Ultra-Flat Tip-Tilt-Piston MEMS Deformable Mirror

Mirror Technology Days

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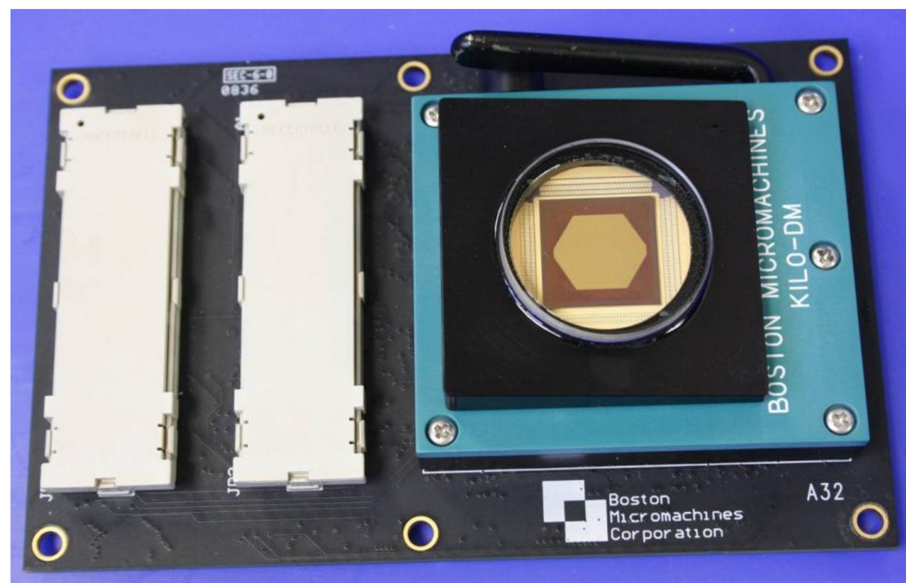
Mirror Development Summary

- 331-element Tip-Tilt-Piston (TTP) MEMS Deformable Mirror (DM) delivered to NASA JPL in January 2009 for use in high contrast imaging test bed

- Mirror segments capable of +/-6mrad tip-tilt and 2µm piston motion, while maintaining <6nm RMS flatness over full range of motion

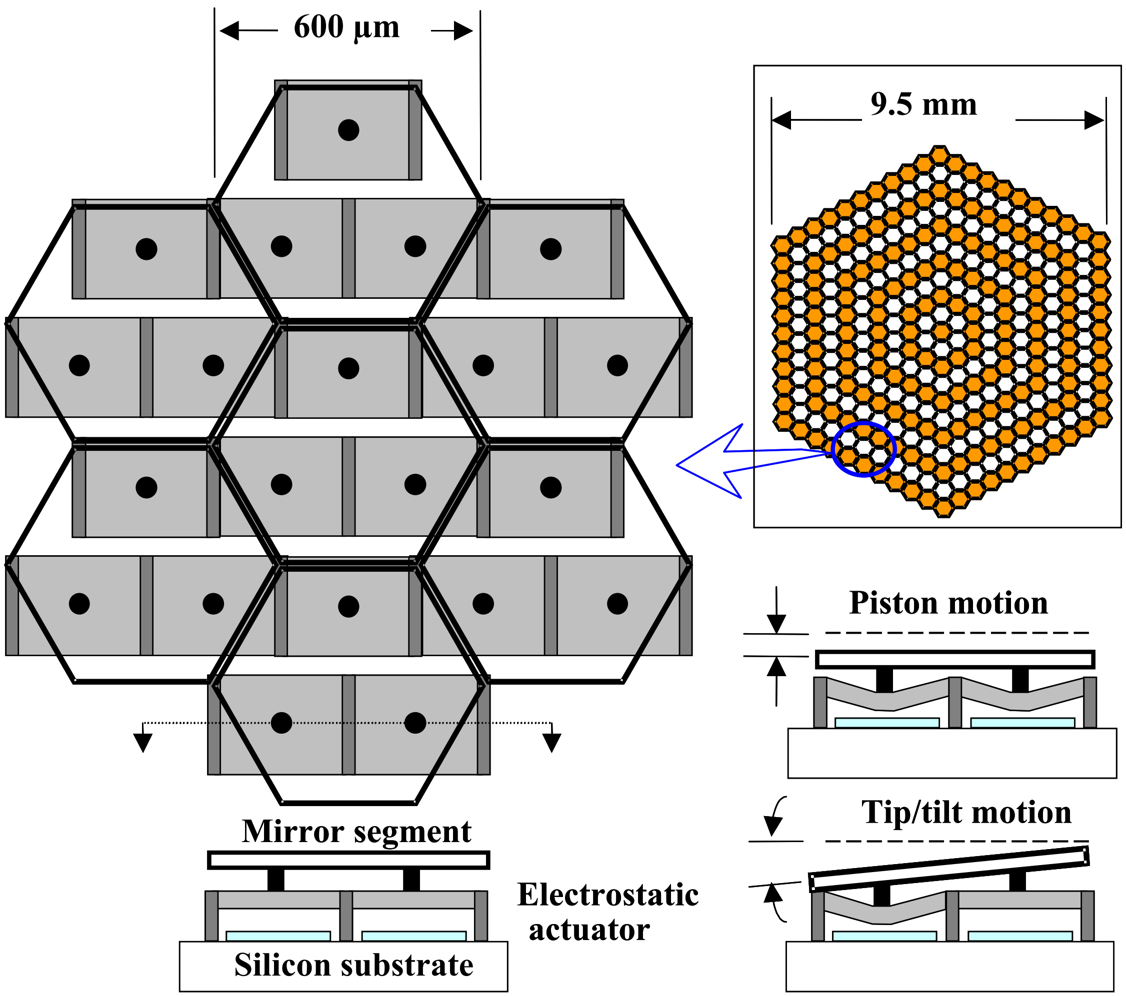
- New micromirror design has reduced print-through and limits segment bending to <1nm RMS during actuation

- Explored capability of scaling DM design to 1027-elements, as well as the use a new algorithm to perform open-loop control of mirror segments



