Lightweight and High-resolution Astronomical X-ray Optics Using Single Crystal Silicon

William W. Zhang

NASA Goddard Space Flight Center

Next Generation X-ray Optics Team

K. D. Allgood[1], M.P. Biskach[1], K.W. Chan[2], J.D. Kearney[1], J.R. Mazzarella[1], R.S. McClelland[1], A. Numata[1], L.G. Olsen, R.E. Riveros[2], T.T. Saha, M.J. Schofield[1], M.V. Sharpe[1], P.M. Solly[1], W.W. Zhang

NASA Goddard Space Flight Center

[1] Stinger Ghaffarian Technologies, Inc.

[2] University of Maryland, Baltimore County

J.M. Carter, J.A. Gaskin, W.D. Jones, J.J. Kolodziejczak, S.L. O'Dell

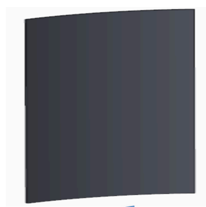
NASA Marshall Space Flight Center

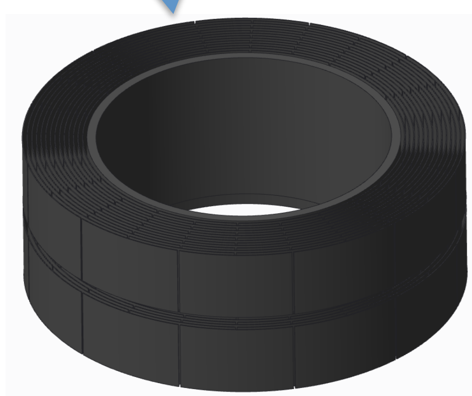
Challenges in Context

- **PSF**
  - Similar to or better than Chandra's: **~0.5"** HPD
- **Mass**
  - Similar to Chandra's: **~1,500** kg
- **Photon collecting area**
  - At least **10X** Chandra's
- **Cost**
  - Comparable to Chandra's in RY$ or
  - Less than **0.5X** Chandra's in constant $

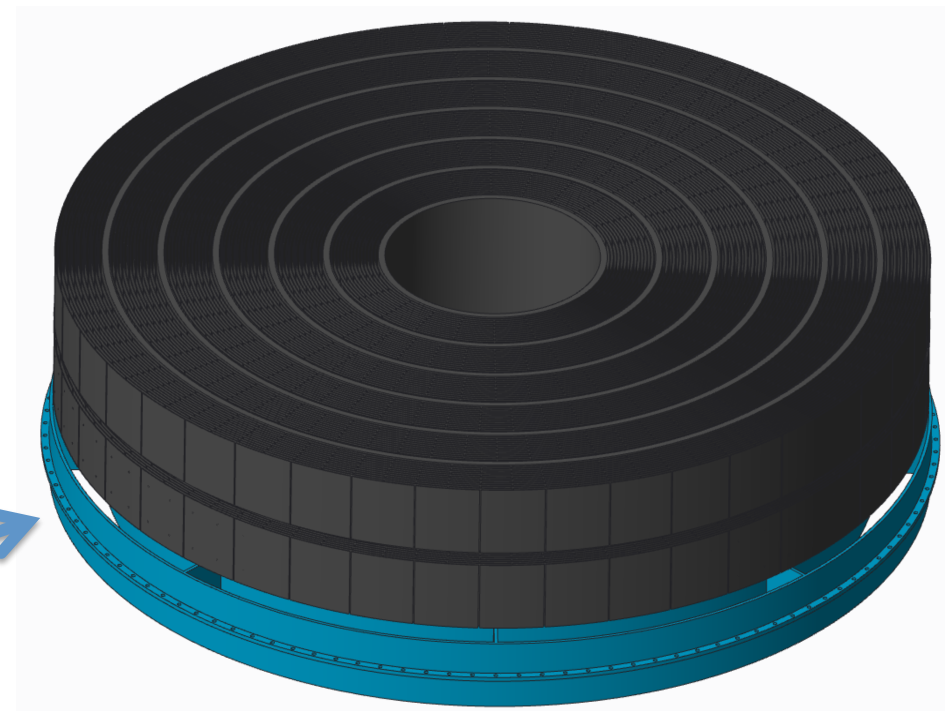
Approach:
Mirrors → Meta-Shells → Assembly

