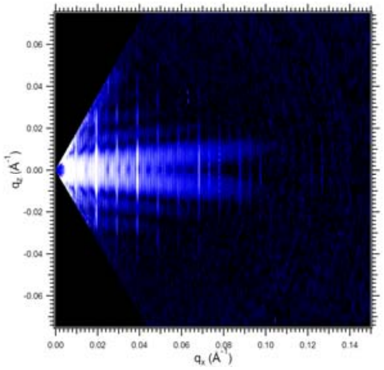

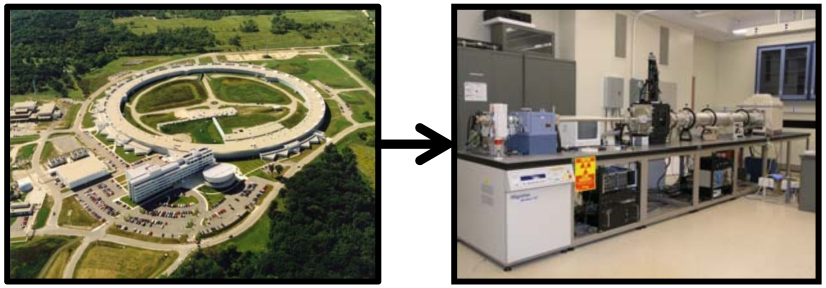

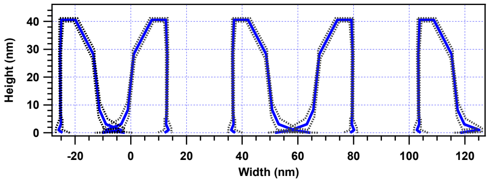

Current Status of CDSAXS: Is it Fab-Ready?

Daniel F. Sunday, Donald Windover,
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Technology Administration
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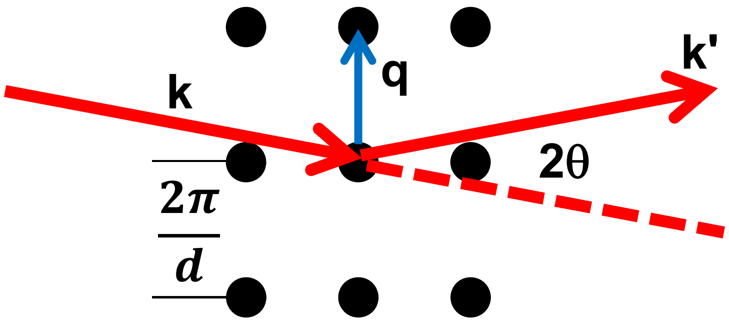
***NIST National Research Council Postdoctoral Fellowship**
2 year, $66k/year stipend to work at NIST, requires US citizenship
Other potential opportunities for foreign postdocs
Contact me at Joe.Kline@nist.gov for more info

X-ray Diffraction

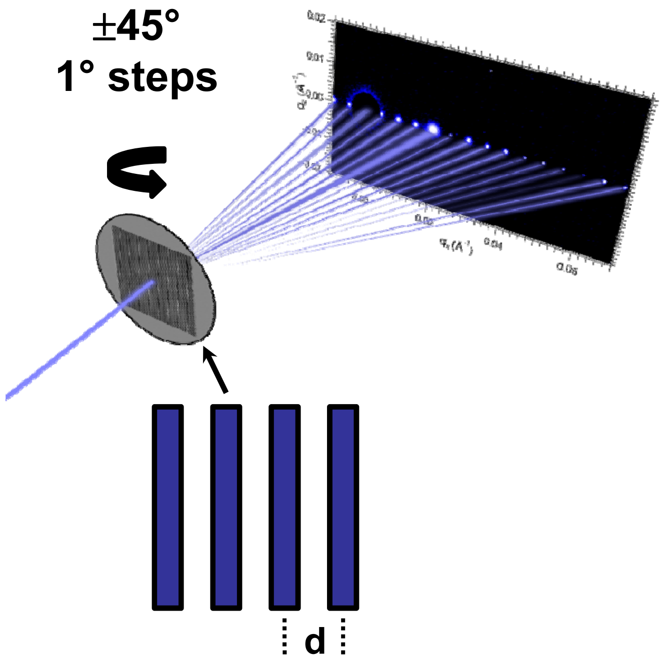
Reciprocal Lattice



$n\lambda = 2d\ \sin\theta$ (Bragg's Law)

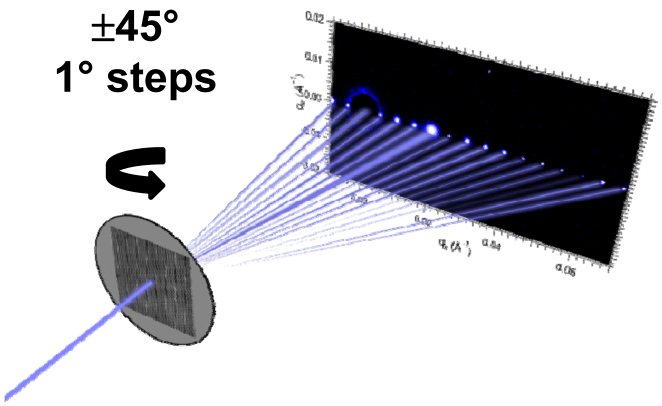
$$\boldsymbol{k} - \boldsymbol{k}' = \boldsymbol{q}, where\ |\boldsymbol{k}| = \frac{2\pi}{\lambda}$$

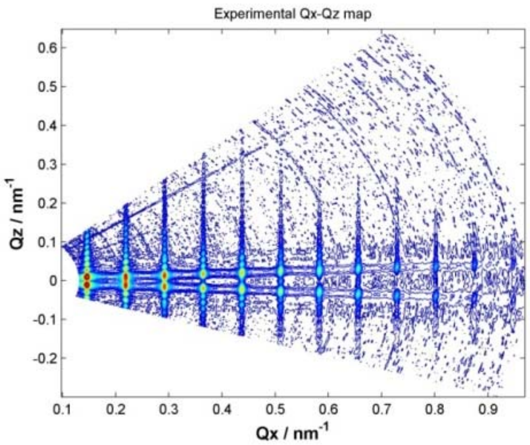
Small Angle X-ray Scattering

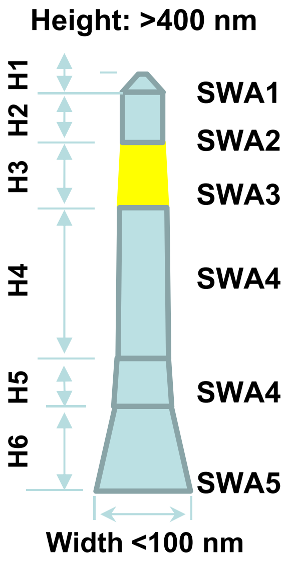


- X-ray diffraction allows the measurement of atomic scale spacings, periodicity, and orientation
- At small angles, the diffraction comes from a periodic nanopattern instead of atoms in a crystal

Critical-Dimension Small Angle X-ray Scattering







Variable-angle transmission SAXS:

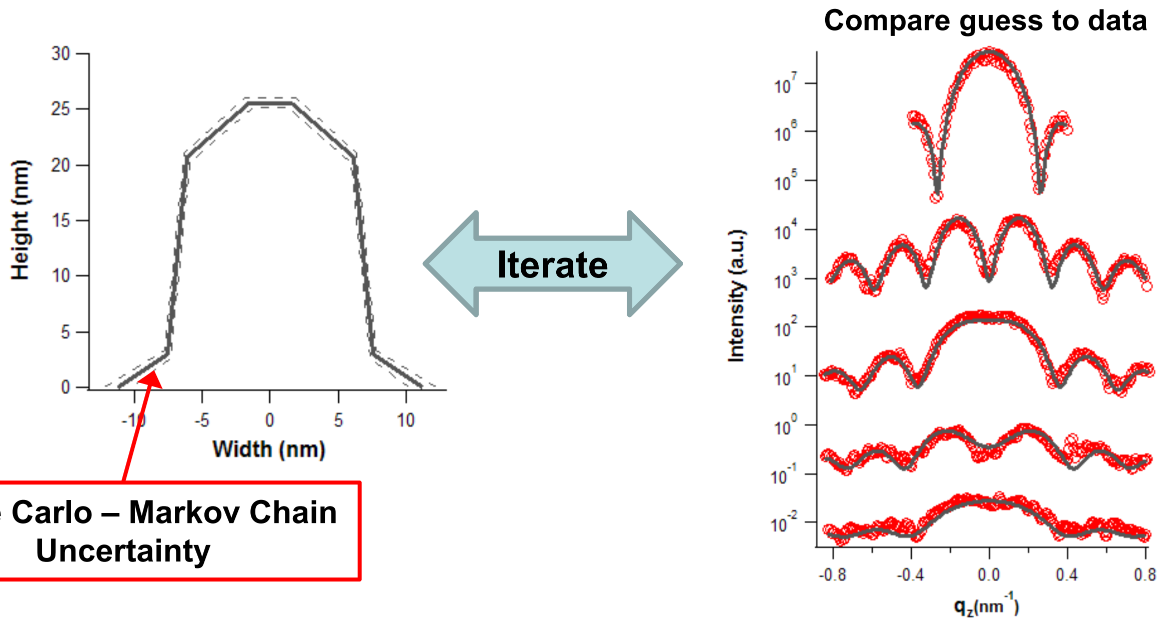
- “Single” crystal diffraction with nanopattern as lattice, pattern shape as atom
- Hard X-rays (>15 keV) for transmission through wafer
- Small spot size (<100 µm)
- Measure 1D, 2D, or 3D periodic nanopatterns
- Result is the average shape of the repeated nanostructure

