X-Ray Metrology for Characterizing Advanced Nanoelectronics Structure

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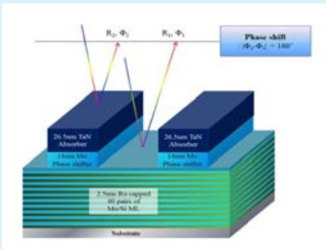
Trend of Semiconductor Devices and X-Ray Metrologies

RS Roadmap 2022

	2022	2025	2028	2031	2037
Litho	193i, EUV	193i, High NA EUV			
Logic	3 nm FinFET	2 nm LGAA	1.5 nm	1.0 nm LGAA 3D	0.5 nm
DRAM	17nm Cell size (µm²) 0.00165	14 nm 0.00118	0.00085	11.5 nm 0.00065	10 nm 0.00025
3D NAND	96 L, 128L Number of layers 128-192	256L 256-384	384L 384-576	5764L 576-768	1024L 1024-1536
Stacking	2/2.5D	3D CoW	3D WoW	3D FP	3D VLSI

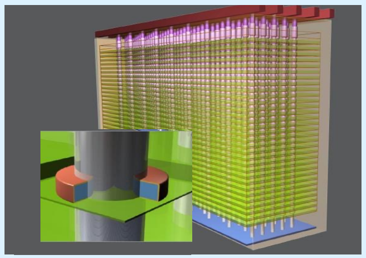
EUV Mask



Source: EUV Litho

- Ultra thin film =>XRR, XRD, XRF
- Contaminations => TXRF

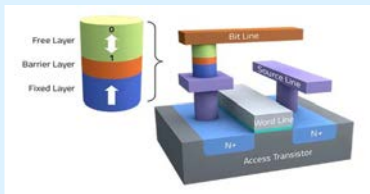
DRAM,3D NAND



Source: Micron

- High AR, 3D => SAXS, X-ray imaging
- W-fill, Si texture => XRF, XRD

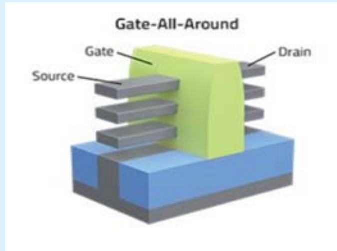
MRAM/FeRAM



Source: SemiEngineering

- Composition => XRF
- 3D structure => SAXS

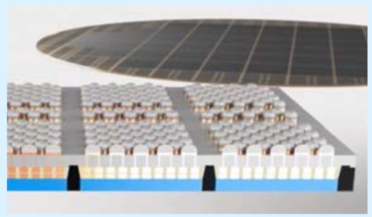
GAA-FET



Source: LAM

- Epitaxial film => HR-XRD, XRR
- 3D Structure => SAXS

2.5/3D Stacking



Source: Intel

- Micro bump, TSV Composition, Defects => Micro XRF => X-ray imaging

Why X-Ray?

- **X-ray photons penetrate through materials and enable to investigate inner structure from the size of sub-nanometer (atomic scale) to micrometer of the materials, non-distractively.**

✓ **X-ray Diffraction/Scattering**

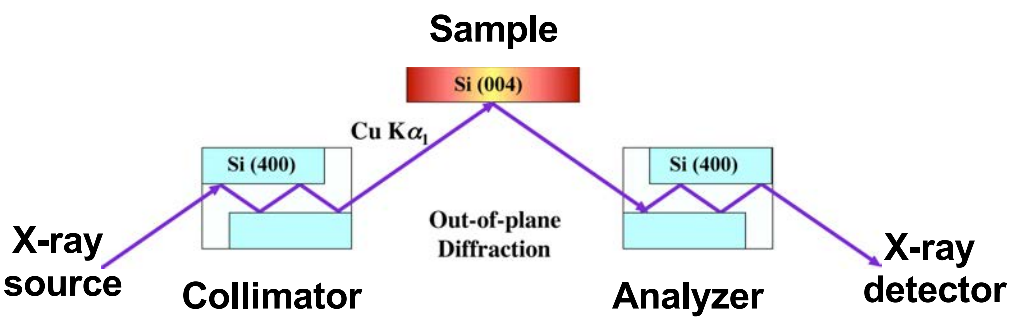
1. **HR-XRD : Composition and thickness of epitaxial layers**
2. **X-ray reflectivity : Thickness and stacking structure of multilayers**
3. **Topography : Crystal defects, dislocations**
4. **GI-SAXS : Nanoimprint mold,** EUV resist structures, FinFET, GAA, etc**.**
5. **T-SAXS : 3DNAND, DRAM structures**

✓ **X-ray Imaging**

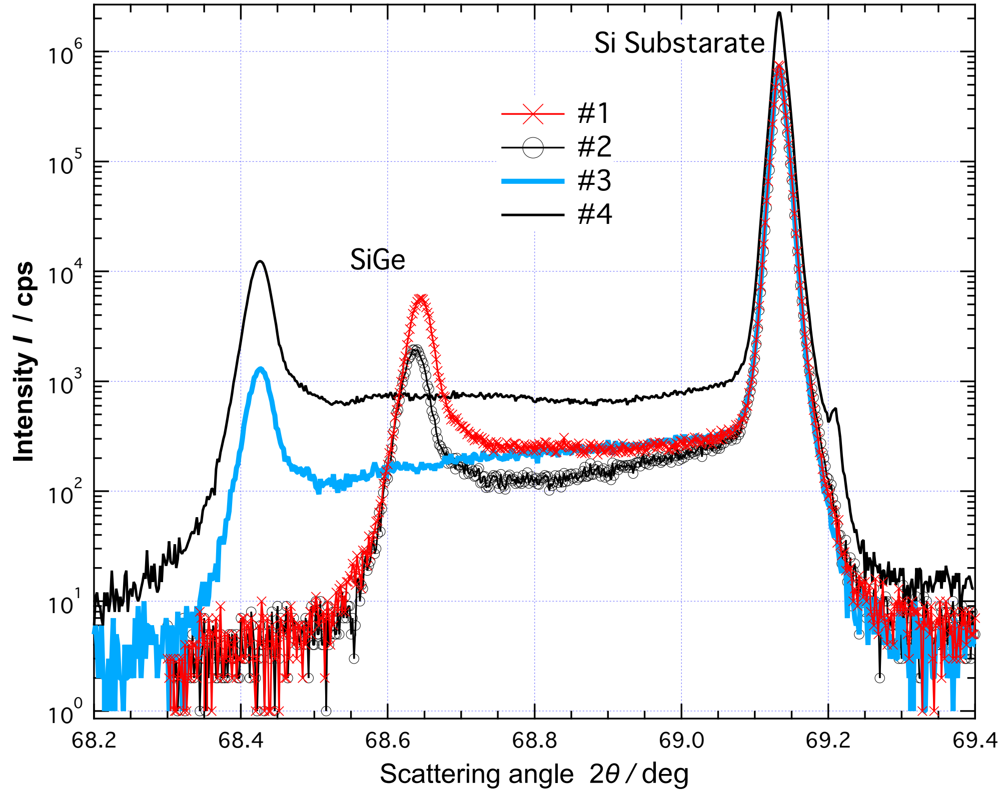
1. **μm Structure : TSV**, Packaging, etc.
2. **nm Structure : Device scale imaging**

X-ray Diffraction/Reflectivity/Topography

Conventional High-Resolution X-ray Diffraction



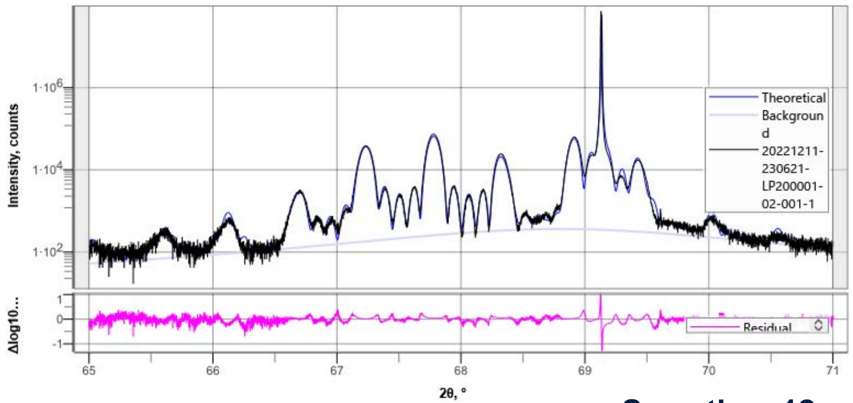
Specimen	Bulk Si			
	#1	#2	#3	#4
Si (nm)	12.54	23.06	12.07	22.90
SiGe	Thick	Thick	Thick	Thick



Parallel beam collimator is utilized for the conventional high-resolution X-ray diffraction and large analysis area is required for obtaining reasonable X-ray intensity.

High-Resolution XRD and XRR for GAA Blanket Wafer

GAA Stack Scan

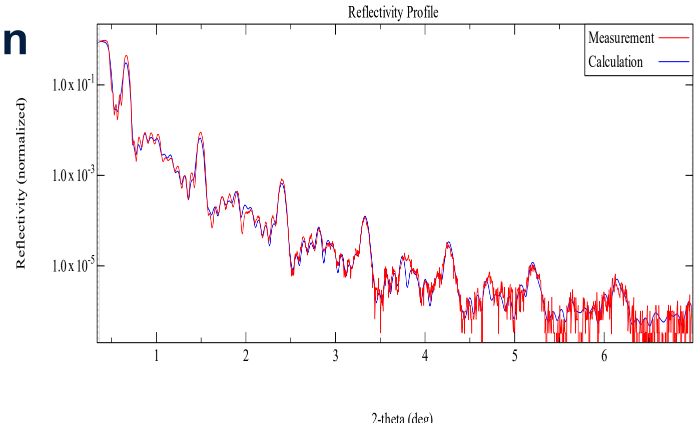


Scan time 12 min

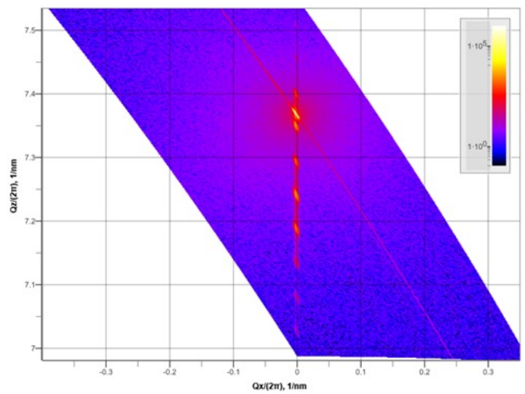
Layer No.	Materials	Thickness (nm)	sigma (nm)	Materials	Concentration Ge(%)	sigma (%)
11	Si	1.652	0.001			
10	Si	16.567	0.001			
9	Si(1-x)Ge(x)	9.871	0.001	Ge conc	28.09%	0.04%
8	Si	10.074	0.002			
7	Si(1-x)Ge(x)	9.740	0.001	Ge conc	28.46%	0.04%
6	Si	9.716	0.002			
5	Si(1-x)Ge(x)	9.349	0.001	Ge conc	28.62%	0.03%
4	Si	9.837	0.009			
3	Si(1-x)Ge(x)	8.993	0.001	Ge conc	28.99%	0.03%
2	Si	9.405	0.002			
1	Si(1-x)Ge(x)	9.574	0.001	Ge conc	27.67%	0.04%
0	Sub					

