

Multilayer Laue Lenses with Focal Length of 10 mm

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Multilayer Laue Lenses with Focal Length of 10 mm

**S Braun¹, A Kubec¹, M Menzel¹, S Niese², P Krüger², F Seiboth³, J Patommel³,
C Schroer³**

¹ Fraunhofer IWS Dresden, Winterbergstr. 28, 01277 Dresden, Germany

² Fraunhofer IZFP Dresden, Maria-Reiche-Str. 2, 01109 Dresden, Germany

³ Technische Universität Dresden, Institut für Strukturphysik, 01062 Dresden, Germany

E-mail: stefan.braun@iws.fraunhofer.de

Abstract. Multilayer laue lenses are diffractive optics with a high potential for producing X-ray foci in the order of 10 nm or even below. Particularly for hard X-rays ($E > 6$ keV) these optics promise better resolution and higher efficiencies than currently available Fresnel zone plates.

Magnetron sputter deposition has been used for the fabrication of multilayer laue lenses using the layer materials MoSi_2 and Si. The lens design has been defined to get focal length in the order of 10 mm. One of the lenses with an aperture of about 20 μm has been used as focusing optics in the nanoprobe beamline P06 at PETRA III. Ptychography has been applied to characterize the caustic of the focused beam and to determine the size of the X-ray focus. A spot size of about 39 nm could be obtained with a photon energy of 21 keV and a focal length of 9.9 mm.

1. Introduction

Due to their short wavelengths the use of X-rays in microscopy experiments has the potential to resolve structures on the length scale of atomic distances. However, despite this theoretical possibility, the experimental difficulty to produce optics that are able to fully use this potential results in typical resolution limits of current X-ray microscopes in the range of several 10 nanometers.

For X-ray focusing or imaging different physical effects can be used: Reflection, refraction and diffraction. For soft X-rays ($E \sim 1$ keV) Fresnel zone plates have been shown to be the most powerful optics type with resolution limits close to 10 nm [1]. A further improvement of Fresnel zone plates requires the reduction of the outermost zone widths and the increase of the zone plate thickness. Because of the lithographic process used for their fabrication, the realization of even one of the requirements is very challenging. Due to the different fabrication approach, multilayer laue lenses (MLL) have a great potential to overcome these limitations [2]. Using thin film coating technologies like magnetron sputtering the zone widths can easily be reduced down to at least 1 nm. Additionally, the thickness of the lenses can be chosen independently from the coating process during the subsequent lens preparation with focused ion beams (FIB).

In the following we describe the multilayer coating technology, typical TEM results of the MLL and the characterization of the lenses by ptychography at the nanoprobe beamline P06 at PETRA III, DESY Hamburg.

2. Multilayer fabrication

For the fabrication of the MLL coatings magnetron sputter deposition (MSD) has been used as described elsewhere [3]. In order to fulfil the zone plate law, every layer has to be coated with a different thickness. Particularly for the outermost zones, i.e. for the thinnest layers, the thickness differences are in the order of only a few picometers. Since there are no techniques available to measure thickness differences in-situ with this precision it has been decided to stabilize the coating process as much as possible and to control the thicknesses just by the deposition time.

The calibration of the deposition rates of MoSi_2 and Si has been done by the fabrication of three-multilayer systems. Each of the three multilayers has 20 periods and is periodic (Fig. 1). The differences between the multilayers are the deposition time of Si (ML1->ML2) and MoSi_2 (ML2->ML3). The period thicknesses of the multilayers can very precisely be measured by Cu-K α reflectometry (Fig. 2). Then the deposition rates R result as $R_{\text{Si}} = (d_{\text{p,ML1}} - d_{\text{p,ML2}}) / \Delta t_{\text{Si}}$ and $R_{\text{MoSi}_2} = (d_{\text{p,ML2}} - d_{\text{p,ML3}}) / \Delta t_{\text{MoSi}_2}$. In order to quantify the stability of the coating process the rate calibration stacks have been fabricated directly before and after a MLL coating having 20 μm total thickness. Over the deposition time of about 30 h the rates decreased by 0.2-0.3 %.

