Toward large-area sub-arcsecond x-ray telescopes

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ABSTRACT

The future of x-ray astronomy depends upon development of x-ray telescopes with larger aperture areas (≈ 3 m^2) and fine angular resolution (≈ 1″). Combined with the special requirements of nested grazing-incidence optics, the mass and envelope constraints of space-borne telescopes render such advances technologically and programmatically challenging. Achieving this goal will require precision fabrication, alignment, mounting, and assembly of large areas (≈ 600 m^2) of lightweight (≈ 1 kg/m^2 areal density) high-quality mirrors at an acceptable cost (≈ 1 M\$/m^2 of mirror surface area). This paper reviews relevant technological and programmatic issues, as well as possible approaches for addressing these issues—including active (in-space adjustable) alignment and figure correction.

Keywords: X-ray telescopes, x-ray optics, slumped-glass mirrors, silicon mirrors, differential deposition, ion implantation, active optics, electro-active devices, magneto-active devices

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1. INTRODUCTION

The *Chandra X-ray Observatory*[1,2] (Figure 1) is NASA's current flagship mission for x-ray astronomy. With its precision High-Resolution Mirror Assembly (HRMA) of four nested grazing-incidence mirror pairs, *Chandra* is a unique astrophysics facility for sub-arcsecond x-ray imaging. Launched in 1999, *Chandra* continues to provide spectrometric x-ray images at an angular resolution an order of magnitude finer than any other telescope for x-ray astronomy. The US x-ray-astronomy community is currently investigating mission concepts and enabling technologies in order to propose as a worthy successor to *Chandra*, for launch late in the next decade.

Figure 1.NASA's *Chandra X-ray Observatory*: 13.8-m length, 4.2-m diameter, 19.5-m wingspan, and 4800-kg mass. The *Chandra* flight system comprises the Telescope System (including mirror assembly and optical bench—"tube"), the Spacecraft Module (surrounding the mirror assembly at one end of the optical bench), and the Integrated Science Instruments Module (containing two focal-plane detector arrays at the opposite end of the optical bench). [Credits: NGST]

A consensus is emerging within this community that NASA's next flagship x-ray mission will require an x-ray telescope with aperture area at least 30 times larger than *Chandra*'s (0.11 m^2) and with comparable angular resolution (< 1″). For example, the mission concept Square-Meter Arcsecond-Resolution Telescope for X rays[3,4] (SMART-X) identifies these performance parameters[5] as essential for reaching previously unexplored realms of the x-ray universe.

Here we update our previous overviews[6,7,8] of progress toward large-area sub-arcsecond x-ray telescopes. First we review considerations relevant to large-aperture-area (≈ 3 m^2) sub-arcsecond x-ray telescopes (§2) and briefly describe philosophies for mounting thin mirrors (§3). Next we provide an overview of methods for precision figuring of thin grazing-incidence mirrors (§4): Initial figuring during fabrication (§4.1) and post-fabrication figure correction—either static (§4.2) or active (§4.3). We conclude with a summary of research toward large-area sub-arcsecond x-ray telescopes (§5).

2. CONSIDERATIONS

The key performance metrics of any telescope are angular resolution and aperture area. Finer angular resolution improves imaging quality (Figure 2), reduces source confusion in crowded fields, and enhances sensitivity for detecting unresolved sources, by reducing the size of and thus number of background events in a telescope resolution pixel.

Larger aperture area increases the signal, thus enhancing sensitivity. Furthermore, better angular resolution provides no improvement in signal-to-noise ratio once the source is resolved. On the other hand, collecting more photons becomes ineffective if adjacent sources are confused due to inadequate angular resolution. Thus, detection, identification, and study of fainter sources require both finer angular resolution and larger aperture area.