High-intensity Rotating-anode, 9 kW X-ray source

XRR Scan



RSM Scan

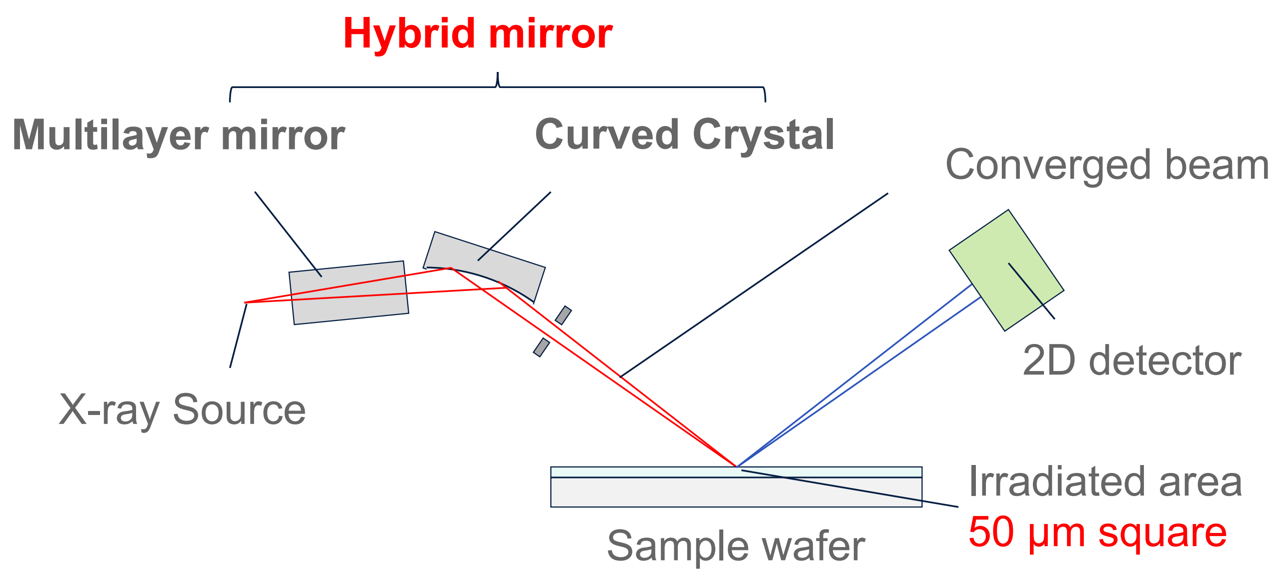


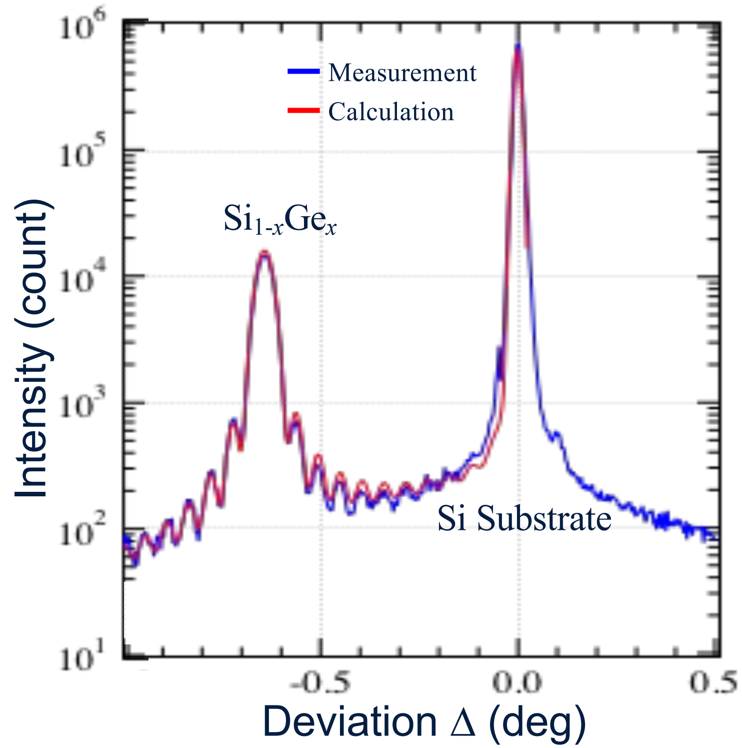
Scan time 10 min

RSM/off-specular scans can assess quality and strain/relaxation

High-Resolution X-ray Diffraction for Small Area

Micro Focus High-Resolution XRD





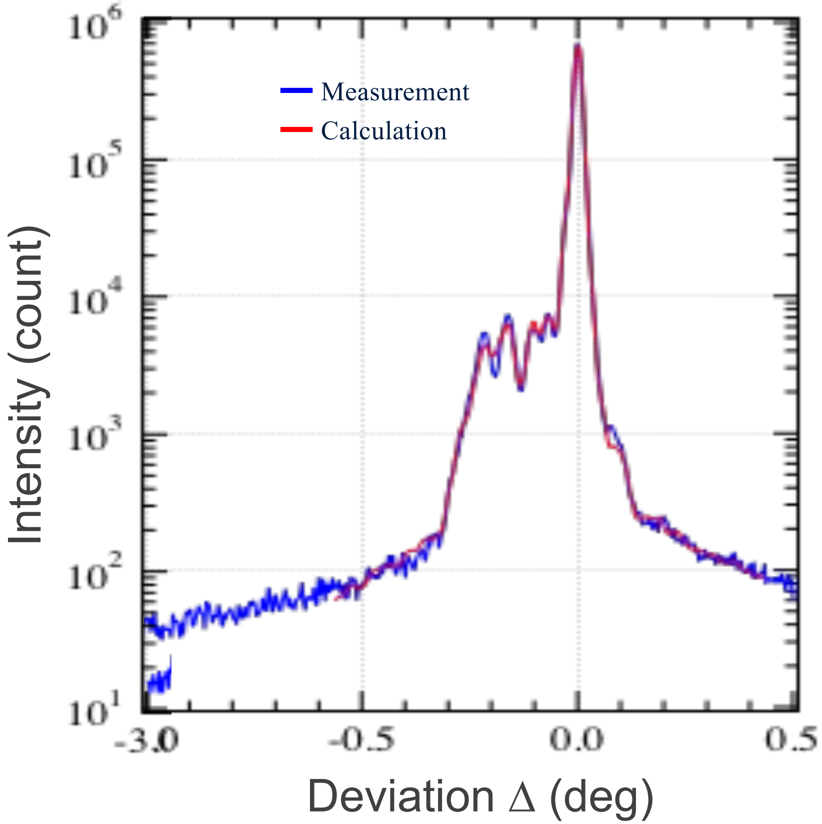
Thickness t = 96.61 nm

x = 23.25 %

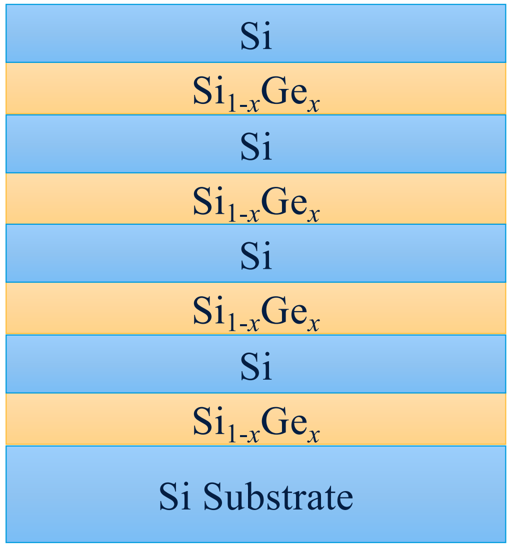
$Si_{1-x}Ge_x$
Si Substrate

Convergent beam enable to measure diffraction pattern of epitaxial layer in small area at once and typical measurement time is 10 s to 100 s.

Analysis for Multi-Stacking SiGe Layer

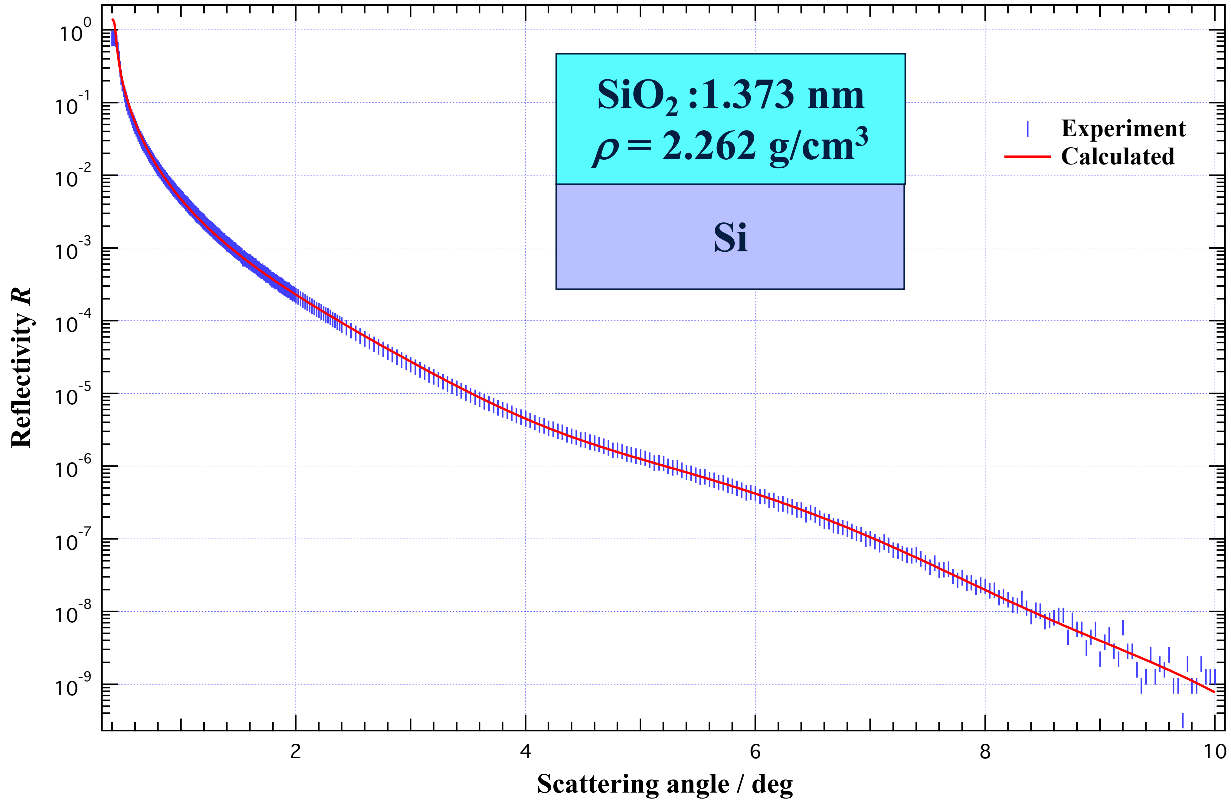


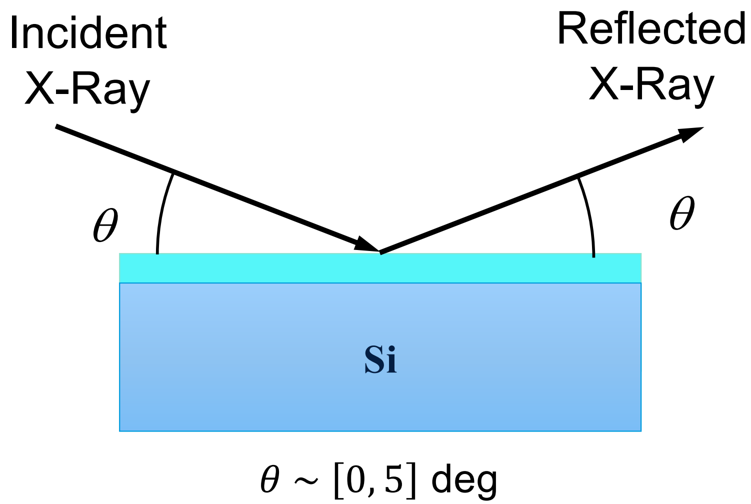
layer	t (nm)	Ge (%)
Si	80.68	-
SiGe	44.12	6.79
Si	65.21	-
SiGe	16.03	4.06
Si	94.12	-
SiGe	50.96	2.58
Si	17.66	-
SiGe	32.71	6.95



Multi-Stacking of Si/SiGe layers can be analyzed by small area HR-XRD

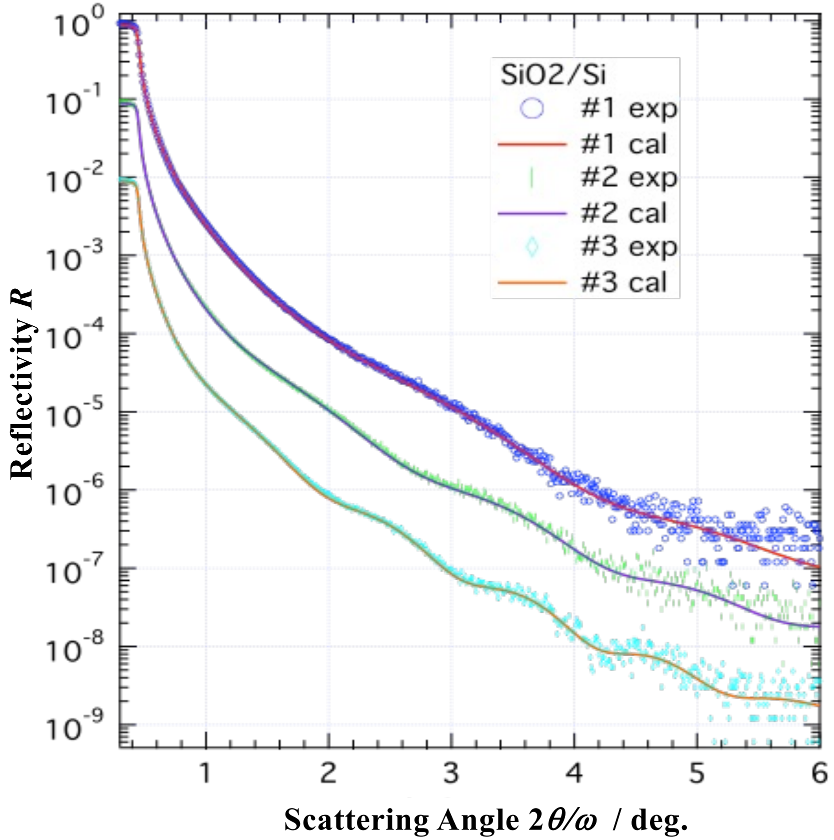
X-Ray Reflectivity (XRR) - Ultra Thin Oxide Film -





