Aberration-free x-ray lenses made of silicon

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ABSTRACT

Brilliant beams of hard x-rays, with geometrical cross-sections below 50×50 nm^2, are a standard research tool for synchrotron users. With the advent of lower emittance sources, such as NSLSII, Petra III and Max IV, and planned upgraded lattices, such as APS-2, SPING8-II, ESRF II and DLS II, nanofocusing optics operating in transmission mode will become more competitive than they are currently. In general, they suffer from lower efficiency than reflective optics, however they often have easier set-up and alignment, combined with a smaller footprint. Fabrication and exploitation of ultra-short focal refractive lenses has not witnessed the same progress in the last decade as other optics, such as multilayer mirrors and multilayer Laue lenses. This paper reports on current status of high-resolution lithography for fabricating silicon lenses and on proposed designs for a new class of refractive lenses with zero aberrations and good efficiency. The new designs are created with geometrical parameters matching the spatial resolution achieved by modern lithography and silicon etch technology.

Keywords: synchrotron optics, x-ray lenses, geometrical optics

1. INTRODUCTION

X-ray Nanoprobe instruments rely on focusing optics with very short focal lengths, typically of order 50 mm. The next frontier in Nanoprobe development is the achievement of smaller and smaller beam cross-sections, of order 10 nm, with sufficient flux for user experiments. Therefore, a reduction of the optic's focal length, to about 10 mm, will be necessary. The ultimate goal is single digit nanometer focusing, which has already been achieved with multilayer coated mirrors and multilayer Laue lenses. Such small beams are not yet widely available to hard x-ray beamline users. Use of such ultra-short focal length optics is limited mainly because of the small apertures required. Their use will become more convenient, on machines with lower emittance electron sources, and higher photon beam brilliance. Single-digit nanometer focusing refractive lenses have not yet been demonstrated. X-ray lens performance is hampered by absorption in the material, non-perfect fabrication results, and by properties of the material used, such as its non-crystalline form. The most recent silicon lens etch results are presented in the next section, as these give an important indication of what quality can be achieved with standard lithography and relatively advanced etch technologies. We show the path towards

achieving short focal length performing lenses, using silicon. Despite its low efficiency at energy values of interest, silicon micro-structures are currently superior to other materials. We follow up the recent work on short focal length aberration-free lenses, with a practical method for producing ultra-short focal length lenses, in the last section. A breakthrough in silicon lens fabrication will only happen in the framework of a strong collaboration between the synchrotron community and the silicon technology experts. Further developments in the field of nano-lithography methods [1] are necessary before the synchrotron community can finally enjoy use of ultra-short focal refractive x-ray lenses. A new class of nanofocusing x-ray lenses [3] will require the use of lithographic techniques with spatial resolution better than 50 nm.

2. FABRICATION LIMITS FOR SILICON LENSES

We have trialled fabrication of a silicon kinoform lens with overall spatial resolution just below 100 nm. Fabrication utilised e-beam lithography and fast-switching Bosch™ deep reactive ion etching with an Oxford Instruments PlasmaPro 100 Estrelas system. Examples of the silicon kinoform structures fabricated by this method are shown in the scanning electron microscopy (SEM) images in Figure 1, where the lenses have an elliptical curvature with a smallest radius at the apex $R = 150$ nm. The whole lens structures are several millimeters long and only the narrow ends of the elliptical nanofocusing surfaces are visible in these images. The smallest feature size (the thickness of lens sidewalls) with these lenses are $t = 1$ µm wide. Etch angles of $\theta = 89.9°$ and scalloping amplitudes lower than 40 nm, were achieved as shown in Figure 2.

A topographical image of the x-ray lens, measured with monochromatic radiation with $E = 12$ keV, is shown in Figure 3. The lens was oriented to provide vertical focusing of the undulator source, with a focal distance of $f = 30$ mm. The data were collected by imaging the x-ray beam on a 5 µm thick Eu:LuAG scintillator. The image was relayed to a PCOEdge CMOS detector by magnifying visible light optics. The spatial resolution of the detector is of order 1 µm. The scintillator was placed at further distance from the lens focal plane, due to geometrical constraints. The line focus from this single-element elliptical lens, visible at the centre of the image, is therefore blurred.

