Deep X-ray Lithography for Production of X-ray Optics

We have commenced a campaign to explore methods in deep x-ray lithography (DXRL) with a view towards an alternative method of fabricating the high aspect ratio optics used in a new design of x-ray telescope. The target design is an extremely challenging one for the technique of DXRL and in this report we describe some recent advances in lobster-eye optics that we have made in order to meet that design.

The lobster-eye optic consists of a square packed array of square channels that are characterized by a large channel opening to length ratio (~ 1:30) (see Fig. 1). The array can be either flat with channels parallel to each other or curved where the long axes of the channels intersect at a distance R from the center of the channels (see Fig.2). The curved optic brings parallel grazing incidence x-rays to a focus at a distance R/2 behind the array. Photons form a point focus if they reflect an odd number of times from both orthogonal walls of a channel. Two orthogonal line focii result from photons that reflect an odd number of times from one wall and an even number of times from the orthogonal wall. Photons reflected even numbers of times from both walls are unfocused and form a diffuse background to the image (Fig. 2). The net image is cruciform with the central focus dominating for an optimized system (Fig. 3).

Any endeavour that needs to increase x-ray flux onto a sample or a detector can benefit from the use of an optic. An example includes x-ray crystallography, where an optic can collect and redirect flux that would miss a small sample and

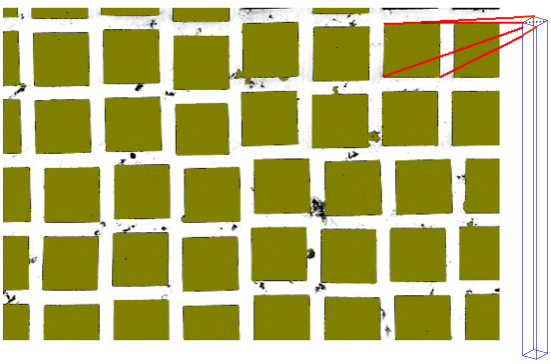


Fig. 1: Front face of a square channel microchannel-plate. The channel openings are 200 μm in this case and stacking misalignments which occur during the production of the microchannel-plate can be seen.

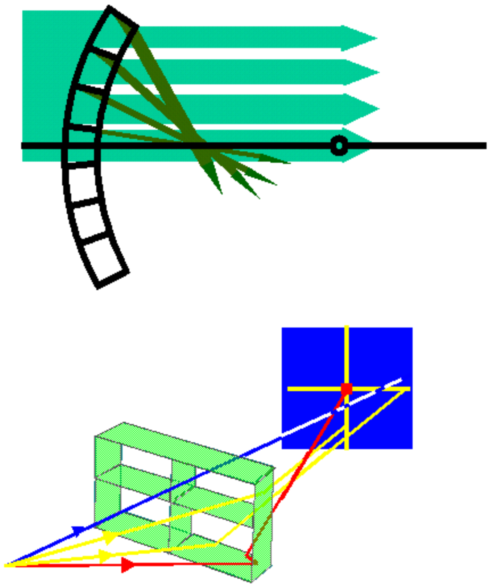


Fig. 2: Lobster-eye focusing schematics for parallel flux incident on a curved array (top) and for flux from a point source incident on a flat array (bottom). Rays reflecting from vertical or horizontal walls will reflect into a vertical or horizontal focal arm (yellow). Rays reflecting from orthogonal walls within a channel will reflect into the intersection of the focal arms - ie the central focus (red). Rays passing through the array will form part of the background (blue) of the focal image.