1 nm thick oxide layer could be analyzed by high-dynamic range XRR measurement

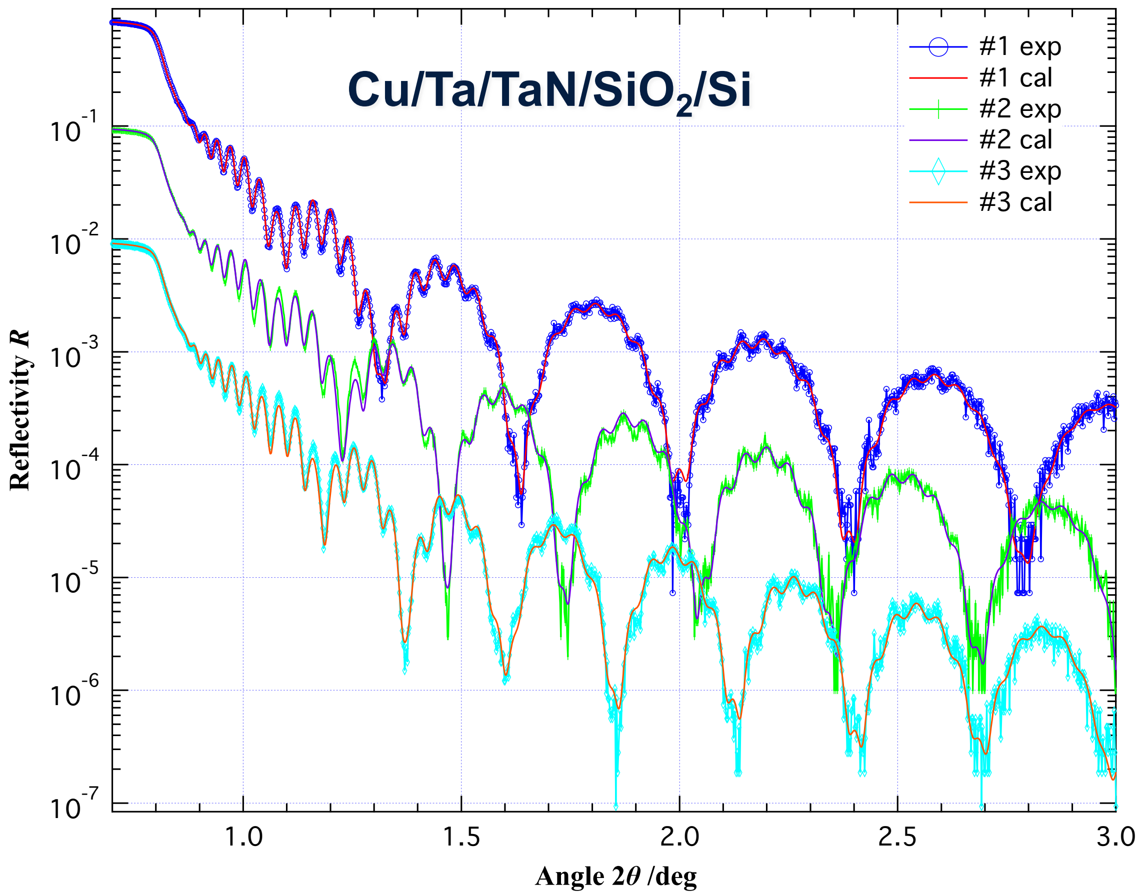
XRR: Structure of Thermal SiO_2 Film



		Thickness (nm)	Density (g/cm^3)	Roughness (nm)
#1	SiO_2	3.26	2.28	0.48
	SiO_2	0.73	2.38	0.30
	Si	-	2.329	0.10
#2	SiO_2	5.26	2.24	0.44
	SiO_2	0.73	2.39	0.49
	Si	-	2.329	0.04
#3	SiO_2	7.33	2.27	0.46
	SiO_2	1.16	2.39	0.33
	Si	-	2.329	0.10

- **Few nanometer thick SiO_2 films are accurately determined**
- **Higher density layers are formed on Si substrate**

X-Ray Reflectivity for Metal Layers

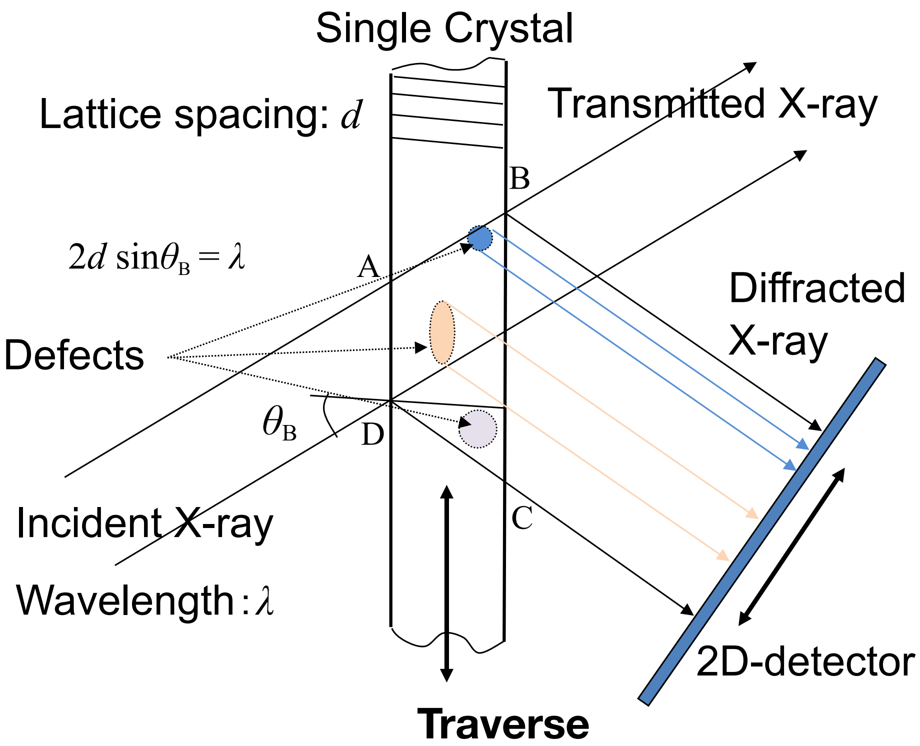


		Thickness (nm)	Density (g/cm^3)	Roughness (nm)
#1	CuO	2.73	5.2	1.45
	Cu	147.74	9.053	1.17
	Ta	10.94	15.94	0.05
	TaN	9.33	14.52	0
	SiO_2	-	2.20	0.423
#2	CuO	2.70	5.8	1.59
	Cu	146.98	9.04	0.97
	Ta	14.55	16.46	0.21
	TaN	10.23	14.91	0
	SiO_2	-	2.20	0.432
#3	CuO	2.79	4.3	1.25
	Cu	146.95	9.089	1.20
	Ta	18.88	16.34	0.427
	TaN	9.34	14.95	0
	SiO_2	-	2.20	0.441

Top Cu oxidation layer thickness was determined by XRR measurements

X-Ray Topography (Diffraction Imaging)

Geometry of the X-ray topography



A. R. Lang, *Acta Cryst*., **12**, 249 (1959)

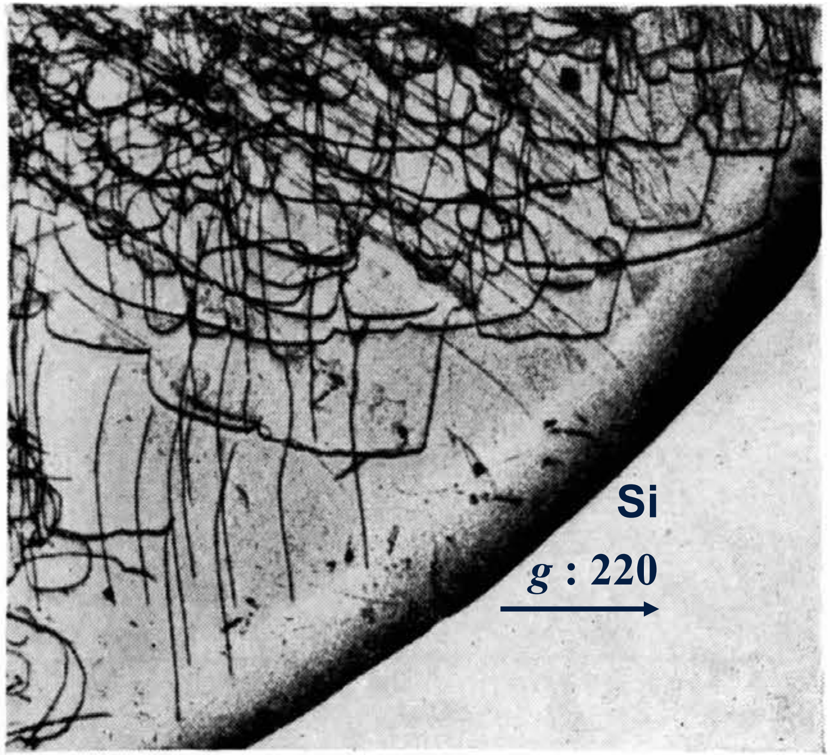
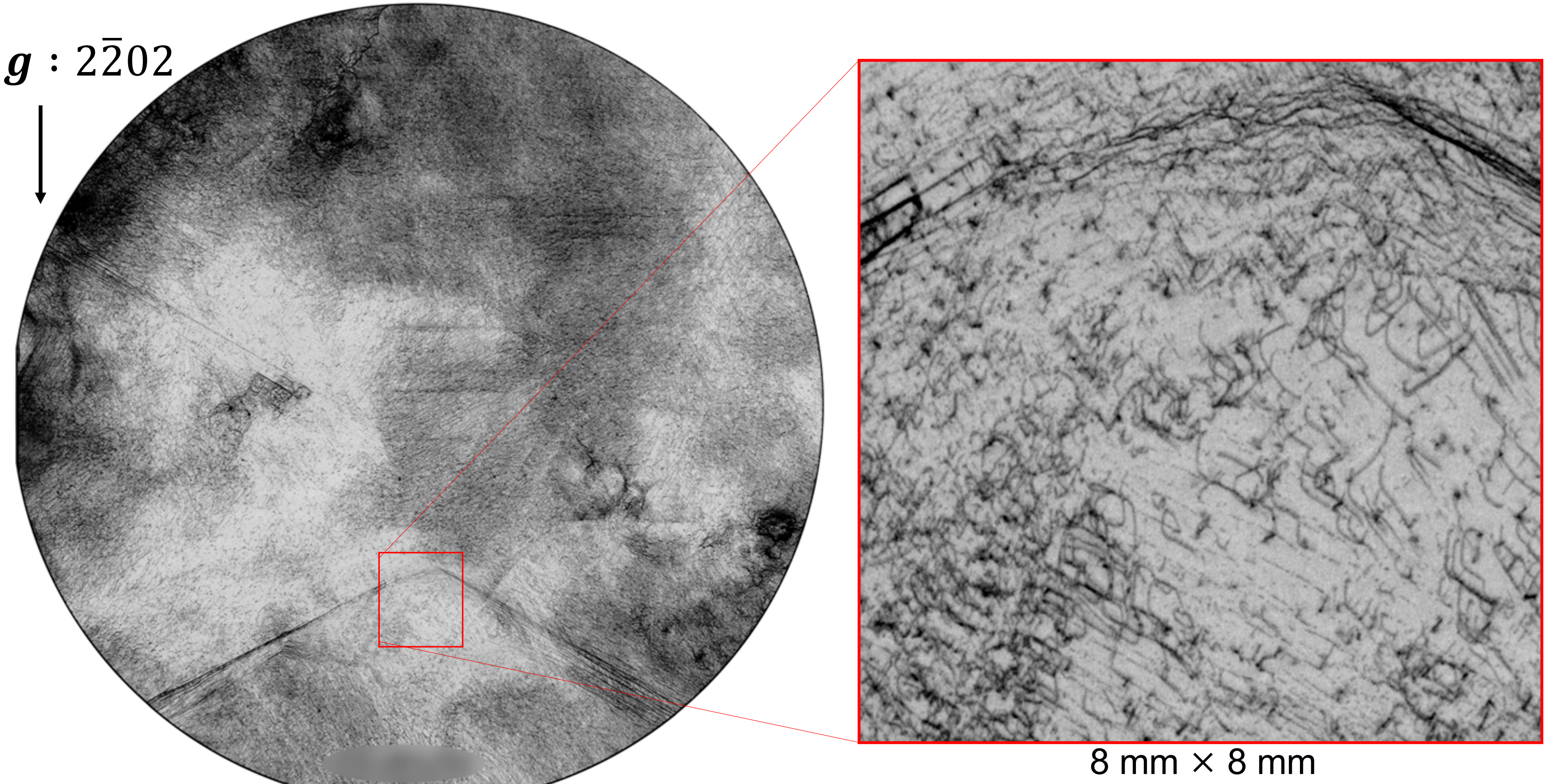


Fig. 2. A projection topograph of dislocations in a {111} slice of silicon, taken with a 220 reflection from planes normal to the slice.

