Silicon pore optics for high-energy optical systems

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Citation

Girou, D. A. (2022, June 14). *Silicon pore optics for high-energy optical systems*. *Casimir PhD Series*. Retrieved from https://hdl.handle.net/1887/3420652

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INTRODUCTION

Parts of this chapter are based on an invited chapter for the Handbook of X-ray and Gamma-ray Astrophysics (Eds. C. Bambi and A. Santangelo, Springer Singapore, expected in 2022). Contributors to this invited chapter are Nicolas M. Barrière[1], Marcos Bavdaz[2], Maximilien J. Collon[1], Ivo Ferreira[2], David Girou[1], Boris Landgraf[1], and Giuseppe Vacanti[1].

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1.1 Silicon Pore Optics (SPO) concept

The high-energy (short wavelength) region of the electromagnetic spectrum corresponding to the X-ray and soft Gamma-ray ranges presents a particular challenge to the development of efficient reflective optical elements such as mirrors for focusing optics. The reason being that at normal incidence, the reflectance of any "regular" mirror is close to nothing. On the other hand, for low grazing incidence angles, total external reflection or multilayer coatings using principle of optical interference can reach reflectances that are several times larger than those possible using normal incidence mirrors. Furthermore, other principles for focusing high-energy photons include Bragg diffraction in the volume of symmetrically cut crystals (referred to as Laue geometry). As a result, these techniques enable opportunities for high-energy optical systems applications in a variety of scientific and technological disciplines ranging from space-based astronomy (see Section 1.2), to medical [1], and material analysis.

Silicon pore optics (SPO) technology uses commercially available monocrystalline double-sided super-polished silicon wafers as a basis to produce high-energy photons mirrors. In addition to its direct bonding property [2, 3], silicon is rigid, has a relatively low density, very good thermal conductivity, excellent surface finish, both in terms of figure and surface roughness, making it a superb base material to build X-ray mirrors. SPO development leverages the massive investments done in the semiconductor and automotive industry, which made high-performance equipment, tools, materials, and processes available on the market allowing high-quality mass production. Standard wafers are produced with outstanding quality for a modest cost: prime grade double-sided super-polished monocrystalline 300 mm silicon wafers have specifications of 0.1 nm root mean square (RMS) surface roughness and total thickness variation (TTV) of less than 0.2 μm [4] (see Figure 1.1).

SPO substrates, also called mirror plates or simply plates, are cut out of wafers and carved out on one side in a regular pattern to leave thin parallel walls called ribs. In other words, plates consist of a thin membrane with a smooth reflective surface on one side and ribs along the plate length on the other. Consequently, stacking plates results in a pore-like structure, hence the name silicon pore optics.

The plates are attached to each other thanks to direct silicon bonding, which requires no adhesives. To produce a focusing optic, the mirrors must be curved. Starting from a mandrel that imposes the shape, plates can be stacked while preserving the mandrel figure in each plate. This results in a self-standing stack of elastically deformed mirror plates reproducing the shape of a mandrel that forms lightweight, high-resolution, X-ray optics (see Figure 1.2). In such a stack, X-ray photons enter pores at low-grazing angles, where they are reflected on the reflective side of each plate, and exit the optics at the opposite end.

Typical X-ray focusing optics uses nested shells to fill the available aperture and maximize effective area because low grazing incidence angles are needed for X-ray reflec-

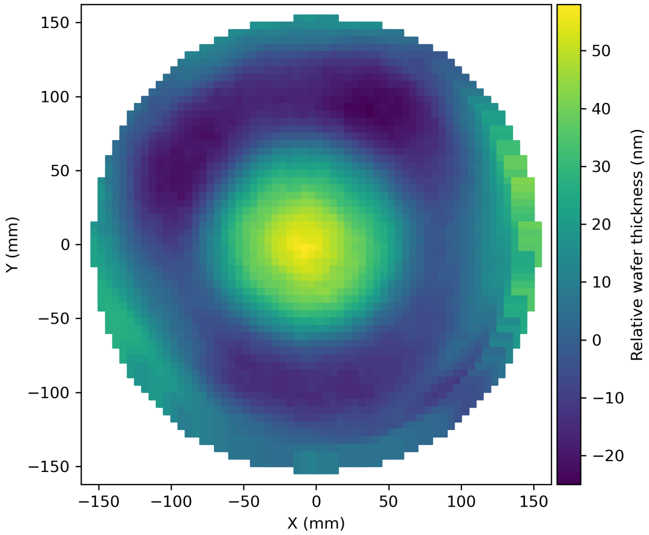

Figure 1.1: Typical relative thickness map of a silicon wafer for SPO plate production. The data is plotted relative to the median thickness of 775110 nm of the wafer. The thickness is measured by Fizeau interferometry.

tions. Because the ribs act as spacers between mirror plates, SPO can achieve an extreme packing density of the shells. The stiffness obtained by the bonded plates makes it possible to reduce the thickness of the membranes without impacting the figure accuracy, in a lightweight structure leading to large open area ratio.

