Small Angle X-ray Scattering Metrology for Sidewall Angle and Cross Section of Nanometer Scale Line Gratings

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Funding

- **NIST Office of Microelectronics Programs**

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ULSI, Richardson, TX
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• **Introduction**

•Measurement of pitch and line width

•Measurement of side wall angle & height

•Line roughness including both side walls & top surface (on-going)

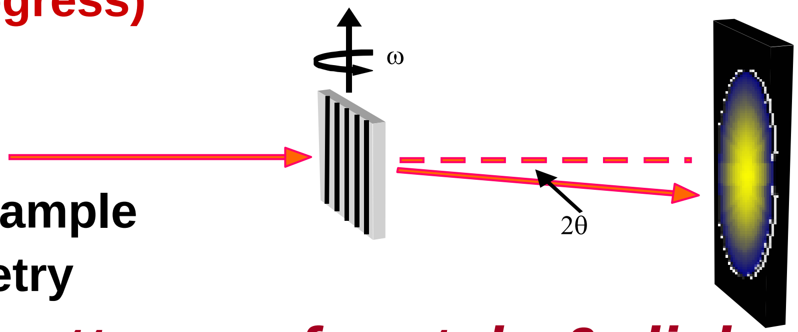
•Conclusions

Critical Dimension Small Angle X-ray Scattering (CD-SAXS)

Transmission SAXS

- **Silicon transparent for E > 13 keV**
- **Developed using synchrotron technology**
- **Non-destructive / No sample prep**
- **Lab-scale device feasibility (in progress)**

- ***Use scatterometry targets***
  - **Beam spot size (40x40) μm**
  - **Collection time: (1 to 5) seconds/sample**
  - **Model fits simpler than scatterometry**



- ***Measure "2-D" and Buried patterns of metals & dielectrics***
  - **Via, post, pads, etc**
- ***High Precision for small line width (10-300 nm)***
  - **Sub-nm precision in pitch and linewidth**
  - **Sidewall angle and Pattern Cross Section**
- **Technique "easier" with smaller structures**

2-D and Buried Structures

•Structures can be buried (metrology of 3-D circuits possible)

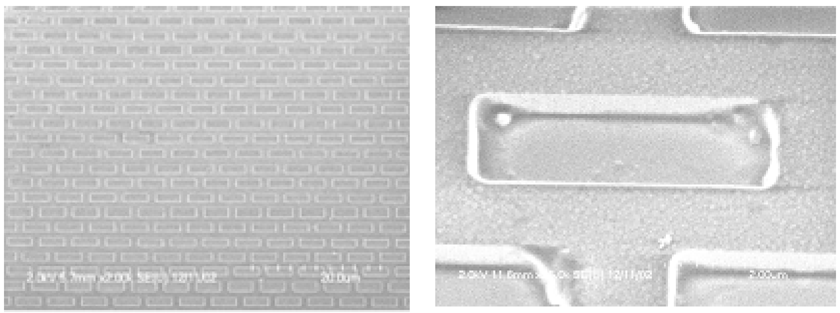
•Transmission measurement samples all depths equally

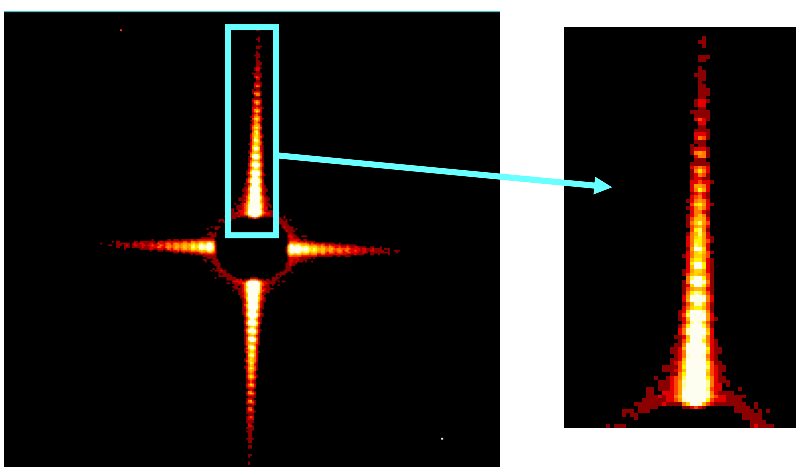
•2-D detector allows single measurement to characterize entire top-down shape.

•Additional measurements provide pattern cross section (I.e. sidewall angle)

•Full 3-D characterization possible of dense, high aspect ratio patterns

Top down SEM of dense array of via pads





Resulting CD-SAXS detector image shows 2 axes of diffraction.
Entire top-down shape can be characterized in one measurement

A Wide Range of Samples

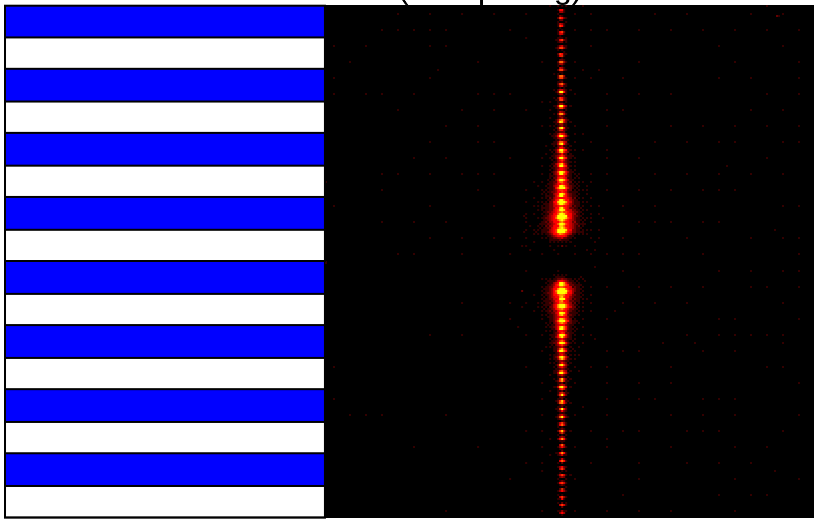
Materials measured non-destructively

- **Photoresists (248 nm, 193 nm, EUV)**
- **Engineering Polymers (PMMA, PS)**
- **Oxides (SiO_2)**
- **Nanoporous Matrices**
- **Barrier layers (SiN, SiCN)**
- **Metal Interconnects (Cu)**

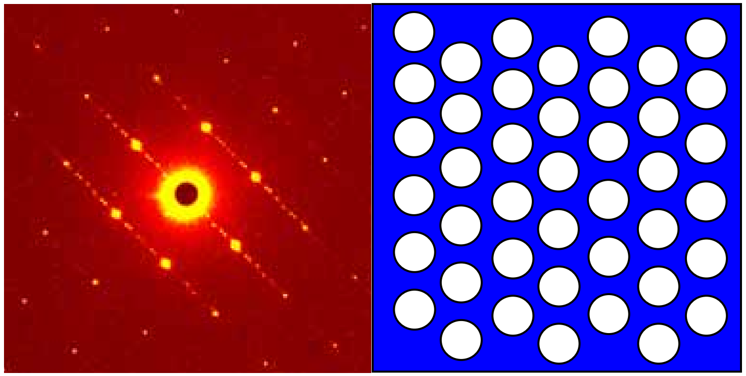
Pattern Geometries

- **Line/Space patterns (gratings)**
- **Arrays of columns**
- **Arrays of holes (vias)**

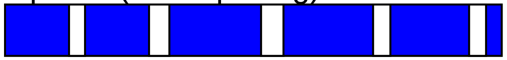
Dense (1:1 spacing) 550 nm lines



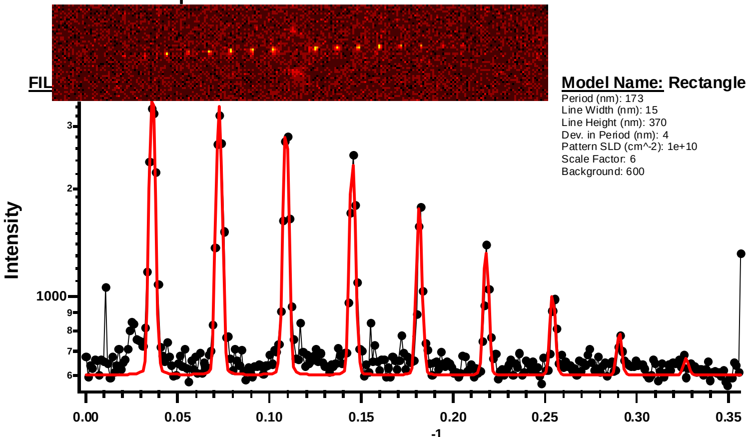
Hexagonal Close Packed 60 nm vias



Sparse (1:10 spacing) 15nm lines



Line/Space Patterns in Oxide



Critical Dimension Small Angle X-ray Scattering (CD-SAXS)

- Probing wavelength < 1 Å → measurement becomes easier as feature size gets smaller
- Weak interaction between materials (Cu, Ta, Si, C, O, H, etc.) → penetration power & Fourier transform (real objects)
- Absorption edge exists for heavy elements including Ta

challenges

- Quantify imperfections of nano-pattern from X-ray data
- Availability of intense x-ray source other than synchrotron

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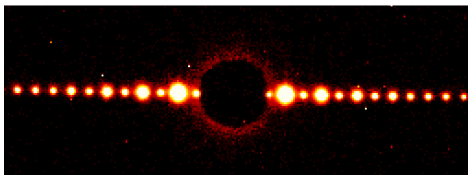
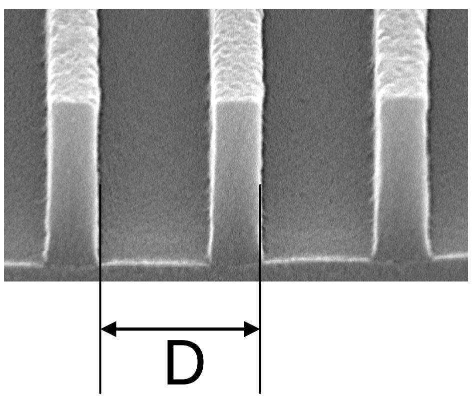
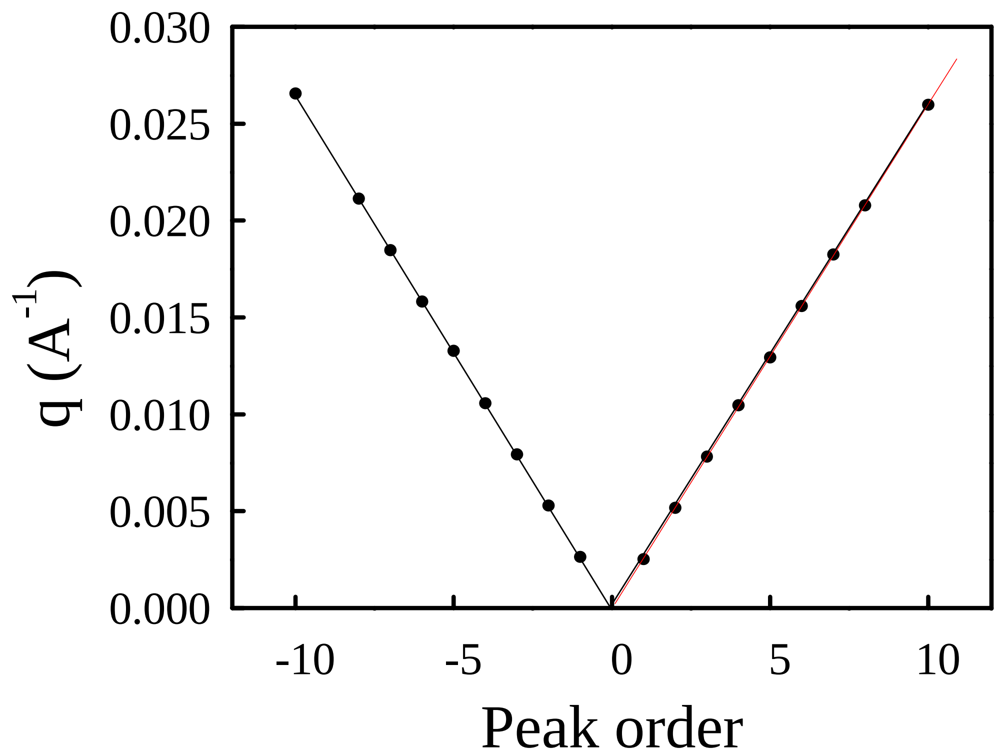
- **Measurement of pitch and line width**
- Measurement of side wall angle and height
- Line roughness including both side walls & top surface (on-going)
- Conclusions