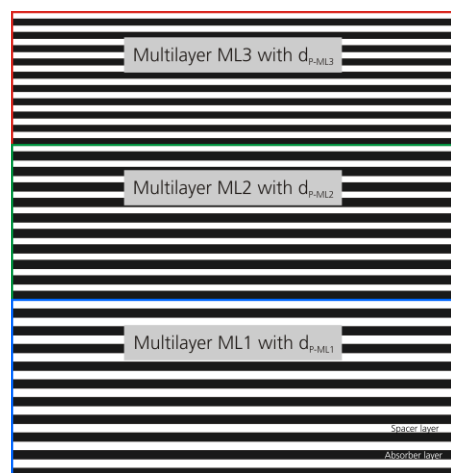


Figure 1. Schema of the multilayer stack for the rate calibration of MLL coatings.

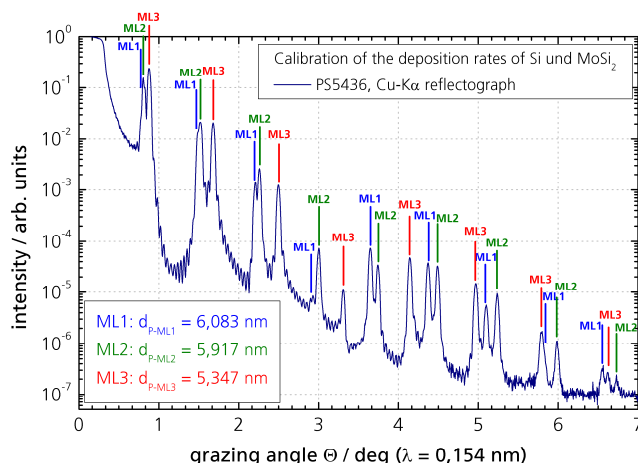


Figure 2. Cu-K α reflectograph of a typical rate calibration stack. From the positions of the Bragg reflection angles the multilayer periods can be calculated.

3. Characterization of the multilayers by TEM

MLL coatings with total thicknesses of several 10 μm are significantly thicker than conventional nanometer multilayer coatings e.g. for X-ray mirrors, which have total thicknesses < 1 μm . Coatings made by MSD often show roughness increase with increasing layer thickness. This effect can be suppressed or even avoided by choosing proper deposition conditions (e.g. low sputter gas pressure) and coating materials with amorphous layer structures. Transmission electron microscopy (TEM) of multilayer cross sections has been used to characterize the layer quality in different depths of the MLL (Fig. 3). The TEM pictures clearly indicate that there is no roughness increase within the multilayer. Even the thickest layers close to the surface are atomically smooth. This result is in agreement with atomic force microscopy experiments which delivered rms roughness values of 0.14 nm within a scanning field of 10 μm x 10 μm . A second important result of the TEM characterization is the observation that the layers close to the substrate with thicknesses of 2-3 nm are also smooth and dense. The intermixing at the interfaces between MoSi_2 and Si is limited to approximately one or two atomic layers and should have no significant influence on the performance of the MLL.

