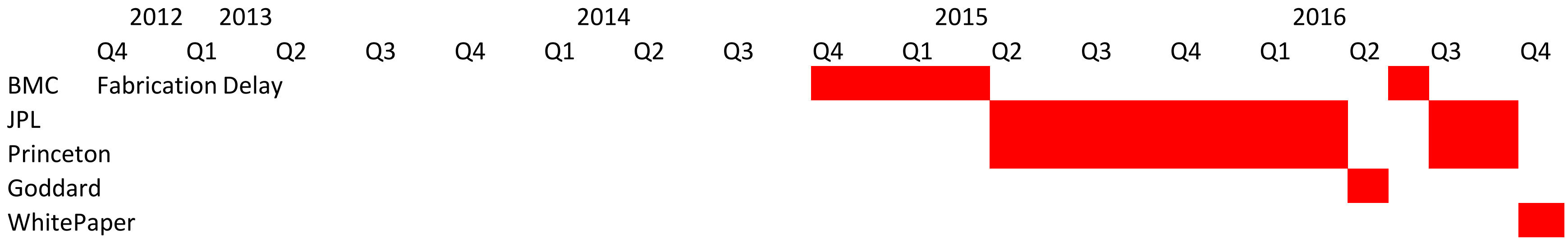


High Contrast Imaging Laboratory (HCIL) at Princeton University

- Test the performance of two DMs in series with a shaped pupil coronagraph
- Vary the size of the dark hole and its separation from the optical axis from 7 to 10 and -2 to 2 λ/D on each side of the image plane.

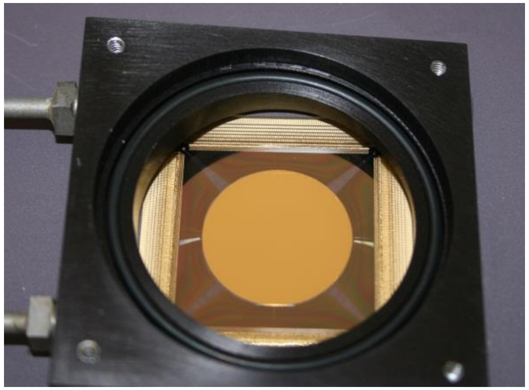
Schedule

Project Start	September 2012
Deliver “Engineering” DM to JPL	March 2014
Deliver Test DMs to JPL	March 2015
Deliver “Engineering” DMs to Princeton	April 2015
Deliver Test DMs to Princeton	July 2015
Characterization at JPL/Princeton	Ongoing
Environmental testing at GSFC	1 month after return (with 1 month notice)
Retesting at BMC	2 Weeks
Retesting at JPL/Princeton	
Submit Whitepaper	1 month after receipt



Outline

- NASA SBIRS
  - Topography Improvements (Phase II)
  - Enhanced Reliability (Phase II)
  - Improved yield, performance, and reliability of high-actuator-count deformable mirrors (Phase I)
- TDEM
- Commercialization of BMC DMs
- BMC mirrors in the field
- 10K+ actuator DM exploratory work

