Advances in CD-Metrology (CD-SAXS, Mueller Matrix based Scatterometry, and SEM)

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Acknowledgements

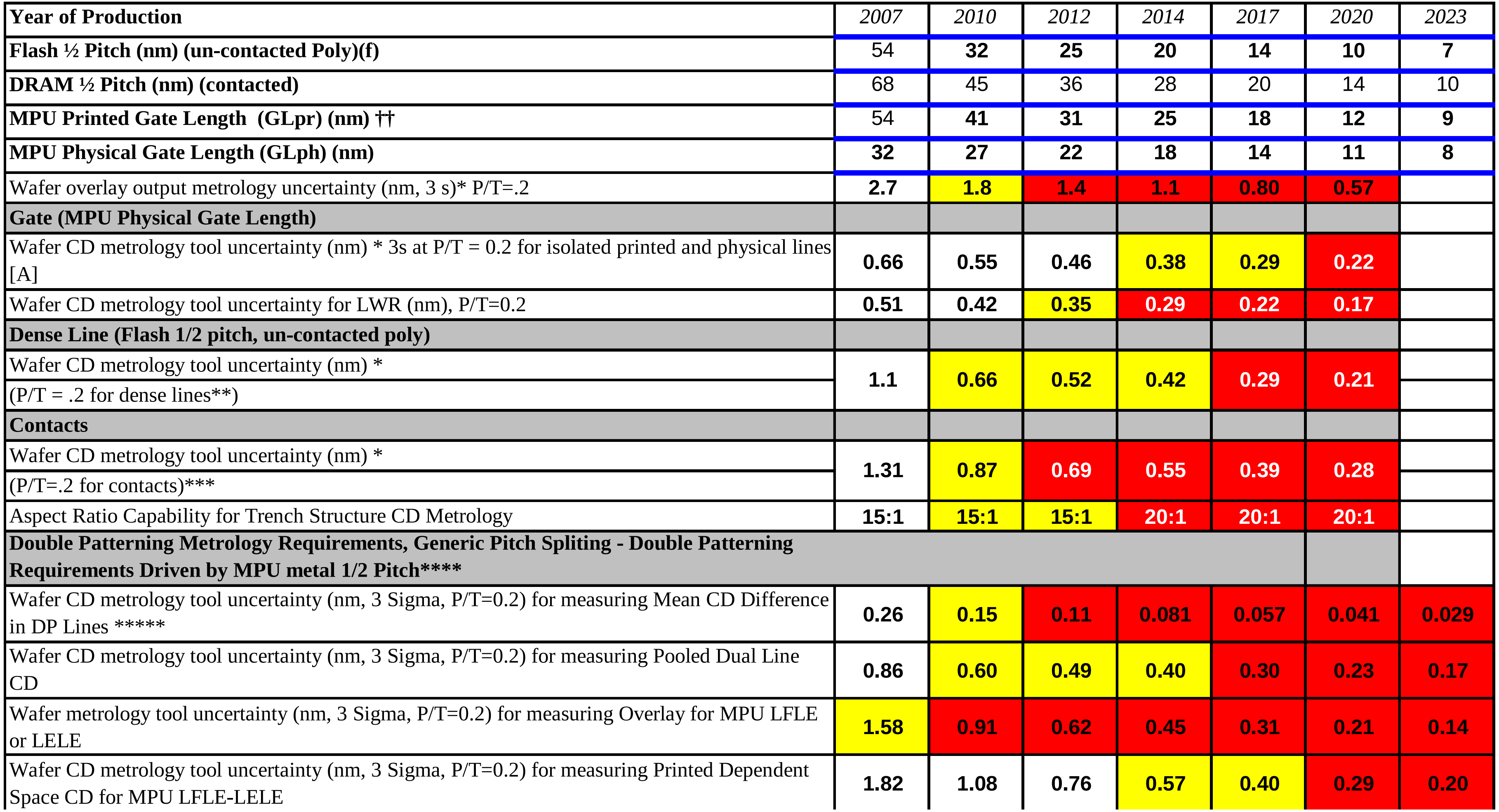
- SEMATECH
  - Ben Bunday
  - Victor Vartanian
  - Akira Hamaguchi
  - Matt Malloy

- NIST
  - Wen-li Wu
  - Andras Vladar

Challenges facing CD-SEM

- CD measurements are currently dominated by scatterometry and SEM, but both face considerable challenges to keep pace with Roadmap requirements:

