X-ray nanometer focusing at the SSRF basing on multilayer Laue lens

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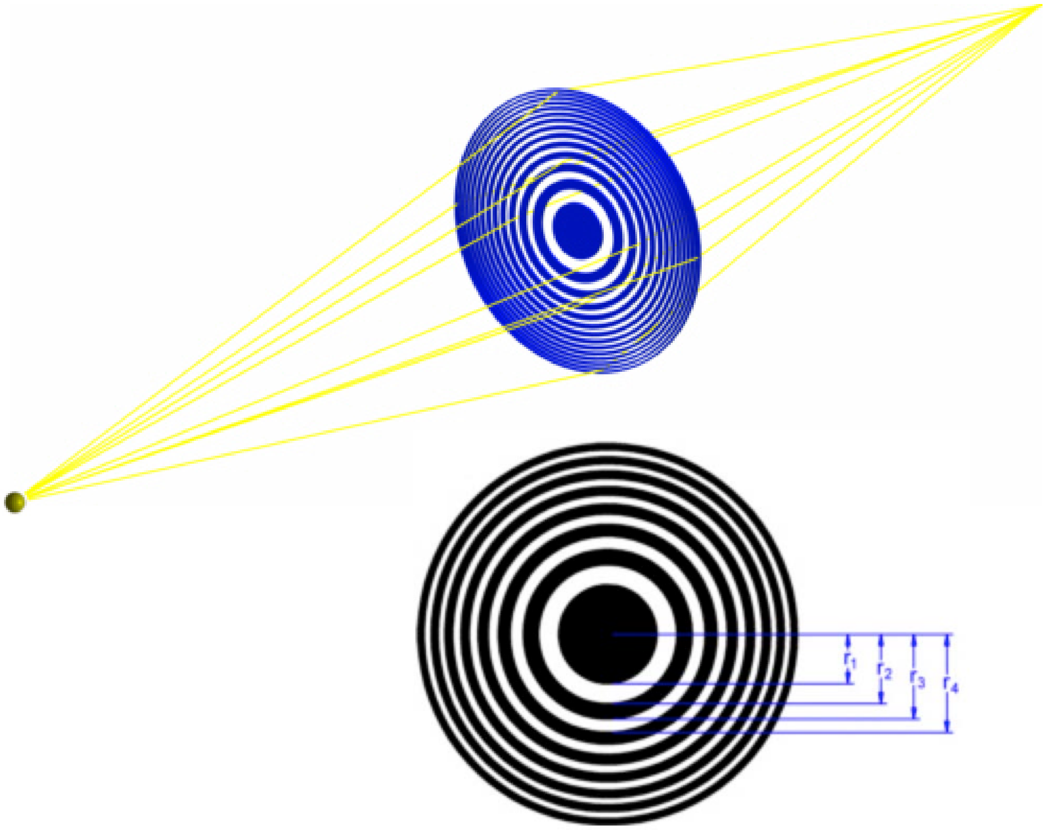
Fresnel zone plate