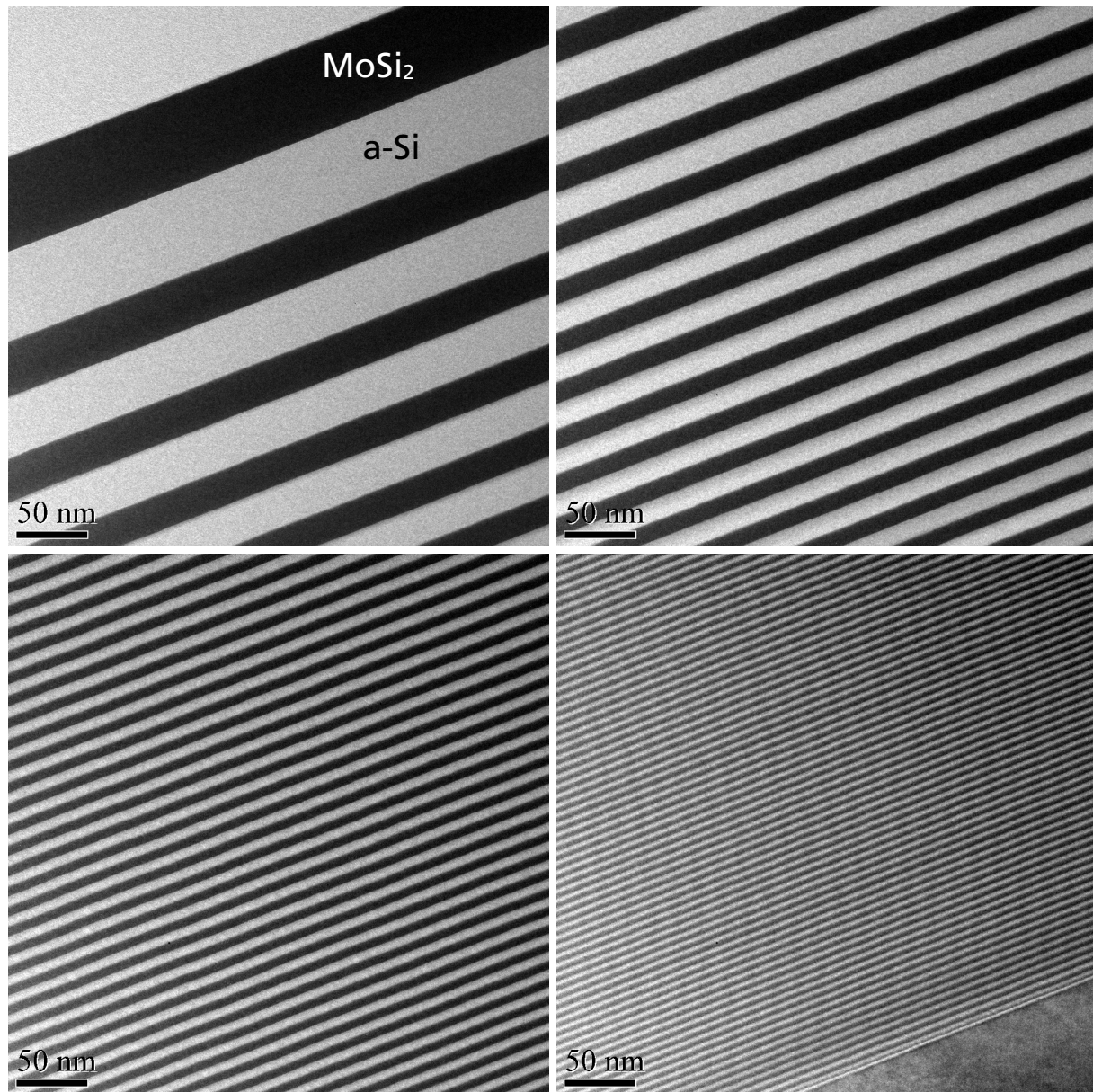


Figure 3. TEM pictures of cross sections from a typical MLL coating taken at different positions within the multilayer starting from the substrate (bottom right) up to the surface (top left).