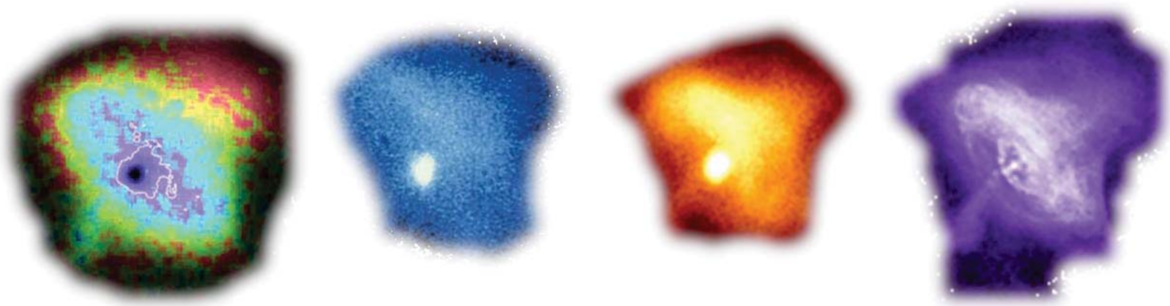

Figure 2. Comparison of x-ray images of the Crab Nebula obtained with high-resolution x-ray telescopes. From left to right, half-power-diameter (HPD) resolutions are approximately 15″ (XMM-*Newton*, 1999–present), 10″ (*Einstein Observatory*, 1978–1981), 5″ (*Röntgen Satellit* ROSAT, 1990–1999), and 0.5″ (*Chandra X-ray Observatory*, 1999–present). *Chandra*'s sub-arcsecond resolution reveals the intricate structure of this pulsar-wind nebula, powered by a rapidly rotating magnetized neutron star, the compact remnant of a supernova explosion in 1054.

As x-ray telescopes utilize grazing-incidence mirror pairs, the surface area is many (typically, >100) times larger than the aperture area. To achieve large aperture areas requires a highly nested configuration, which calls for thin grazing-incidence mirrors to maximize aperture within a limited envelope and to minimize mass—important constraints for in-space operation. The technical challenge is that thin, lightweight mirrors are inherently not stiff, which makes fabrication, metrology, and mounting difficult. The programmatic challenge is to apply any technical solution to the timely and cost-effective production of large areas of precision figured mirrors that are precisely aligned and mounted.

For reference, the *Chandra* x-ray mirrors have a 20-m^2 surface area and 1000-kg mass and cost about 600 M$ (2014 US dollars), which corresponds to a 50-kg/m^2 areal mass and 30-M$/$m^2$ areal cost. Hence, increasing the aperture area by a factor of about 30, within similar mass and cost constraints[3,5] as *Chandra*, sets a goal of < 2 kg/m^2 at < 1 M$/$m^2$ (per unit mirror surface area) for sub-arcsecond x-ray mirrors[6].

3. APPROACHES TO MOUNTING THIN MIRRORS

How might one construct a sub-arcsecond x-ray telescope using lightweight, thin, (relatively) inexpensive mirrors? As mounting-induced and gravity-induced distortions of thin mirror are potentially severe at long spatial wavelengths, the mounting and assembly scheme needs to prevent or correct low-spatial-frequency deviations. As mounting is unlikely to correct figure errors at mid and short spatial wavelengths, the mirrors should be inherently sub-arcsecond quality at least at mid and higher spatial frequencies.

Recall that the bending stiffness of a simple beam is proportional to $E\, w\, (h/l)^3$, with E the material's elastic modulus, w the width, h the thickness, and l its length or span. Thus, stiffness is a sensitive function of the thickness-to-span ratio (h/l). One philosophy is to overconstrain significantly the mirrors by the mount—e.g., using longitudinal ribs. Such a rigid mount is robust to gravitational distortion and vibration, but severely limits any correction of mirror figure after mounting, as the mount tends to impose its figure on the mirror. The opposite philosophy is to strive for perfectly figured mirrors and to constrain them as little as practical by the mount, so as to avoid degradation of the figure by the mount. For much of what follows, we assume that we indeed want to start with precision figured thin mirrors (§4).

4. PRECISION FIGURING OF THIN MIRRORS

We separate precision figuring into two steps: initial figuring (§4.1) and figure correction (§§4.2–4.3). The goal of the initial figuring during fabrication is to produce a mirror that is as close to the prescription as needed to meet the performance requirements—i.e., sub-arcsecond resolution. If that goal is met and maintained after mounting the mirrors, then the job is done. However, realistically, the thin mirror—especially in its mounted state—may require relatively small figure corrections in order to meet the sub-arcsecond requirement. These post-fabrication figure corrections generally provide a comparatively small range of adjustment, so their objective is to turn a good mirror into an excellent mirror.

4.1. Initial figuring

4.1.1. Replication

Replication starts with a precision figured mandrel and copies the surface figure onto a complementary mirror. It has two advantages over direct replication. First, the mandrel can be thick-walled and very stiff, thus relatively insensitive to distortion during figuring and polishing. Second, replication itself is typically an inexpensive process compared to precision figuring and polishing, so it becomes much more cost-effective to use replicated mirrors if the design calls for many mirrors of the same size and shape. The one disadvantage of replication is that the replica—especially if it is very thin—seldom conforms perfectly to the shape of the mandrel

The predominant replication method for full-shell x-ray mirrors is nickel electroforming, used for ESA's XMM-*Newton* mission[9] and several smaller satellite[10,11,12,13] and sub-orbital[14,15] missions. The half-power diameters of replicated-nickel telescopes typically range from 15″ to 30″, but individual shells may be as good as ≈10″ before mounting. Other replication technologies[16,17]—such as plasma spray[18,19]—can produce thicker and thus stiffer full-replicas through the use of ceramics or other materials less dense than nickel.