Diffraction optics



Structure parameters：

$$r_n^2 = nf\lambda + \frac{n^2\lambda^2}{4}$$

$$d_{r_n} = r_n - r_{n-1} = \frac{\lambda f + \frac{n\lambda^2}{2}}{2r_n}$$

Resolution：

$$\delta = 1.22 d_{r_{out}}$$

Higher resolution
Higher efficiency

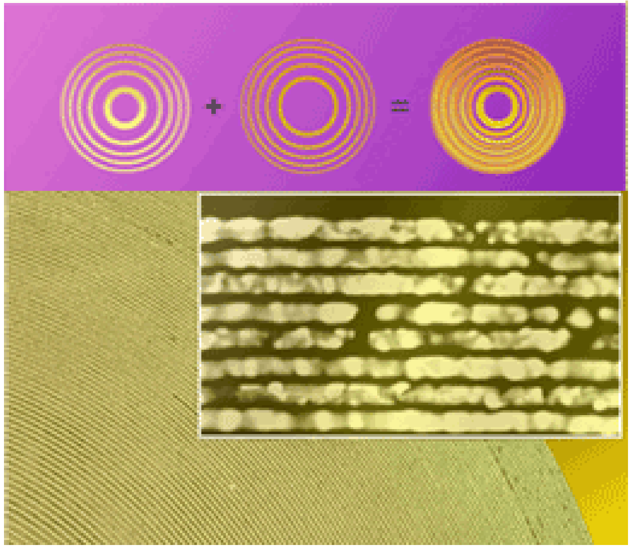
→

Smaller outmost layers
Much larger aspect-ratio

http://x-ray-optics.de/

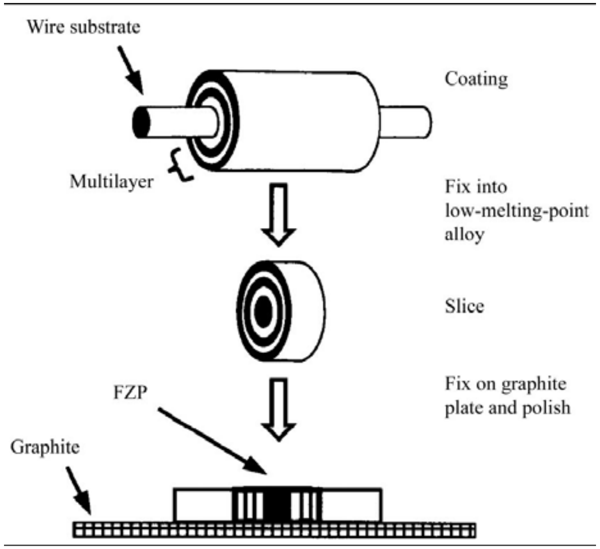
Fresnel zone plate

Zone plate achieving
resolution of 12 nm using EBL



Weilun Chao et al, OE, 2009

Suptter-sliced zone plate



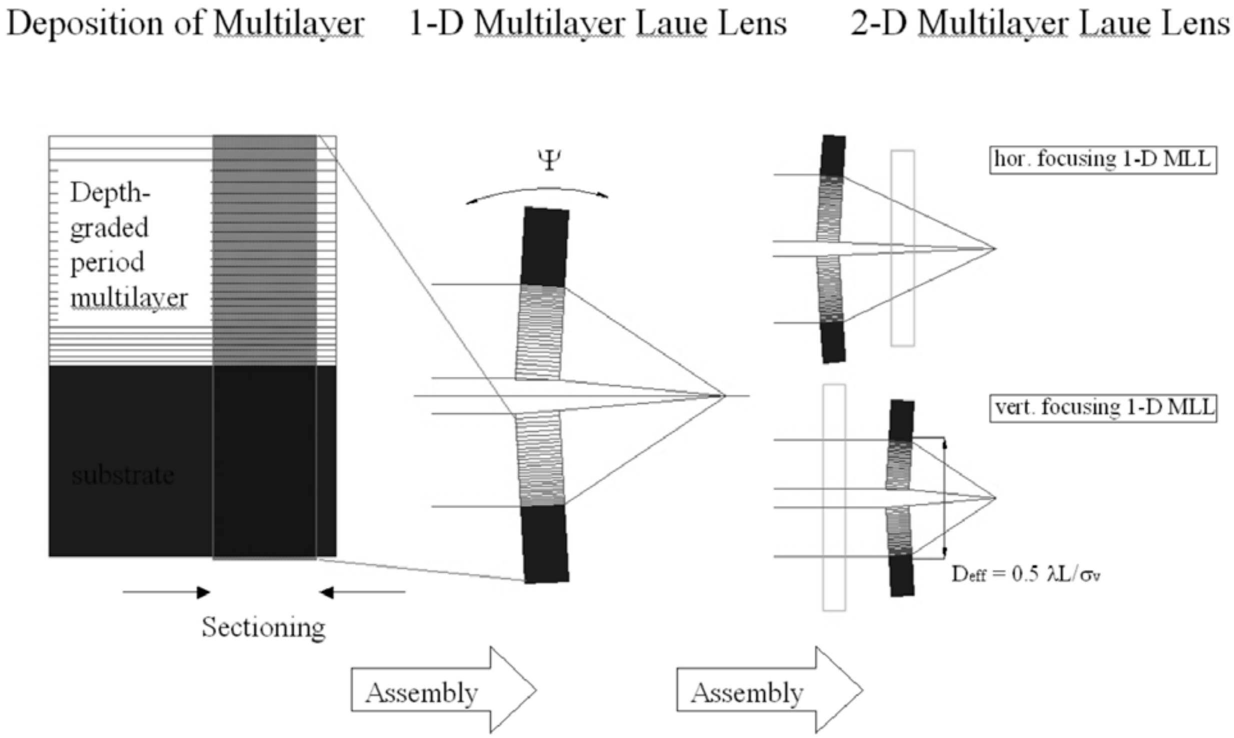
Tamura et al, J. Synchrotron Rad, 2002

Fabrication	EBL	Sputter-Sliced
Resolution	12nm	~100nm
Aspect-ratio	<20	>1000
Energy range	EUV & Soft x-ray	Hard x-ray

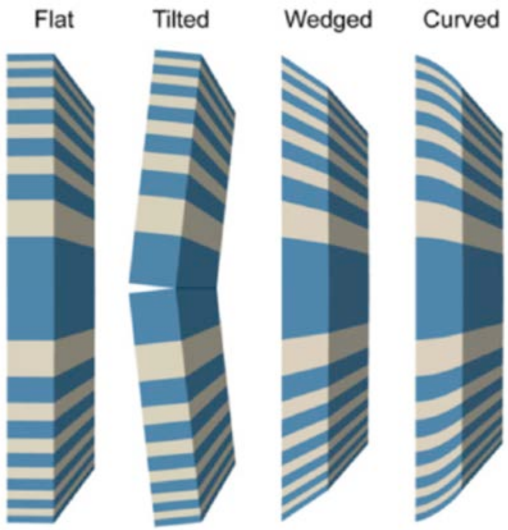
Hard X-ray

nano-focusing

Multilayer Laue Lens（MLL）



Maser J et al,Proc Spie, 2004



Yan H et al, Journal of Physics D Applied Physics, 2014

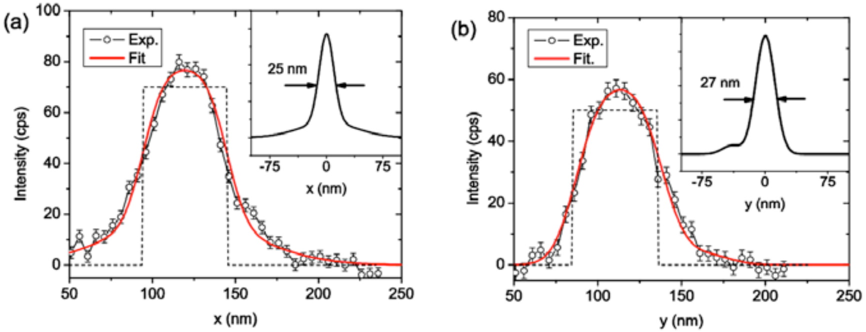
Advantages：

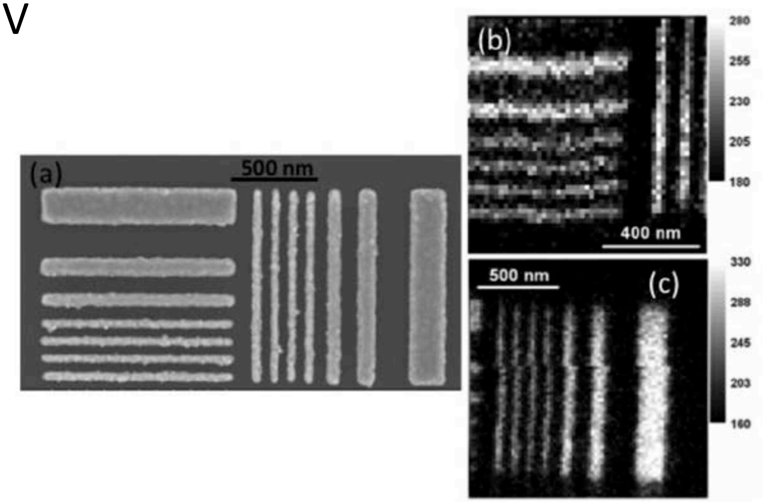
- Depositing on flat substrate
- Outmost layers which determine the resolution is deposited firstly, better control

- Much larger aspect-ratio： ~1000
- Smaller outmost layers： ~10nm

Review on MLL studies

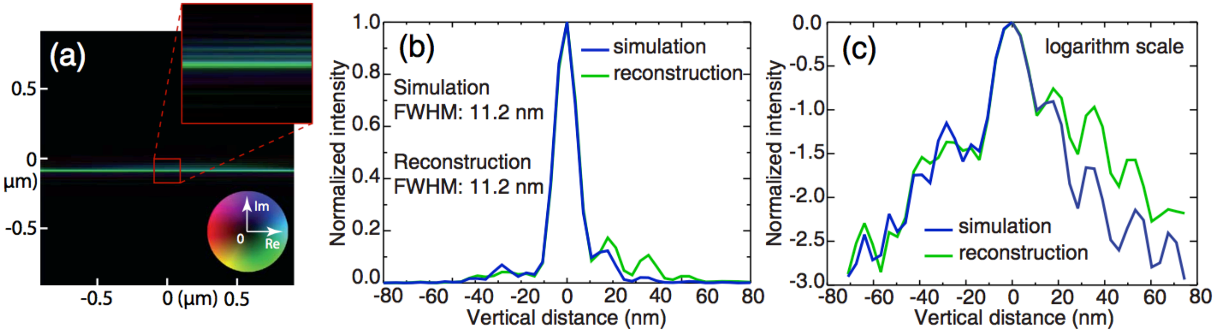
Achieving a 2-D focus of 25×27nm^2 at 12keV