CDSAXS Data Modeling

$$F(\boldsymbol{Q}) = \int_V e^{-i\boldsymbol{Q}\boldsymbol{v}} dV$$

$$I(\boldsymbol{Q}) = |F(\boldsymbol{Q})|^2 e^{-\boldsymbol{Q}^2 DW^2}$$

Inverse Fitting

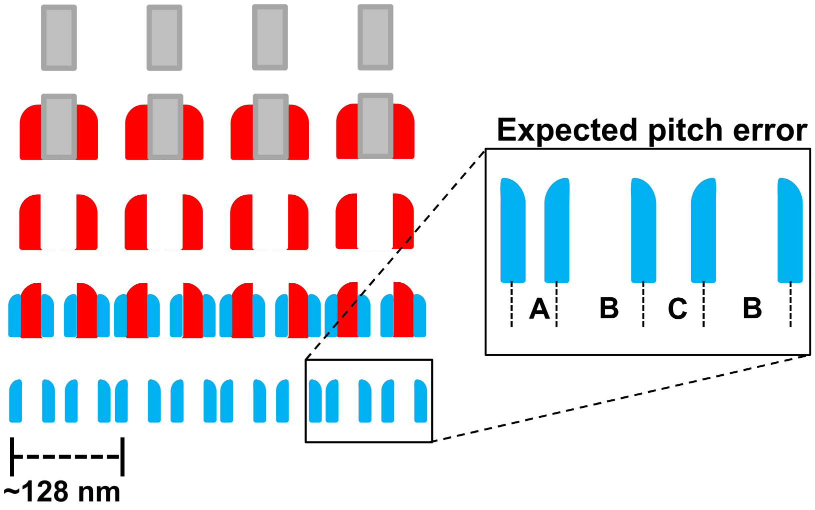


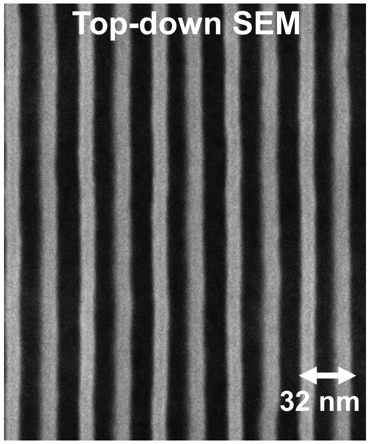
Monte Carlo – Markov Chain Uncertainty

- Diffraction pattern is Fourier transform of electron density distribution
- Partially coherent scattering cannot be directly converted to image
- Use inverse, iterative method to calculate simulated pattern from trial solution
- Use Monte Carlo – Markov Chain algorithm to sample parameter space for parameter sensitivity to data

Example Semiconductor Nanopattern

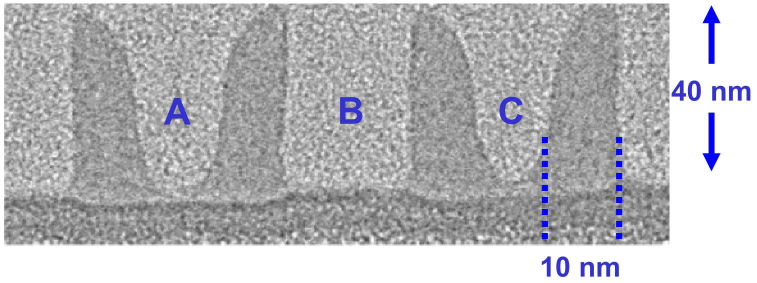
Spacer-Assisted Quadruple Patterning (SAQP)





From Andras Vladar

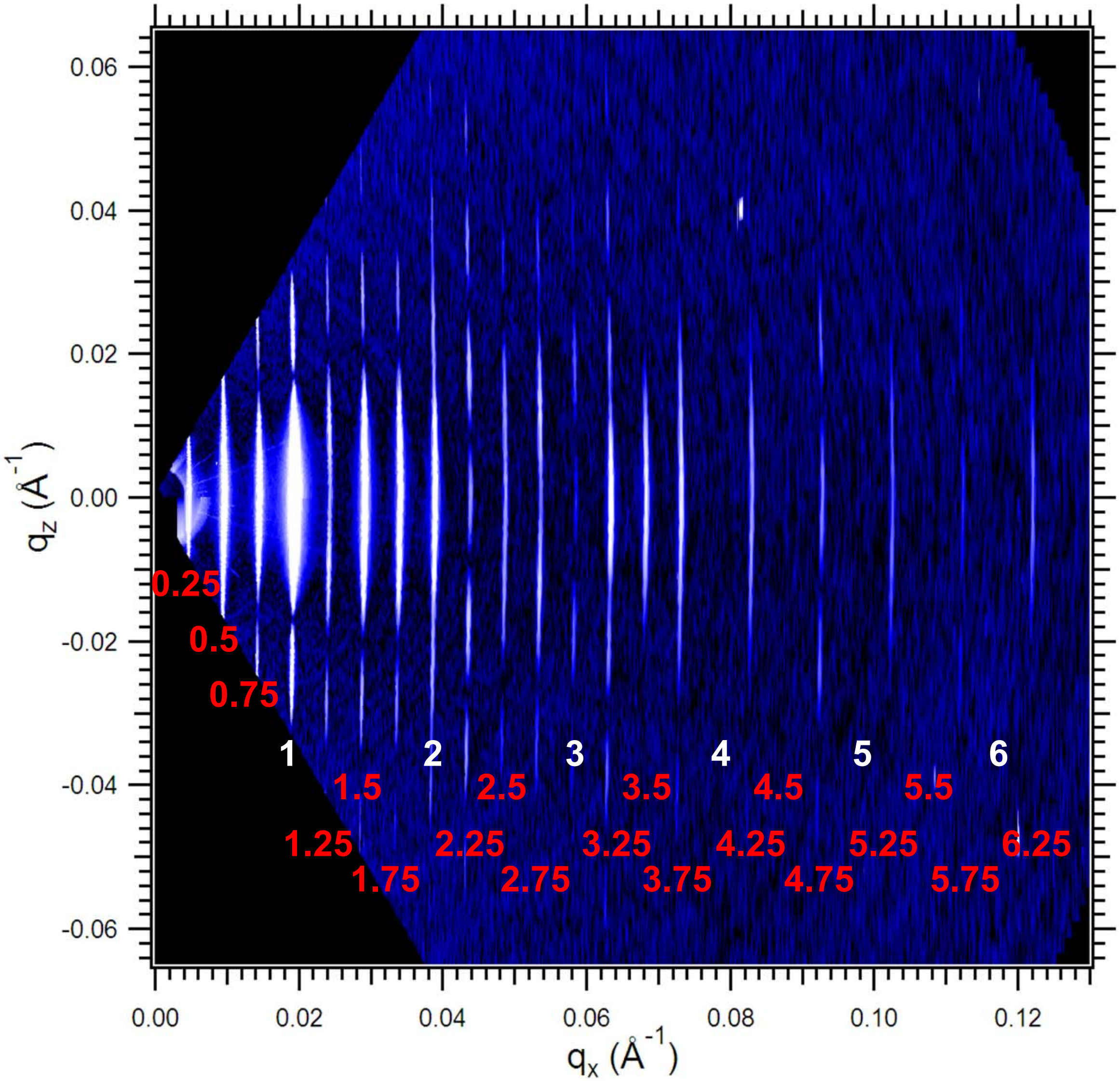
Cross-section TEM

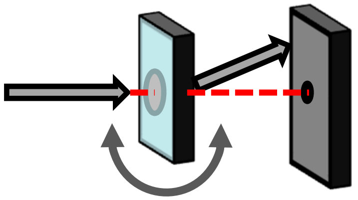


- Measurement goals
  - Average 2D shape, pitch error, and edge roughness
- Sample set with sub-nm controlled variation in pitch error and nominal 32 nm pitch

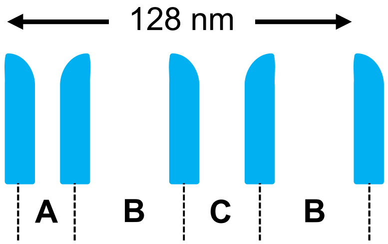
van Veenhuizen et al. Interconnect Technology Conference, 2012