Segmented optics offer advantages in modularity and in scalability to very large collecting areas. The predominant replication method for high-resolution segmented optics is glass slumping[20,21,22,23,24,25,26,27] (Figure 3 left panel), used for NASA's NuSTAR satellite[28] and sub-orbital[29] missions. The half-power diameter of the NuSTAR telescope is about 50″; however, individual mirrors are significantly better.[†] Indeed, NASA Goddard Space Flight Center is now regularly slumping glass mirrors that could produce a (two-reflection) half-power diameter HPD ≈ 6″ (Figure 3 right panel) and has demonstrated HPD ≈ 8.3″ for a development module containing 3 co-aligned (primary–secondary) mirror pairs[30].

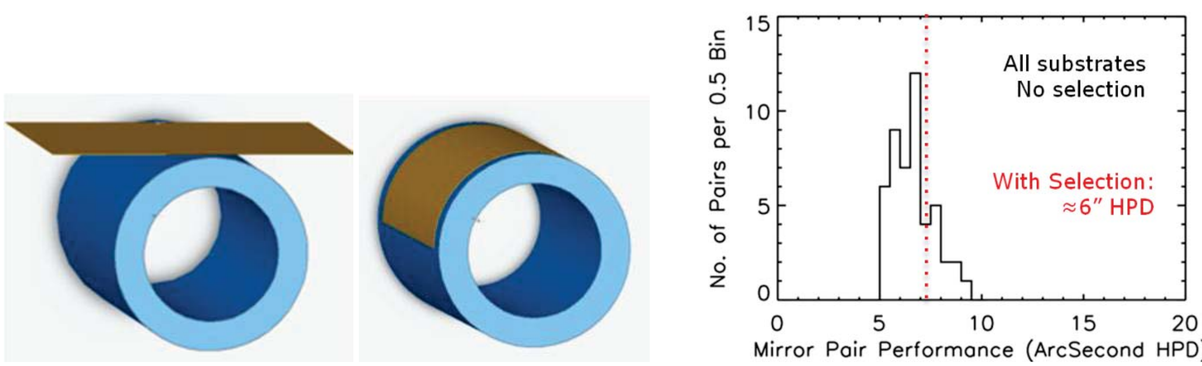

Figure 3. Illustration of thermal slumping a glass sheet over a precision mandrel to obtain a segmented mirror substrate (left panel); histogram of mirror-pair half-power diameters for state-of-the-art slumped-glass mirrors (right panel). [Credits: GSFC/Zhang]

Even with perfect mandrels, residual stress in the replication process may limit the angular resolution of thin replicated x-ray optics to HPD > 5″. Achieving sub-arcsecond resolution will likely require post-replication figure correction—either static (§4.2) or active (§4.3) or in combination.

4.1.2. Direct fabrication

The exquisite *Chandra* mirrors were produced using very precise metrology and conventional direct fabrication—i.e., grinding and polishing. The Osservatorio Astronomico di Brera is pursuing direct fabrication of full-cylinder x-ray mirrors that are nearly an order of magnitude thinner than the Chandra mirrors[31,32]: The fused silica mirrors are about 0.5-m diameter but only about 2-mm thick. To fabricate such mirrors, Brera is adopting an innovative approach—including hot slumping of fused-silica tubes into a double-cone net shape; use of a special shell support structure during metrology, machining, and handling; and ion figuring (§4.2.1) to correct residual low-frequency errors.

[†] NuSTAR uses precision machined ribs to stack and glue layers of segmented mirrors into an assembly. While this provides a robust, rigid mirror assembly, it highly overconstrains the mirrors, distorting the figure from its free state.

4.1.3. Mono-crystalline silicon

NASA Goddard Space Flight Center is developing a novel approach[33] to direct fabrication of thin segmented x-ray mirrors. A significant source of distortion in direct fabrication of thin mirror substrates is the release of internal stress during the removal of material from the substrate. For a perfect single crystal in its free state, there is no internal stress; thus, in principle, the only residual stress after removing material results from subsurface damage, which is mitigated by etching the surface. Figure 4 (left panel) identifies the steps in obtaining a thin x-ray mirror substrate from a block of mono-crystalline silicon.