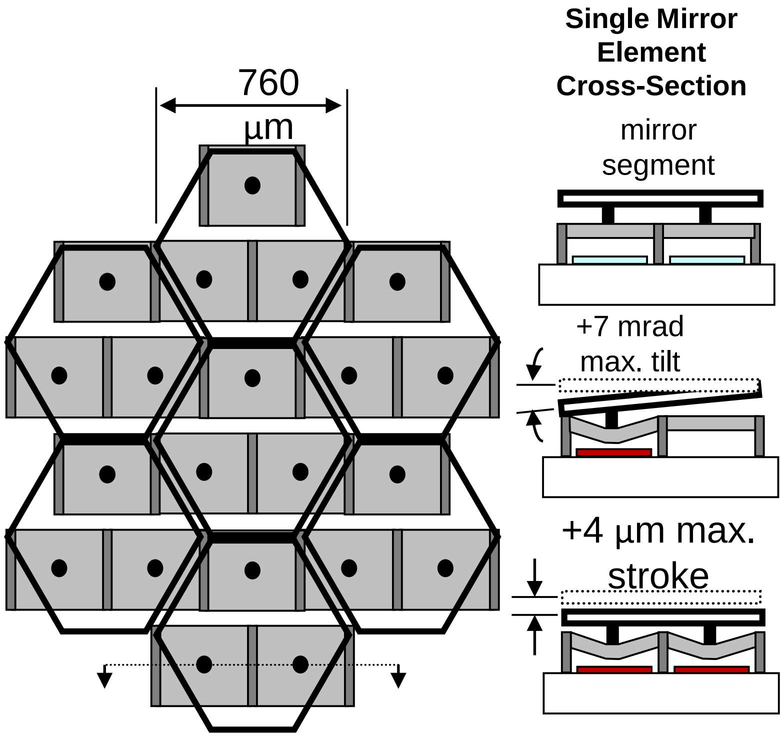


2040 Actuator (2K) Continuous Facesheet DM

New DMs for Commercialization

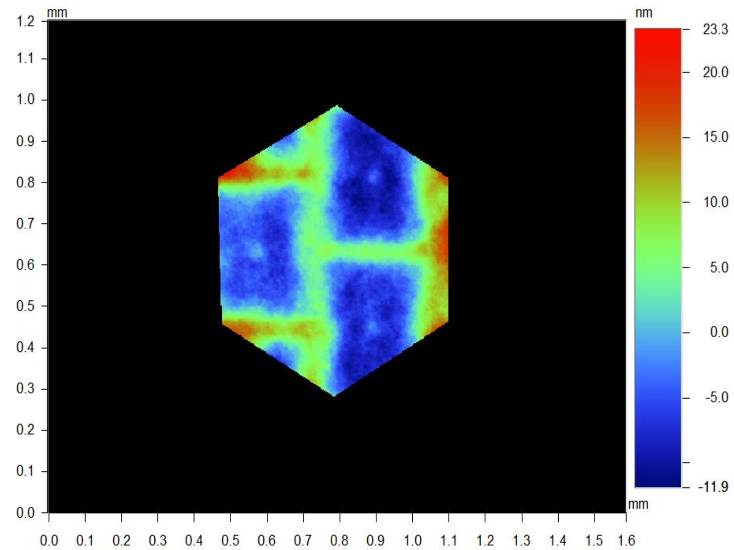
Tip-Tilt-Piston (TTP) MEMS DM

Device Architecture



Individual segments with underlying actuators

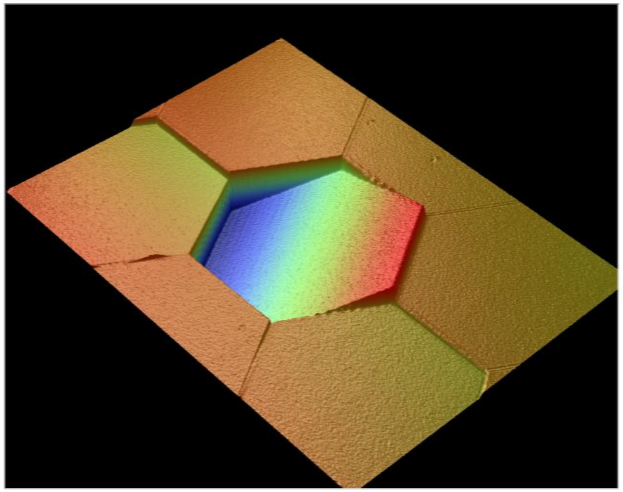
Surface Figure

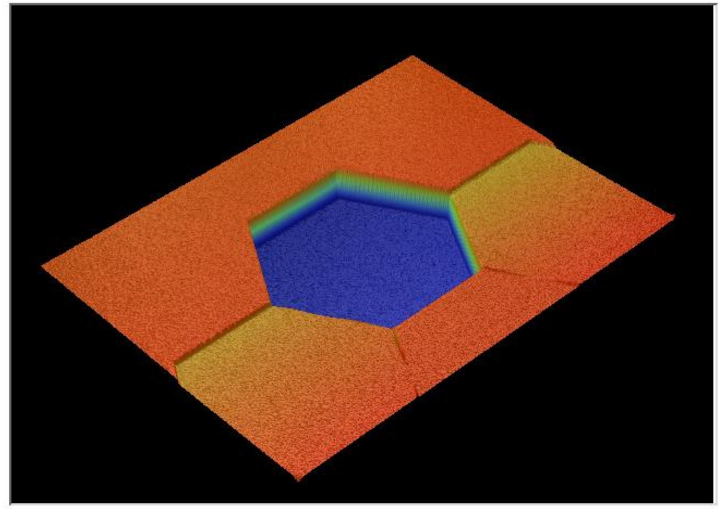


Individual segment 7 nm RMS over 760um

Used for Biomedical Imaging (2-photon)