Table MET3 Lithography Metrology (Wafer) Technology Requirements



Year of Production	*2007*	*2010*	*2012*	*2014*	*2017*	*2020*	*2023*
Flash ½ Pitch (nm) (un-contacted Poly)(f)	54	**32**	**25**	**20**	**14**	**10**	**7**
DRAM ½ Pitch (nm) (contacted)	68	45	36	28	20	14	10
MPU Printed Gate Length (GLpr) (nm) ††	54	**41**	**31**	**25**	**18**	**12**	**9**
MPU Physical Gate Length (GLph) (nm)	**32**	**27**	**22**	**18**	**14**	**11**	**8**
Wafer overlay output metrology uncertainty (nm, 3 s)* P/T=.2	**2.7**	**1.8**	**1.4**	**1.1**	**0.80**	**0.57**	
Gate (MPU Physical Gate Length)							
Wafer CD metrology tool uncertainty (nm) * 3s at P/T = 0.2 for isolated printed and physical lines [A]	**0.66**	**0.55**	**0.46**	**0.38**	**0.29**	**0.22**	
Wafer CD metrology tool uncertainty for LWR (nm), P/T=0.2	**0.51**	**0.42**	**0.35**	**0.29**	**0.22**	**0.17**	
Dense Line (Flash 1/2 pitch, un-contacted poly)							
Wafer CD metrology tool uncertainty (nm) * (P/T = .2 for dense lines**)	**1.1**	**0.66**	**0.52**	**0.42**	**0.29**	**0.21**	
Contacts							
Wafer CD metrology tool uncertainty (nm) * (P/T=.2 for contacts)***	**1.31**	**0.87**	**0.69**	**0.55**	**0.39**	**0.28**	
Aspect Ratio Capability for Trench Structure CD Metrology	**15:1**	**15:1**	**15:1**	**20:1**	**20:1**	**20:1**	
Double Patterning Metrology Requirements, Generic Pitch Spliting - Double Patterning Requirements Driven by MPU metal 1/2 Pitch******							
Wafer CD metrology tool uncertainty (nm, 3 Sigma, P/T=0.2) for measuring Mean CD Difference in DP Lines *****	**0.26**	**0.15**	**0.11**	**0.081**	**0.057**	**0.041**	**0.029**
Wafer CD metrology tool uncertainty (nm, 3 Sigma, P/T=0.2) for measuring Pooled Dual Line CD	**0.86**	**0.60**	**0.49**	**0.40**	**0.30**	**0.23**	**0.17**
Wafer metrology tool uncertainty (nm, 3 Sigma, P/T=0.2) for measuring Overlay for MPU LFLE or LELE	**1.58**	**0.91**	**0.62**	**0.45**	**0.31**	**0.21**	**0.14**
Wafer CD metrology tool uncertainty (nm, 3 Sigma, P/T=0.2) for measuring Printed Dependent Space CD for MPU LFLE-LELE	**1.82**	**1.08**	**0.76**	**0.57**	**0.40**	**0.29**	**0.20**