One drawback of the silicon etch is that perfect verticality is not reached leading to the appearance of geometrical aberrations, because the shape of the refractive surface is not conserved along the lens height. Furthermore, the thickness of the phase conservation kinoform features is not constant and intensity and phase variations appear along the lens height. Our previous experiments have often shown variations in beam focused profile and intensity along the lens height [4]. These effects are visible in Figure 3, where the line focus intensity is not uniform and has a constant variation with position. If the variation in thickness and curvature of the lens could be controlled and modelled, methods to design and align the lens could be developed to minimise its effect. However, it is not straightforward to assume that these imperfections can be completely controlled or compensated.

A simplified approach can be used to model the effect of the non-zero etch angle: $\varphi = 90° - \theta$. We assume that the ellipse semi-axes a and b change linearly along the z axis:

$$\Delta a(z) = D(z)\tan\varphi \qquad (1)$$

$$\Delta b(z) = D(z)\tan\varphi \qquad (2)$$

To a first approximation, these changes have an impact on the effective focal length. The major contribution to its relative change is:

$$\Delta f / f = \Delta a / a \qquad (3)$$

or

$$\Delta f(z) = \frac{D(z)}{\sqrt{\delta(2-\delta)}}\tan\varphi \qquad (4)$$

The change in focal length Δf in a silicon single element lens, integrated over a lens thickness $D = 80$ μm, and using a conservative value for the angle $\varphi = 90 - \theta = 0.1°$, is a function of energy, like the lens depth of focus (DOF), which can be calculated as in [5]:

$$DOF = \frac{\lambda}{4(1-\delta)\left[1 - \sqrt{1 - \left(\dfrac{NA}{1-\delta}\right)^2}\right]} \qquad (5)$$

With

$$NA = A_{eff} / (2f) \qquad (6)$$

And

$$A_{eff} \sim \frac{2\delta f}{\mu t}\left(1 - \exp^{-\frac{\mu t A}{\delta f}}\right) \qquad (7)$$

The negative impact of the etch angle on the lens effective focal length can balanced by the relatively large depth of focus for lenses with small numerical aperture. However, the etch angle $\varphi \neq 0$ will potentially be an obstacle to effective and real improvement of the numerical aperture of the lens and may be a significant barrier to achieving single-digit nanometer focusing. The total lens thickness D should be optimised to ensure that the total focal length variation is smaller than the depth of focus.

The minimum sidewall thickness, t, is another important factor and is determined by the aspect ratio that can be achieved during etching, currently around 50:1. Material thickness hugely affects the amount of absorption by the lens and, therefore, its numerical aperture NA and diffraction limit s. These quantities are plotted in Figure 4. The kinoform lenses currently fabricated by our group, with minimum $t = 1$ and 2 μm, can reach $NA = 1$ mrad, which is currently the best numerical aperture possessed by a refractive nano-focusing lens. In order to improve performance, the desired sidewall thickness should be decreased. For instance, a value of $t = 0.4$ μm provides an ambitious lens fabrication plan, bringing

the numerical aperture to $NA \sim 2$ mrad. The diffraction limited spot size is then $s < 30$ nm for $E > 10$ keV (Figure 4). A realistic proposal for fabricating the next batch of silicon nanofocusing lenses would be to use $D = 30$ μm, and an aspect ratio of 75:1.
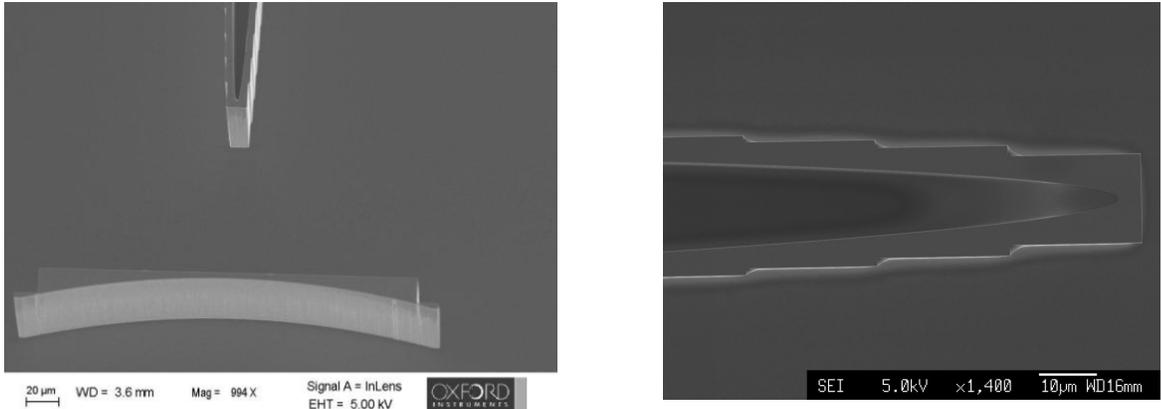

