Advances in Telescope Technology: Mirror Alternatives for the Far IR

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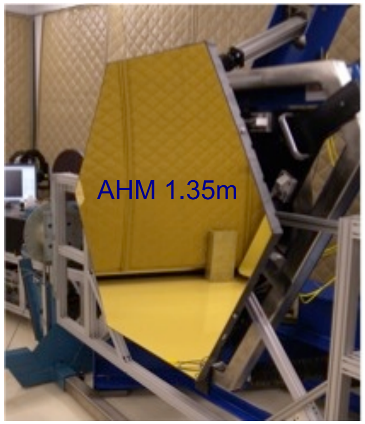
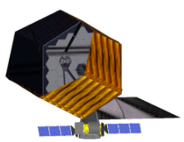
Silicon Carbide Primary Mirrors

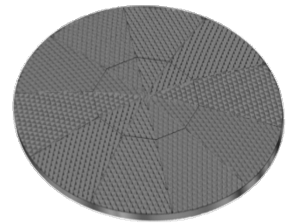
Actuated Hybrid Mirrors (AHMs)

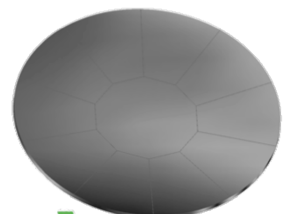


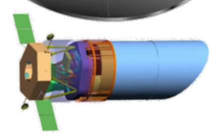


- 0.5 to 1.35 m size demonstrated
- <14 nm rms SFE demonstrated
- <10 Å microroughness (projected)
- 10-15 kg/m^2 substrate
- <25 kg/m^2 total
- Active mirror
  - 37 to 414 actuators
  - Solid state, integrated into SiC substrate
- Testable in 1G to 0G specs
- Made by replication

Superpolished Si/SiC Mirrors (SSMs)







<u>Proposed 4m class mirror</u>

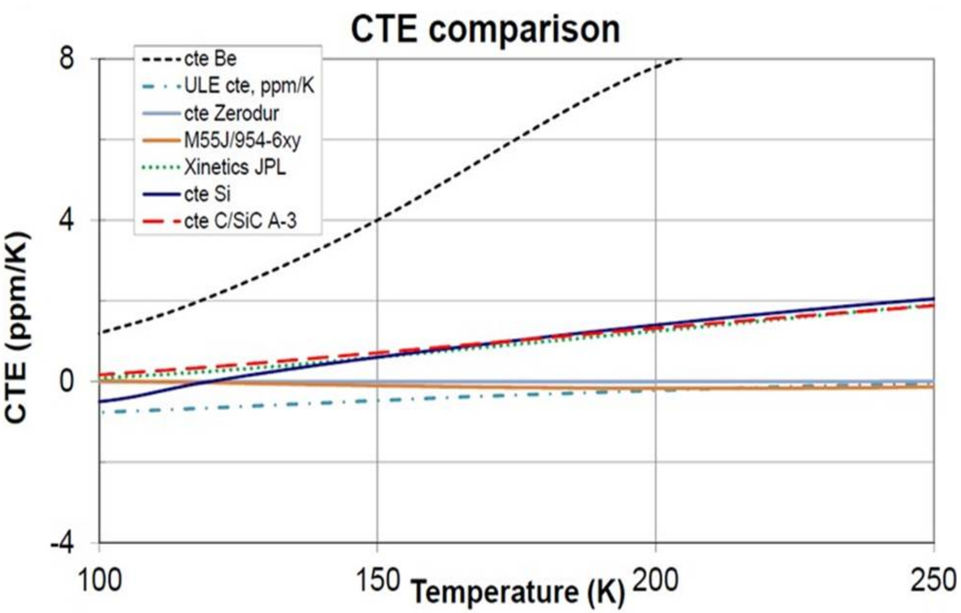
- Passive or active
- Made by casting, joining, cladding and polishing
- Si clad SiC
- <14 nm rms SFE (projected)
- <5 Å microroughness (projected)
- <25 kg/m^2 total
- If active:
  - 0 to 10,000 actuators
  - Solid state, integrated into SiC substrate
- Active version is testable in 1G to 0G specs