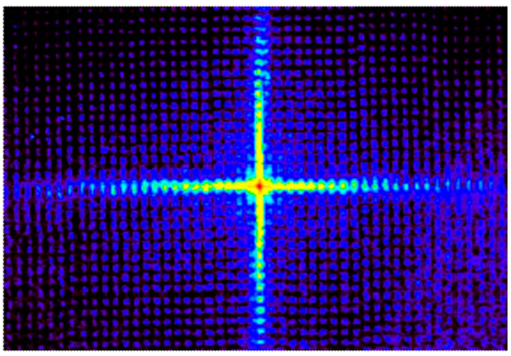


Fig. 3: Actual focal image produced by a lobster-eye array imaging 1.5 keV x-rays.

otherwise be wasted. X-ray fluorescence mapping can also benefit greatly. Here, a focusing optic has a large advantage over the pinhole optics that must otherwise be used. However, the immediate target of researchers into lobster-eye optics is to make an optic suitable for use in an x-ray all-sky monitor to be flown on a small satellite payload or as an external experiment on the International Space Station. A comprehensive study of this idea was made in Priedhorsky, Peele and Nugent MNRAS 279, 733-750 (1996), which showed that a telescope based on the lobster-eye design offers:

- an order of magnitude increase in sensitivity over any previous or current all-sky monitor;
- a large increase in resolution over previous or current instruments; and
- a portion of the soft x-ray band not previously monitored.

With these advances the opportunities for long term monitoring, cataloguing and new scientific discovery are all enormous.

The key to the implementation of this technology is the ability to make small (~1-100 μm) and long (30 - 3000 μm) channels with precisely aligned and smooth walls. Lobster-eye optics are currently made using square-channel microchannel plates (MCPs). This technology involves the drawing and restacking of glass fibres. The final step is an etch which removes the fibre core from its cladding. This method of manufacture introduces certain characteristic defects that make a real lobster-eye depart from the ideal system:

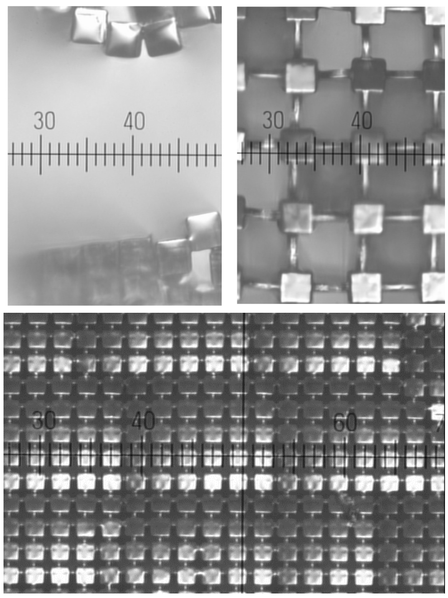
- channels can be misoriented in both a random and systematic manner;
- surfaces have a degree of roughness from the etch process;
- the flat MCP initially produced must be slumped (using a heat treatment) to conform to the desired spherical curvature thus introducing more misalignments; and
- the glass surfaces preferably require coating with metal to enhance x-ray reflectivity.

The importance of DXRL is that it offers an alternative method of making a lobster-eye optic that may avoid some of the inherent problems with MCP manufacture. Additionally, an optic made by DXRL offers the advantage that it can be made of metal and will not require coating. The initial challenge for this method is in producing a densely packed array of high aspect ratio features. Two failure mechanisms are common for these types of structures. First, the developed resist (which is formed of many tall columns) loses adhesion with the plating base and the structure collapses. Second, the tall columns are attracted to and stick to each other often exacerbating the adhesion failure. This latter problem is referred to as the 'stiction' problem.

In experiments at beamline 18B we have demonstrated that both of these problems can be overcome. We used as a mask a 15 μm thick Gold mask with 50 μm holes and 63 μm spacing between the holes. This provides more than sufficient contrast for the exposure. In the preparation of the resist we used glass and Silicon substrates. Thick layers (≥ 1 mm) of SU-8 were cast by pouring SU-8 epoxy onto a cleaned substrate and allowed to spread to the edges. After Oxygen quenching a pre-bake cycle was followed. After the x-ray exposure a post-bake cycle is also applied. An exposure dose is calculated according to the mask and beamline parameters used in the exposure. A typical dose calculated for a 1.5 mm thick resist was 300 mA min cm^{-1} which corresponds to a top dose of ~ 0.1 kJ/cm^3. After the post exposure bake the resist was developed in a PGMEA based developer from MicroChem Corp until the substrate base is reached. This step is of the order of 10 hours for our structures depending on the open area.