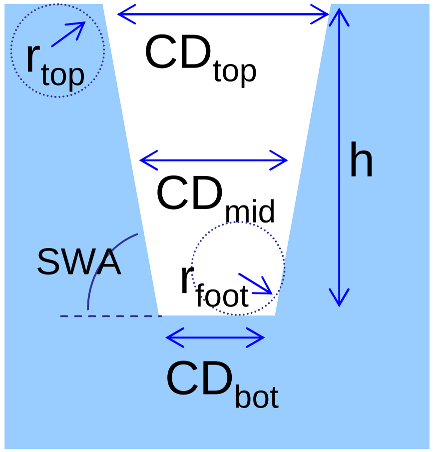
2010 ITRS Metrology requirements

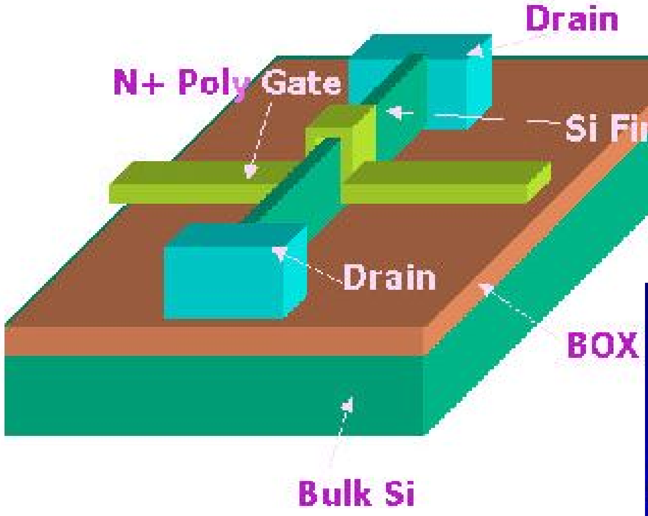
Challenges facing CD Metrology

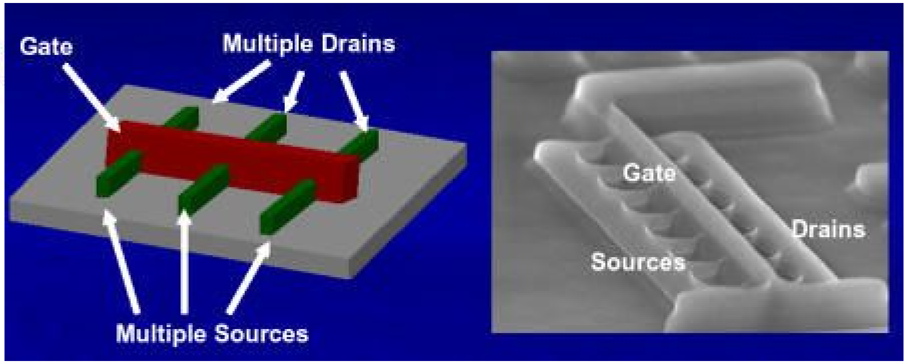
- The incumbent techniques for CD measurement face considerable challenges to keep pace with Roadmap requirements:
- 3D device architectures
  - FinFETs, trigates
  - Memory devices
- Wider variety of materials
  - Phase discrimination
- SEM performance
  - Shrinking CD values
    - Ultimate limit is mfp of secondary electrons
  - Charging
  - Contamination
  - Engineering limits

CD Challenges

- Advanced 3D transistor structures present unique challenges to existing metrology due to critical measurements that must be made on vertical structures, as well as more complex geometric structures.
- High aspect ratio structures and deep holes also present challenges. Ultimately, memory needs 40:1 up to 60:1.







SEMATECH FinFET flow Critical Measurements

✓= higher priority

Fin Module

- ✓ Fins after fin etch—CD-bottom, CD-top, fin height, Side Wall Angle (SWA), Line width Roughness/Line Edge Roughness (LWR/LER), sidewall roughness, top corner rounding, foot, profile taper, BOX recess.
- ✓ Fin pitch after SpDP
- ✓ Etch residue on fins after SpDP

Gate Module

- ✓ High-k dielectric deposition thickness/composition, profile, roughness, taper
- ✓ Metal gate deposition thickness/composition, profile, roughness, taper
- Poly deposition thickness over fin
- Amount of material on fin after CMP
- ✓ Gate profile, roughness after gate etch
- ✓ Fin integrity, roughness after gate etch; corners
- ✓ High-k gate dielectric, BOX recess after gate etch

S/D Implant Module

- Nitride spacer CDbot, CDmid, CDtop, h, SWA, LWR/LER, top corner rounding, profile taper after spacer etch
- ✓ Dopant profile after implant
- ✓ Active dopant profile following anneal

Silicide Module

- Silicide phase uniformity

Contact Module

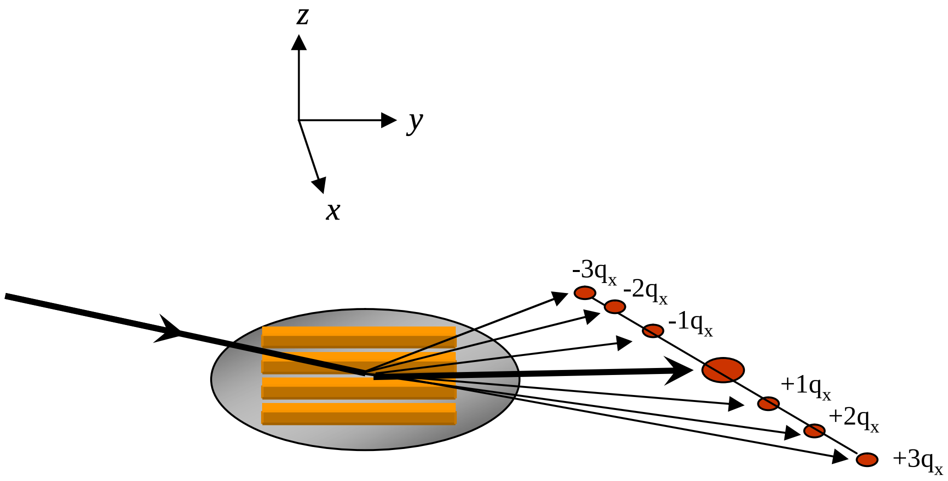
- Potentially, HAR contact holes

Scatterometry Solutions

- Scatterometry can in principle extract the relevant parameters.
- Two flavors:
  - – Small angle X-ray Scattering (SAXS)
    - Transmission mode
    - Reflection mode
  - – Optical- Spectroscopic Ellipsometry with Mueller Matrix analysis

