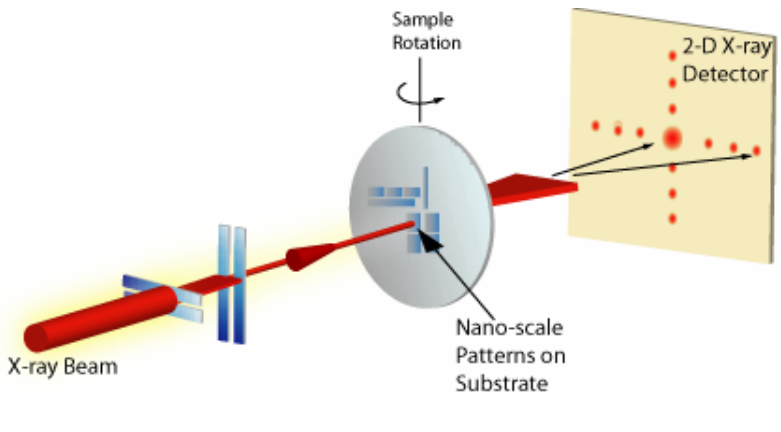
# Line Edge Roughness and Cross Sectional Characterization of Sub-50 nm Structures using CD-SAXS

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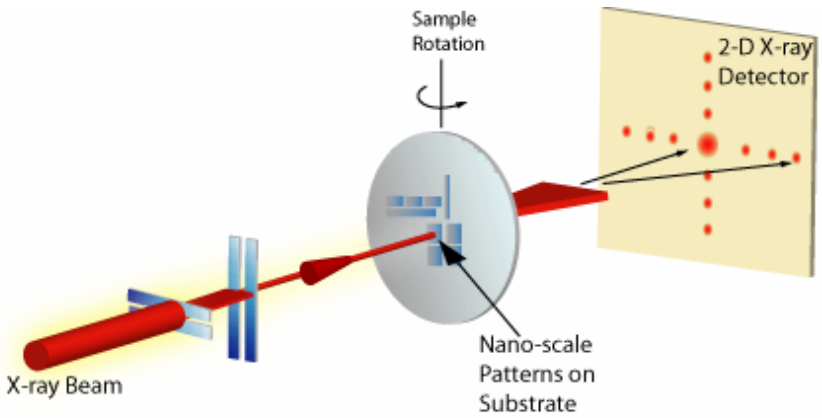
*Intel assignee to NIST*

**Bryan J. Rice, Michael J. Leeson**
*Intel*

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




**Transmission SAXS**

- Silicon transparent for E > 13 keV
- Non-destructive / No sample prep

**Use scatterometry targets**

- Beam spot size (40x40) μm

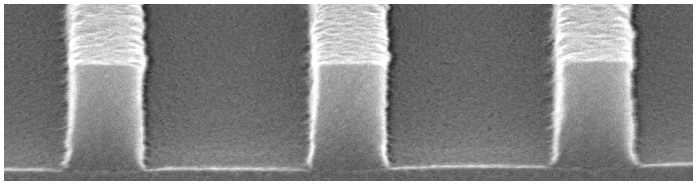
**Measure "2-D" and Buried patterns**

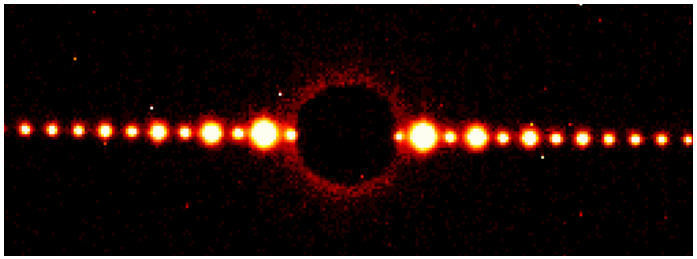
- Contact holes
- Multilevel interconnects

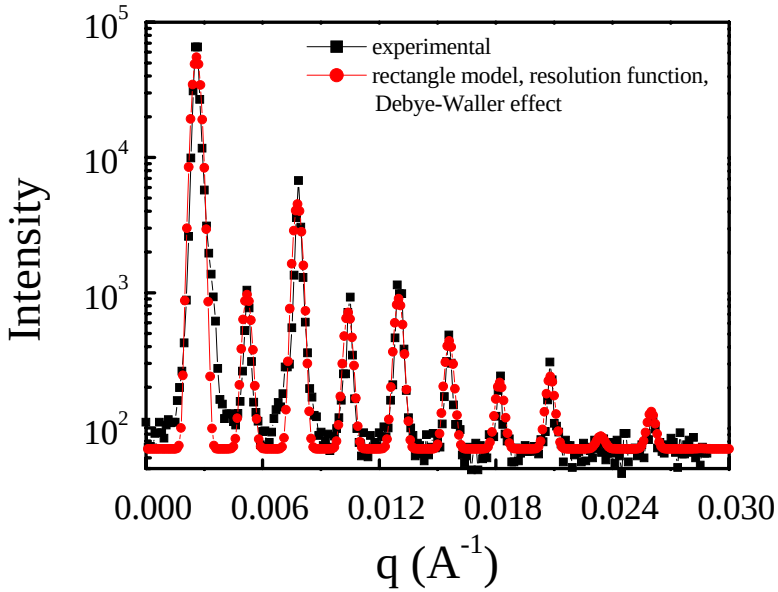
**High Precision for sub-45 nm**

- Sub-nm precision in pitch and linewidth
- Pattern Cross Section
- Technique easier with smaller structures

# Quantities Readily Available from CD-SAXS








**Pitch:**

5 to 800 nm Pitch
Sub-nm resolution

**Line Width:**

2 to 400 nm line width
Sub-nm resolution

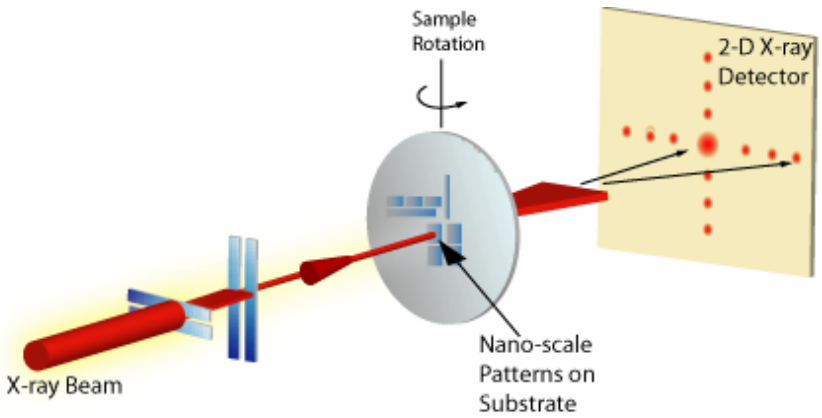
**Line Height:**

30 to 500 nm line height
10 nm resolution

**Sidewall Angle:**

0 to 45 deg
Sub-deg resolution

# LER measurement with CD-SAXS




**Potential for LER related quantities:**

- Distribution in Periodicity
- Frequency spectrum of sidewall roughness
- Periodic errors (stitching and standing wave)
- Distribution in cross sectional shape