Single Crystal Silicon Mirrors





Meta-shell: mirrors bonded onto a silicon structural shell using silicon spacers and epoxy



Assembly: Many meta-shells aligned and flexure-mounted onto an aluminum or composite spider web

Notional Design of an X-ray Surveyor Mirror Assembly

- Focal length: **10 m**
- Outer diameter: **2 m**
- Inner diameter: **0.3 m**
- No. of mirror layers/shells: **~400**
- Physical mirror surface area: **~250 m^2** (cf. Chandra's 19 m^2)
- Effective area at 1 keV: **~1.2 m^2** (cf. Chandra's 0.08 m^2)
- Diffraction limit at 1 keV: **0.36"** (90% Power Diameter)

→ 25,000 mirrors, each 100 x 100 x 0.5 mm^3

Magnitude of the Challenge

- **Fabricate ~25,000 mirrors**
  - Typical mirror: 100mm by 100mm by 0.5mm
  - Technical, cost, and schedule challenges
- **Align and bond these mirrors onto ~20 meta-shells**
  - Technical and schedule challenges
- **Integrate ~20 meta-shells into an assembly**
  - No challenge. Substantially similar to XMM-Newton's and Chandra's mirror integration.

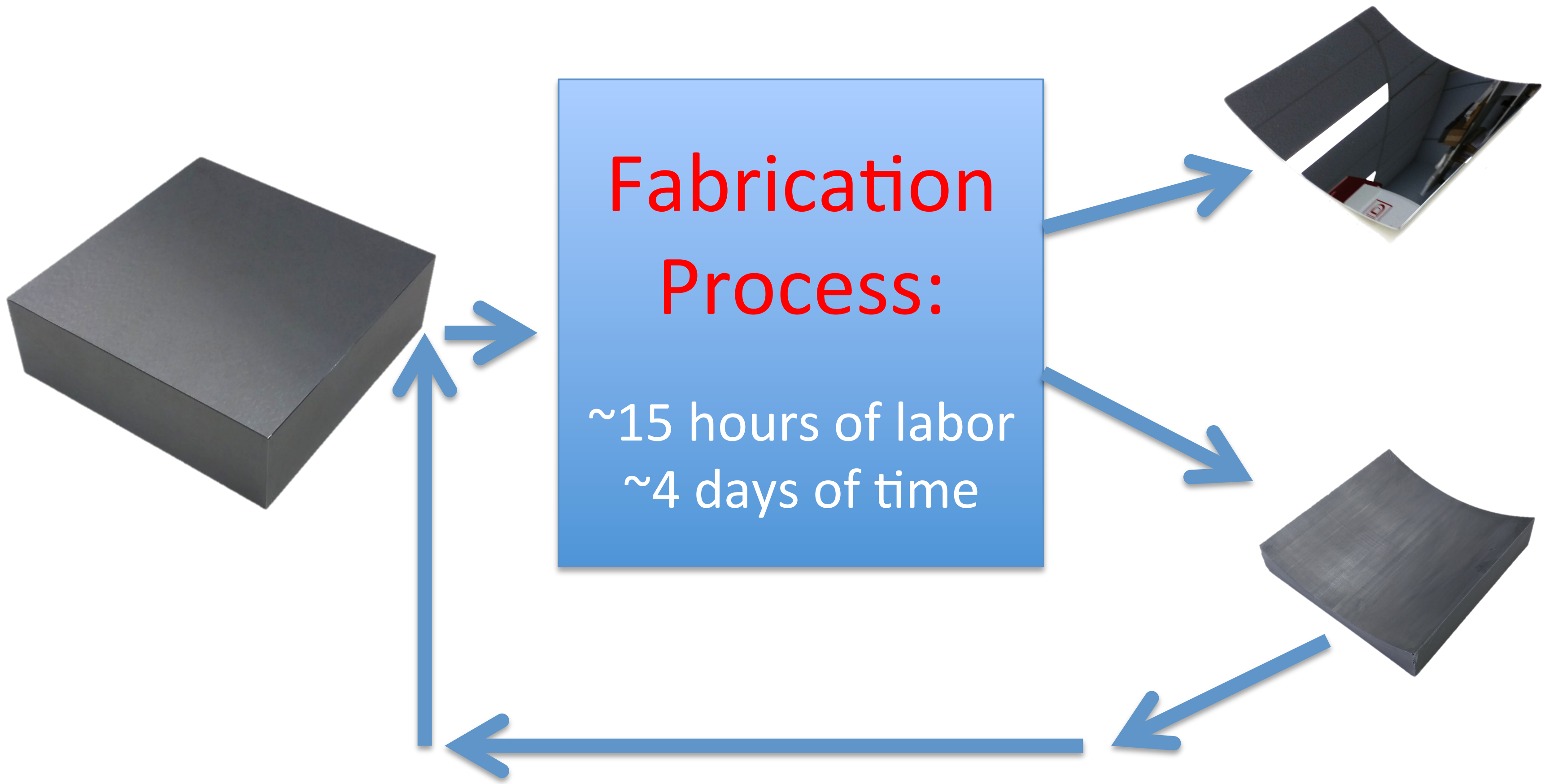
Mirror Fabrication

- **So far the ONLY way to fabricate mirrors that meet requirements is precision polishing.**
- **Polishing has two problems**
  - It has only made thick mirrors
    - Typical aspect ratio (size/thickness): **~6 to 10**
    - X-ray Surveyor requirement (size/thickness): **~200**
  - It is slow and expensive
- **We are developing two solutions**
  - Use single crystal silicon
  - Adopt mass production techniques

Why Single Crystal Silicon?

- **It has no internal stress**
  - Damage-free removal of material from the surface does not lead to unpredictable figure change, in contrast to thin sheet of glass.
- **It has excellent properties**
  - Low density
  - High thermal conductivity
  - Low thermal expansion
  - High elastic modulus
- **It is commercially and inexpensively available**