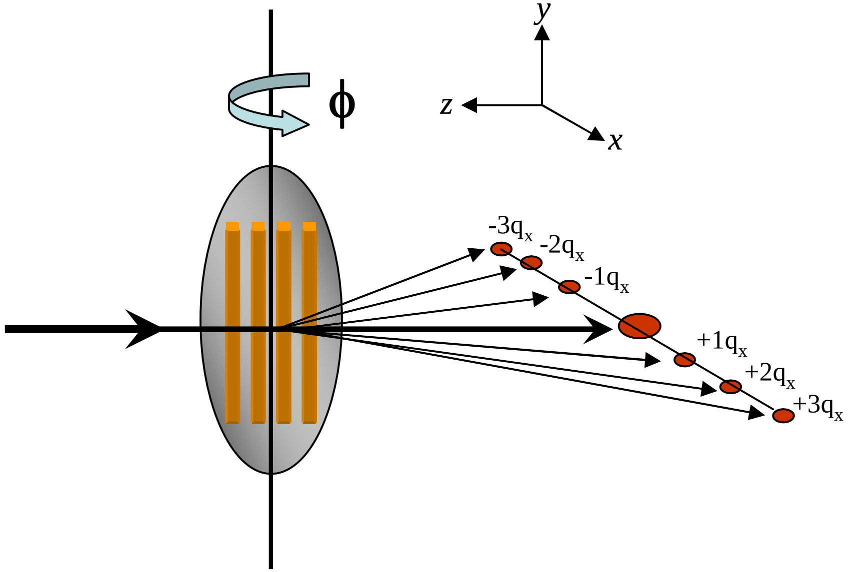
Two Configurations for CD-SAXS

Grazing Incidence



- ~8 keV
- Large spot
- z-dimension probed by examining scattering in the +q_z direction

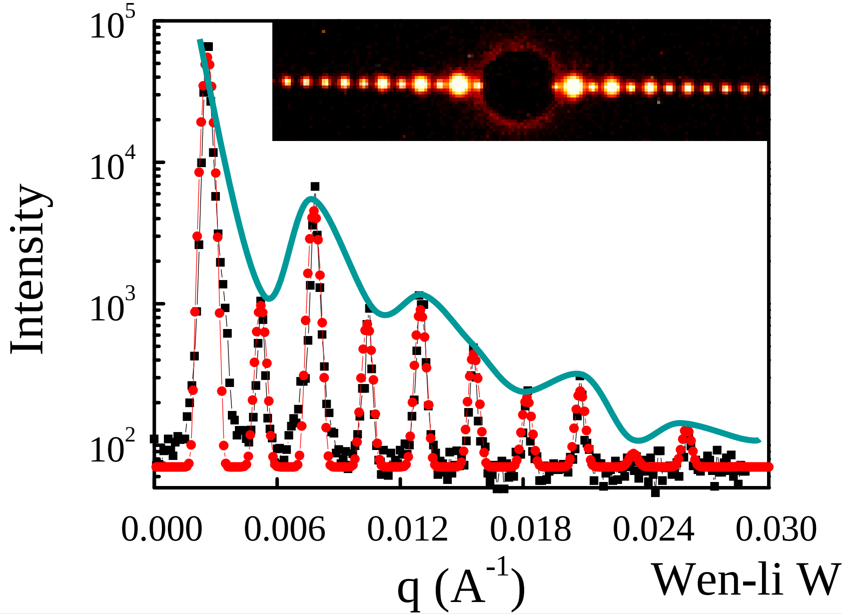
Transmission



- >13 keV
- Small spot
- z-dimension probed by varying angle of incidence ϕ.

