Smart X-Ray Optics

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Abstract. This paper describes reflective adaptive/active optics for applications including studies of biological radiation damage. The optics work on the polycapillary principle, but use arrays of channels in thin silicon. For optimum performance the x-rays should reflect once off a channel wall in each of two successive arrays. This reduces aberrations since then the Abbe sine condition is approximately satisfied. Adaptivity is achieved by flexing the arrays via piezo actuation, providing further aberration reduction and controllable focal length.

1. Introduction

The UK Smart X-ray Optics programme is developing advanced adaptive x-ray optics; large scale for astronomy and small scale for terrestrial applications, specifically radiation damage studies in biological systems. This paper describes optics for the latter, a Micro-Structured Optical Array (MOA), similar to but more flexible than a polycapillary optic [1]. MOAs use grazing incidence reflection to focus x-rays along aligned channels (figure 1); x-rays from a source $S$ are reflected twice at grazing incidence, first by an unbent array, then by an array curved to a radius $R$ by piezoelectric actuation. An image of the source is formed a distance $f$ from the second array. Changing either array’s radius of curvature changes the focal length; by varying the bending across the array, aberrations can be reduced. Arrays can be circular, for 2-D focusing, or linear, providing a line focus from a point source. Work so far has concentrated on the latter for radiobiology at 4.5 keV [2] with 10:1 aspect ratio channels in 2×2 mm arrays of 100–200 μm thick silicon and with $R=4.7$ cm, $f=5$ cm.

Figure 1. MOA configuration.
2. Modelling
Modelling of the MOAs has been carried out using finite element analysis (FEA), to assess the amount of bending achievable, and ray tracing, to determine the quality of the focus.

2.1. Finite Element Analysis
Array bending has been modelled by FEA using COMSOL Multiphysics™. The actuator arrangement assumed in the modelling is shown in figure 2a. Because of the symmetry the FEA could be carried out on a quarter of the chip as in figure 2b, to minimise computing overheads. The FEA indicates high stress points, as shown in figure 2c, where fracture would occur if the bending radius was too small. Note that only a small number of channels was modelled, due to computing overheads.

The modelling indicates that, for the parameters and actuator arrangement used, it is not possible to obtain the amount of bending needed. This result has been verified by Talysurf measurements on 200 µm thick silicon. The required bending can only be achieved by using very thin silicon and very thin piezo material; neither of these is technically easy but ways of overcoming the problems are currently being addressed.

![Figure 2](image2.png)

**Figure 2.** (a, left) The arrangement of the piezo actuators (grey) and the area modelled (rectangle). (b, centre) the geometry of the FEA model. (c, right) FEA result showing the high stress points (light).

2.2. Ray Tracing
A software package, Q, developed at the University of Leicester specifically for grazing incidence optics [1,3], is used for ray tracing the MOAs. Summarising the results briefly, with the design parameters of section 1, a focal line width of 0.3 µm is predicted for a 4.5 keV point source, with 2 µm for a 5 µm diameter source (the source size planned for radiobiology is 1 µm). Figure 3 shows the reduction in focal width using a two-reflection MOA compared to a single reflection. More significantly, for radiobiology, which requires a high throughput of samples, such a MOA should provide over two orders of magnitude focused flux than a zone plate working at the same source demagnification.

![Figure 3](image3.png)

**Figure 3.** Comparison of the focal widths provided by single and double reflection MOAs for radiobiology.

3. Manufacturing Issues
The results of the modelling discussed above rely on the reflective channel walls being smooth; to provide the 100× advantage over a zone plate, the wall rms roughnesses must be less than about 2 nm. Initial structures were made via the Bosch process of deep silicon etching [4], which uses successive etch and passivate cycles to reduce lateral etching. However, even with post processing (oxidation and
removal) it was not possible to reduce the rms roughness below \(\approx 3\) nm over small areas at the channel tops, increasing to \(\approx 13\) nm at the bottoms, where the channels were also narrower. For larger areas the roughnesses are significantly higher than these values.

Latterly the silicon etching has been done using a directional wet etch process on the \(<110>\) crystal surface [5], giving a wall roughness of 1.2 nm, independent of depth in the channel (figure 4). In addition, the channel walls show no significant curvature.

**4. The Future**

As discussed previously, a first application of MOAs will be in studies of radiation induced cancers, providing orders of magnitude more focused flux than a zone plate using a microfocus x-ray source. This improvement will result from the larger geometric aperture and the ability to focus polychromatic radiation. It will allow studies of tissue samples and effects leading to cell mutation (rather than death, which is less important in terms of cancer); neither of these have yet been possible.

The dependence of the wet etching process on crystal orientation means that currently only linear arrays can be manufactured. However, the line focus that such a MOA could provide would be useable in radiobiological studies, since cell samples could be arranged in a linear fashion, and linear irradiation of tissue samples could also be undertaken. Irrespective of that, several technical problems still need to be addressed, including (i) obtaining sufficient bending in one or both arrays, e.g., by using a different actuator arrangement, and (ii) design and manufacture of arrays for 2-D focusing to enable, e.g. irradiation of single cells and for other applications including imaging and lithography.

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