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

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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
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) \( \mu m \)
- 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

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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*

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A Wide Range of Samples

Materials measured non-destructively
• Photoresists (248 nm, 193 nm, EUV)
• Engineering Polymers (PMMA, PS)
• Oxides (SiO2)
• Nanoporous Matrices
• Barrier layers (SiN, SiCN)
• Metal Interconnects (Cu)

Pattern Geometries
• Line/Space patterns (gratings)
• Arrays of columns
• Arrays of holes (vias)

Hexagonal Close Packed 60 nm vias
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
• Introduction

• **Measurement of pitch and line width**

• Measurement of side wall angle and height

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

• Conclusions
• **Pitch Measurement**

\[ D = 237.1 \pm 0.5 \text{ nm} \]

![Graph showing q vs. Peak order](image)

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- Average line width

### Graph

- **Intensity** vs. **q (Å⁻¹)**
- **Intensity** scale: 10^2 to 10^5
- **q (Å⁻¹)** range: 0.000 to 0.030

**Legend:**
- Black squares: experimental data
- Red circles: rectangle model, resolution function, Debye-Waller effect

**Note:**
- Width = 128 nm
- Image of experimental rectangle model, resolution function, Debye-Waller effect

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• Introduction

• Measurement of pitch and line width

• **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

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3-D Lineshape from Sample Rotation

Model

Transformed

Raw Data

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CD-SAXS: Pattern Cross Section

real space

Fourier transform

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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

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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

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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 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

Experimental Data

Trapezoid Model

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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

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

**Experimental Data**

**Trapezoid 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

Missing peaks possibly due to footer.
IBM DOF p2

$+0.2 \text{ micron}$

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

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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

Experimental Data

Trapezoid Model

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More Complicated Structures

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• Measurement of pitch and line width

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• 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

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Sidewall Correlations: High vs. Low LER

Samples with more defects demonstrate higher intensity “streaking”

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Streaks decay with increasing $q_x$
Diffraction peaks become isotropic at high $q_x$

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SAXS characterization technique

- Line-edge roughness

\[ A \sin(\pi \nu y + \phi) \]
CD-SAXS: a model LER – single sine wave
SAXS characterization technique

Dependence of satellite peak intensity

\[
I_{\text{s}atellite} / I_{\text{Bragg peak}} = \left[ \frac{\sin\left(\frac{2N+1}{2}q_{x}D\right)}{\sin\left(\frac{q_{x}D}{2}\right)} \right]^2 \left[ \frac{2\sin\left(\frac{q_{x}W}{2}\right)}{q_{x}} \right]^2 \left[ \delta(q_{y}) + (A^2 + 4q_{x}\Delta D^2)(\delta(q_{y} - \nu) + \delta(q_{y} - \nu)) \right]
\]

0th order

1st order

2nd order

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Line roughness of copper interconnect
Probing Cu Interconnects

Sample: Cu filled Silicon Oxide lines

Effects demonstrated previously are magnified

→ Higher density of defects ??

→ Higher x-ray contrast

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Measuring pattern quality: the diffuse “halo”

Intensity integrated +/- 45 deg normal to diffraction axis

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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)

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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
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