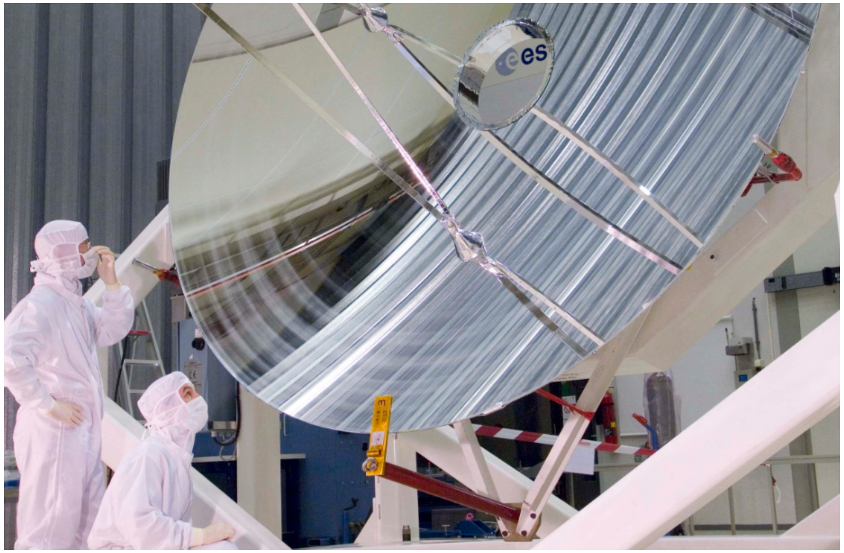
- **Silicon carbide (SiC) has superior stiffness, strength, and thermal properties, making it well suited for space optics**
- **"Actuated Hybrid Mirrors" (AHMs), made by replication using SiC substrates, provide an active option for mirrors up to 1.5 m**
- **"Superpolished Si/SiC Mirrors" (SSMs) use SiC substrates that can be joined, then clad with Silicon, and then polished, for passive or active mirrors**

Silicon Carbide (SiC) for Mirrors

- **SiC has many good properties**
  - Stiff for the weight
  - Robust
  - High thermal conductivity
  - Polishable to <20Å (unclad), and to 2 Å (Si clad)

Property	Units	Aluminum	Beryllium	SiC	ULE	Desire
ρ, Weight	g/cm3	2.71	1.85	2.95	2.21	Low
E, Stiffness	GPa	68.3	303	364	67.6	High
E/ρ,Specific Stiffness	KN-m/g	25	164	123	31	High
σ/ρ, Stress Loading	N-m/g	46	11	24	3.2	High
α,Thermal Soaks	ppm/°C	22.7	11.4	3.38	±0.03	Low
Δα Homogeneity	ppb/°C	100	100	30	10	Low
K/α, Thermal Gradients	MW/m	6.9	19	51	44	High
K/rCp,Thermal Diffusivity	m2/s	6.55	6.07	8.7	0.08	High
K/αE, Thermal Stress	MW-m/N	101	63	140	646	High





- **The ESA Herschel 3.5 m Primary Mirror (PM)**
  - Multiple segments joined by brazing

Cryo Mirror Substrate Materials

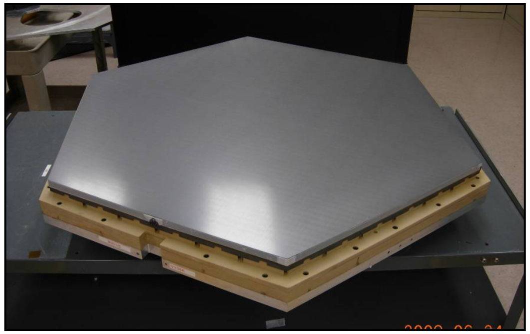
- **Beryllium – proven but very slow and expensive (JWST mirrors took 10 years to make)**
  - Precision metallurgy required to avoid thermal and mechanical hysteresis
  - Machining and polishing brings difficulties – poisonous dust, e.g.
  - High CTE at warmer temperatures necessitates cryo-null figuring
- **Aluminum**
  - High CTE at warmer temperatures necessitates cryo-null figuring
- **Glass – ULE, Zerodur, Borosilicate**
  - Low CTE at warmer temperatures, not lowest at cryo though
  - Space qualified mirror sizes < 2.4 m (Hubble)
- **Composite/CFRP**
  - Near-zero CTE from warm to cold temperatures can be achieved
  - Material creep issues probably means mirror must be actuated
  - Surface quality may be a challenge