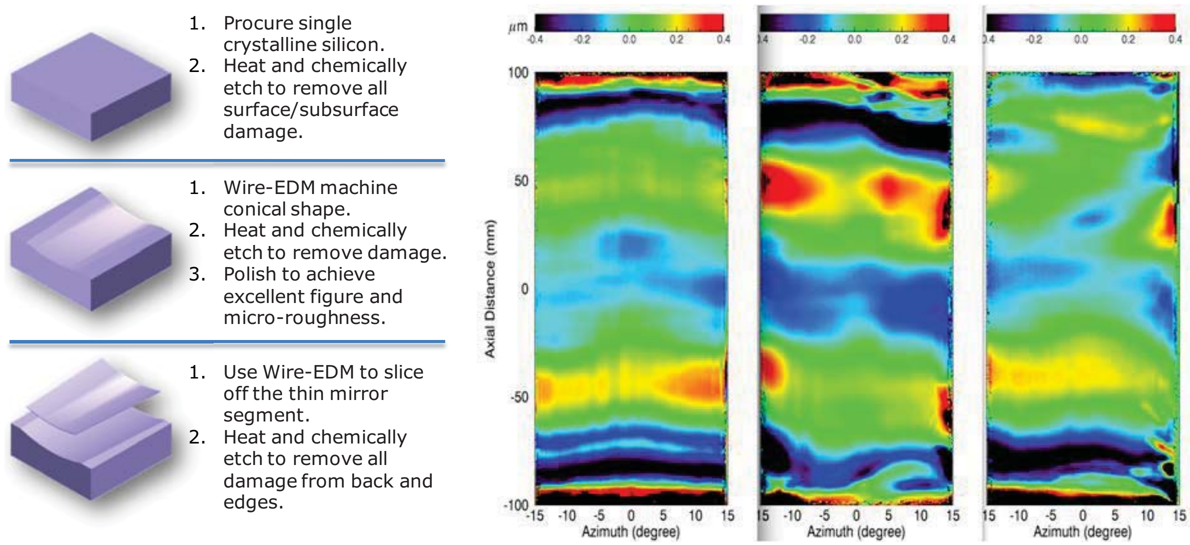

Figure 4. Steps for fabricating a thin segmented mirror substrate from an block of mono-crystalline silicon (left panel); comparison of surface errors prior to slicing from block, after slicing to obtain a thin substrate, and after etching to reduce damage-induced surface stress on the thin substrate (right panel). [Credits: GSFC/Zhang]

Figure 4 (right panel) displays maps of surface errors (a) of figured and polished region of a mono-crystalline-silicon block; (b) after slicing a thin mirror substrate from the block; and (c) after etching the cut surface on the back of the thin substrate to relieve stress due to sub-surface damage. The goal is to refine this process to achieve HPD ≈ 5″ in a couple years and HPD ≈ 1″ by the end of this decade[30].

4.2. Static figure correction

The initial figuring during fabrication might leave residual figure errors that require correction in order to achieve the desired angular resolution. In addition, mounting-induced stress might distort the mirrors in the alignment and assembly of a mirror module. For thin mirrors, the challenge is to correct these figure errors with minimal force and, if possible, to do so *in situ*. As described below, several technologies potentially allow for figure correction of thin mirrors, perhaps in their mounted state.

4.2.1. Ion figuring

Ion-beam figuring of x-ray mirrors[34,35,36] allows low-force correction of figure errors. Indeed, it has been proposed[37] as a method for correcting mounted thin mirrors for x-ray telescopes. Care must be taken to minimize microroughness degradation during ion figuring, but this seems to be achievable when the amount of material to be removed is not large.

4.2.2. Differential deposition

Rather than removing material to correct the surface figure of a mirror, differential deposition[38,39,40] adds material—effectively filling in valleys rather than abrading the hills. Figure 5 illustrates this "additive machining" process, which deposits a coating onto the mirror surface, preferentially filling in low regions of the surface. Based upon metrology of the surface, the mirror translates at a position-dependent rate, such that low regions of the surface spend more time over the sputtering target. The selected width of the slit in the sputtering mask determines the shortest spatial scales that can be corrected in a given run. Typically, the process starts with a wide-slit run to correct longer spatial wavelength errors and then progresses to narrower slits to correct shorter spatial wavelength errors.