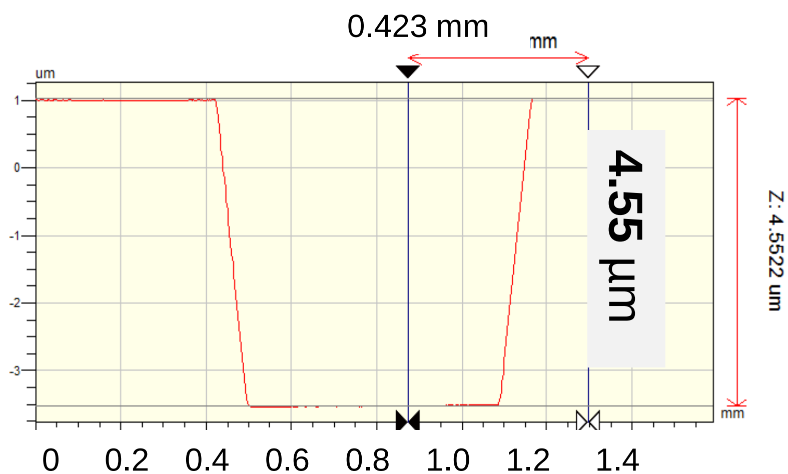
Tip-Tilt-Piston MEMS DM



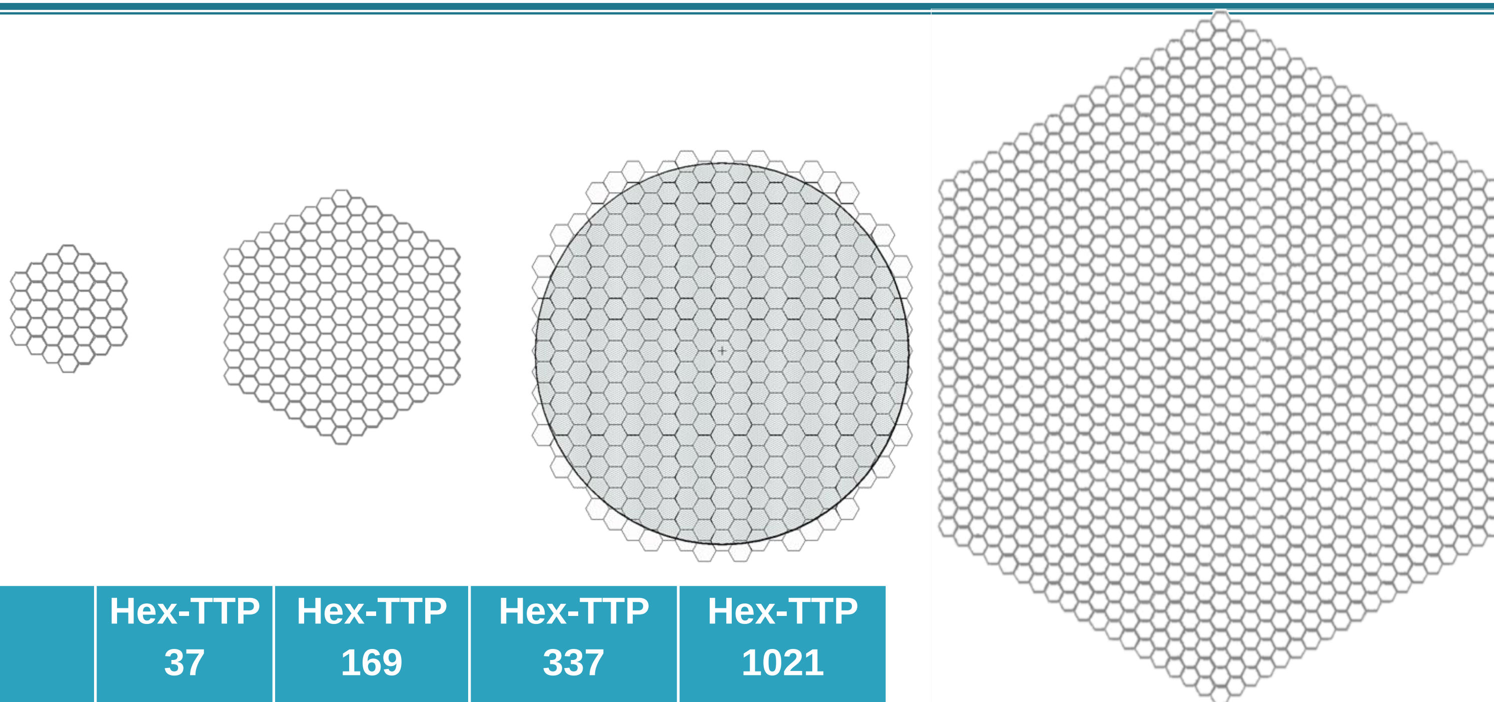


Stiff actuators results in low influence function, allowing for steeper tilt.

Pure piston (all 3 actuators) provides >4 um of stroke



TTP Electromechanical Performance

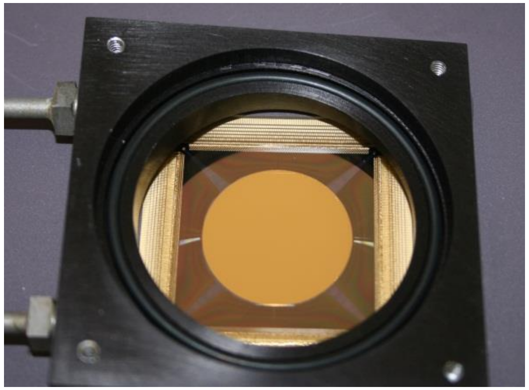


	Hex-TTP 37	Hex-TTP 169	Hex-TTP 337	Hex-TTP 1021
Actuator Count	111	507	1011	3063
Segments	37	169	337	1021
Stroke	3.5 µm	3.5 µm	3.5 µm	1.5 µm

Actuator A Actuator B A+B+C

Outline

- NASA SBIRS
  - Topography Improvements (Phase II)
  - Enhanced Reliability (Phase II)