4. Ptychography with MLL at PETRA III

Ptychography is a very powerful method for the characterization of nano-beams [4,5]. The experiments have been carried out at the beamline P06 at PETRA III, DESY Hamburg. Usually refractive lenses are installed at this beamline in order to produce the nano-focus. For our experiments one of the refractive lenses has been replaced by a MLL with a focal length of 9.9 mm at a photon energy of 21 keV. Initially, different lens thicknesses resulting from the thinning process with focused ion beams have been evaluated with respect to the diffracted intensity. The segment with the highest intensity has been selected for the subsequent experiments. From ptychography measurements and reconstruction a MLL focus size of approximately 39 nm has been derived (Fig. 4). The corresponding caustic of the beam produced by the MLL is shown in Fig. 5. It should be noted, that the focus of the MLL is still not perfect. The fringes appear probably due to a stack irregularity and remaining misalignments of the optic. If this will be avoided and the aperture of the MLL is increased, further

resolution improvements are expected. Additionally the structure of the test sample (Siemens star) has successfully been reconstructed (Fig. 6).

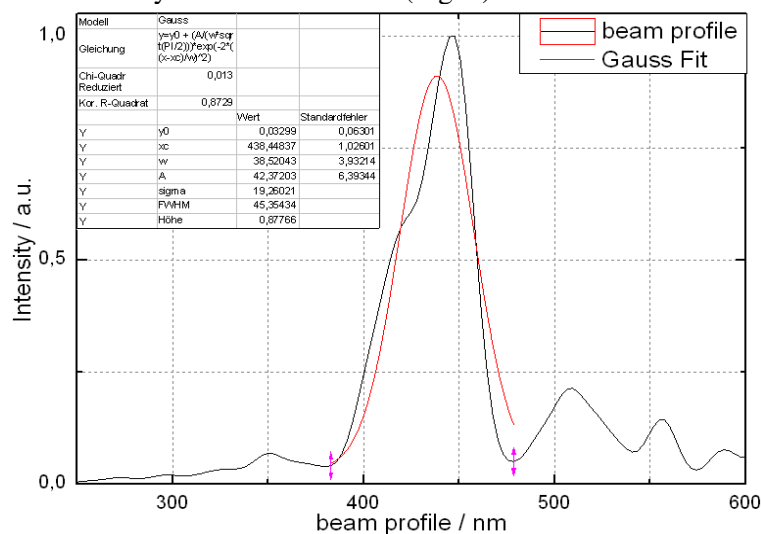


Figure 4. Beam profile of the MLL focus. The half width of the peak is about 39 nm.

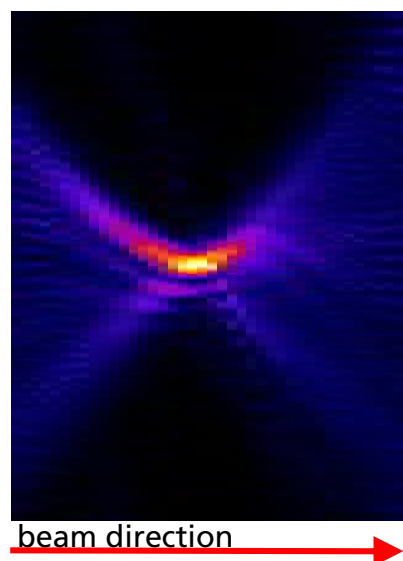


Figure 5. MLL caustic showing beam and focusing direction.

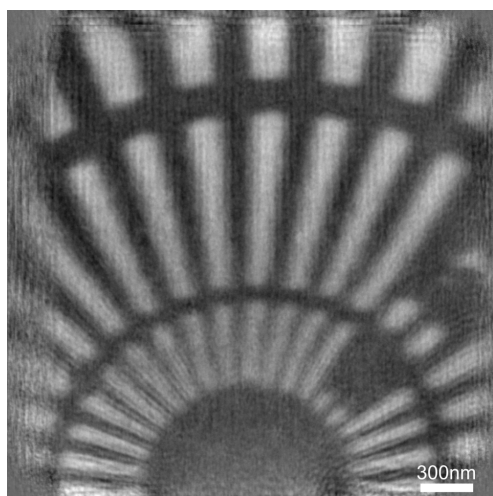


Figure 6. Reconstruction of the structure of a Siemens star used as test sample for the ptychography experiments. The results have been obtained by combining a refractive lens and a multilayer laue lens.

Acknowledgements

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