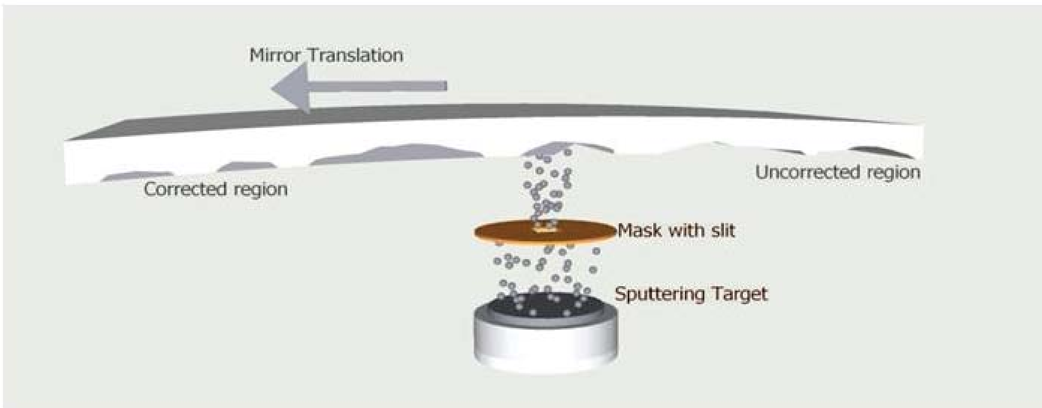

Figure 5. Differential deposition to correct figure errors on a mirror's surface. [Credits: MSFC/Kilaru]

NASA Marshall Space Flight Center is developing this process[41,42] to correct the surface figure of light-weight grazing-incidence mirrors. Initial tests are quite promising: Figure 6 shows that the process can indeed achieve a deposition profile that closely matches the targeted profile, which would represent the profile needed to correct surface errors.

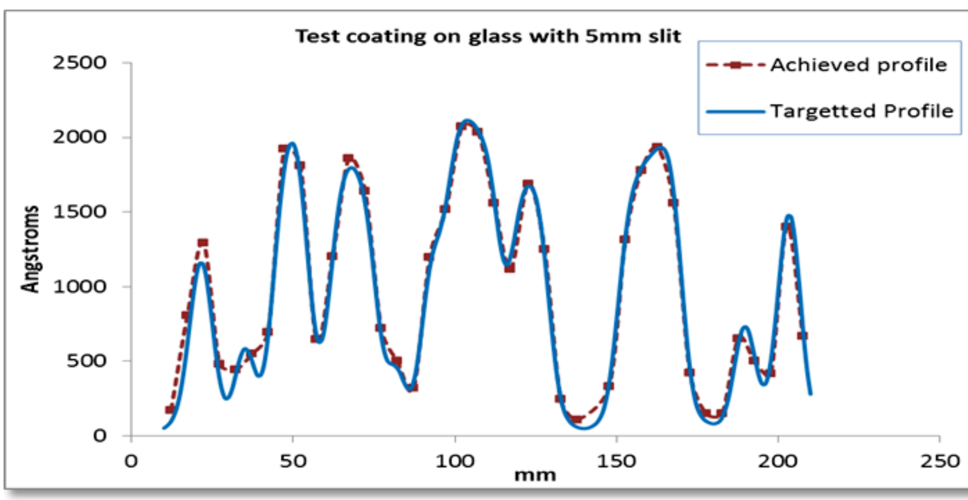

Figure 6. Test results for differential deposition, demonstrating the capability for achieving the coating profile needed to correct surface errors on a mirror. In this test, nickel is sputtered through a 5-mm-wide slit onto a glass substrate, translated at a variable rate to produce the desired profile. [Credits: MSFC/Kilaru]

In using differential deposition to correct the figure of a thin mirror, any coating stress could deform the mirror due to a bimorph effect. Thus, an important aspect of this research is to control and to minimize coating stresses, in order to avoid unwanted deformation of thin mirrors.

4.2.3. Coating stress

Most x-ray mirrors utilize an optical coating on the figured substrate in order to enhance the x-ray reflectance. As mentioned in the description of differential deposition, any stress in the coating will distort a thin mirror due to the bimorph effect. Thus, obtaining low-stress coatings—by optimization of deposition parameters or by annealing—is an important objective in depositing films onto thin x-ray mirrors[43,44,45,46]. Achieving low microroughness and good adhesion are also important objectives in depositing optical coatings. Of course, microroughness, adhesion, and coating stress all depend upon the deposition parameters and surface properties of the substrate.

On the other hand, precisely controlled coating stress can be used to correct long-spatial-wavelength errors—e.g., cone angle and curvature—using the bimorph effect[47]. These errors may be intrinsic to the fabricated substrate or introduced by other films[47,48] deposited onto the substrate. Correcting shorter spatial-frequency errors would require a precision translating slit, similar to that used for differential deposition (§0).

