Cross Sectional Characterization of Planar and Non-planar Nanostructures using X-ray Scattering

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CD-SAXS: measuring diffraction pattern at multiple sample orientation

Methodology:

1) Measure diffraction pattern at varying angles of incidence

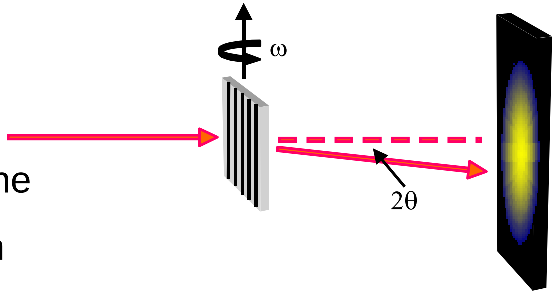
2) Compile data into Intensity vs. q_x,rotation angle

3) Transform data from sample rotation to Q_x,Q_z coordinate plane

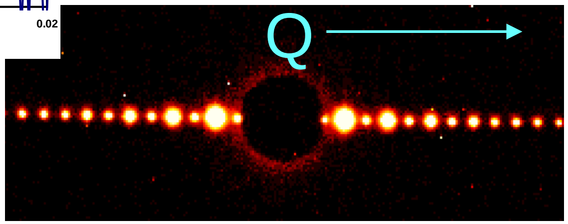
4) Fit data using Fourier transform of ideal pattern cross section

5) **Applicable to buried structure with multiple materials- Si, Cu, Ta, Hf etc.**

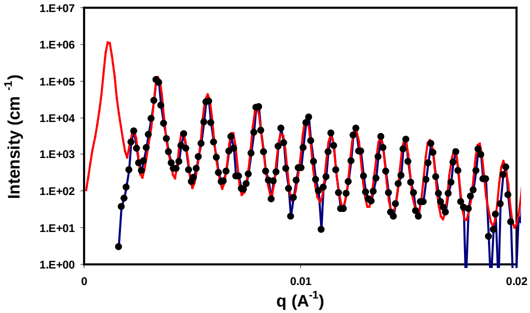
CD-SAXS

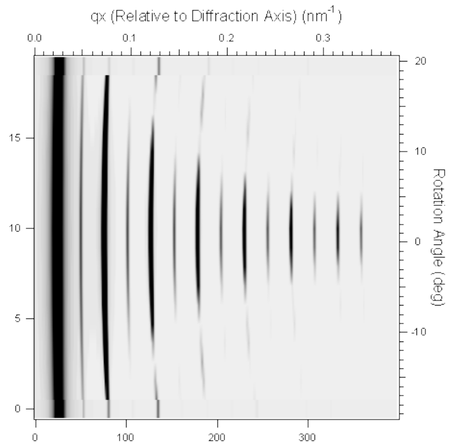


Resulting X-ray detector image at a fixed rotation angle ω



"Single-slice" data set obtained in ≈ 1 min



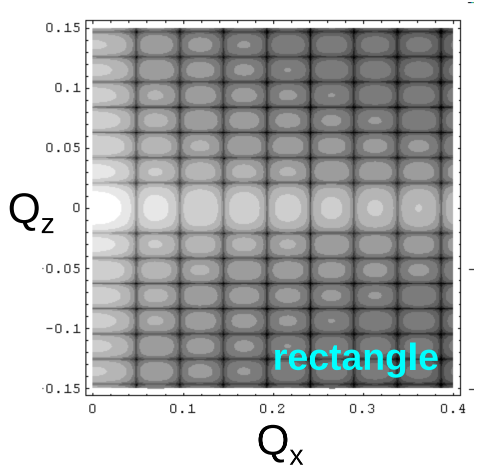


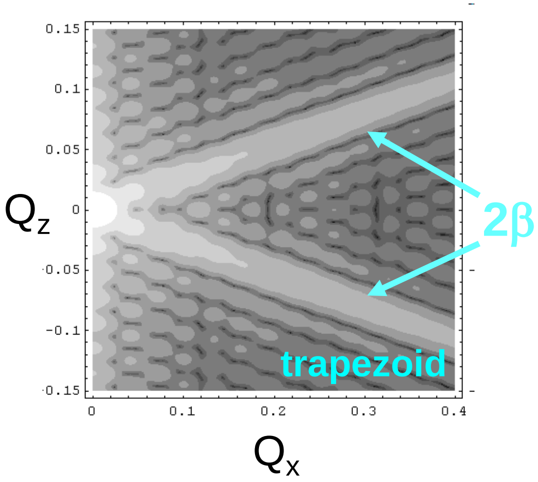
"Multi-slice" data set obtained in ≈ 1 h

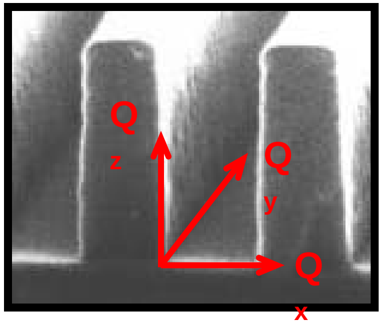
Composite X-ray detector image after large anglular rotation ω

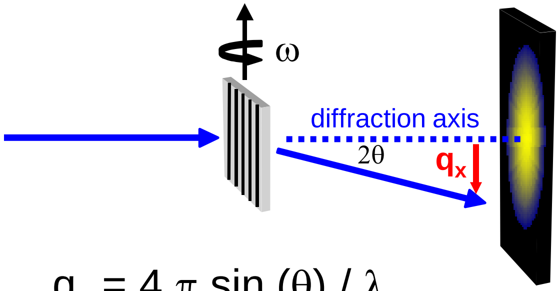
Transform raw data to Q_x and Q_z coordinate plane

Model ⇄ **Transformed** ⇄ **Raw Data**





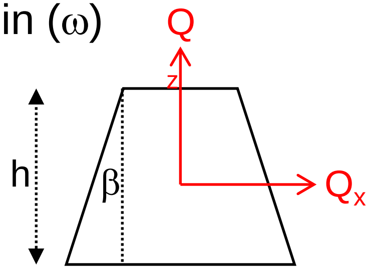


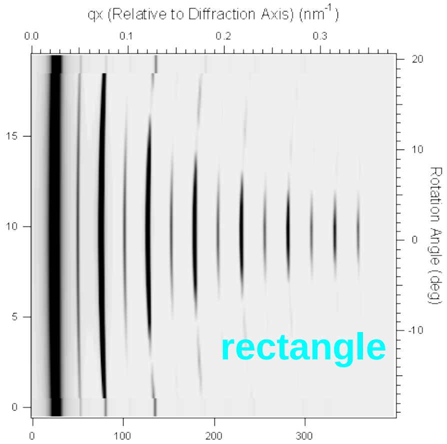


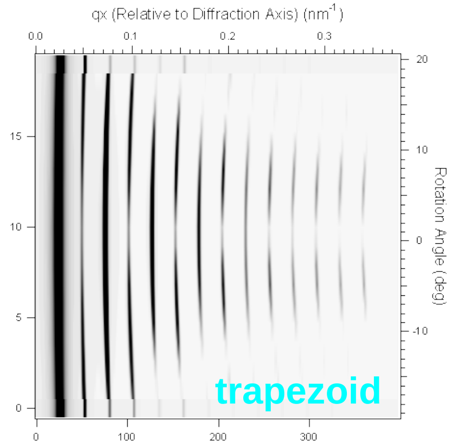
$$q_x = 4\,\pi\,\sin(\theta)\,/\,\lambda$$

$$Q_x = q_x\cos(\omega)$$

$$Q_z = q_x\sin(\omega)$$







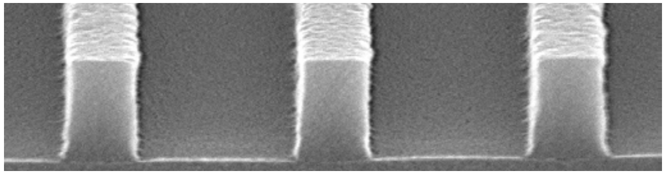
Quantities Readily Available from CD-SAXS