Individual dislocations in the entire crystal are identified

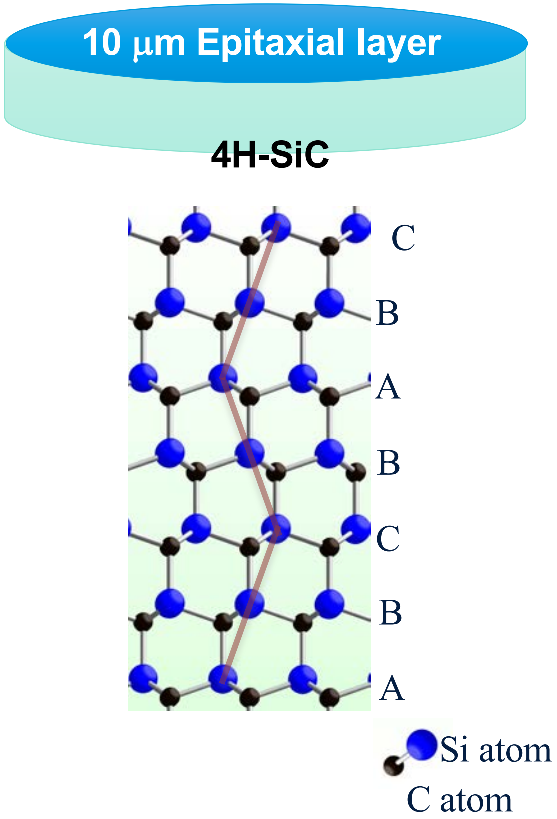
4H-SiC 3 inches wafer Transmission Topography

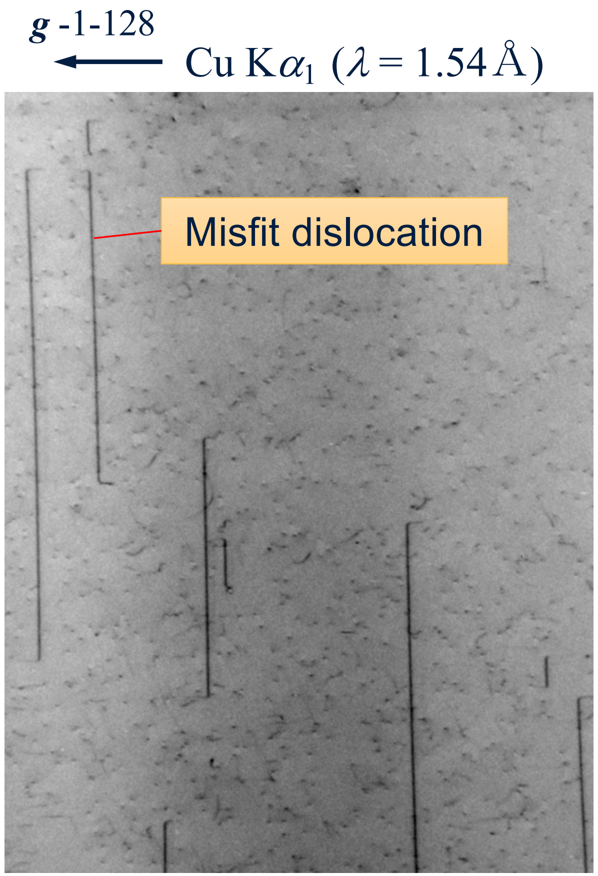


SiC crystals for the industrial use still contain a lot of dislocations

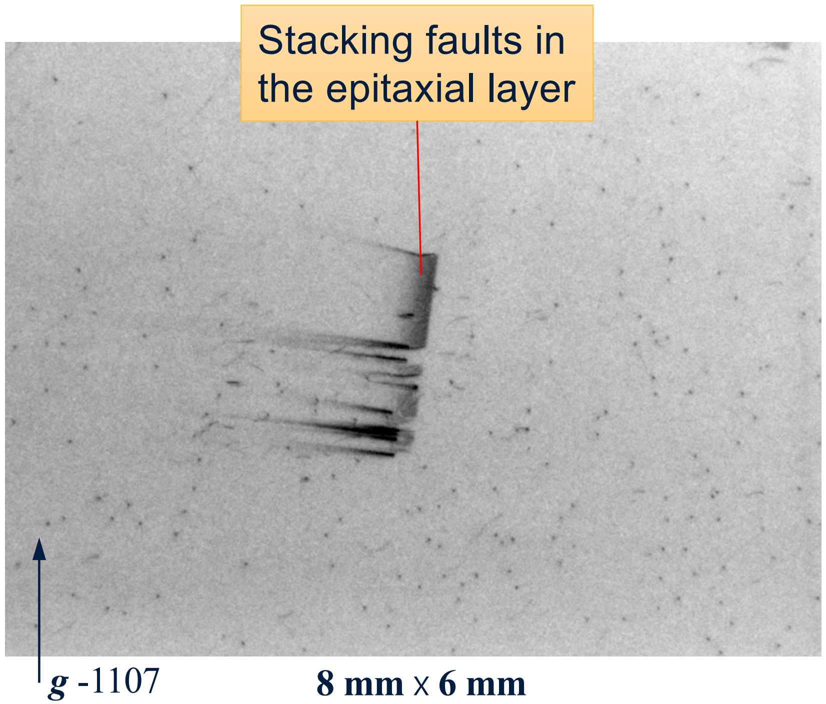
Reflection Topography for 4H-SiC

<u>**High-resolution x-ray camera (pixel size: 2.4 μm) is used for the measurements**</u>



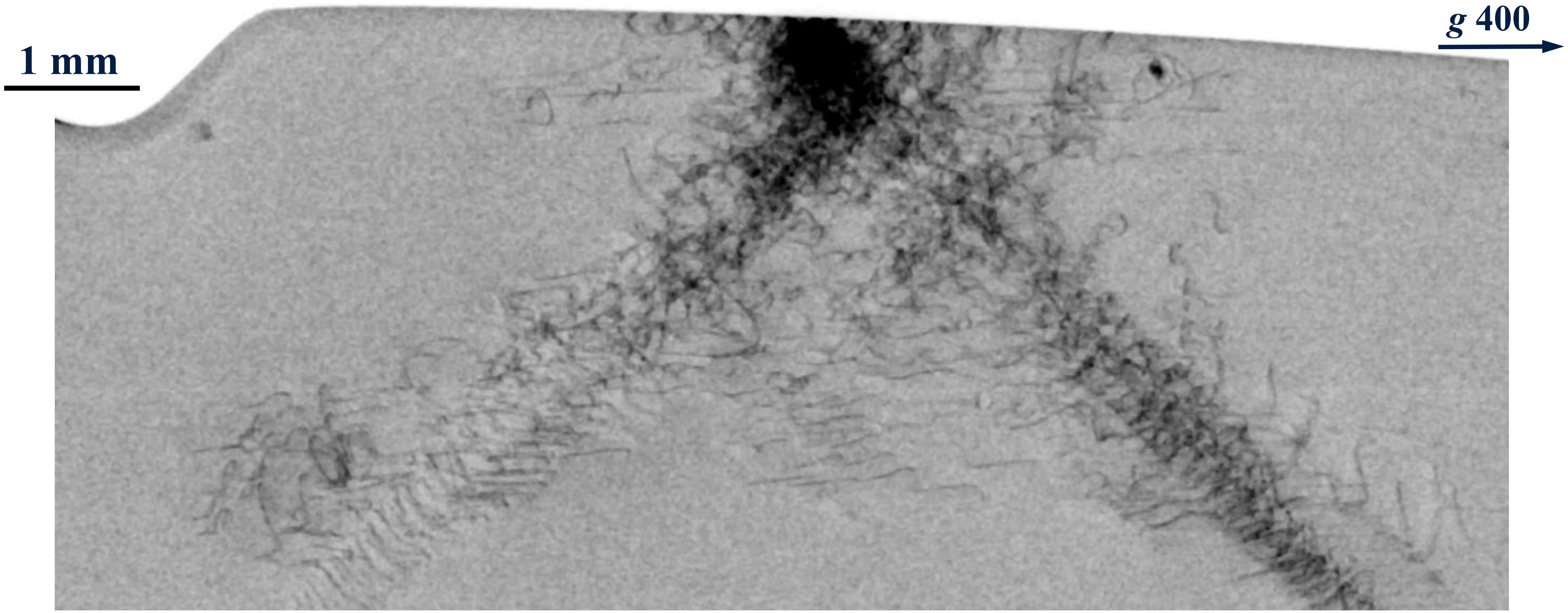


6 mm x 8 mm



8 mm x 6 mm

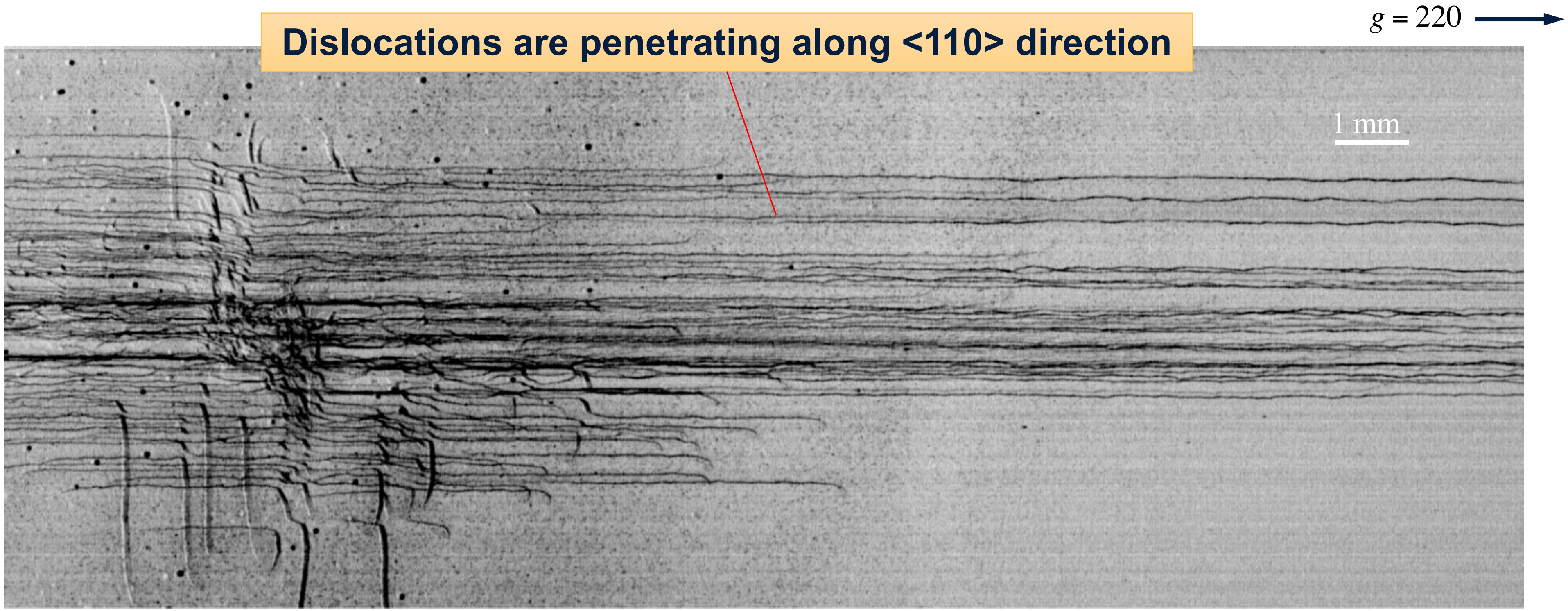
Topography for Process Induced Defects in Si Wafer



Original Si wafer is dislocation free, but can be created by the device manufacturing process

3D Visualization of Dislocations in Si Wafer

Dislocations are penetrating along <110> direction

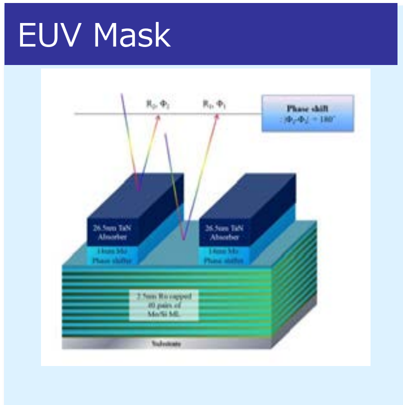


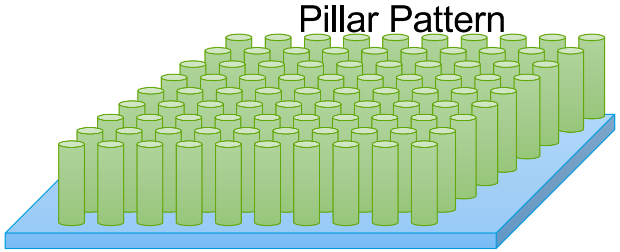
Dislocations are penetrating center of wafer plate

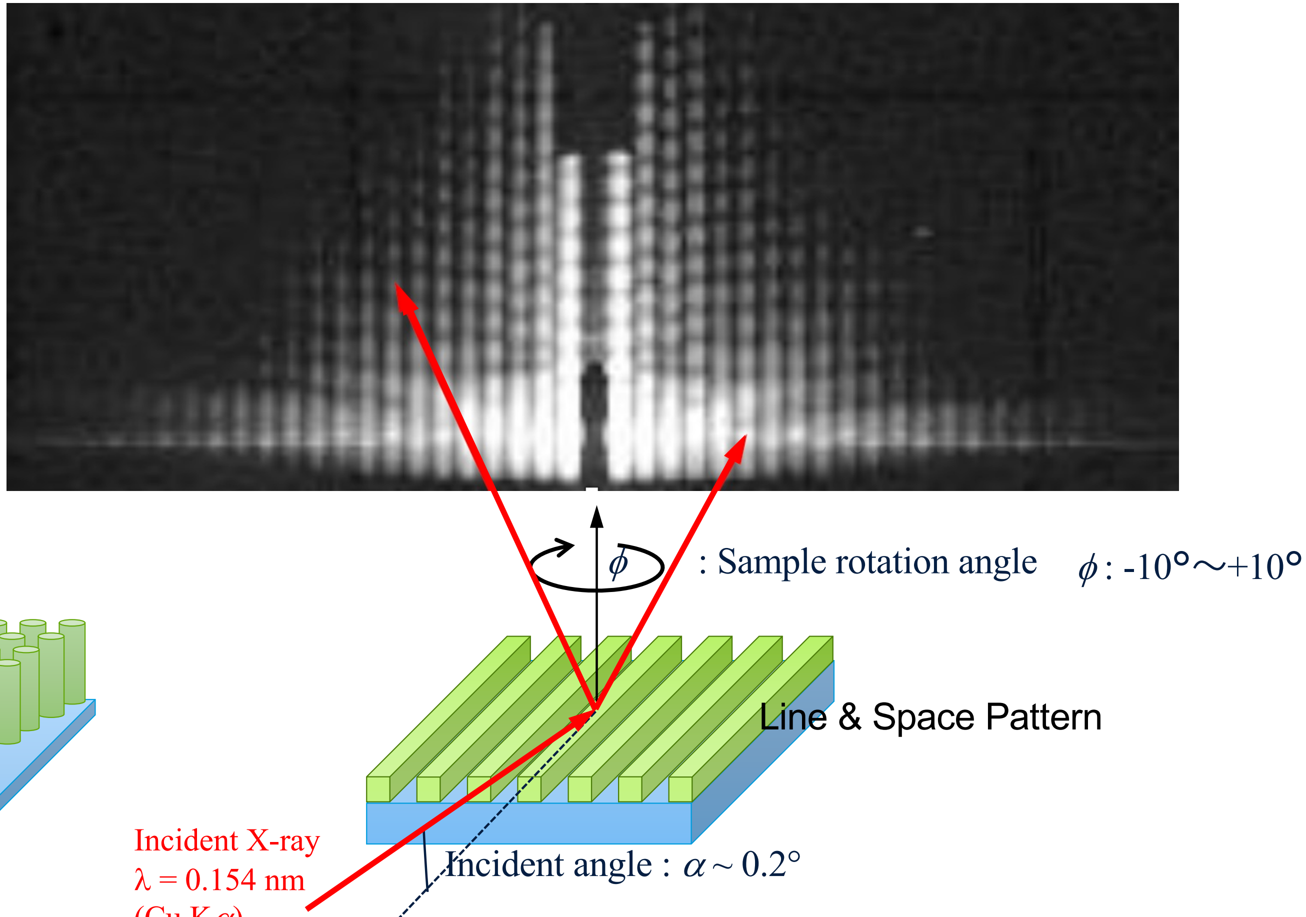
Small Angle X-ray Scattering (SAXS) for Device Nano-pattern Analysis