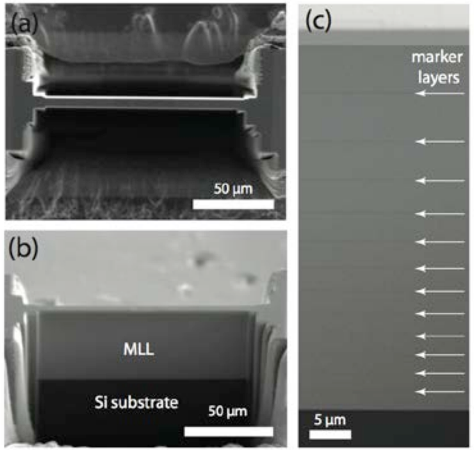




H. Yan et al, OE, 2011

Achieving a 1-D focus of 11nm at 12keV





X. Huang et al,Scientific Reports, 2013

Design of the Multilayer Laue Lens

One dimensional Coupled wave theory (1-D CWT)

Tilted

Fourier expansion of MLL’s permittivity:

$$\varepsilon_r(\vec{r}) = \varepsilon'_{ra} - i\varepsilon''_{ra} + (\varepsilon''_{rd} - i\varepsilon''_{rd})C\sum_{h=1}^{\infty} N_h \sin\left(h\vec{G}\cdot\vec{r}\right)$$

Wave equation:

$$\nabla^2 E(\vec{r}) - \gamma^2 E(\vec{r}) = 0$$

Trial solution of wave equation:

$$E(\vec{r}) = E_0 \sum_{l=-\infty}^{\infty} A_l(z) exp(-i\vec{k_l}\cdot\vec{r})$$

$$\left(-l\frac{G}{k_0}\sin\psi + \cos\theta\right)\frac{dA_l}{dz} + (\alpha + i\beta_l)A_l + \kappa C\sum_{h=1}^{\infty} N_h(A_{l+h} - A_{l\text{-}h}) = 0$$

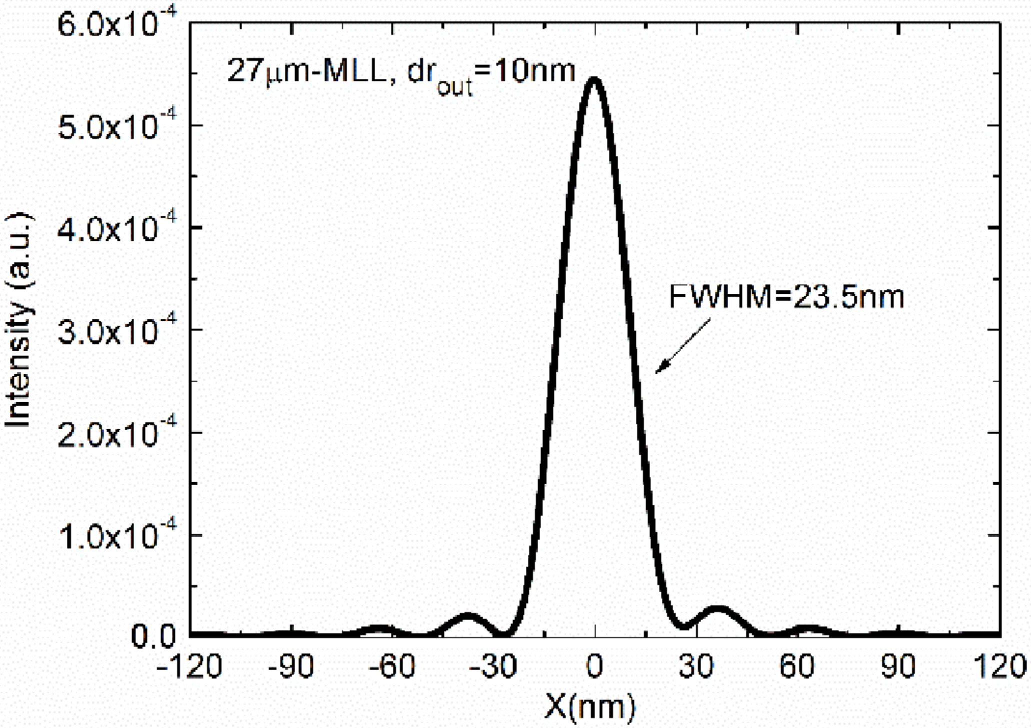
$$\kappa = \frac{k_0}{4\varepsilon'_{ra}}(\varepsilon''_{rd} - i\varepsilon''_{rd}), \qquad \alpha = \frac{1}{2}k_0\varepsilon''_{ra}, \qquad k_0 = \frac{2\pi}{\lambda}\sqrt{\varepsilon'_{ra}}$$

Design of the Multilayer Laue Lens

E=14keV	r_{out} (μm)	*f* (mm)	dr_{out} (nm)	t_{dep} (μm)	N_{dep}
WSi_2/Si	34.1	7.95	10	27	1582

Advantage of WSi_2/Si :

- stable stress property
- sharp interfaces

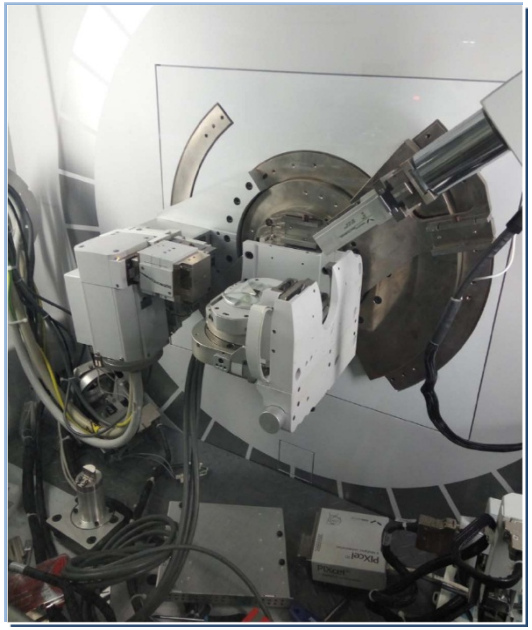


Fabrication of the Multilayer Laue Lens

Facilities for fabrication and measurement

Circular Magnetron Supttering Machine

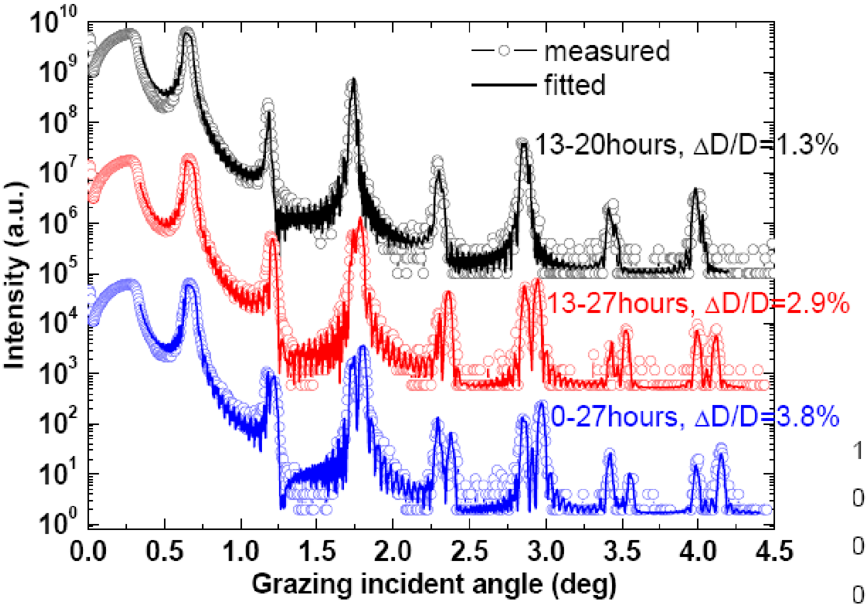
Linear Magnetron Supttering Machine



XRR(Cu k-alpha)

