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Silicon Compound Refractive Lenses

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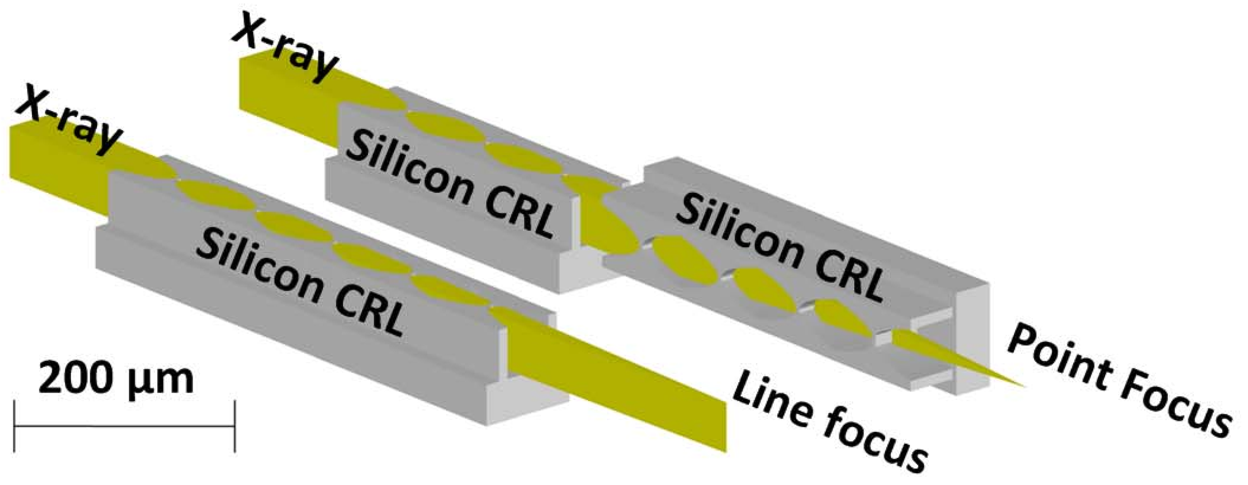
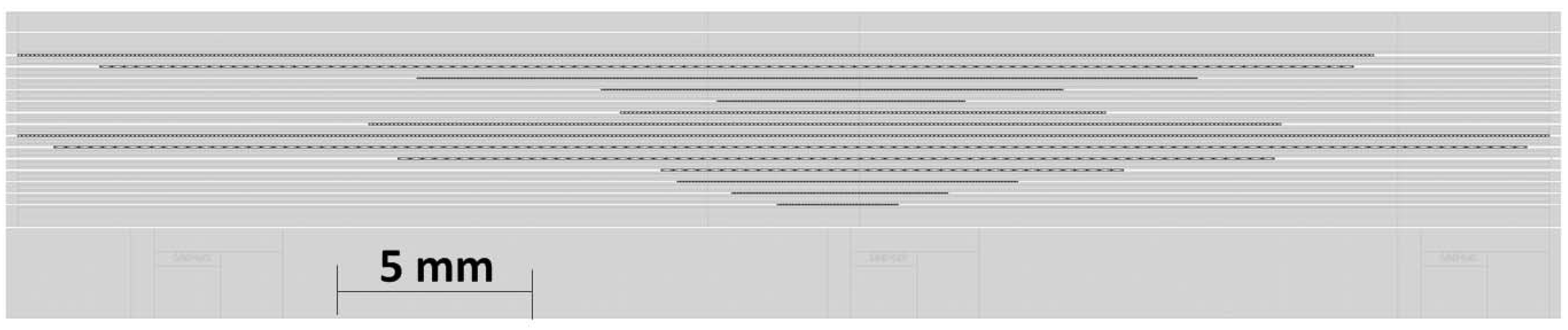
Motivation

Compound refractive lenses (CRLs) are used to collimate and to focus hard (E > 10 keV) x-ray beams, and to enable imaging with an increase in sensitivity and spatial resolution [1,2]. Manufacturing techniques which are well established in the semiconductor industry allow producing CRLs with a precision in the range of nanometers [3]. In this way, focusing of high energy x-rays to a beam waist of 50 nm with a gain in flux density above 10^4 was already achieved [4]. By improving the manufacture and the characterization of silicon CRLs, the authors aim to generate hard x-ray beam waists below 40 nm, thereby approaching the diffraction limit.



