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Fabrication of Monocrystalline Silicon X-ray Mirrors

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ABSTRACT

Progress within the field of x-ray astronomy depends on astronomical x-ray observations of ever-increasing quality and speed. Fast and high-resolution x-ray observations over a broad spectral range promise amazing new discoveries. These observations, however, require a spaceborne x-ray telescope of unprecedented imaging power. Of the numerous technological concerns associated with the design and construction of such a telescope, the x-ray focusing optics present a particularly complex and arduous set of challenges. An x-ray optical assembly comprises many thousands of x-ray mirrors, a most critical element.

Our group at NASA Goddard Space Flight Center (GSFC) pursues the development of an x-ray mirror manufacturing process capable of meeting the stringent quality, production time, and cost requirements of the next-generation of x-ray telescopes. The manufacturing process employs monocrystalline silicon: a lightweight, stiff, thermally conductive, and readily available material which is free of internal stress; it is a nearly ideal material for a thin mirror substrate. The process involves various traditional optical fabrication techniques adapted to x-ray mirror geometry. Presently, our process is capable of fabricating sub-arcsecond half-power-diameter (HPD) resolution mirror pairs (primary and secondary) at a mirror thickness of 0.5 mm and of virtually any x-ray optical design (e.g. Wolter-I, Wolter-Schwarzschild, etc.). The mirror substrate surface quality is comparable to, and sometimes exceeding, that of the mirrors on the Chandra X-ray Observatory. This paper describes the various manufacturing steps involved in the production of x-ray mirror substrates and a present status report.

Keywords: X-ray optics, X-ray mirrors, silicon, polishing, optical manufacturing

1. INTRODUCTION

Future x-ray telescopes aim to study a variety of high energy objects and processes throughout the universe. Telescope designs focusing on soft x-ray (0.2–10 keV) observations aim to understand galaxy formation and evolution by observing early supermassive black holes and mapping hot gas around galaxies.[1] Higher energy (1–80 keV) focusing telescopes are planned to perform advanced spectroscopic observations of supermassive and intermediate mass black holes as well as other highly energetic systems including neutron star binaries and pulsars, among others.[2] These telescopes will also study diffuse gas emissions and other hidden mechanisms of galactic evolution. By obtaining such x-ray observations and coupling them with other advanced observations (JWST, gravitational waves, etc.), we will enrich our understanding of the history of the universe and the physics that govern the most violent processes observed.

The quality of the optics available for x-ray telescopes has historically been a significant limiting factor on the quality of observations and therefore the insights gained.[3] The high-energy nature of x-rays precludes normal-incidence reflection off mirror surfaces and only permits total reflection off mirror surfaces at small angles (0–3 deg), called grazing-incidence reflection. A focusing mirror system must therefore employ extremely off-axis mirrors to form an x-ray image. This extreme tilting of the mirror surfaces (relative to the optical axis) severely reduces the available photon-collection area while still requiring relatively large polished-mirror surface area. To increase the photon-collection area, many telescopes are nested within each other and co-aligned to focus on a single point. Although designing a high-performance telescope is possible, manufacturing one has proven difficult for decades.

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The need for larger photon collection areas motivate designers to include more nested telescopes (i.e. shells) by requiring thin mirrors and increasing the diameter of the telescope's aperture. Thus, x-ray optics, in reality, are complex assemblies of unwieldy mirrors which are difficult to manufacture, measure, align, and integrate robustly for spaceflight. As mirrors are made thinner, their surface quality suffers. As more shells are included, the co-alignment and support structures of the mirrors increases in complexity and difficulty. Increased complexity in an optically precise structure results in increased susceptibility to misalignments and other failures from mechanical loads and environmental inputs. The combination of a complex structure, large astronomical-quality mirror area of unusual geometry, limited cost and time budgets, and a dizzying myriad of spaceflight constraints results in a daunting challenge. Appreciating these challenges elucidates the difficulties and compromises faced by those who dared to build x-ray telescopes in past efforts.