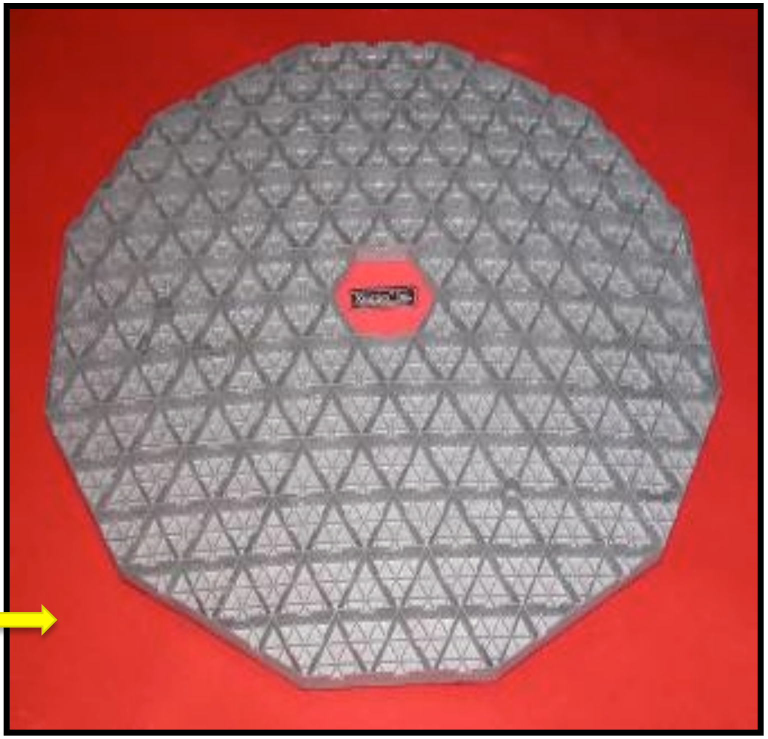
Cryo Active SiC Mirrors

- **Replace cryo-null figuring with actuators**
  - Fabricate and test at warm temperatures, in 1G, to spec performance
  - Use actuators to compensate cool-down figure changes (and most other optical errors system-wide)
- **Reduce mission cost**
  - By reducing mission mass
  - By relaxing fabrication and assembly tolerances
  - By reducing or even eliminating cryo testing
  - By speeding up I&T
  - By reducing mirror cost
- **Reduce mission risk**
  - Correct nearly any optical errors that might arise on orbit
  - SiC materials are more resilient than glass, lowering risk of failure

Ceraform Silicon Carbide

- **AOX Ceraform SiC:**
  - Fugitive core foam mold created by CNC machining
  - SiC nanopowder slip fills mold
  - Part is freeze-dried
  - Mold core is leached out
  - First firing creates green state “prefired” part
  - Part is machined
  - Second firing to full hardness
- **Final rough grind of SiC front surface matches the curvature of the mandrel/nanolaminate to ±5 um**