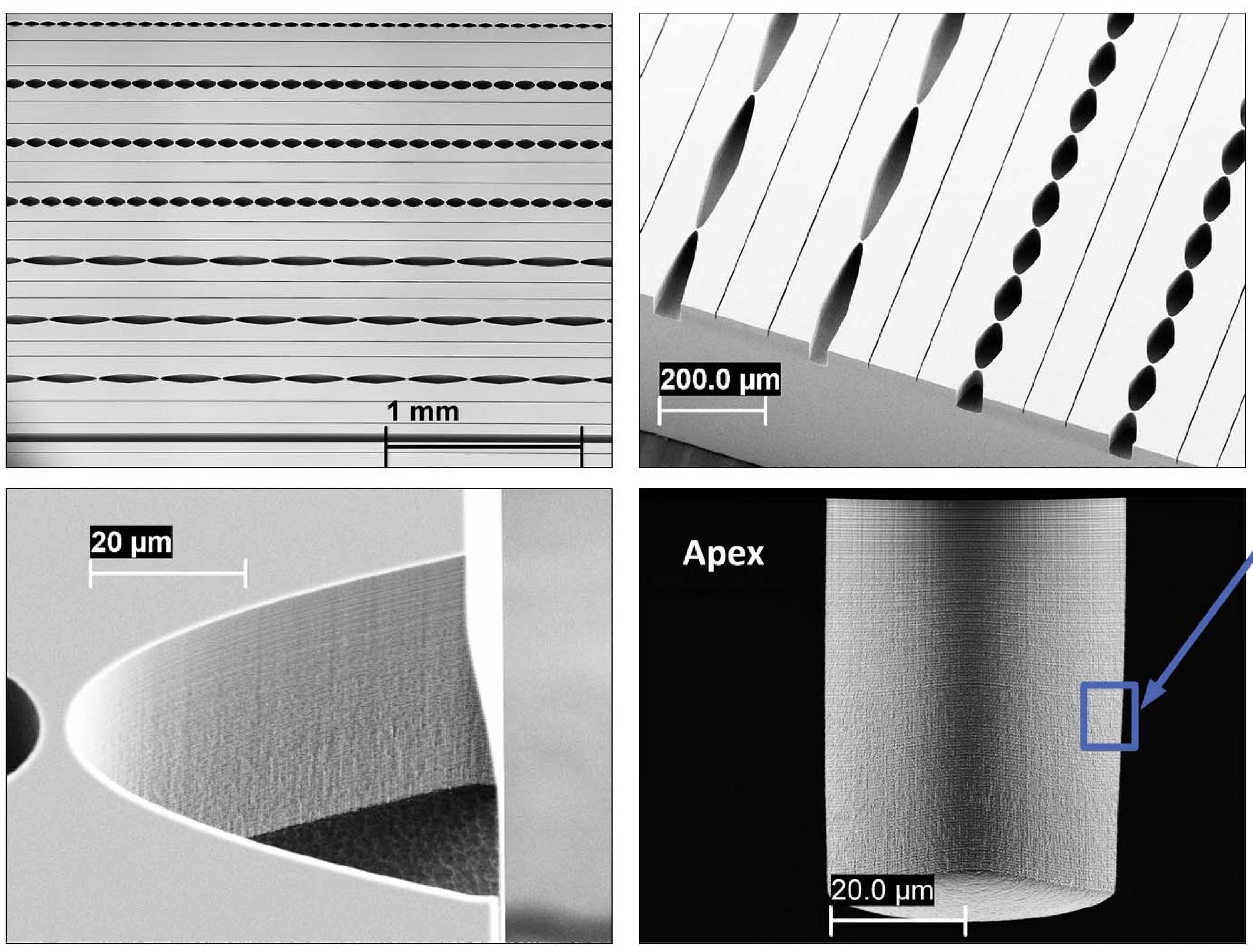
↑ Conceptual drawing for focusing X-rays. The planar process only allows the fabrication of lenses focusing in one dimension. Nevertheless, two crossed CRLs generate a point focus.