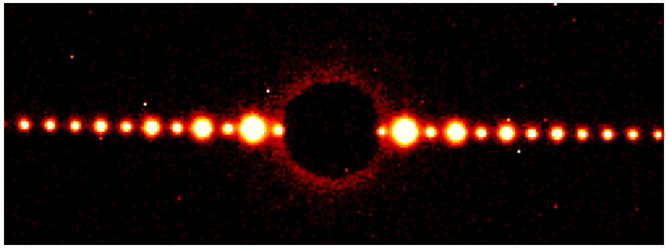
Pitch

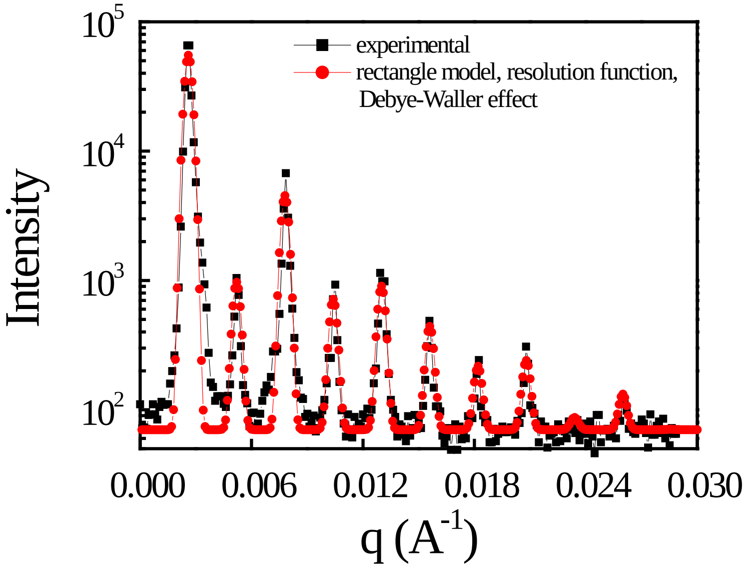
Line Width

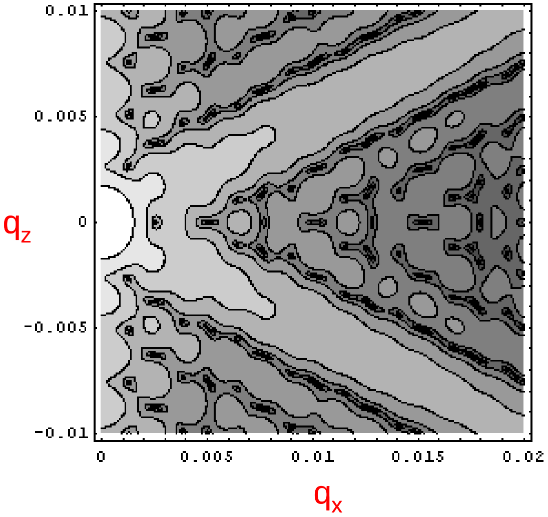
Line Height

Sidewall Angle



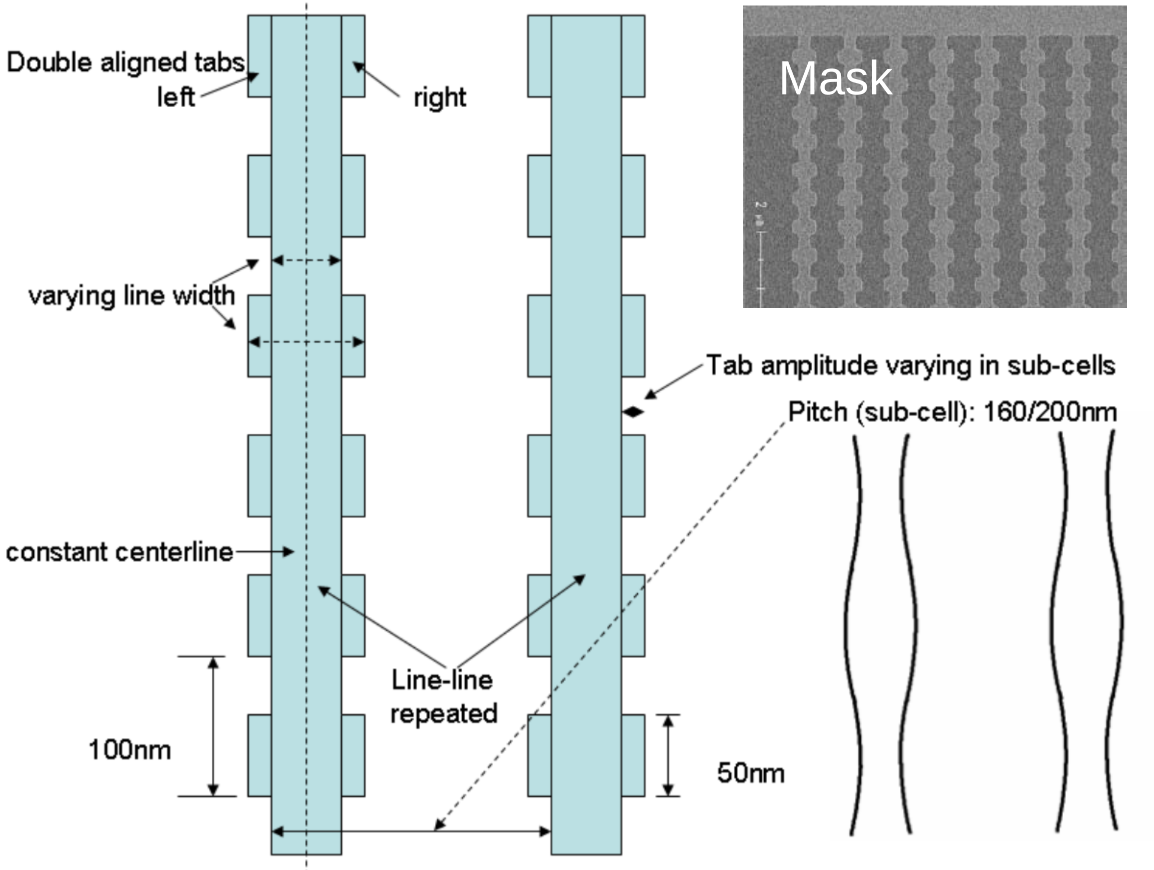




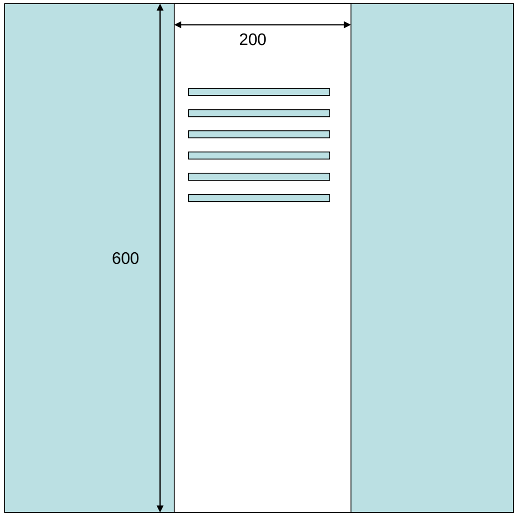


Line Width Roughness Test Vehicle

Cell 1 (S1): LWR [effect of tab amplitude]



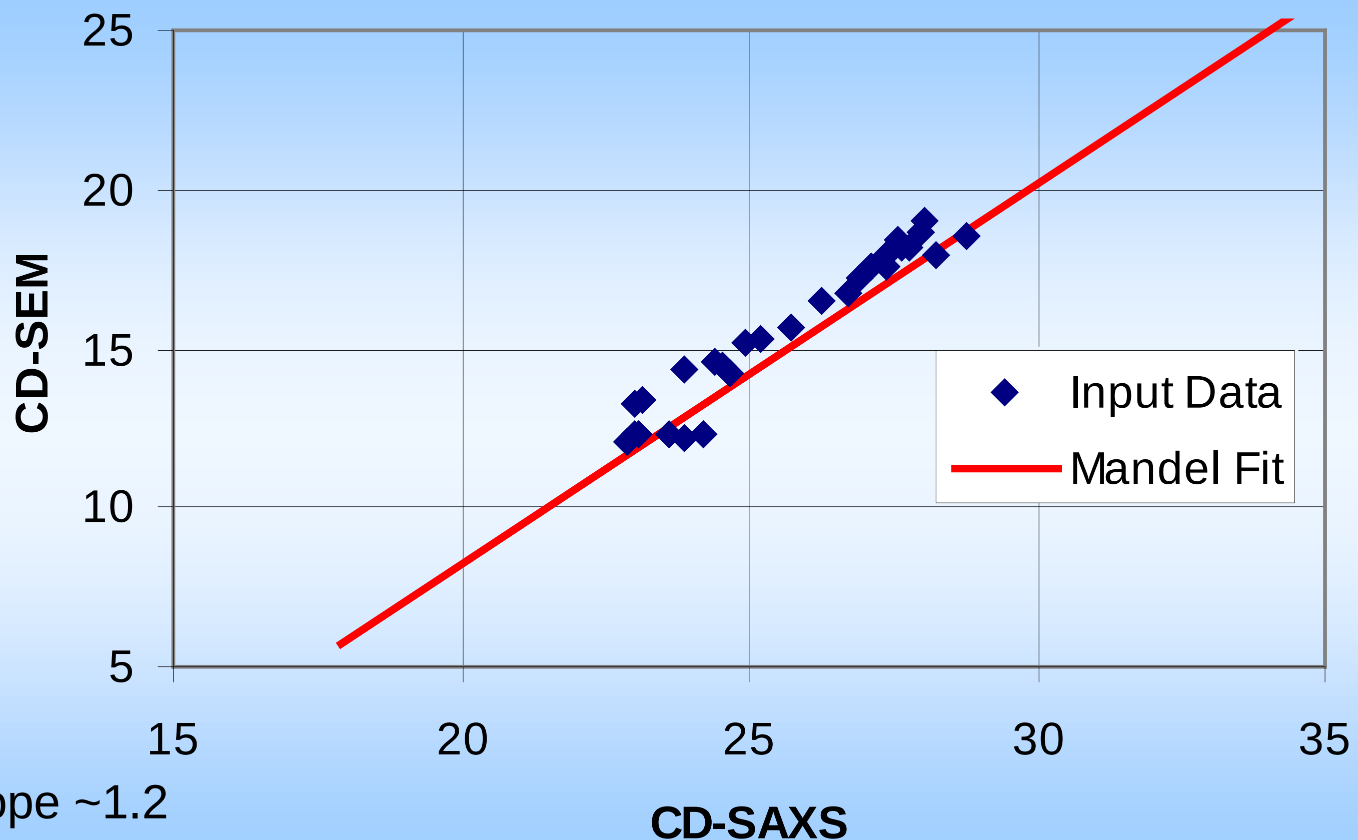
(200 x 600) µm Grating



35nm Line / 175nm Pitch / 100nm tab period / 15nm tab ampl /50nm tab width

LWR- total DWF - Mandel Plot (30L/150P/tab 15nm)

	Slope			Average Offset		TMU		
Num Pair	Estimate	3 Sigma	Intercept	Estimate	3 Sigma	Estimate	Upper limit	Lower limit
54	**1.193**	0.293	-15.61	**10.45**	0.472	**4.098**	4.91	3.53



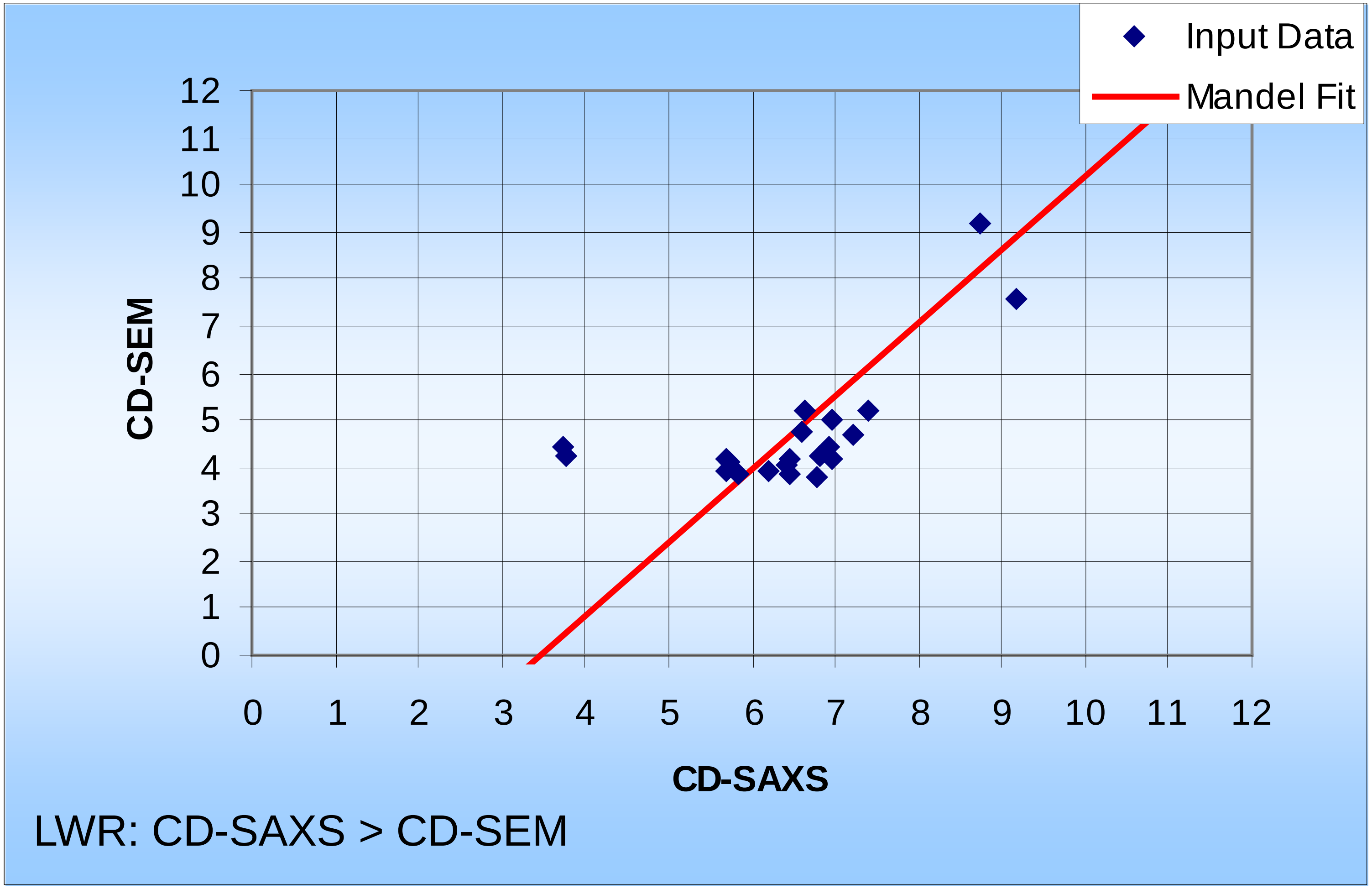
Slope ~1.2

Offset ~10.5

LWR Comparison- NO- preprogrammed roughness

DWF/removed SWA component

	Slope			Average Offset		TMU		
Num Pair	**Estimate**	**3 Sigma**	**Intercept**	**Estimate**	**3 Sigma**	**Estimate**	**Upper limit**	**Lower limit**
21	**1.558**	1.198	-5.40	**1.78**	0.867	**4.498**	6.18	3.56

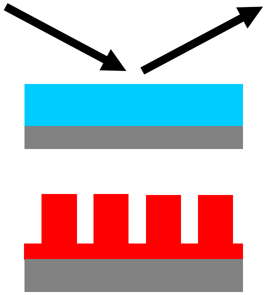


LWR: CD-SAXS > CD-SEM

CD-SAXS detects overall line shape fluctuations

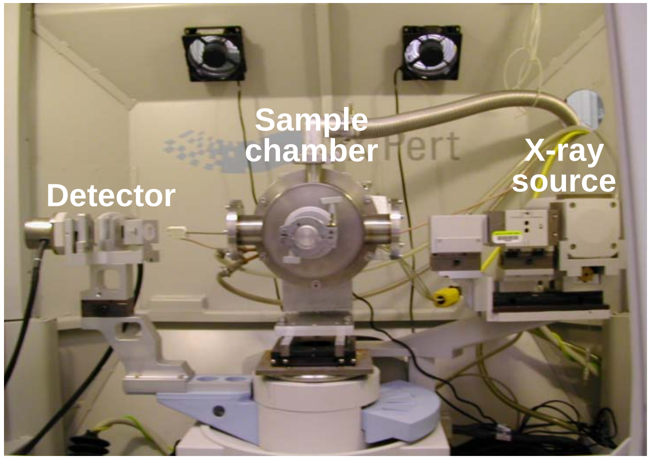
Measurement Needs: Why X-ray reflectivity (SXR)

Extending applicability from planar films to line gratings



- Planar films
  film thickness
  electron density through film
  interfacial roughness
- Patterned (imprinted) films
  pattern height
  line-to-space ratio (*vs.* pattern height)
  residual layer thickness
  fidelity of pattern transfer