**CD-SAXS and CD-SEM, CD-AFM:**

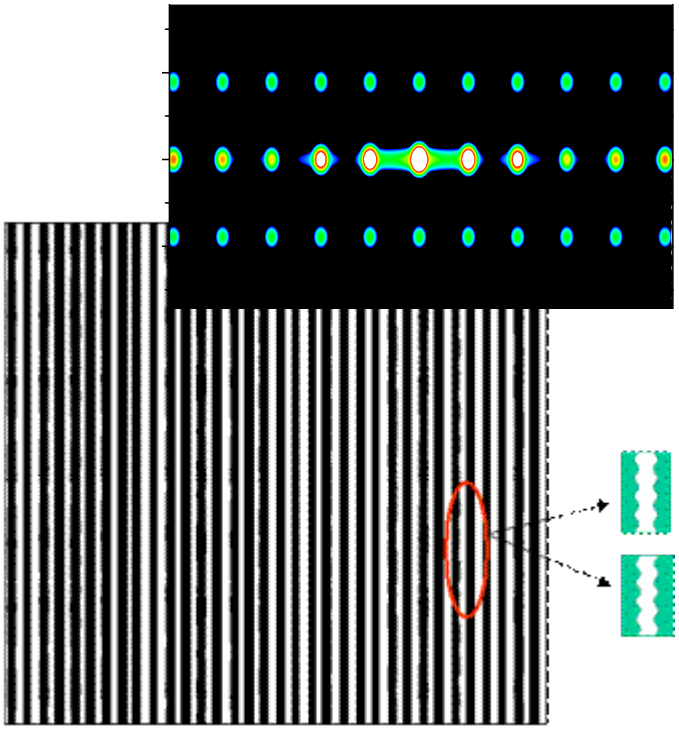
- Average vs. Single line
- Deconvolution of LER, LWR, and possible other classes of variation.
- 3-D Average vs. top-down image

**CD-SAXS and OCD:**

- Measure same targets
- Help develop OCD in current nodes
- Potential workhorse for sub-45 nm

# LER measurement with CD-SAXS

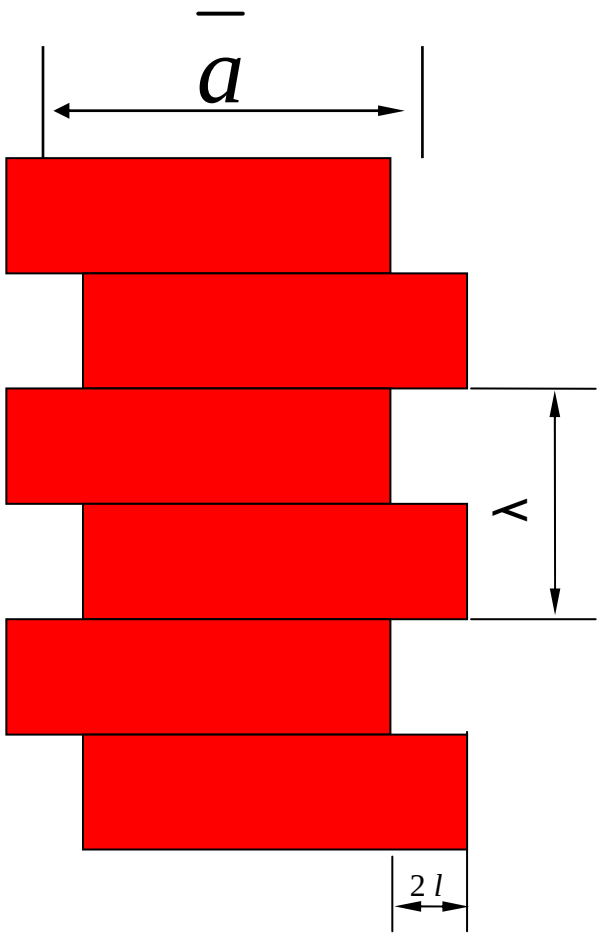
Simulated CD-SAXS pattern



**Signatures of LER**

- Diffraction parallel to line edge
  *Accessible frequencies are on the order of the inverse linewidth*
- Decay of intensity along main diffraction axis may provide integrated RMS over large range in frequencies.
- Other measures possible with more refined models.

# LER (Constant Line Width):




**Analytical Equations:**

$$I_0 = \frac{1}{8}\left(\frac{\lambda \sin(q_x \bar{a}/2)}{q_x}\right)^2 (1+\cos 2q_x l)\sum \delta(q_x - \frac{u}{L}2\pi)$$

$$I_1 = \frac{1}{2}\left(\frac{\lambda \sin(q_x \bar{a}/2)}{q_x \pi}\right)^2 (1-\cos 2q_x l)\sum \delta(q_x - \frac{u}{L}2\pi)$$

