Germanium and silicon kinoform focusing lenses for hard x-rays

L. Alianelli1, K.J.S. Sawhney1, M.K. Tiwari1, I.P. Dolbnya1, R. Stevens2, D.W.K. Jenkins3, I.M. Loader2, M.C. Wilson2 and A. Malik2

1 Diamond Light Source Ltd Didcot - OX11 0DE UK
2 STFC Central Microstructure Facility Didcot - OX11 0QX UK

Email: lucia.alianelli@diamond.ac.uk

Abstract. Progress in synchrotron radiation instrumentation and successful fabrication of novel x-ray optics enables probing the matter at micro- and nano-scales from virtually any sciences – from biomedical, environmental to material sciences. In-line, compact focusing optics, based on refraction, are designed and fabricated for use in hard and very hard x-ray beamlines at Diamond. The first test results at a Diamond beamline, using micro-focusing silicon and germanium lenses, are discussed in this paper.

1. Introduction
The availability of bright third generation synchrotron sources has driven the development in the past decade of optical devices capable of concentrating the x-ray beam into spots that are less than 100 nm in diameter. Several upgrade programs exist for storage ring renewal capable of lower emittance [1 - 3], with the aim to focus the hard x-ray beam to few nanometres. Exploitation of micro- and nano-focused x-ray beams on a daily basis is seen as a priority by the international synchrotron community. At Diamond Light Source and STFC we work to innovate refractive focusing devices [4, 5] for use with hard and very hard x-rays. We are designing, fabricating and testing lenses that will eventually focus the high intensity monochromatic synchrotron beams to nano-sizes. By employing single crystal silicon and germanium, we are able to reduce scattering of the x-rays that is responsible for the limited resolution of other types of compound refractive lenses. Refractive focusing or collimating optics can be easily kept and used in vacuum hence they do not require any window between optics and sample. Moreover they do not produce diffraction effects, and their use is preferred to the use of slits even when the gain is not very high.

Planar technologies offer high accuracy for the fabrication of planar focusing lenses. Curved surfaces can be made with radii of about 1 μm, therefore focal length in the meter range are achieved with a single refractive surface. A kinoform profile is the most suited for applications requiring high flux and lateral resolution at a fixed energy [6]. The elliptical or parabolic internal wall produces focusing, while the kinoform profile reduces absorption but permits phase conservation between different parts of the electromagnetic wave. The low absorbing kinoform lens is the best candidates for nanofocusing because of the high lens effective aperture. The function of a kinoform lens has been described in the past by several authors [6 - 10]. Typical minimum wall thickness of few micrometers is needed to make an efficient lens. Therefore state-of-the-art hard masks and etching tools are
necessary in order to replicate the lens profile with high aspect ratio. For nano-focusing applications, array of refractive surfaces with changing eccentricity have to be carefully simulated and designed in order not to introduce aberrations [11, 12].

2. X-ray lenses fabrication and test
Pre-patterned silicon and germanium lenses were etched by using a modified Bosch process. The maximum depth achieved so far is just above 100 micrometres. SU8 was used as a mask for the Si lens shown in Figure 1. A deposition process to deliver aluminium nitride and silicon oxide hard masks with very high selectivity and purity is being developed for the future lenses. The aim is to be able to etch 500 µm high structures in silicon and germanium. We have made Si lenses for x-ray energy E = 8 to 20 keV, and Ge lenses for E = 20 to 150 keV.

The bending magnet Test Beamline B16 is equipped with an optics table carrying three stages for the optics, the diagnostics, and the detector. The beam from the bending magnet source was imaged by the lens, after diffraction from a double crystal Si 111 monochromator. We used E = 8, 12 keV (Si lenses) and 20 keV (Ge lens) with F = 1000 mm, and beam demagnification in the vertical plane only. The source size FWHM at B16 is 50 µm and, for this experiment, the monochromatic beam before the lenses was unfocused. The experiment was located at 47 m from the source. A profile of the vertical focus from the germanium lens is shown in Figure 2: the derivative of the fluorescence signal, from a gold wire, can be fitted by a Lorentzian with FWHM = 1.06 µm.

In the same experiment we used crossed wafers for 2-dimensional focusing [13] and tested lenses with F = 200 mm and F = 600 mm. The gold wire scans of the beams focused by these lenses give a FWHM of 0.5 µm or less, depending on the method used to smooth the data. We do not include these data here as they suffer from vibrations of the experimental set-up.

The measured one-dimensional gain from the fluorescence data is 32, at least one order of magnitude less than expected. The measurement of the gain via the fluorescence scan is not very precise: using measured transmission data T = 50% [7] and an effective aperture of A = 200 microns (Figure 3), we obtain instead G = 100.

3. Future work
Kinoform lenses are efficient focusing optics for hard x-rays. Germanium lenses are presented here for the first time and tests at energy larger than 20 keV (up to 80 keV) are planned at Diamond in the coming months. Improved fabrication methods using modern plasma etchers will be used for the next lenses, which will deliver smoother walls, therefore better gain. There is much scope for improvement of kinoform lens testing as well, for instance using smaller and more coherent sources. Therefore we are confident that higher gain will be achieved during this project.

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Figure 1. Detail of a Si kinoform lens. The step length $L$ is equal to the ratio of the wavelength to the refractive index decrement. $L$ varies between 20 and 100 µm, depending on energy and material. The step width decreases with increasing the aperture, starting from a few microns at the center. Small widths are difficult to fabricate, therefore some extra thickness is added as can be seen here. The total aperture of lenses reaches 800 µm.

Figure 2. Derivative of the fluorescence signal from a gold wire scan, in the focal plane of a germanium lens, with $F = 1000$ mm and $E = 20$ keV. The red line is the fit result, with a Lorentzian curve with FWHM of 1.06 micrometer. The experimental data were not smoothed.

Figure 3. Peak intensity at focused beam versus size of incident beam. These data are recorded with a spatial resolution detector with low resolution, and effective pixel size of 6.5 µm.