CDSAXS on 32 nm Pitch Nanopattern

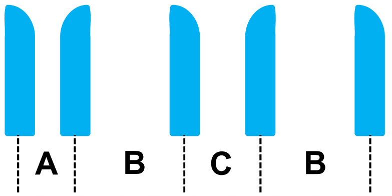


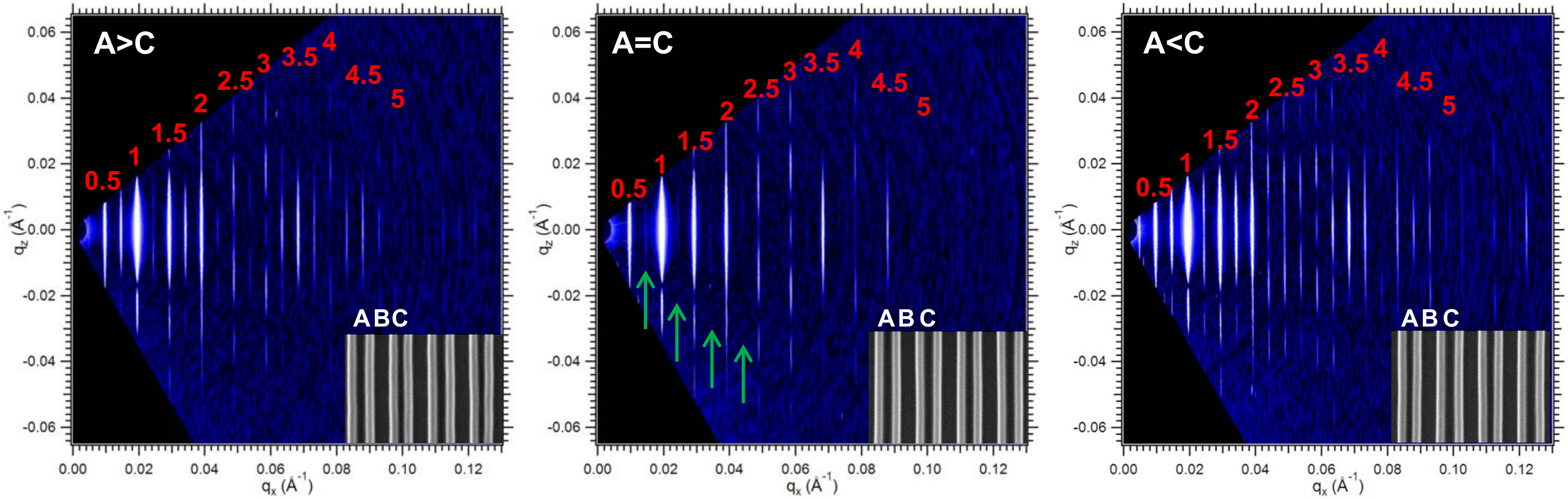


- Composite from 121 images
  - ±60° sample angle
  - 10 s/image = ~30 min/scan
  - Data highly oversampled
- 32 nm, 64 nm, and 128 nm pitches clearly visible
  - Non-integer peaks from pitch quartering error



CD-SAXS Measurements on Offset Bias Series

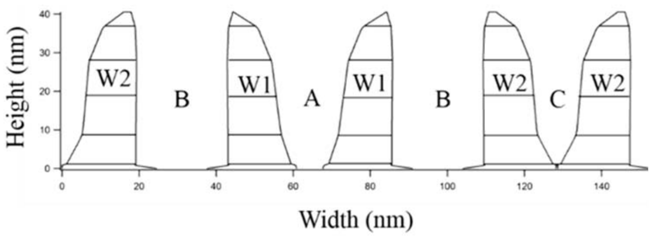


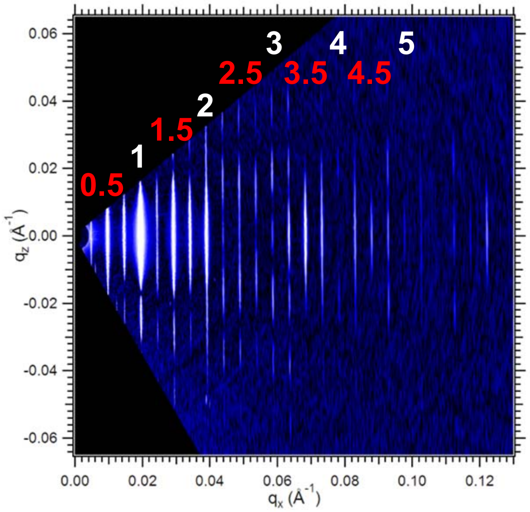


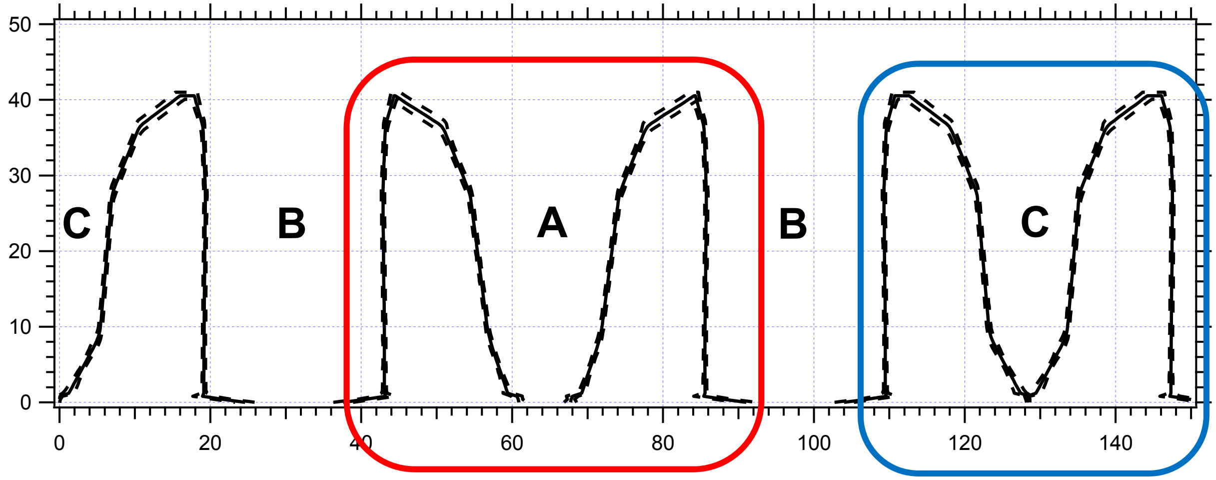
- Sample series has controlled sub-nm variations in A and C
- CD-SAXS measurement is highly sensitive to changes as patterns are visually different
- Sample A=C has weak x.25 and x.75 peaks, indicating 64 nm pitch
  - – A = C ≠ B

SEMs from Andras Vladar

Example CD-SAXS Fit on 32 nm Pitch Nanopattern

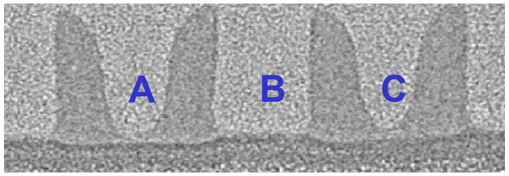




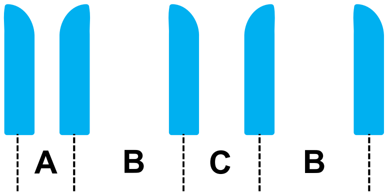


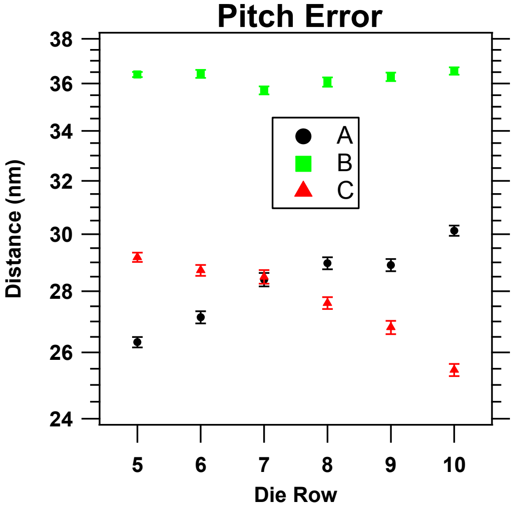
- Sample periodicity is 128 nm
- Uses 6-trapezoid stack with two mirrored line pairs
- Shape matches up to expected value
- Fit uncertainty very small