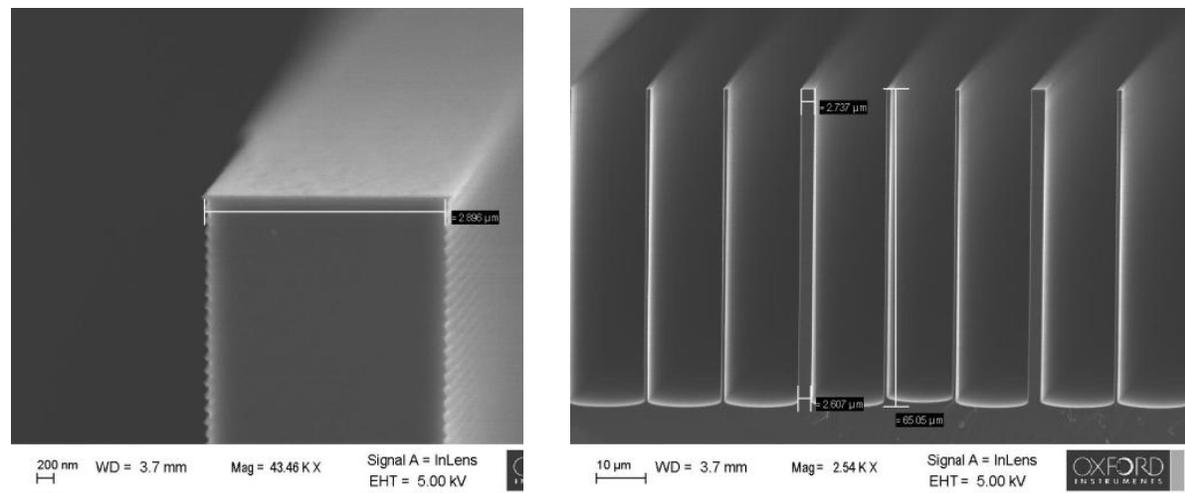**Figure 1.** SEM images of planar silicon kinoform lens detail, with a radius at the apex of $R = 150$ nm

Figure 2. SEM image of a 65 μm thick test structures etched with the planar silicon kinoform lenses in the etch optimisation process. Scalloping < 50 nm and etch angle $\theta = 89.9°$.
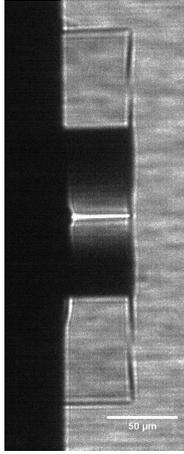
Figure 3. X-ray topographic images of a kinoform lens with focal length f = 30 mm, acquired on highly coherent synchrotron beamline I13-1 at Diamond Light Source. The lens is aligned to provide vertical focusing. The bright line at the centre is the focused radiation. The dark area on the left is the supporting wafer; the dark area around the focal line is the shadow of the lens body. Refraction from borders of a pre-collimating large radius elliptical surface, visible in the SEM in Figure 1 can be observed.
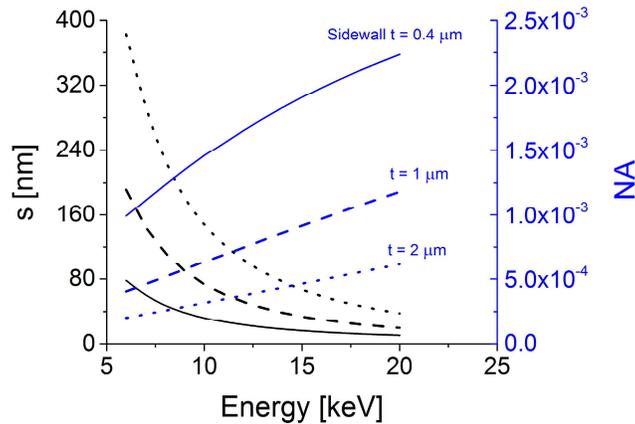

Figure 4. Diffraction limit s for silicon kinoform lenses (black curves) and numerical aperture NA (blue curves). The solid curves are calculated for t = 0.4 μm, the dashed lines for t = 1 μm and the dotted lines for t = 2 μm.