  - Improved yield, performance, and reliability of high-actuator-count deformable mirrors (Phase I)
- TDEM
- Commercialization of BMC DMs
- BMC mirrors in the field
- 10K+ actuator DM exploratory work

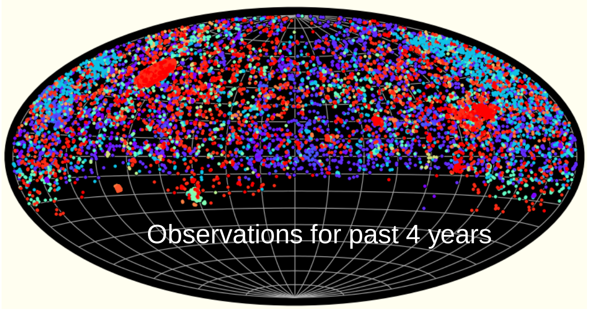


2040 Actuator (2K) Continuous Facesheet DM

On-Sky Instruments using BMC Mirrors

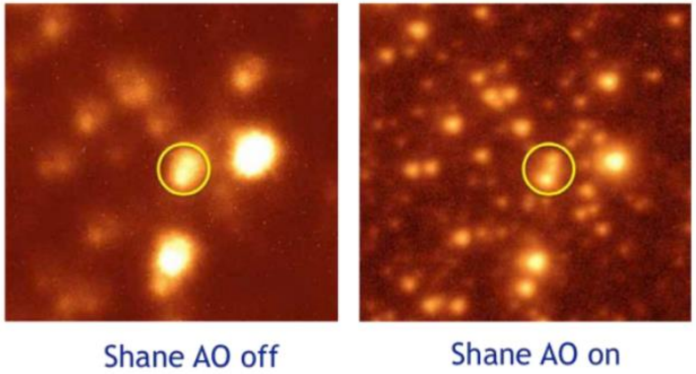
ROBO-AO/Palomar Observatory

- **Multi-DM** Installed 2011
- Low-cost, autonomous, integrated laser adaptive optics system
- Over 19,000 targets from exoplanet follow-up to young-star binarity surveys