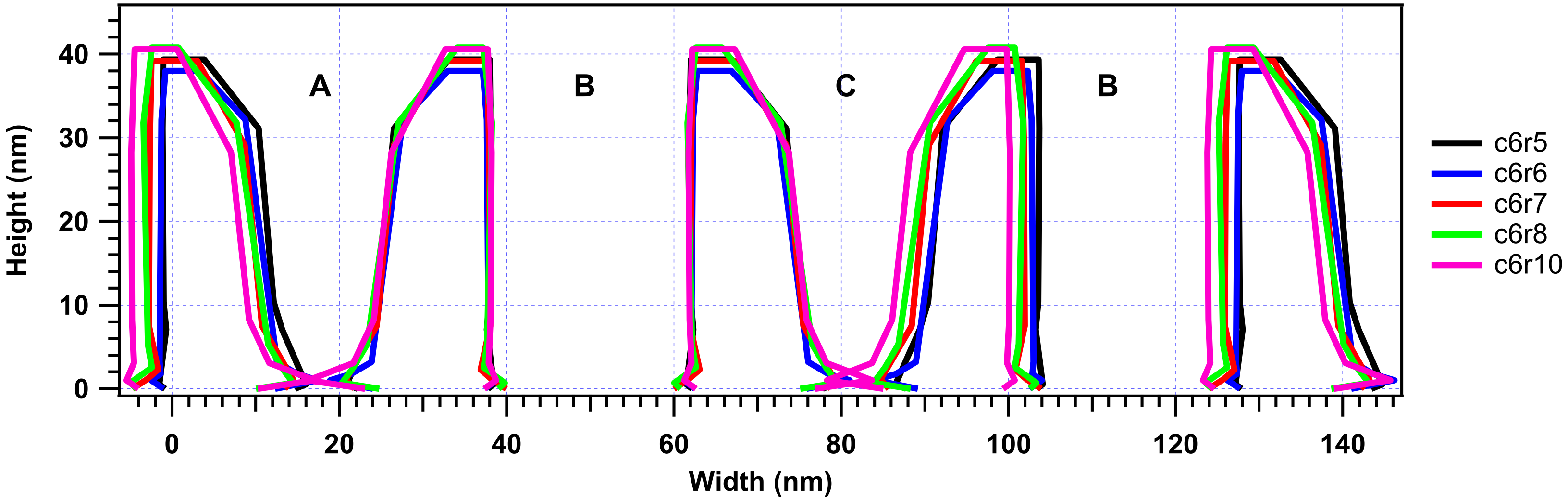
Cross-sectional TEM



CD-SAXS Measurement of Pitch Error

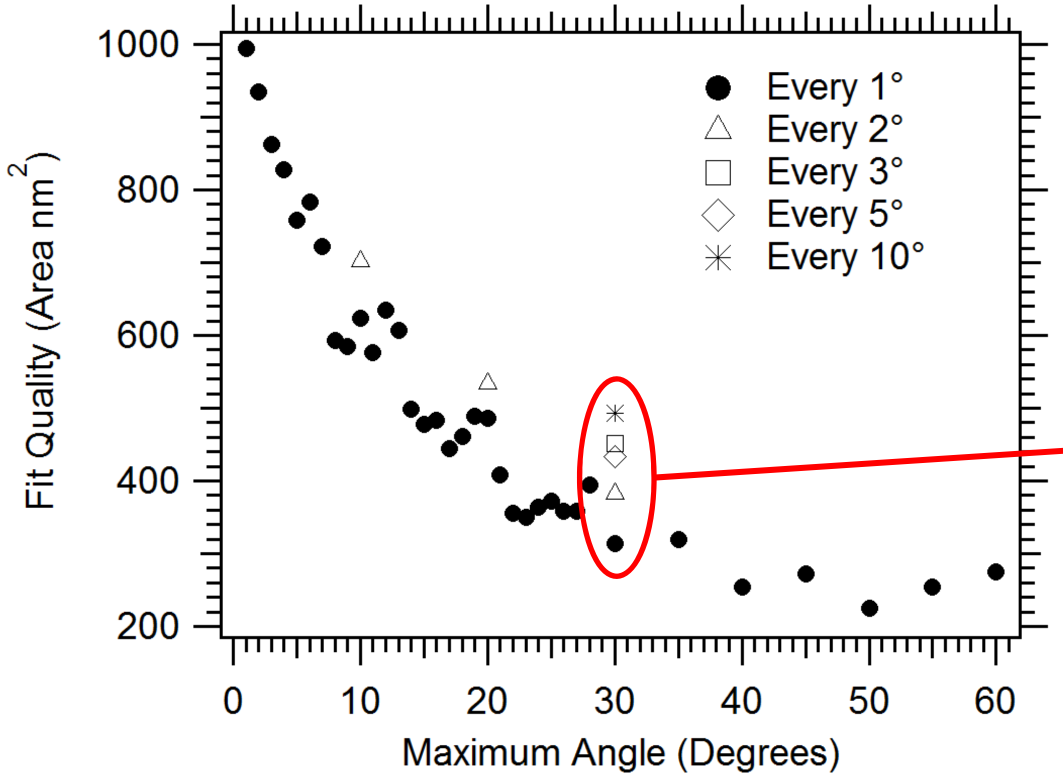




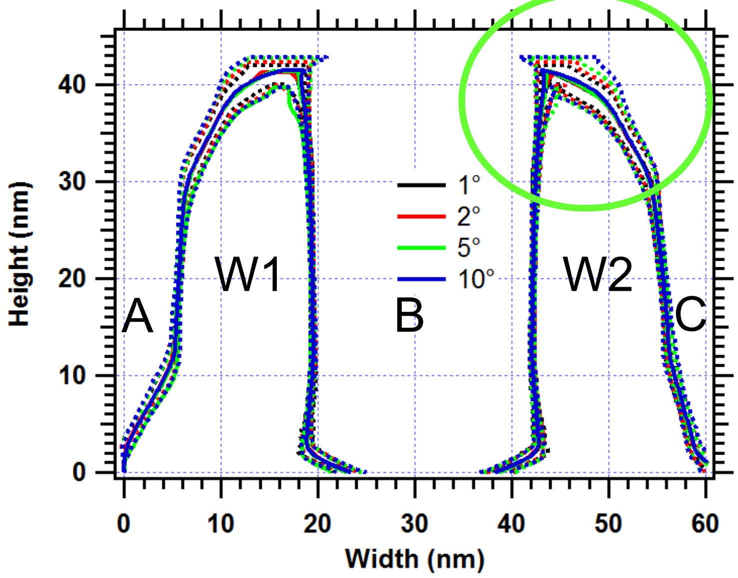


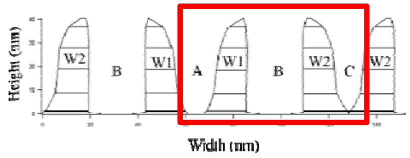
- CD-SAXS resolves sub-nm changes in the pitch offset (matches xTEM)
- Samples had similar line shape with primary difference being shift

Effect of Number of Angles on Fit



Lose ability to differentiate two line model

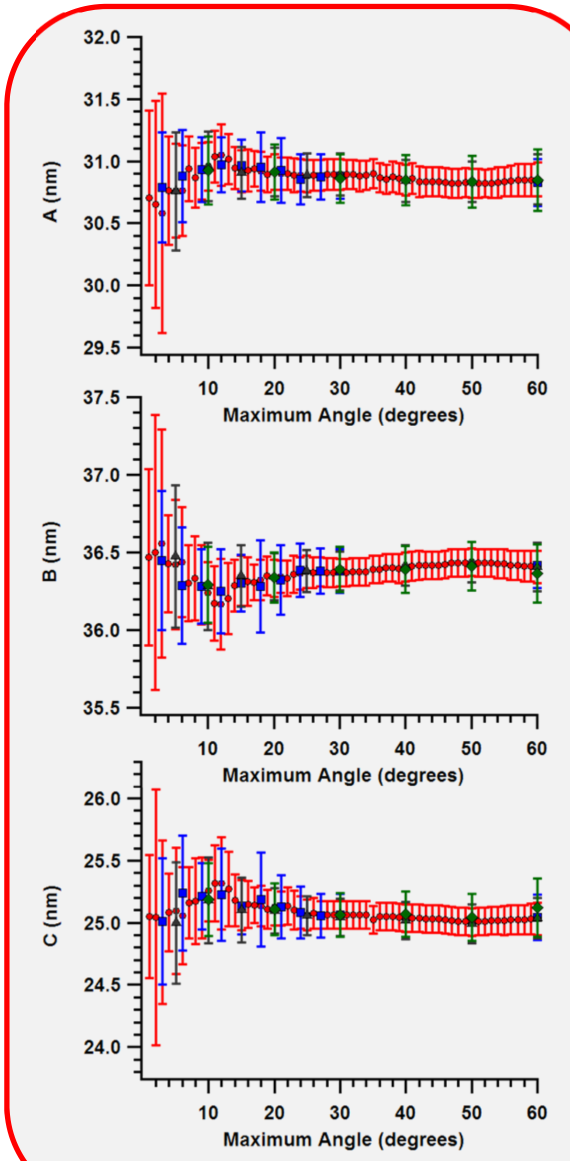


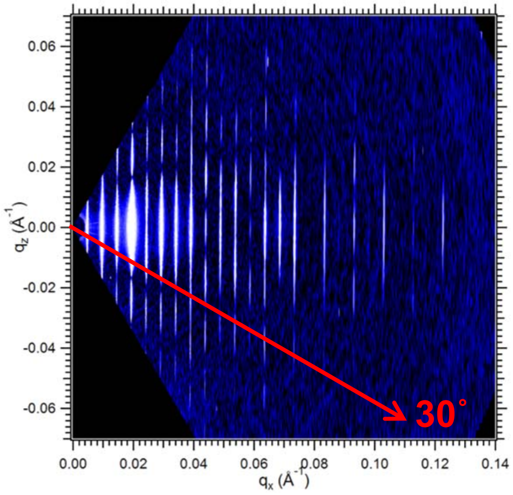


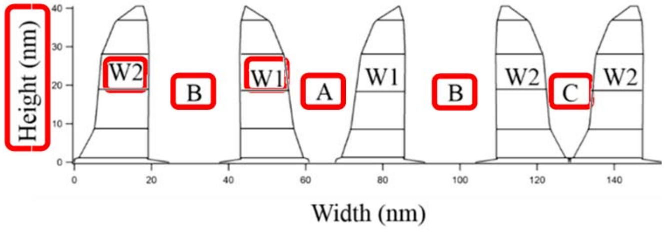
- Data is highly oversampled (121 angles)
- Compare uncertainty from MCMC algorithm vs number of angles used
- Four angles with 10˚ step gives reasonable fit