The particular design and build of previously launched x-ray telescopes represent a real-world solution to the competing demands between science drivers and the limitations imposed by the technology and budgets available at the time of construction. The Suzaku telescopes minimized cost and maximized photon-collection area at a sacrifice to angular resolution. It used a very thin foil-type x-ray mirror technology which, although inexpensive, achieved a relatively low angular resolution of 2 arcminutes HPD.[4] The telescope onboard Chandra maximized angular resolution at great monetary cost and sacrifice to photon collection area. It used extremely accurately polished and relatively thick mirrors shells which were costly to produce and heavy to launch. Only a small number of these shells could be included and therefore the photon collection area was reduced, which hinders certain astronomical observations.[5] The next generation of x-ray telescopes will undoubtedly face similar challenges and be forced into a compromise between the same factors; however, as always, advances in available technology promise bigger and better x-ray telescopes.

Current x-ray telescope proposals demand angular HPD resolutions in the single arcsecond range (or better) and large photon collection areas in the 1 square meter range.[1,2,6–8] The proposed budgets for these telescopes are similar to previous telescopes on a per-unit-mirror area basis. To date, no existing mirror technology has been totally proven to meet these requirements. One of these candidate mirror technologies is pioneered by our group at GSFC.[9]

Our group takes a quasi-traditional approach to fabricating x-ray optics. In general, we aim to produce the highest quality x-ray mirrors possible. These excellent mirrors are then integrated into a carefully designed structure which preserves the mirror quality as much as possible.[10,11] Our mirrors are fabricated using a manufacturing process that harnesses the best that traditional optical manufacturing methods have to offer, while tailoring each process to the desired x-ray mirror geometry. A deep understanding of optical fabrication techniques allows for improvements to them enabled by modern technologies. Thus, where optical fabrication processes were formerly manual and iterative, they can now be automated and open-loop. Our group at GSFC has, in a laboratory setting, demonstrated that this type of improvement in optical manufacturing technology can enable the mass manufacture of extremely high-quality x-ray mirrors for a future x-ray telescope of virtually any prescription.[12]

Since 2011, our group at GSFC has been working to identify and perfect a mirror manufacturing process which can produce an x-ray telescope for future missions.[13–15] By exploring current technologies and developing our own, we have made significant progress since then. This paper will review our current method of x-ray mirror production and present a status report on our progress.

2. X-RAY MIRROR FABRICATION PROCESS

2.1 Monocrystalline silicon

For ages, astronomical mirrors have been made of either a metal alloy, glass, or ceramics. These materials are sufficiently stiff and stable to maintain precise shapes over time. Their surface hardness permits specular surfaces by polishing. These materials have suitable properties and meet the requirements of their respective telescopes. Their inadequacies would only arise if the mirror thickness is reduced significantly. Normal incidence mirrors are often thinned using an isogrid pocket pattern to save weight, this can lead to print-through of stresses into the mirror surface, costly corrective action is needed thereafter. In the case of x-ray mirrors, the mirrors must be even thinner (<1 mm). Corrective processes such as sub-aperture polishing can improve surface quality, but only to a limit imposed by the material of the mirror.

A freestanding thin mirror substrate is susceptible to many mechanical stressors which can deform and deteriorate its shape. Gravity constantly deflects thin mirrors. Surface and subsurface crystal damage from cutting and abrading processes can leave stress fields which can easily ruin a mirror's accuracy. Thermal gradients combined with high thermal expansion and low thermal conduction will have a similar effect. Assume gravity effects can be minimized and characterized, environmental controls eliminate thermal distortions, and careful and gentle polishing processes are used to remove surface and subsurface stresses from a thin mirror. The remaining errors could be measured and a non-damaging, highly accurate surface polishing process is applied to correct these remaining errors. This correction will only converge to a certain level of accuracy, beyond which corrective actions will give non-deterministic results. This occurs primarily because of internal stresses within the material itself.

A glass is a vitrified solid wherein constituent molecules of a highly viscous liquid are frozen in place upon cooling, their arrangement nearly as random as that of its liquid state. Intermolecular forces are therefore randomly distributed throughout the solid, some compressed, some in tension. The surface of this solid is influenced by the stress balance within the material at all times. Removing material from this solid changes the random internal stress balance and therefore changes the surface shape accordingly; these changes are unpredictable because the exact internal stress balance is unknown. Metals and ceramics have even more complex internal structures involving randomly oriented crystal grains and the grain boundary interactions between them. The heat and pressure energy used to form these stiff and tough materials is forged into the microstructure as tensile and compressive stresses between the molecules and crystal grains that comprise the bulk of the material. Attempts to correct the shape of a thin mirror made of glass, metal, or ceramic will only converge to a level permitted by the material's internal stresses and the mirror's thickness. It is unlikely that sufficiently accurate thin x-ray mirrors for future x-ray telescopes could ever be successfully fabricated using glass, metal, or ceramics.

