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Silicon pore optics for high-energy optical systems

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CONCLUSIONS AND OUTLOOK

This thesis details silicon pore optics (SPO) through its manufacturing process and applications. As described in **Chapter 2**, SPO uses spin-in technology developed for decades by the semiconductor and automotive industry, which have massively invested in the fabrication and processing of silicon wafers. SPO technology has become very mature thanks to the continuous development efforts to prepare the industrial production of Athena[1], the largest X-ray optics yet to be launched into space. In essence, patterned coated silicon substrates are assembled into high-performance, self standing X-ray optics by direct bonding them on top of each other[2, 3]. Direct silicon bonding is key to controlling the paraboloid and hyperboloid shapes of Wolter-type telescope designs[4]. Moreover, the work reported in **Chapter 3** concludes that the combination of thin film metallic coatings and direct silicon bonding is essential to increase the effective area of SPO-based X-ray telescopes[5].From this work, one can infer that SPO technology will extend the breadth and scope of future astrophysical observations. In effect, high-sensitivity observations in the X-ray band are needed to improve the understanding of high-energy phenomena of all classes of astrophysical objects, from large-scale hot gas structures, to compact objects such as black holes. For example, observing the X-ray emitting plasma of the intra-cluster medium would shed light on how hot baryons accrete and evolve [6]. Also, detecting X-ray emissions from accreting super massive black holes with high redshift ($z>6$) could reveal the processes responsible for their early growth, as well as their influence on larger scales in the early Universe [7–9].

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Put another way, this work shows that SPO is a mature technology enabling large space-borne X-ray telescopes by combining large effective area, good angular resolution, and low-mass. However, several challenges remain. First, mirror plate maximum dimensions are constrained by the wafers that are used as base material. Standard silicon wafers come in diameters ranging 50 to 300 mm, each with their own thickness increasing from 275 μm to 775 μm, respectively. At present, the semiconductor industry is widely making use of 300 mm diameter wafers. Larger wafers with 450 mm diameter and 925 μm thickness are emerging, but are not yet widespread due to the significant investments needed to transition mass-processing facilities and tools from 300 mm to 450 mm. Therefore, at present, SPO mirror plates are limited to length shorter than 300 mm, which bounds optical designs they can be used for. At the other end, although there is no clear minimum, it would become difficult to handle plates shorter than ~ 10 mm with the current equipement. Second, the pore height, which is related to the plate length, can be decreased by using thinner wafers. Thinner wafers are produced in smaller series and present higher roughness and larger thickness variations than the standard 300 mm ones, which has, until recently, made them less attractive to use. However, some of these defects can be eliminated with the use of ion beam figuring (IBF), which now offers a way to reduce thickness variations and reduce roughness. Thus, it is possible to think of SPO with mirror plate pitch smaller than 0.775 mm, increasing shell packing density. At the other end, it would also be possible to bond wafers together and then process them. This method opens the possibility to create stacks of mirror plates with double-pitch of 1.55 mm, and would be useful in case of large incidence angles, where the plate length would become too short otherwise. Moreover, SPO stacks replicate the shape of the mandrel, whether it is flat, cylindrical or conical. It can also feature a meridional curvature, parabolic, hyperbolic, circular, or any other shape. The minimum radius of sagittal curvature is only linked to the material properties, and in turn to the membrane thickness. Membrane thickness of 100 μm has been tested successfully, while 110 μm has been manufactured routinely for Athena. With these thicknesses, the plates can be bent to about 150 mm diameter while remaining comfortably far from critical stress that would lead to breakage. Also, the width and spacing of the ribs determine the open area ratio of the optics, affecting on-axis effective area and vignetting. These parameters affects the final stiffness of the system, and have impact on the optical performance. The higher the density of ribs, the smaller the open area ratio, the stronger the support of the mirror membrane.