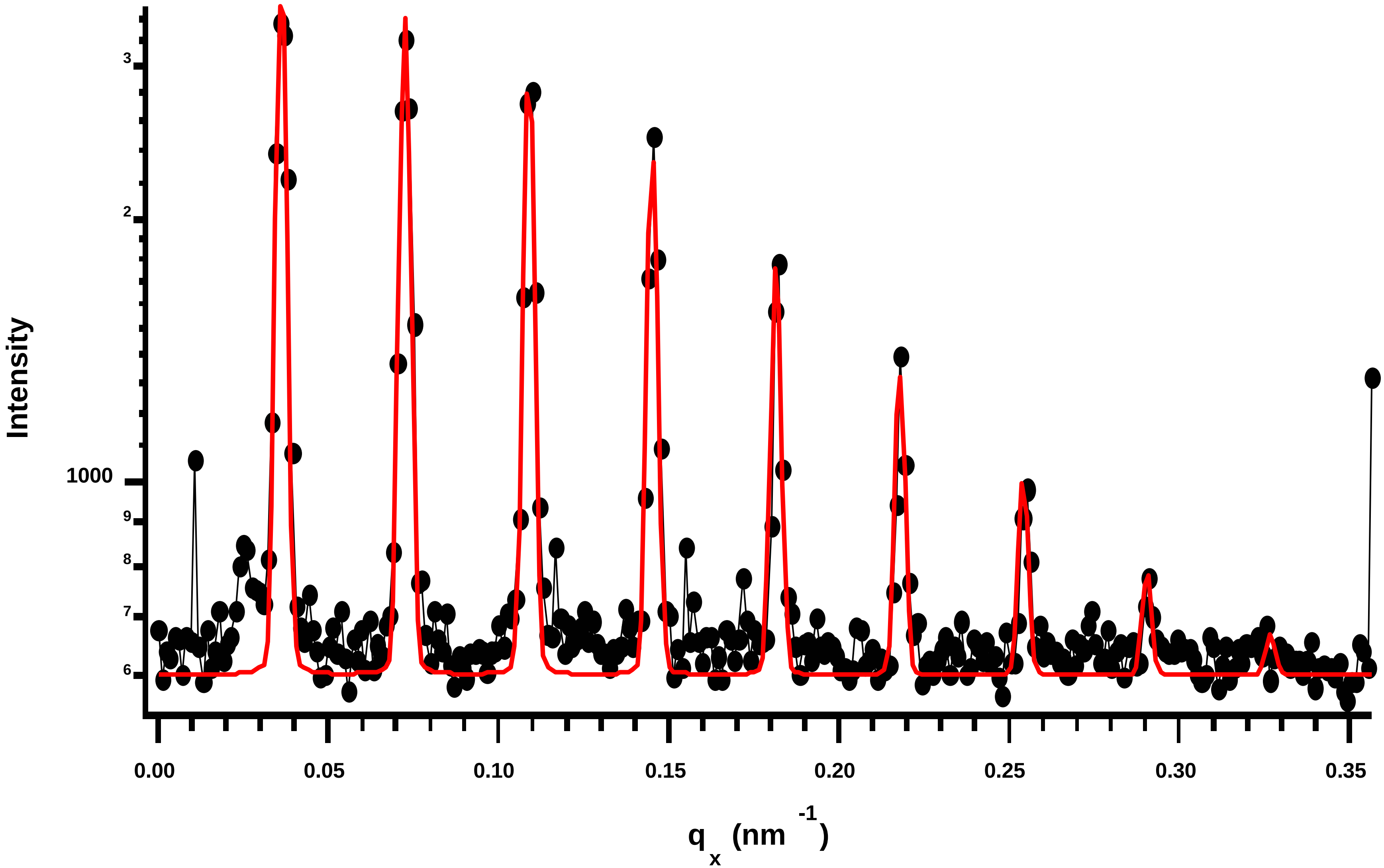
- <u>Pitch Measurement</u>







D = 237.1 ± 0.5 nm



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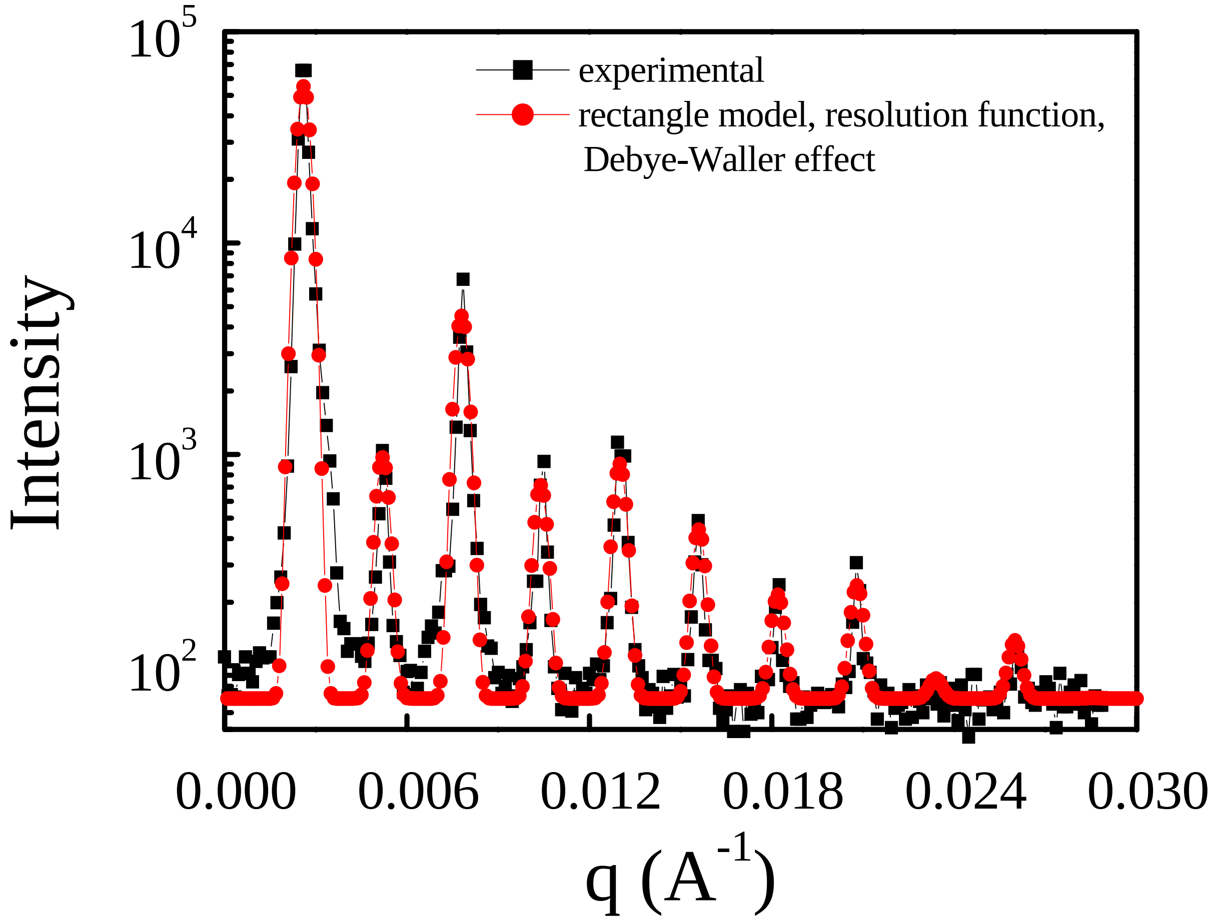
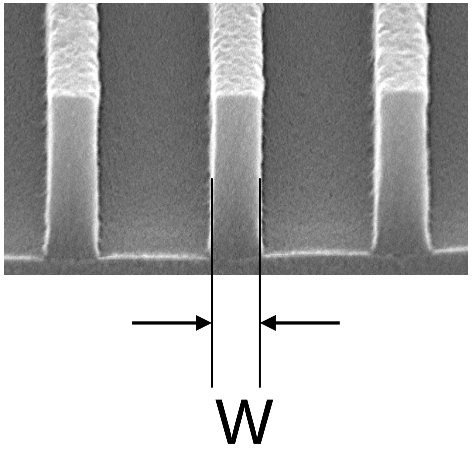
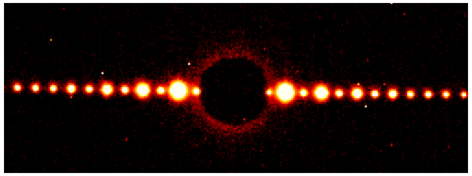
- <u>Average line width</u>







Width = 128 nm

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- Introduction
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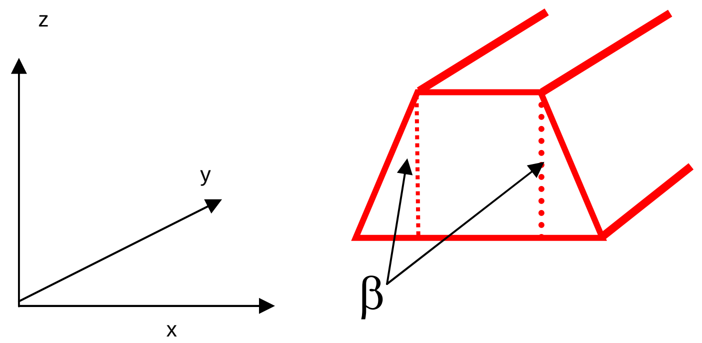
- **Measurement of side wall angle**
- Line roughness including both side walls & top surface (on-going)
- Conclusions

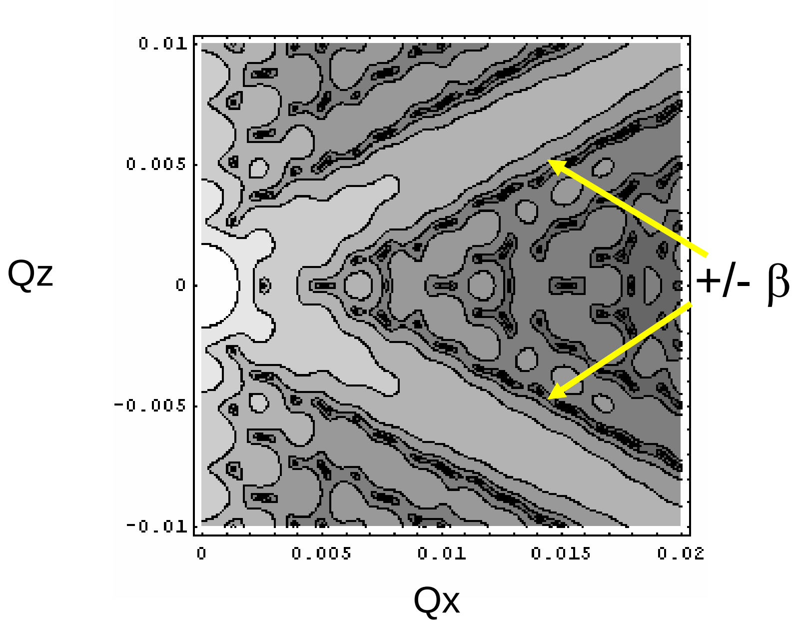
Trapezoid as a starting point

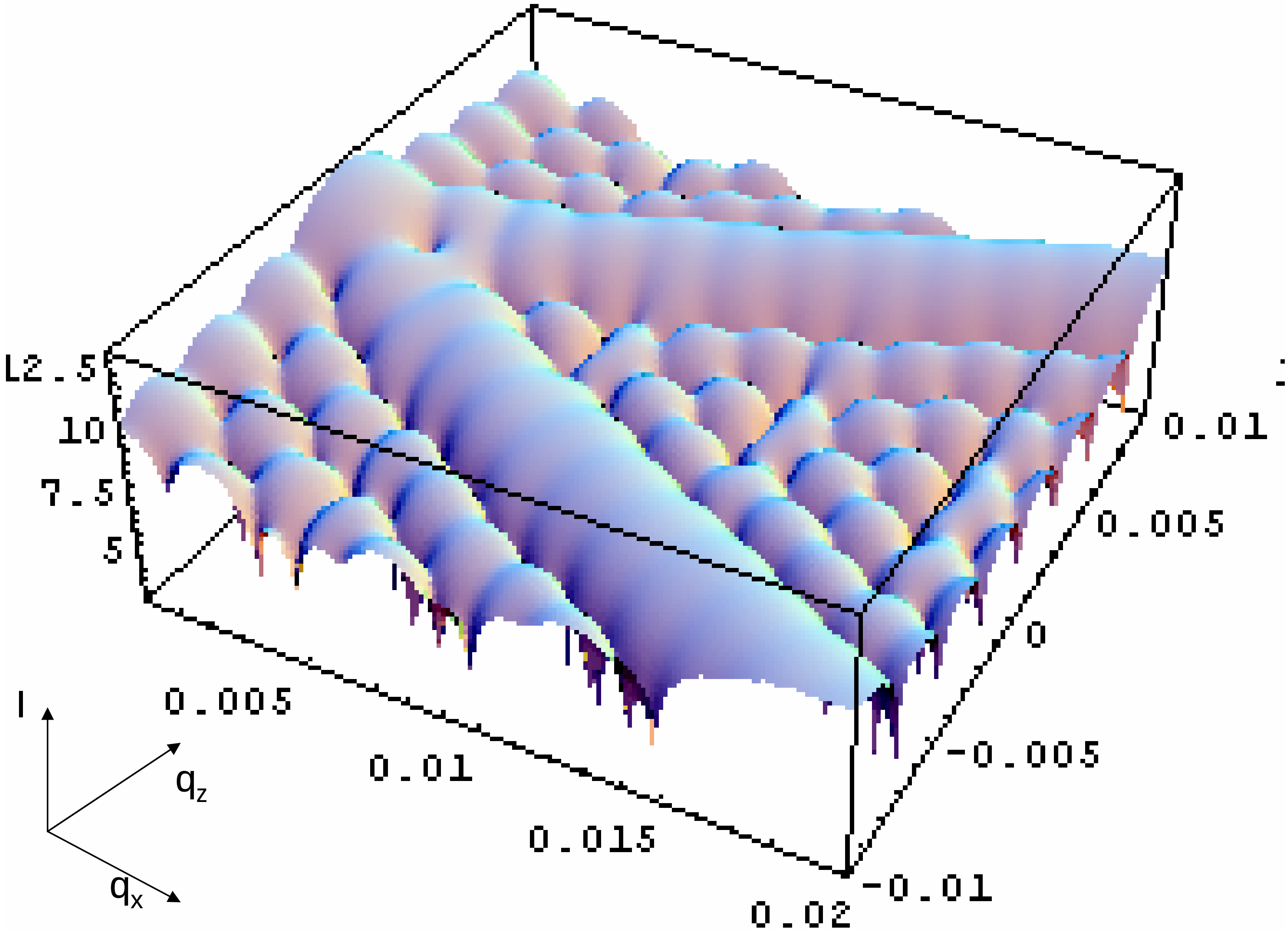
Sidewall Angle Metrology

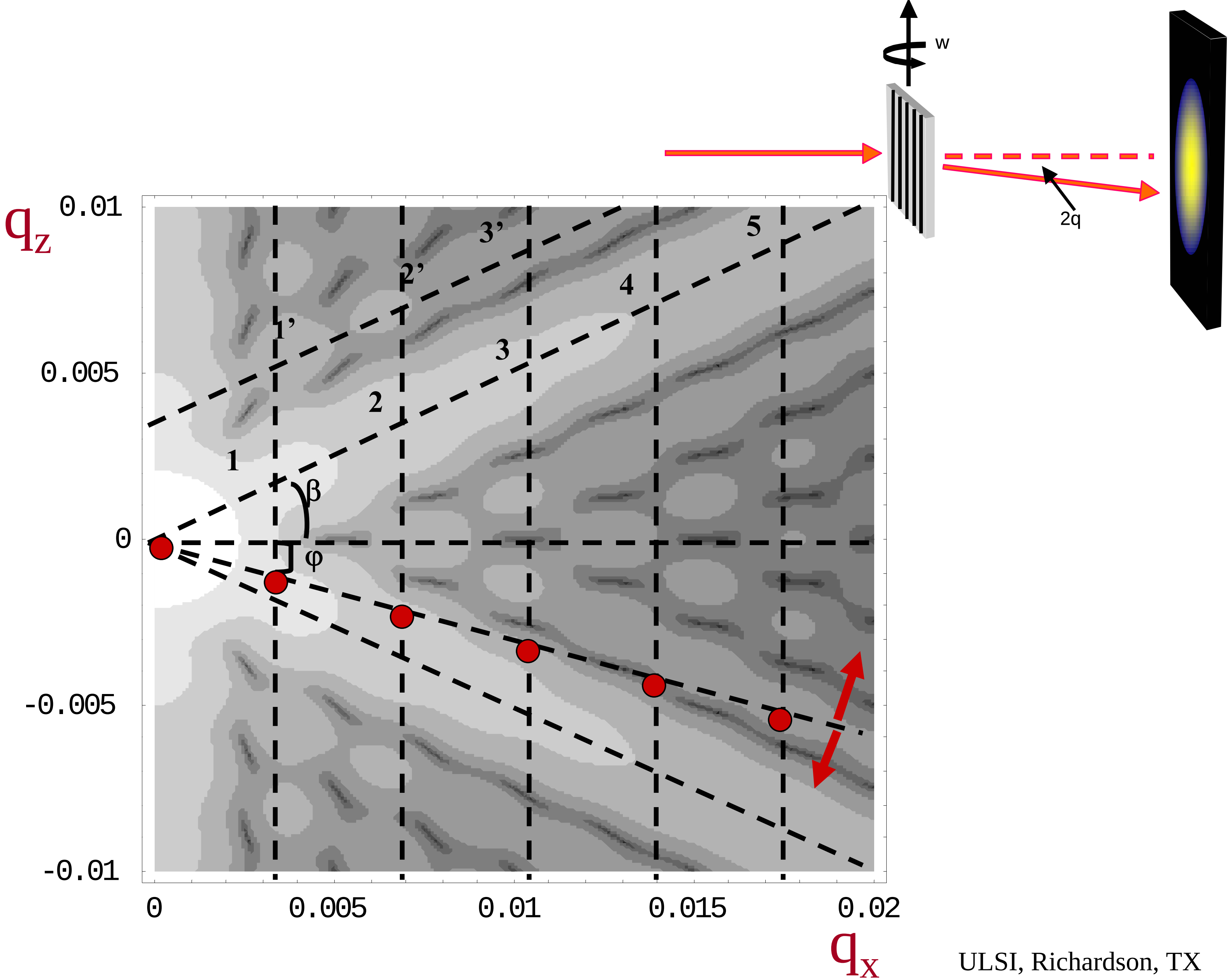
Theoretical Model of Trapezoidal Cross Section