SPO can be made to comply to many optical geometries, with the Wolter I [5] configuration being in general the most attractive for high-energy astrophysics applications. Two reflections are required to form an imaging system at grazing angles of incidence; this is achieved by placing two stacks, a primary stack and a secondary stack, in series along the path of the incoming photons. Two brackets, to which the stacks are glued, are used to fix the relative orientation of stacks, and provide a mechanical interface for integration in a larger structure.

1.2 The astrophysics case

The launch of the high-energy astrophysics observatories XMM-Newton [6] and Chandra [7], in 1999, marked the culmination of two major optics development efforts, and made observations of the X-ray sky with unprecedented sensitivity. Significant investments were required, and two different optics technologies developed to make these missions possible. The optics of XMM-Newton is based on electro-formed nickel, replicated from precision mandrels; it maximises effective area to make high-resolution spectroscopy of distant sources possible [8]. The Chandra optics, on the other hand, optimises the angular resolution at the cost of mass and effective area to provide high-

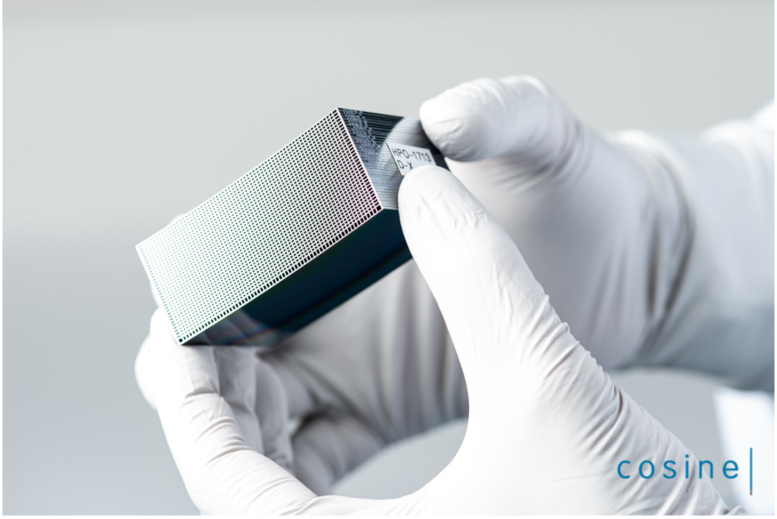

Figure 1.2: A stack of 34 SPO plates, with an outer radius of 737 mm.

resolution imaging. After more than two decades of active operations, these two missions remain in high demand for their stand-alone capabilities and the synergies with observations at other wavelengths. Their systems are, however, ageing, and the need for higher performance continues to increase.

The next generation of high-energy astrophysics observatories will have to reach deeper into the Universe, keeping pace with the present and future ground and space-based observatories like the James Webb Space Telescope, the Square Kilometer Array (SKA), and the Extremely Large Telescope (ELT). More photons will have to be collected from very distant sources, requiring larger effective area, a good angular resolution to avoid source confusion, and more sophisticated detector instruments.

In 2014, the European Space Agency (ESA) selected the Advanced Telescope for High-ENergy Astrophysics (Athena) as the second large-class mission designed to address the "Cosmic Vision" science theme "The Hot and Energetic Universe" [9]. This X-ray space telescope will rely on a novel type of optics, which was specifically invented and developed for the Athena mission: the Silicon Pore Optics (SPO) [10, 11].

The challenge of the Athena optics is the need to simultaneously comply with three technical requirements:

- Provide a large effective area (1.4 m^2 at 1 keV),
- Provide a good angular resolution (5 arcsec HEW),
- Remain in the mass allocation (around 1000 kg).

XMM-Newton and Chandra required different optics technologies, because they had to deliver different combinations of these three parameters. This is also true for the other X-ray missions flown to date, from Exosat [12], Einstein [13], ASCA [14] and Rosat [15], to BeppoSAX [16], Hitomi (Astro-H) [17], NuSTAR [18], and eRosita [19]. The optics for each of these missions is an engineering masterpiece, and each required substantial effort, skill, time, and funding to be developed, as well as for the flight models to be produced.

In Figure 1.3 the optics for each of these missions is compared, considering the aforementioned three parameters. The area density of the respective optics, expressed as effective area per mass of the optics is plotted against the resolving power of the optics, expressed as angular resolution elements per arcminute [20]. A clear correlation is observed despite the fact that the optics technologies are very different, ranging from foil-based optics to replicated optics and monolithic optics. Each of these systems was developed and built with large effort, and each represents a major achievement, but they all follow a power law correlation. Even the Chandra optics, the result of extraordinary investment in engineering and funding, manages to move only very slightly to the upper right side of the correlation line. The same is true for eRosita, which represents the highly optimised third generation of electroformed nickel technology.