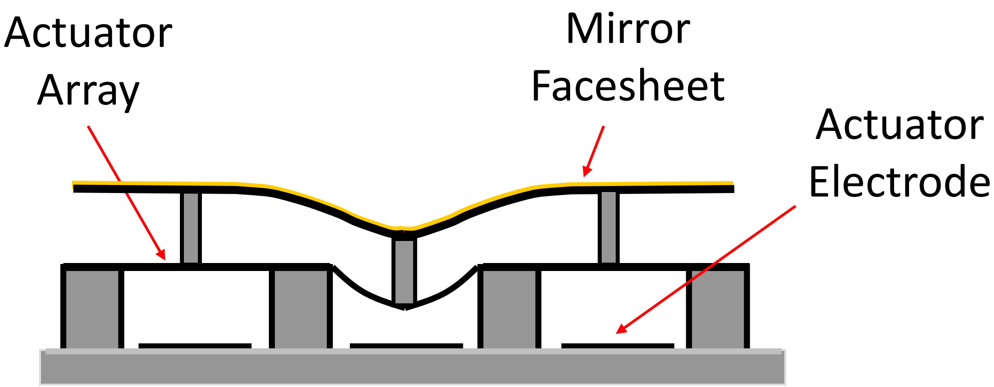
331 Element Tip-Tilt-Piston MEMS DM

- <u>Application</u>: *Visible Nulling Coronagraph*
  - DM provides instrument with phase control using piston motion and amplitude control using tip-tilt motion
  - **Requires <10nm RMS segment flatness**
- Tip-tilt-piston degrees of freedom provided by three piston-only electrostatic actuators
- <6nm RMS mirror segment flatness achieved throughout full range of motion



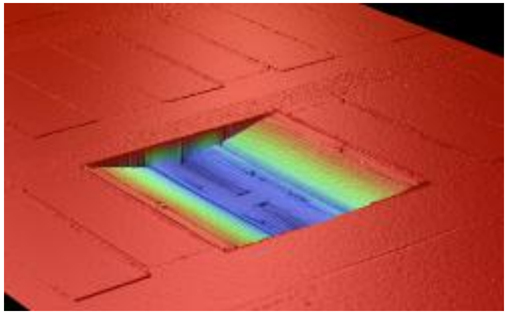
331 segments, pitch ≈ 600µm
TTP limits: +/-6mrad tip-tilt, 2um piston

BMC Deformable Mirror Architecture

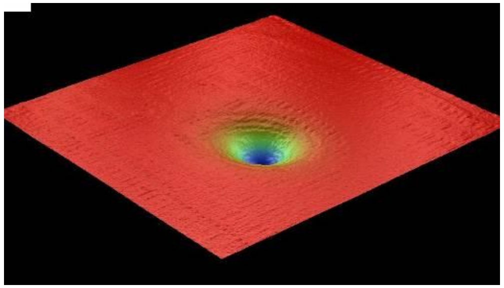


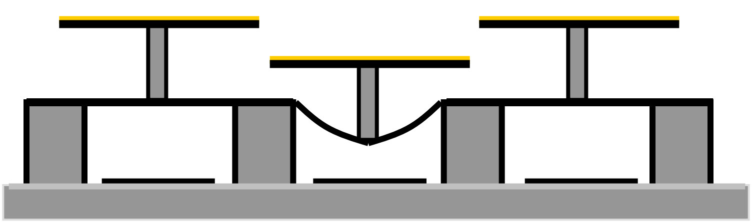
Continuous mirror (smooth phase control)

Deflected Actuator



Deformed Mirror Membrane

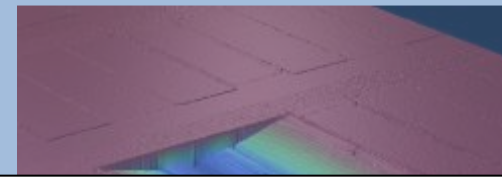




Segmented mirror (uncoupled control)

Deformed Segmented Mirror

BMC Deformable Mirror Architecture



Key Features

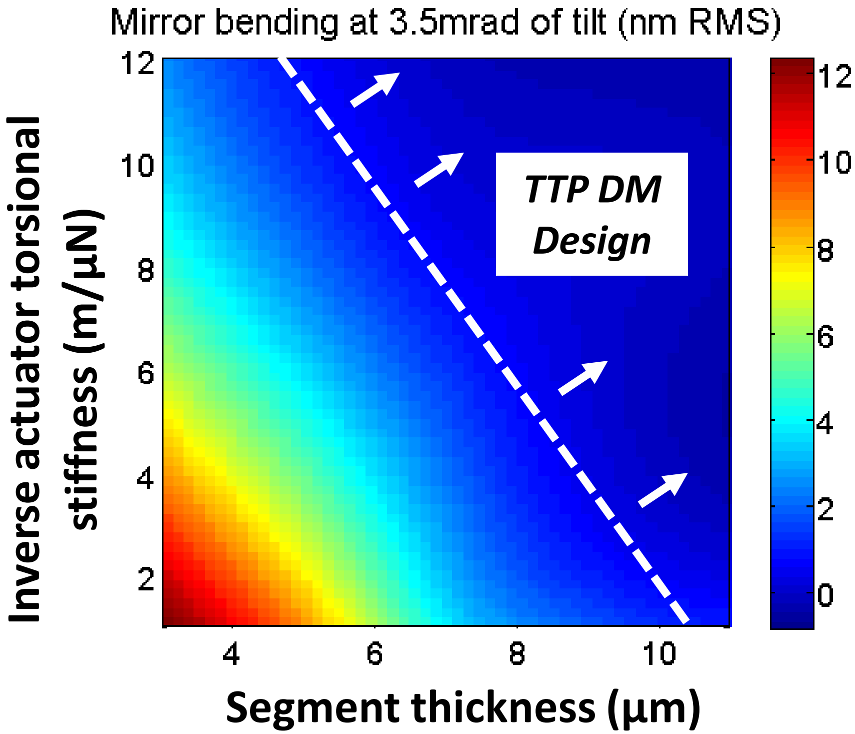
- **Electrostatic Actuation**
- **Hysteresis-Free**
- **High Speed Response**
- **Large Actuator Arrays**
- **High Spatial Resolution Control**

Segmented mirror (uncoupled control)

Fabrication of Ultra-Flat MEMS DMs

Challenges:

1. Mirror segments **bend** during actuation due applied moments from the actuator post connections
2. Mirror segments **curl** after release due to embedded stress gradients in the polysilicon layer
3. Optical quality is reduced by **print-through** of underlying layers



Solutions:

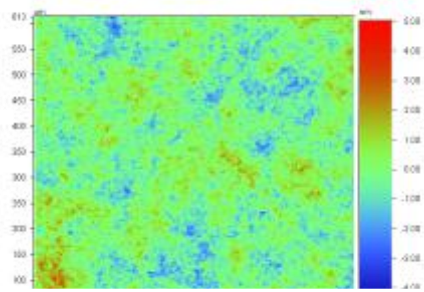
1. Bending-
   - **a) Resist** applied bending moments => increase rigidity with mirror thickness
   - **b) Reduce** applied bending moments => decrease actuator torsional stiffness
2. Counteract residual stress gradients through anneals of mirror polysilicon
3. Deposit thicker polysilicon for additional polishing to reduce print-through