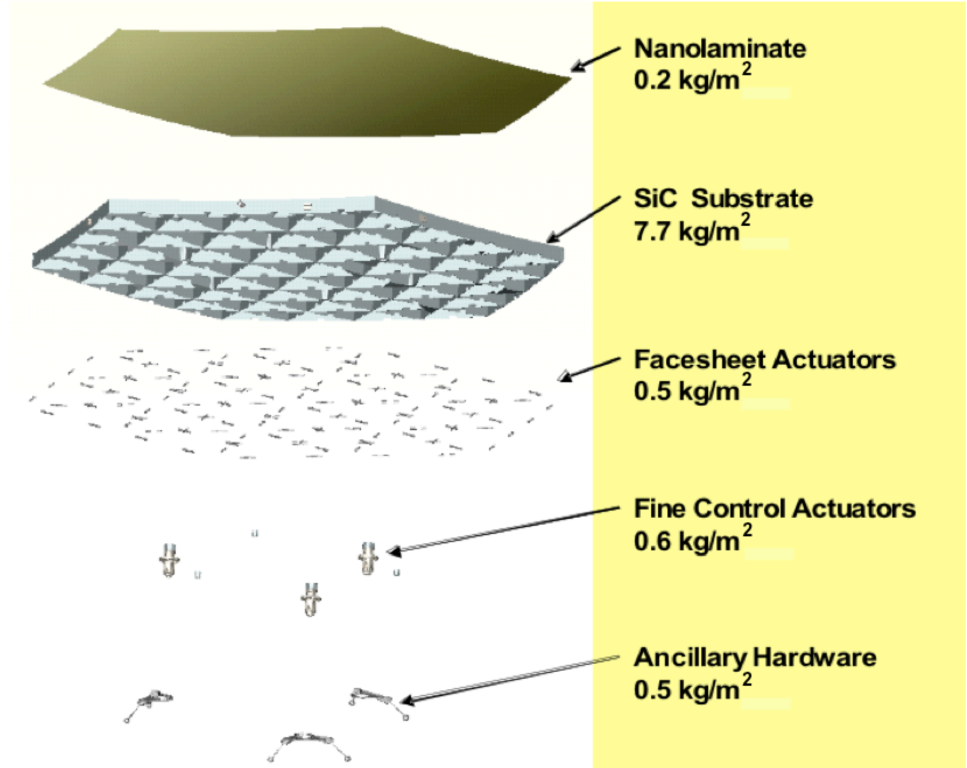




Typical finished substrate

Actuated Hybrid Mirrors (AHMs)

- **AHMs are large mirrors**
  - PMs or PM segments
  - Made by replication
- **Nanolaminate facesheet**
  - Multilayer metal foil, made by sputter deposition on a super-polished mandrel
- **SiC substrate**
  - Reaction-bonded Ceraform SiC is cast in a mold, fired, then bonded to facesheet
- **Electroceramic actuators**
  - Surface-parallel embedded actuators give large stroke and high accuracy, by design



- **AHMs are low mass and high strength**
  - Areal density < 25 kg/m^2 including electronics for meter-class AHMs
- **AHMs are made by replication for high optical quality and low cost**

Polished SiC Active Mirrors

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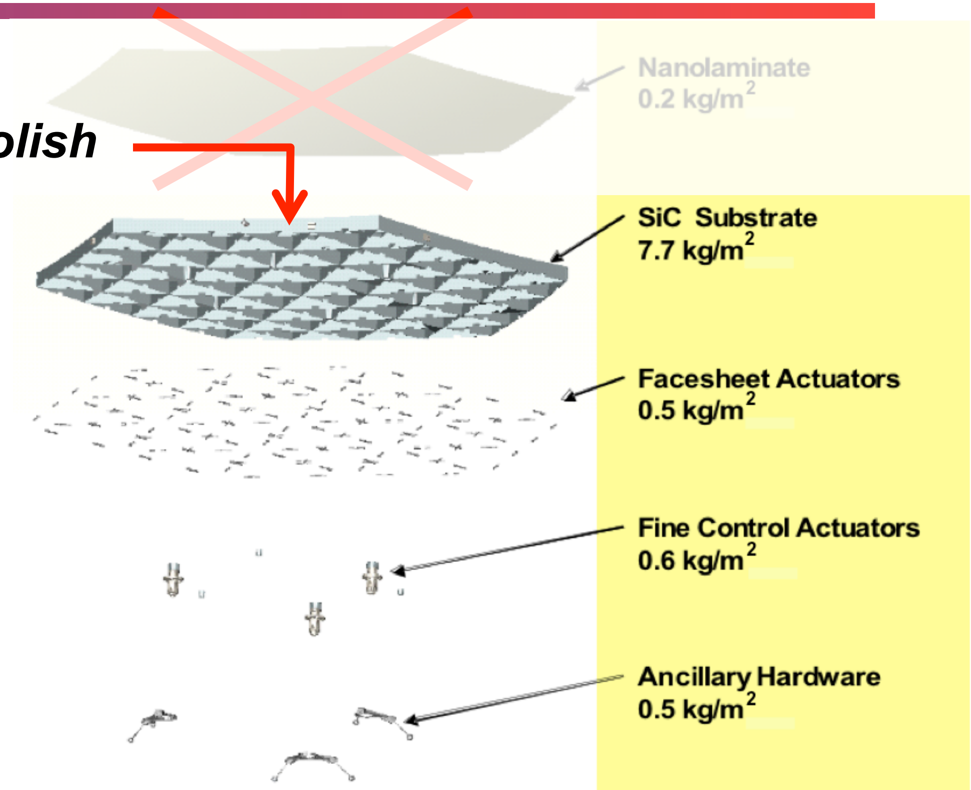
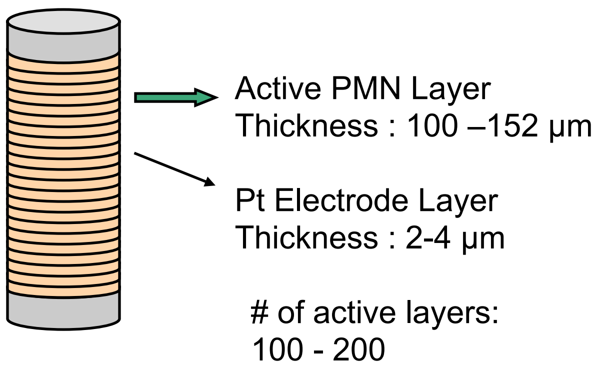
Direct polish