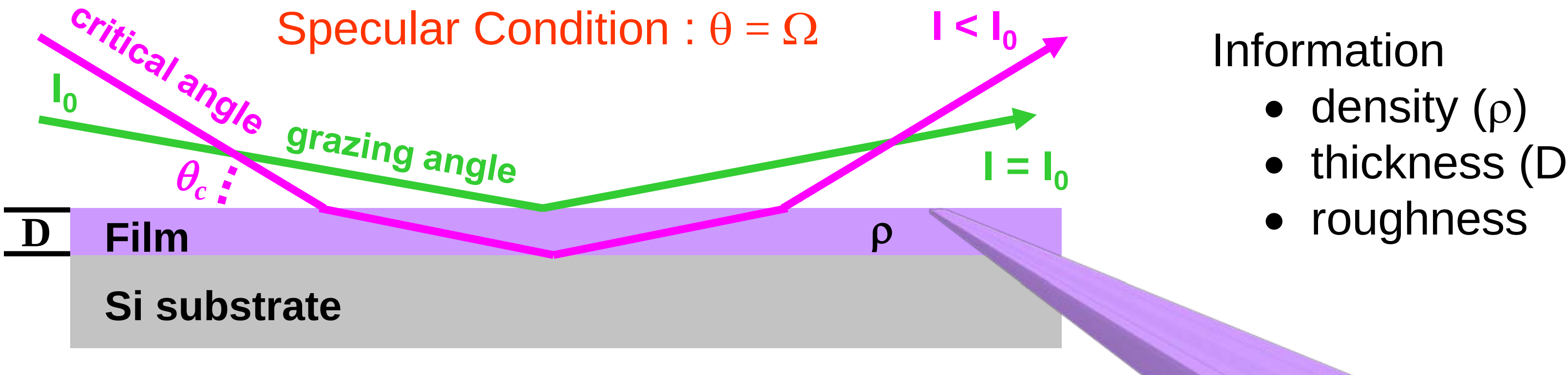
High resolution X-ray reflectometer



High precision settings

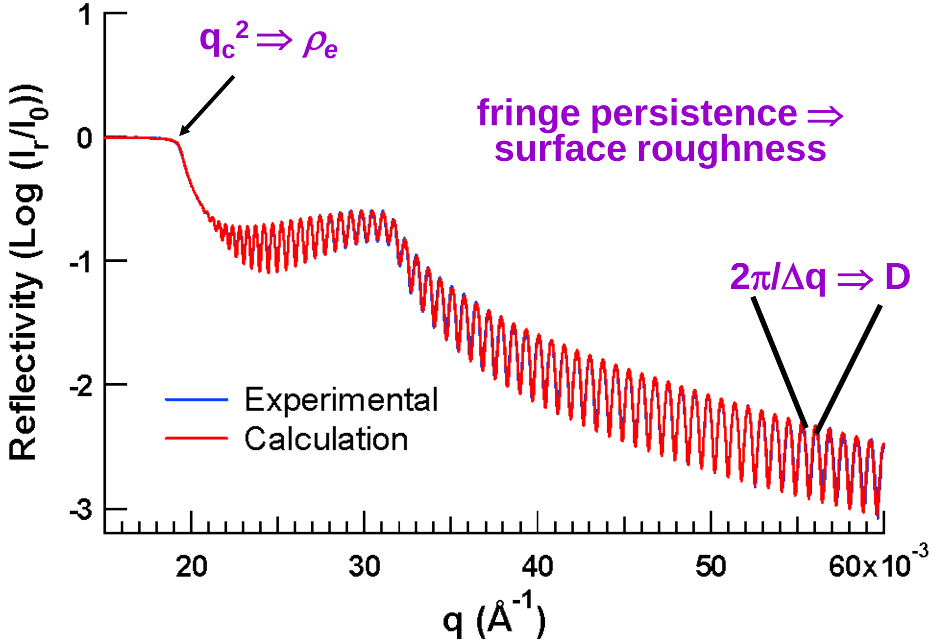
X-ray optics
goniometer control

Principle of Specular X-ray Reflectivity (SXR)



Information

- density (ρ)
- thickness (D)
- roughness



fringe persistence ⇒ surface roughness

$q = (4\pi/\lambda) \sin\theta$

λ : wavelength of the incident radiation

r_e : classical electron radius

ρ_e : electron density

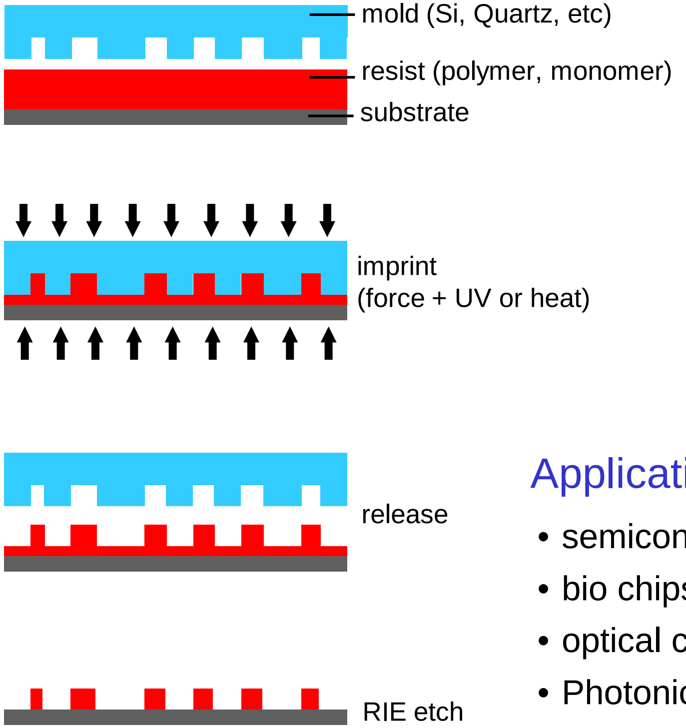
θ : incident angle Ω : detector angle

$$q_c^2 = 16\,\pi\,\rho_e\,r_e \propto \rho_{mass}$$

If atomic composition is given, q_c is converted into ρ_{mass}

NIL as a Next Generation Lithography

Schematic illustration of nanoimprint

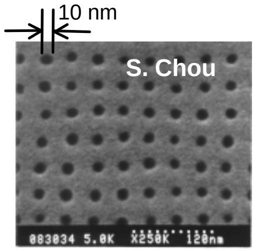


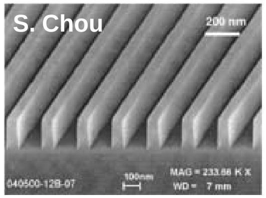
Advantages

- Resolution (sub-10 nm)
- High throughput (min/wafer)
- Low cost ($0.2M vs $25M)
- Simplicity (flow vs rxn-diff)
- Flexibility (UV, heat, excimer)

Applications

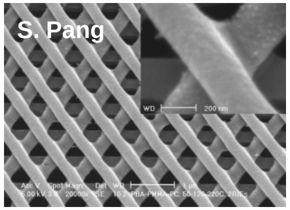
- semiconductors
- bio chips & microfluidics
- optical components
- Photonic devices
- memory & logic devices
- display (wire grid polarizers)
- high brightness LEDs
- digital camera lens arrays



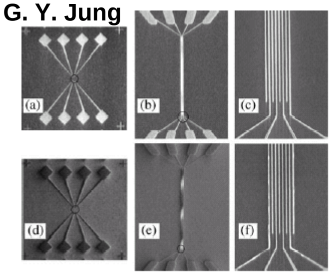


1. SEM of a 200 nm period grating mold etched into (110) Si
ral of the SiO_2 mask. Note the smooth sidewalls obtained.

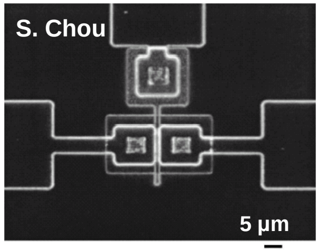
fabricate complex structures…



build functional devices!

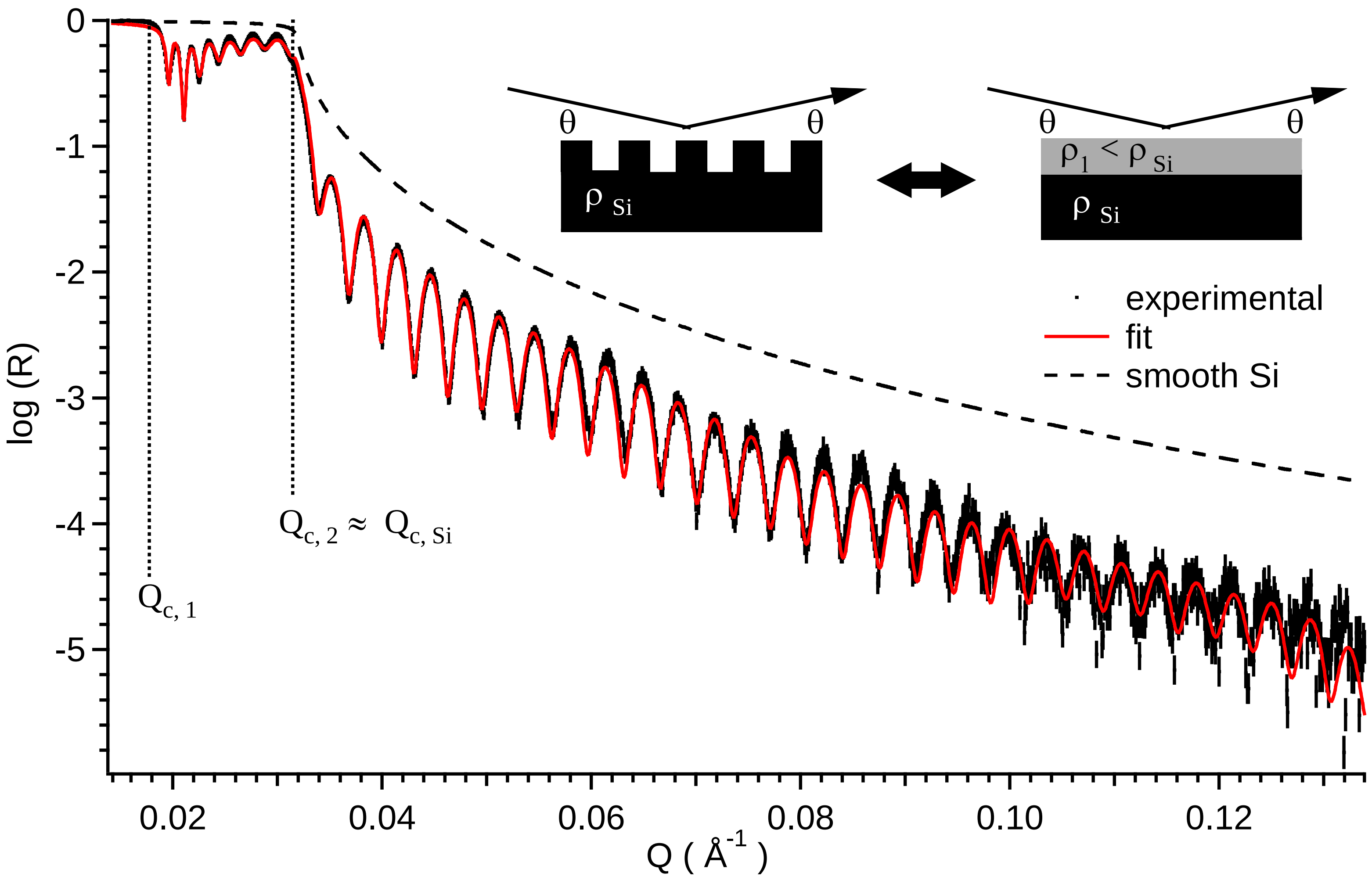


Molecular electronic circuits: Imprinted electrode (top) and imprint mold (bottom)