Mirror Segment Design

- Use thick, eptiaxial-grown polysilicon layer (6-10µm) to achieve surface figure requirements
  - Improved polishing
  - Increase segment stiffness

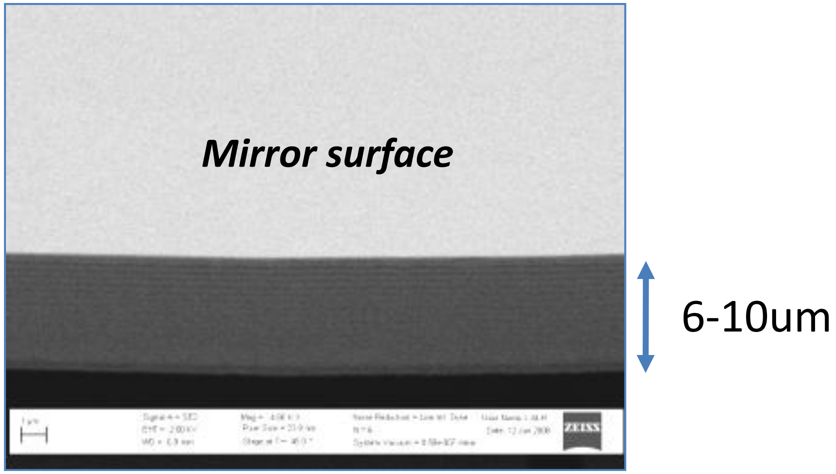
Rq = 2.3um RMS

Pre-Polish



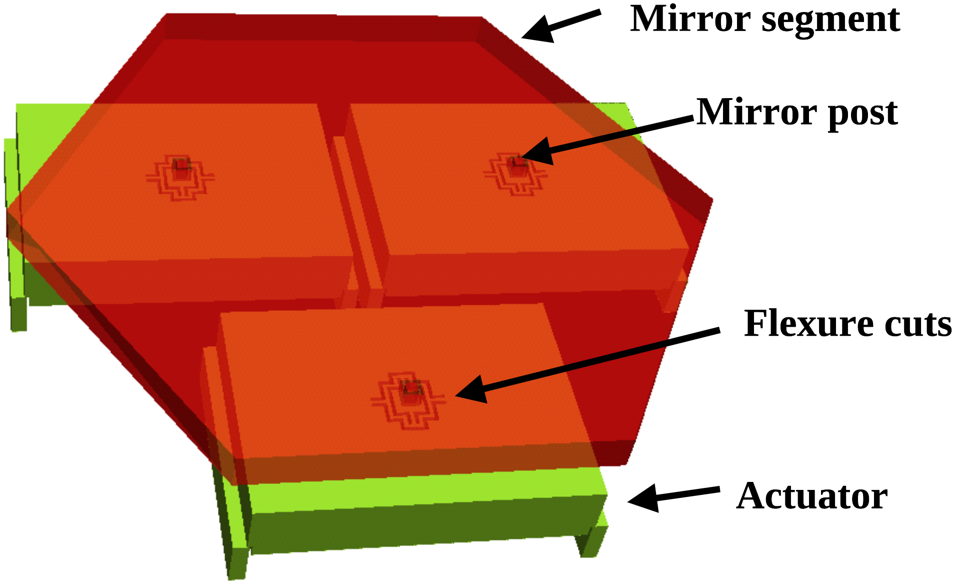
Rq = 0.8nm RMS

Post-Polish



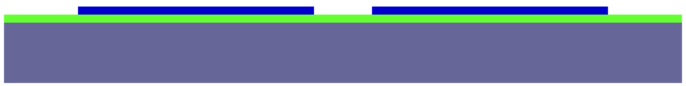
- Introduce flexure cuts around the actuator mirror post connection to reduce bending moments imparted to surface

- Torsional stiffness at the post interface is reduced by ~30X compared to conventional BMC actuator technology

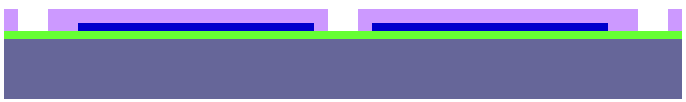


Device Fabrication Process

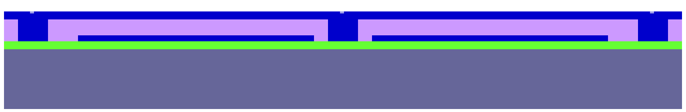
Start with silicon wafer coated with Nitride dielectric layer



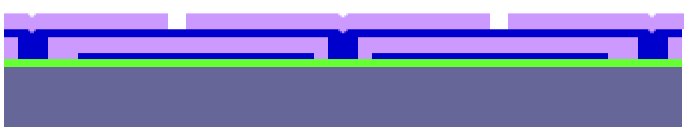
Deposit & pattern polysilicon actuator electrodes

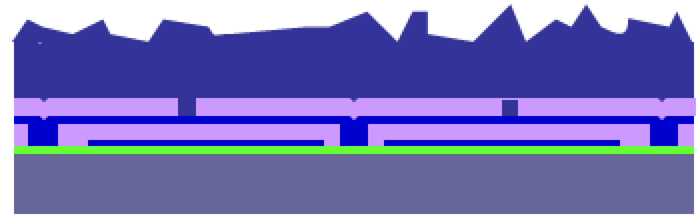


Deposit sacrificial PSG layer and pattern actuator anchors

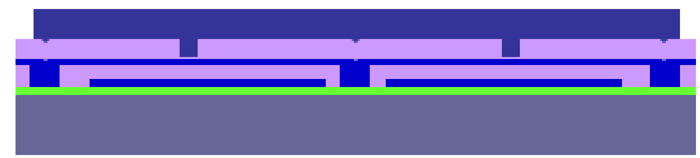


Deposit 2nd polysilicon layer to form actuators

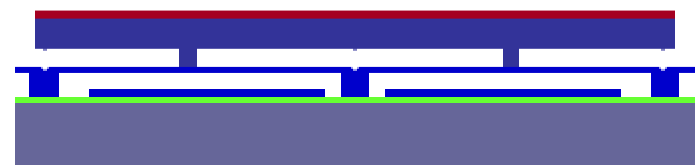




Grow thick Epi-Poly to form mirror layer



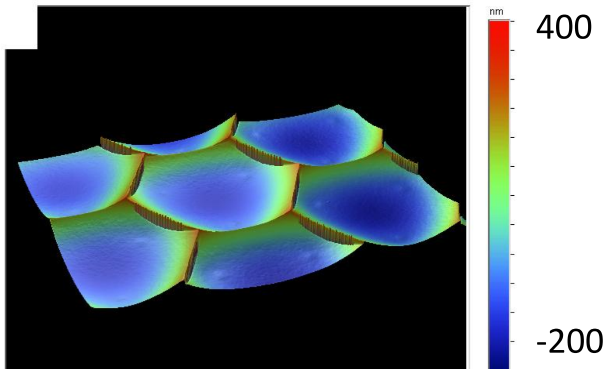
Polish Epi-Poly and pattern hexagonal mirror segments and anneal