2-D Fast Fourier Transform




12.5
10
7.5
5
0.005
0.01
0.015
0.02
0.01
0.005
0
-0.005
-0.01
I
q_z
q_x



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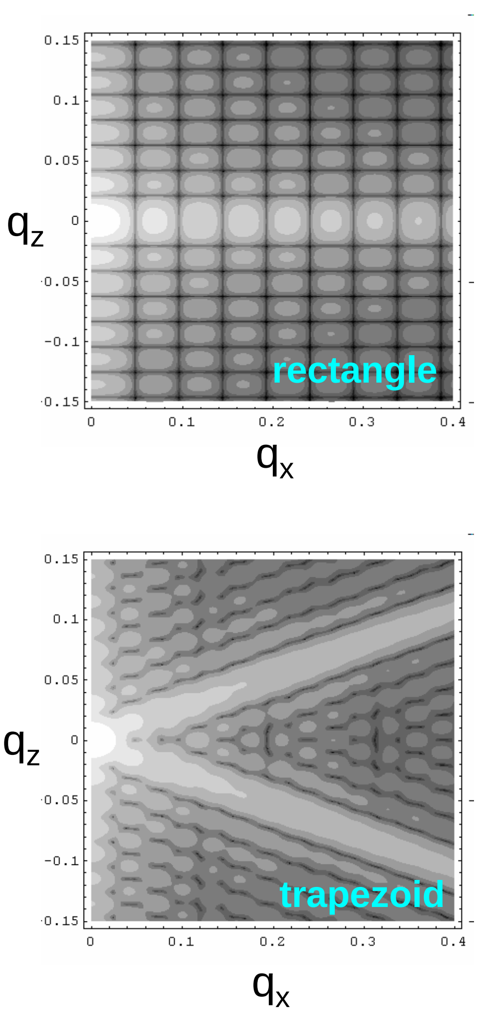
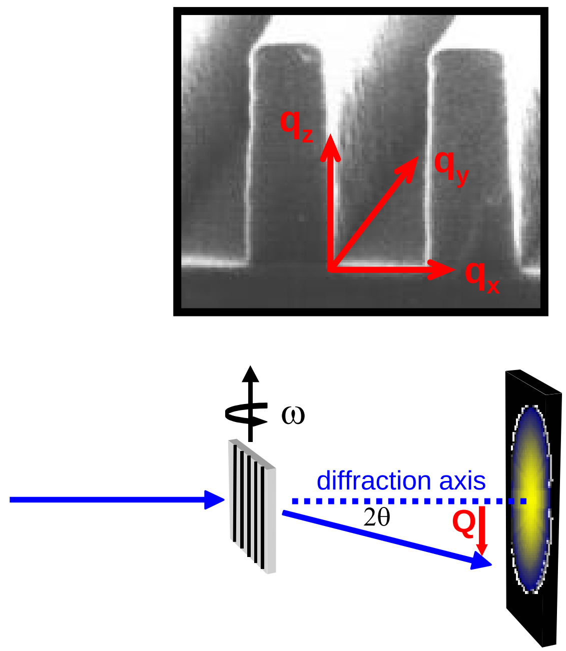
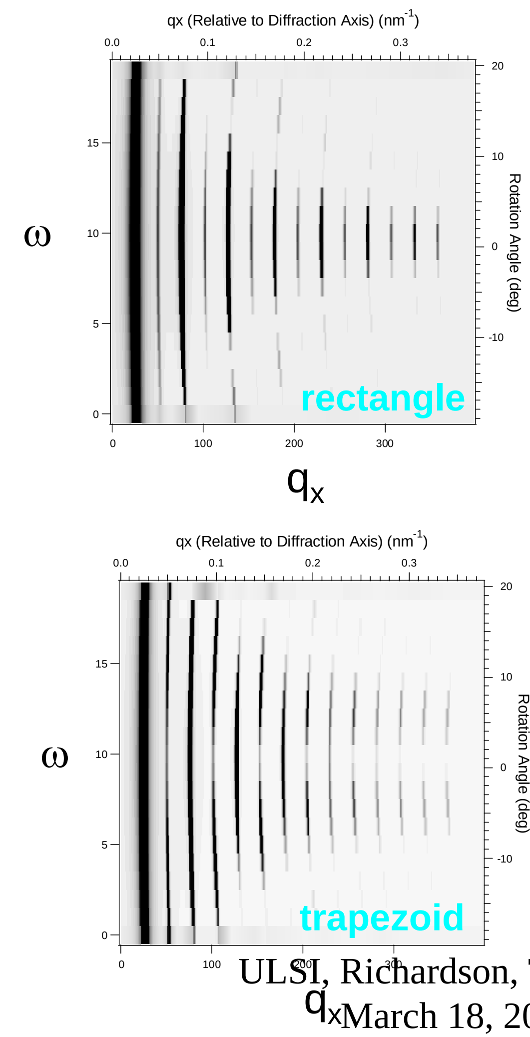
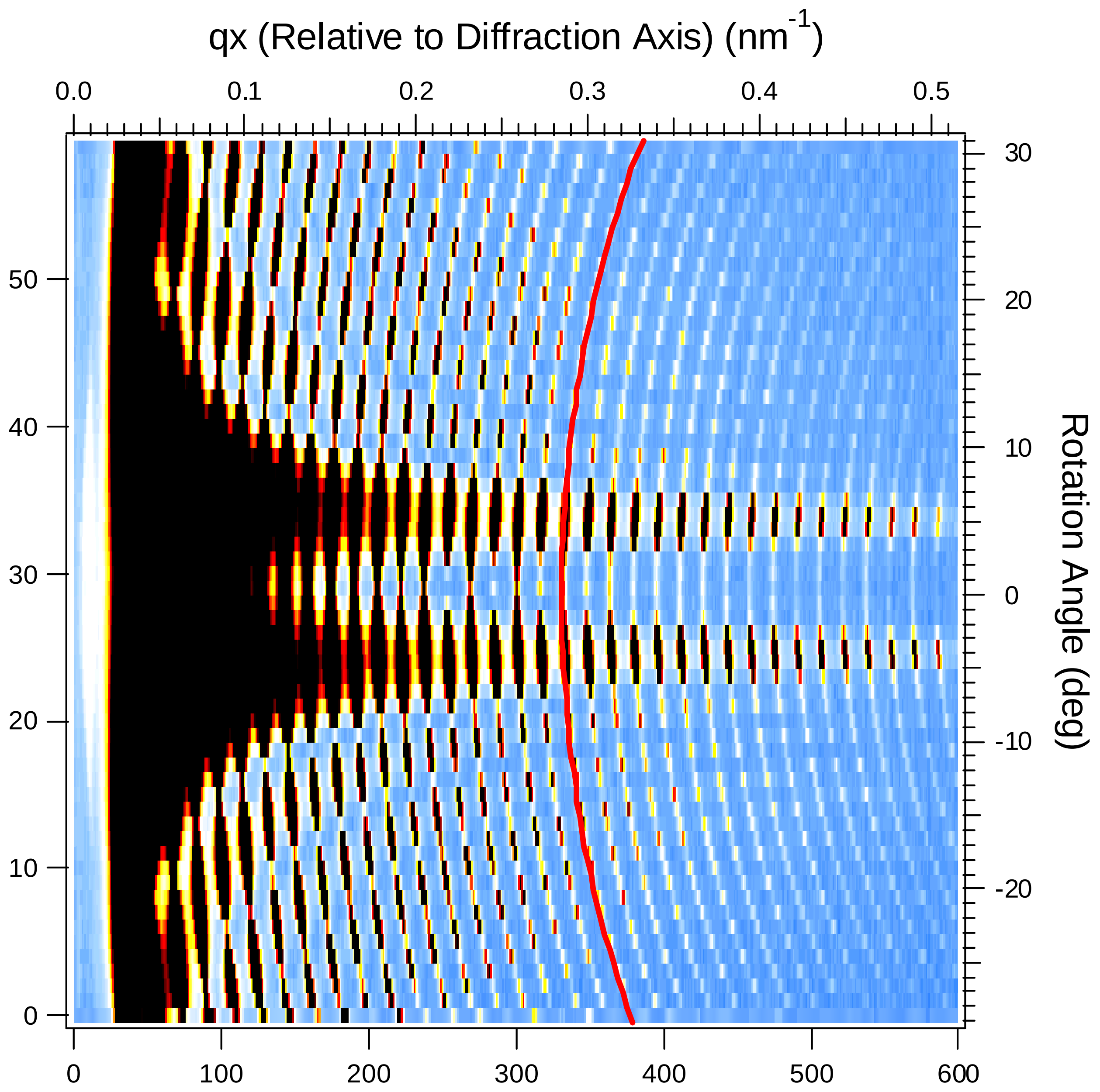
3-D Lineshape from Sample Rotation









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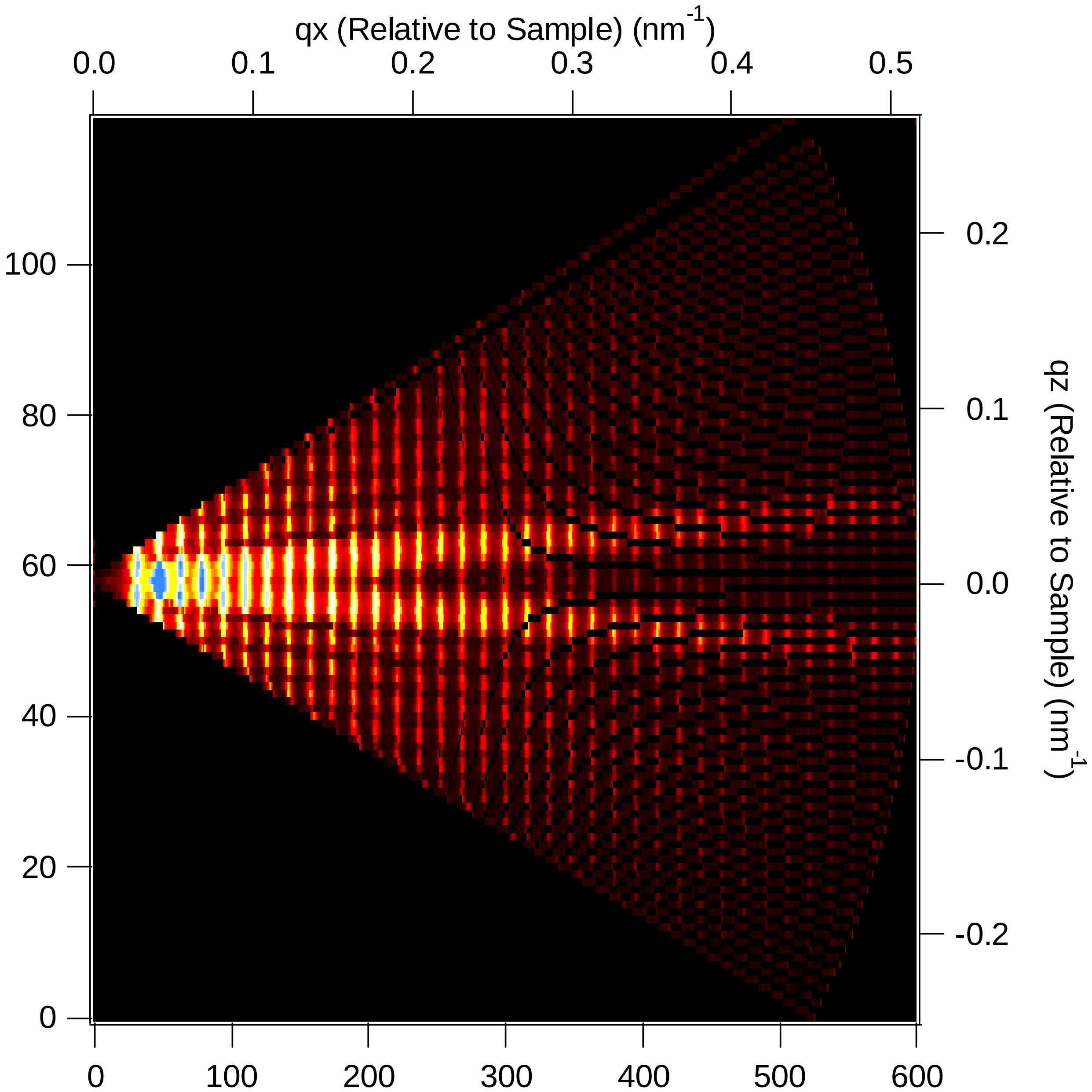