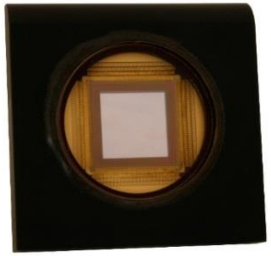


Shane-AO, Lick Observatory

- **Kilo-DM** installed 2013
- Visible Light Laser Guidestar Experiments



Portion of the M92 globular cluster taken in H band.



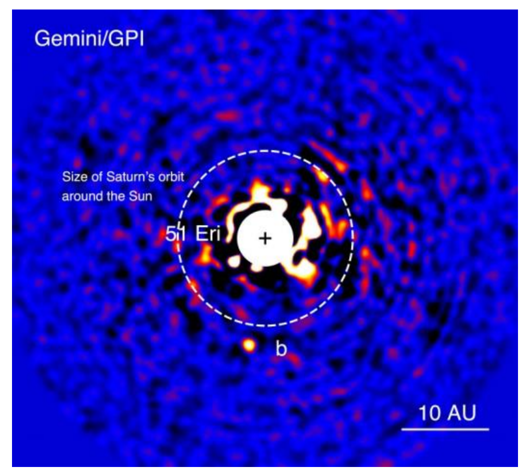
On-Sky Instruments using BMC Mirrors

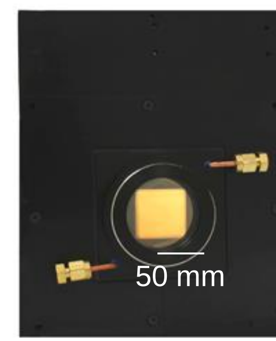
The Subaru Coronographic Imager with Extreme Adaptive Optics (SCExAO)

- **<u>2k-DM</u>** Installed at the Subaru Telescope in 2012
- First light achieved 2013
- Results showed improvement in Strehl from 23.9% - 94.4%
- On sky testing going on now

The Gemini Planet Imager

- **<u>4092 actuator DM</u>** with 3.5µm stroke,
- Deployed on the 8-meter Gemini South Telescope
- First light in 2013
- ***2015 Discovered a 'Young Jupiter' 51 Eridani b shows strongest methane signature ever detected on an alien planet.***

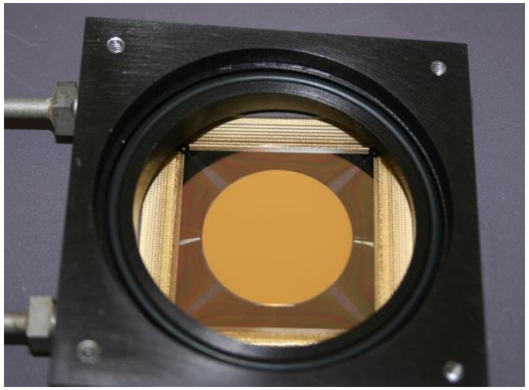




Science 2 October 2015: Vol. 350 no. 6256 pp. 64-67

Outline

- NASA SBIRS
  - Topography Improvements (Phase II)
  - Enhanced Reliability (Phase II)
  - Improved yield, performance, and reliability of high-actuator-count deformable mirrors (Phase I)
- TDEM
- Commercialization of BMC DMs
- BMC mirrors in the field
- 10K+ actuator DM exploratory work