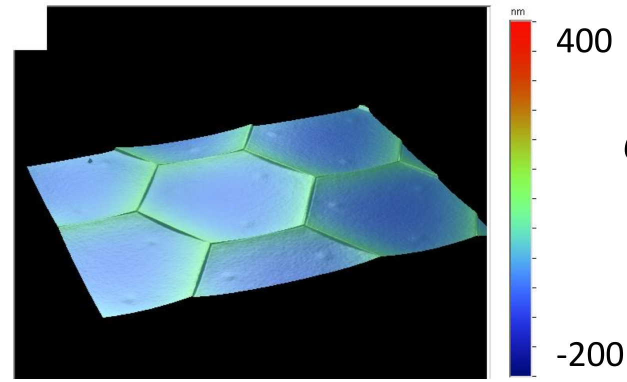
HF Release and apply reflective coating

Stress Gradient (Curvature) Control using Anneal Process

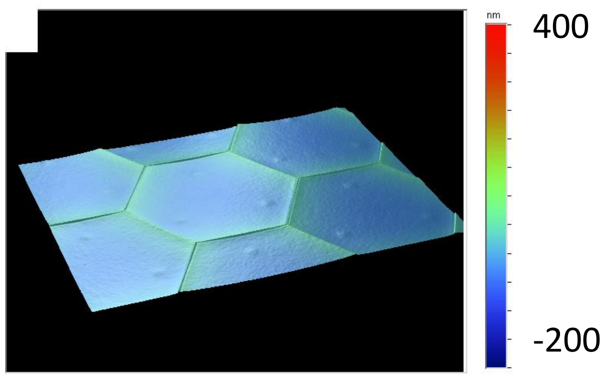
Condition I



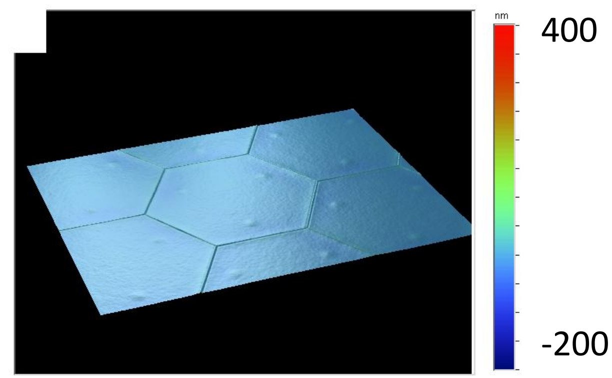
Condition II



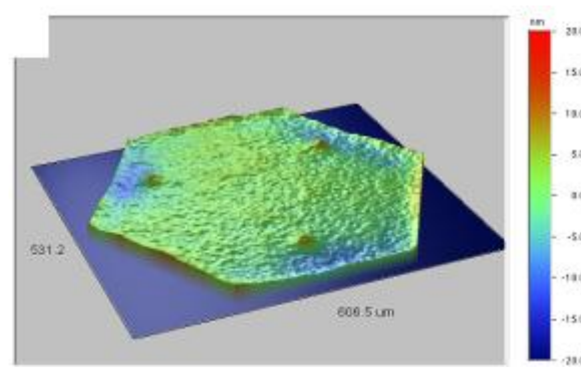
Condition III



Condition IV



2.2 nm RMS surface flatness on mirror segments achieved in Phase I

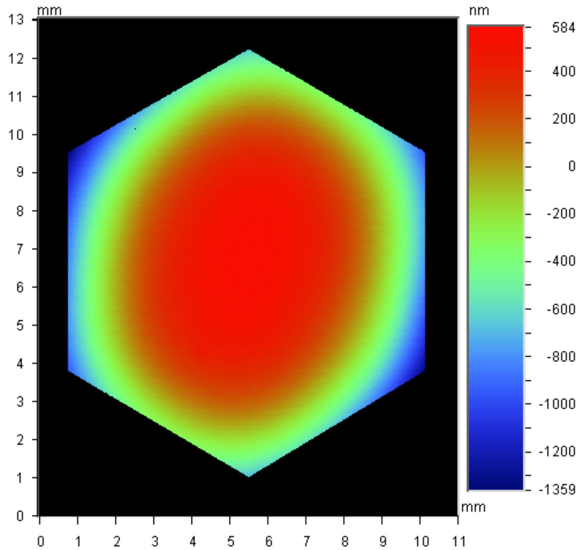


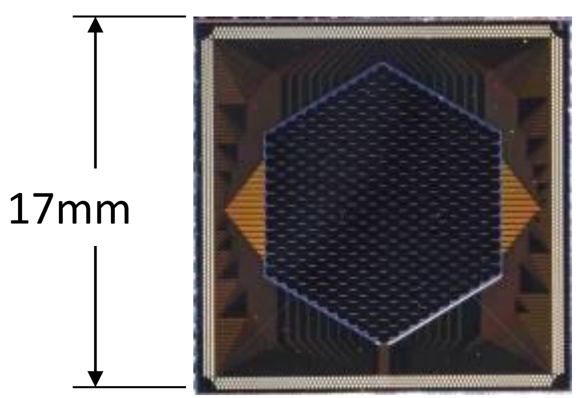
Surface Figure Results

Full DM Aperture

9.8m ROC over aperture (unpowered)

