X-ray nanometer focusing at the SSRF based on a multilayer Laue lens*

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Abstract: We designed and fabricated a multilayer Laue lens (MLL) as a hard X-ray focusing device. WSi_2/Si multilayers were chosen owing to their excellent optical properties and relatively sharp interface. The multilayer sample was fabricated by using direct current (DC) magnetron sputtering technology and then was sliced and thinned to form an MLL. The thickness of each layer was determined by scanning electron microscopy (SEM) image analysis with marking layers. The focusing property of the MLL was measured at Beamline 15U, Shanghai Synchrotron Facility (SSRF). One-dimensional (1D) focusing resolutions of 92 nm are obtained at photon energy of 14 keV.

Key words: hard X-ray, nano-focusing, multilayer Laue lens (MLL), synchrotron radiation

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1 Introduction

X-ray focusing optics is widely used to perform X-ray microscopy and X-ray microanalysis at the nanoscale for numerous applications in material sciences, medicine, biology, environmental sciences and many other fields [1]. Much effort is being made to realize X-ray focusing elements with high resolution, signal strength and contrast [2]. There are many types of hard X-ray focusing devices such as Kirkpatrick–Baez mirrors [3], compound refractive lenses [4] and Fresnel zones [5]. The best reported result is 7 nm line focus at 20 keV using reflective multilayer mirrors, breaking the 10 nm barrier in the hard X-ray range [1]. Another approach is to use a multilayer Laue lens (MLL) working in transmission Laue geometry. An MLL consists of multilayer structures and takes advantage of the Bragg diffraction effect to improve spatial resolution and diffraction efficiency [6]. Based on this method, a line focus of 11 nm width has been obtained at photon energy of 19.5 keV [7]. Thus MLL is a promising method for X-ray nano-focusing.

Our previous studies show how to make and characterize an MLL [8]. A 7.9 μm-thick multilayer Laue lens with an outermost layer thickness of 15 nm was designed and fabricated and one dimensional focusing resolutions of more than 200 nm were obtained. To further improve the resolution of the MLL, in this paper, we present an MLL structure with thicker total thickness of 27 μm and improved methods of measurement, including characterization of the multilayer structure using a scanning electron microscope and nano-focusing measurement in a synchrotron radiation beam line.

2 Design and fabrication of MLL

The optical properties of the MLL due to the dynam-

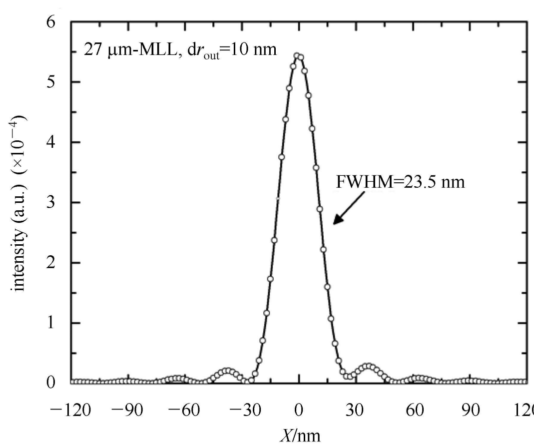

Fig. 1. Intensity profile in the focal plane of the MLL.

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ical diffraction effect were studied theoretically by the coupled wave theory [6]. The MLL was designed at photon energy of 14 keV using WSi2 and Si as the material combination. For the depth-graded multilayer structure, the minimum layer thickness was designed to be 10 nm, while the total multilayer thickness was 27 μm, and the number of layers was 1582. The focusing property was calculated using the Fresnel–Kirchhoff diffraction formula [9]. The calculated intensity profile in the focal plane of the MLL is shown in Fig. 1 and the full width at half maximum (FWHM) of the peak is 23.5 nm. More details of the MLL fabrication have been described in Ref. [8].