Monocrystalline materials yield better results. Within the bulk of a crystal, each atom lies in its respective lattice position, which is energetically favorable. Bond energies throughout the crystal are evenly and predictably distributed. This uniform lattice structure does not contain the stress fields found throughout the microstructure of glass, metal, or ceramics As such, the material, on scales slightly larger than a unit cell, is effectively free of internal stress. The net effect of this property is that, theoretically, removing a section of the crystal does not distort the rest of the crystal structure in any appreciable way. A thin monocrystalline mirror can therefore be corrected to much higher accuracy than any other material.

The predominant monocrystalline material available for use as an engineering material is silicon. Thanks to billions of dollars invested over decades into its research and development, monocrystalline silicon is readily available for purchase in large blocks. In our experience, its cost is generally lower than that of optical glass. Further, monocrystalline silicon has highly favorable material properties, some of which are listed in Table 1. Monocrystalline silicon is lightweight, stiff, thermally conductive, has low thermal expansion, and most importantly, it is free of internal stress. Additionally, the semiconductor industry has developed tools, materials, and techniques to process the material efficiently; these are also readily available for purchase. Thus, monocrystalline silicon is our group's chosen material for the production of x-ray mirrors and connected support structures.

Table 1. Favorable material properties of monocrystalline silicon.

Property	Value
Stiffness	130-169 GPa
Density	2.33 g/cm^3
Thermal expansion	$2.6\ 10^{-6}$ K^{-1}
Thermal conductivity	148 W/(m-K) @ 300 °K

2.2 Fabrication process overview

Our x-ray mirror process closely resembles that of the flat monocrystalline silicon wafer production process for the semiconductor industry. In essence, many requirements placed commercial on flat silicon wafers also apply to silicon x-ray mirrors. Both must be accurately shaped, polished smooth, and mechanically resilient. Of course, x-ray mirrors must have paraboloidal, hyperboloidal, or even more complex surface profiles, increasing the complexity of manufacturing and metrology. Figure 1 shows our production process in its current form.

The process begins with a silicon boule grown with a purity suitable for prime silicon wafers. The boule is cut into blocks of convenient dimensions which for us is 15×15×7.5 cm. Using a diamond abrasive bandsaw, computer controlled grinding, and precision lapping, a conical polish-ready surface is produced on a broad face of the block. This set of procedures sets a precise radius and cone angle of the x-ray mirror to be manufactured. Next, the block is mounted on the diamond bandsaw, and the surface is sliced off at a thickness suitable for withstanding polishing forces, typically between 1 and 2 mm. The edges of the sliced surface are treated to eliminate fractures generated by the bandsaw process. Then, the mirror surface is masked and the substrate is immersed in an isotropic acid etch solution which removes 80–100 μm of material from all exposed surfaces. This relieves surface stresses from all exposed surfaces by simply removing damaged material, effectively strengthening the substrate.

The substrate is then subjected to a set of chemical-mechanical polishing (CMP) processes which simultaneously improve the figure and microroughness of the mirror surface while removing sufficient material from the surface to expose the undamaged monocrystalline structure. These CMP processes borrow heavily from the CMP processes of the silicon wafer manufacturing process, and they are adapted to x-ray mirror geometry. Unfortunately but not unexpectedly, these polishing processes leave undesirable edge roll-off effects. We are familiar with these edge effects and have determined a suitable central region of interest (ROI) from which our final mirror will be produced. The mirror substrate is mounted on a computer controlled grinding machine, and the backside of the mirror is thinned only within the ROI. The thickness of the mirror inside the ROI nears the final desired thickness. The thinned ROI section is trimmed away from the mirror substrate and masked on its mirror side only. Since the thinning and trimming process have left damaged crystal surfaces, they are etched one final time. This final etching yields a truly monocrystalline silicon x-ray mirror substrate. Since the CMP polishing processes are imperfect however, the mirror surface exhibits errors of about 200 nm peak to valley. To remove these, the mirror is profiled on our cylindrical interferometer system and the measured errors are removed in about 1 hour on our ion beam figuring machine. After one or two iterations of measurement and correction the surface errors total in single nanometers. The x-ray mirror is now ready for coating and subsequent integration into an x-ray mirror assembly. Figure 2 shows photographs of a complete mirror. In this case, a mirror thickness of 0.4 mm was targeted and achieved.