Curvature can be removed using DM actuators



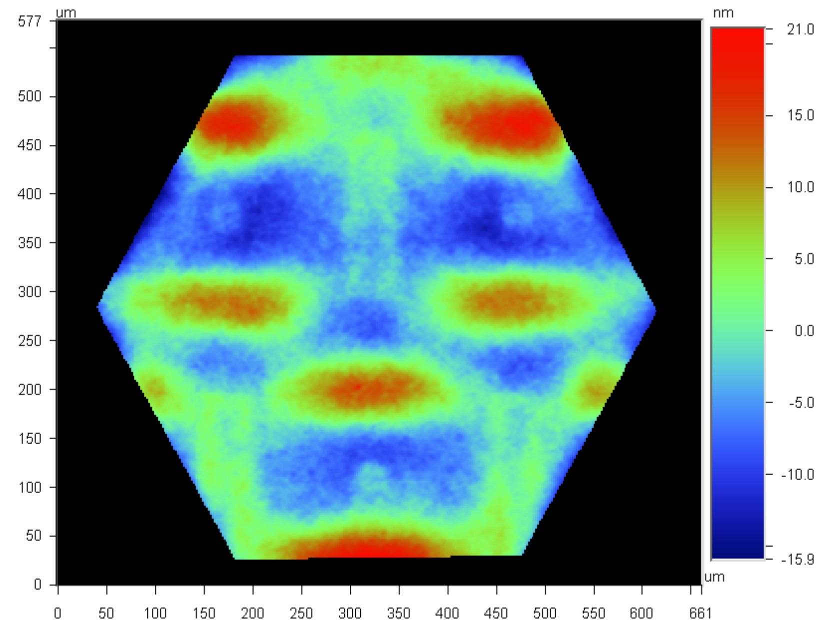


Die Dimensions

Single Mirror Segment

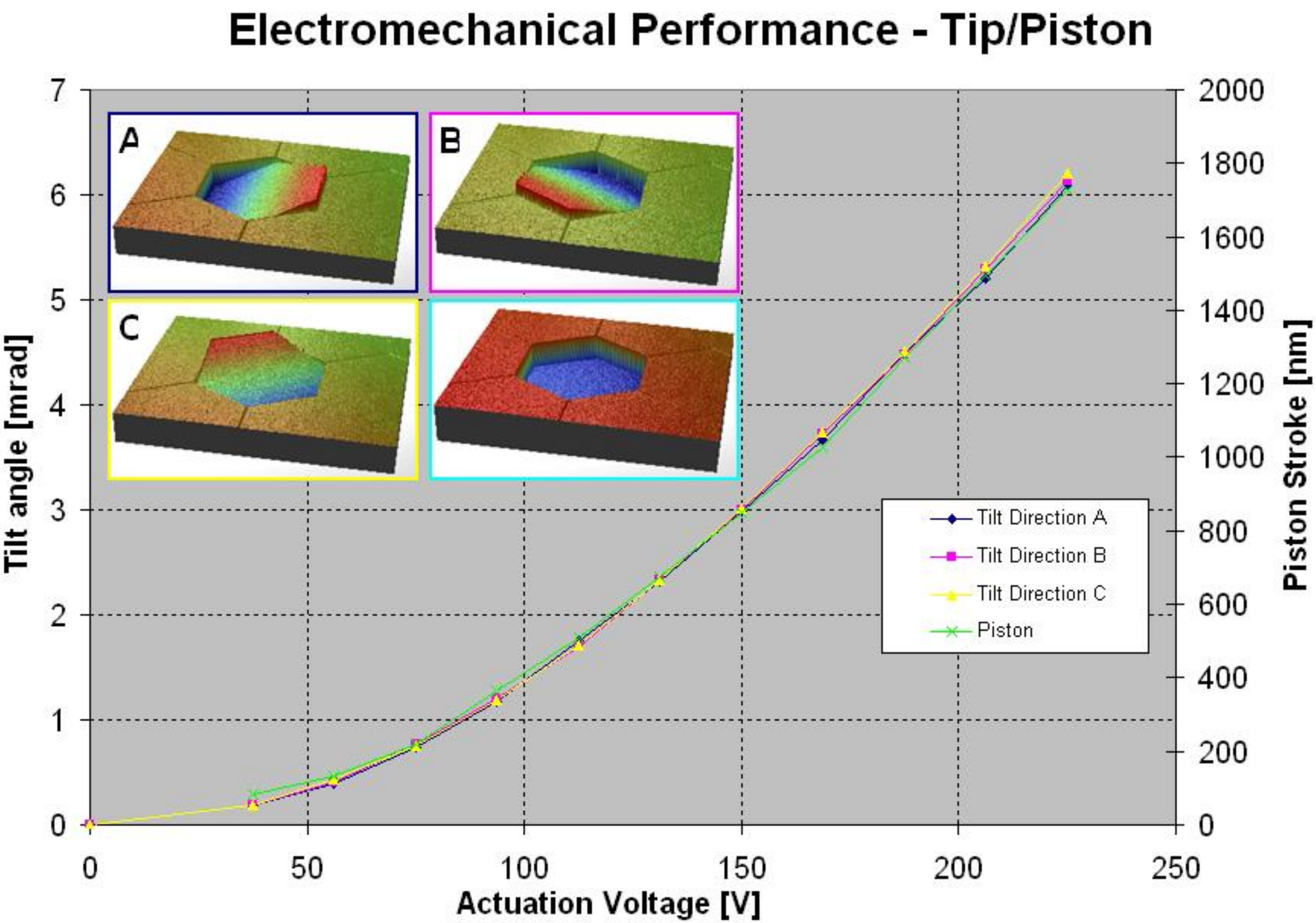
5.9 nm 0.2nm RMS over DM aperture

Flatness of segment below = 5.2nm RMS



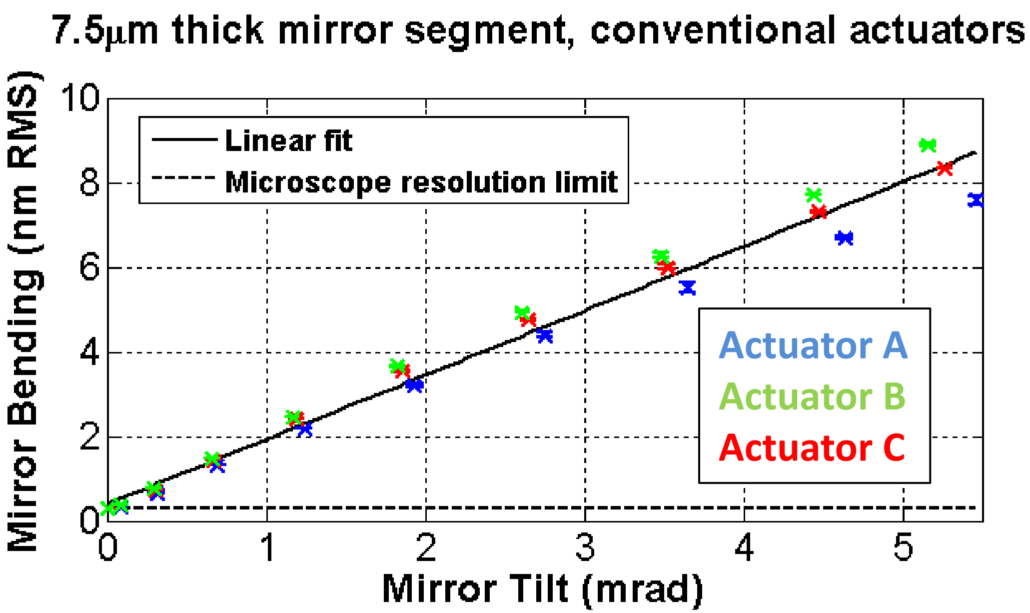
Actual Segment Thickness: 7.5mm