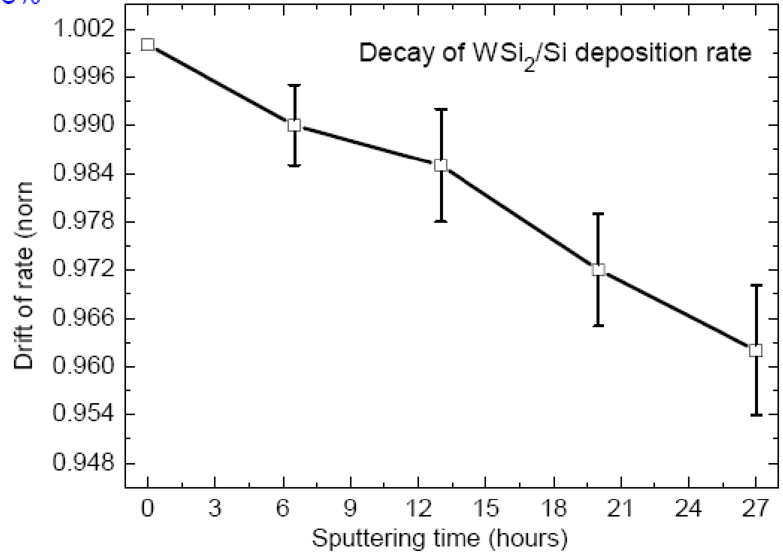
Fabrication of the Multilayer Laue Lens

Deposition rate drift



Systematic drift during 27 hours sputtering

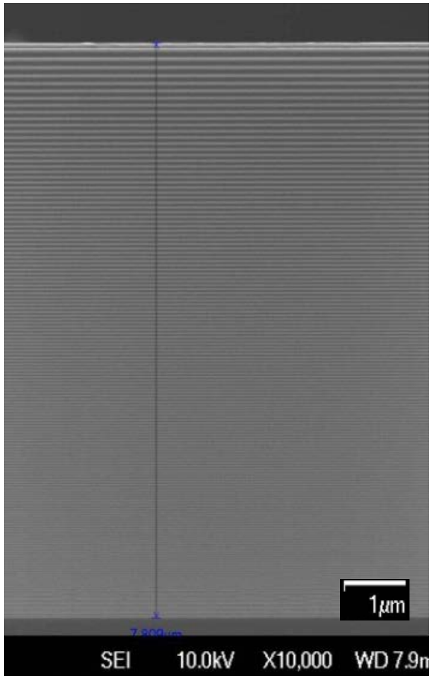
Periodic WSi_2/Si test multilayers

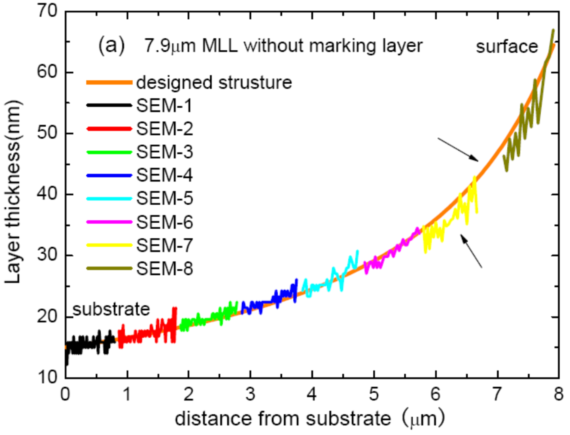


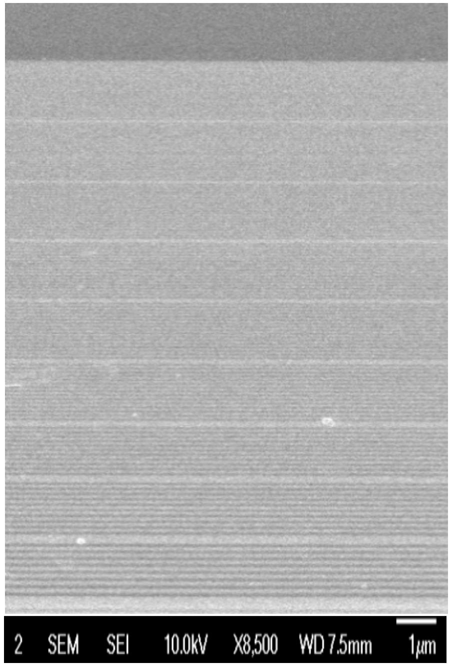
Deposition rate decreased ~3.8%

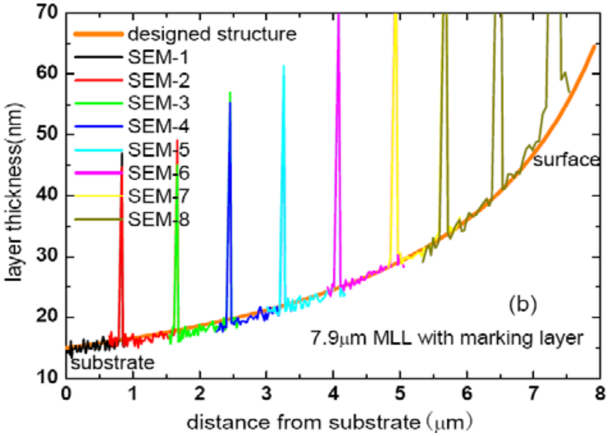
Characterization of Multilayer Laue Lens