**Ratios provide insight into data:**

$$\frac{I_1}{I_0} \sim \tan^2 q_x l$$

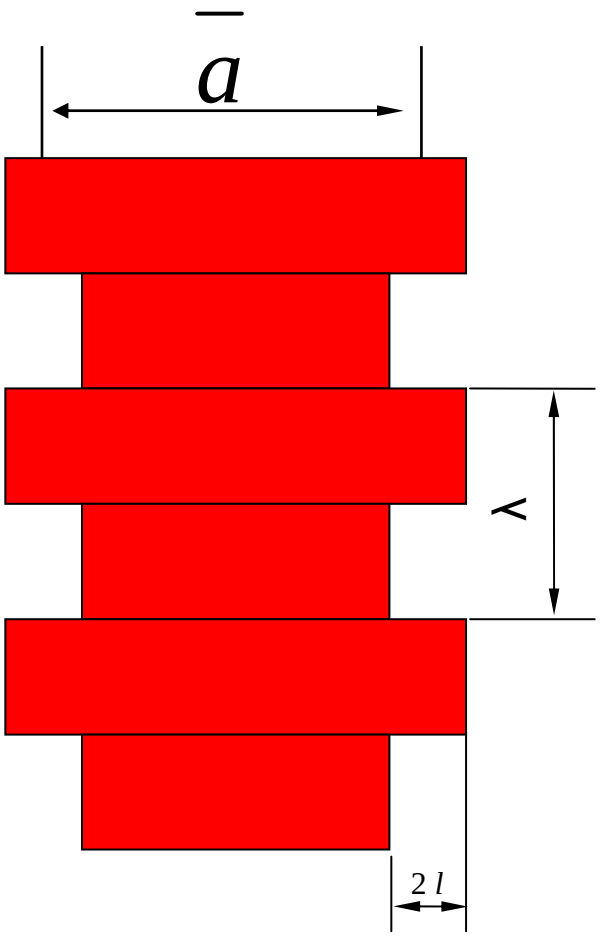
In-phase when $q_x l \leq \pi/2$

$$\frac{I_0}{I_{0,ideal}} \sim 1+\cos 2q_x l \sim 1 - q_x^2 l^2 + o(q_x^2 l^2)$$

Apparent Debye-Waller factor

For all simulations, we set a = 120 nm, L = 450 nm, λ = 200 nm

# LER (Constant Centerline):




**Analytical Equations:**

$$I_0 = \frac{1}{4}\left(\frac{\lambda}{q_x}\right)^2 \sin^2 q_x \frac{\bar{a}}{2} \cos^2 q_x l \sum \delta(q_x - \frac{u}{L} 2\pi)$$

$$I_1 = \left(\frac{\lambda}{q_x \pi}\right)^2 \cos^2 q_x \frac{\bar{a}}{2} \sin^2 q_x l \sum \delta(q_x - \frac{u}{L} 2\pi)$$

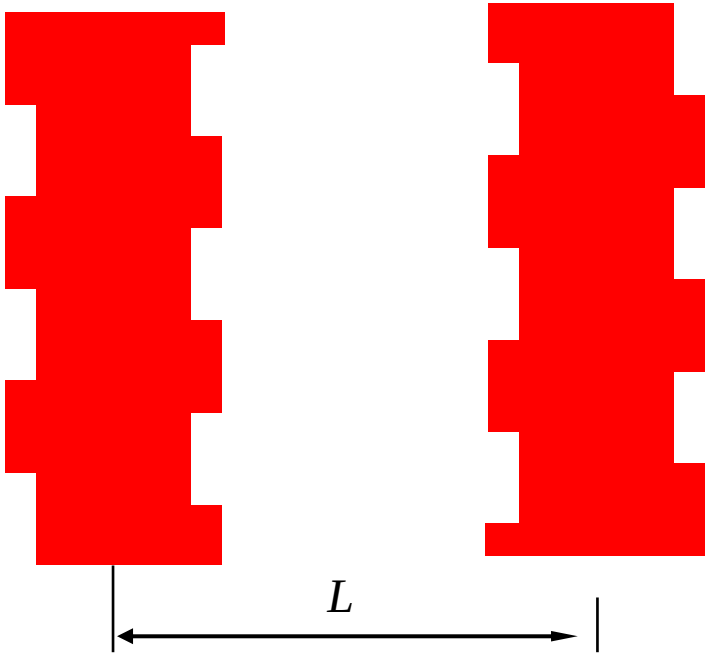
**Ratios provide insight into data:**

$$\frac{I_1}{I_0} \sim \cot^2\left(q_x \frac{\bar{a}}{2}\right) \tan^2 q_x l$$

$$\frac{I_0}{I_{0,ideal}} \sim \cos^2 q_x l \sim 1 - q_x^2 l^2 + o(q_x^2 l^2)$$

Apparent Debye-Waller factor

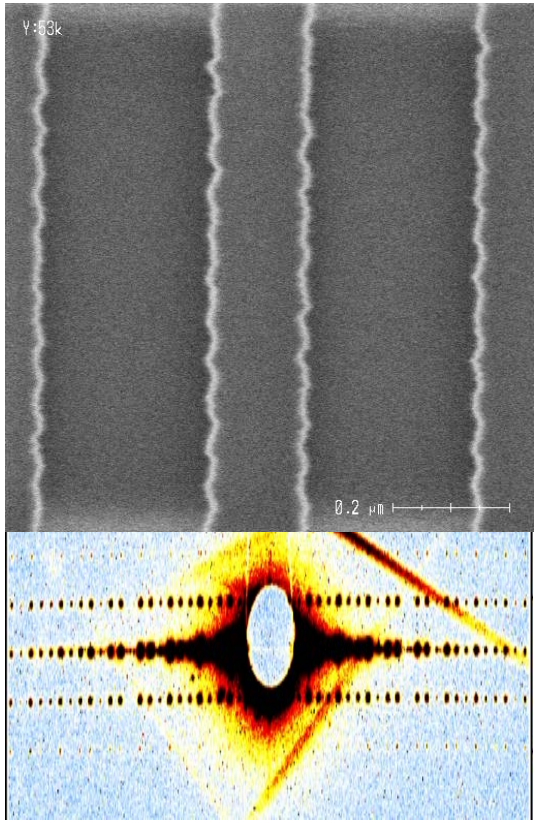
# LER ("Random Roughness"):



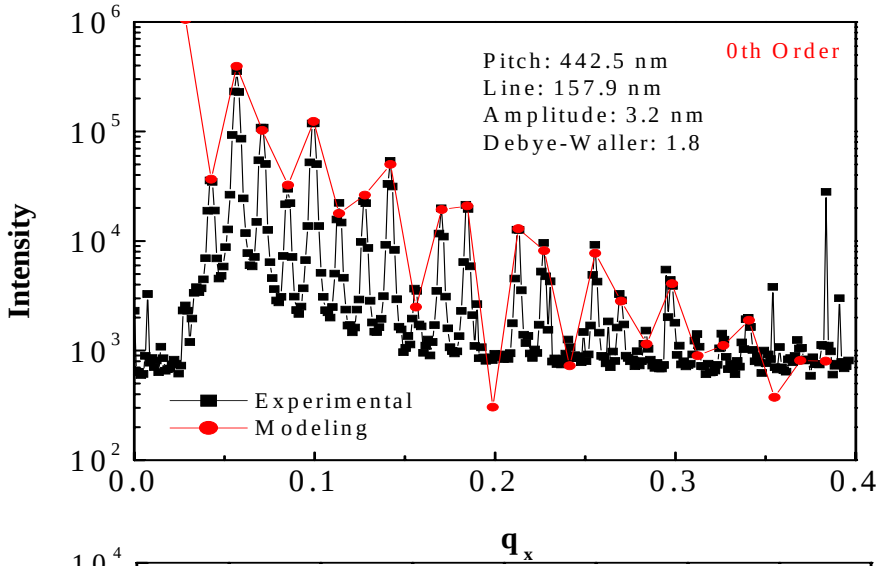

$$I_0 = 2\left(\frac{\lambda \sin q_x a}{q_x}\right)^2 (1+\cos 2q_x l) * \sum \delta(q_x - \frac{u}{L} 2\pi)$$