Extraction of Parameters

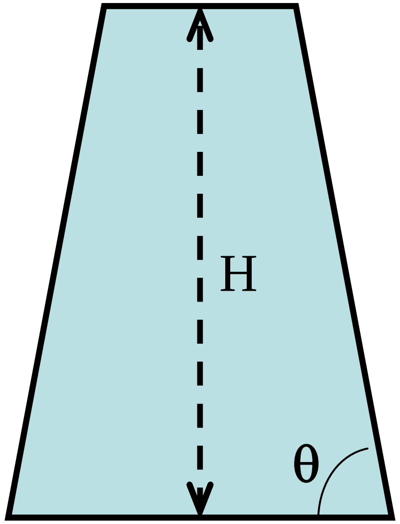
- Pitch obtained from spacing of major reflections
- Pitch variation obtained from overall intensity decay behavior with increasing **q**.
- Profiles obtained from envelop functions correlating to geometric form factors.
- LWR/LER information obtained from Debye-Waller type broadening of peaks (uncorrelated spacing variation).
- Conformal layer information obtained similar to crystal structure analysis (that is, e^- density distribution associated with each lattice point).



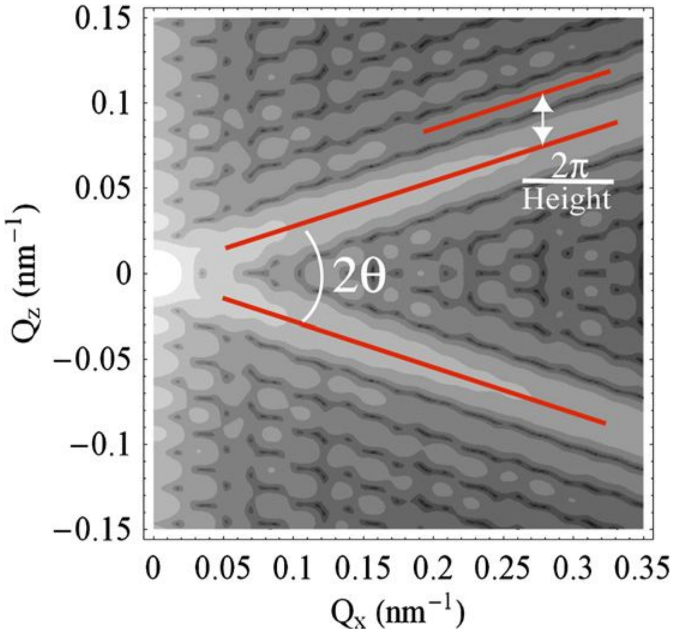
Wen-li Wu (NIST)