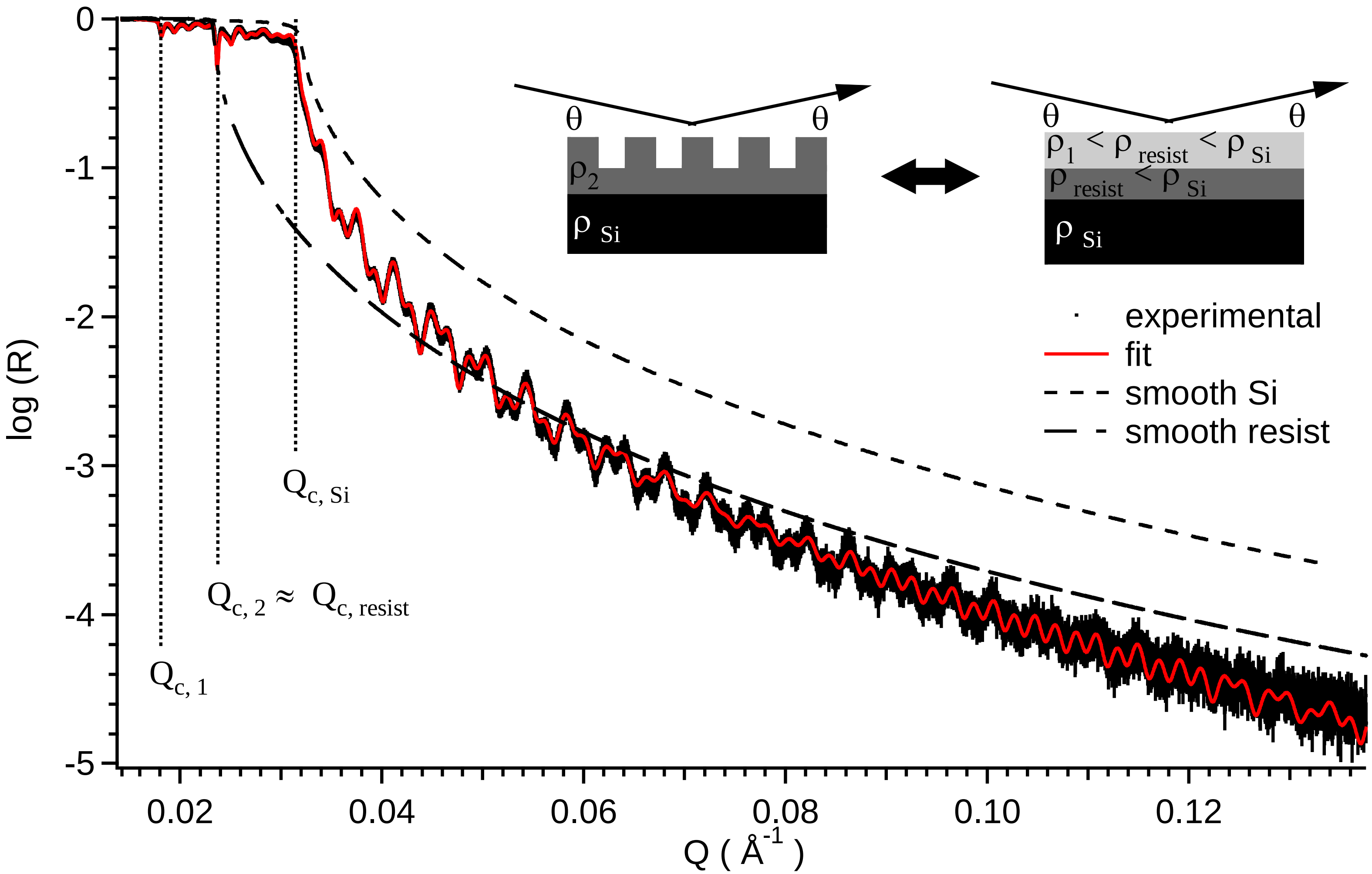
MOSFET fabricated by NIL at 4 lithographic levels (channel length: 60 nm)

SXR of Mold



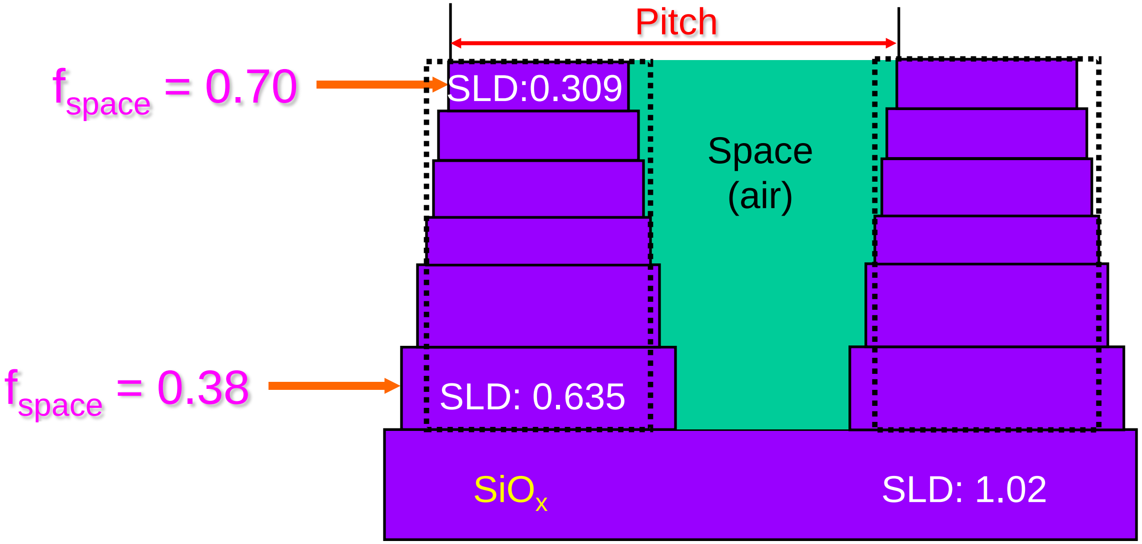
0
-1
-2
-3
-4
-5
log (R)
0.02
0.04
0.06
0.08
0.10
0.12
Q (Å^{-1})
$Q_{c,1}$
$Q_{c,2} \approx Q_{c,Si}$
θ
θ
θ
θ
ρ_{Si}
$\rho_1 < \rho_{Si}$
ρ_{Si}
experimental
fit
smooth Si

SXR of Imprinted Resist



Line to space ratio

Comparing SLD in the patterned region to the fully dense material



$$SLD\ (layer) = SLD\ (Si/SiO_2) \times (1 - f_{space}) + SLD\ (air) \times f_{space}$$

SLD (layer): SLD of each layer in the patterned region

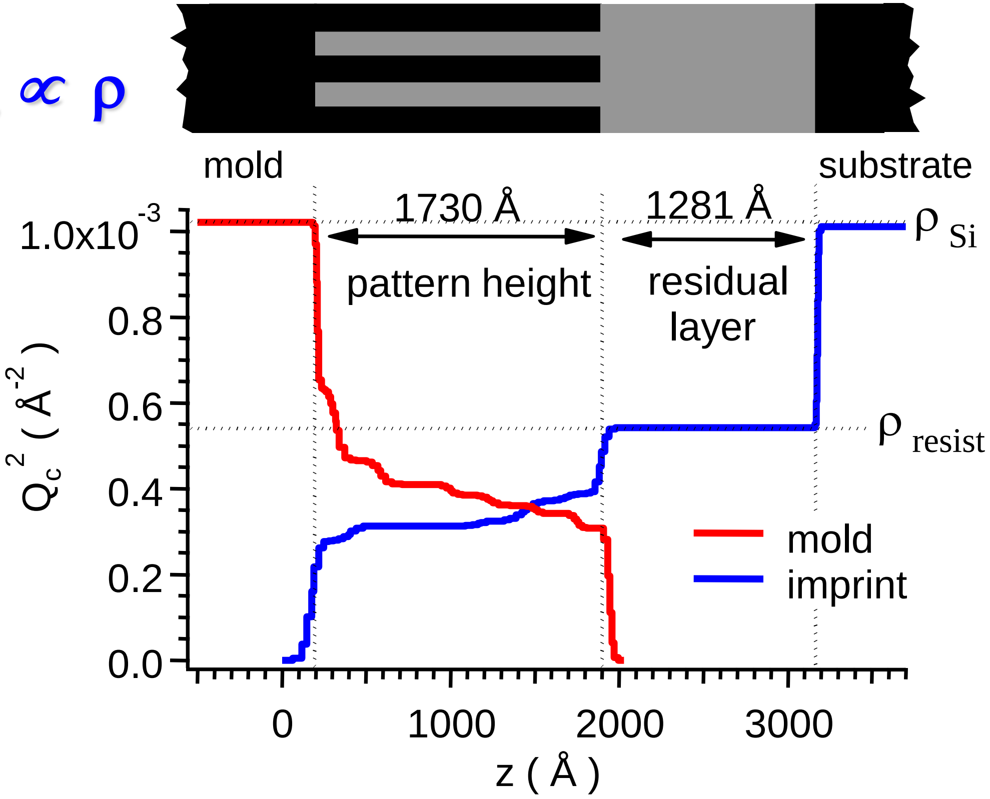
SLD (Si/SiO_2) and SLD (air): SLD of Si substrate and air, respectively

f_{space}: lateral fraction of space between the lines in the pitch.

*Line-to-space ratio can be determined via XR **BUT not** the dimension of line or space*

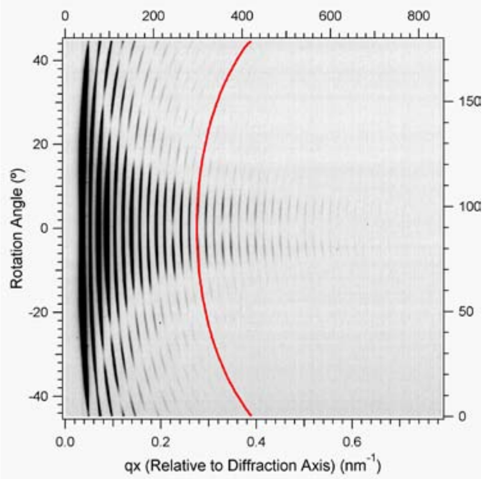
X-ray Scattering Length Density Profiles

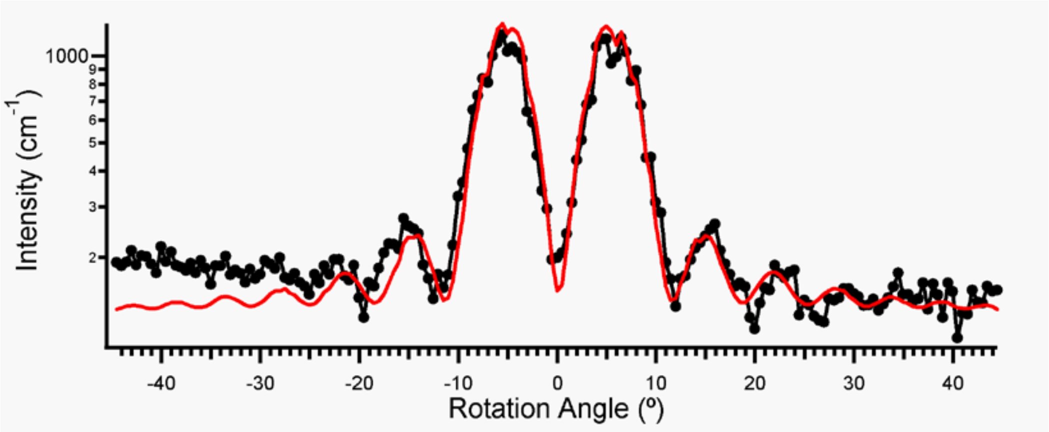
$$Q_c^2 = 16\,\pi\, r_o\, \rho_e \propto \rho$$

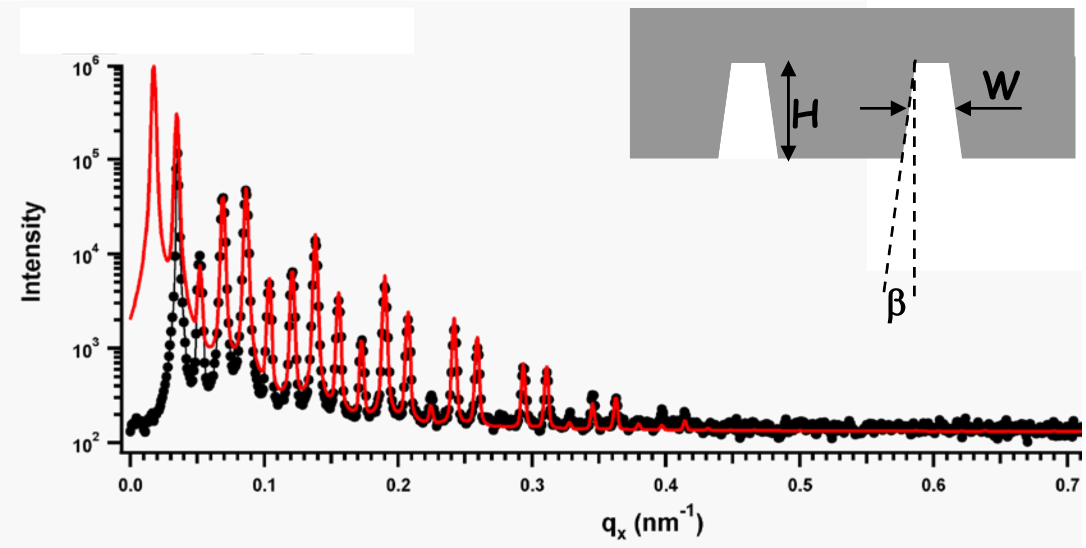


- Residual layer thickness is 1281 ± 10 Å
- Imprint pattern height is 1720 ± 10 Å
- Mold pattern height is 1730 ± 10 Å
- Excellent mold filling!