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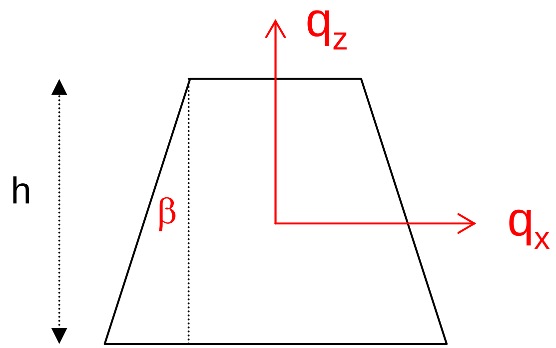
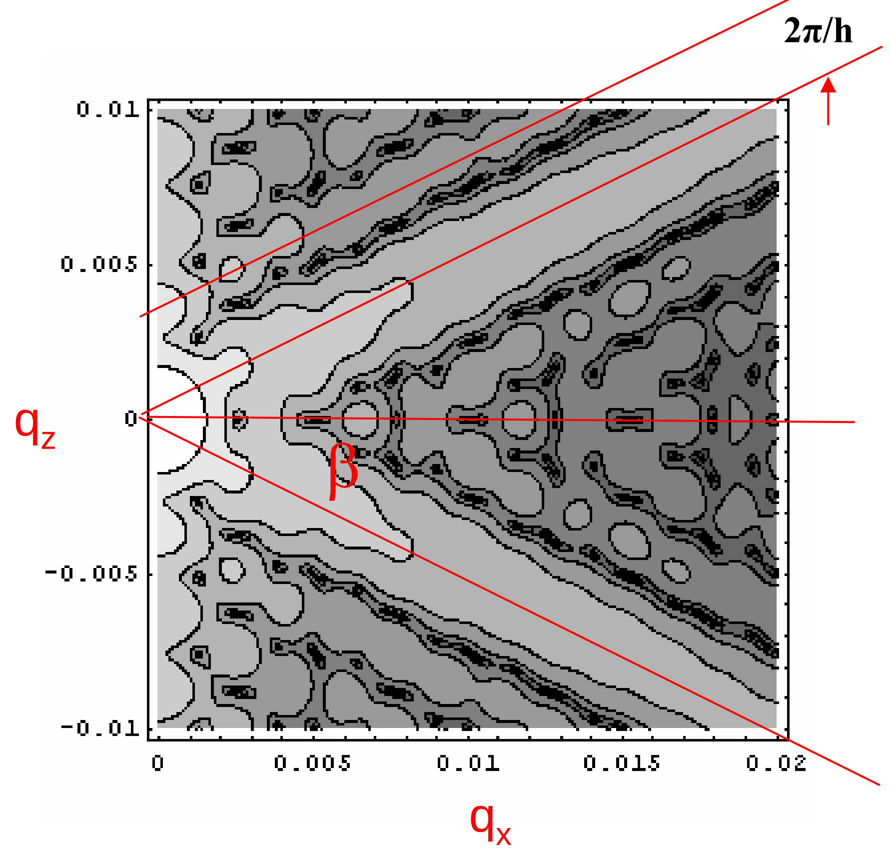
CD-SAXS: Pattern Cross Section

real space ⟷ Fourier transform





Summary: Cross section measurement-

1. Pitch – periodicity along q_x at q_z =0
2. Line width – intensity modulation along q_x at q_z =0
3. Line height – periodicity along q_z at a fixed q_x
4. Sidewall angle

Photoresist Patterns

Data measured on 5-ID SAXS (DND-CAT)
Advanced Photon Source, Argonne National Lab

Data collection and analysis performed by
Ron Jones, Tengjiao Hu, Wen-li Wu
Beamline Scientists: Steve Weigand, John Quintana
Samples: provided by Qinghuan Lin (IBM T.J. Watson Research)

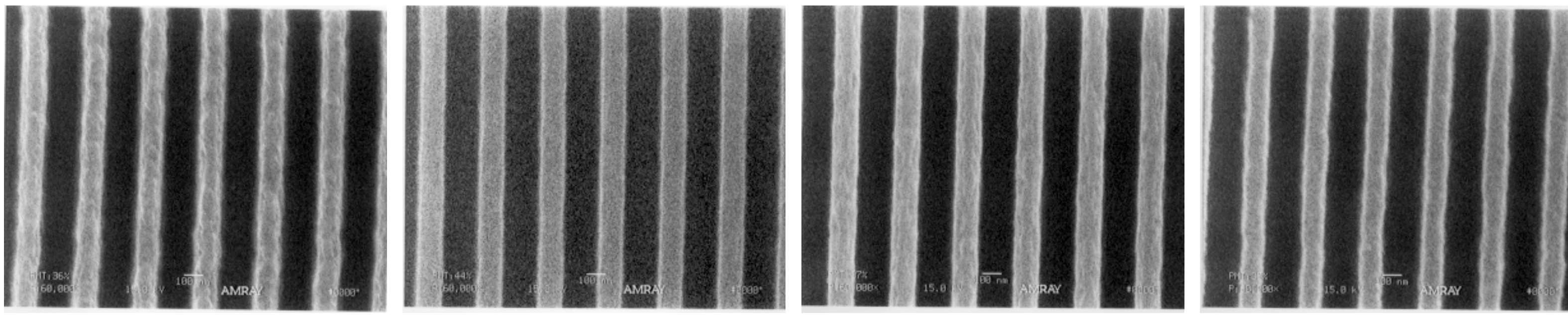
Sample List:

1) IBM DOF m2 - 248nm PR, -0.2micron Depth of Focus
2) IBM DOF p0 - 248nm PR, “Optimal” Depth of Focus
3) IBM DOF p2 - 248nm PR, +0.2micron Depth of Focus
4) IBM DOF p4 - 248nm PR, +0.4micron Depth of Focus

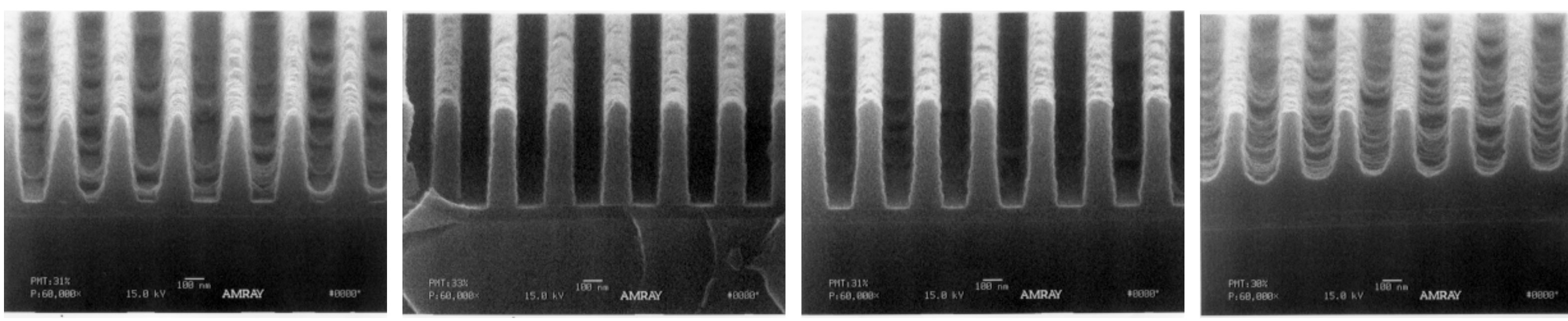
150nm L/S Patterns Through Focus

Images provided by Q. Lin

Top Down

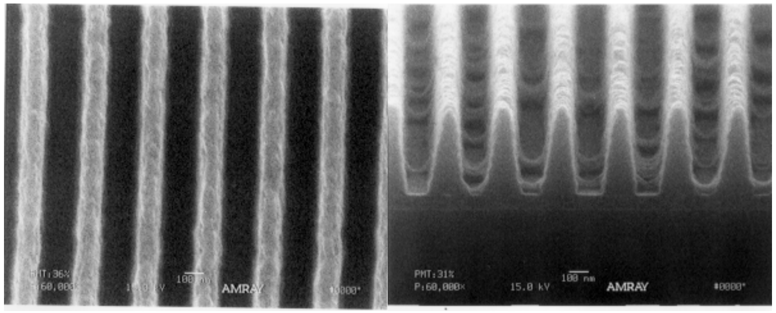


Cross-section



+0.4 um	+0.2 um	0.0 um	-0.2 um

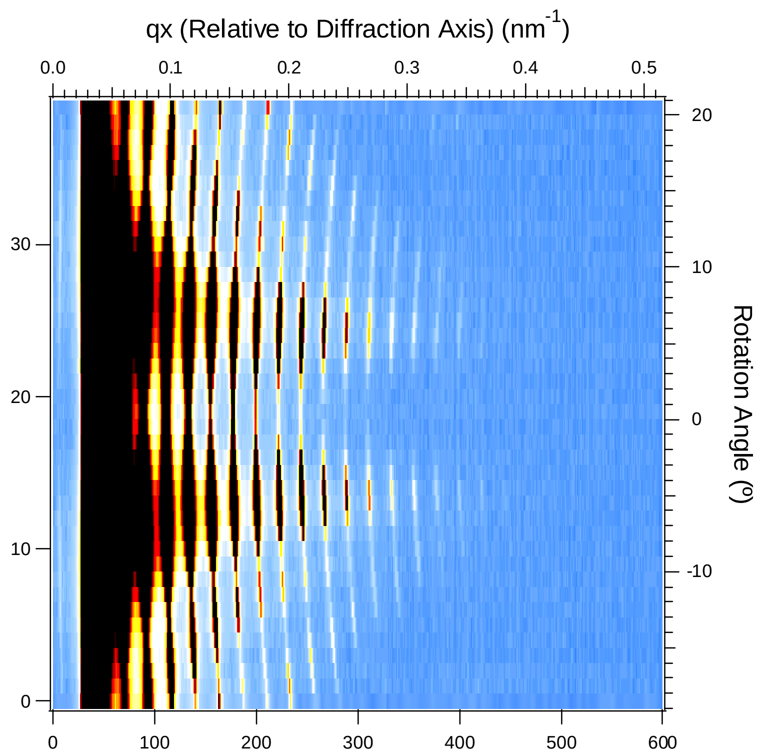
Wafer: EPPX

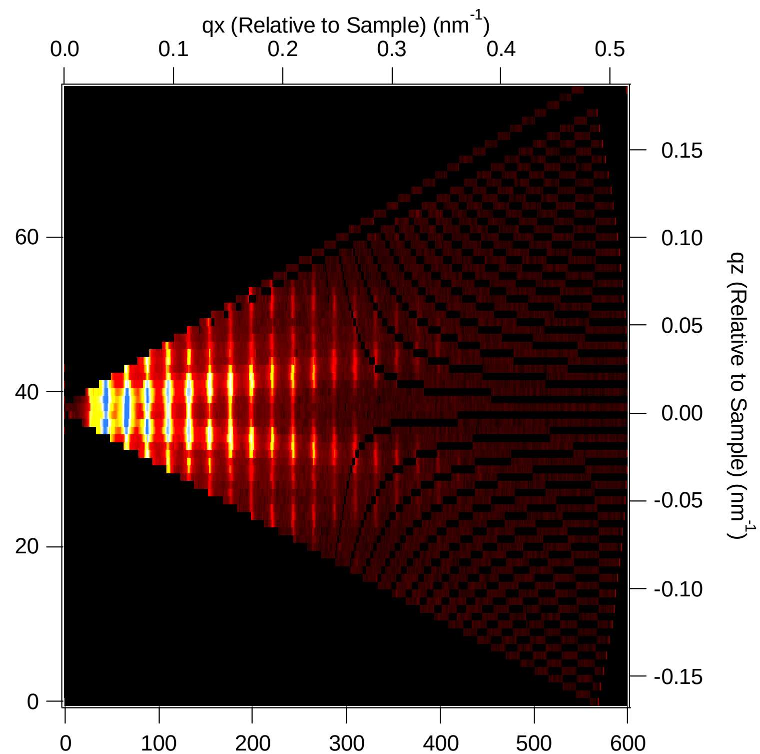


IBM DOF p4

+0.4 micron

Period = 330.5 nm +/- 0.5 nm
Linewidth = 160 +/- 1 nm
Height = 460 +/- 10 nm
Sidewall Angle = 5.6 +/- 0.5 deg
Random Deviation = 5 nm