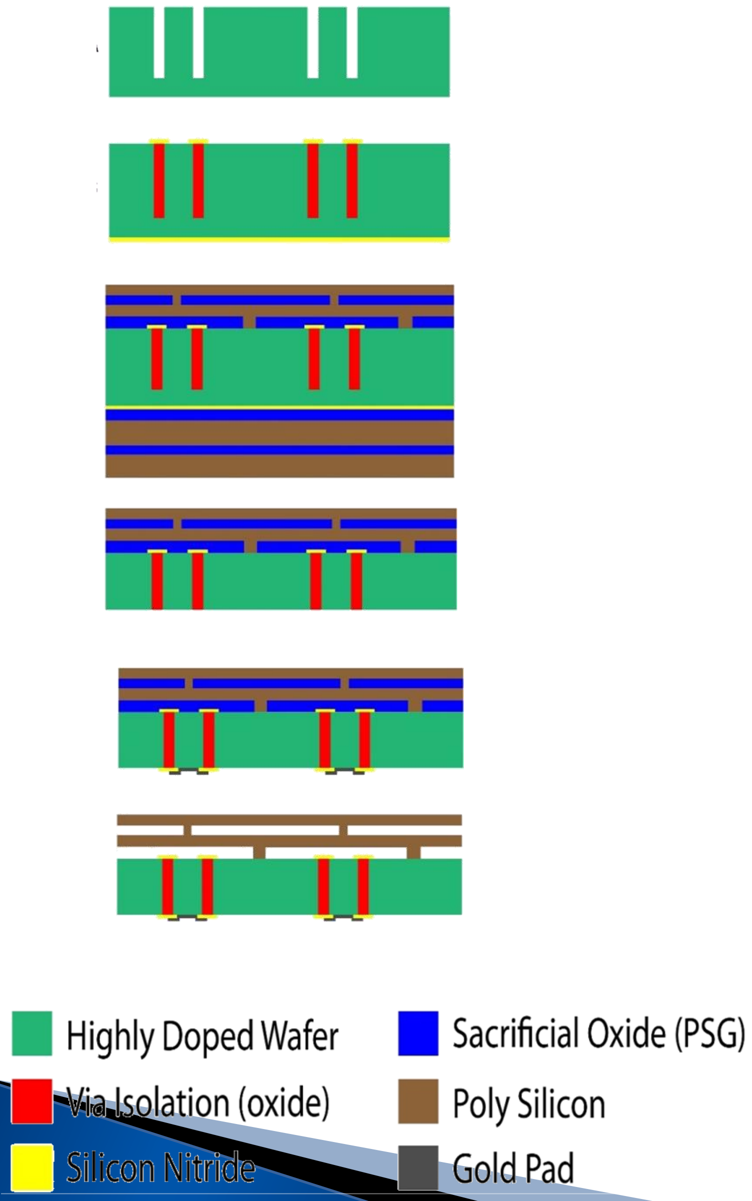
2040 Actuator (2K) Continuous Facesheet DM

10k + exploratory development work

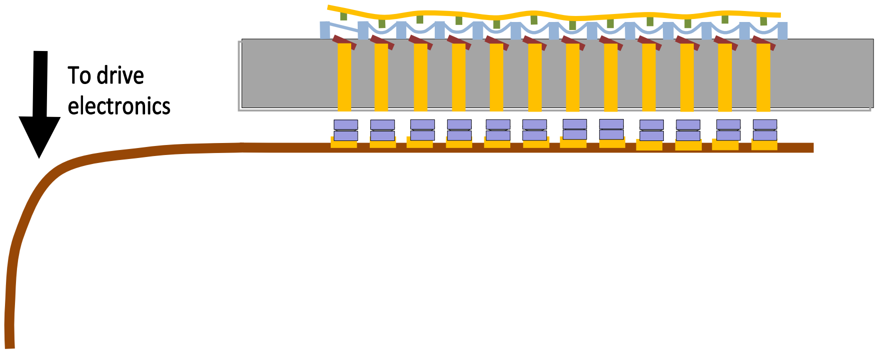
Boston University NSF Award# AST-1105615
BMC Subaward# 4500000912

- **Limited by electrical interconnects**
  - Wirebond for each actuator
  - Span of active optical surface scales with N
  - Span of the chip scales with N^2
  - Limits number of die on a wafer
  - Increases the likely hood of a single point defect causing short/failure
- Plan for development of high density Through Wafer Via (TWV) interconnects

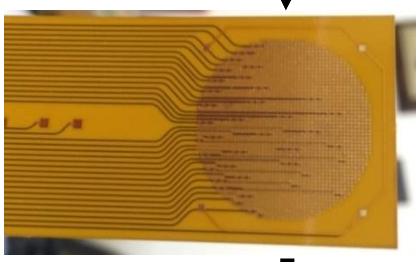
Through-Wafer-Via DM Fabrication Prototype