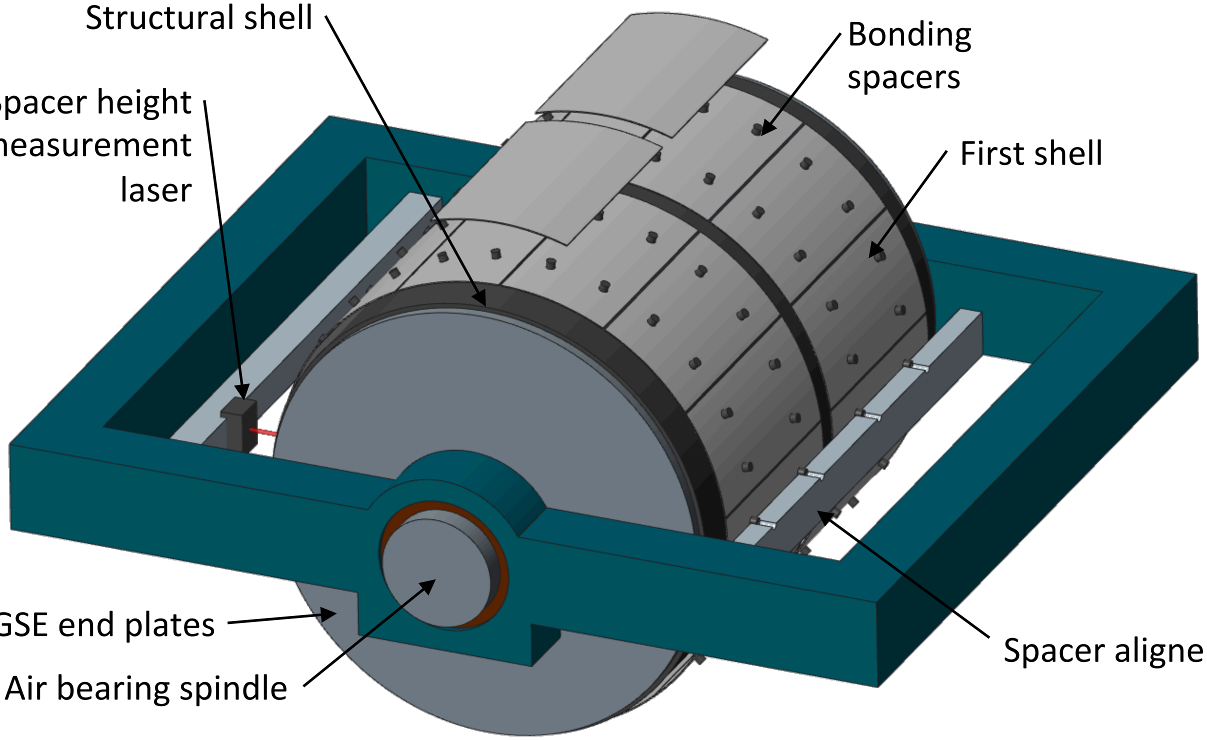
Mirror Fabrication



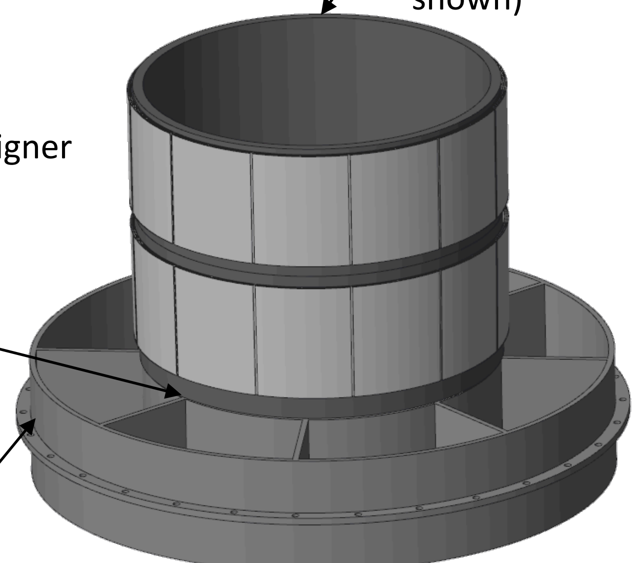
Mirror Fabrication Process

- **Generation:** setting radius and cone angle
- **Light-weighting:** removing the extra pounds
- **Acid etch:** removing damage and stress
- **Stress-polishing:** making precise optics
- **Trimming:** making it fit
- **Edge treatment:** preventing breakage
- **Metrology:** verifying figure quality

Building a Meta-shell



Meta-shell Makeup: Silicon mirrors, Silicon spacers, and trace amounts of iridium and epoxy



- **Spindle defines the optical axis.**
- **Each mirror is bonded at 4 locations.**

System Level Issues

- **Structural**
  - A meta-shell of many mirrors bonded with Hysol 9309 epoxy can withstand generic launch load.
- **Thermal**
  - A meta-shell can achieve better than 1” PSF performance under typical on-orbit thermal conditions.
- **Gravity release**
  - A meta-shell constructed with its optical axis in the horizontal direction can achieve better than 1” PSF once gravity is released.

Areas of Development

- **Mirror Fabrication**
  - Figure quality improvement (currently at ~3” HPD)
  - Fabrication time reduction
- **Coating**
  - Atomic layer deposition or magnetron sputter
  - Reduction/elimination of figure distortion
- **Alignment and Bonding**
  - Precision machining of spacers
  - Fast application and cure of epoxy
- **System level studies**
  - Complete end-to-end structural, thermal, and optical performance (STOP) analysis
  - Construction and test of meta-shells: performance and environmental

Prospects

- **2016-2017**
  - Demonstrate possibility of making sub-arcsec lightweight single crystal silicon mirrors
  - Build mirror stacks that can produce X-ray images close to 1" HPD
- **2018-2019**
  - Demonstrate mass-production process for making sub-arcsec mirrors; Team up with industry for implementation
  - Build and test meta-shells that meet X-ray Surveyor requirements: performance and environmental (TRL-6); Team up with industry for systems engineering

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