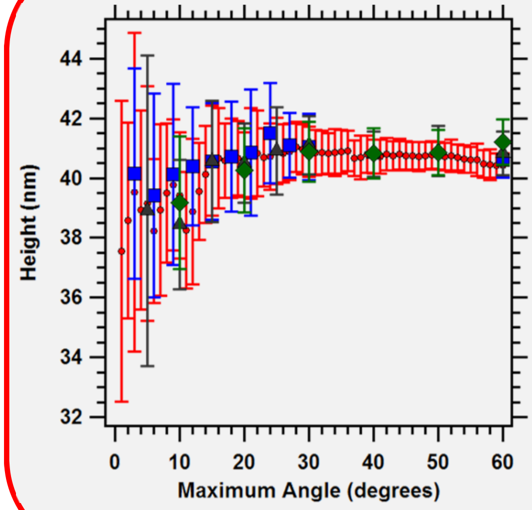
***Fit quality = area between error bars**

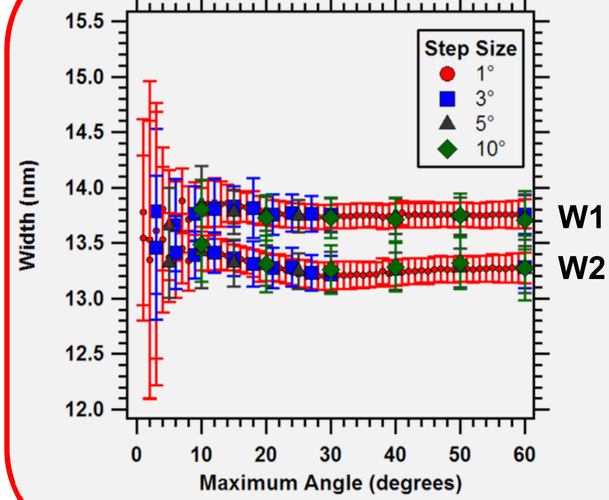
Effect of Maximum Angle on Fit Parameters