Without marking layer





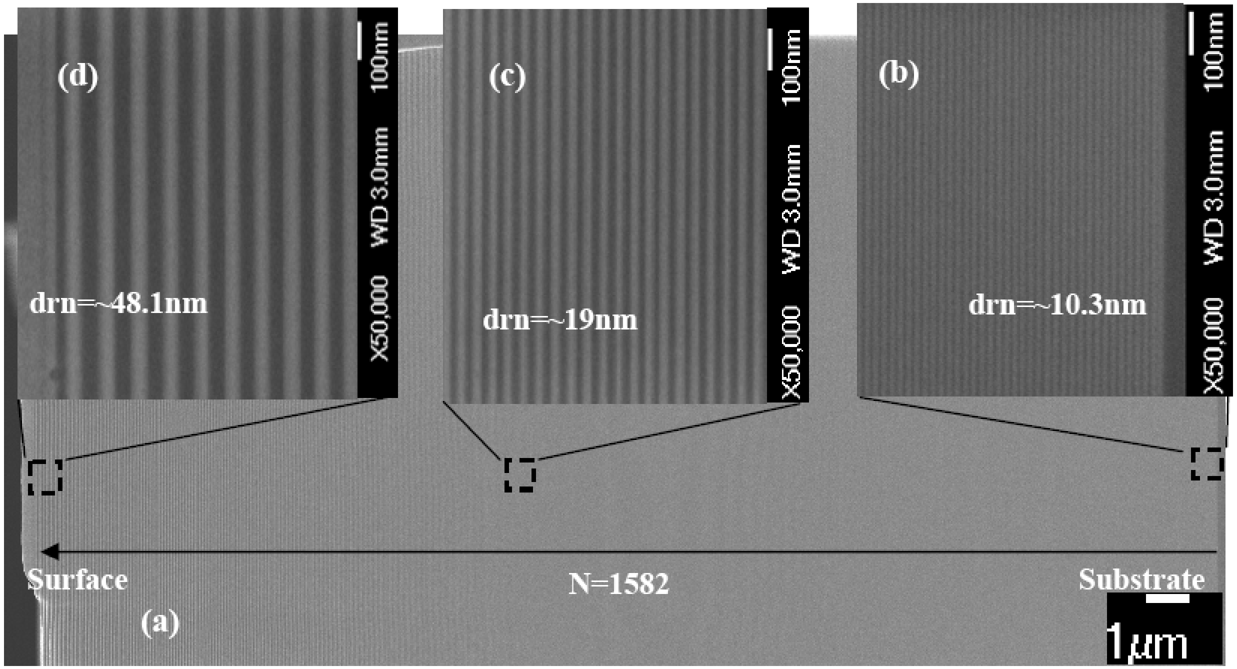




With marking layer

Characterization of Multilayer Laue Lens

SEM images of the MLL cross-section

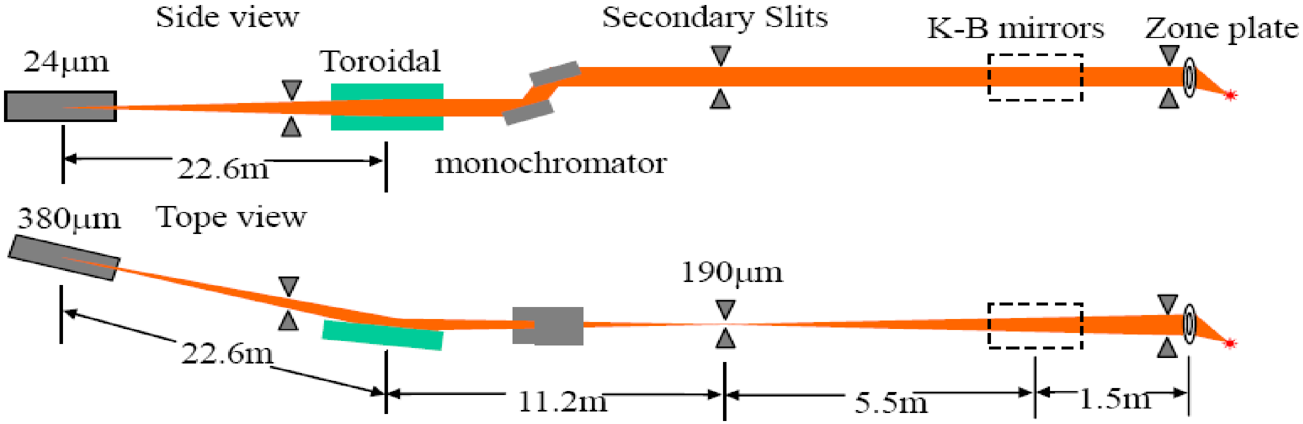


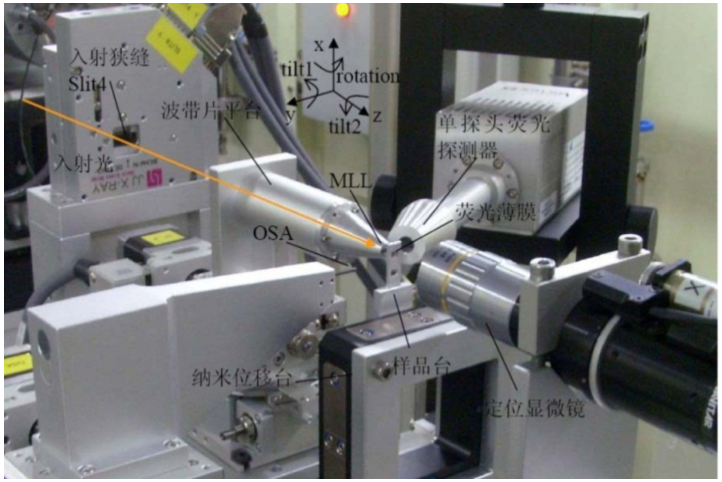
Total thickness of 27 µm with layer number of 1582

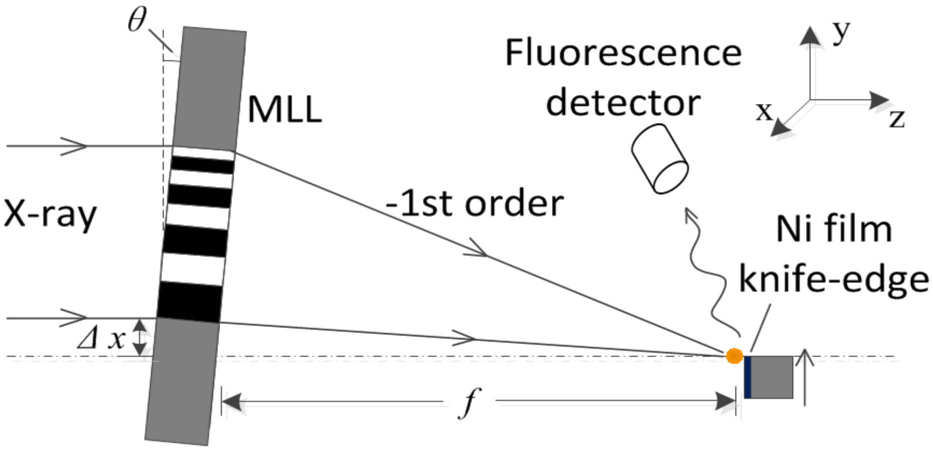
- Flat and sharp interface
- No buckling or peeling
- Remain undamaged after the repeated grinding and polishing