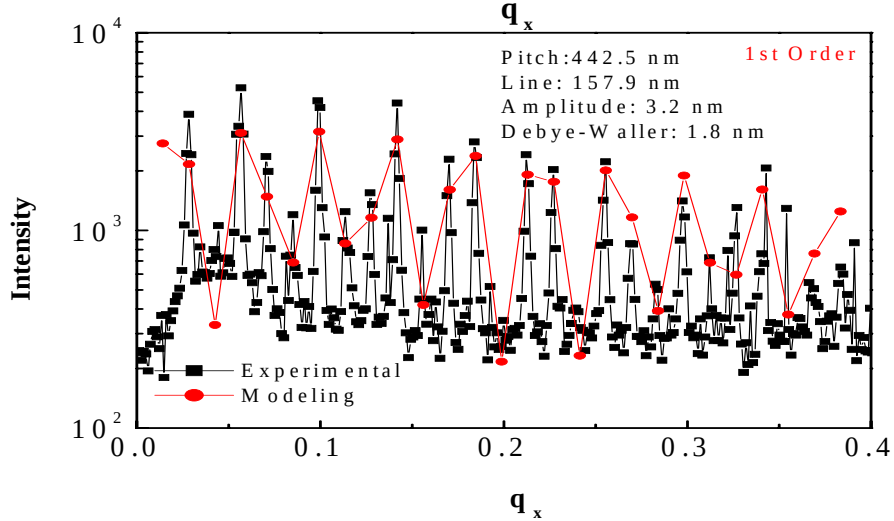
$$I_1 = 8\left(\frac{\lambda \sin q_x a}{q_x \pi}\right)^2 (1-\cos 2q_x l) * \left(\frac{\sin(q_y \lambda / 2)}{q_y \lambda} * \sum \delta(q_x - \frac{u}{L} 2\pi)\right)$$