Grazing Incidence X-ray Scattering (GI-SAXS)

Analysis for Surface Nanostructure



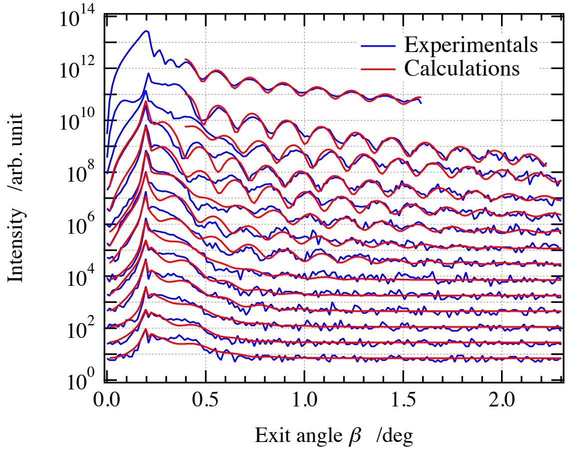


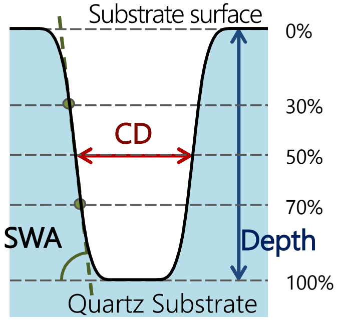


K. Omote, Y. Ito, and Y. Okazaki, *Proc. of SPIE,* 7638, 763811 (2010)

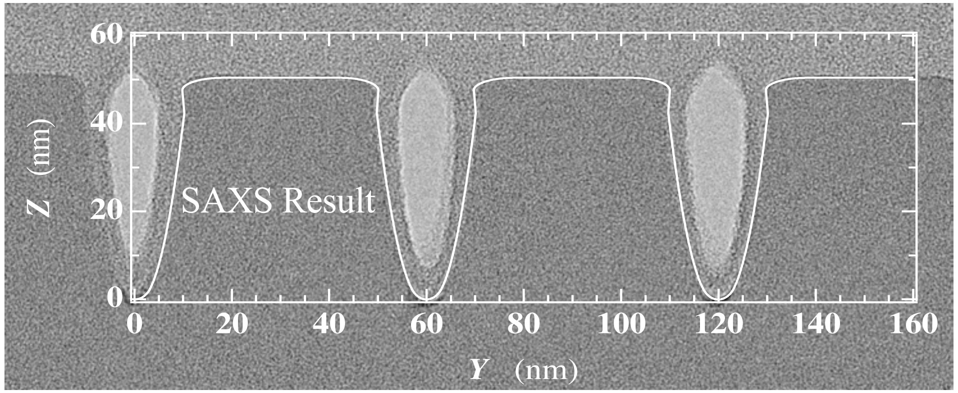
GI-SAXS enables to analyze surface structure for the nanoscale device patterns

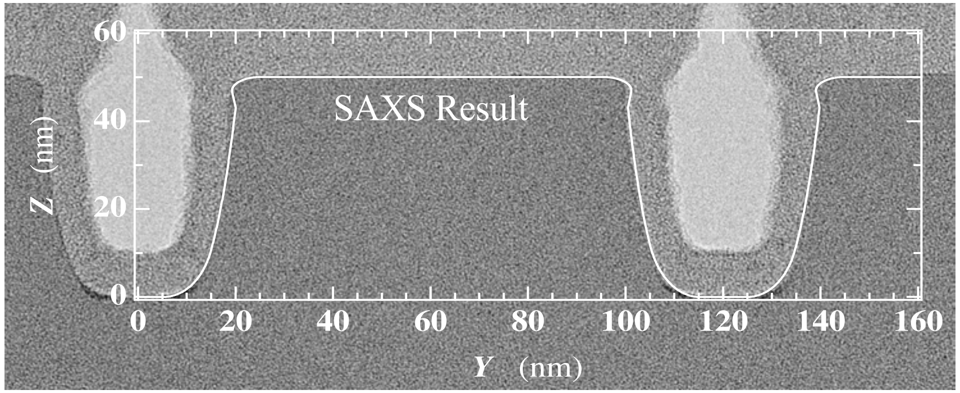
Nano-Imprint Mold L&S Cross-Section Profile

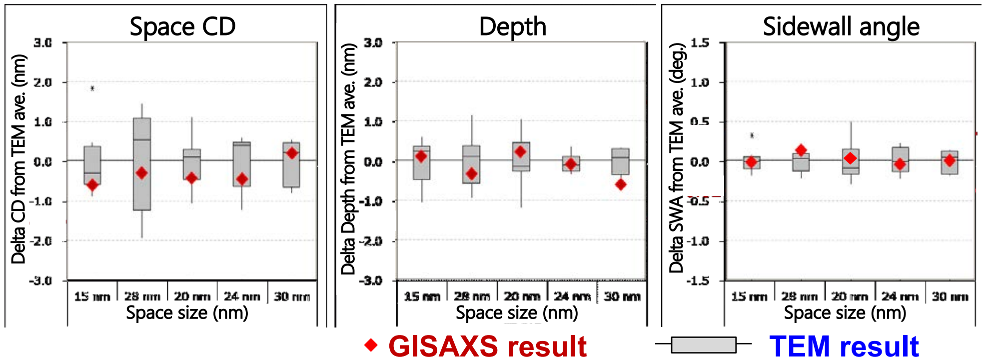




Cross-section TEM image





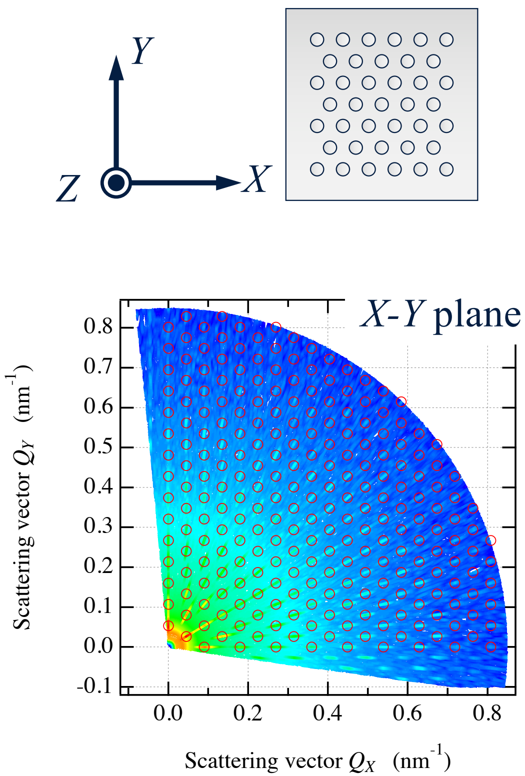


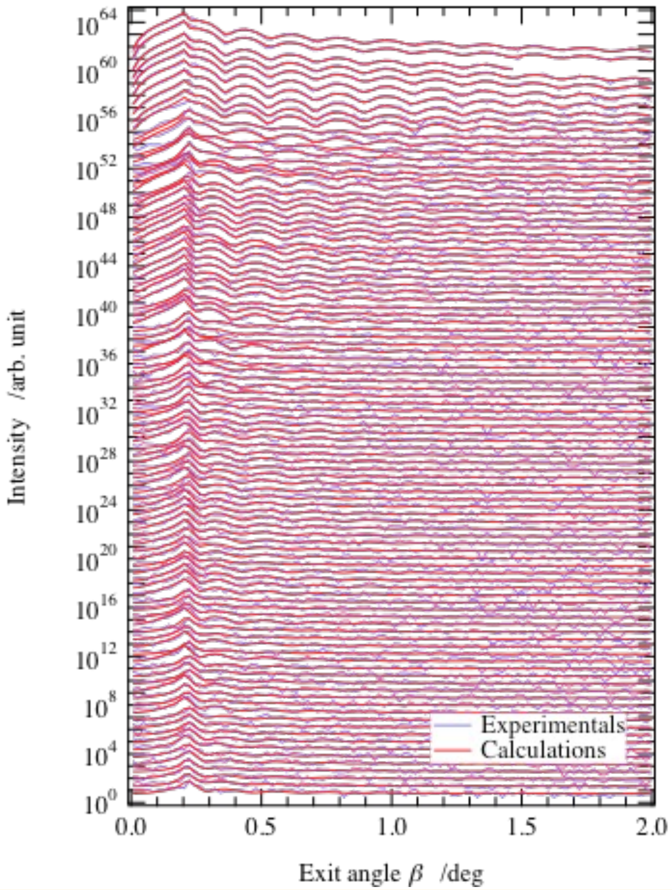
GI-SAXS results agree very well with that of cross-section TEM

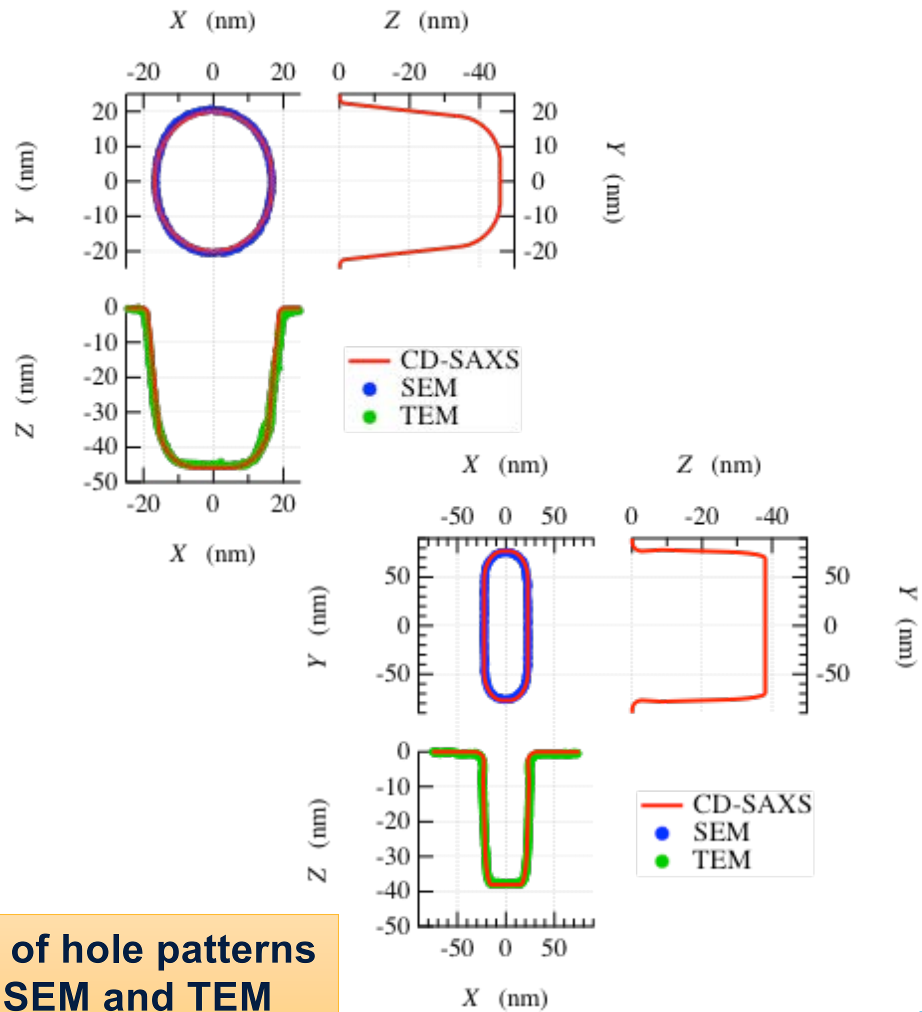
E. Yamanaka, et. al., *Proceedings of SPIE,* 9984, 99840V, (2016)