Characterization of Multilayer Laue Lens

Schematic of the focusing measurement of MLL on BL 15U, SSRF

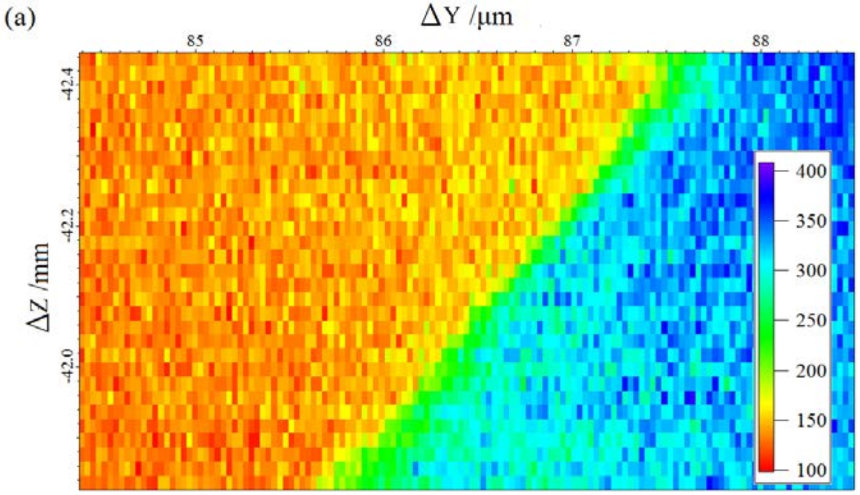


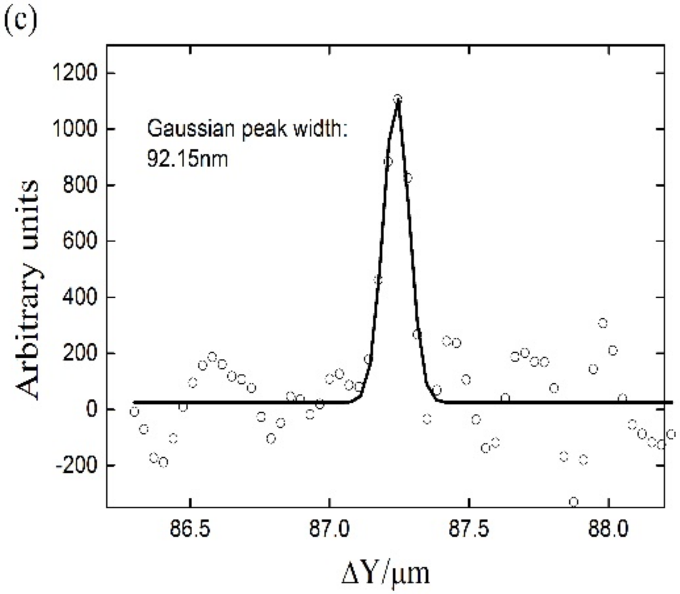


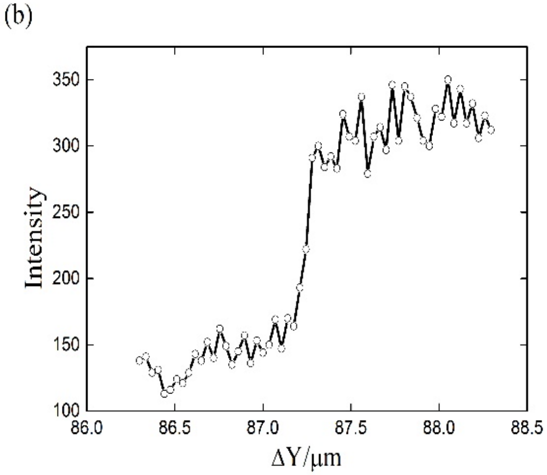


Characterization of Multilayer Laue Lens

WSi$_2$/Si MLL achieving a 1-D focus of 92nm







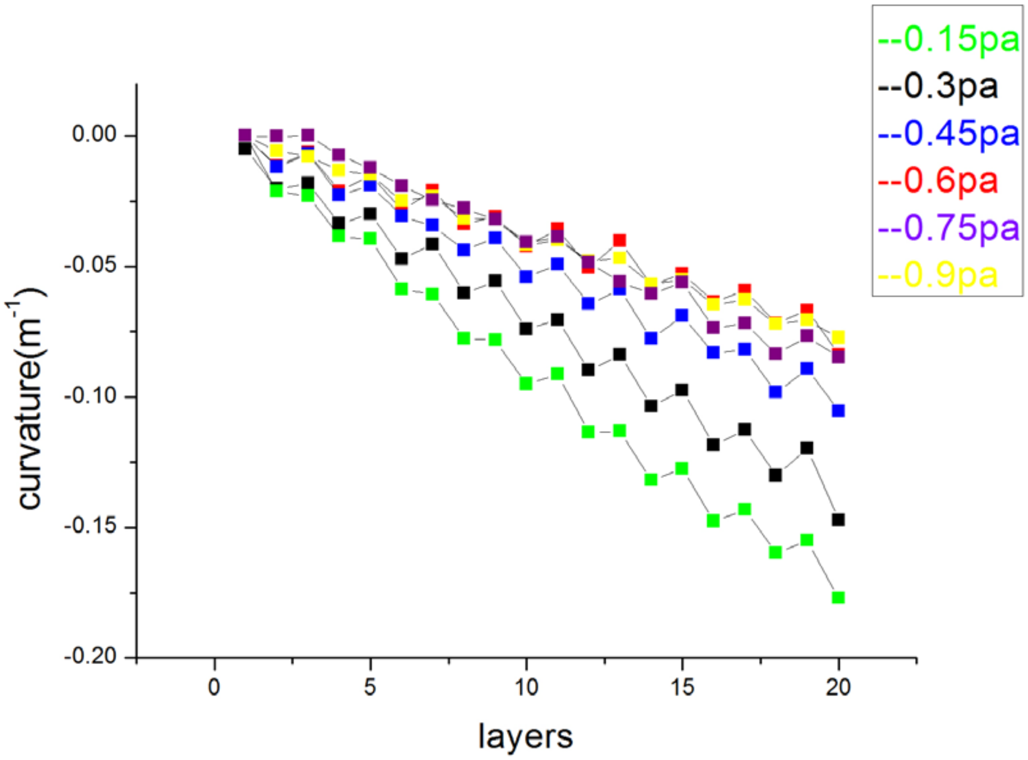
(a) (color online) The 2D fluorescence intensity scanning near the focal plane;

(b)The 1D fluorescence intensity scanning at the position of focus;