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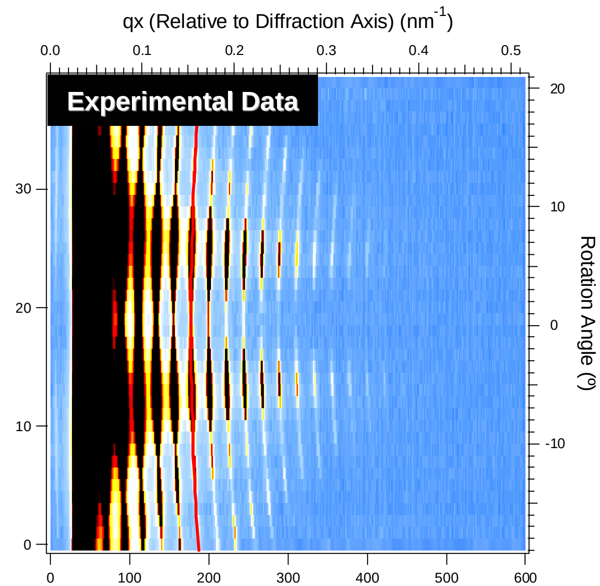
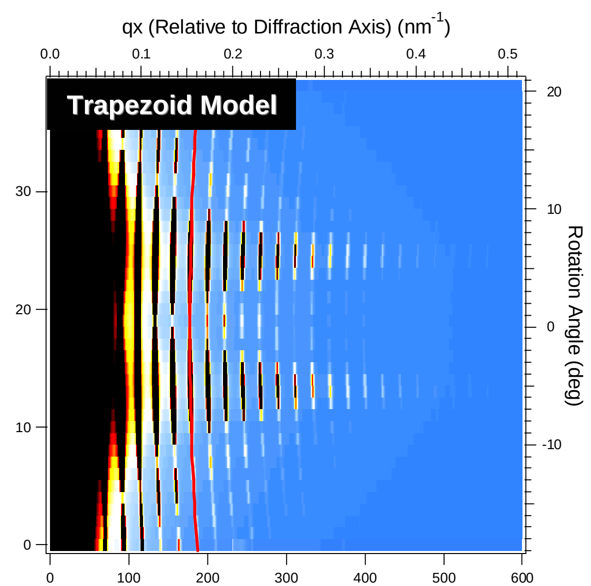
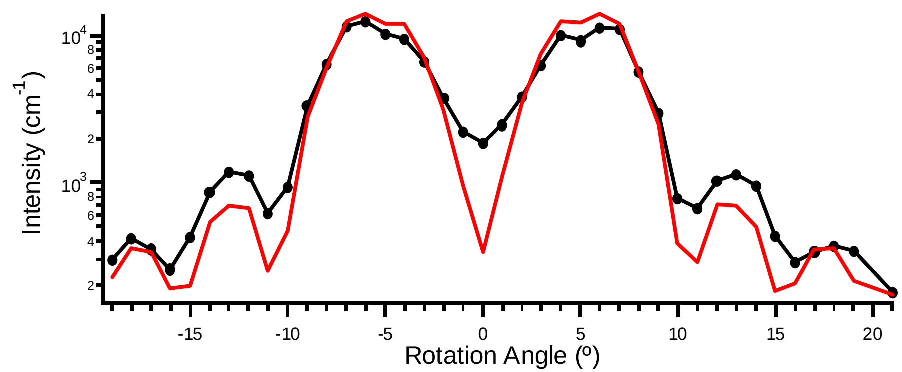
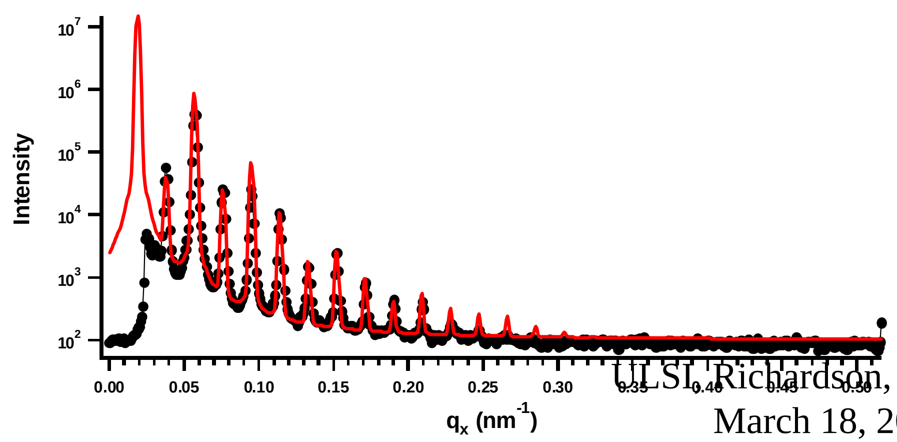
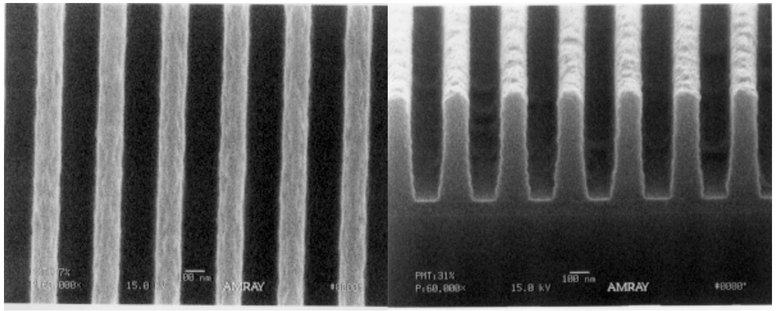






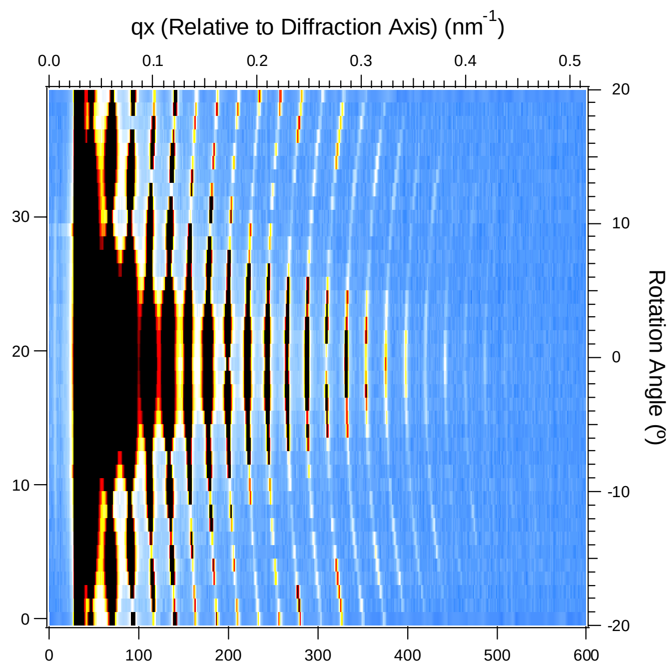


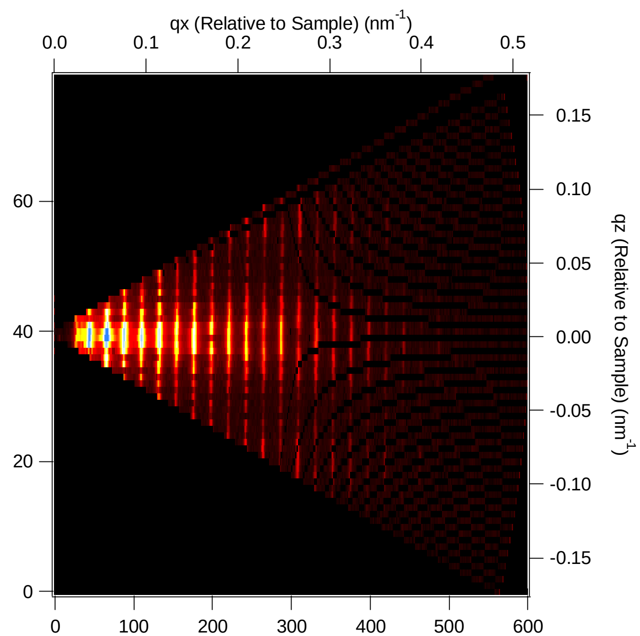


IBM DOF p0

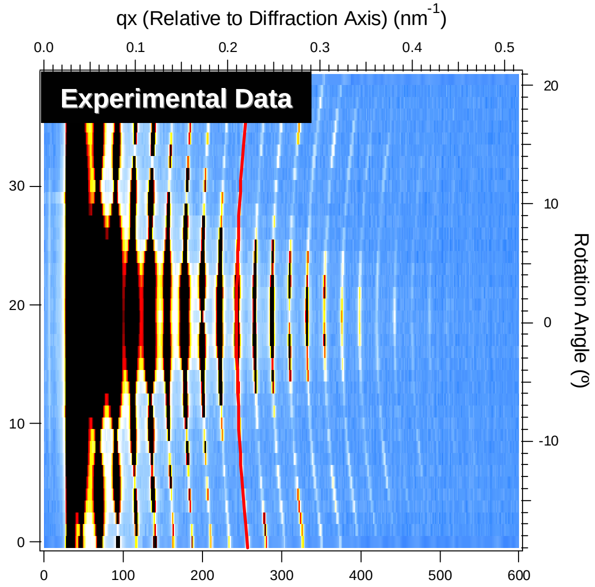
+0.0 micron

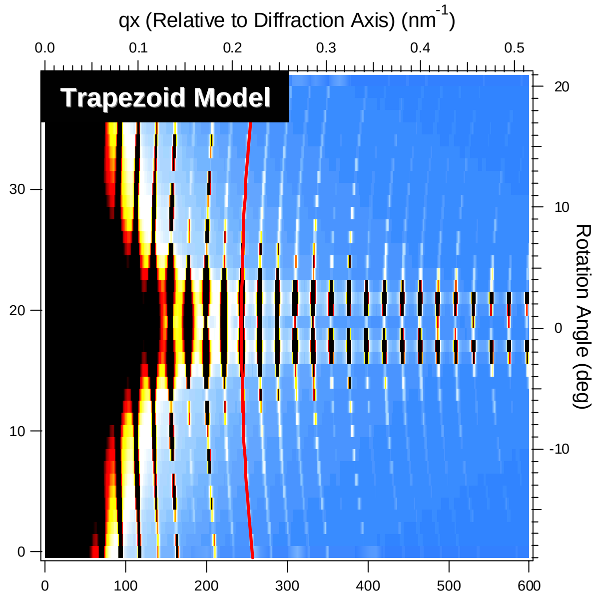
Period = 330.5 nm +/- 0.5 nm
Linewidth = 148
Height = 550
Sidewall Angle = 2 +/- 0.3 deg





Experimental data spread more evenly across 2-D plane than model

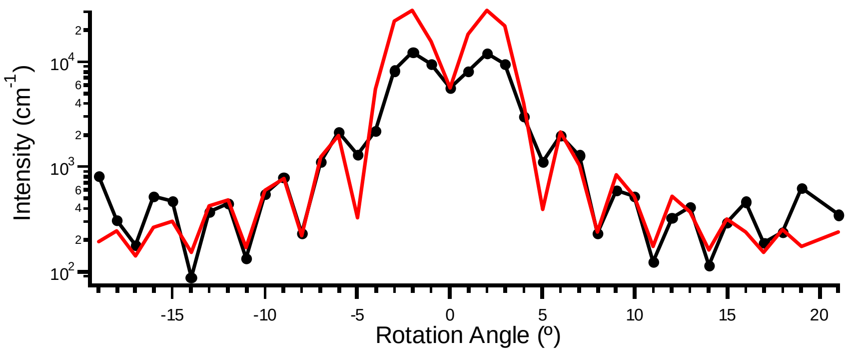


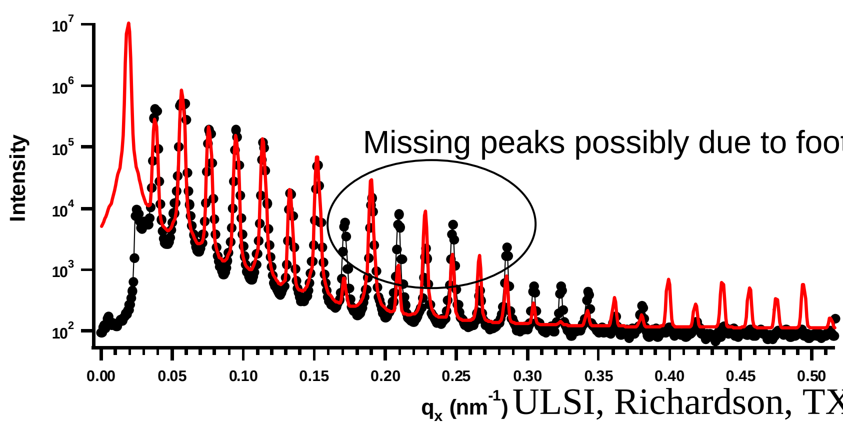


IBM DOF p0

+0.0 micron

Period = 330.5 nm +/- 0.5 nm
Linewidth = 148 +/- 1
Height = 550 +/- 10
Sidewall Angle = 2 +/- 0.5 deg





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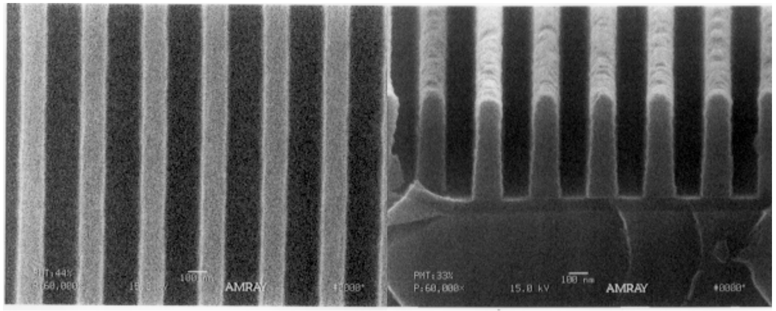
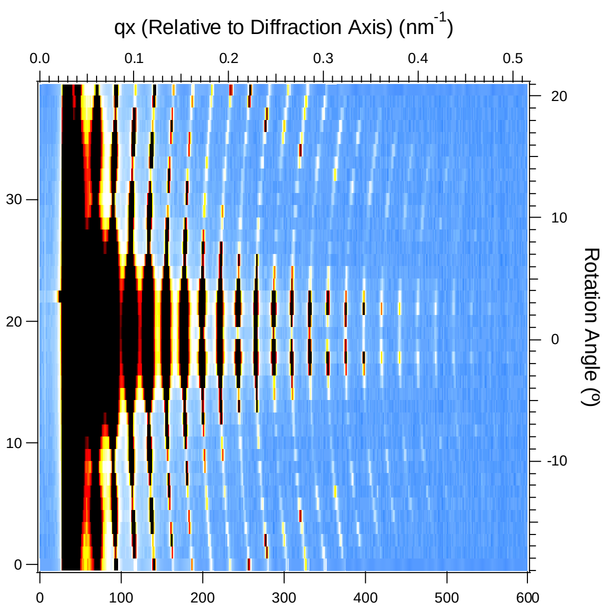
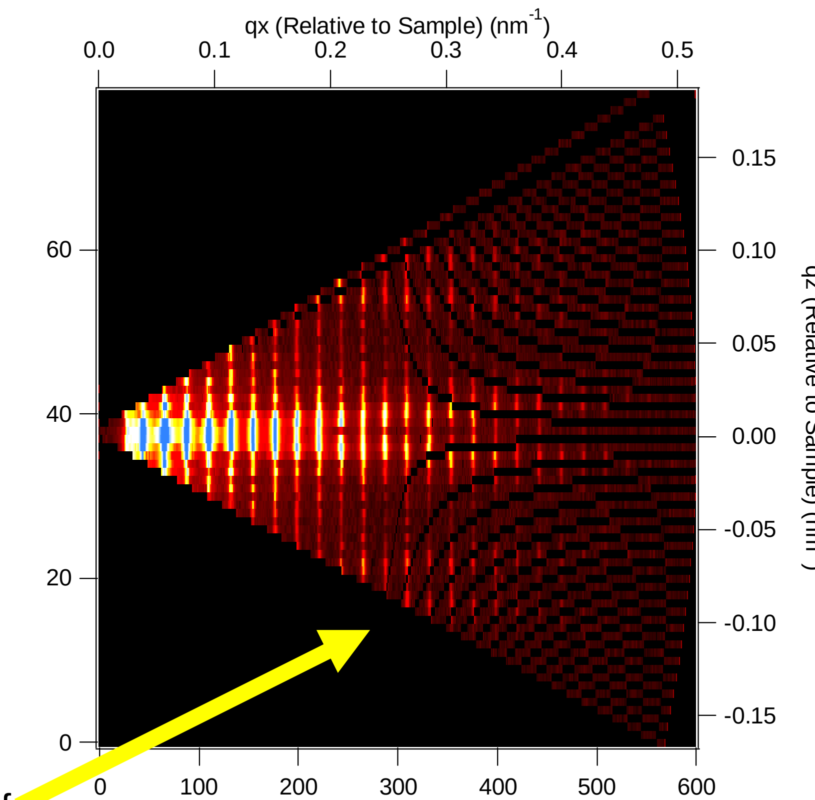