3. PRESENT STATUS

3.1 Production capacity

Within our limited laboratory production operation, about 5 days are needed to produce a mirror from start to finish. Parallel processing allows us to produce 8 x-ray mirrors per week at full capacity. The labor hours required per mirror is ≤15 hr. Efforts are constantly underway to simplify and streamline our procedures. Automation efforts are possible though costly. We regularly test various automation concepts which may one day replace certain manual processes.

3.2 Latest results

Figure 3 shows a completed mirror surface acquired by our fizeau interferometer + cylindrical transmissive null lens metrology system. The raw data captured by the interferometer is processed to remove the conical profile. Figure 3(a) shows the resulting surface. The sagittal depth of this particular mirror is relatively deep at 967 nm. This mirror was produced for the short 3.5 m focal length telescope onboard the Off-plane Grating Rocket Experiment (OGRE) sounding rocket mission.[16,17] Removing the paraboloid from the measured data yields the residual errors remaining on the mirror surface, shown in Figure 3(b). In this case, their root-mean-square height is 3 nm, which approaches the confidence limit of our metrology. Figure 3(c) shows a microroughness measurement by our scanning white light interferometer of a typical mirror showing ∼0.2 nm average area roughness over a 416 μm x 416 μm area.

Figure 3(d) plots the power spectral density of a Chandra mirror over 100 mm to 1 mm of surface error wavelengths.[18] A particularly good mirror produced by our fabrication process is also plotted in Figure 3(d).