↑ The layout of one silicon chip comprises 14 CRLs. In a beamline an individual CRL can be chosen by vertical displacement of the chip. One CRL contains up to 200 single elements. Different CRLs are designed for photon energies from 30 keV to 50 keV and for focal lengths between 14 mm to 100 mm measured from the exit of the respective lens.

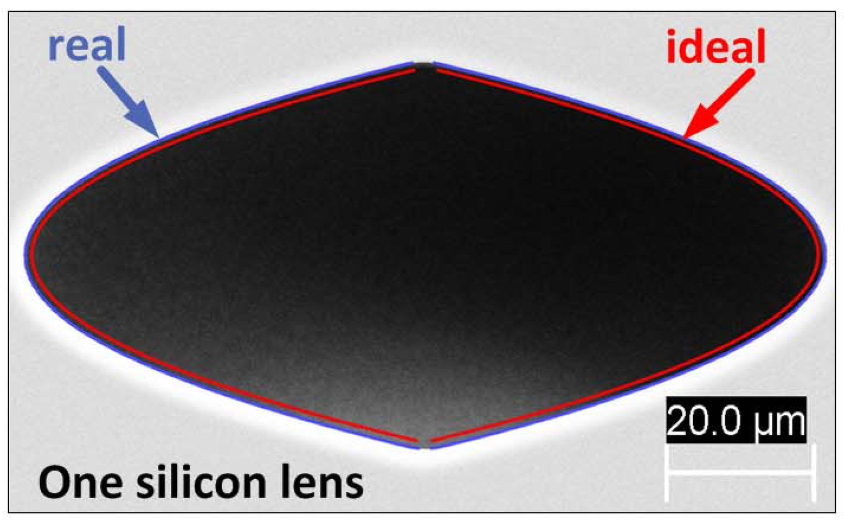
Microfabrication

The CRLs are manufactured in the cleanroom facilities of the Technical University of Denmark. The main processing steps are UV contact lithography for defining the lens pattern and deep reactive ion etching for transferring that pattern into the bulk silicon. Both steps need to be optimized in order to attain a lens with a minimized deviation from the ideal three dimensional shape. Below are some scanning electron micrographs of etched lenses viewed from different angles.