Using the procedure outlined above we exposed a 1.5 mm thick resist. The sample was developed down to the substrate layer. No adhesion failure was observed and with an aspect ratio of 30:1 this exceeds the best repeatable results previously

(a) (b)



(c)

Fig. 4: (a) An optical microscope top view of the sample, (b) bridges defined by the top plate are successful in maintaining the columnar structure of the developed resist, (c) the same initial mask dimensions except that the spacing has been reduced to 21 μm.

reported. An optical microscope top view of this sample is shown in Fig. 4(a). It can immediately be seen that the stiction problem has occurred leading to clumping over large areas of the resist.

Our solution to the stiction problem is to use a top plate to hold the columns in place. The x-ray exposure is performed as usual but then a top plate mask exposing a series of narrow lines joining the columns together is used to perform a low dose UV exposure (see Fig. 5). If the dose is kept low enough then the top plate structure will only form to a shallow depth – < 100 µm in these >1 mm structures. After the holes defined by the top plate mask have developed beyond this depth the developing volume becomes joined thus allowing flow of the developer between columns as before. In the final structure the columns are now spanned by "bridges" which prevent them from moving. The structure may then be electroplated in the usual way to just below the bottom of the bridges to produce the final metal structure as designed.

The mask and procedure used to obtain the result shown in Fig. 4(a) were repeated with an additional top plate exposure before development. The top plate mask defined 10 µm wide lines on a 113 µm pitch and it was aligned so that all columns were joined. The UV dose was 65 mJ/cm^2 applied for 3.5 s. The resist was developed to the substrate. Microscope images show in Fig. 4(b) that the bridges defined by the top plate are successful in maintaining the columnar structure of the developed resist and that the stiction problem has been overcome. In Fig. 4(c) the initial mask dimensions are the same except that the spacing has been reduced to 21 µm. It can be clearly seen that the bridges still hold the columns in place and that stiction has been overcome even in when the features are densely packed. Viewing the developed resist from the side allows us to measure the thickness of the top plate structures at about 70 µm.

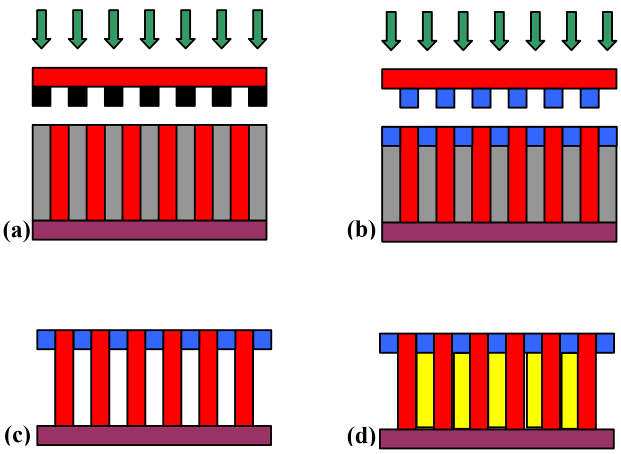


Fig. 5: Steps in the top plate process. (a) Standard x-ray exposure through an x-ray mask creating the red structures. (b) Low dose UV exposure using a mask that exposes the blue regions that link the structures exposed in step (a). (c) Develop. (d) Electroplate followed by resist removal.

This work provides an expanded ability to produce densely packed arrays of high aspect ratio structures and may find application in devices such as collimators for mammography screening and in fluid cells. Importantly for our research these results now pave the way towards overcoming the next hurdles in the DXRL manufacture of lobster-eye optics. In future work we will optimize the top plate process and then investigate factors such as surface roughness of the channel walls and the degree of control over the inclination of channel walls.

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Beamline

18B Micromachining beamline

Experimental Station

Micromachining end station

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