# LER (Constant Line Width):

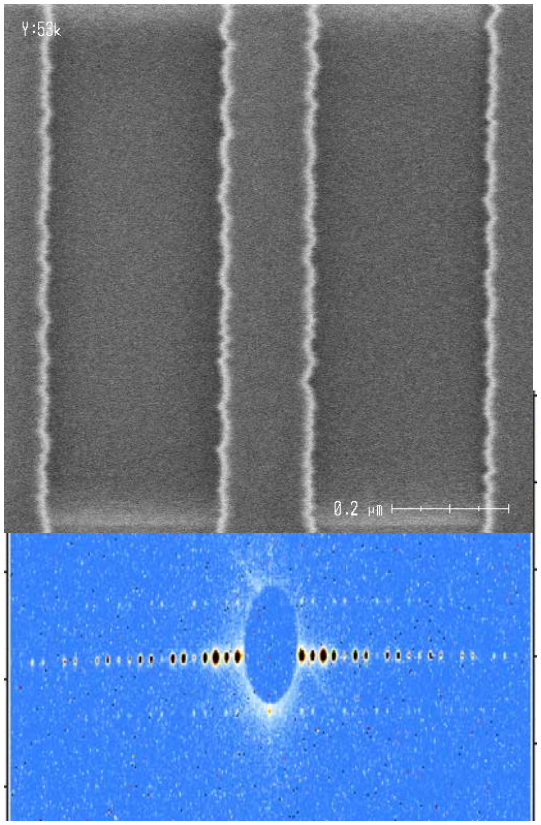


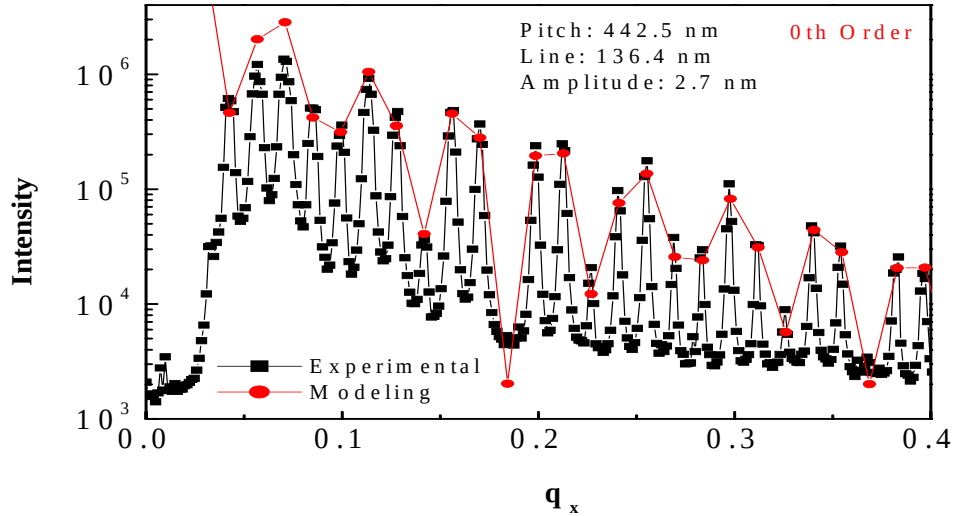

**Satellite peaks mirror main diffraction axis**

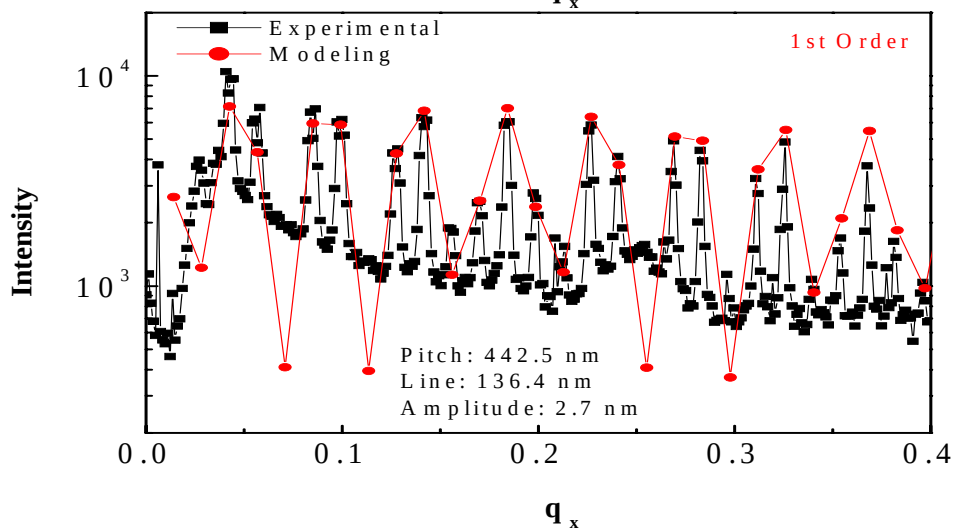


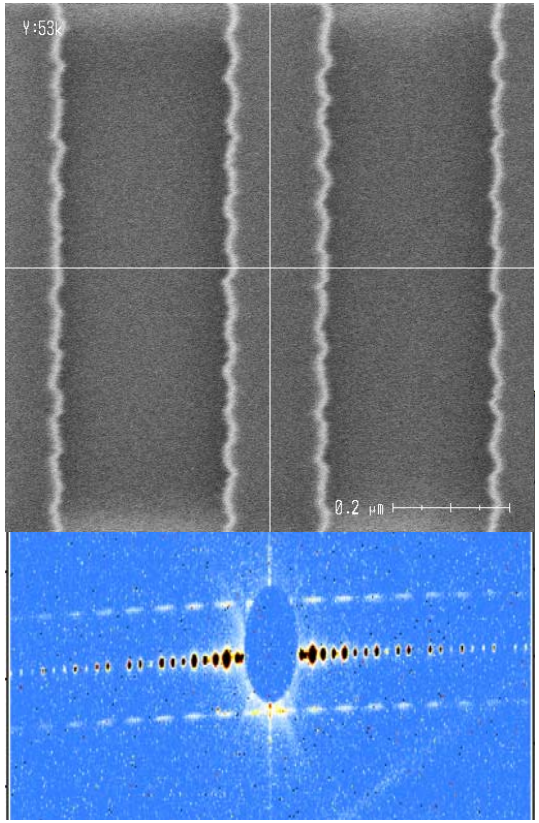
# LER (Constant Centerline):

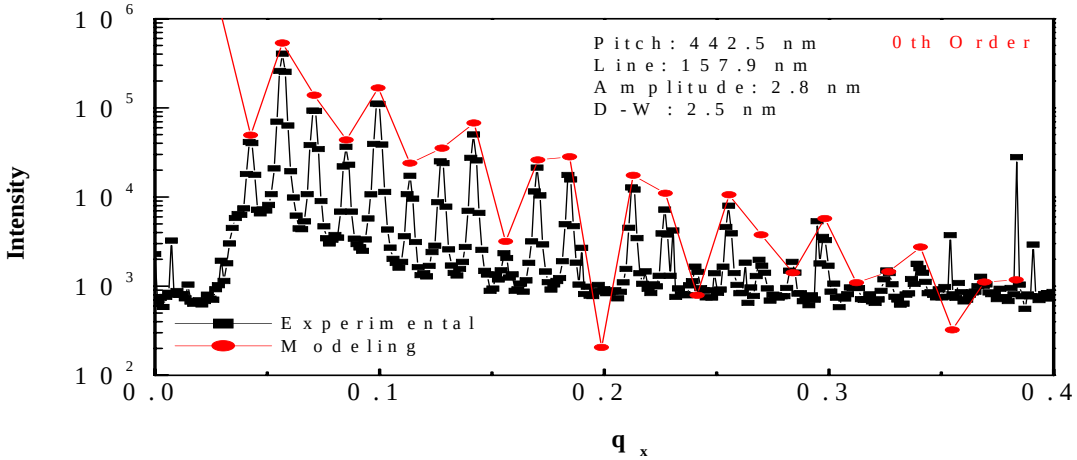


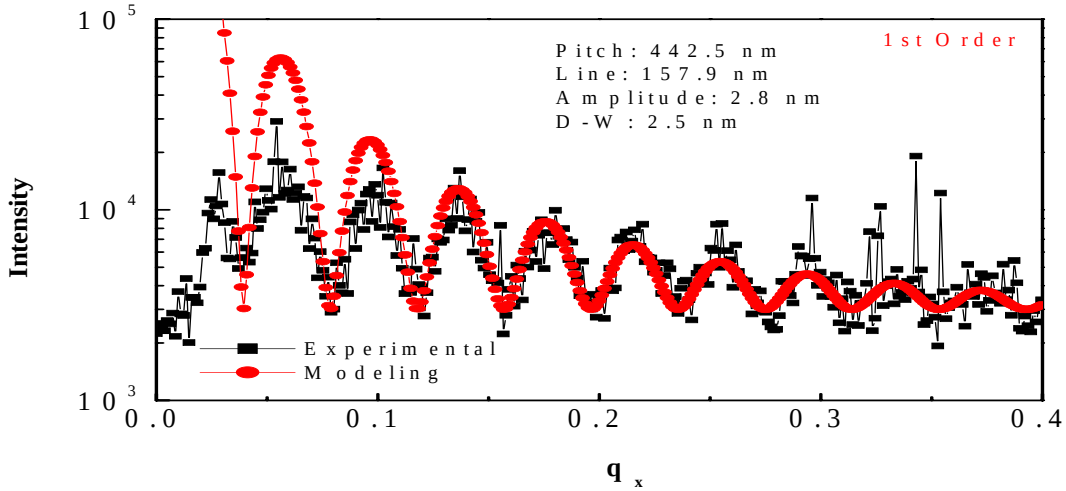



# LER (“Random Roughness”):



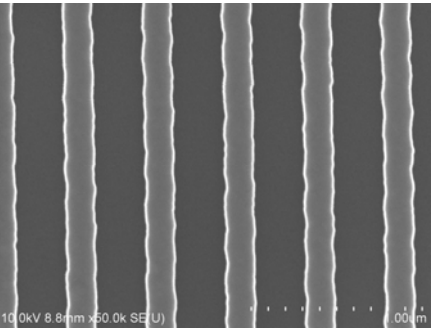
# AMAG LER Structures: CD-SEM vs CD-SAXS

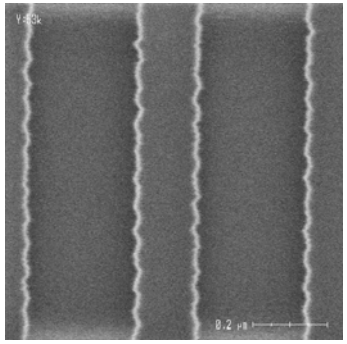
| | | SEM (line edge fitting model) | | | CD-SAXS |
|---|---|---|---|---|---|
| | | Sigmoid | Maxderiv | Regress | |
| **AMAG5LPoly-402** | Av R_q | 3.39 | 3.52 | 3.43 | 3.20 |
| **AMAG5LPoly-603** | Av R_q | 3.36 | 3.45 | 3.38 | 2.80 |