IBM DOF p2

+0.2 micron

Period = 330.5 nm +/- 0.5 nm
Linewidth = 153 +/- 1
Height = 605 +/- 10
Sidewall Angle = 2 +/- 0.5 deg



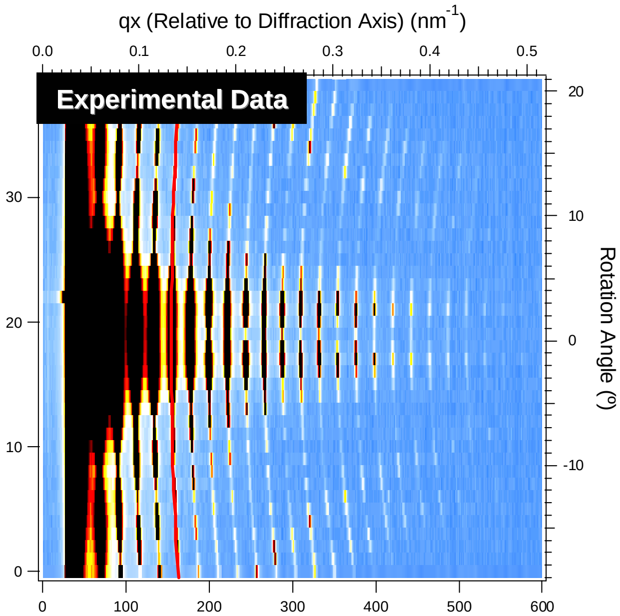


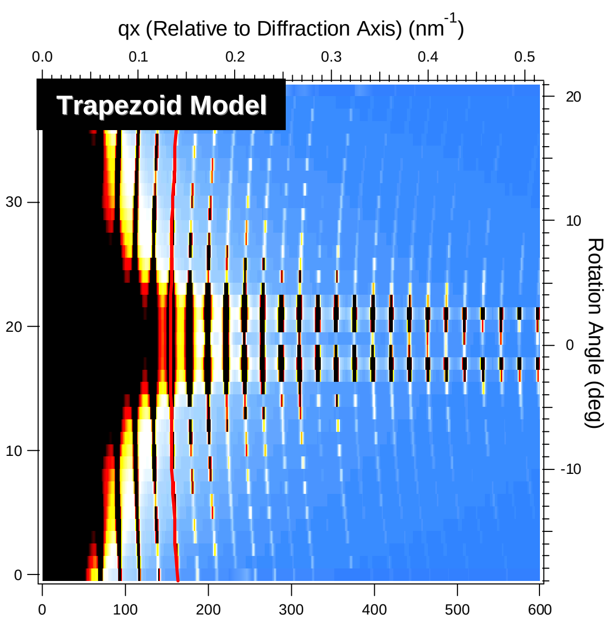
Possible evidence of small standing wave effect

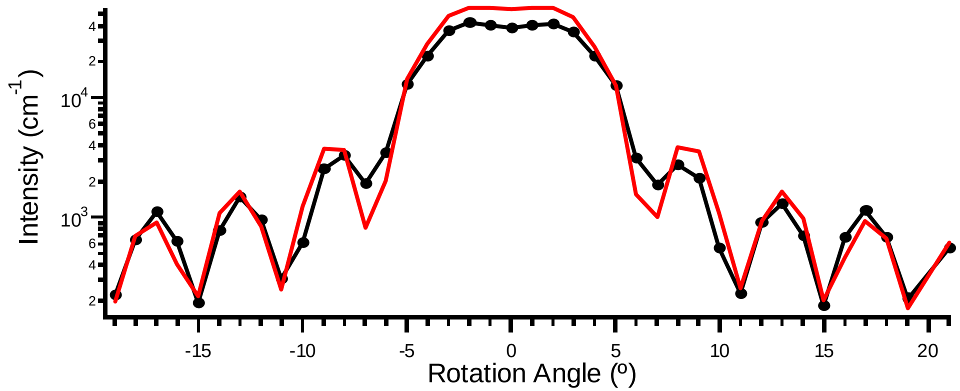
IBM DOF p2

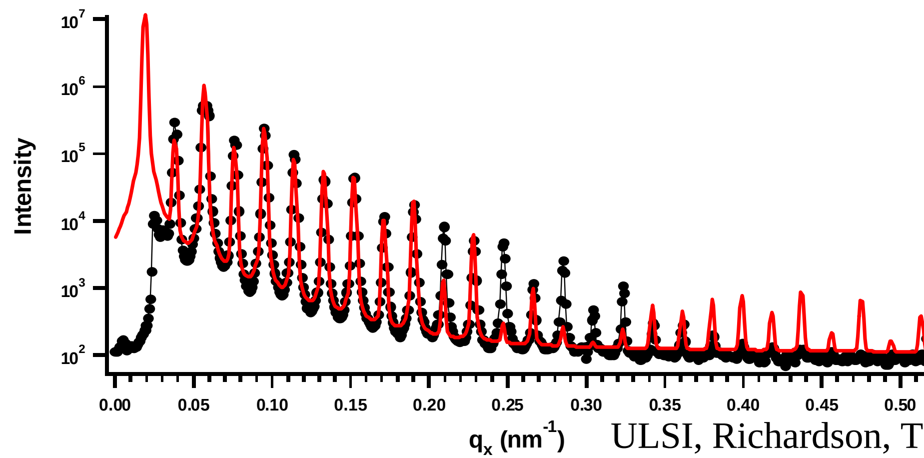
+0.2 micron

Period = 330.5 nm +/- 0.5 nm
Linewidth = 153 +/- 1
Height = 605 +/- 10 nm
Sidewall Angle = 2 +/- 0.5 deg









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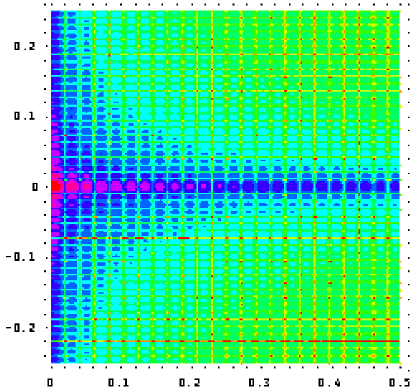
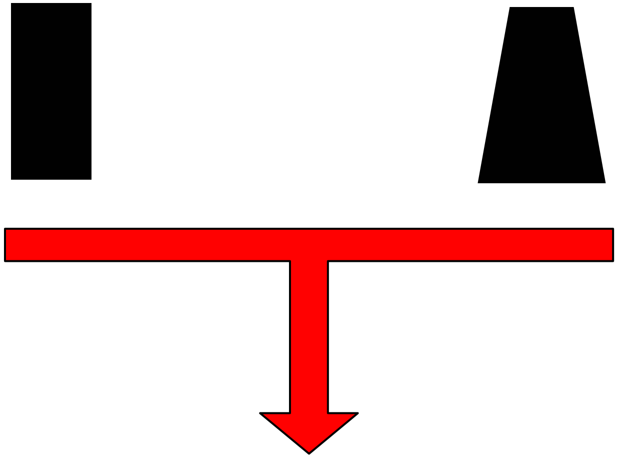
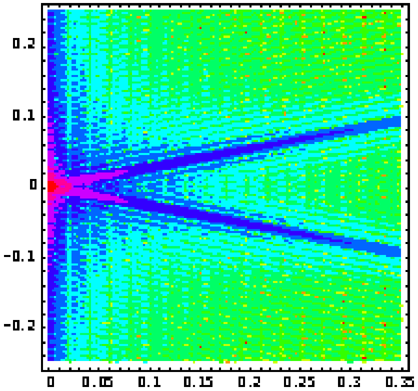
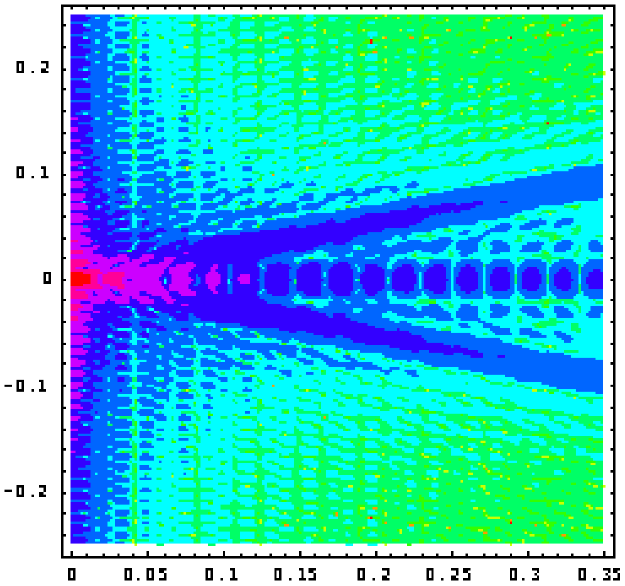
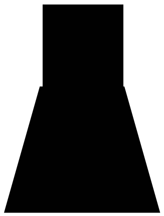
More Complicated Structures











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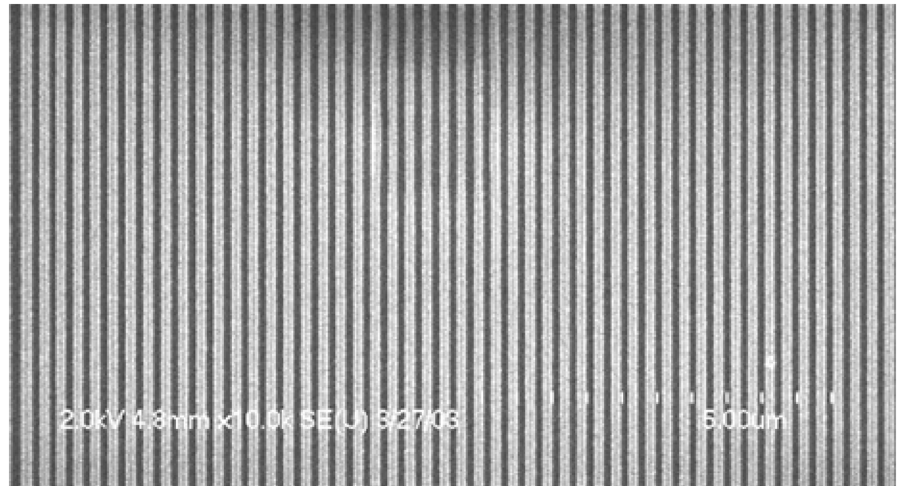
- Introduction
- Measurement of pitch and line width
- Measurement of side wall angle & height
- **Line roughness including both side walls & top surface (on-going)**
- Conclusions

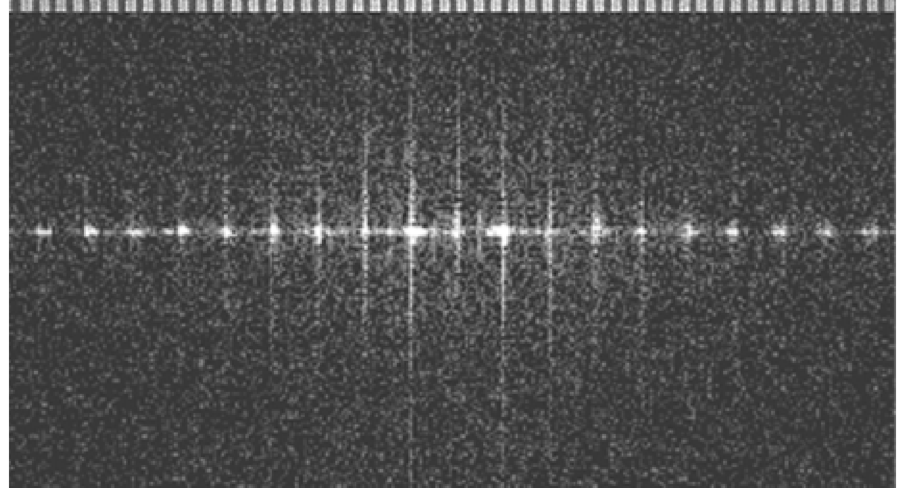
Line roughness probed by CD-SAXS includes both **side wall and top surface**, this is different from LER by SEM

photoresist patterns

SEM micrograph

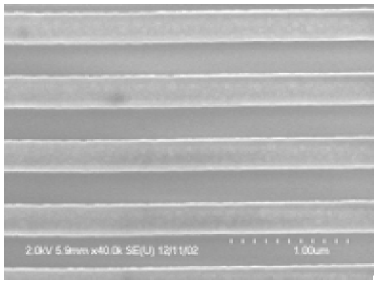


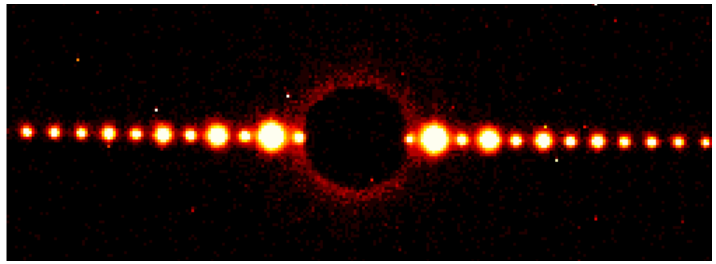
Fourier transfer of the above



CD-SAXS: New Metrology for LER and CD

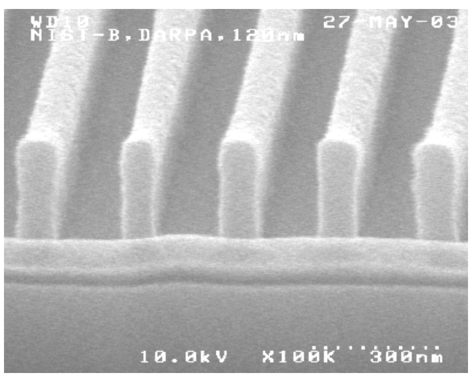
Low "LER":