(c)The differentiation of the smoothed curve of intensity

Stress study on WSi_2/Si multilayer

Stress of WSi_2/Si multilayer under different pressure

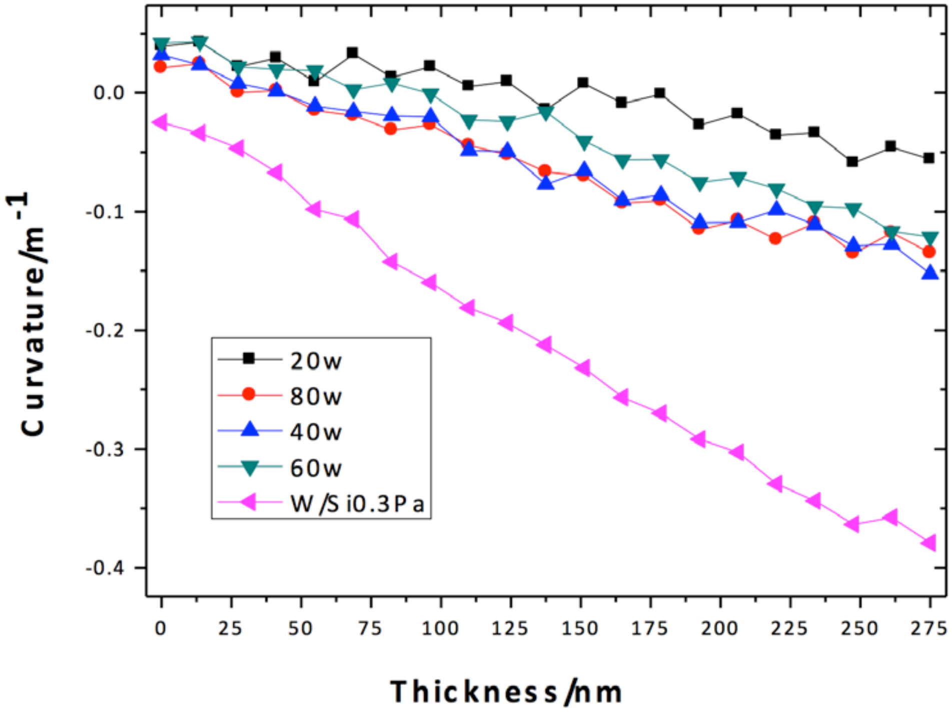


Pressure	Curvature change (m^{-1})	Stress(GPa)	Roughness(Å)
0.15pa	-0.1771	-0.214 GPa	WSi_2:1.244 Si:1.359
0.3pa	-0.1471	-0.160 GPa	WSi_2:2.04 Si:2.24
0.45pa	-0.1054	-0.129 GPa	WSi_2: 3.04 Si:2.59
0.6pa	-0.0838	-0.098 GPa	WSi_2:3.796 Si:2.988
0.75pa	-0.848	-0.102 GPa	WSi_2: 5.245 Si: 3.012
0.9pa	-0.802	-0.094GPa	WSi_2: 11.41 Si: 13.87

Stress study on WSi_2/Si multilayer

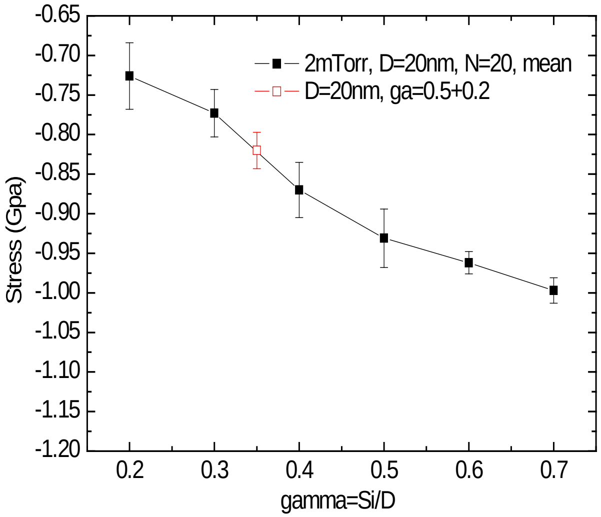
Stress of $W_{1-x}Si_x$/Si multilayer with different ratio x

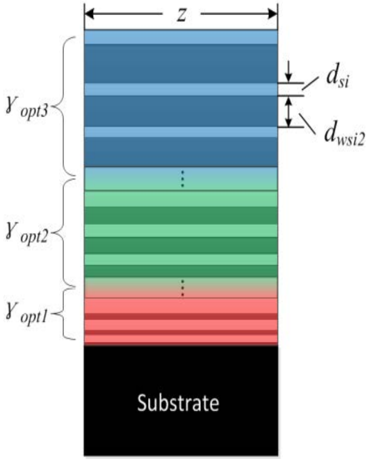
Sample	S1	S2	S3	S4
Power for Si (W)	20	40	60	80
Power for W (W)	30	30	30	30