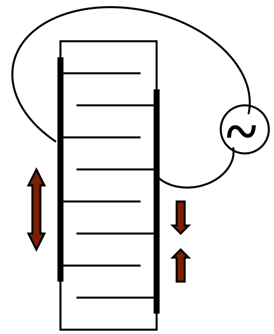


Actuators

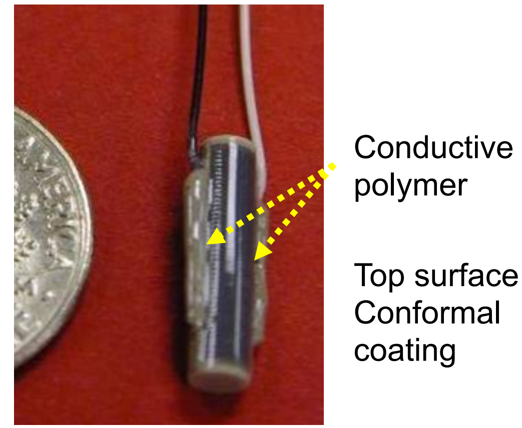
Sintered body



Electrical Connection (conceptual)



XiRE 0313 Photo, XiRE 0416 similar



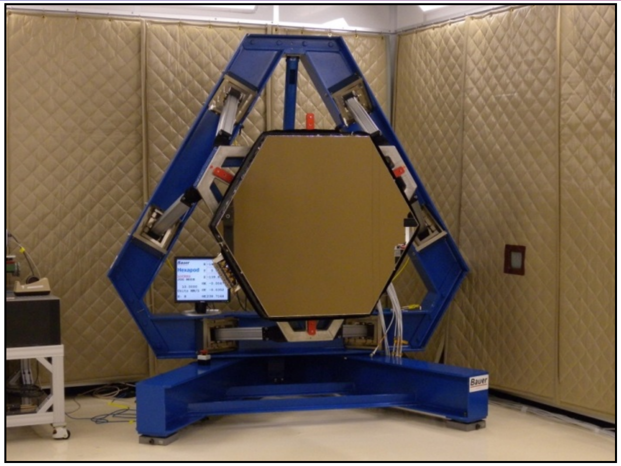
- **AOX actuators use PMN-PT electrostrictive ceramics**
  - Multiple layers of ceramic and conductive electrode are co-fired to form a solid body
  - Conductive polymers for external electrode and wire bonding (no soldering)
  - Conformal insulating polymer coating
- **High stroke, low voltage**
  - ±2.5 um stroke at 20C
  - 0-100V operating range
- **Used for astronomical Deformable Mirrors**
  - High reliability