4.2.4. Differential ion implantation

Rather than using ions to correct the surface through erosive ion-beam figuring (§4.2.1), differential ion implantation introduces compressive stress near a substrate's surface. By controlling exposure of the surface to ions as a function of location[26,49], differential induced stress can in principle correct small figure errors through the bimorph effect (Figure 7).

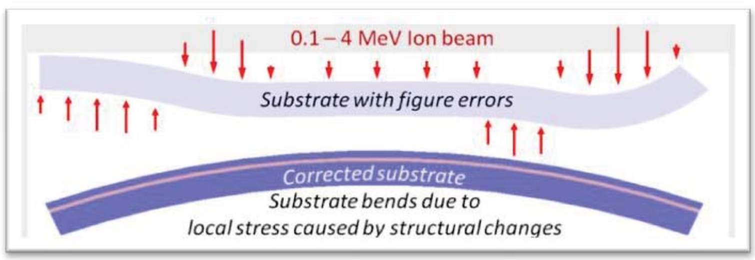

Figure 7. Depiction of figure correction using differential ion implantation. [Credits: MIT/Chalifoux]

The Massachusetts Institute of Technology is developing differential ion implantation at its Space Nanotechnology Laboratory, for figure correction of thin x-ray mirrors. Thus far, this research has characterized the dependence of integrated stress upon ion energy and fluence (Figure 8 left panel), which is the relevant parameter for determining the amplitude of correction achievable, at a given spatial wavelength, dependent upon the substrate's thickness and elastic modulus. Importantly, the research has also shown that the ion implantation does not significantly degrade the surface microroughness (Figure 8 right panel).

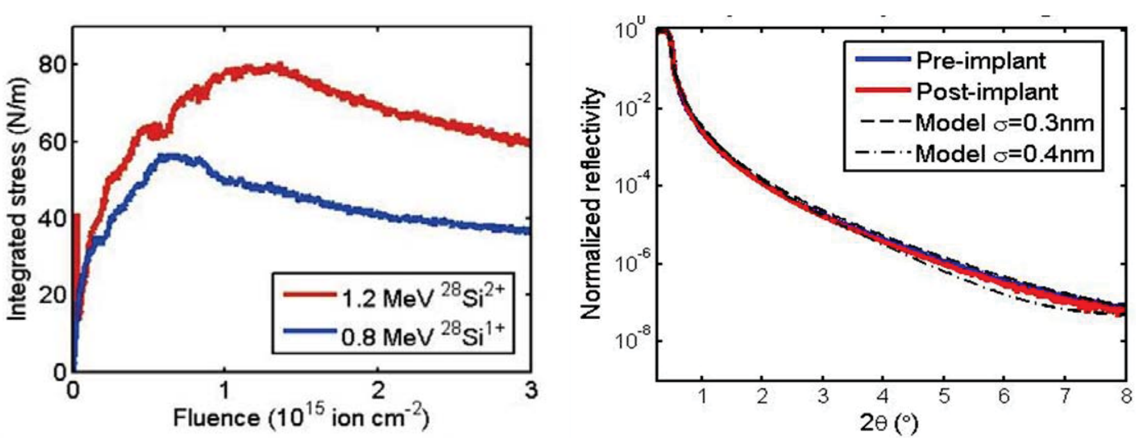

Figure 8. Studies of ion implantation for figure correction of thin x-ray mirrors, showing dependence of integrated stress upon ion energy and fluence (left panel); relative insensitivity of surface microroughness to ion implantation (right panel). [Credits: MIT/Chalifoux]

4.3. Active figure correction

Ultimately, it is the figure of the mirror in its mounted—not free—state that matters. Even if the initial figuring (§4.1) or static figure correction (§4.2) produce a perfect mirror surface in its free state, subsequent induced stresses—due to mounting, thermal issues, gravity release, etc.—could preclude satisfying the angular resolution requirement for the mirror assembly. During assembly, *in situ* static figure correction of a mounted mirror is possible for some approaches (§4.2); however, static corrections are not feasible after assembly.

There are two broad categories of actuation, dependent upon how force is applied to the mirror. *Surface-normal actuation* (SNA) acts as a piston to move the mirror for rigid-body alignment, or to effect a global or local deformation of the mirror. *Surface-tangential actuation* (STA) acts as a bimorph with the mirror substrate to effect local deformation of the mirror. Due to the highly nested nature of large-area x-ray mirror assemblies, only (STA) bimorph figure correction is practical. On the other hand, discrete (SNA) pistons are suited for adjusting alignment.