Trapezoidal Cross Section

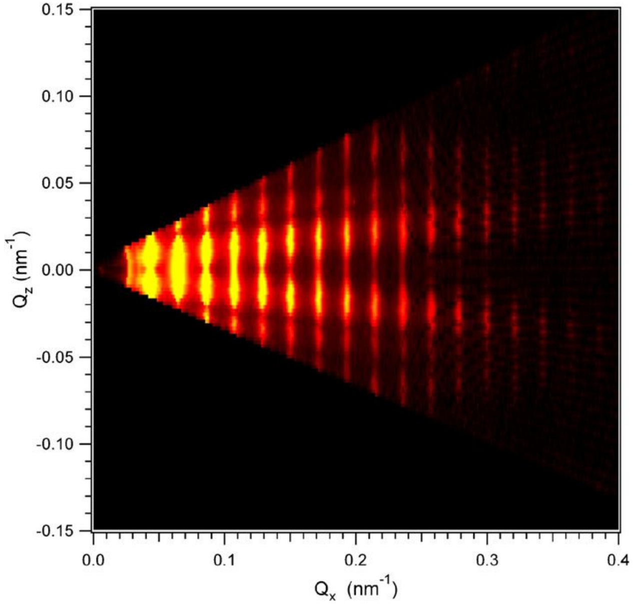
Profile



Simulation



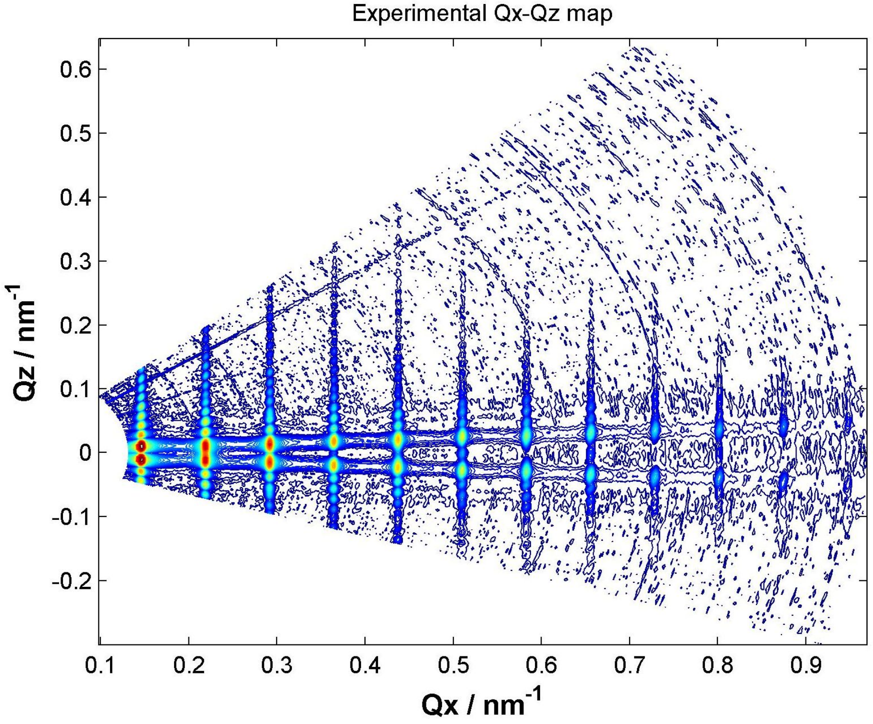
Experiment

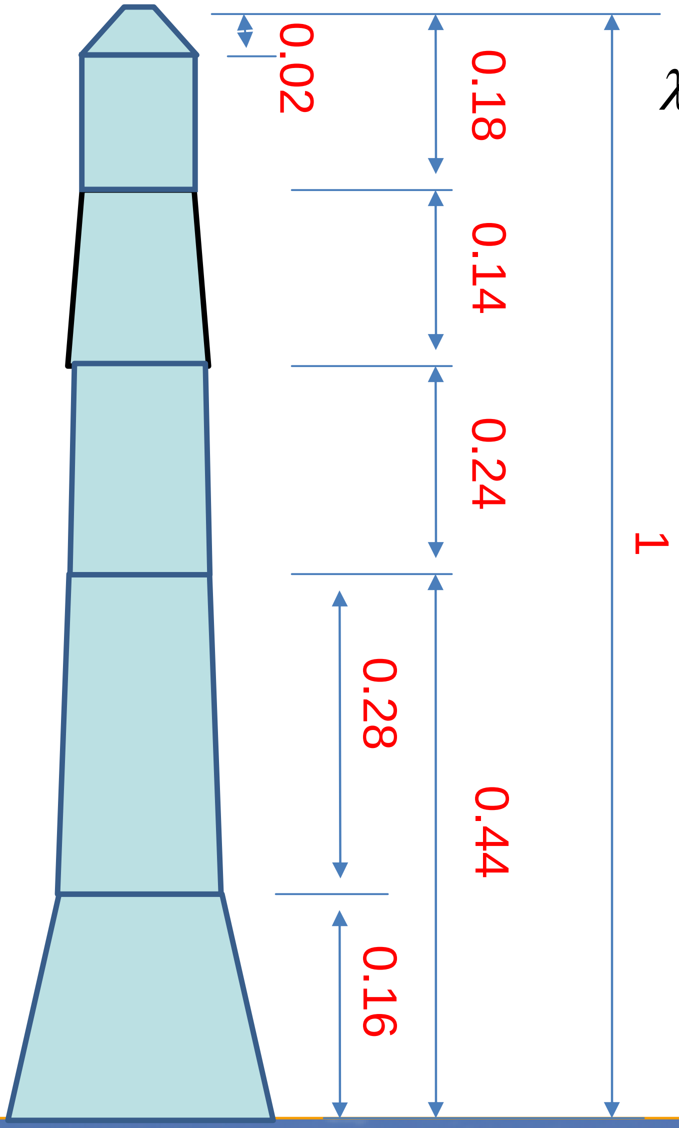


- Maxima streaks form an angle equivalent to twice the sidewall angle.
- Streak spacing is inversely proportional to feature height.