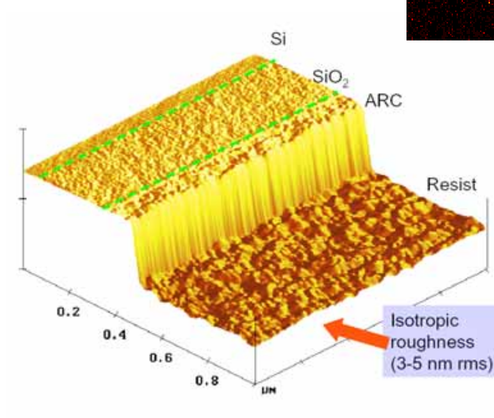


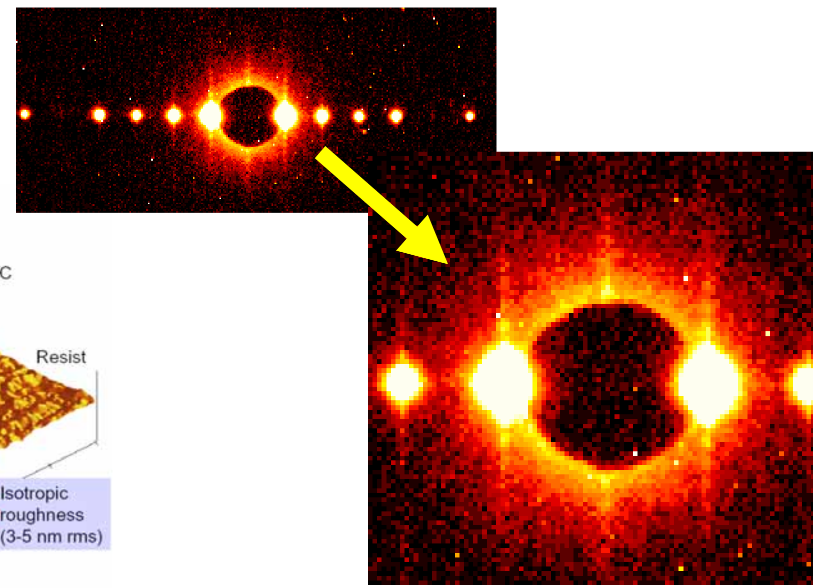


- > 40 orders of diffraction
- Peaks isotropic

Large "LER":

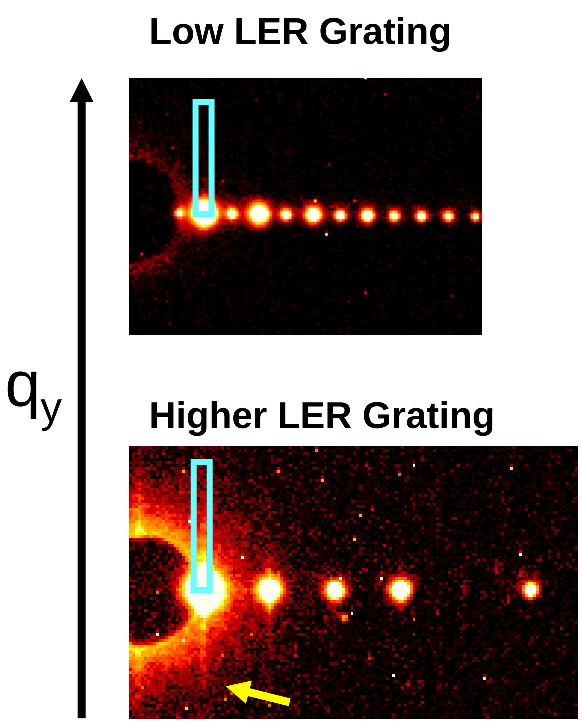


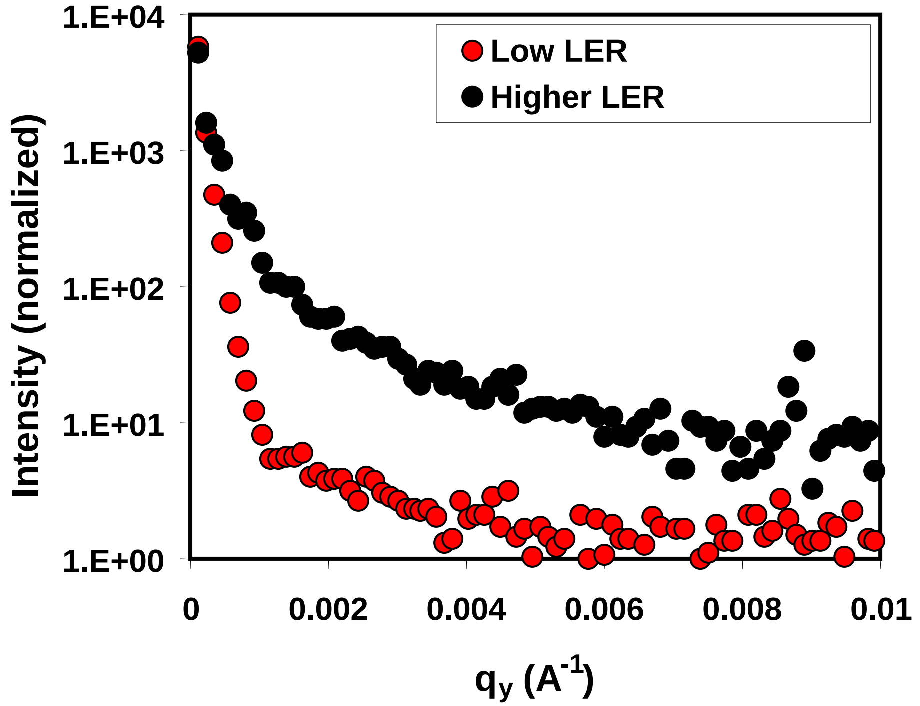




- Photoresist with (3 to 5) nm RMS sidewall roughness (1 σ)
- Peaks intensities decay more rapidly (20 orders observed)
- Broadened diffraction peak widths
- Diffuse "halo" around beam center
- "Streaks" perpendicular to diffraction axis

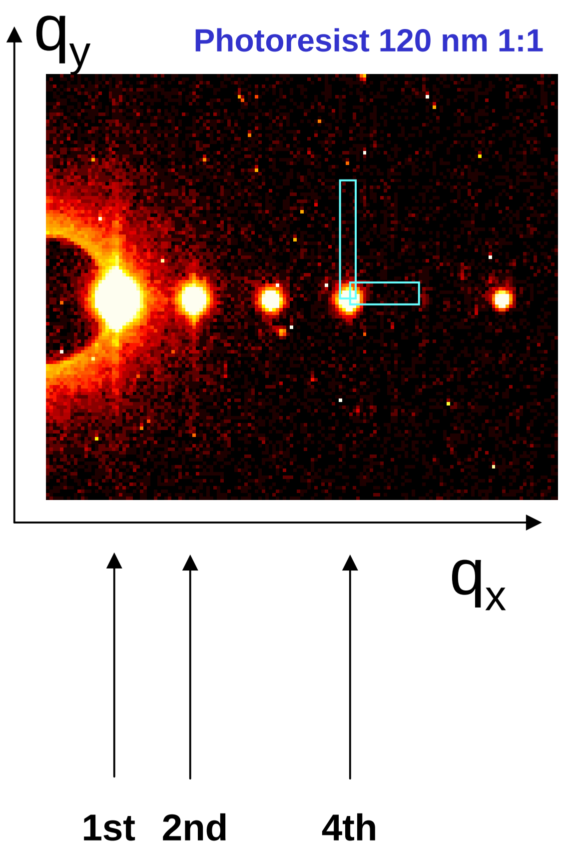
Sidewall Correlations: High vs. Low LER

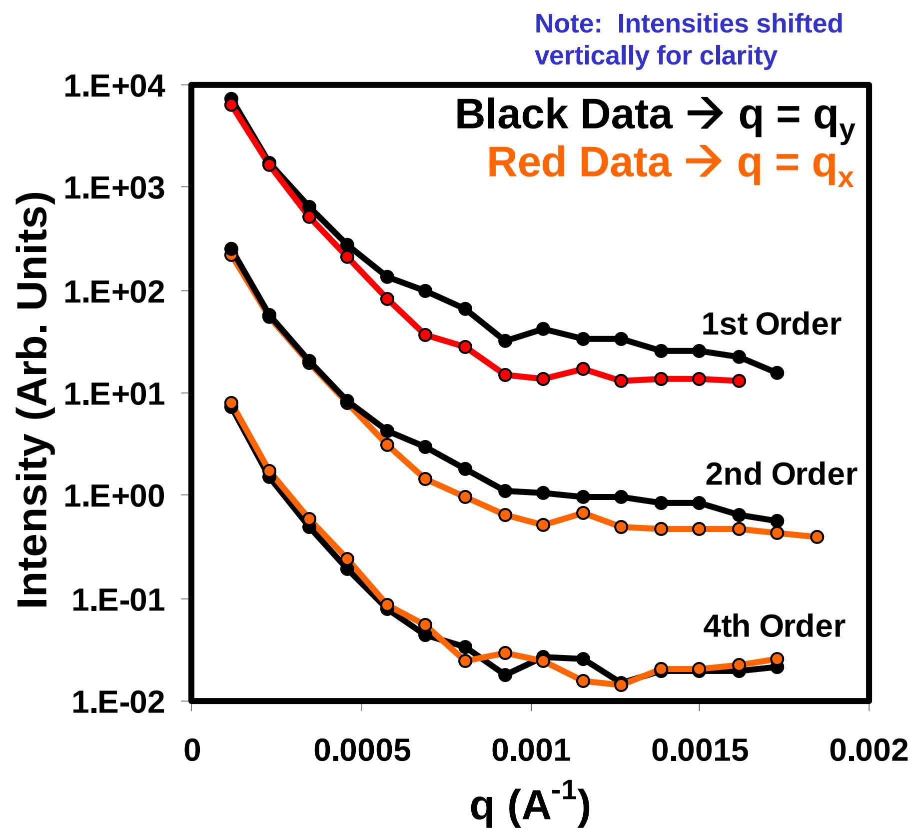




Samples with more defects demonstrate higher intensity "streaking"