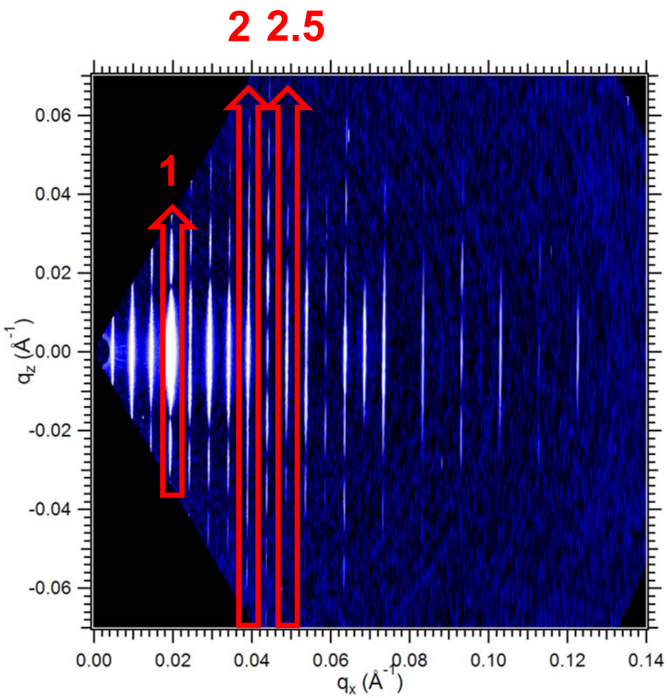


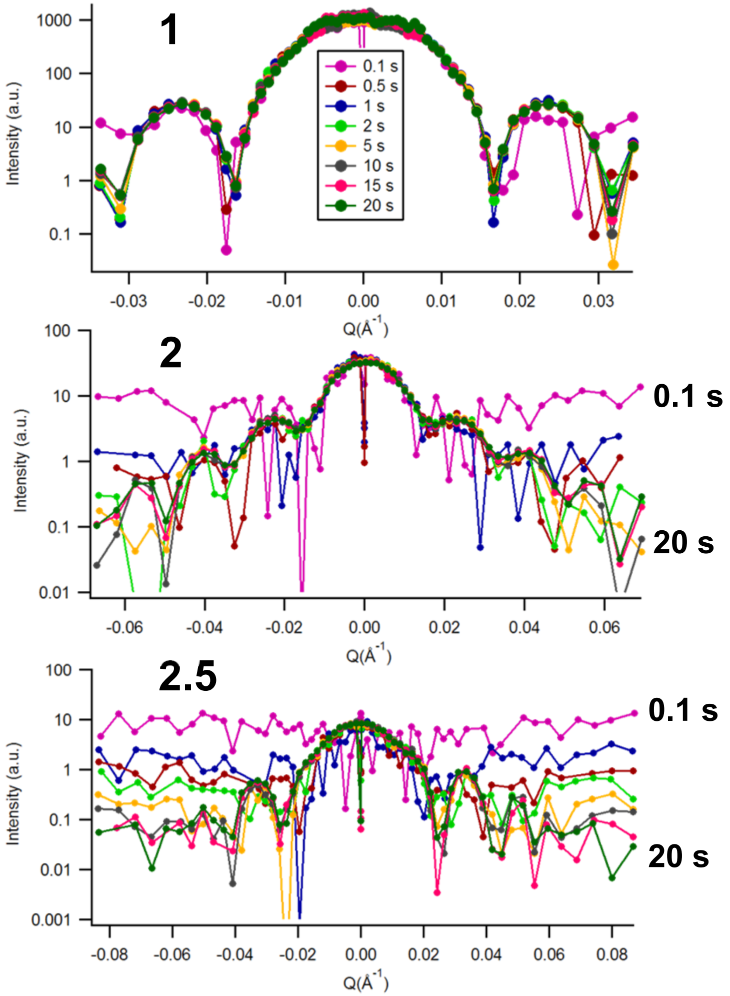






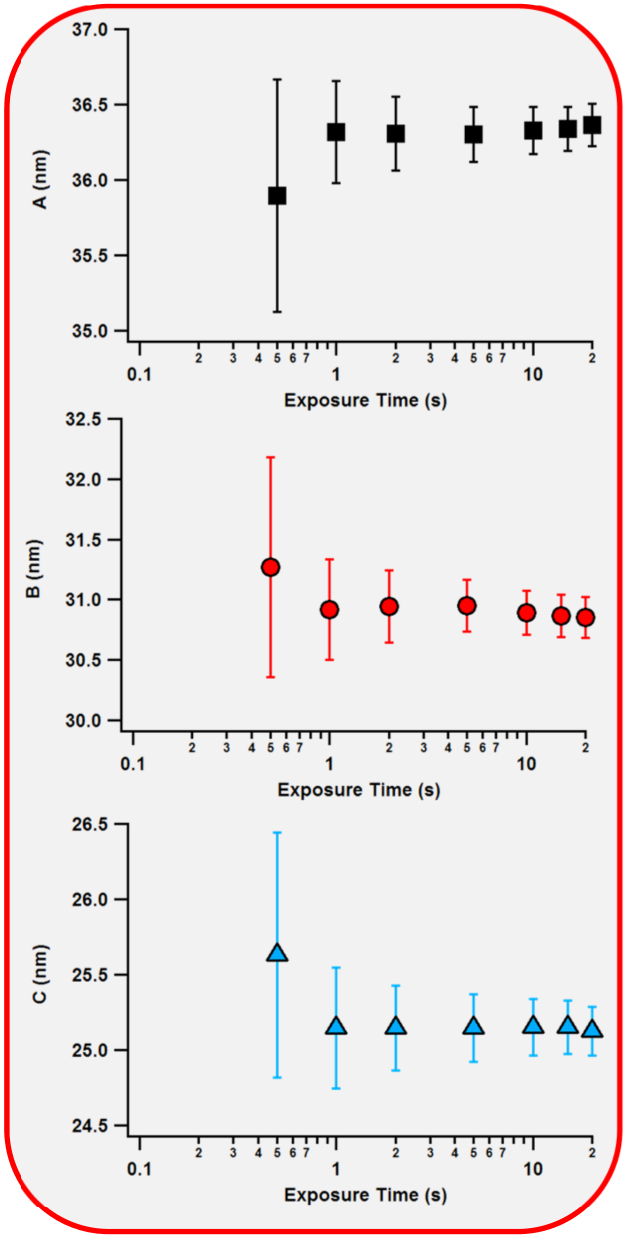
Effect of Signal to Noise on Fit

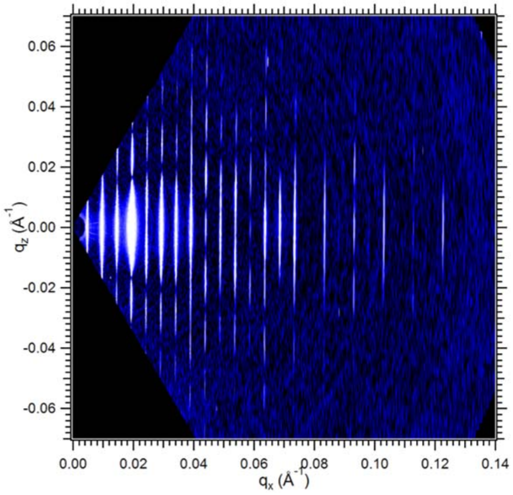


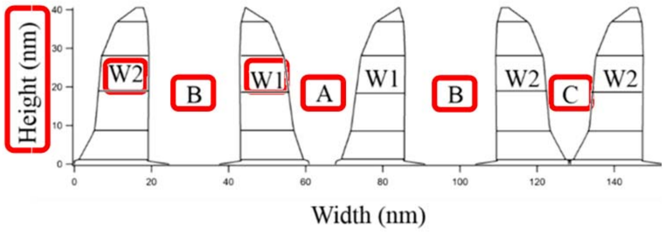


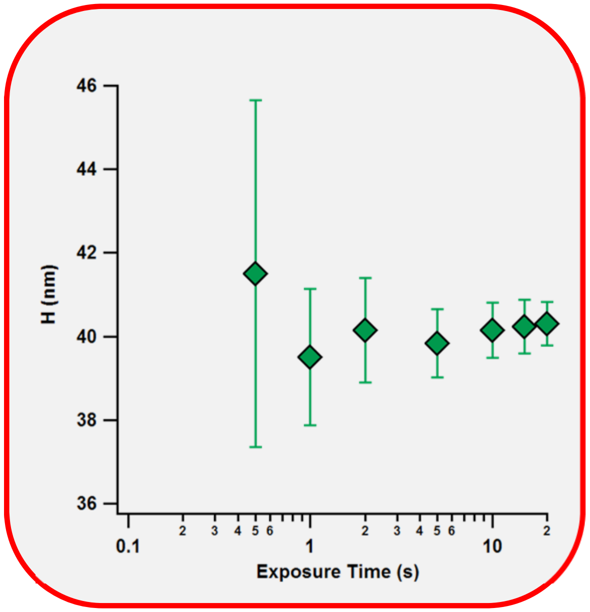
- Exposure times from 0.1 s to 20 s
- Compare uncertainty from MCMC algorithm vs. time

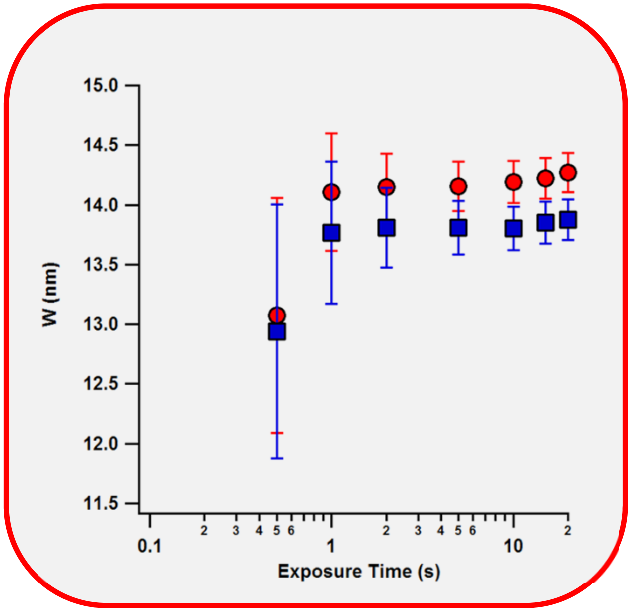
Effect of Signal to Noise on Fit Parameters



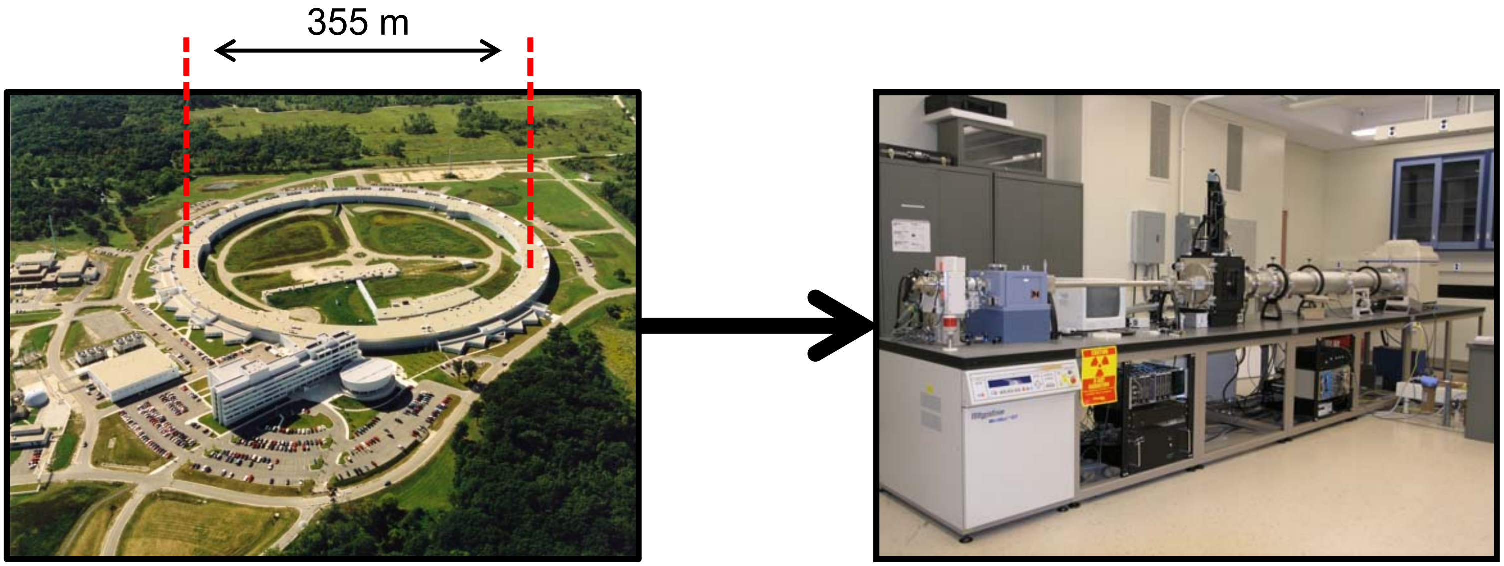






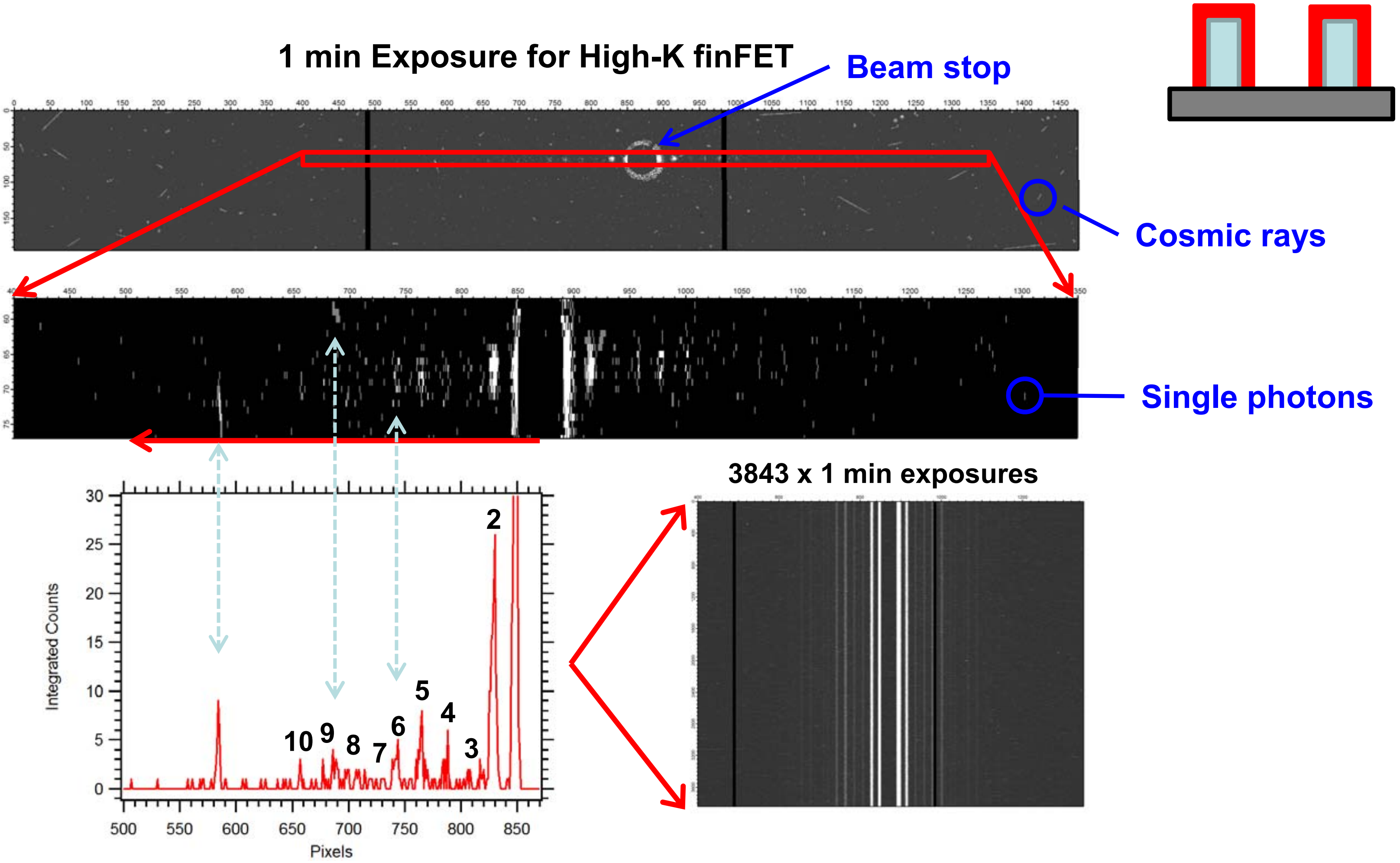


What can a lab source do now?