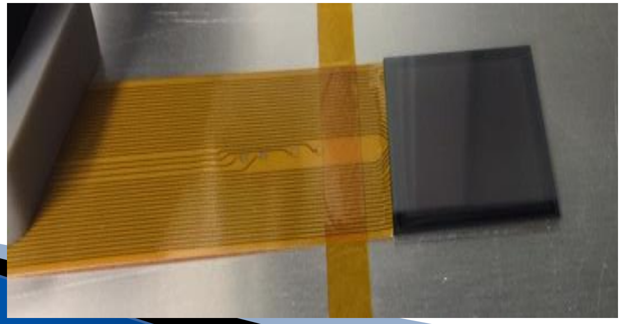


- A new process was developed
- Eliminates wire bonds
- Instead Uses through-wafer-via (TWV) technology
- Challenge is now in packaging of TWV devices
- 140 actuator, 500 actuator, and 2000 actuator devices were fabricated and tested



Flex cable packaging of 2000 actuator TWV devices

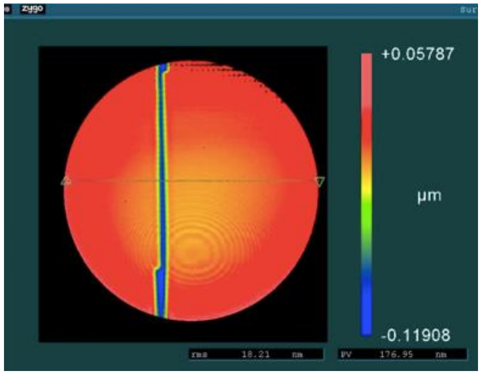




Polymer bump bonds

Chip and cable curvature over large area device diminished bond yield (~70%)

Testing of well-bonded sections yielded reliable actuation performance



Conclusion

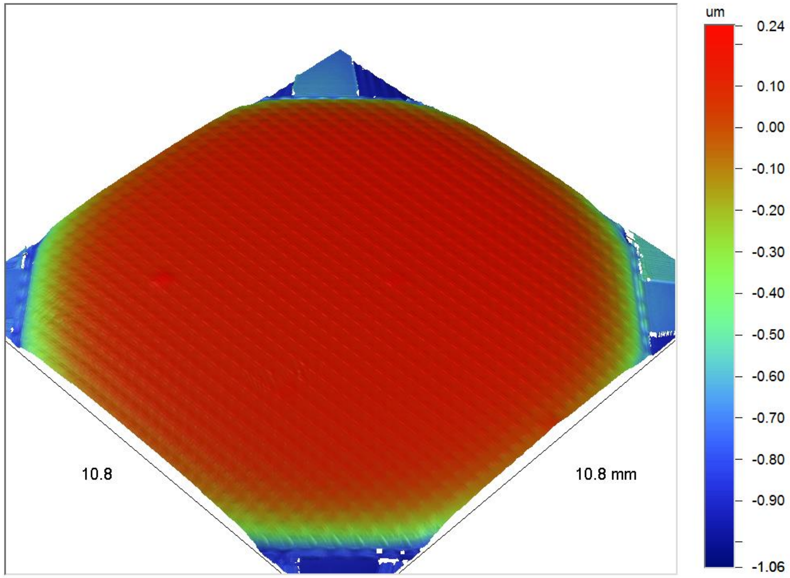
- Results from our Phase II reliability and topography programs show good promise for next generation MEMS DMs.
- Testing is ongoing with our TDEM program. Parts are ready to test at JPL, and Princeton.
- A phase I effort to address fabrication issues is making progress.
- New TTP mirrors are now commercially available.
- Some exploratory work on 10K+ actuator devices has been performed.

Acknowledgements

- Funding from NASA
  - **Contract#: NNH12CQ27C TDEM/ROSES**
  - **Contract #: NNX12CA50C NASA Phase II SBIR**
  - **Contract#: NNX13CP03C NASA Phase II SBIR**
  - **Contract#: NNX15CP39P NASA Phase I SBIR**

Thank You

Questions?



Peter Ryan, pjr@bostonmicromachines.com