Deviation from the ideal shape

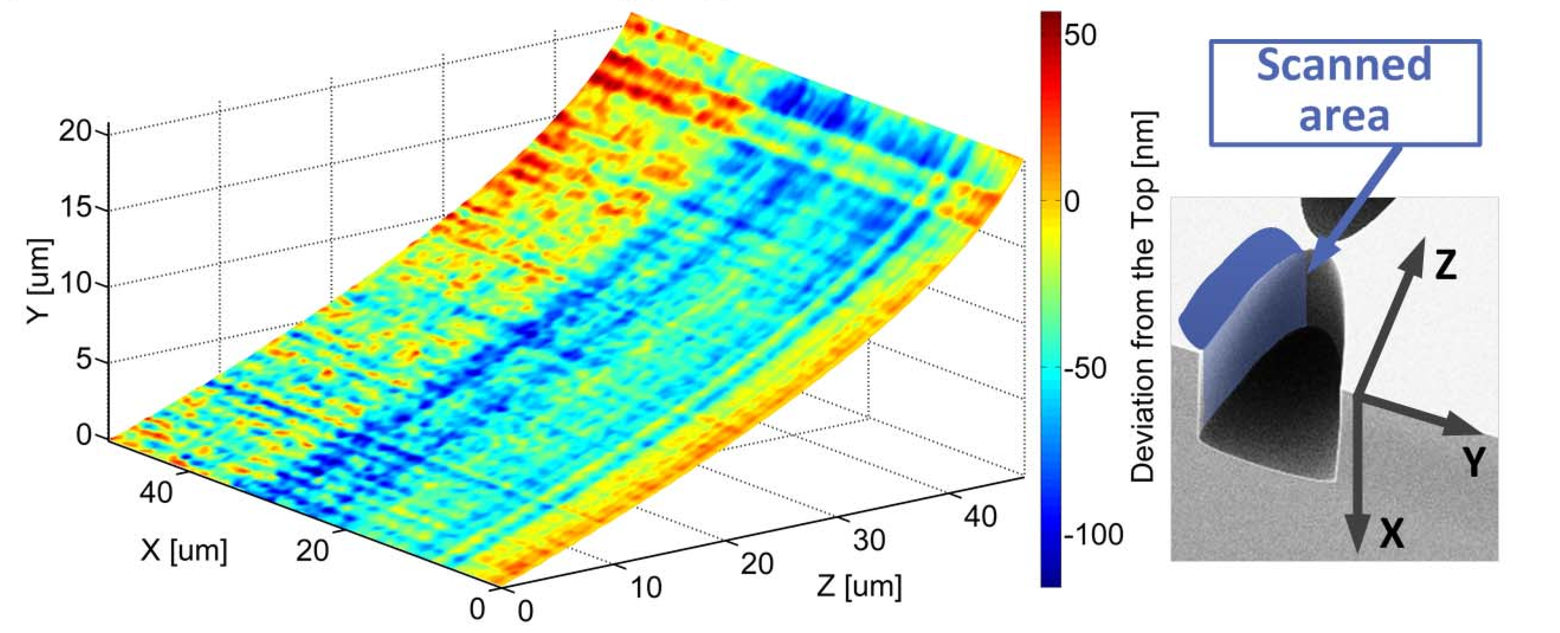
The photolithographic step and the etch step induce a lateral offset from the designed shape. This effect can be compensated for by considering it in a future layout of the photo mask for the lithography.

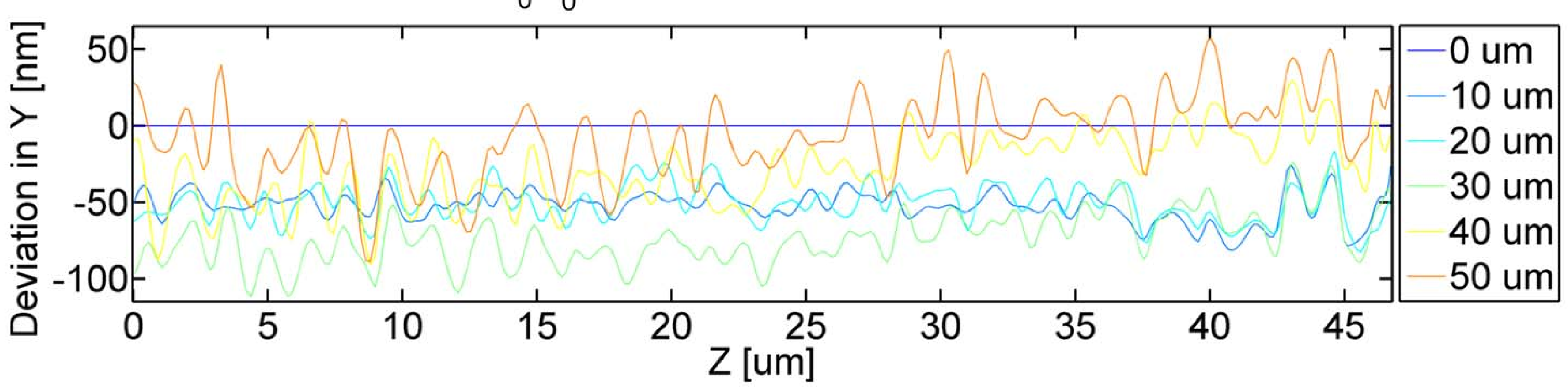


← A parabola is assumed as the ideal shape for focussing x-rays. The nominal radius of curvature at the apex is 6 µm and the nominal physical aperture is 50 µm. The real shape shows a lateral offset of 1 µm.