In effect, SPO is not only an enabling technology for large space-borne X-ray telescopes such as Athena, it is also a versatile technology that can be further developed for a wide range of applications. For instance, Kirckpatrick-Baez designs or lobster eyes could also be implemented. The technique of replication of a mandrel in self-standing stacks of mirror plates can be used for any medium to large series manufacturing of mirrors, with potentially any figure. For instance, as presented in **Chapter 4**, SPO technology is being actively developed to create advanced gamma-ray focusing elements via the use of diffraction in the volume of the crystalline plates. Self-standing single or double-curvature stacks of plates can be used as Laue lens elements providing improved focusing capability compared to other methods. Consequently, we have designed and modeled 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[10]. 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. As descibed in [11], radiation therapy plays an essential role in the treatment of cancer, with more than 60% of patients receiving radiation therapy, mainly in the form of high-energy photons (2-20 MeV), in the course of their disease management. Therapy beams at low energies may also be attractive in their ability to achieve increased sensitivity when used in combination with high-Z nanoparticles. Recent high-profile studies have shown that tumor cell survival is significantly reduced by combining X-ray irradiation with gold nanoparticles [12]. However, it is not currently possible to deliver low-energy irradiation in the clinical setting without unacceptable toxicity to the skin and normal tissue. In our study case, we designed and studied a Laue lens that can focus radiation in a cylindrical volume of 0.7 mm diameter and 10 mm length when coupled to an X-ray tube with a source size of 2 mm diameter. The Laue lens is made of Silicon Laue Components (SiLCs), which exploit the SPO technology. A dose rate of 0.2 Gy/min can be achieved at the focus placed 10 cm within a water phantom considering a 15 mA anode current set to 200 kV. This dose rate is 72 times more than the dose rate at the entrance of the volume. Thus this system can produce a very high focus-to-skin ratio with a small, sharp focus and relatively low dose rate. It should be noted that we studied here an ideal case and that errors in positioning and alignment will affect the performance of an actual system. A sensitivity study will be performed at a later stage. Yet, several hurdles, such as the dose rate, need to be overcome before this could be translated into a meaningful clinical device. Since a typical radiation therapy treatment requires a dose of approximately 2 to 10 Gy to the tumor in a single fraction, at the dose rates simulated here the treatment time is 10 to 50 minutes. While this is not unreasonable the irradiated volume is a small 0.7×10 mm cylinder whereas typical target volumes might require a $10 \times 10 \times 10\ cm^3$ volume. At the current dose rate the time would be prohibitively long if the spot were scanned over this volume, and the skin sparing effect would be reduced. However, the technology is attractive since such a device could be a cost-effective option for treatment tumors particularly where sharp gradients in dose distribution is needed. Given the dose rate and geometry constraints this might be better suited to smaller target regions < 10 cm deep in tissue. Also, with the increasing use of MRI machines, it is predicted that tumors will be detected at earlier stages in the future, which would make such a tool well suited to treat them.

Finally, the work presented in **Chapter 4** can be extrapolated to X- and gamma-ray astronomy[13, 14], a field that could also benefit from SiLC. For example, hard X-ray astronomy in the energy range up to 200 keV is currently limited by the low signal to noise ratio above ~78 keV, at which point the effective area afforded by the current generation multilayer mirrors decreases quickly[15], while the background does not. Laue lenses use Bragg diffraction to concentrate gamma-rays and therefore decouple the collecting area and the detector volume leading to an increase in sensitivity. Furthermore, many areas of astrophysics would, benefit significantly from new observational constraints in the 78 - 200 keV range. Polarization measurements combined with timing capabilities could distinguish between competing models for pulsar magnetospheres; the emission mechanisms in the jets of microquasars and AGN could be distinguished (synchrotron or inverse Compton); Also, the regions of strong gravitational fields near black holes where high-energy emission is produced could be studied.

Ultimately, the silicon pore optics technology is a maturing solution for high-energy optical systems. With further advances, this technology can enable more applications that require imaging and focusing of high-energy radiation.

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