Fourier transform of ideal pattern cross section





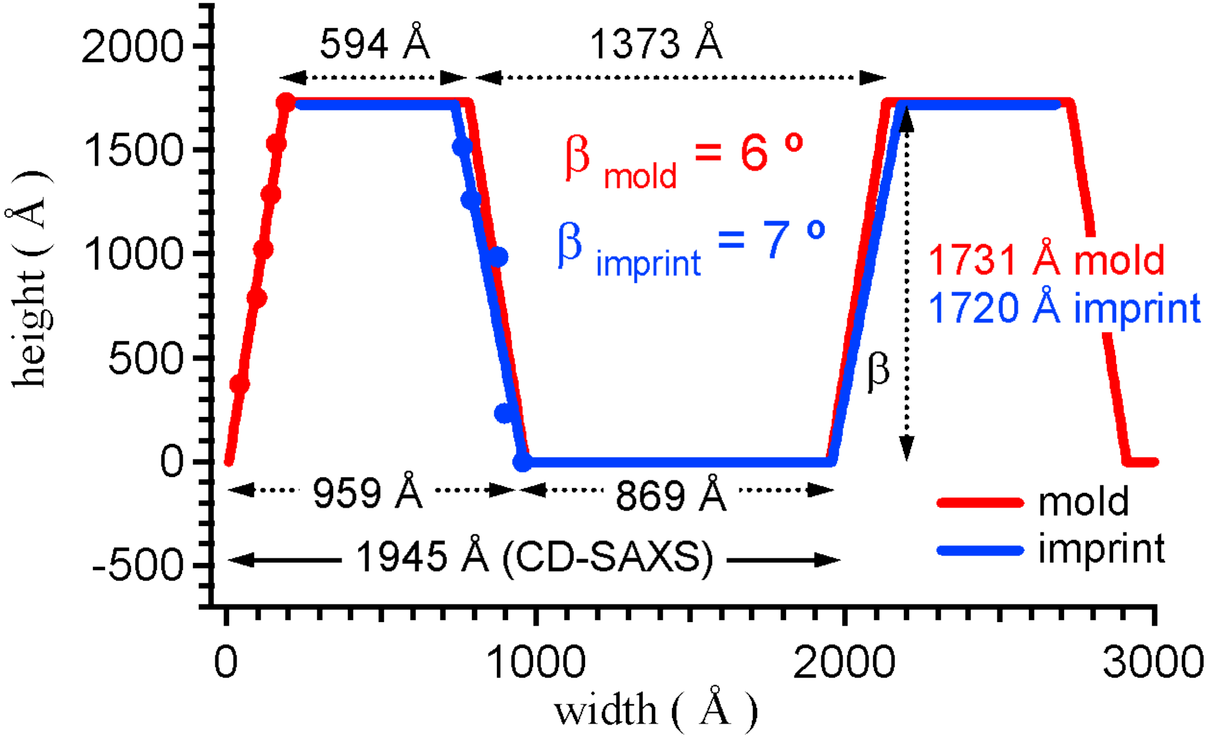


mold

W_{gap} = 772 ± 10 Å
W_{line} = 1173 ± 10 Å
H = 1650 ± 50 Å
β_{right} = 5.4 ± 0.5 °
β_{left} = 6.3 ± 0.5 °

1945 Å

Profiling real pattern Structure



average line widths

mold = 1120 Å
imprint = 777 Å

CD-SAXS model: mold

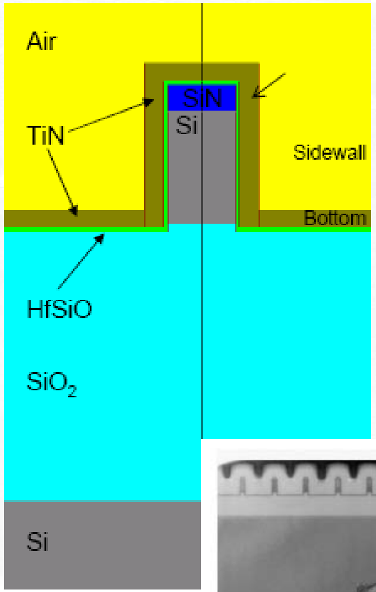
W_{gap} = 772 ± 10 Å
W_{line} = 1173 ± 10 Å
H = **1650 ± 50** Å
β_{right} = 5.4 ± 0.5 °
β_{left} = 6.3 ± 0.5 °

- CD-SAXS pitch & SXR line-space ratio defines absolute length scale
- Full line shape profile as a function of pattern height are quantified
- Excellent fidelity of pattern transfer
- Side wall angles and line/space ratio are consistent with CD-SAXS
- Less agreements w/ CD-SAXS line height; SXR is probably superior

Summary

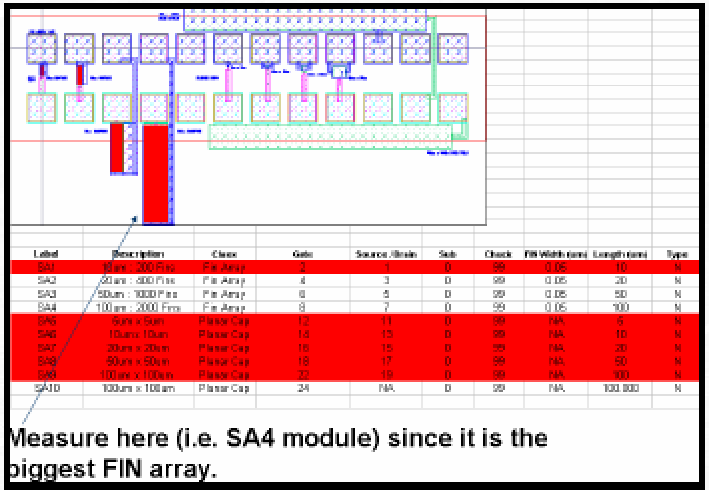
- SXR is utilized as a powerful methodology to quantify relative line-to-space ratio as a function of pattern height in periodic patterns
- For periodic patterns an external lateral length scale calibration can be used to convert the relative line-to-space ratios into absolute values
- SXR complements CD-SAXS for 3D dimensional metrology in nano-structures

FinFET Structure Sample: CD=35nm, no TiN, HfSiO=3nm (100x250um cell)



DOE experiment:

All CD-SEM, IR-Reflectivity and scatterometry measurements were made on the SA4 module. This metrology test array consists of a 100um X 500um box of 2000 repeating Fin lines.

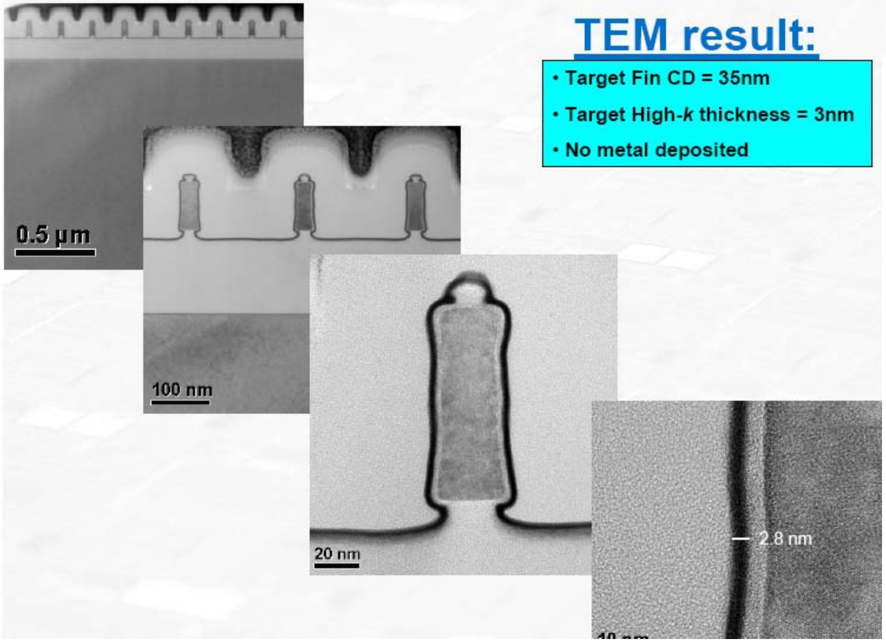


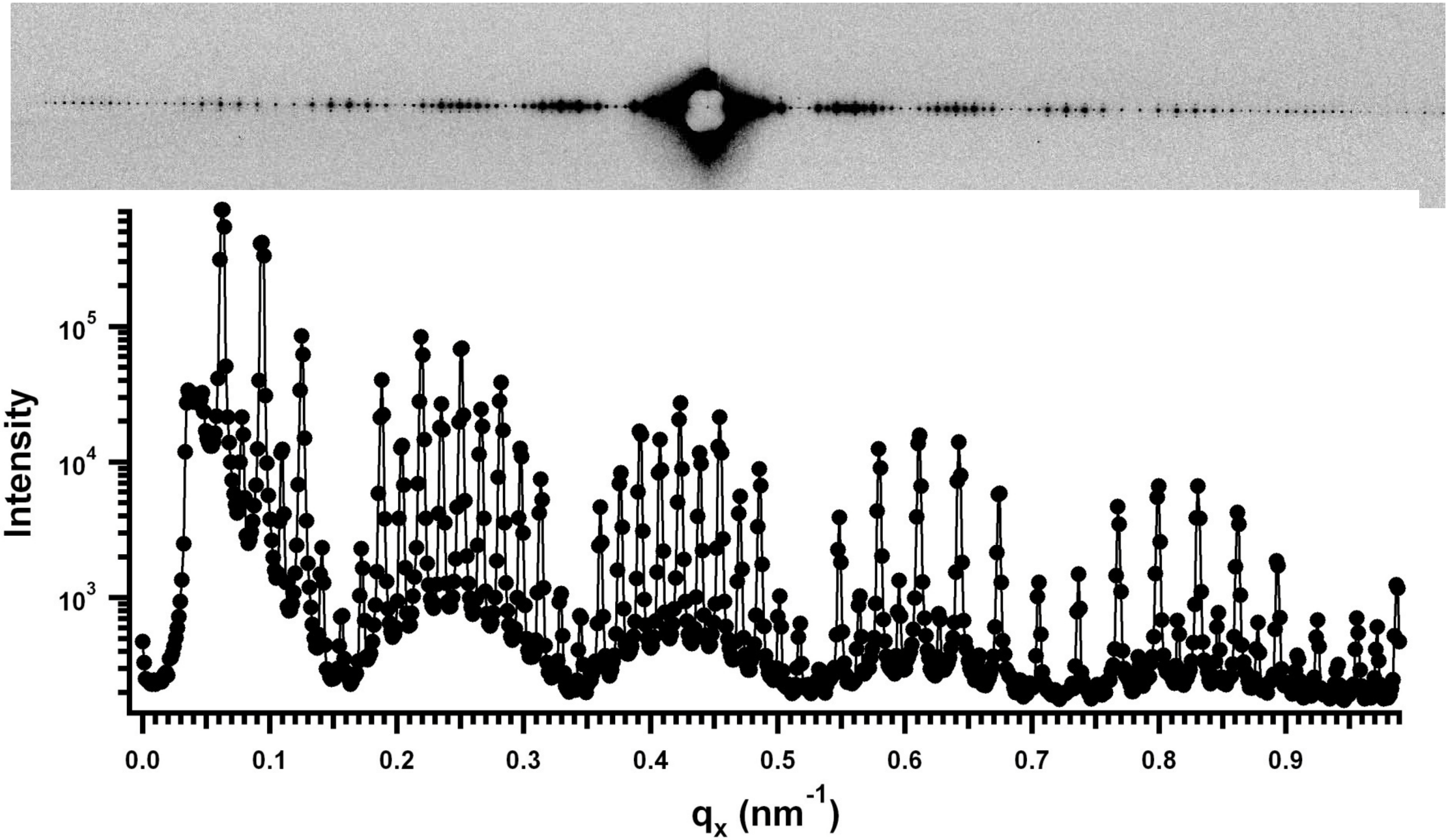
Label	Description	Class	Gate	Source /Drain	Sub	Chuck	FIN Width (um)	Length (um)	Type
SA1	10um : 200 Fins	Fin Array	2	1	0	99	0.05	10	N
SA2	20um : 400 Fins	Fin Array	4	3	0	99	0.05	20	N
SA3	50um : 1000 Fins	Fin Array	6	5	0	99	0.05	50	N
SA4	100um : 2000 Fins	Fin Array	8	7	0	99	0.05	100	N
SA5	5um x 5um	Planar Cap	12	11	0	99	NA	5	N
SA6	10um x 10um	Planar Cap	14	13	0	99	NA	10	N
SA7	20um x 20um	Planar Cap	16	15	0	99	NA	20	N
SA8	50um x 50um	Planar Cap	18	17	0	99	NA	50	N
SA9	100um x 100um	Planar Cap	22	19	0	99	NA	100	N
SA10	100um x 100um	Planar Cap	24	NA	0	99	NA	100,000	N

Measure here (i.e. SA4 module) since it is the biggest FIN array.