3 Characterization of the MLL

3.1 Scanning electron microscope (SEM)

The cross-section of the multilayers was observed by a scanning electron microscope (SEM) after the sampling process, as shown in Fig. 2. Figure 2(a) shows the entire multilayer structure. Figures 2(b) and (d) are magnified images of the areas close to the surface and substrate, and Fig. 2(c) shows the middle area of the entire multilayer. It can be seen that the multilayer structure is undamaged after repeated grinding and polishing. All the layer interfaces stay flat and sharp. The image was converted into a binary one and the layer thicknesses were directly calculated as reported in Ref. [10]. The measured layer thickness distribution is shown in Fig. 3, where the designed distribution is also shown for comparison. Different sub-areas from the substrate to the surface are represented by numbers 1–17 in Fig. 3. Figure 3(a) is the result for the layer structure while (b) shows the relative errors between the deposited and designed layer thicknesses, $(d_{\text{meas}}-d_{\text{desi}})/d_{\text{desi}}$. The result demonstrates that the fabricated structure conforms to the design and the error of the thickness curve is less than ±7%.

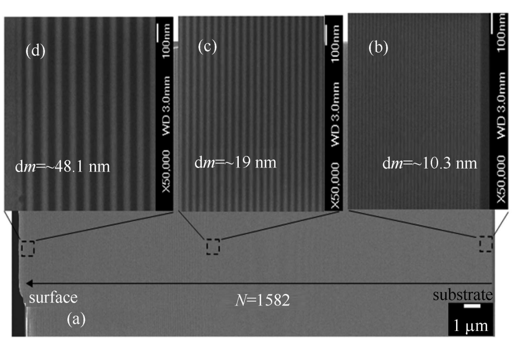

Fig. 2. SEM images of the cross-section of the MLL.

3.2 Nano-focusing measurement

The X-ray nano-focusing measurements reported here were performed at beamline 15U of the Shanghai Synchrotron Radiation Facility (SSRF). The focal beam size was measured by the knife-edge method. In our previous study [8], the cross-section of an 8 nm-thick Cu film performed as the knife-edge. This requires a high alignment precision, and any divergence between the focal line and the Cu film will enlarge the measured result. Here, the surface of a Ni film was scanned across the focus using a nanometer translation-stage. Geometrical relationships among the incident X-ray, the MLL, and the Ni film are shown in Fig. 4. The intensity of Ni Kα lines was monitored by the fluorescence detector and show an abrupt change when the Ni knife-edge passes through the focal line. Compared with the cross-section of Cu film, it is easier to keep the surface of the Ni film parallel to the focusing line. The knife edge was first aligned close to the parallel tilt angle. The tilt angle was then varied through a range of 0.3° with a step of 0.05°. The width of the focal line was measured at the same time. It is believed that the knife edge is parallel

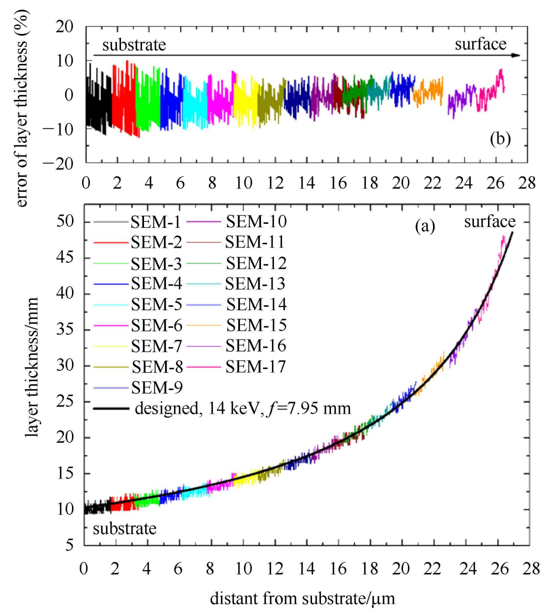

Fig. 3. (color online) Layer thickness distribution of the MLL.

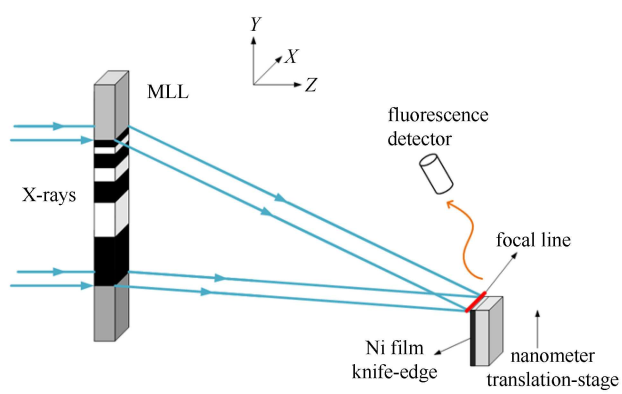

Fig. 4. (color online) Schematic of the focusing measurement of MLL on BL 15 U, SSRF.