Extracting the "Streaks" along q_y



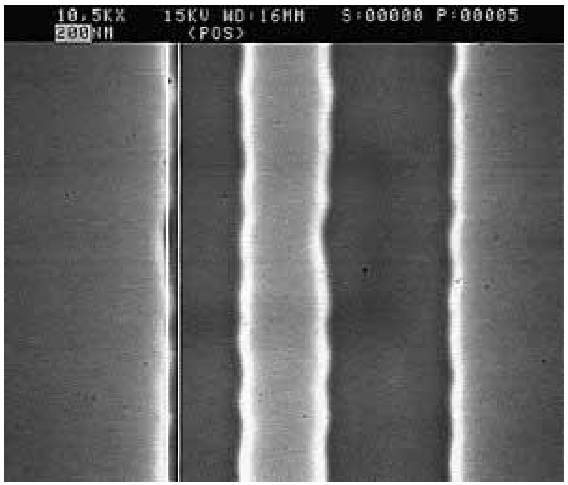


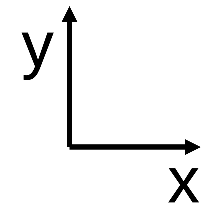
Streaks decay with increasing q_x

Diffraction peaks become isotropic at high q_x

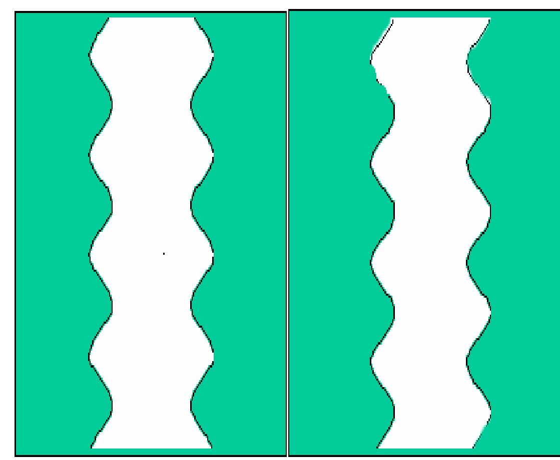
SAXS characterization technique

- <u>Line-edge roughness</u>

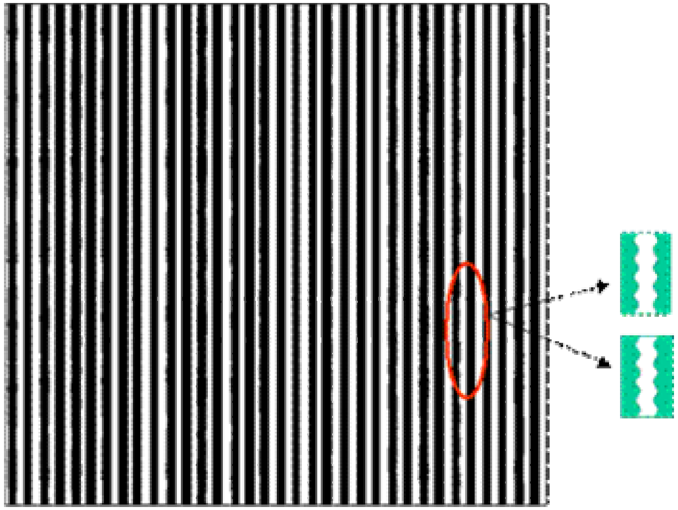


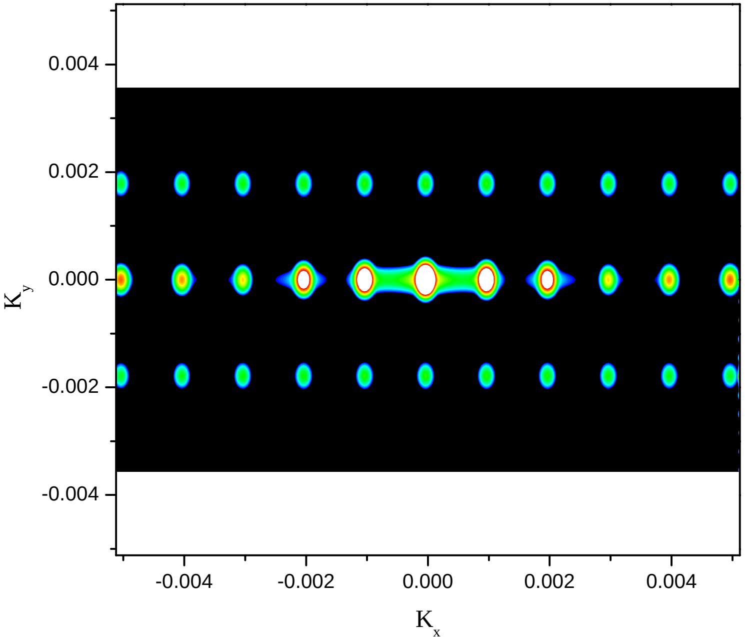


$ASin(2\pi\nu y+\varphi)$



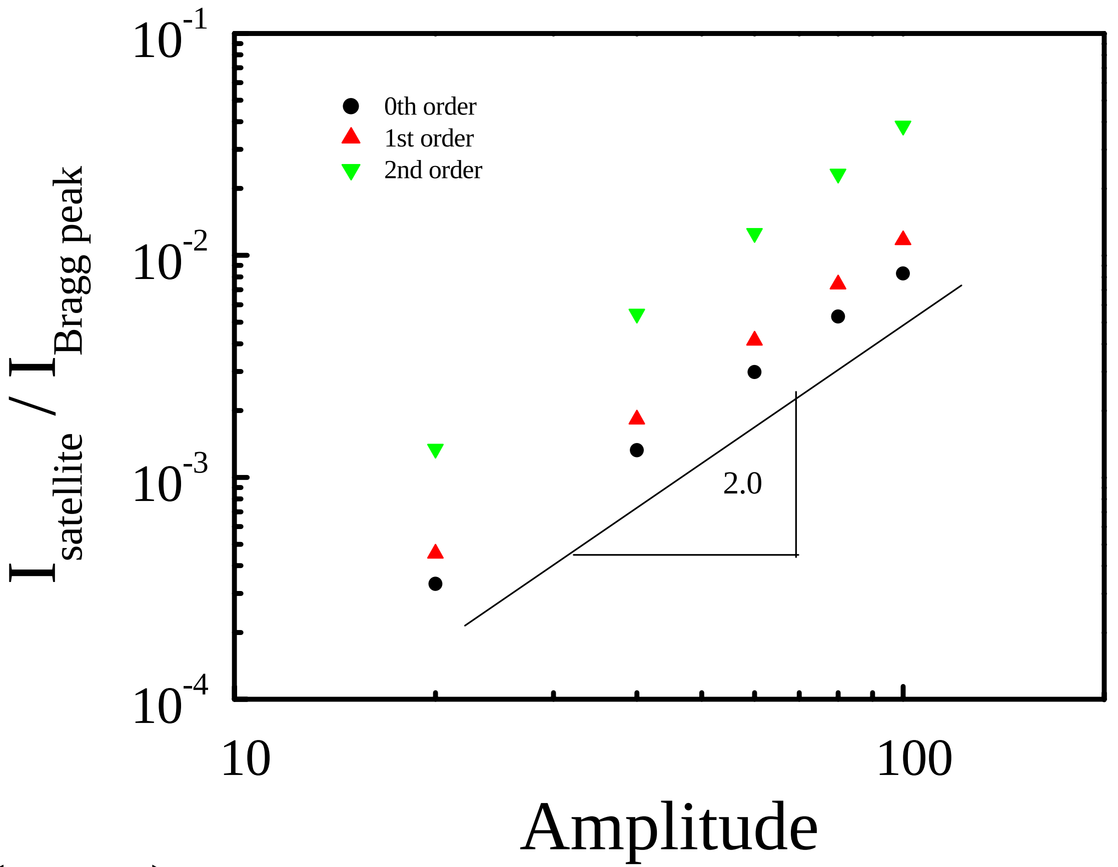
CD-SAXS: a model LER – single sine wave





SAXS characterization technique

Dependence of satellite peak intensity



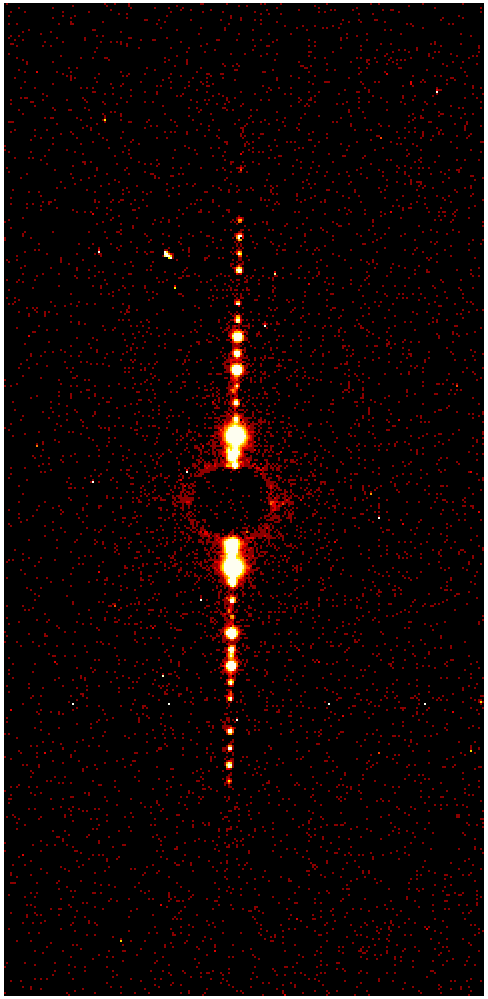
$$I = \left[\frac{Sin\left(\frac{(2N+1)q_x \bar{D}}{2}\right)}{Sin\left(\frac{q_x \bar{D}}{2}\right)}\right]^2 \left[\frac{2Sin\left(\frac{q_x \bar{W}}{2}\right)}{q_x}\right]^2 \left[\delta(q_y) + (A^2 + 4q_x \Delta D^2)(\delta(q_y - \nu) + \delta(q_y - \nu))\right]$$

Line roughness of copper interconnect

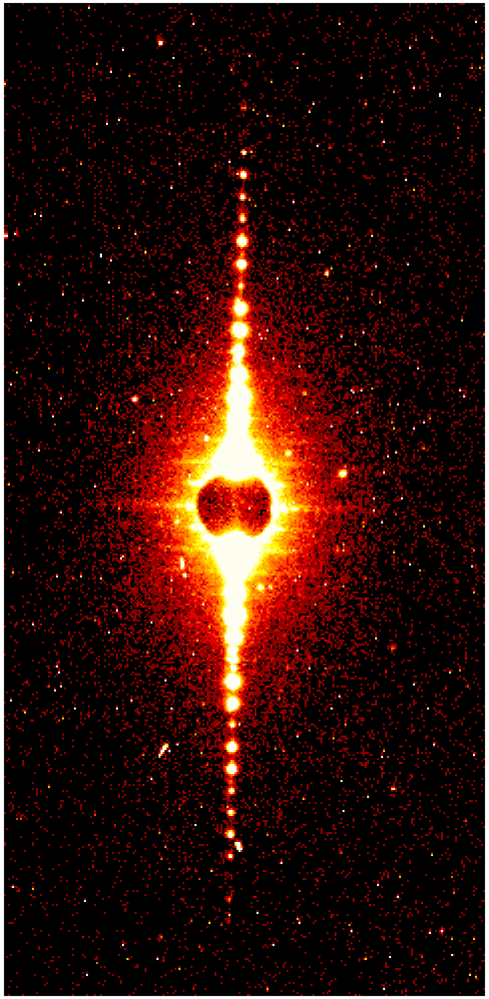
ULSI, Richardson, TX
March 18, 2005

Probing Cu Interconnects

160 nm 1:1



120 nm 1:1



Sample: Cu filled Silicon Oxide lines

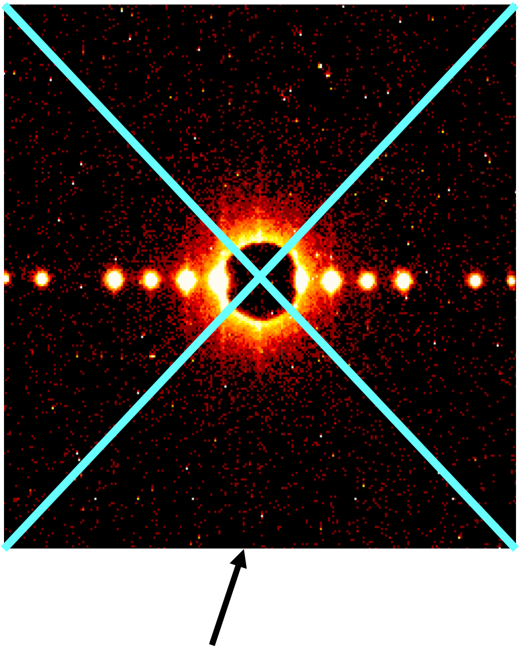
Effects demonstrated previously are magnified

→ Higher density of defects ??

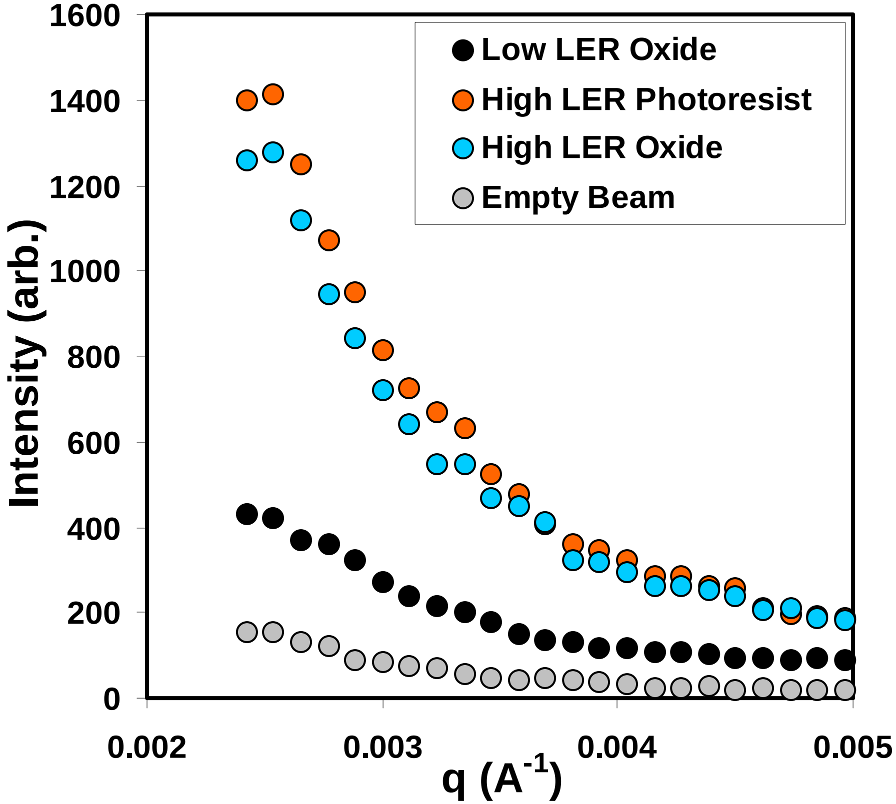
→ Higher x-ray contrast

ULSI, Richardson, TX
March 18, 2005

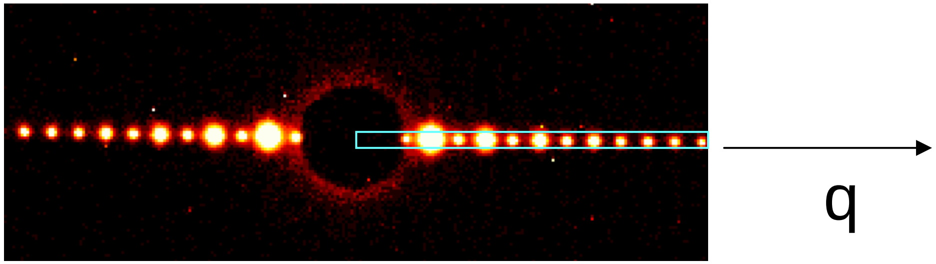
Measuring pattern quality: the diffuse "halo"

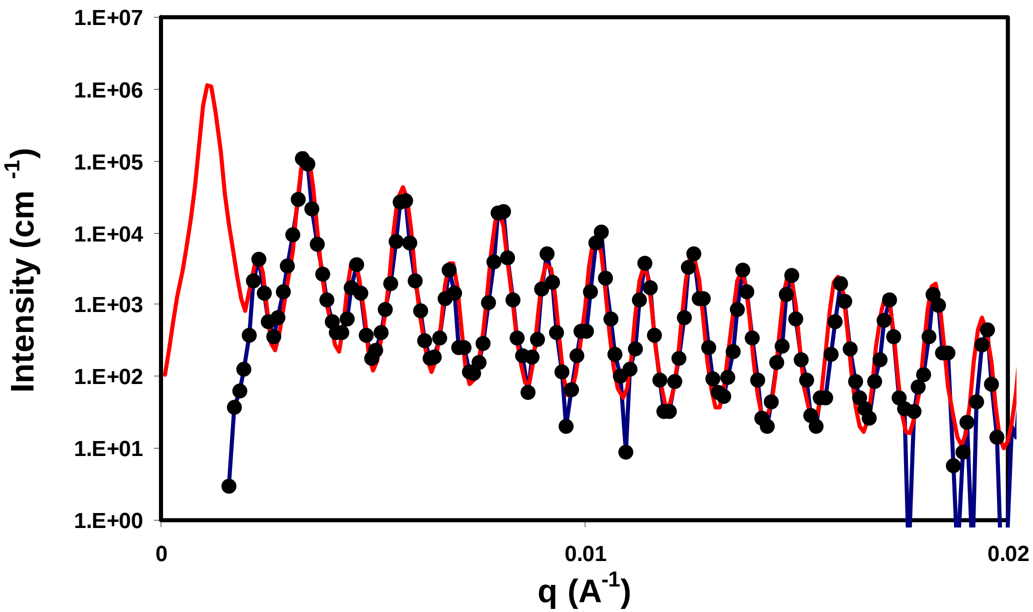


Intensity integrated +/- 45 deg normal to diffraction axis



CD-SAXS: Measuring CD and Pitch





Basic Model:

- Simple Rectangular Profile
- Pitch determined from period of diffraction peaks
- Line width determined from relative intensities
- **Decay of intensities fit with Debye-Waller factor**
- Peak profiles fit with Voigt function

Data fitting performed rapidly due to simplicity of modeling and data analysis procedures (I.e. no libraries of solutions required)

Observable defects in SAXS patterns

Fourier space

- Strikes along q_y direction
- Amorphous halo
- Debye-Waller factor

→ ←

Real space

- Side wall & top surface roughness
- Mass fluctuations along each line
- Position fluctuation of the center of each lines

Conclusions

- Methodology for pitch, line width, side wall angle is in place, detail cross sectional modeling is within reach
- Methodology for line surface roughness, linear mass fluctuation and center position fluctuation is in research stage

Conclusions (cont.)

- The wavelength of the probing x-ray beam can be calibrated with great precision; there is no need to calibrate the resulting dimensions from x-ray measurements

- A potential laboratory based metrology complementary to SEM, AFM and optical scattometry

Acknowledgements

• *X-ray measurements were conducted at Advanced Photon Source of Argonne National Laboratory*

• *Test samples obtained from Intel, IBM, ISMT & Shipley (now Rohm Haas)*