Nano-Imprint Mold Hole Pattern 3D-Shape

Hole Pattern



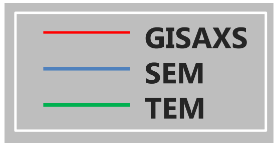


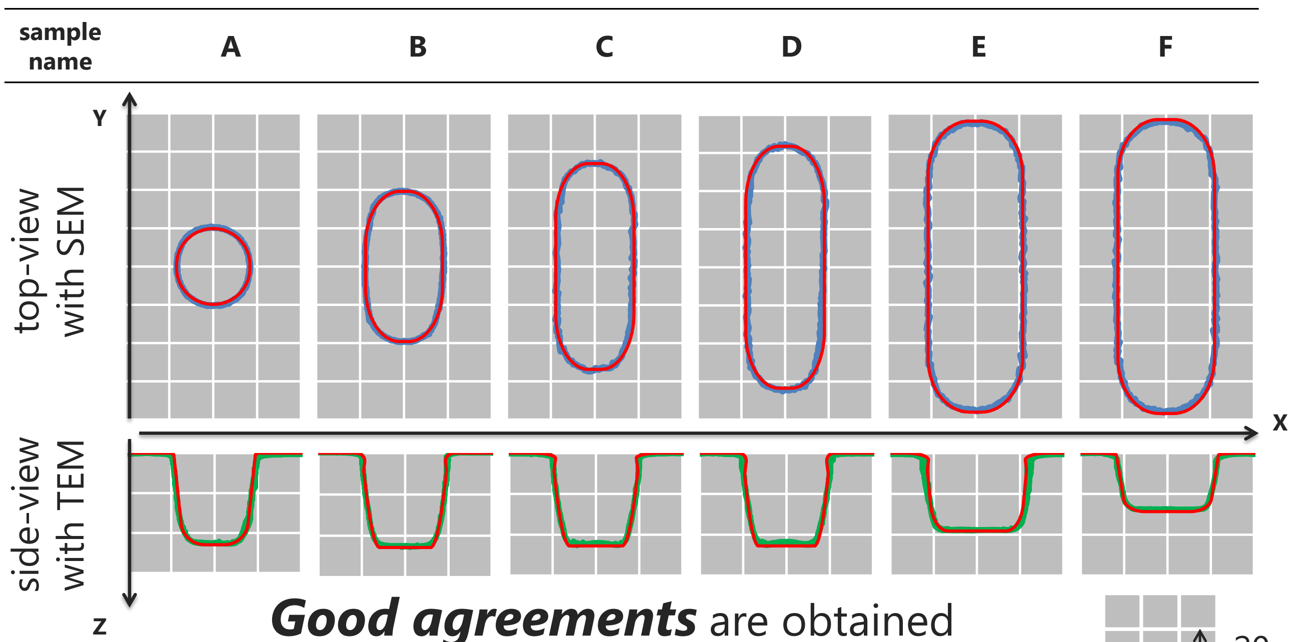


GI-SAXS can also analyzed three-dimensional structure of hole patterns and the results agree very well with that observed by SEM and TEM

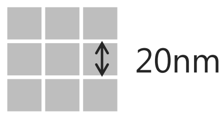
Nano-Imprint Mold Hole Pattern SAXS vs. SEM & TEM

The profile of GISAXS was overlapped on that of SEM & TEM.





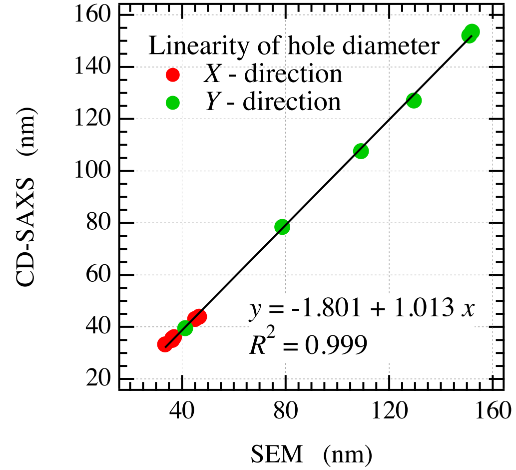
Good agreements are obtained in each of the profiles.

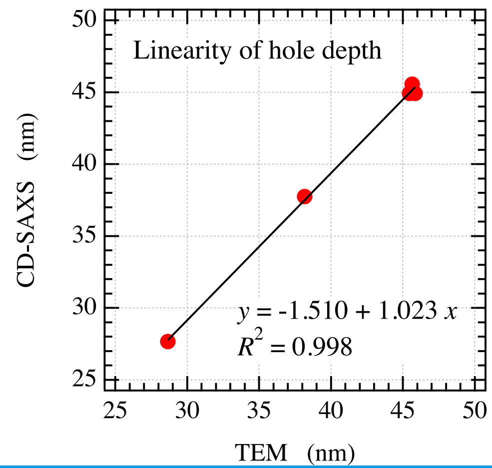


GI-SAXS results agree very well with that of SEM and cross-section TEM

K. Hagihara, et. al., *Proceedings of SPIE,* 10451, 104510H (2017)

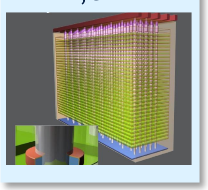
Linearity with SEM & TEM



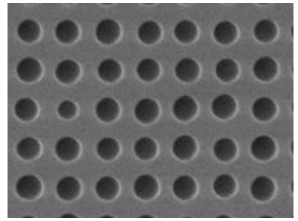


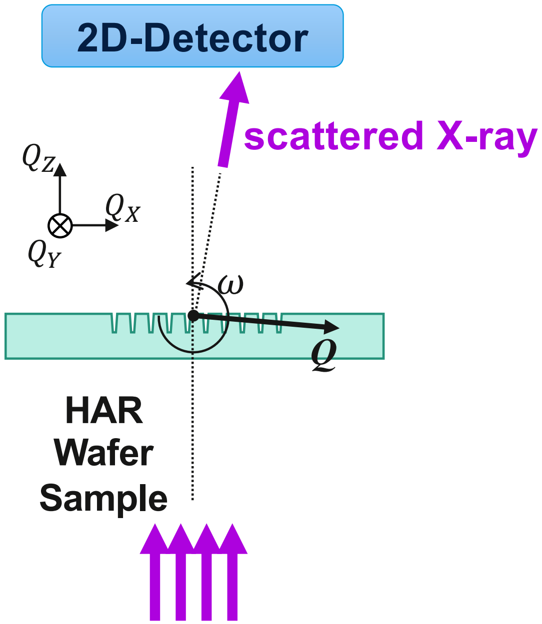
Transmission X-ray Scattering (T-SAXS)

DRAM,3D NAND

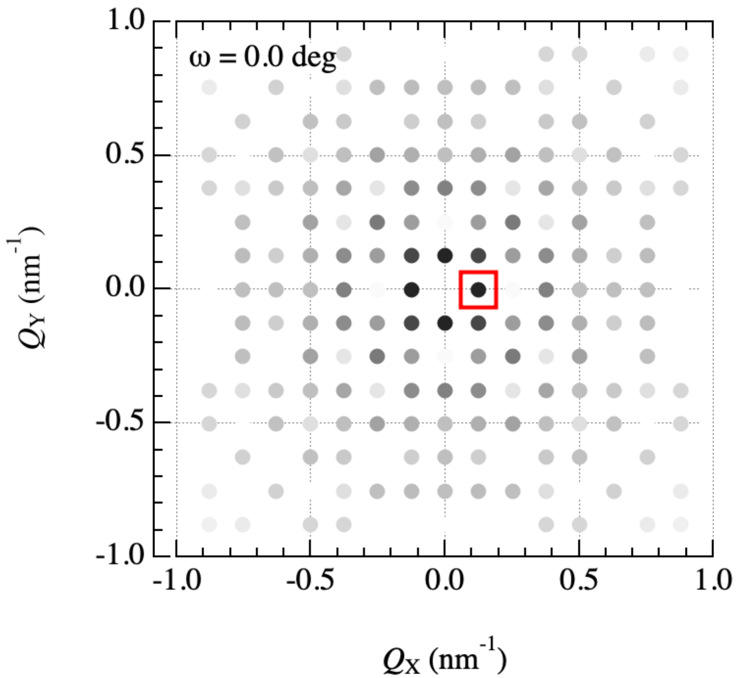


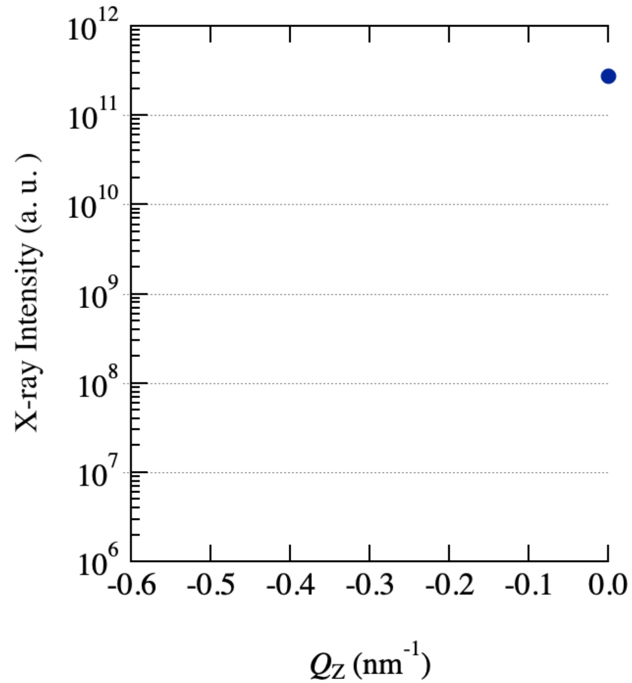
Analysis for HAR (High Aspect Ratio) Structures





2D-Detector

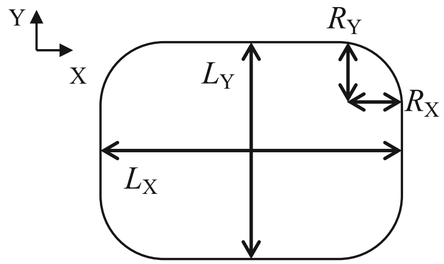




T-SAXS enables to analyze HAR structure for the process wafers as is

Shape Modeling for HAR Hole Structure

- The X-Y cross-sectional shape of the hole was represented with "Koban model".
  Parameters: Koban parameter R_X/L_X (R_Y/L_Y)
- The structure in the depth direction of the hole was represented by stacking of a number of thin layers.
  Parameters: diameter, center line shift, thickness, etc.



$R_X/L_X = 0.5$ -> ellipse
$R_X/L_X = 0.0$ -> rectangular

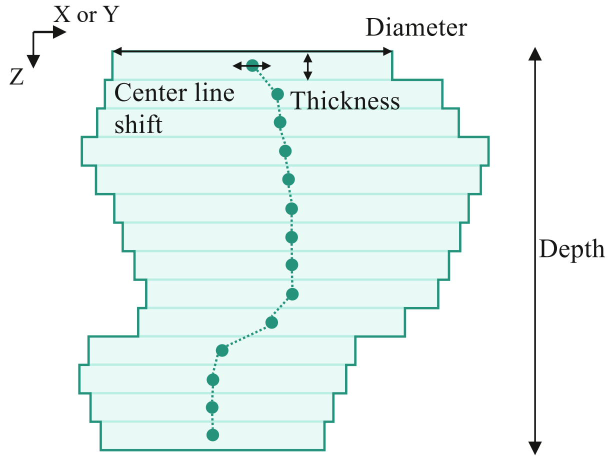
"Koban"
Japanese oval gold coin in Edo period

$$F_j(\boldsymbol{Q}) = \sum_{l=1}^{M} \int_{X,Y} \rho_j(z_l, x, y) e^{-i(Q_x x + Q_y y + Q_z z_l)} dxdy \, \Delta z_l$$

$$I(\boldsymbol{Q}) = (r_c P)^2 \langle F_j(\boldsymbol{Q}) F_k^*(\boldsymbol{Q}) e^{-i \boldsymbol{Q}\cdot(\boldsymbol{u}_j - \boldsymbol{u}_k)} \rangle \sum_{j,k=1}^{N} e^{-i \boldsymbol{Q}\cdot(\bar{\boldsymbol{R}}_j - \bar{\boldsymbol{R}}_k)}$$

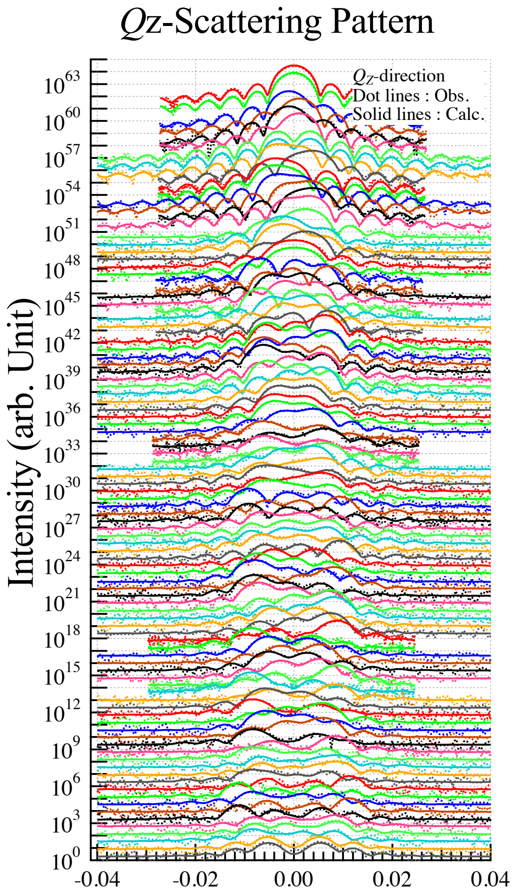
$$= (r_c P)^2 \langle F_j(\boldsymbol{Q}) F_k^*(\boldsymbol{Q}) e^{-i \boldsymbol{Q}\cdot(\boldsymbol{u}_j - \boldsymbol{u}_k)} \rangle \frac{\sin\left(\frac{N_x Q_x L_x}{2}\right) \sin\left(\frac{N_y Q_y L_y}{2}\right)}{\sin\left(\frac{Q_x L_x}{2}\right) \sin\left(\frac{Q_y L_y}{2}\right)}$$