L150P450: Alternating Tabs on Left/Right

Amp 40nm/200nm

Standard SEM 402 Y 53K

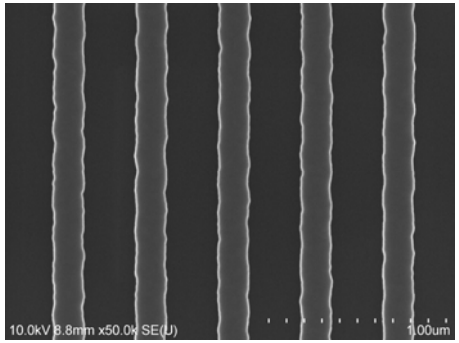


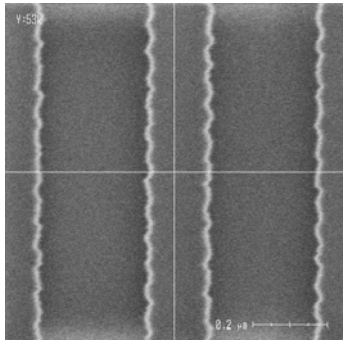



L150P450: Alternating Tabs on Left/Right, staggered

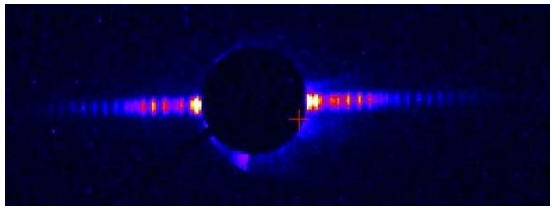
Amp 20nm/200nm

Standard SEM 603 Y 53K

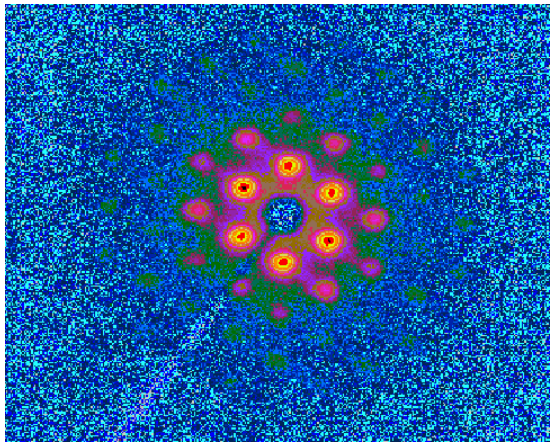


# Lab Scale CD-SAXS Prototype



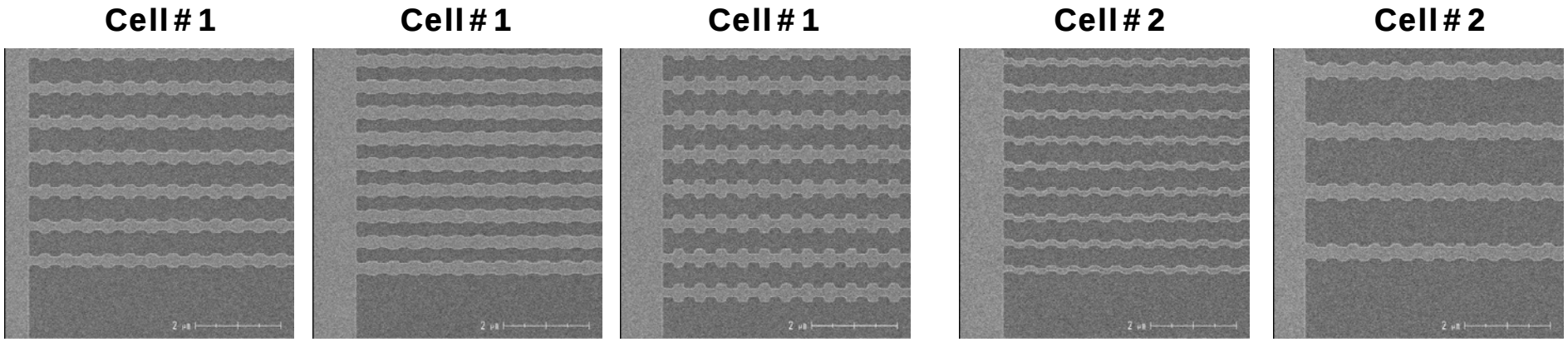
Intel test grating with 400nm pitch Cu seeded lines



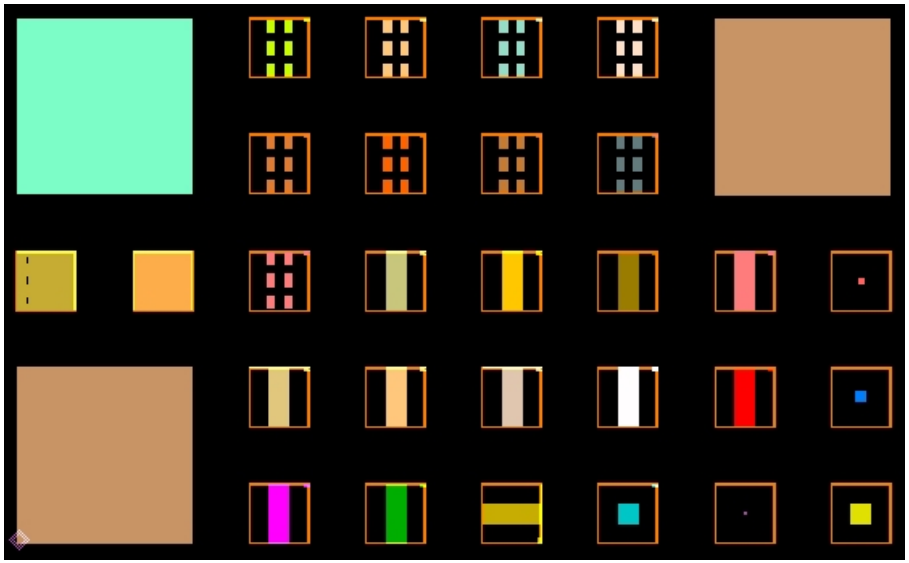
Nanoimprint array of 60 nm holes

- **Source flux 9 orders of magnitude below synchotron source (Argonne Natl Lab)**
- **Flux on sample ~4 to 5 orders of magnitude below Synchotron Source**