- Current system
  - – Mo Kα micro-focus rotating anode with a multilayer mirror
  - – Beam size on sample = 300 µm
  - – Small sample chamber (no 300 mm wafers)
  - ❖ Noiseless, fast detector
    - Single photon counting with 10^6 dynamic range

Initial Results from New Detector with Mo Kα



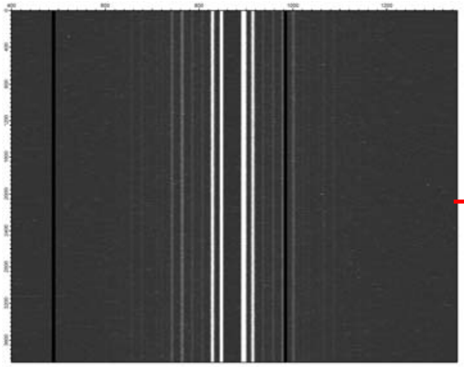
1 min Exposure for High-K finFET

3843 x 1 min exposures

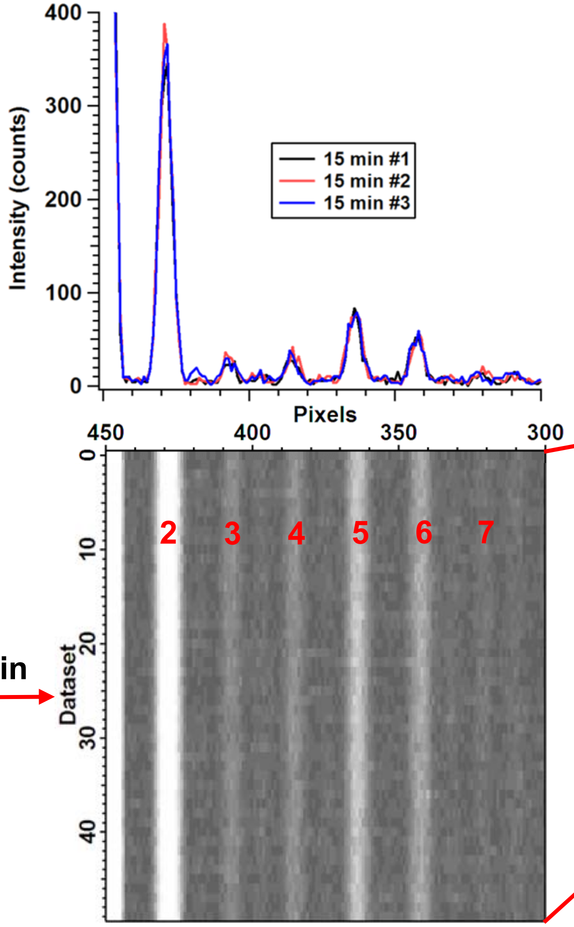
- Detector measures single photons and has no readout noise with fast readout
  - Many short exposures can be combined and allows separation of cosmic from sample scattering

Synthetic Exposure Series and Statistical Analysis

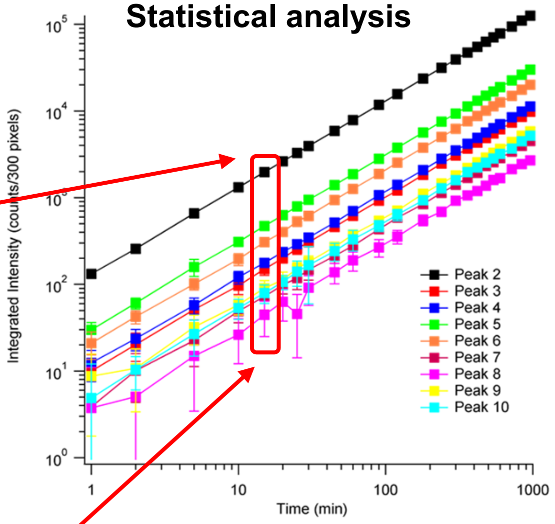
3843 x 1 min exposures



50 x 15 min

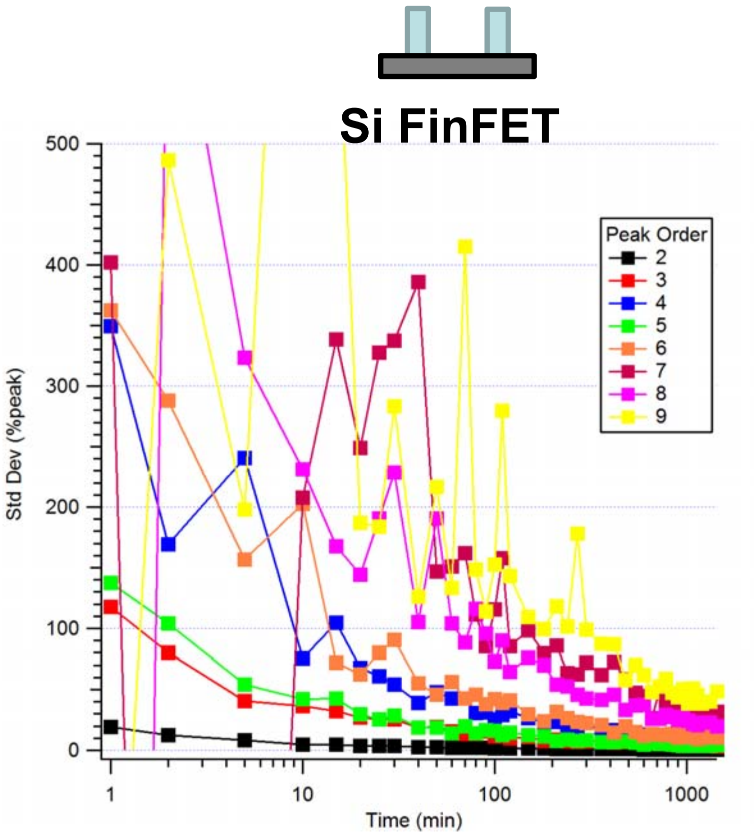


Statistical analysis

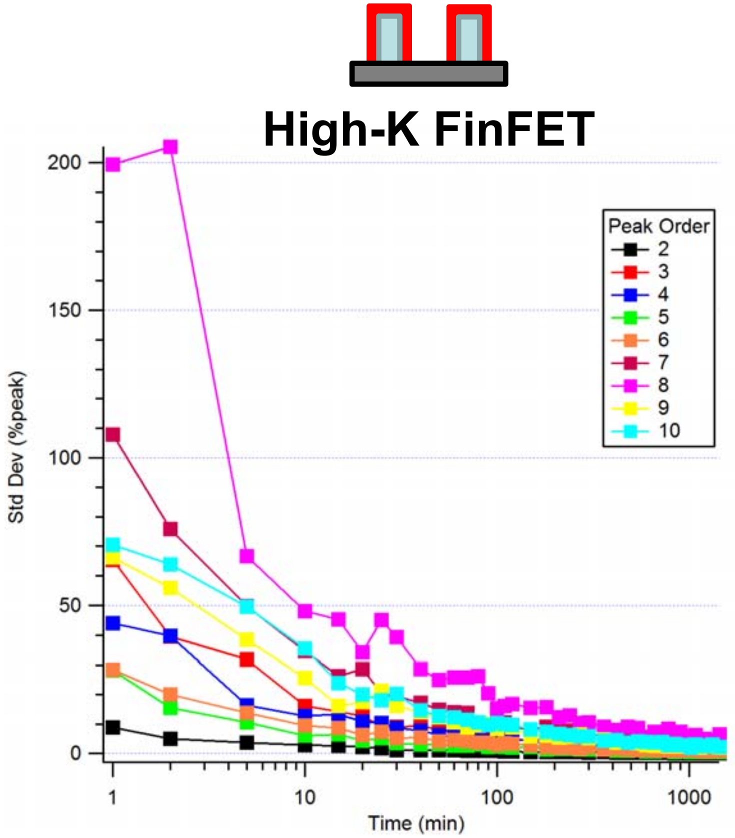


- Resample datasets by randomly combining 1 min exposures into longer time exposure
- Run statistics on synthetic datasets
  - Compare variance in peak intensities across 50 synthetic exposures at each exposure time