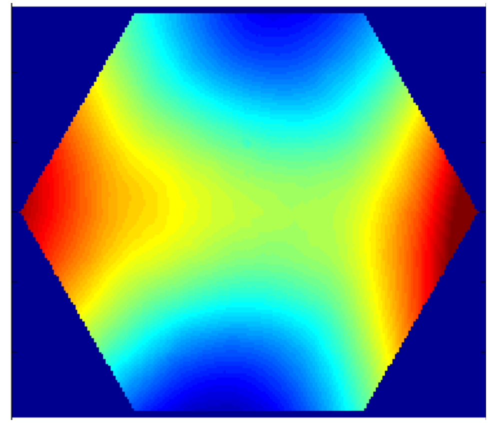
Actuator with Mounting Tabs

Cryo Mirror Actuators

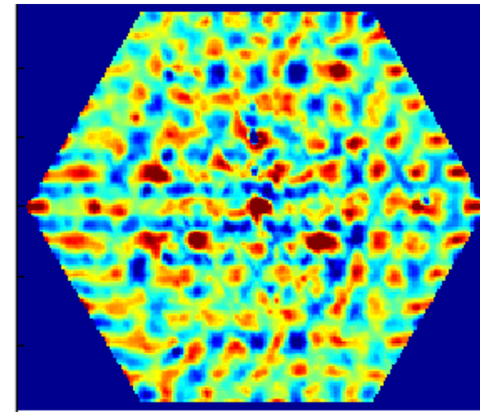
- **Piezoelectric cryo actuators**
  - Excellent strain at 20C, drops significantly going to <25K
  - Can explore poling strategies to reset the 0-volt strain state at target temperature...
- **Electrostrictive cryo actuators**
  - PMN/PT, single-crystal shows wide actuation range, with strain dropping 5x from room temperature to 77K (ref. Jiang et al)
  - Other materials provide significant strain at cryo, not so much at ambient (ref. Xinetics SBIR-II report)
  - Decreased strain could be compensated: by taller stacks of thinner layers in multi-layer actuators; or by mechanical amplification; or...
- **Magnetostrictive cryo actuators???**
- **Athermalization is needed, to compensate actuator/substrate CTE mismatch**
  - Athermalizing actuator mounting structures: bi-metallic effect
  - Voltage bias for warm ops, to provide 0V bias for cold ops