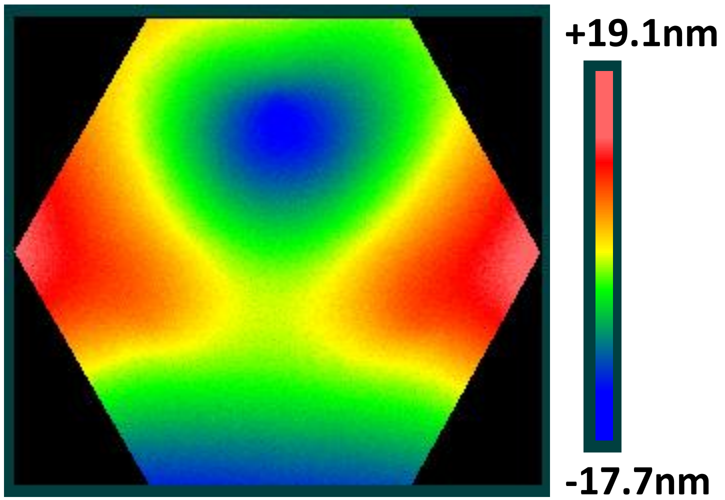
Target Thickness = 9µm



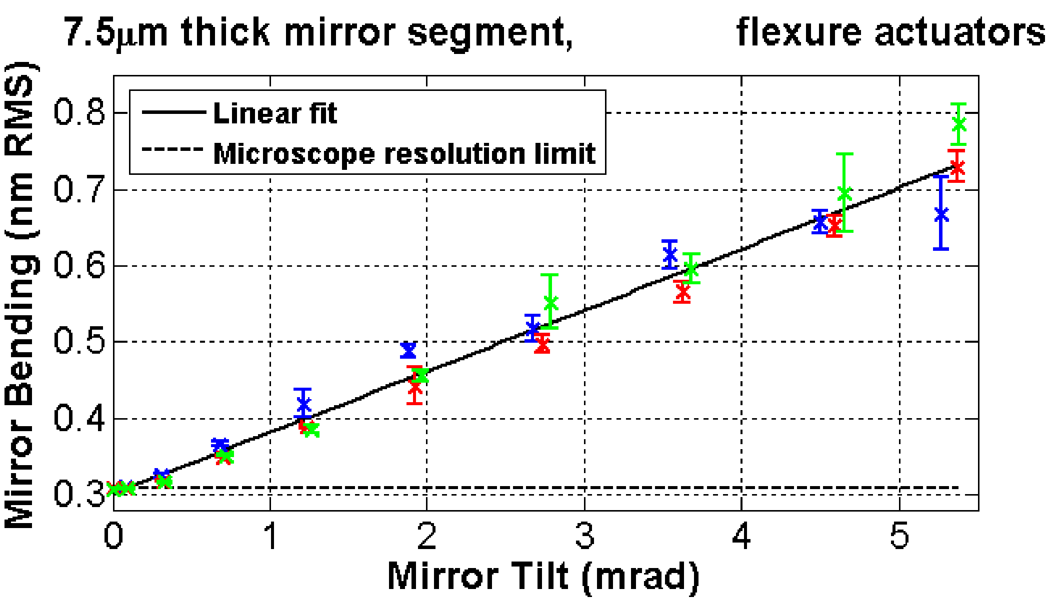
Electromechanical Performance - Tip/Piston
A
B
C
Tilt angle [mrad]
Piston Stroke [nm]
Actuation Voltage [V]
Tilt Direction A
Tilt Direction B
Tilt Direction C
Piston
0
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
50
100
150
200
250