3. DESIGN OF SHORT FOCAL LENGTH LENSES

The efficiency and resolution of ideally fabricated kinoform lenses are limited by absorption, which is strongly affected by the sidewall thickness. The main technological issue to be solved is achieving sub-μm sidewalls in silicon. The theoretical issue is to design arrays of lenses with zero-aberrations. Arrays of refractive surfaces are necessary for ultra-short focal lengths due to the small radii required [6,7]. Aberration-free lenses are not a simple array of surfaces with same shape, but rather arrays with decreasing radii, which make the x-ray beam progressively more convergent [6].

An ideal compound lens design, as proposed in [3], is illustrated in Figure 5(a). In Figure 5(b), we show the lens design which would result by employing Cartesian oval surfaces to refocus the convergent beam from the first elliptical refractive surface, with each oval increasing the angle of any given paraxial ray from the optical axis. Using solely elliptical surfaces or a combination of elliptical and ovoid surfaces to design a lens without aberrations is possible as seen by comparing the designs in Figures 5(a) and 5(b). For reduced absorption, when a kinoform lens design is used, it is important to provide each kinoform step with a tilting angle equivalent to the angle of the rays to the optical axis. The compound kinoform lens design in Figure 5(c) is a simple elegant solution to the angle problem, as it inherently provides kinoform steps that are always parallel to the rays. Performance of a similar system, with focal length f = 21 mm, is summarized in Table 1. Fabrication of kinoform lenses for E > 15 keV will not be possible unless the resolution of lithographic patterning increases due to the small refractive index decrement and to the small radius required at such energy values.
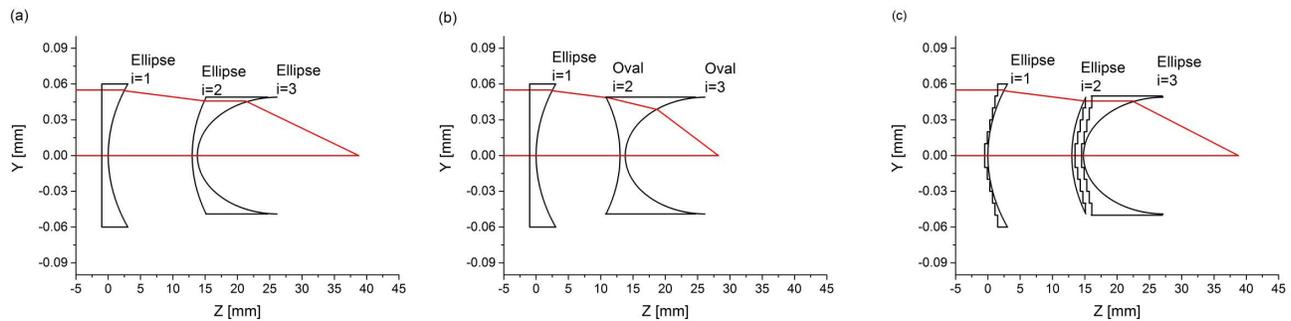

Figure 5. Schematic representation of aberration-free x-ray lens designs composed of (a) elliptical refractive surfaces, (b) ellipses and Ovals of Descartes and (c) compound elliptical kinoform structures [3].. The principal rays are shown in red. All geometrical rays refracted through the single elements are parallel to the kinoform steps. This is a necessary condition for phase preservation of the x-ray beam in the lens material.

Table 1. Performance of silicon kinoform lens design illustrated in Fig. 5(c), with f = 21 mm, and t = 0.4 µm.

E (keV)	Smallest Radius [nm]	Effective Aperture [µm]	NA [mrad]	Diffraction limited spot size [nm]
8	290	94	1.25	46
12	130	82	1.9	21
16	71	106	2.4	12
20	45	125	2.85	8

4. CONCLUSIONS

We have offered a simple yet analytically correct design for planar nano-focusing refractive optics and discussed current micro-fabrication technological limits. Silicon x-ray lenses are not currently available commercially although the fabrication tools exist to make them a standard beamline optics component. Several fabrication methods are being trialled for achieving similar results in diamond, including moulding, laser cutting, and dry etching. Higher effective apertures and transmission values are possible with diamond, leading to smaller focused beams. This justifies the current trend in diamond micro-fabrication research for synchrotron optics applications.

A correct formulation of the optical layout is a necessary condition to improve performance of x-ray lenses for high-resolution synchrotron applications. Such lenses will rely on the use of refractive surfaces of elliptical, hyperbolic, or Cartesian oval form.

Acknowledgments

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