Here we briefly describe three bimorph actuator technologies under development for correcting the figure of thin x-ray mirrors. This Volume and previous editions of *Adaptive X-ray Optics* (SPIE 8503 and 7803) provide more detailed descriptions and references.

4.3.1. Bonded electro-active lattice

Northrop-Grumman AOA-Xinetics utilizes electrostrictive (PMN = lead magnesium niobate) ceramic lattices that provide (STA) bimorph figure correction when bonded to back of an x-ray mirror. Since 2008, AOA-Xinetics has been developing active optics for potential x-ray applications—including x-ray telescopes[50,51,52] and synchrotron light sources[53,54]. Figure 9 depicts two such PMN actuator arrays, the latter of which has been characterized[50,55] using various actuator settings.

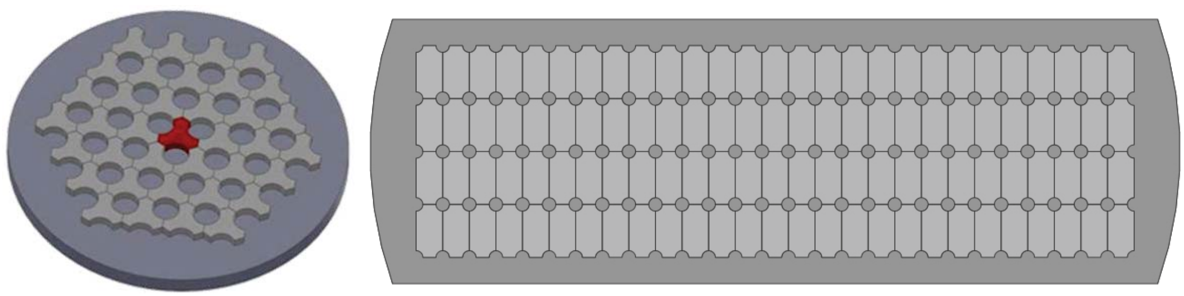

Figure 9. Lattice of individually addressable electro-active surface-tangential actuators (STA) bonded to the back of a lightweight mirrors. Each electro-active trefoil node is electrically isolated and individually activated by voltage applied to the (red) node (left panel); a 4×27 array of PMN pads is bonded to the back of a 10×30 cm^2 2.5-mm-thick silicon face sheet. [Credits: AOA-Xinetics/Lillie]

4.3.2. Thin-film electro-active array

Motivated initially by the Generation-X mission concept and more recently by the SMART-X mission concept[3,4,5], the Smithsonian Astrophysical Observatory (SAO) is leading a comprehensive research program[56,57,58,59] to develop, model[6061], characterize[62], and test technologies for active x-ray telescopes. Pennsylvania State University (PSU) is developing thin-film piezoelectric (PZT, lead zirconate titanate) ceramic actuator arrays[48,63,64,65] for thin x-ray mirrors. The thin-film processing sputters (Figure 10 left) a uniform ground-electrode layer, a uniform PZT layer, and then a patterned electrode layer with conductive traces onto the back of a segmented mirror (Figure 10 right). Recent work[48] has improved yield and added a thin-film transistor (TFT) array to provide row–column addressing of the piezoelectric pixels.

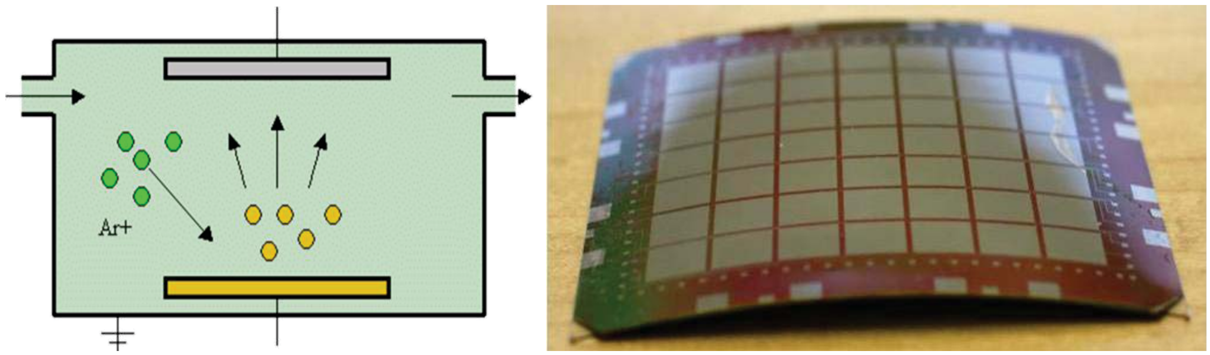

Figure 10. Patterned array of individually addressable electro-active surface-tangential actuators (STA), electrodes, and traces deposited (left panel) onto the back of a lightweight (≈ 1 kg/m^2) slumped-glass grazing-incidence mirror (right panel). [Credits: PSU/Johnson-Wilke]