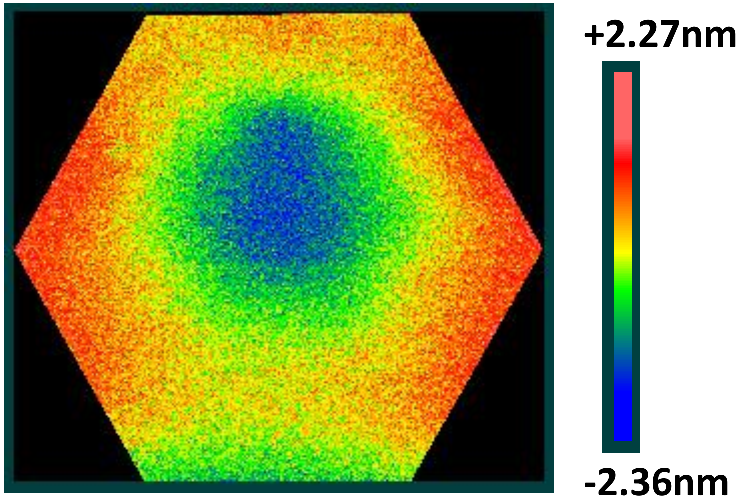
Mirror Segment Bending Results





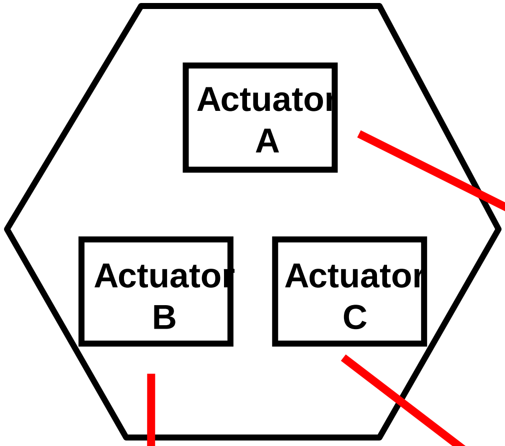
5.5mrad tilt
7.6nm RMS bending

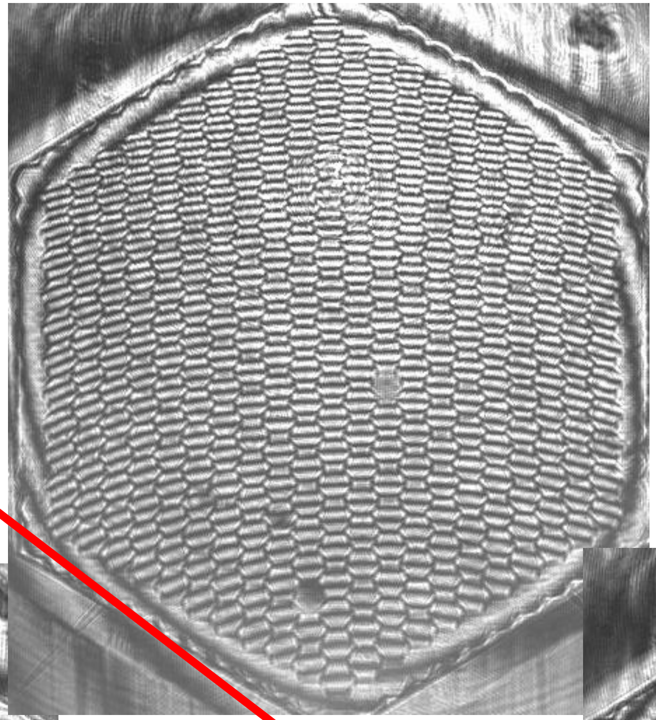




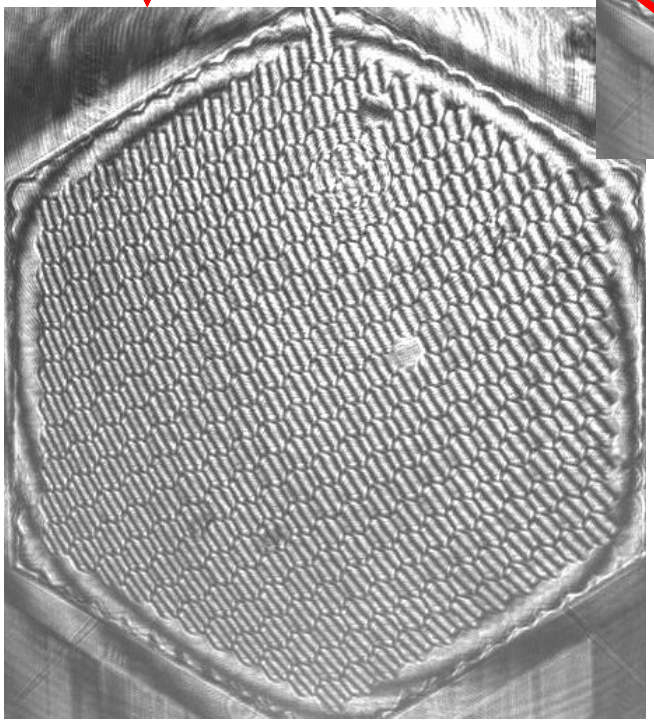
6mrad tilt
0.68nm RMS bending

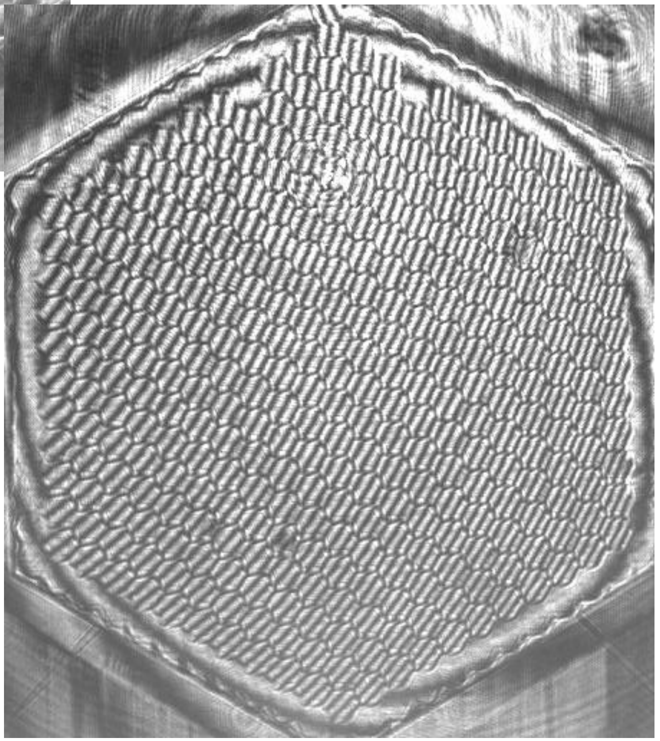
Device Yield





5 anomalous actuators on first tested device (99.4%)

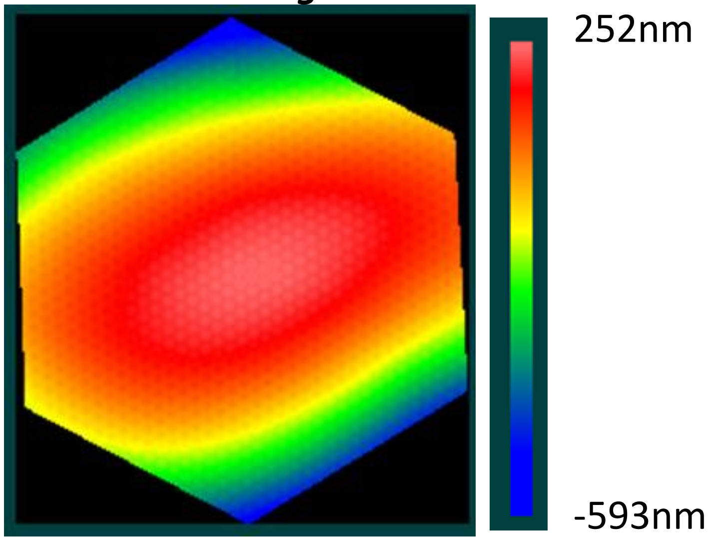


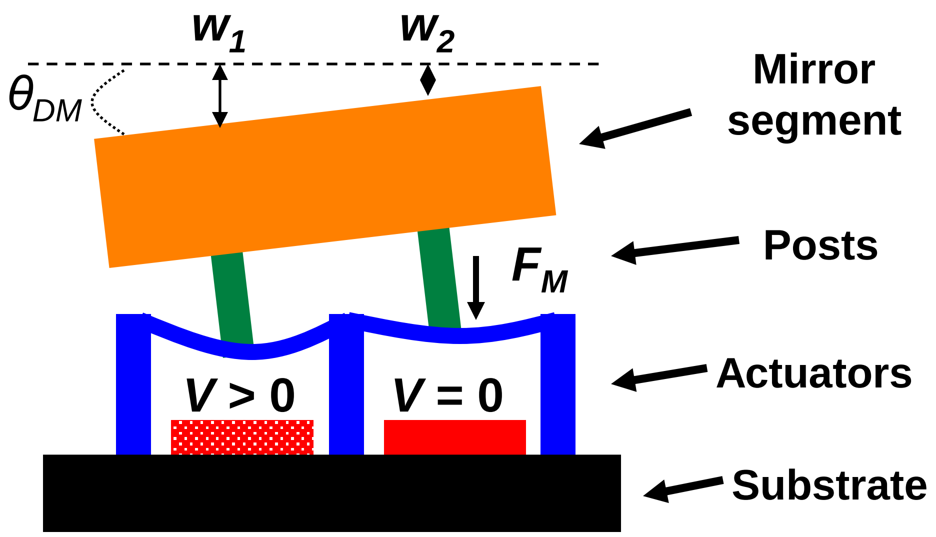


Exploratory Work for 1027-element TTP DM

- The Epi-Poly deposition process (only) has also been scaled to hexagonal arrays of 1027-elements with similar success, achieving <10nm RMS mirror segment flatness
- The extension of an open-loop control algorithm developed for continuous-facesheet DM technology [1] is being explored for the TTP DM
  - Combines analytical model describing actuator mechanical coupling with empirical model describing actuator deflection to predict voltages