S. Knight, et al., “Advanced Metrology Needs for Nanoelectronics Lithography” *C. R. Physique*, **7**, 931 (2006).

Profile Fitting Model: 6 Trapezoids





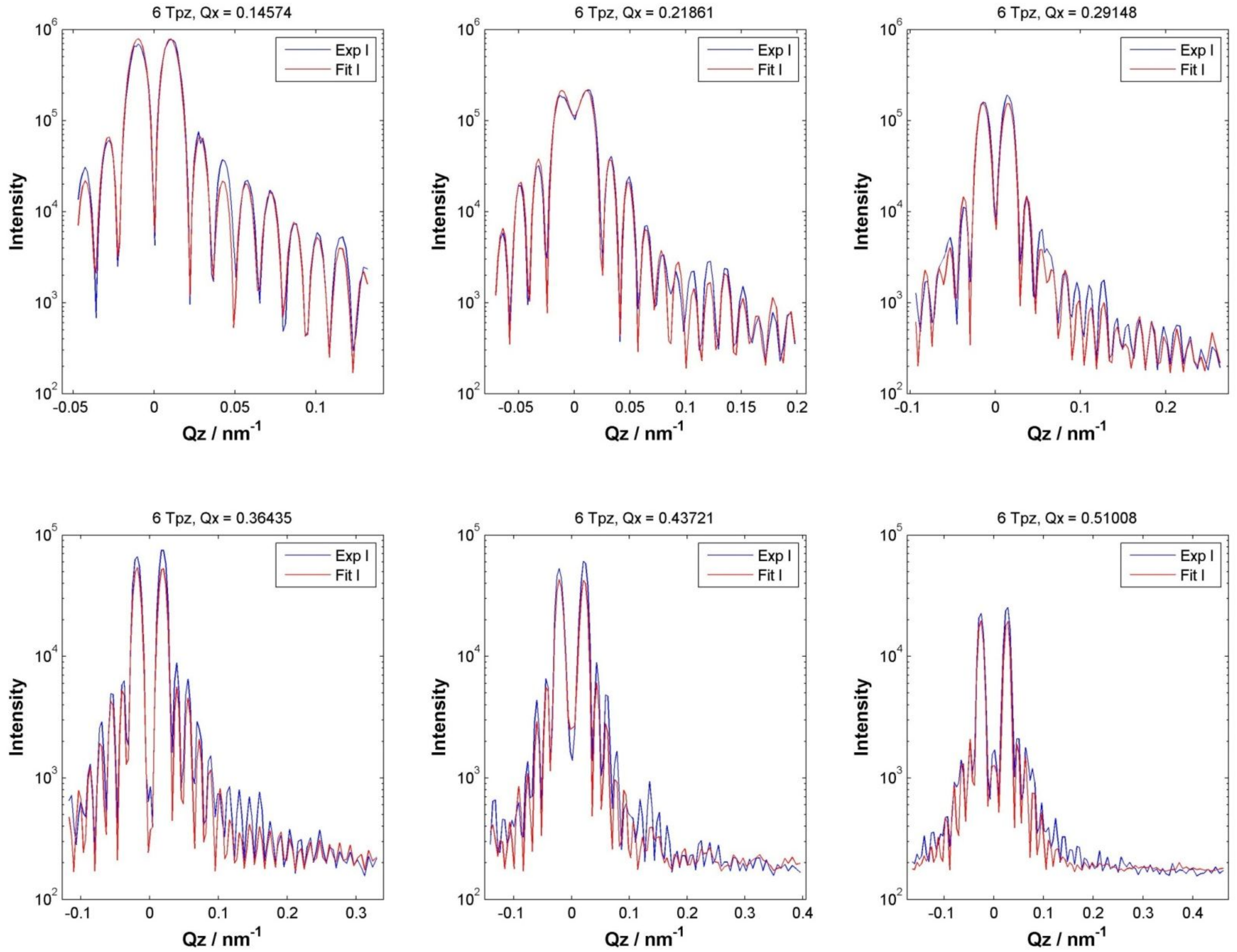
$$\chi^2 = 88.0$$

Wen-li Wu (NIST) with
ISMI/SEMATECH Metrology