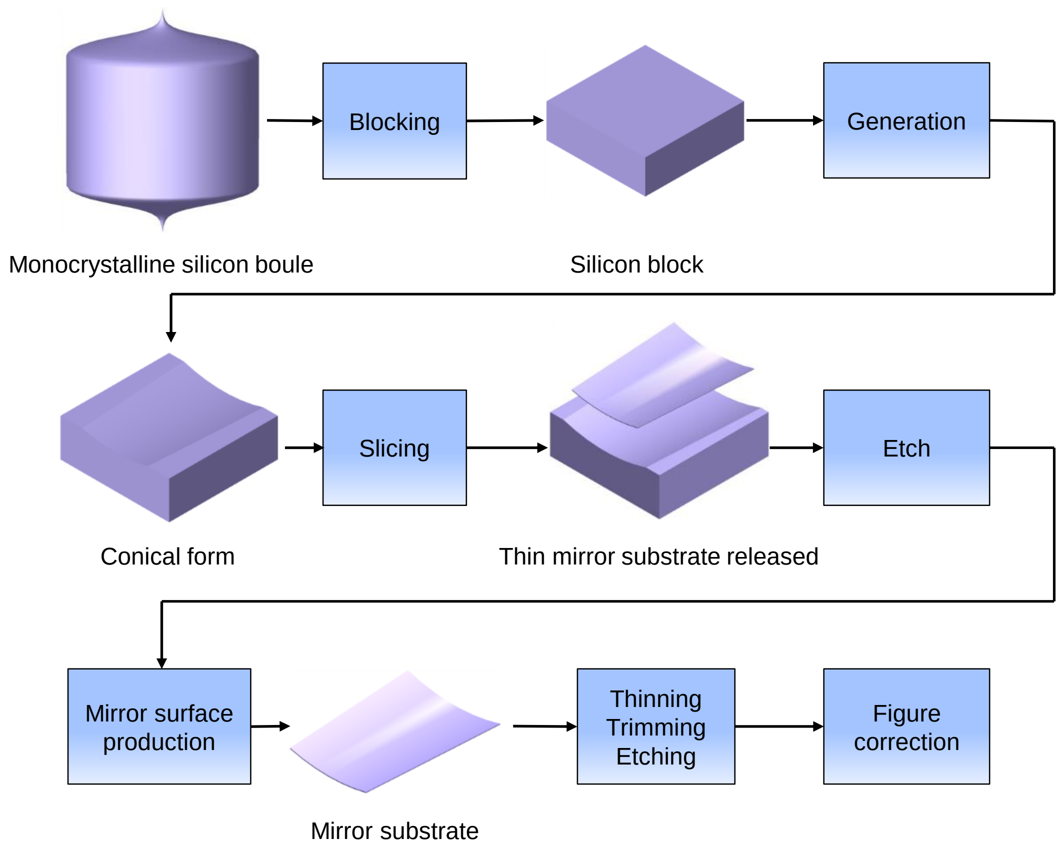
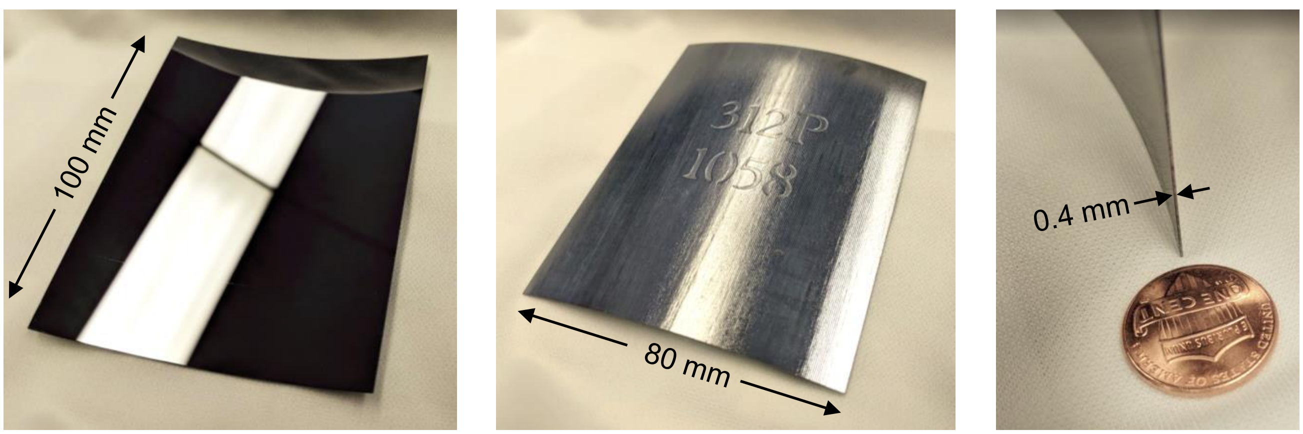


Figure 1. Schematic of the monocrystalline silicon mirror substrate production process.



(a) Front view (b) Back view (c) Edge view

Figure 2. Photographs of a completed x-ray mirror.

This comparison demonstrates that the achievable surface quality is equivalent to, sometimes exceeding that of, Chandra's mirror surface quality. Since the majority of our thin finished mirrors match the surface quality shown in Figure 3, we claim to be able to produce Chandra-quality mirrors regularly.

3.3 Remaining challenges

So far, we have focused on producing Wolter-I mirrors; however, we will begin testing the fabrication of Wolter-Schwarzchild mirrors which have complex 2nd, 3rd, and 4th order axial surface components.[19] Further improving