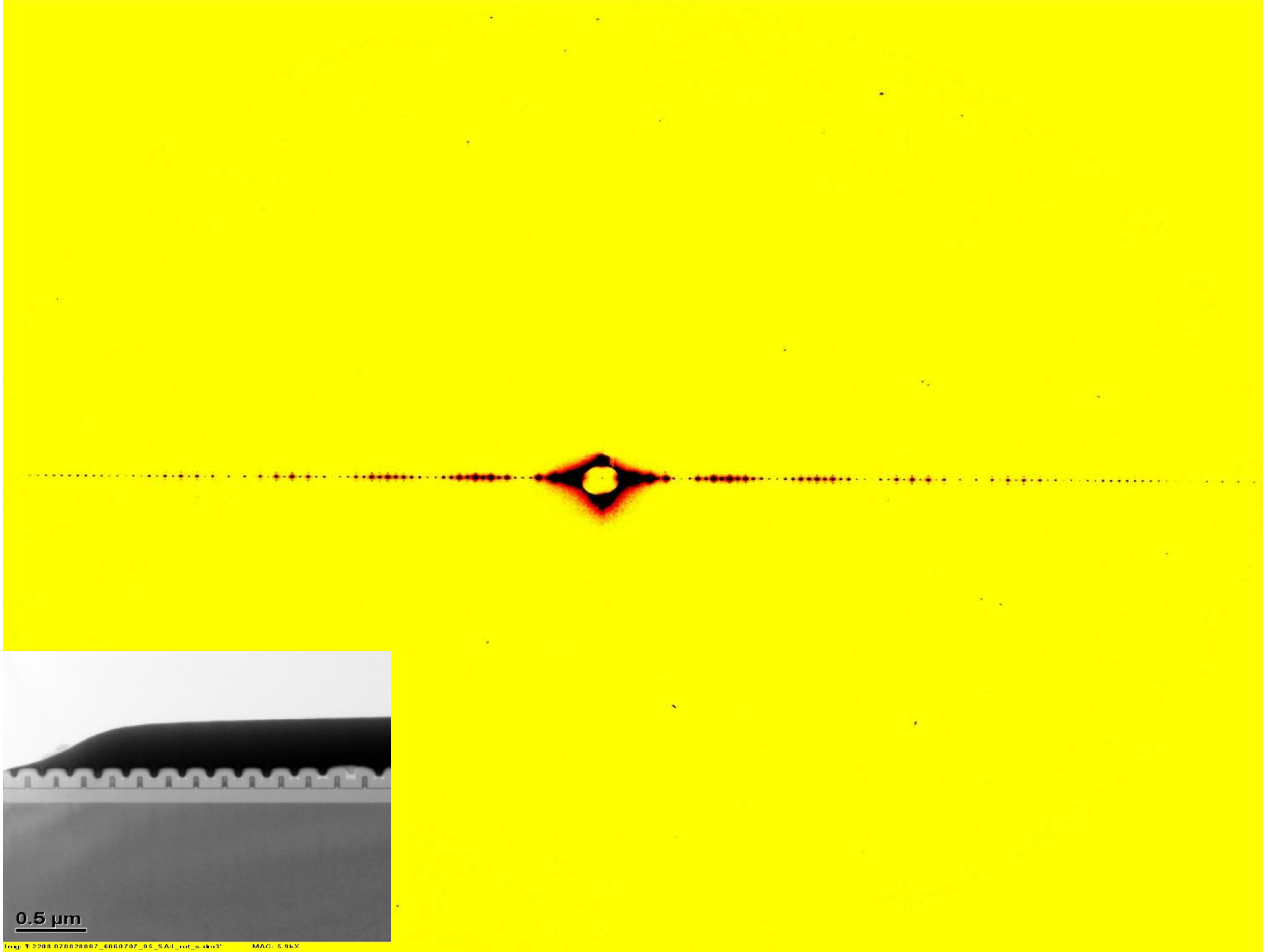
TEM result:

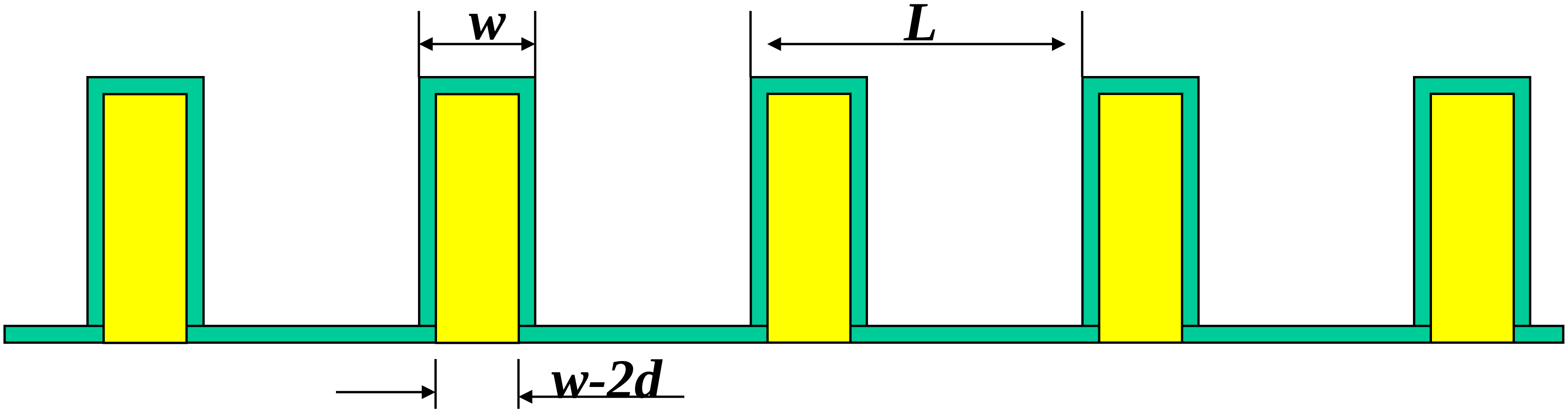
- Target Fin CD = 35nm
- Target High-*k* thickness = 3nm
- No metal deposited





There are at least THREE modulation frequencies in the intensity profile. And the repeating length (pitch?) is 400 nm instead of 200 nm. It indicates there might be sort of super structures in the dense gratings.


0.5 µm
Img: 'T:2208 070828007_6060707_05_SA4_rot_s.dm3'
MAG: 5.9kX



Definitions:

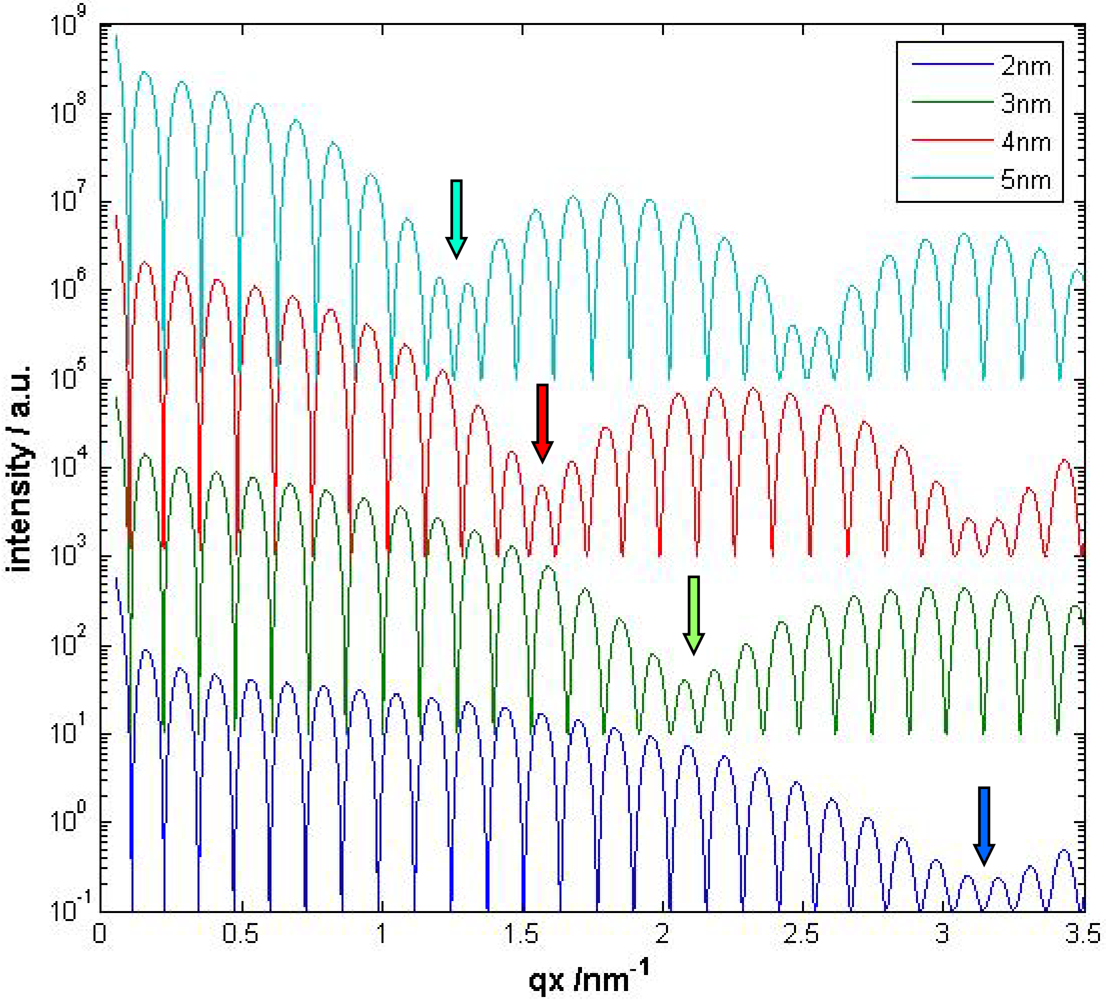
w: **line width**

d: **High-K dielectric thickness**

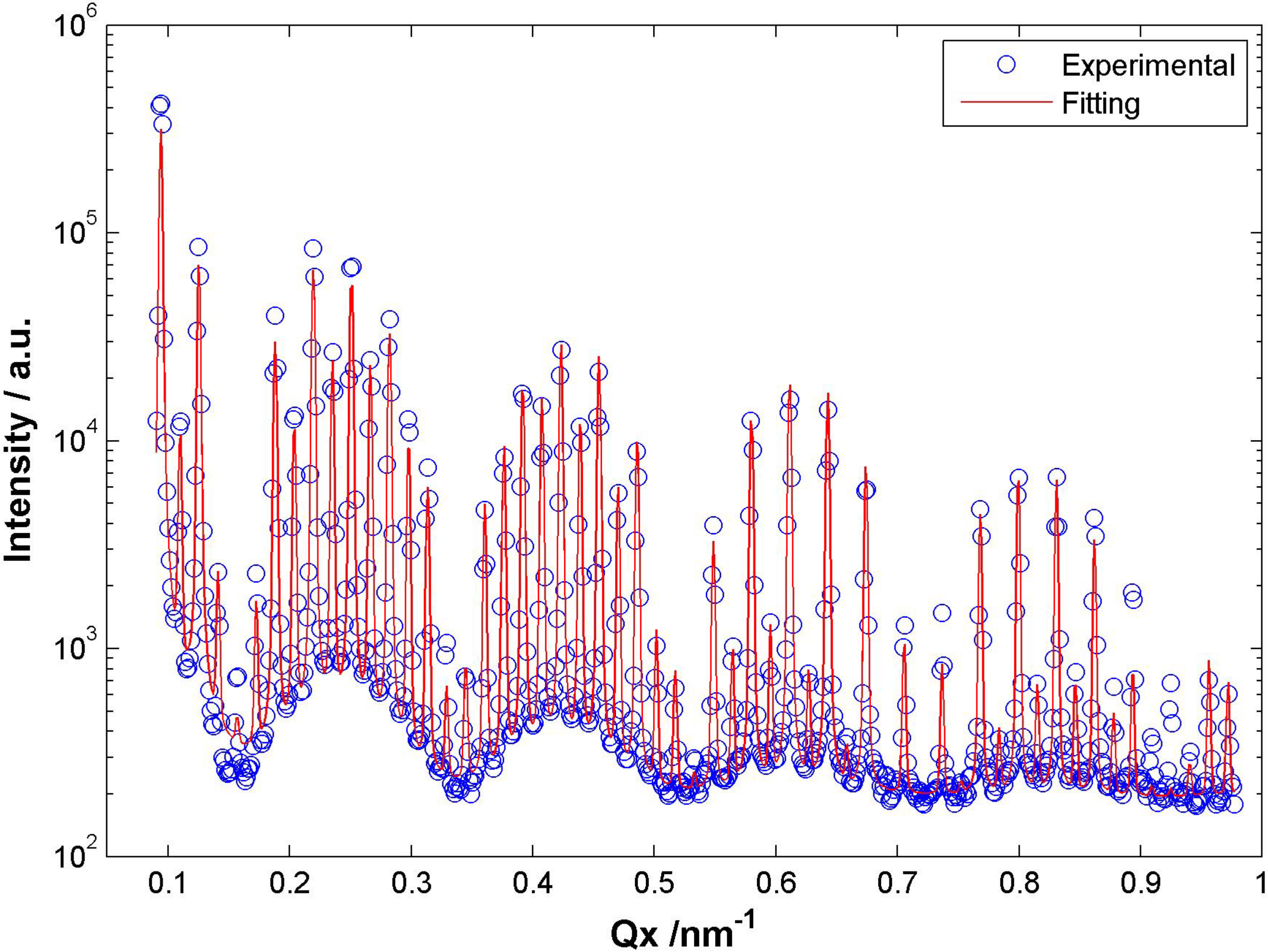
L: **pitch**

ρ_1: **electron density of High-K dielectric**

ρ_2: **electron density of silicon node**

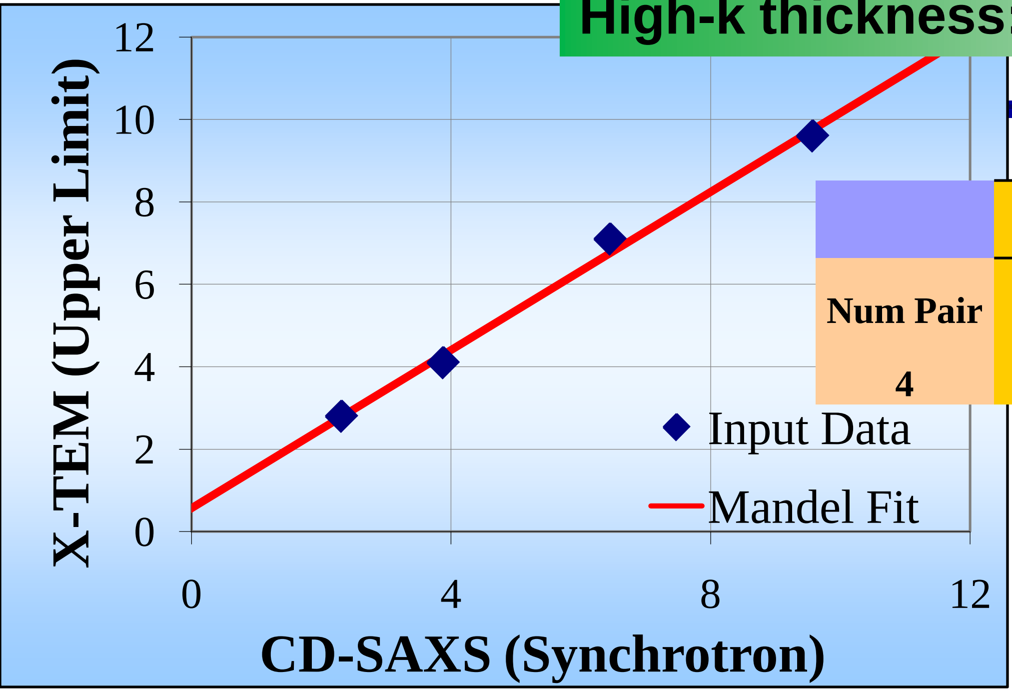


From the position of the intensity minimums, we can get the t High-K dielectric

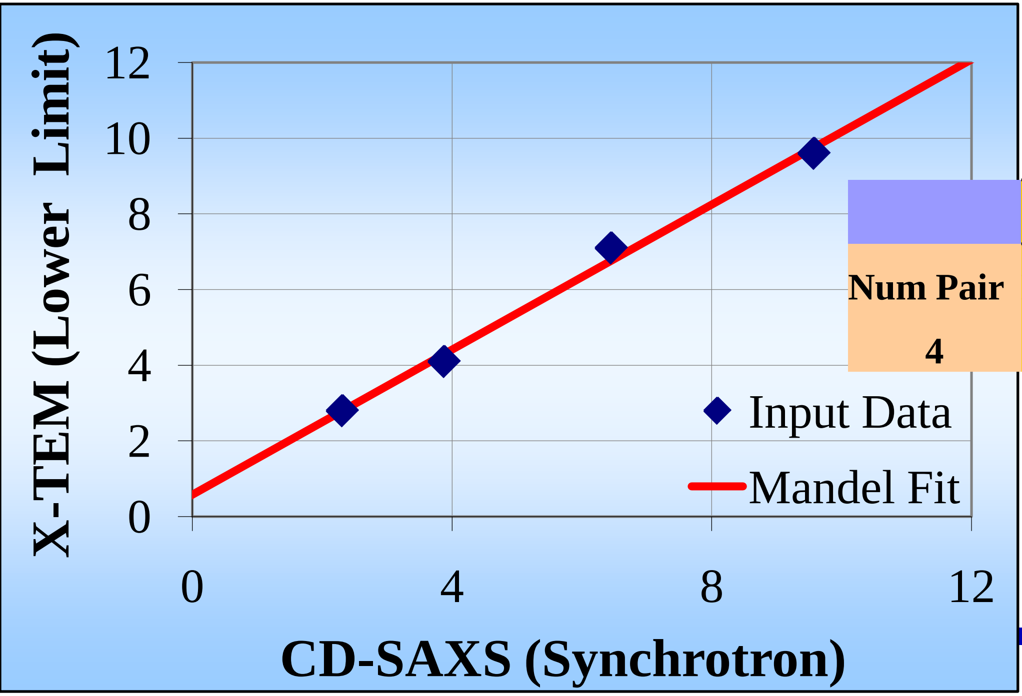


Experimental
Fitting
Intensity / a.u.
10^2
10^3
10^4
10^5
10^6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Qx /nm^{-1}

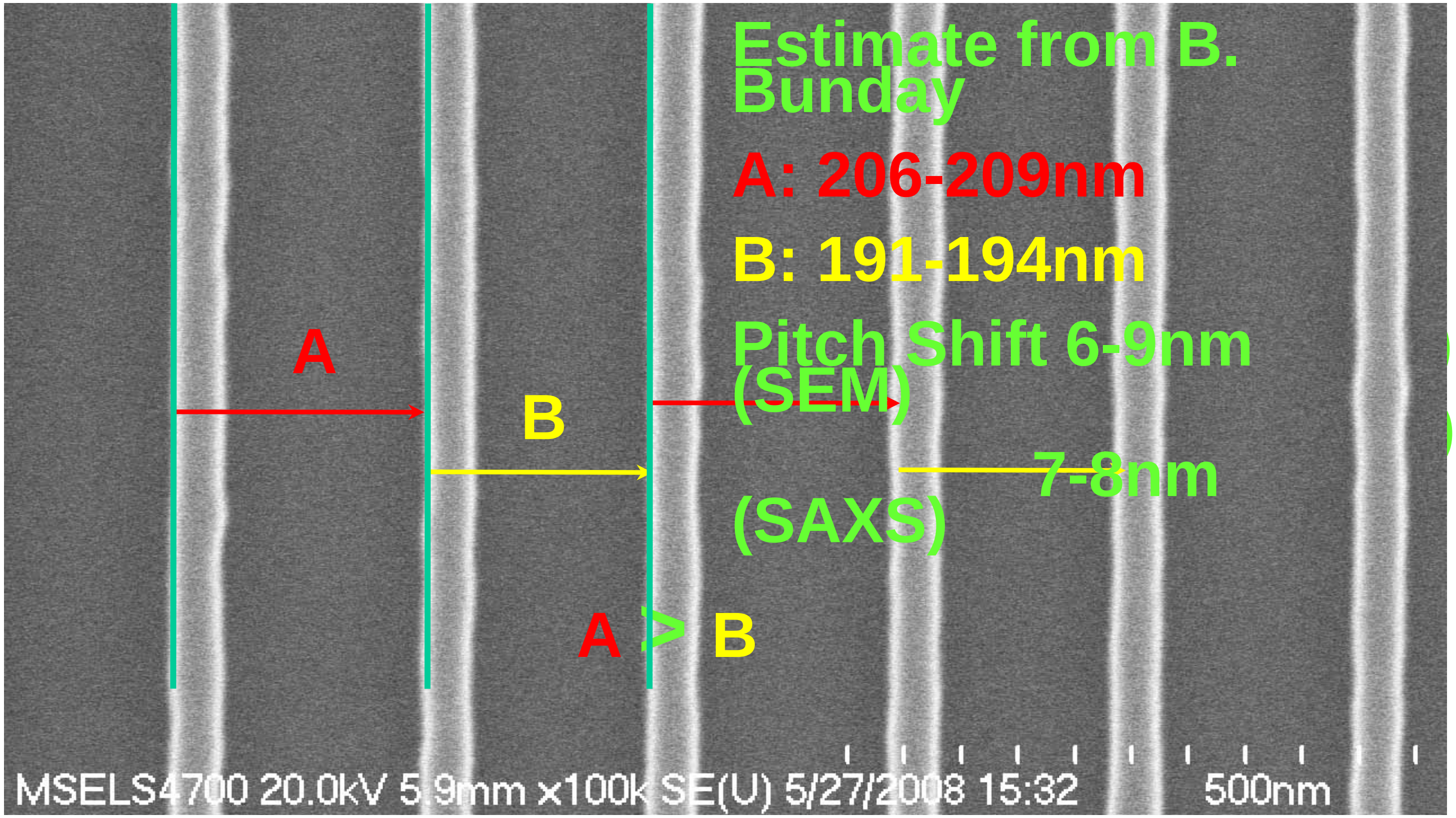
High-k thickness: X-TEM vs. Synchrotron CD-SAXS



	Slope			Average Offset	
Num Pair	Estimate	3 Sigma	Intercept	Estimate	3 Sigma
4	1.005	0.219	0.94	-0.97	0.859



	Slope			Average Offset	
Num Pair	Estimate	3 Sigma	Intercept	Estimate	3 Sigma
4	0.959	0.162	0.58	-0.35	0.859



Estimate from B. Bunday

A: 206-209nm

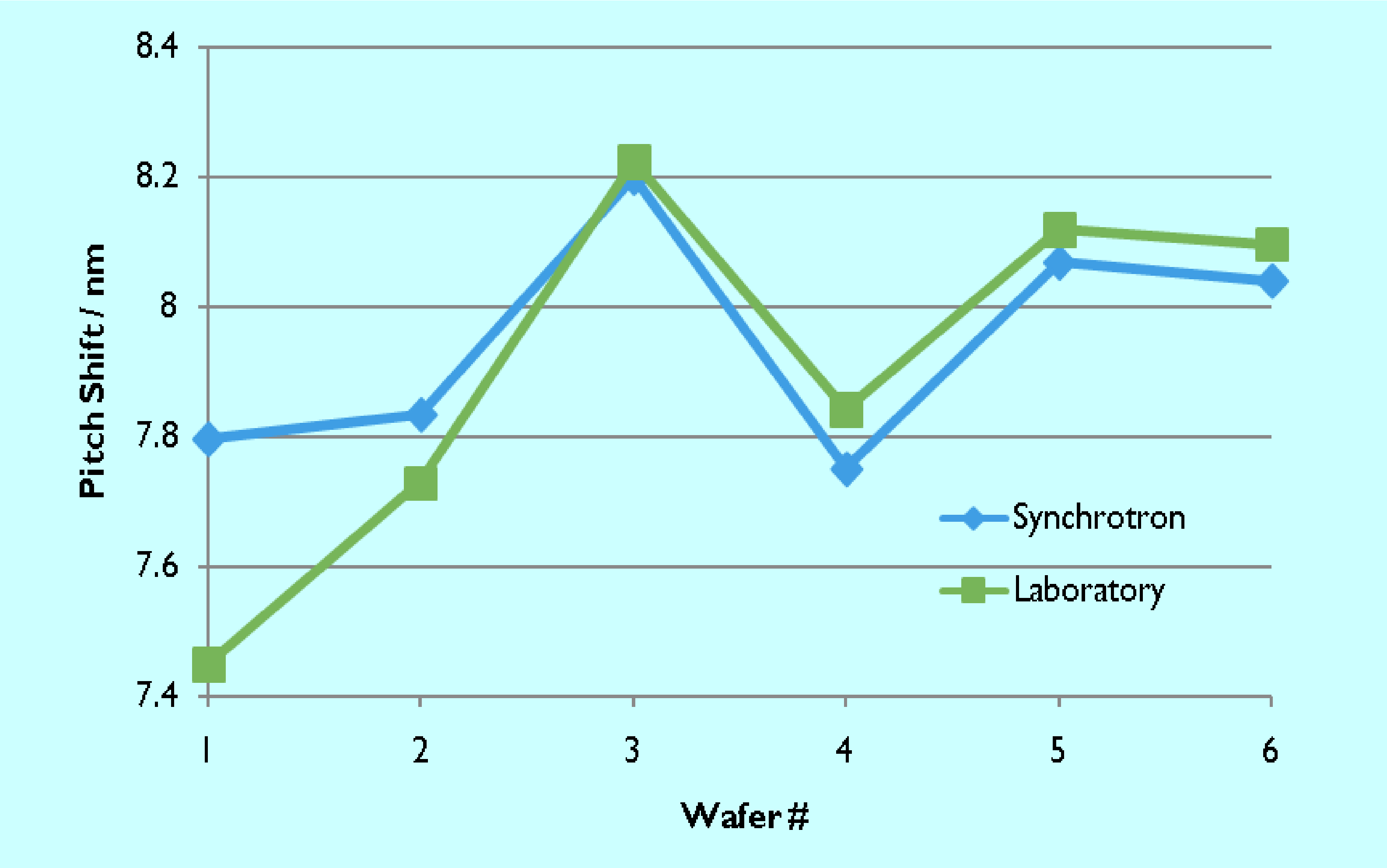
B: 191-194nm

Pitch Shift 6-9nm (SEM)