Stacked layer structure schematic diagram



Free slicing for the HAR structure is used and analyzing without any specific models of the hole structure

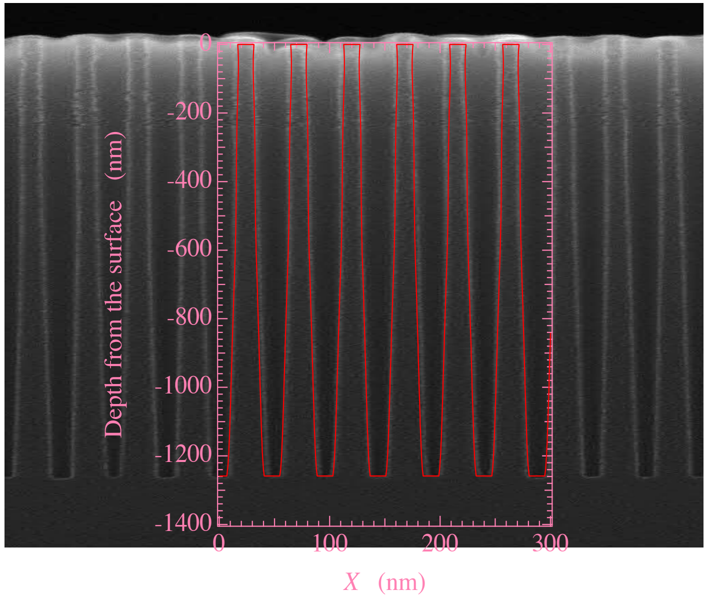
Example of HAR Structure Analysis by SAXS



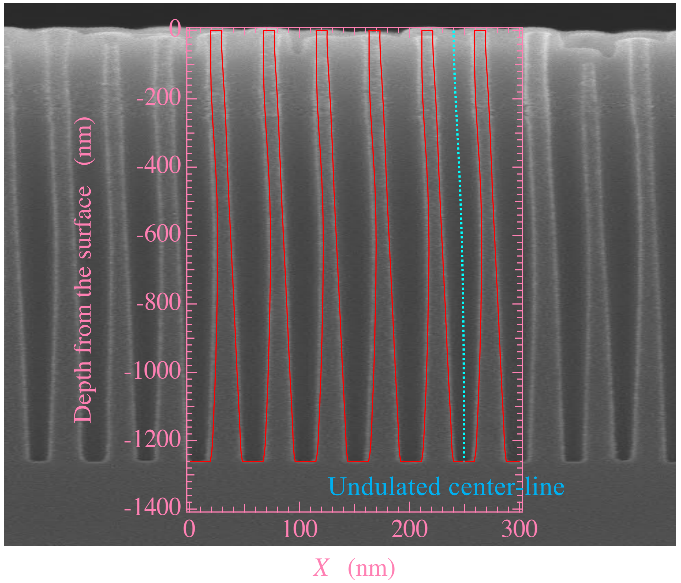
Site B scattering pattern

Red line indicates the obtained profile to optimize measured and calculated scattering intensity.

Site A



Site B

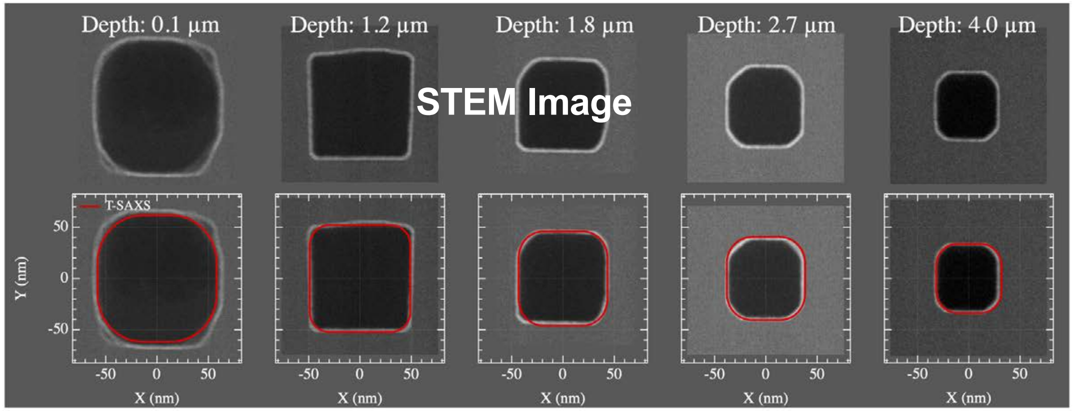


The *X-Z* cross section profile estimated by SAXS are consistent with that measured by the cross-sectional SEM as a reference.

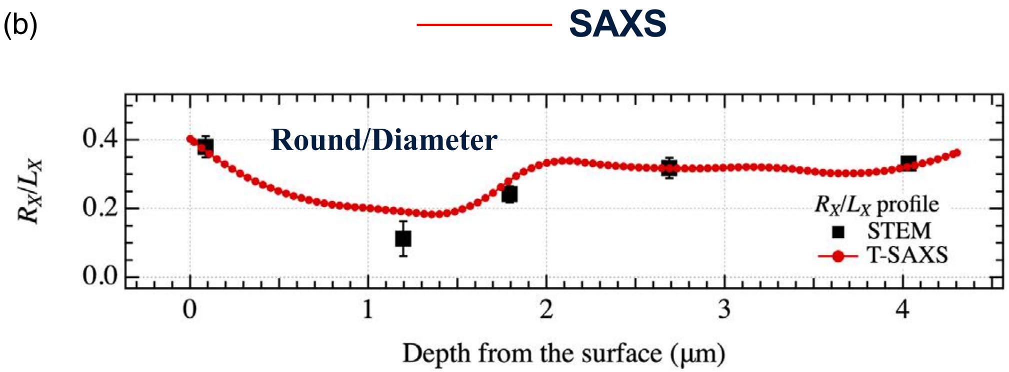
Yoshiyasu Ito, *et. al.*, Japanese Journal of Applied Physics, **62**, 046501 (2023).

Precise Analysis for The Hole Shape by SAXS

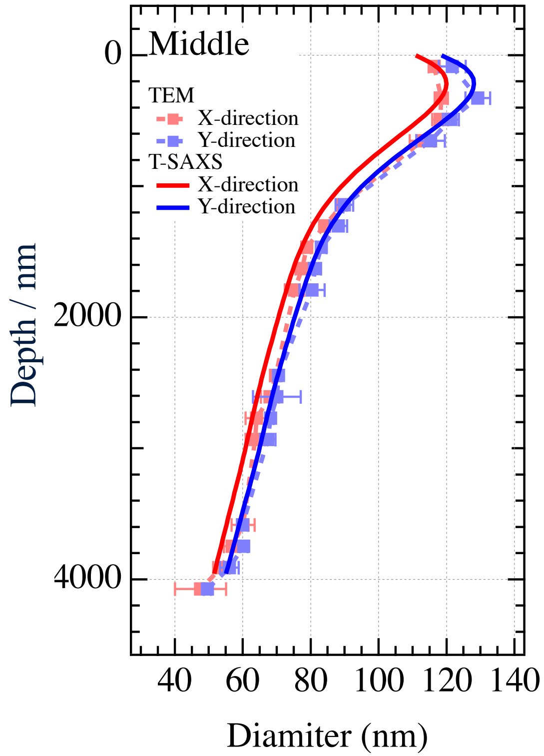
(a)



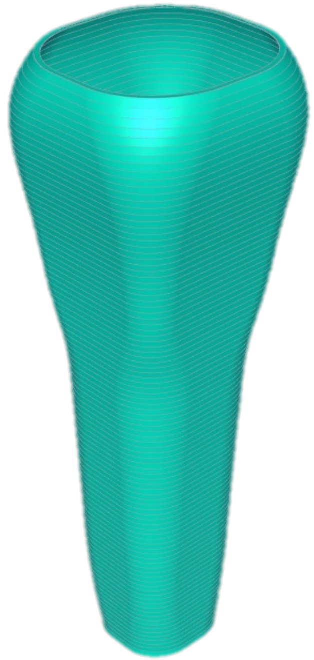
(b)



Hole depth shape



Hole 3D shape



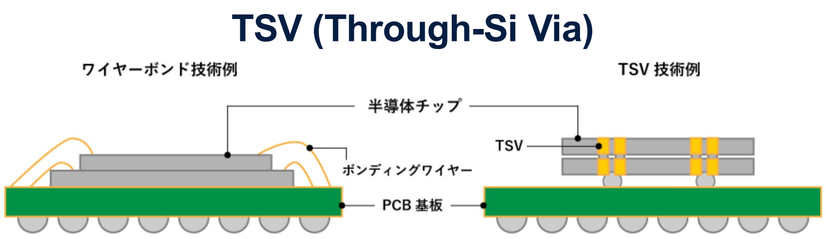
Similar result with TEM was observed for cross sectional shape

Rieko Suenaga, *et. al*., Japanese Journal of Applied Physics, **62**, 096502 (2023).

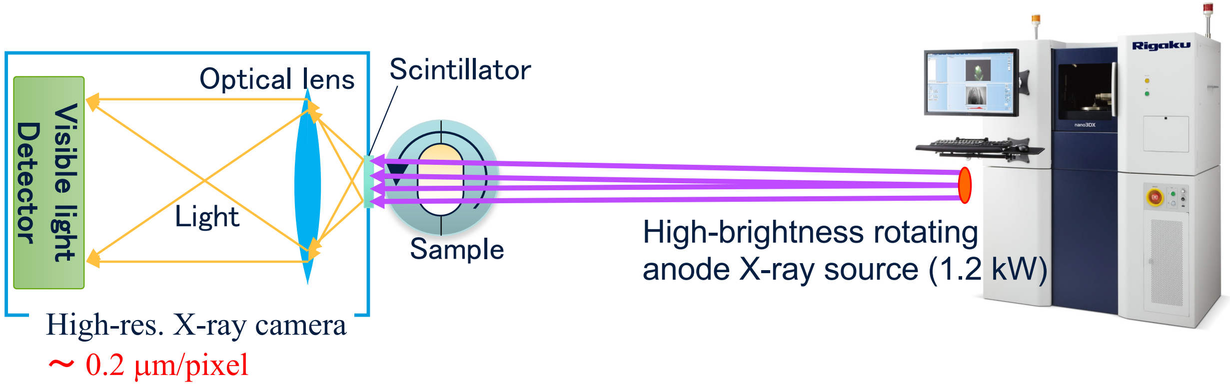
X-ray scattering is superior to analyze average structure with 0.1 nm resolution, non-destructively, but not good for detecting local defects. Therefore, it is strongly demanded a metrology to observe local defects.

X-ray Imaging

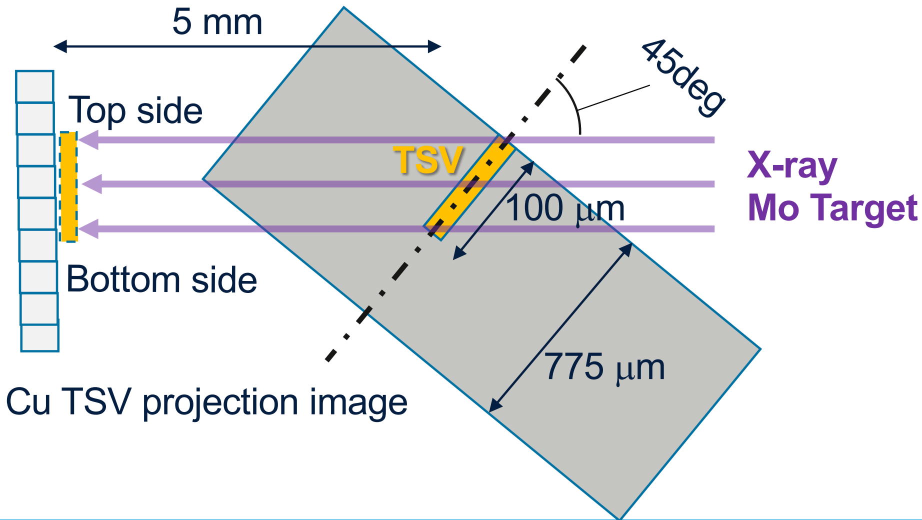
Needs for Visualization of Buried Metal Structure



