Current Status of CDSAXS: Is it Fab-Ready?

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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
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X-ray Diffraction

Reciprocal Lattice

\[ \frac{2\pi}{d} \]

Small Angle X-ray Scattering

\[ n\lambda = 2d \sin \theta \text{ (Bragg’s Law)} \]

\[ k - k' = q, \text{ where } |k| = \frac{2\pi}{\lambda} \]

- 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

\[ F(Q) = \int_V e^{-iQv} dV \]
\[ I(Q) = |F(Q)|^2 e^{-Q^2DW^2} \]

- 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

Inverse Fitting

Monte Carlo – Markov Chain Uncertainty

Compare guess to data
Example Semiconductor Nanopattern

Spacer-Assisted Quadruple Patterning (SAQP)

- 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

![Graph with q_z and q_x axes showing scattering patterns and labels for pitches.](image)
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
  \(-\ A = C \neq B\)
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
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

- 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

- $A$ (nm)
- $B$ (nm)
- $C$ (nm)

Maximum Angle (degrees)

- Height (nm)
- Width (nm)

Step Size:
- $1^\circ$
- $3^\circ$
- $5^\circ$
- $10^\circ$

W1
W2
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

- 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
• 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

- 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

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

2.2x10^6 ph/s

FWMH_{det} = 1 mm

ΔT = 27%
Absolute Scattering Intensity and Source Requirements

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

Relative Scattering Intensity

Ideal Source Requirements

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Energy</td>
<td>&gt;20 keV</td>
</tr>
<tr>
<td>Energy res</td>
<td>&lt;2 % (5 %)</td>
</tr>
<tr>
<td>Divergence</td>
<td>&lt;0.5 x 1.5 mrad</td>
</tr>
<tr>
<td>Spot size</td>
<td>&lt;100 μm</td>
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Flux for 10 sec Measurement

<table>
<thead>
<tr>
<th>Material</th>
<th>High-K</th>
<th>Si</th>
<th>Resist</th>
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</thead>
<tbody>
<tr>
<td>Photons</td>
<td>$10^8$</td>
<td>$10^9$</td>
<td>$10^{10}$</td>
</tr>
</tbody>
</table>

- 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

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