4.3.3. Magnetic writing

This approach envisions using magnetic smart materials to enable writing figure corrections into a mirror[66,67], analogous to a magnetic head writing data onto a hard drive (Figure 11 left panel). An applied magnetic field produces (STA) bimorph response in a highly magnetostrictive layer and also magnetizes a highly coercive (magnetically hard) under-layer or substrate. The magnetically hard material retains the magnetic field after the writing magnet is removed and thus maintains the bimorph deformation. Varying the applied magnetic field as the "write head" moves over the mirror effects non-uniform bimorph deformation, in order to correct intrinsic figure errors.

Northwestern University is pursuing a program to demonstrate this technology[68,69]. The process includes electroforming nickel mirrors that serve as the high-coercivity ferromagnetic substrate, sputtering a magnetostrictive material onto the back of the mirror, measuring the magneto-active deformation, and comparing experimental results with FEA predictions. Recent work[47] provides proof of concept and indicates a need to speed up relaxation and stabilization (Figure 11 right panel).

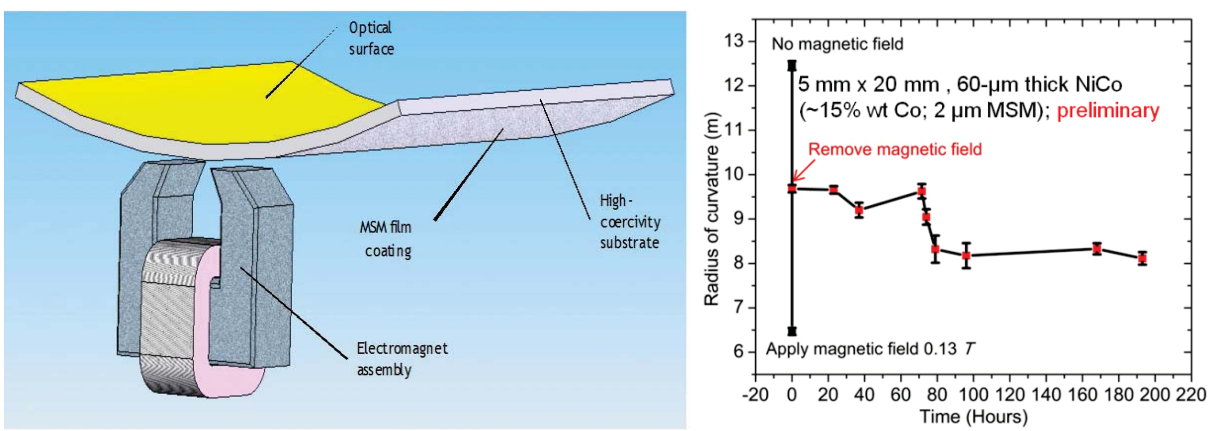

Figure 11. Magnetic writing of corrections to the figure of a grazing-incidence mirror. The schematic illustrates this proposed approach, in which an applied magnetic field produces surface-tangential actuation in a magnetostrictive coating over a high-coercivity magnetic substrate (left panel). Recent testing measures the bimorph response before, during, and after applying an external magnetic field (right panel). [Credits: Northwestern/Ulmer]

5. SUMMARY

Creating a large-aperture-area ($\approx 3\ m^2$) sub-arcsecond x-ray telescope will be technologically and programmatically challenging. Achieving sub-arcsecond imaging with the thin, lightweight ($\approx 1\ kg/m^2$ areal density) mirrors needed to satisfy mass and envelope constraints requires significant advancement of technologies. Further, to be programmatically viable, areal costs for mirror fabrication and alignment and assembly must be relatively low ($\approx 1\ M\$/m^2$) for the hundreds of m^2 of precision mirror surface areas needed for a grazing-incidence telescope with 3-m^2 aperture area.

Several technologies are under development for producing precision figured, thin x-ray mirrors. These include processes for initial figuring during fabrication and for post-fabrication figure correction—either static or active. Some methods are suitable for *in situ* figure correction of mirrors in their mounted state. Achieving precise and stable alignment and figure control may entail active (in-space adjustable) x-ray optics.

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