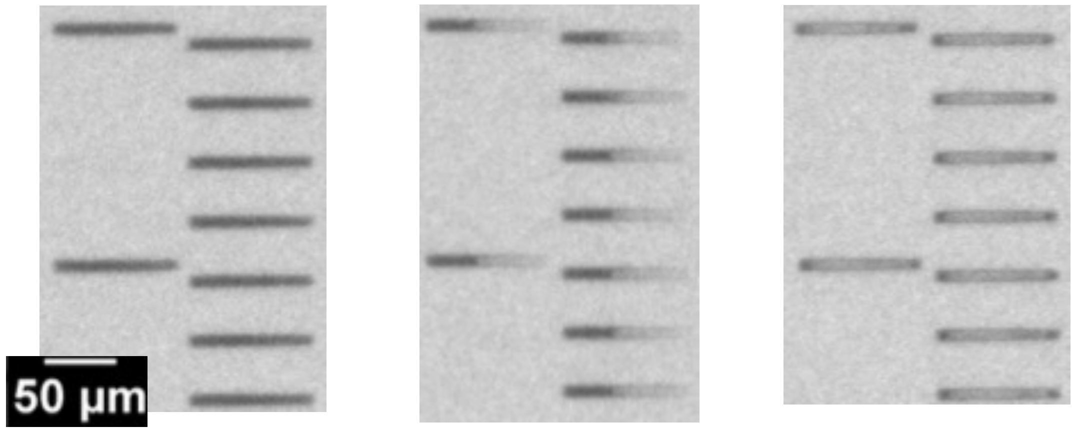
https://www.inrevium.com/pickup/tsv/#03



Measurement geometry



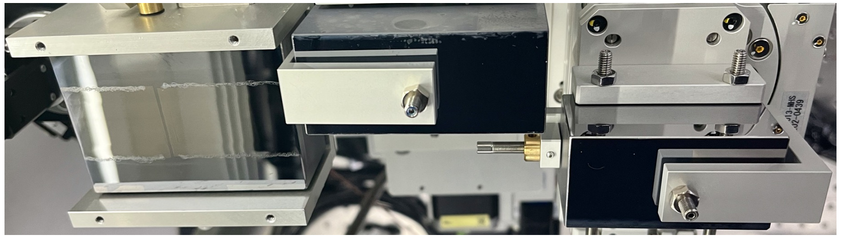
X-ray projection images for TSVs



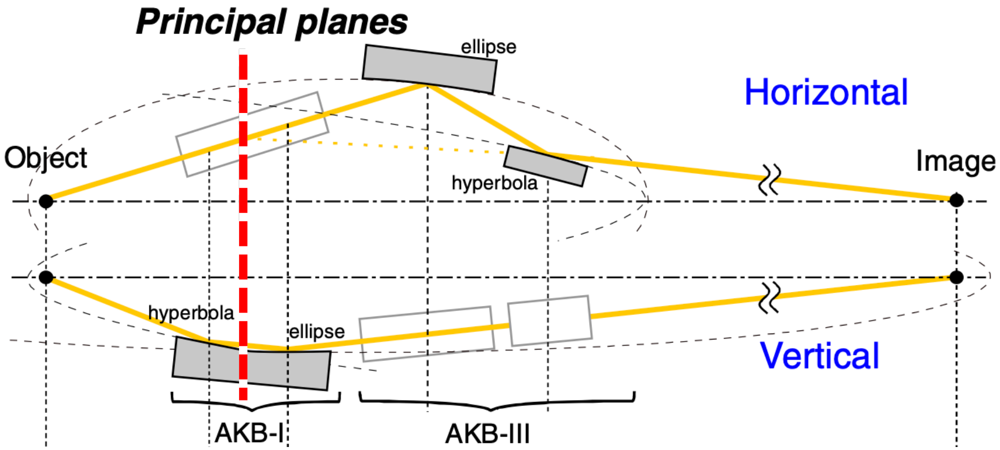
Cu filling structures are clearly visible

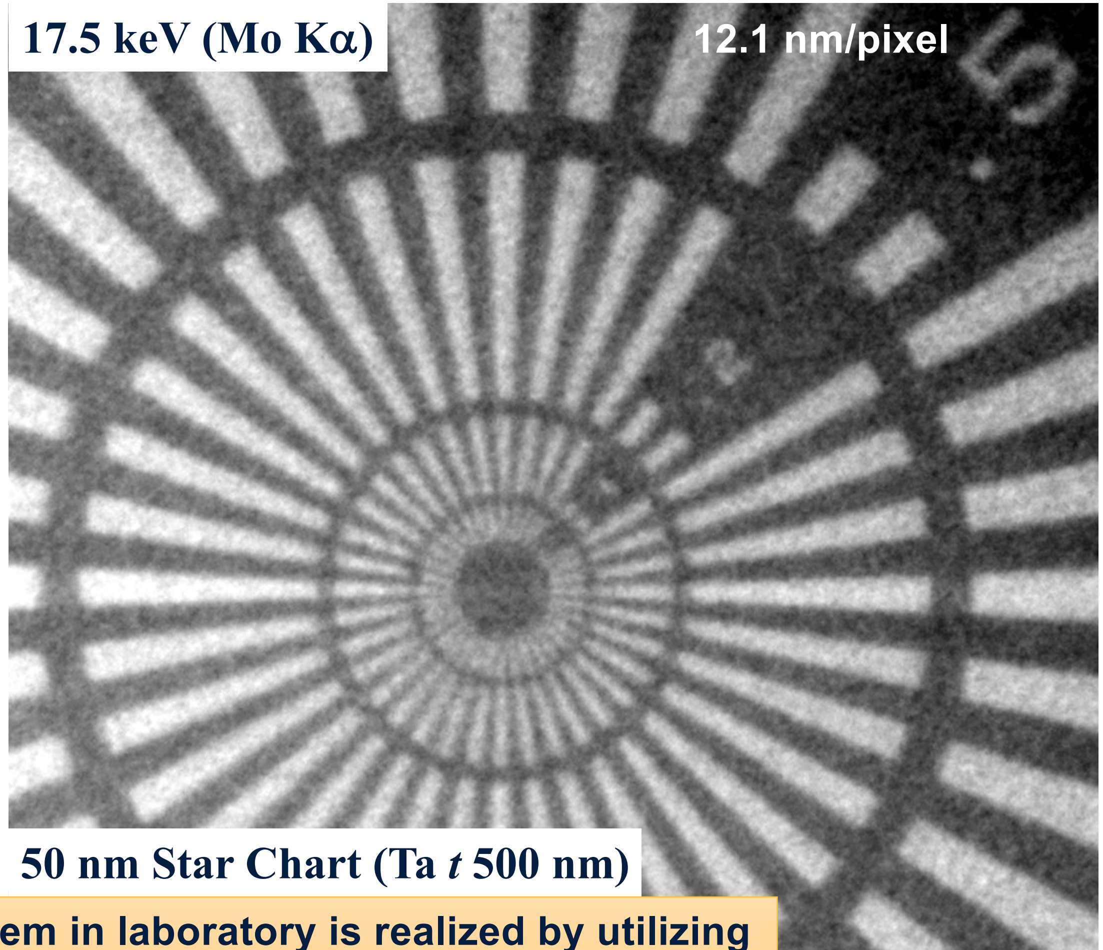
Developing Reflective Imaging Lens for Hard X-Ray

X-ray imaging lens



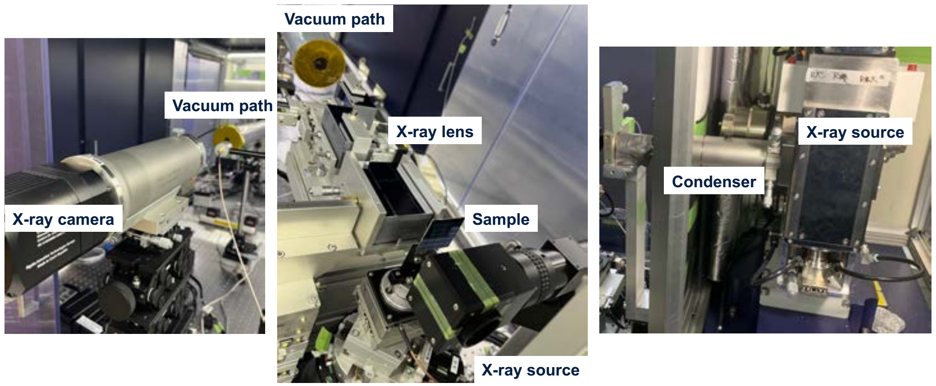
Advanced Wolter type KB mirror for 17.5 keV X-ray

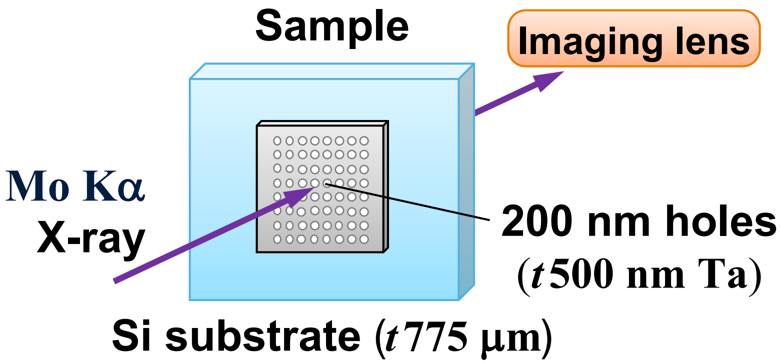


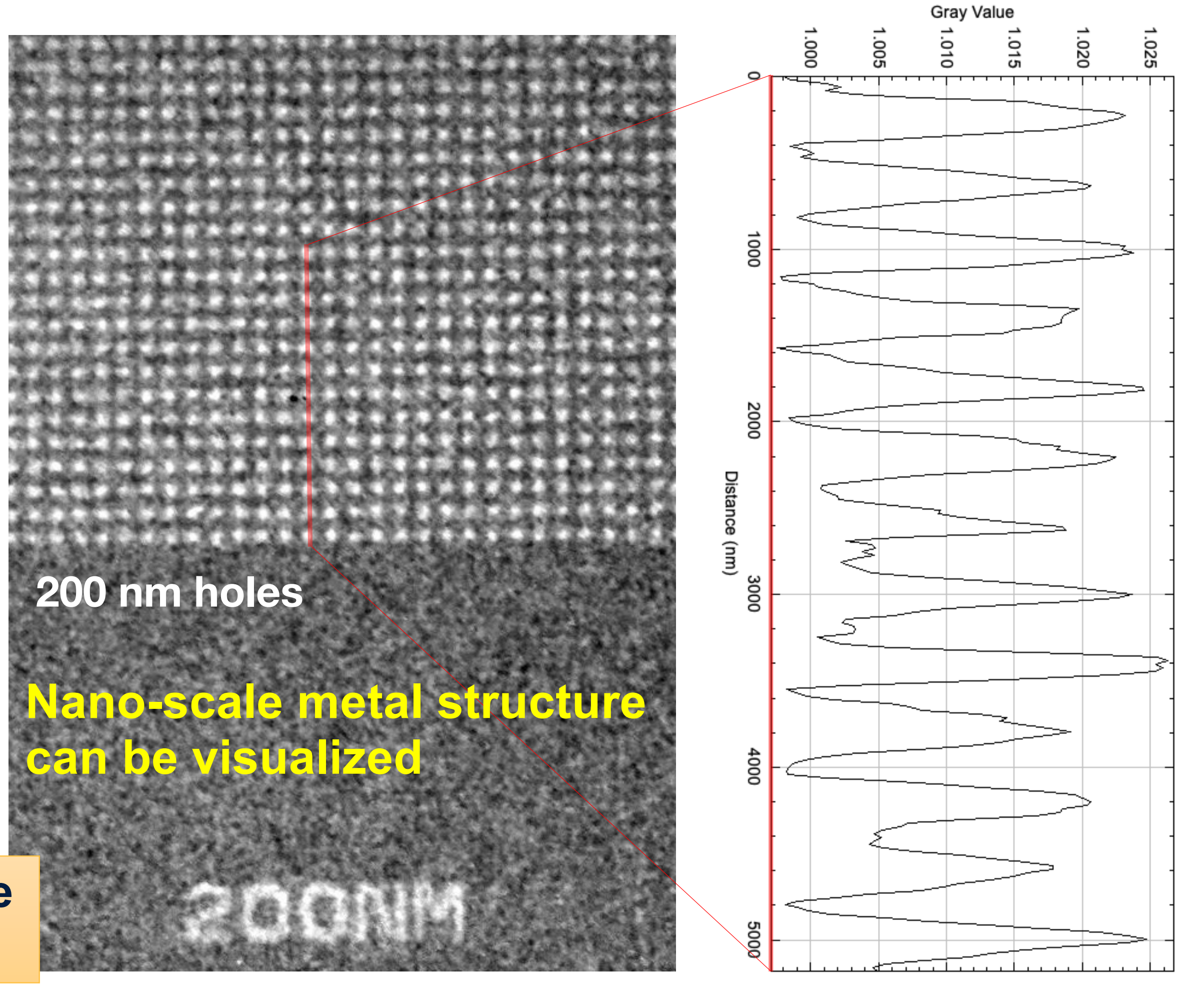


Hard X-ray nanoscale imaging system in laboratory is realized by utilizing reflective lens and High-brightness X-ray source

Nanometer Resolution Hard X-Ray Imaging in Lab







We can measure nanoscale metal structure without destroying Si substrate

Future Challenges

- **X-ray Diffraction/Scattering**
  - ✓ **Measurement for thinner film crystallinity, more complex film characterization, e.g. GAA**
  - ✓ **Higher sensitivity for crystal distortion and identification of the defect species**
  - ✓ **Shorter footprint for Grazing Incidence SAXS**
  - ✓ **More accurate shape analysis for HAR structures by Transmission SAXS**

- **X-ray Imaging**
  - ✓ **Higher resolution and shorter exposer time**

Continuing improvements for X-ray sources, optics, and detectors are the key!