AHM Closed Loop Optical Performance



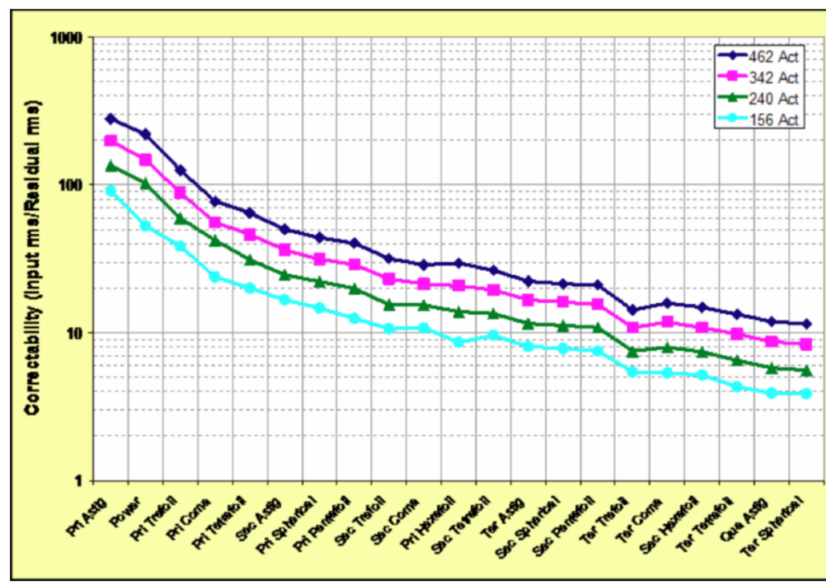


SFE = 1.88 µm RMS



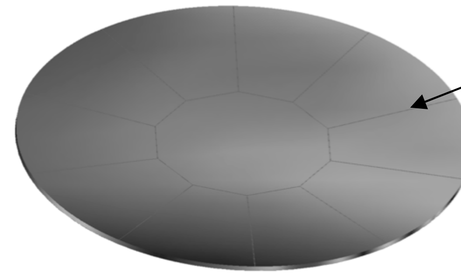
SFE = 0.014 µm RMS

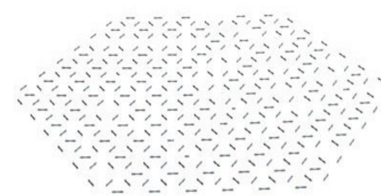
- Wavefront sensing and control technology to command the embedded solid-state actuators gives the active SiC mirror the ability to correct nearly any optical error, occurring anywhere in the optical system
  - Allows relaxation of fabrication and assembly tolerances from optical to mechanical levels, speeding I&T
  - Enables rapid system testing to within required performance levels, even in 1 G, lowering mission risk
- AHMs and active SSMs mirrors can reduce cost, risk and schedule for future astrophysics missions



Polished SiC Mirrors

- **Polished SiC mirrors for use in space telescopes**
  – *Passive* (no actuators): polished to final figure
  – *Active:* high WF control range and accuracy
- **Leverage AHM technology elements**
  – Lightweight SiC substrate with high stiffness and strength
  – Surface Parallel Actuation with solid-state actuators integrated into SiC rib structure
- **Technical objectives**
  – Growth to 4 m size class
  – 1 um rms SFE at cryogenic temperatures
  – Active to avoid cryo-null figuring
  – <20 Å microroughness
  – 25 kg/m^2 substrate, and 30 kg/m^2 total mass areal density (with elex, actuators, etc.)
  – Testable over wide temperature range
  – Testable in 1G to 0G specs if active





SiC Joining Methods

- **Brazing is a lower-temperature approach to joining large SiC segments**
  - Reactive and non-reactive methods are available
  - Introduces small amounts of non-SiC material
  - Excellent joint surface quality and substrate strength can be achieved
- **SiC Interlayer Joining requires higher temperatures and a vacuum furnace**
  - Can produce isotropic SiC structures, with no discernable joint
  - Excellent substrate strength
- **Companies with joining experience:**
  - BoosTek (Herschel PM) and CoorsTek
  - Ceramatec
  - AOA Xinetics

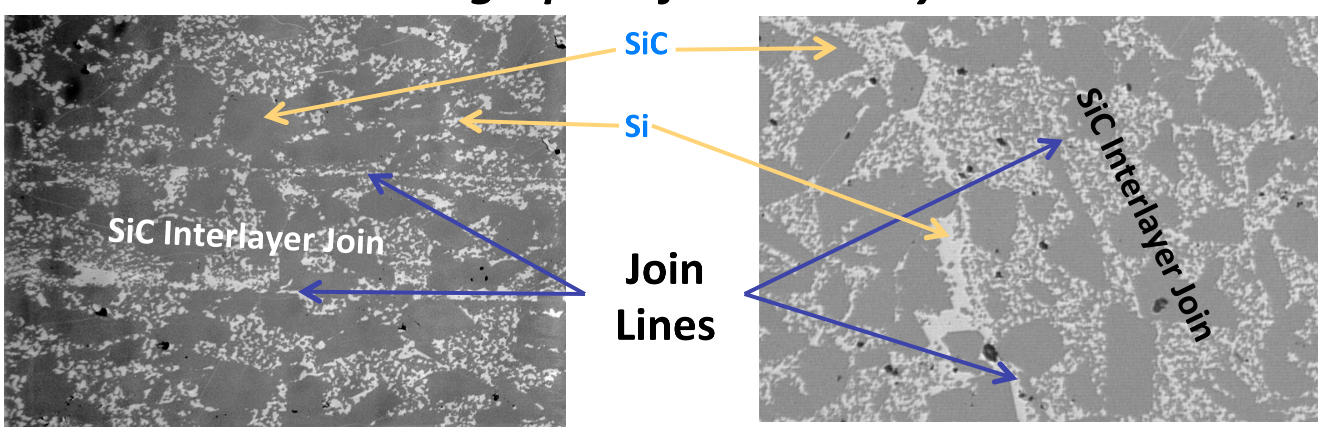
SiC Substrate Interlayer Joining

- **SiC mirrors can be made from multiple substrates that are joined together**
- **Requirements for joining**
  - High strength
  - Thermal stability
  - Polishability across bond joint
  - Process scaling to 4m and larger