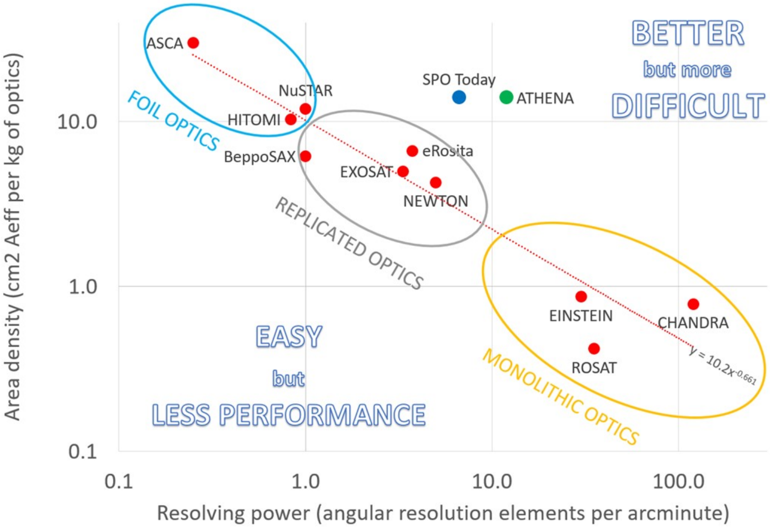

Figure 1.3: Characteristics of the optics flown on X-ray missions to date (red dots), plotting the area density of the optics (i.e. cm^2 of effective area per kg of optics) as function of the resolving power of the optics (i.e. number of angular resolution elements resolved by the optics in one arcminute). The characteristics of the X-ray optics flown to date show a clear correlation, described by a power law. Athena requires optics which cannot be achieved with the X-ray optics technologies flown to date. Adapted from [20].

The graph illustrates that it is possible to build lightweight optics with a large effective area, but lower angular resolution, or high resolution but heavy optics with a limited effective area. The power law allows only two of the three parameters (effective area, angular resolution, and mass) to be optimised, but not all of them simultaneously. The optics required for the Athena mission (green dot in Figure 1.3) requires, however, a technological change to move away from this empirical power law into the "difficult corner" in the upper right of the graph. Linear extrapolation of all the X-ray missions flown to date using the three previous conventional technologies suggests that it would be possible to deliver the resolution and effective area, but it would require a mass of about 7000 kg, which is the mass of the complete Athena mission. Or it could respect the mass allocation of 1000 kg and deliver the effective area, but with a severely degraded angular resolution of about 1.6 arcminutes.

The SPO technology has already demonstrated the compliance with the Athena effective area and mass requirements. The angular resolution is approaching the Athena requirement as well, being already one order of magnitude better than what the established technologies could deliver for the same mass and effective area. The ongoing technological developments are focused on pushing the angular resolution to the required value. The technology pull generated by Athena resulted in the creation of a new type of X-ray optics, the SPO technology, which will undoubtedly also find other applications in demanding future space missions (the ARCUS mission studied by NASA is an example [21]).

1.3 Thesis outline

This thesis examines silicon pore optics by studying its design, modeling, manufacturing, testing, and characterization. Silicon pore optics is both an enabling technology for large space-borne X-ray telescopes such as Athena, and a versatile technology that can be further developed for gamma-ray optics, medical applications, and material research. The contents of this thesis are organized as follows:

In **Chapter 2** we explore how silicon pore optics are manufactured. We start by presenting how silicon pore optics plates are produced, coated, activated, and stacked into high-performance, self standing X-ray optics. Then, we further investigate how these stacks are assembled into mirror modules and characterized.

In **Chapter 3** we study in details how plasma eching enables the compatibility of thin film metallic coatings and direct bonding of silicon pore optics. First we ensure that plasma etching does not impact the low surface roughness required to achieve high imaging performance. Then we demonstrate that plasma etching before thin film deposition prevents unintentional removal of the metallic coatings during the activation step, making coating deposition compatible with direct bonding of silicon pore optics plates.

Finally **Chapter 4** proposes the design and modeling of a novel optical system composed of a Laue lens coupled to an X-ray tube that produces a focused beam in an energy range near 100 keV (λ = 12.4 picometer). One application of this system is radiation therapy, where it could enable treatment units that are considerably simpler and lower in cost than present technologies relying on linear accelerators. The Laue lens is made of Silicon Laue Components (SiLCs), which exploit SPO technology, underlying the versality and potential of this technology.

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