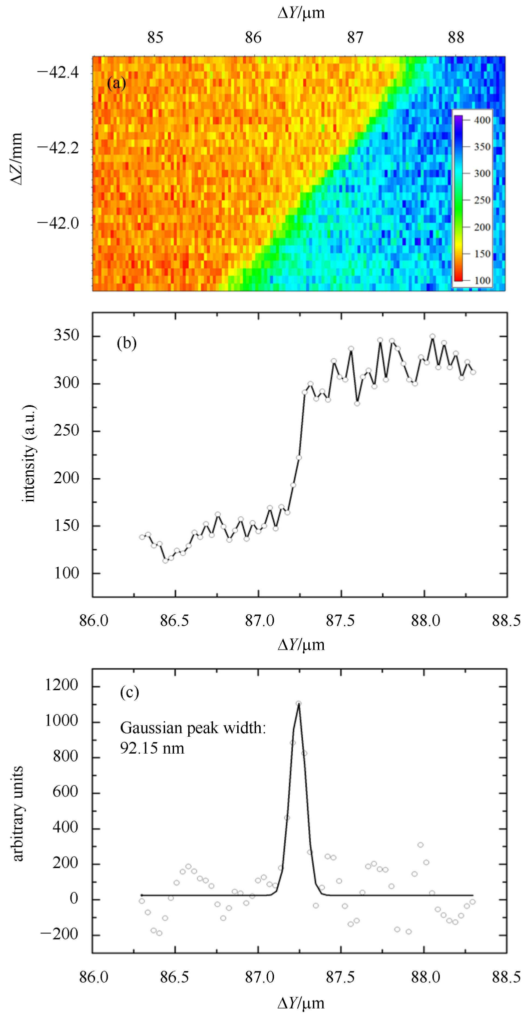

Fig. 5. (color online) (a) 2D fluorescence intensity scanning near the focal plane; (b) 1D fluorescence intensity scanning at the position of focus; (c) Differentiation of the smoothed intensity curve.

to the focusing line when the width of the focal line is at a minimum.

The measured focusing results of the 27 μm-MLL are shown in Fig. 5. Fig. 5(a) is a color map of fluorescence intensity by two-dimensional scanning of the Ni knife-edge. It suggests that the width of the focal line is at its minimum between 42.1 mm and 42.2 mm in the beam direction, which demonstrates the focus. Fig. 5(b) is a curve of fluorescence intensity along the scanning direction at the position of focus. The differentiation of the smoothed intensity curve displays a peak and the FWHM of the peak closely approximates to the focusing resolutions. The width of the focal line of 92 nm (FWHM) at 14 keV is shown in Fig. 5(c). This measurement was performed several times to ensure repeatability.

It should be noted that the focus of the MLL is far from the theoretical value. Firstly, the layer thickness errors of the multilayer and the structural damage in fabrication process broaden the focal line. Secondly, the minimal scanning step of the nanometer translation-stage is 35 nm, which is not very precise relative to the width of the focal line. Thirdly, the vibration of the measurement system cannot be ignored. If these are improved, better resolution can be expected in the future.

4 Conclusion

A 27 μm-thick multilayer Laue lens with an outermost layer thickness of 10 nm has been designed and fabricated. The focusing property of the MLL was measured at the SSRF. The measured results show that a focusing resolution of 92 nm was achieved at 14 keV. This is the best result to date for MLLs in the hard X-ray region in China but is falling behind the international advanced level achieved by Argonne National Laboratory (an FWHM peak size of 11.2 nm) [7]. On the one hand, in order to minimize the surface damage, they used focused-ion beam methods to etch the multilayer sample after deposition. On the other hand, a ptychography measurement based on wavefront reconstruction was applied to focusing optics characterization. This method does not need to be performed at the exact location of a focal plane, therefore relaxing the alignment complexity of a nano-focusing system. In our future works, more effort should be made to improve the fabrication process and the nano-focusing experiment method to further increase the resolution of the MLL.

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