Metric	Value	Comments
Joint Thickness	5-600 microns	Demonstrated.
Joint Bending Strength	80% of monolithic SiC	Demonstrated.
Joint Shear Strength	80% of monolithic SiC	Demonstrated.
Joint Surface Quality	No voids	Assured by filling and refiring before silicization.
Joint Surface Continuity	<30Å step discontinuity	Measured after surface generation.
Joint Length	30 cm scalable to 4 m	Need to demonstrate.

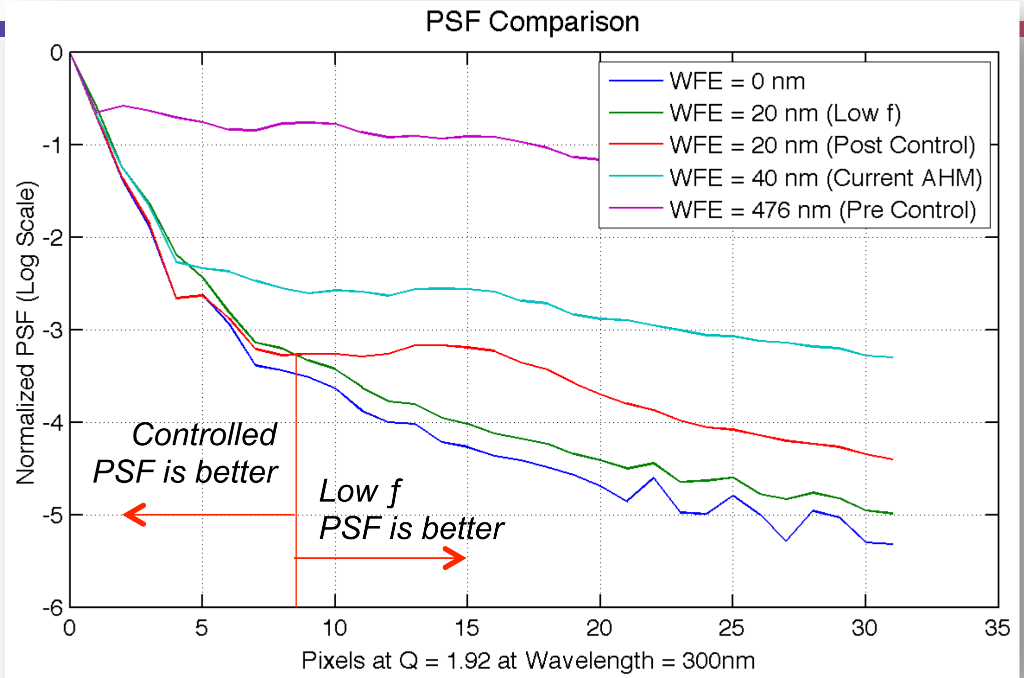
- **SiC Interlayer Joining**
  - Separate segments are prefired, and then joined using a special SiC slip material
  - A second prefiring creates a monolithic structure
  - Final siliconization firing at high temperature hardens and fully densifies the mirror
  - Final join surfaces can be polished without any discontinuity

Photomicrographs of SiC Interlayer Joins



- Unpolished, as-cast surfaces following siliconization firing
- Join width ≅ 0.5 mm

Active Mirror PSFs



Simulated PSFs for a UV telescope, nominally:

- PSFs assessed at 200 nm wavelength
- Detector is critically sampled at 300 nm wavelength
- 400 actuators for control case
- WFE as shown

- **AHMs and active SSMs, like Deformable Mirrors generally, have a different distribution of WFE vs. *f* than conventional optics**
  - Lower error in the low spatial frequencies
  - Higher error at and beyond the actuator spatial frequency
- **This results in a tighter PSF core, but a raised "halo" in the PSF sidebands**
  - Resolution vs. contrast – choice drives actuator density