Array of 1027 Epi-Poly Hex Mirror Segments



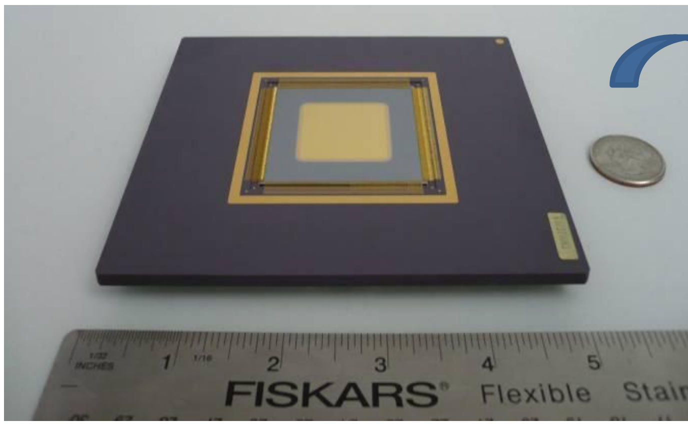


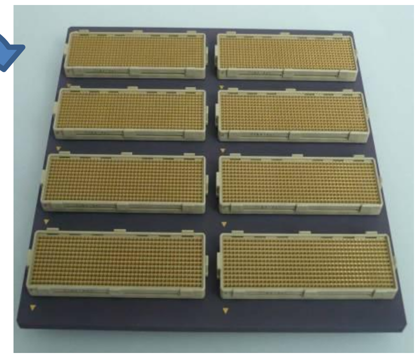
*[1] J. B. Stewart, A. Diouf, Y. Zhou, and T.G. Bifano, "Open-loop Control of a MEMS Deformable Mirror for Large Amplitude Wavefront Control," JOSA – A **24**(12), 3827-3833 (2007)*

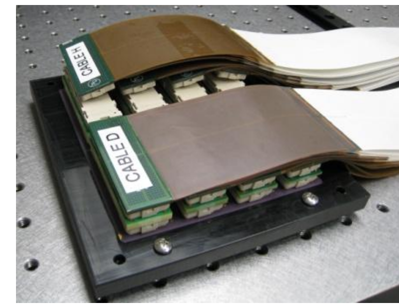
Packaging and Electronics for a 1027-element TTP DM

- A larger 1027-element TTP DM is needed for the visible nulling coronagraph instrument
- BMC has developed packaging & electronics for DMs with up to 4096 connections

BMC 64x64 continuous surface DM







DIO Interface	32-bit LVDS (200 MB/s)
Interface HV	16x 300pin Megarray (4096 channel)
Form factor	3U Chassis (5.25” x19” x14”)
Frame Rate	34 kHz / 60 kHz (Low Latency)
Cross-talk	< 1% peak amplitude
Power draw	40W
Current limitation output	0.7 mA max.
Maximum Output voltage	285V
Resolution	14-bit

4096 High Speed Driver Electronics

Acknowledgements

- Funding from NASA/JPL SBIR Phase II #NNC07CA31C

- Boston University Photonics Center

Thank you!!

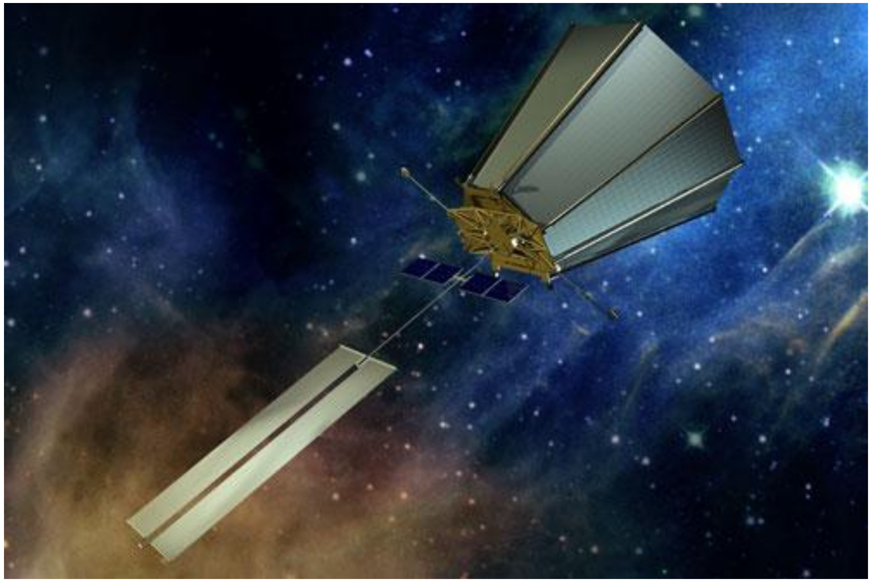
Extra slides…

Applications

- NASA's Terrestrial Planet Finding Mission – The Visible Nulling Coronagraph (VNC)
  - Demands control of wavefront phase and amplitude to achieve high contrast imaging of extrasolar planets
- Extremely Large Telescope (ELT) Wavefront Sensing
  - Large primary mirrors are capable of resolving depth of Laser Guide Stars (LGS), creating blur in AO wavefront sensors (WFS)
  - Demands dynamic wavefront tilt control

Application: The Visible Nulling Coronagraph

- The VNC is a competing architecture for NASA’s Terrestrial Planet Finder (TPF) Coronagraphic Imaging Observatory, which aims to find and study Earth-like extrasolar planets
- For successful planet imaging in the visible, the observatory must suppress parent starlight by ~10^{10}
- The nulling coronagraph architecture blocks starlight using a combination of interference and spatial filtering



NASA’s TPF Coronagraphic Imaging Observatory

Application: The Visible Nulling Coronagraph

- Starlight located on the telescope axis is destructively interfered; off-axis planet light is not
- To deepen the starlight null, the TTP DM controls subaperture wavefront phase using piston motion and amplitude using tip-tilt motion