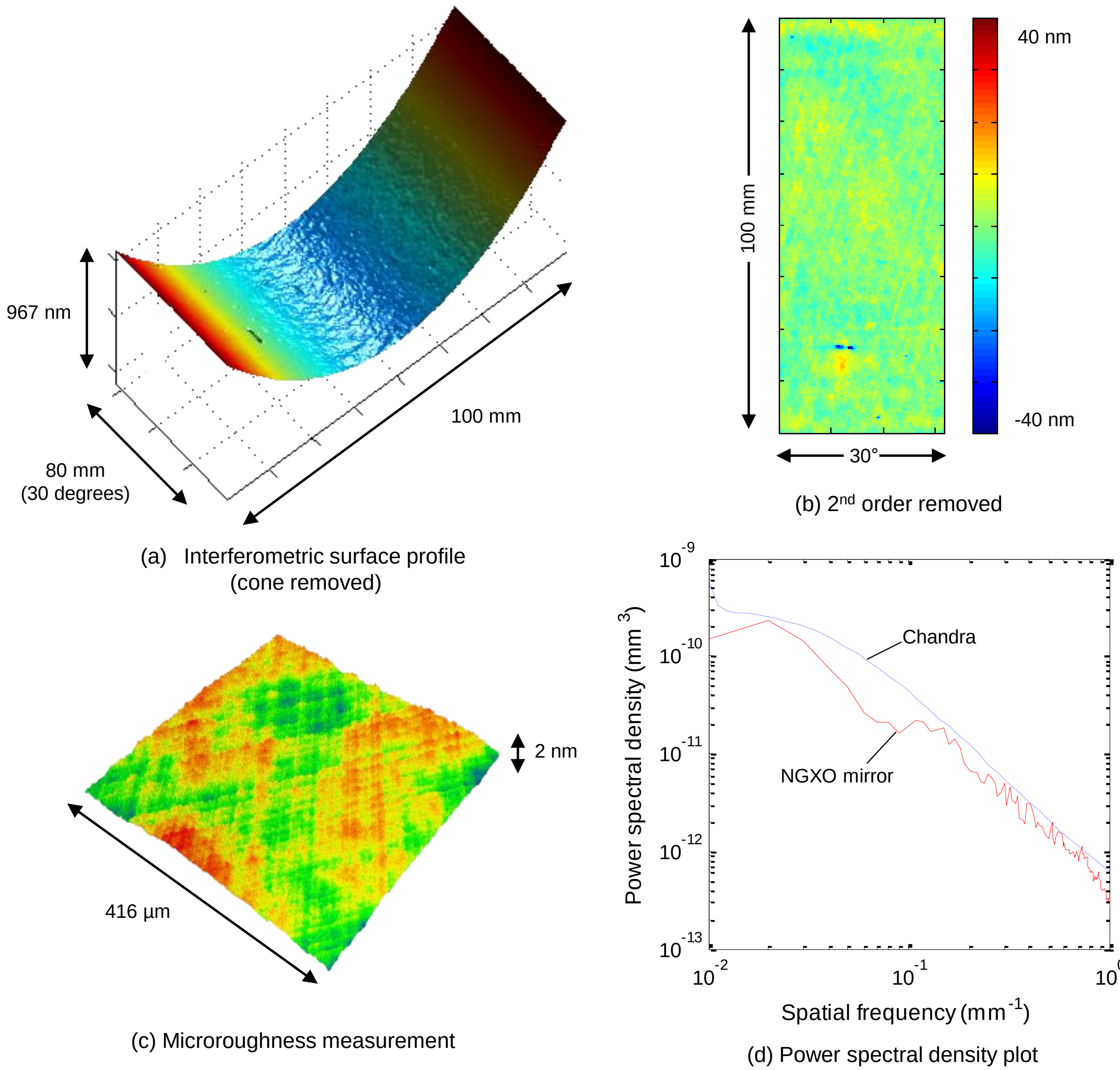


Figure 3. Interferometric surface profiles and power spectral density measurements of a high quality X-ray mirror surfaces made by our fabrication process.

our metrology limitations presents a general challenge to be addressed by improved environmental controls and careful calibration. Presently our sagittal depth control is limited to ± 5 nm which results in focusing errors equivalent to 0.1 arcsec half-power diameter (2-reflection). Efforts to incorporate tighter environmental controls and absolute calibrations are being investigated. Our goal will be to produce diffraction-limited mirrors.

Our mirror manufacturing process, although capable of producing high quality mirrors, still has many improvements to be incorporated which will increase throughput and yield. Further, as we produce more mirrors, statistics can be gathered which will ease the frequency of quality checks needed.

4. SUMMARY

This paper presented a background on the difficult challenge that is building an x-ray telescope. Our group works to adapt and update traditional optical manufacturing techniques to meet the extraordinary challenge set by future x-ray telescope designs. The use of monocrystalline silicon as a nearly ideal substrate was presented, and the present version of our x-ray mirror manufacturing process was reviewed. Our group regularly produces mirrors having Chandra-like surface quality on mirror substrates that are 50 times thinner than a Chandra shell. Further, we estimate the cost of a telescope built using mirrors made by our process will be lower by a factor of 10 to 20 per unit mirror area. We continue to refine and perfect our techniques as we dive deep into the technical details and challenges which lay ahead. With this type of technological advancement, the future of x-ray telescopes may be a bright one.

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