Peak Noise vs. Exposure Time



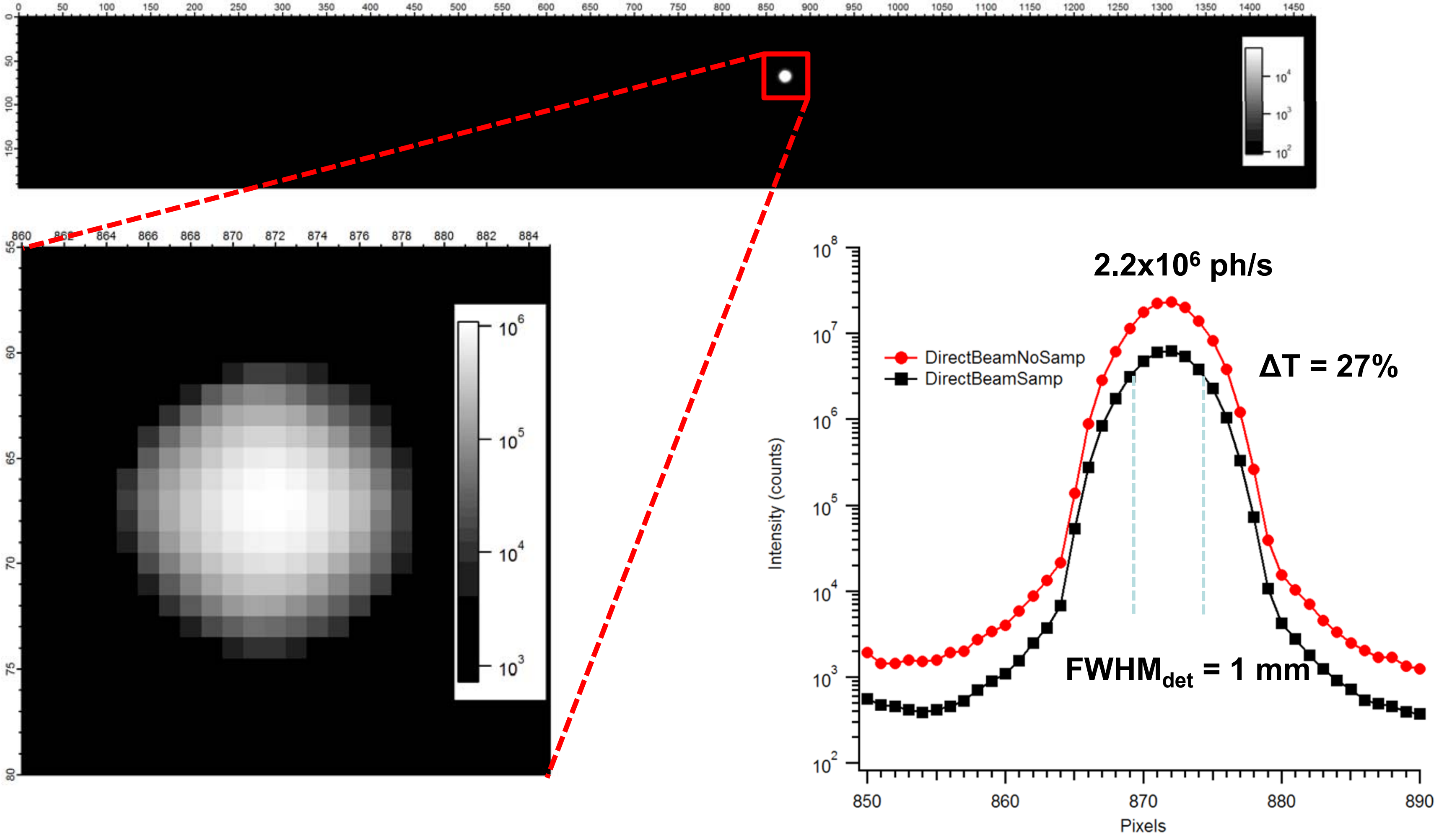
Si FinFET



High-K FinFET

- Values are based on std. dev. of 50 resampled datasets
  - Plot of std. dev. relative to peak intensity
- Noise level much higher in Si FinFET sample
  - Noise is combination of Poisson statistics and cosmic background

Direct Beam Imaging



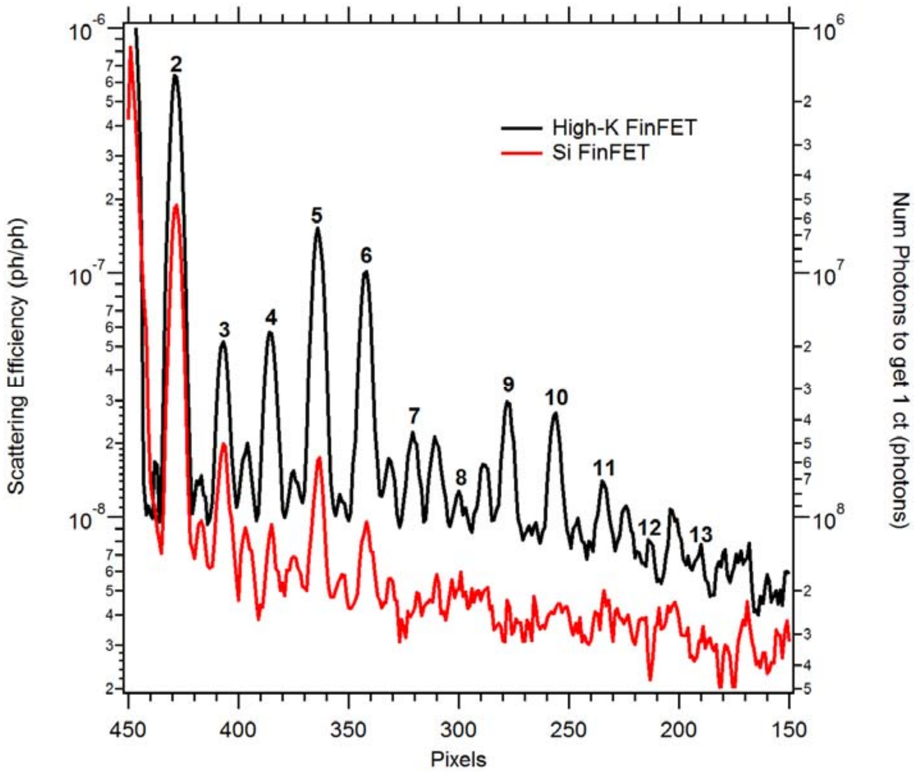
2.2×10^6 ph/s

$\Delta T = 27\%$

FWHM_{det} = 1 mm

- Direct measurement of beam flux and size
- Allows easy comparison between scattering and beam intensity

Absolute Scattering Intensity and Source Requirements


Relative Scattering Intensity

Ideal Source Requirements

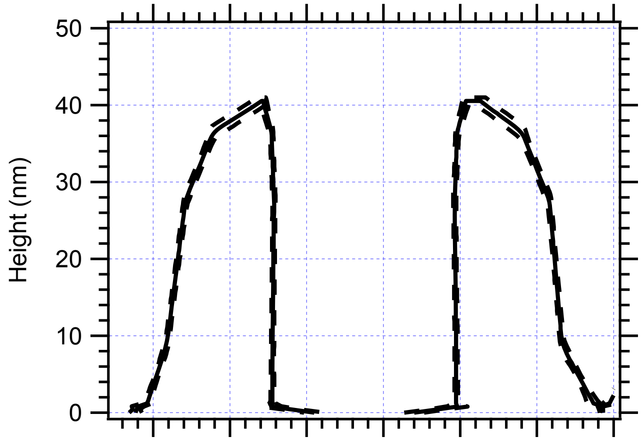
Property	Value
Energy	>20 keV
Energy res	<2 % (5 %)
Divergence	<0.5 x 1.5 mrad
Spot size	<100 μm

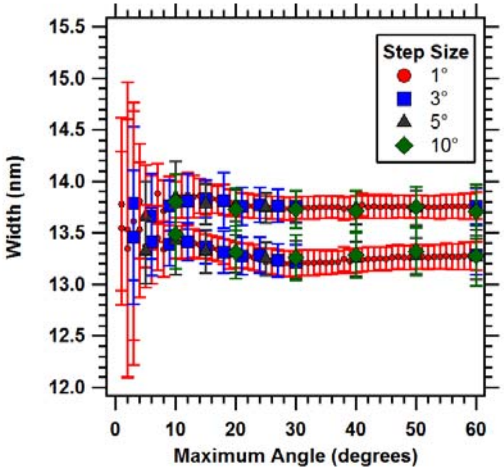
Flux for 10 sec Measurement

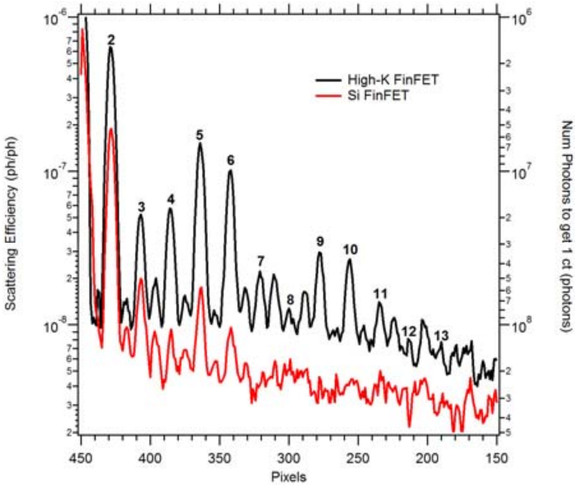
Material	High-K	Si	Resist
Photons	10^8 ph/s	10^9 ph/s	10^{10} ph/s

- Data is normalized to beam intensity and silicon absorption
- Assume >10 cts/peak for significance at high q (10th order)

CDSAXS: Is it Fab Ready?







- CDSAXS works great in limit of excess photons
- Evaluated effects of data quantity and quality
- Number of potential new X-ray sources on the horizon
  - Identified critical source requirements for CDSAXS
  - New sources key to success of CDSAXS

***NIST National Research Council Postdoctoral Fellowship**
2 year, $66k/year stipend to work at NIST, requires US citizenship
Other potential opportunities for foreign postdocs
Contact me at Joe.Kline@nist.gov for more info