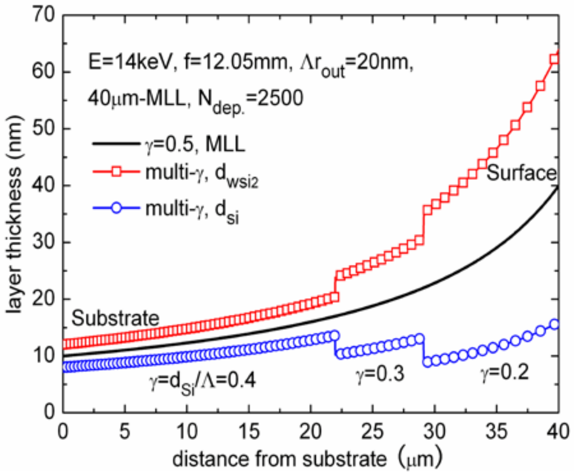


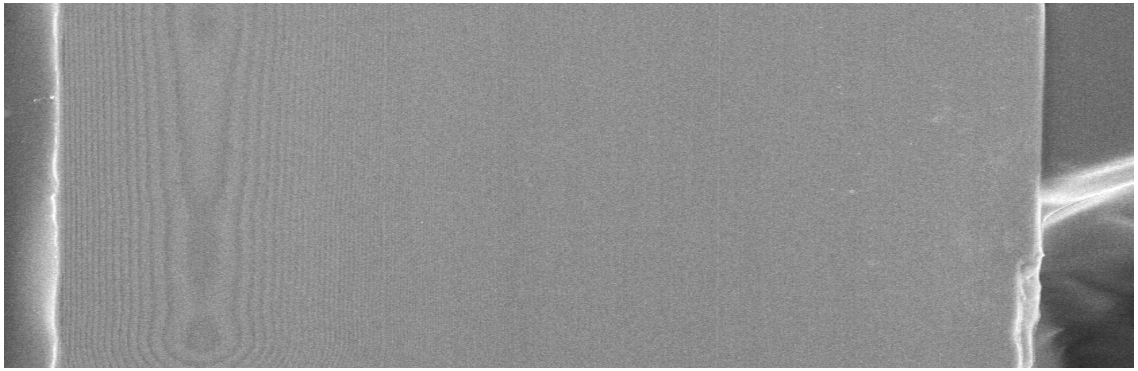
Si contributes more in stress than W

WSi_2/Si multilayer with different gamma





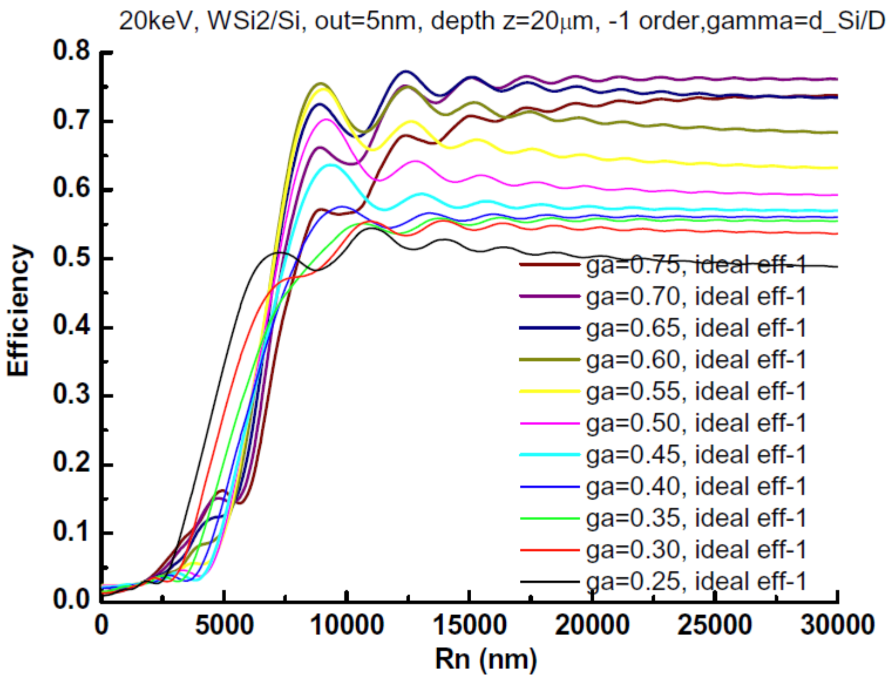


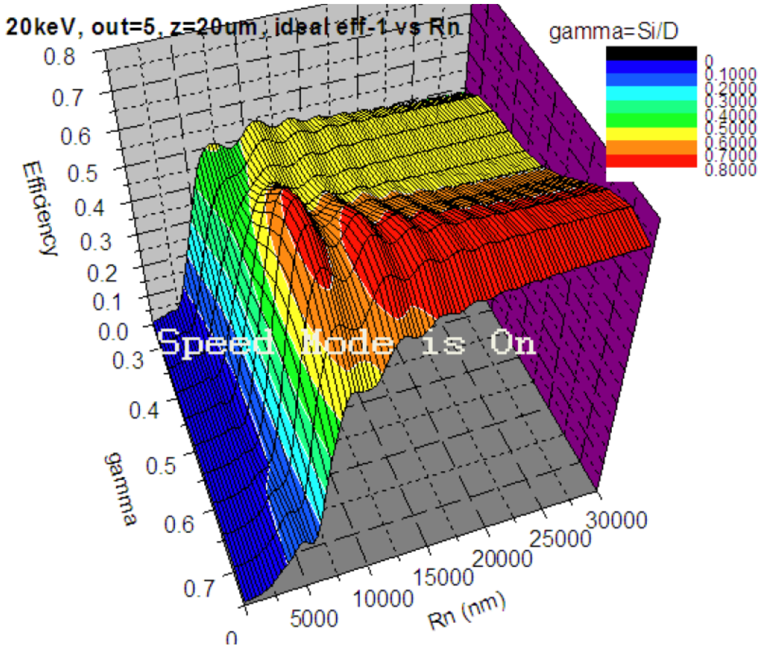


Total thickness 38.1μm and total layers number 2500

WSi_2/Si multilayer with different gamma

MLL efficiency with different Gamma

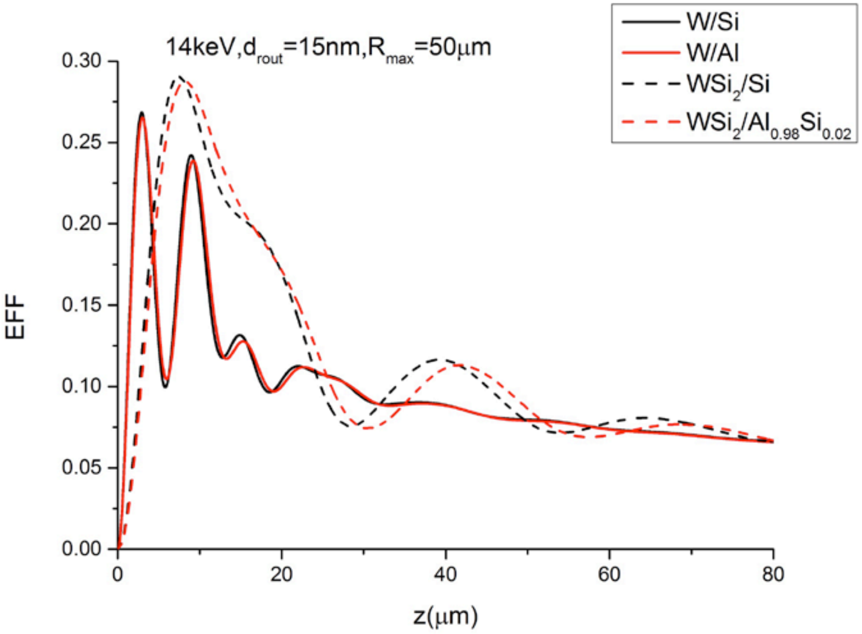




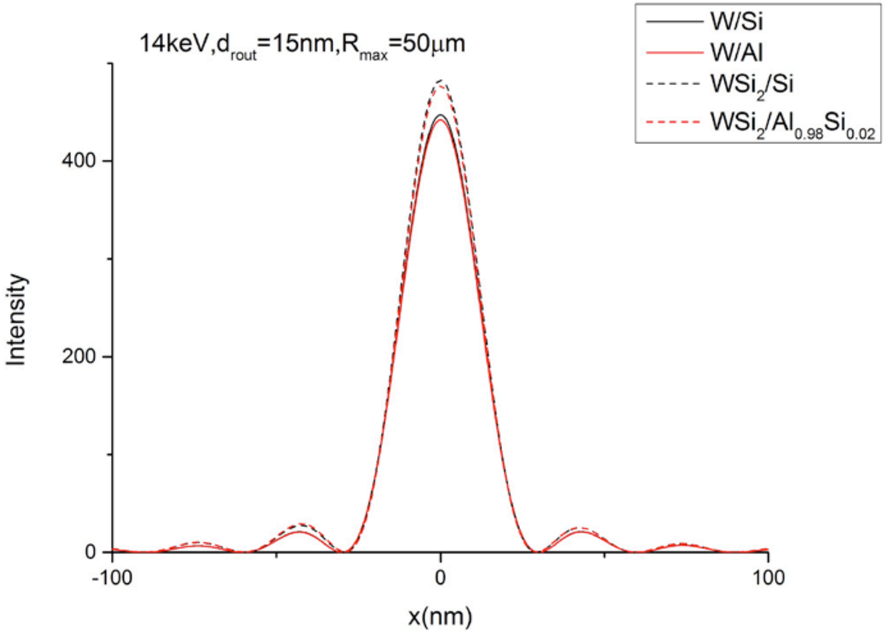
Design of $WSi_2/Al_{0.98}Si_{0.02}$ MLL

Energy of 14keV with thickness of 50 μm

D_{rout}=15nm	Optimal depth (μm)	Average efficiency (%)	Focal length (mm)	FWHM (nm)
W/Si	2.91	26.84	17.51	26.80
W/Al	3.00	26.52	17.51	26.80
WSi_2/Si	7.42	29.05	17.51	26.40
$WSi_2/Al_{0.98}Si_{0.02}$	8.20	28.75	17.51	26.40



a) Efficiency versus depth of MLL with different materials



b) Intensity of different MLL at the focal length

Summary

- MLL was designed by CWT;
- WSi_2/Si MLL with thickness 27µm and N=1582 was fabricated by DC magnetron supttering;
- The position of each layer is determined by marking layers
- MLL was characterized at SSRF, 92nm 1-D focusing at 14kev
- $WSi_2/Al_{0.98}Si_{0.02}$ MLL was designed to improve the stress problem and enhance the aperture.

Thank you for your attention!