# Design of the EUV NIST-Intel LER structures Reticle




SEM of Reticle

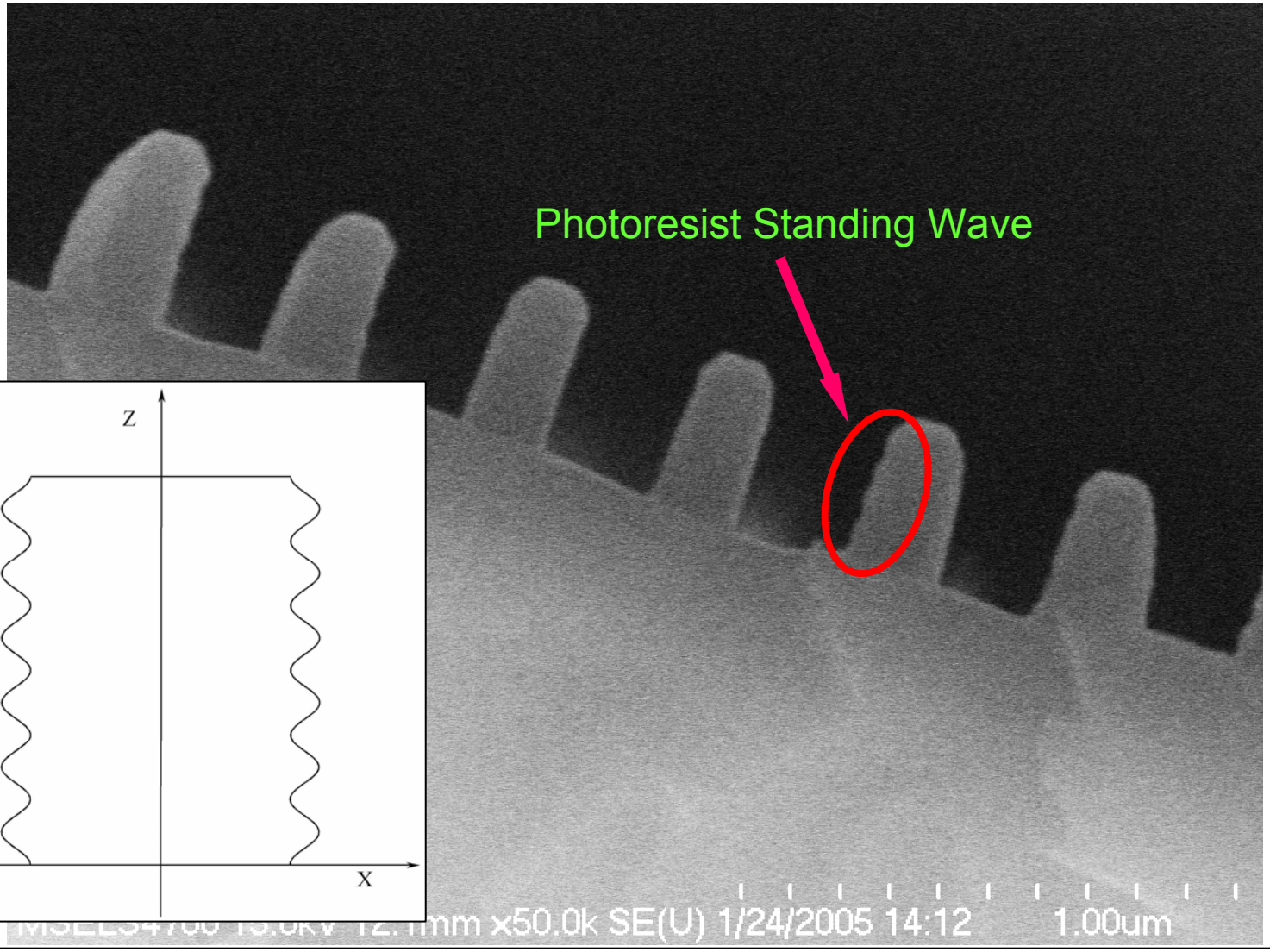


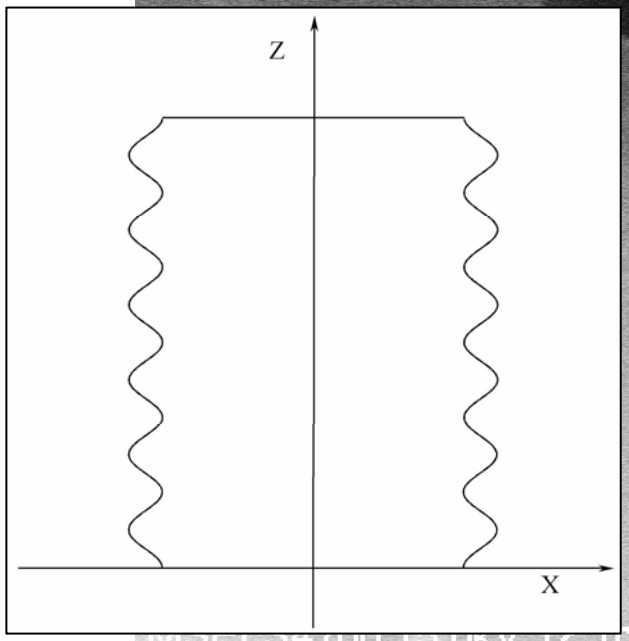
- **Controlled LER on the scale of EUV nodes**
- **Wider variation in controlled LER**
- **Mask based on experience with AMAG features**
- **Designed for measurements on NIST lab-scale prototype**