Characterization of the 3D shape

Cleaving of a wafer and scanning one of the lenses with confocal microscopy revealed almost one quarter of its three dimensional shape shown in the following figure:

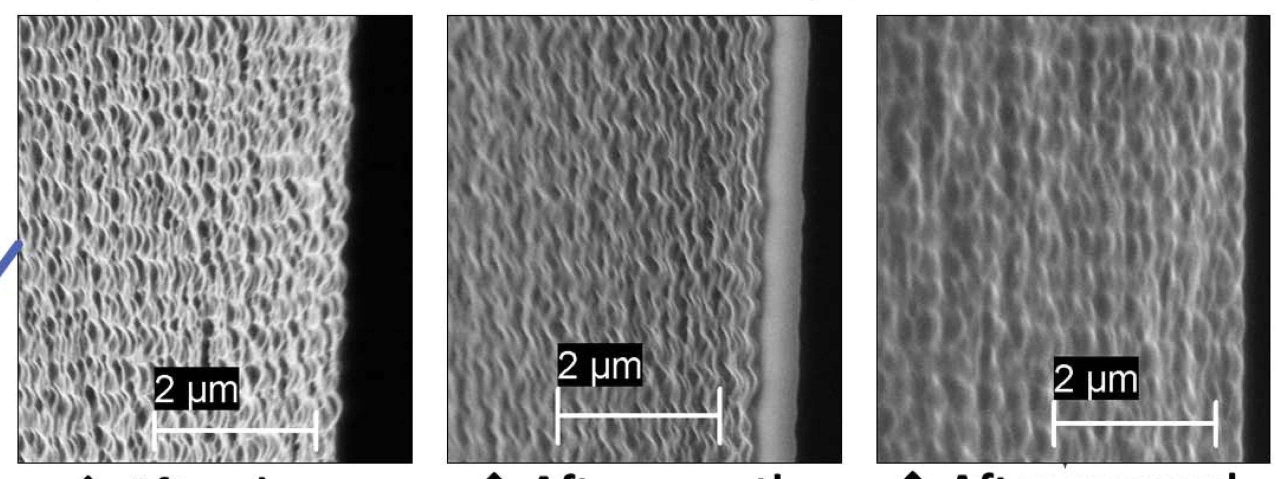




↑ Extracting profiles along the Z axis every 10 µm in the X direction and subtracting from each profile the topmost profile, indicates the quality of the etch. Along the 50 µm etch profile a shape displacement of ± 100 nm is observed, according to a steepness of the sidewalls of 90°± 0.2°.

Minimizing the surface roughness

Thermal oxidation with subsequent etching of the grown oxide layer with buffered hydrofluoric acid reduced the surface roughness of the etched lenses from 90 nm to below 20 nm, measured by scanning electron microscopy.



↑ After deep reactive ion etching

↑ After growth of 500 nm SiO_2

↑ After removal of the grown SiO2 with BHF

Further challenges

The shape fidelity of the etched CRLs is the most crucial criterion when it comes about focusing x-rays close to the diffraction limit. In order to attain the perfect shape, each manufacturing step has to be optimized, which is enabled by a huge accessible parameter space of the involved manufacturing equipment. But the optimization task asks in turn for reliable methods for the measurement of the three dimensional micrometer large features with an accuracy in the nanometer range. Thus, future work will also include the development of techniques capable of doing this characterization.

References

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