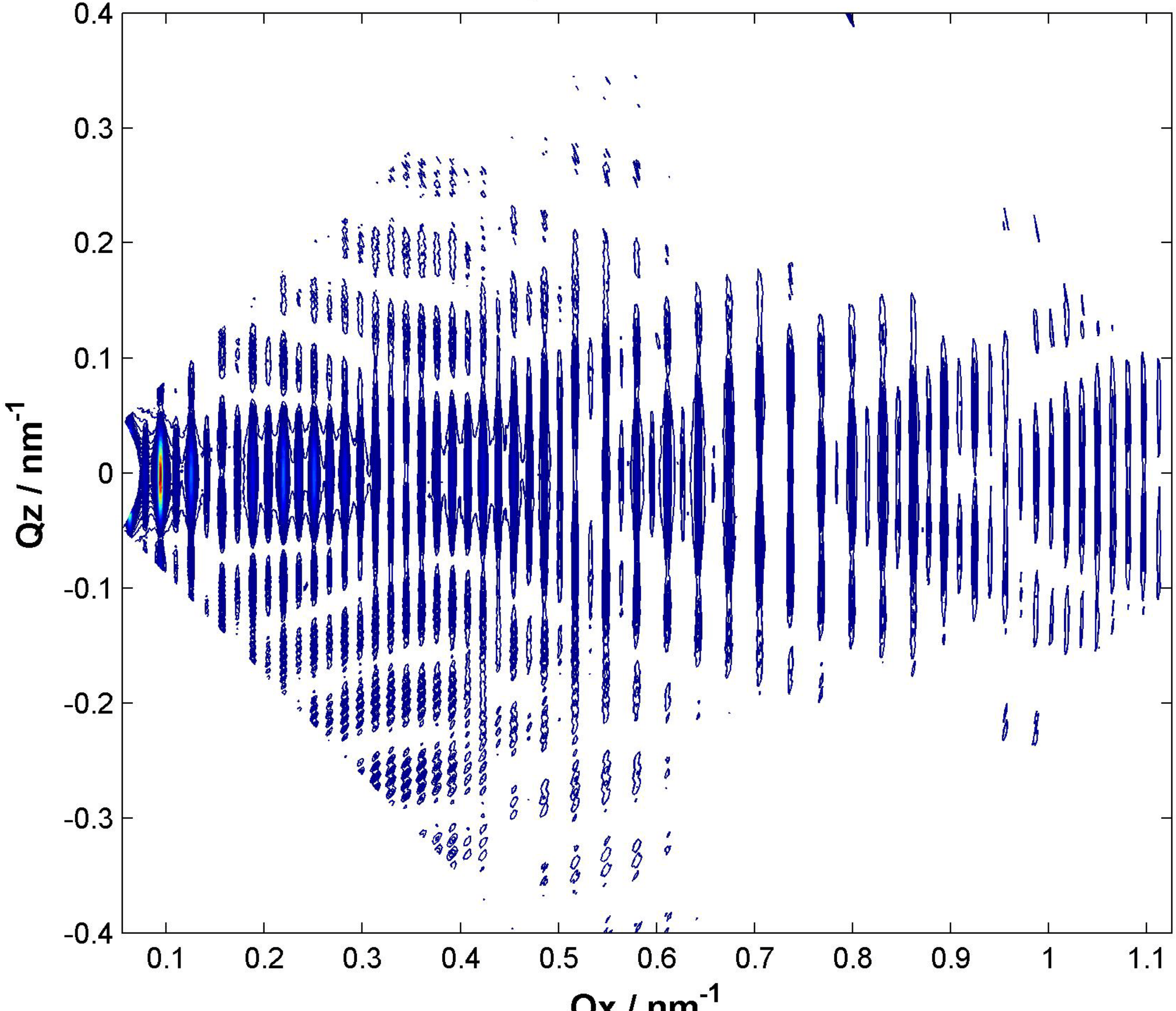
7-8nm (SAXS)

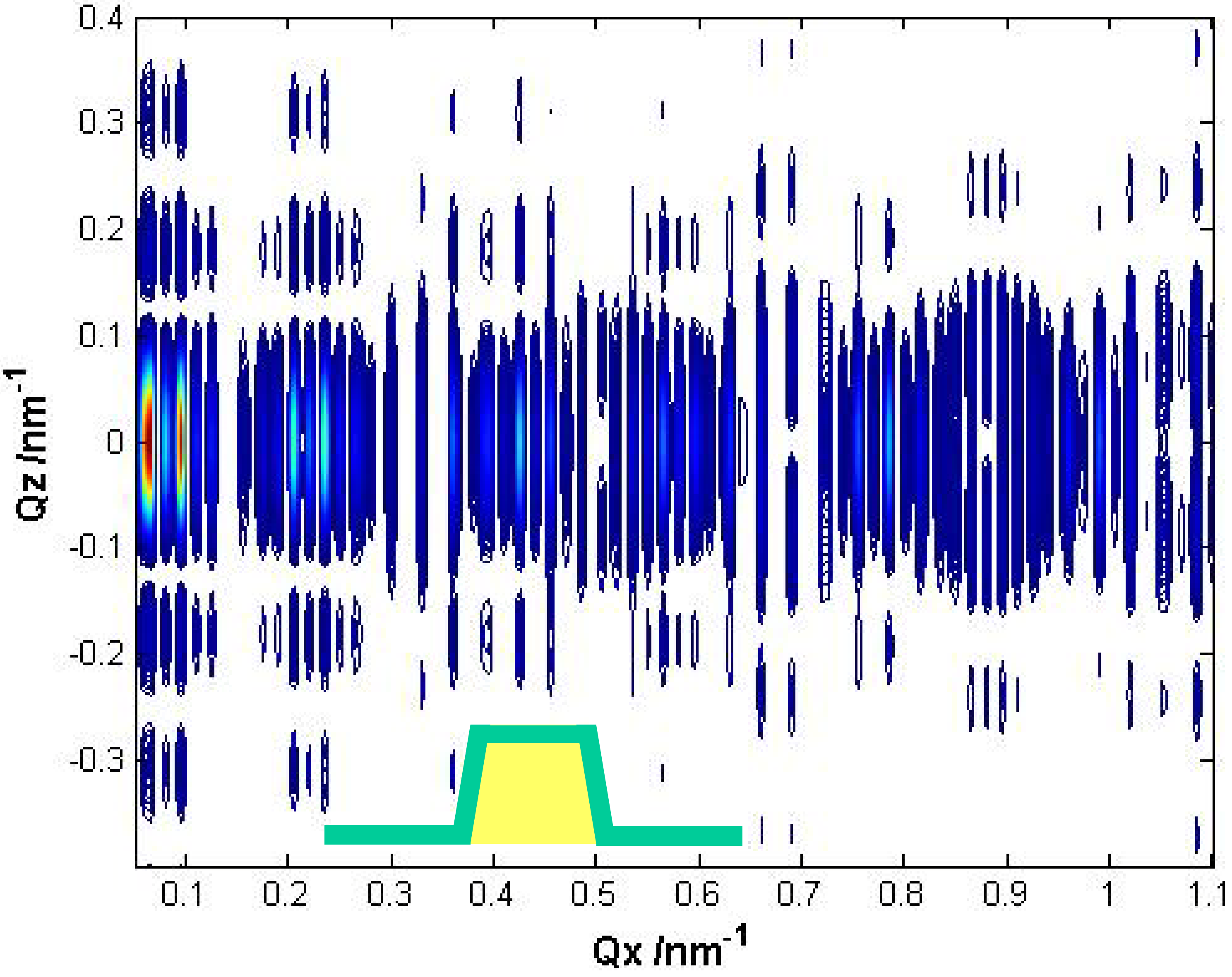
A > B

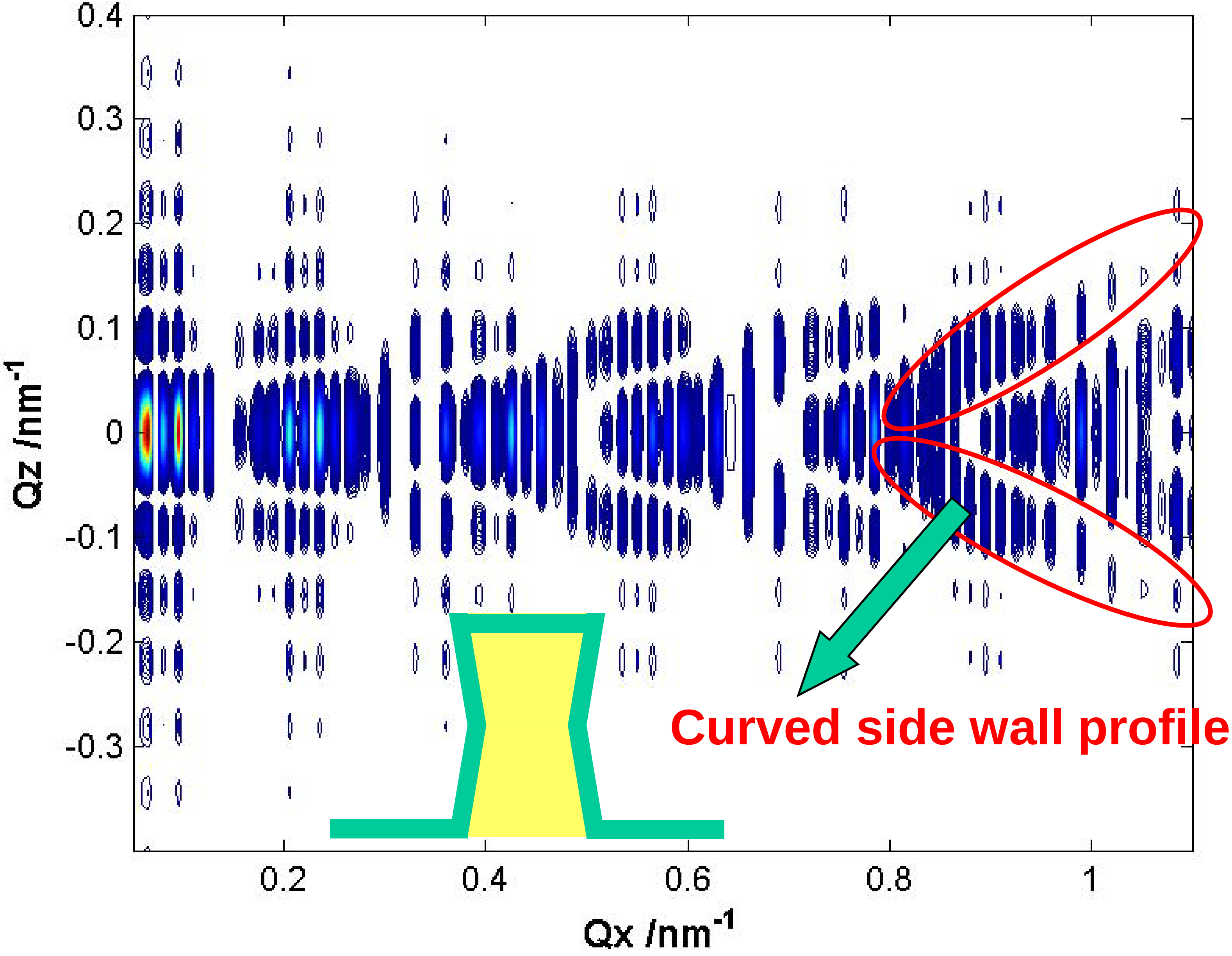
Mask overlay error – Pitch Shift



Amazing FinFET Qx-Qz map




0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Qz /nm^{-1}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Qx /nm^{-1}



Curved side wall profile

Conclusions

- X-ray scattering has been demonstrated as a viable reference metrology for nanostructure characterization – line width, side wall angle, line height and side wall roughness
- 3D nanostructures e.g. FinFET can be characterized using X-ray
- Buried 3D structures are our next targets

CSTIC Conference

March 16-18 2010, Shanghai, China

Symposium on Metrology, Testing and Reliability

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