NIST

intel

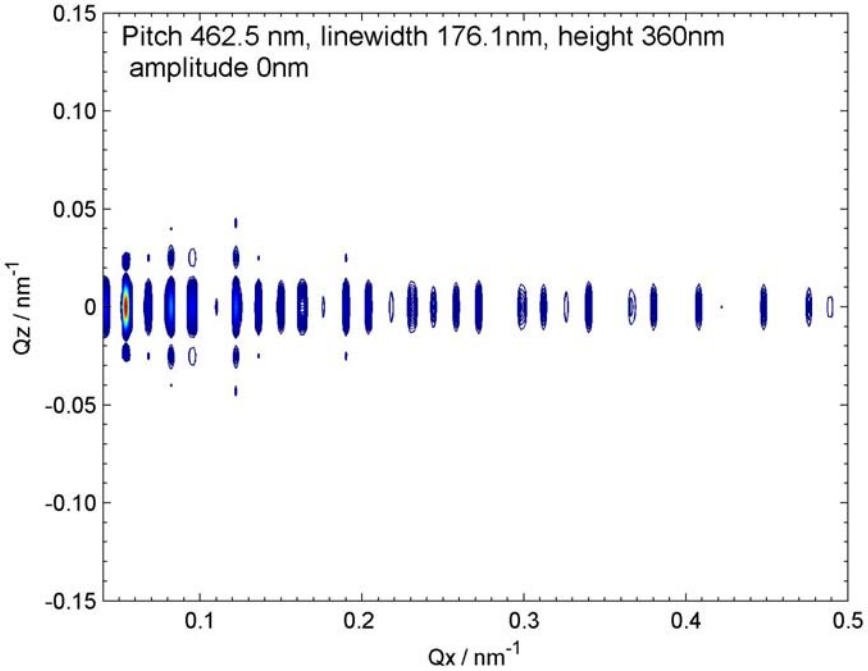
# Vertical Standing Wave Roughness



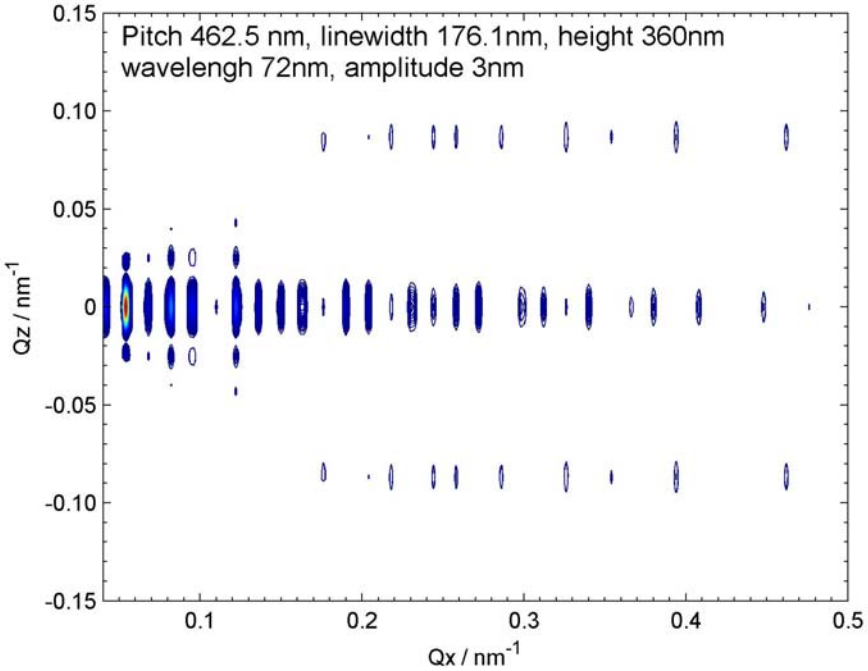



# Sensitivity of LER Measurement

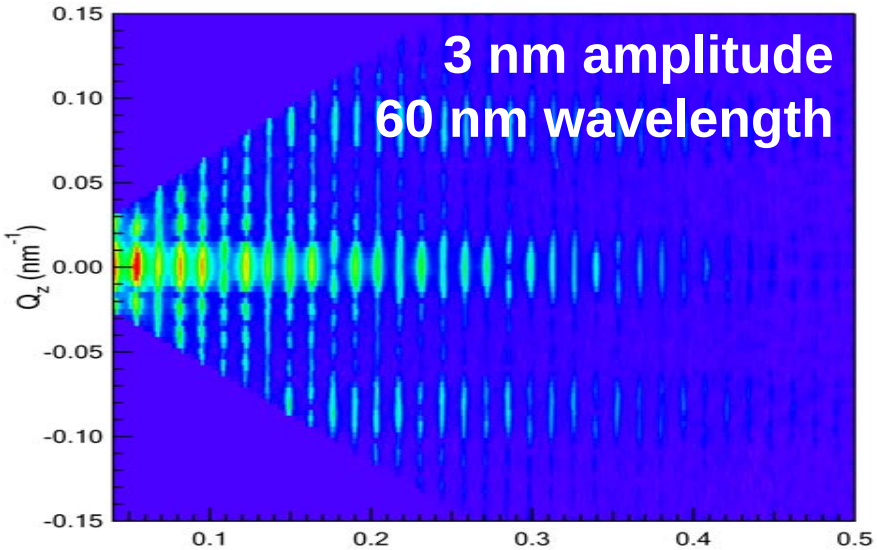
Amplitude = 0 nm

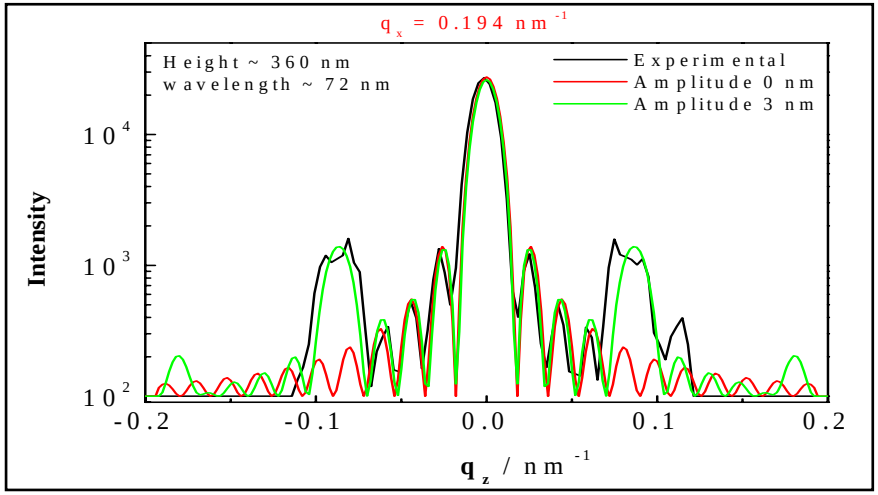



Amplitude = 3 nm



# Vertical Standing Waves: CDSAXS Data




- **Standing waves readily observed in CD-SAXS**
- **Non-destructive measurement (no cross-sectioning req'd)**
- **Small amplitude challenges SEM measurements**
- **Intensity grows as (LER Amplitude)^2**
- **Intensity relationship same in more conventional LER**

# Summary of CD-SAXS LER work to date

## Design of Controlled LER Structures

- Printed AMAG series has amplitudes significantly smaller than designed
- Small differences in the RMS amplitude from pattern to pattern which challenges model verification.
- EUV based reticle design and fabrication completed by Intel
- Preliminary CD-SEM data collection completed by Sematech (B. Bunday)

## Preliminary CD-SAXS results

- Qualitative differences observed between classes of LER.
- Intensity of satellite peaks should provide measure of RMS amplitude of periodic component.
- Model development in progress to make measurements quantitative.

# Ongoing work and future plan

## Planned Measurements

- **Direct comparison of CD-SAXS measurements, in both LER and cross sectional measurements, with CD-SEM and OCD (with Sematech)**
- **Evaluation of lab-based CD-SAXS capabilities using Intel-NIST EUV patterns.**

## Technique Development

- **Develop other measures of LER, including the total RMS value over all accessible frequencies.**
- **Development of new models for LER and quantitative analysis of CD-SAXS data.**

# Acknowledgements

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SEMATECH
Ben Bunday

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