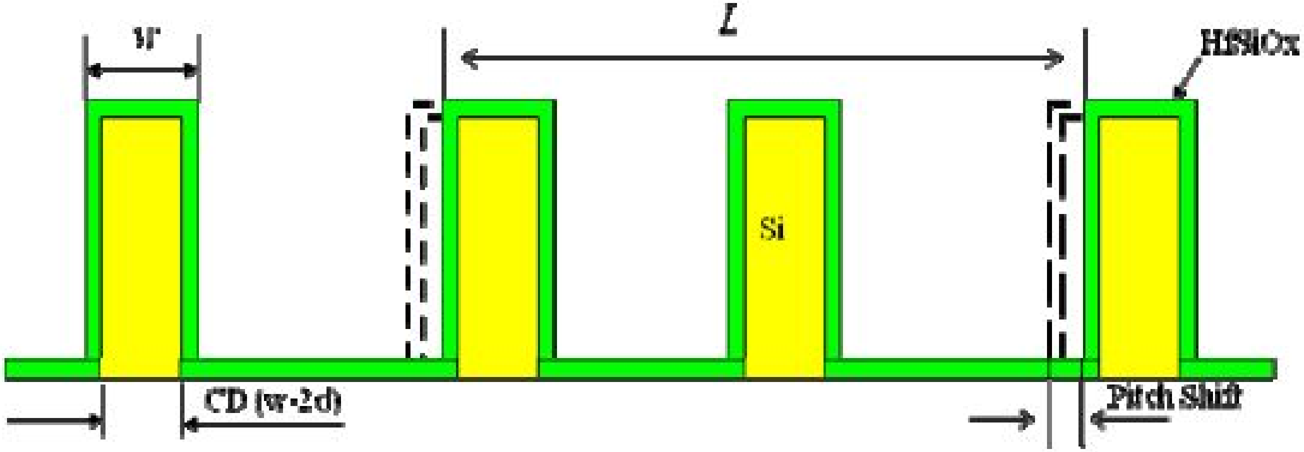
1D Fitting Details

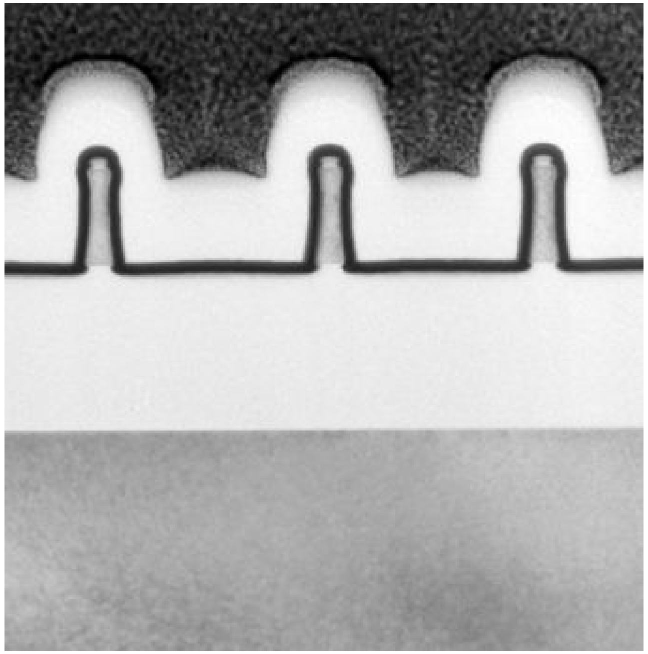
Details of simultaneous fits along Q_z at 6 different Q_x positions

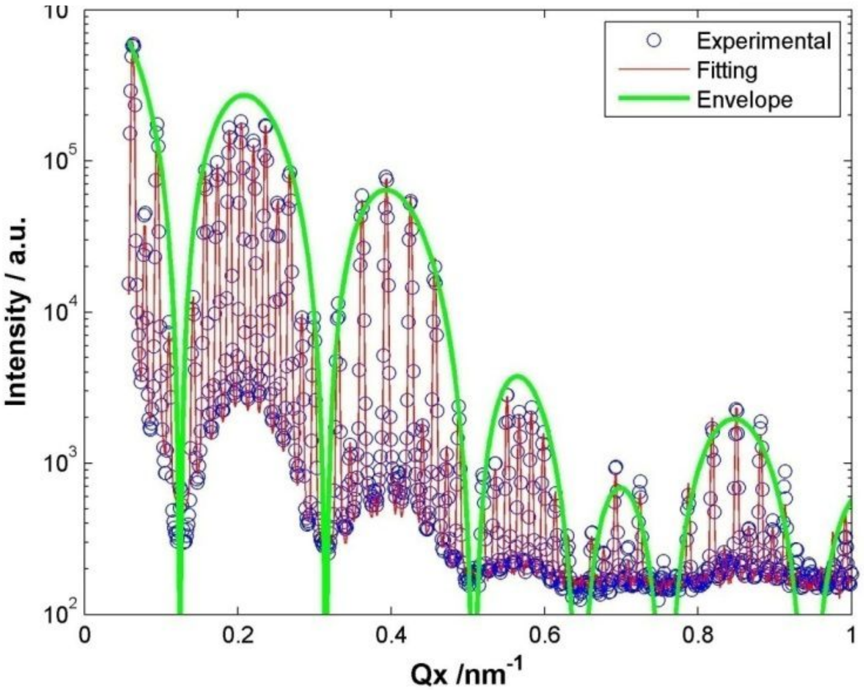
$$\chi^2 = 88.0$$



Conformal high-*k* Thickness







CD-SAXS Summary

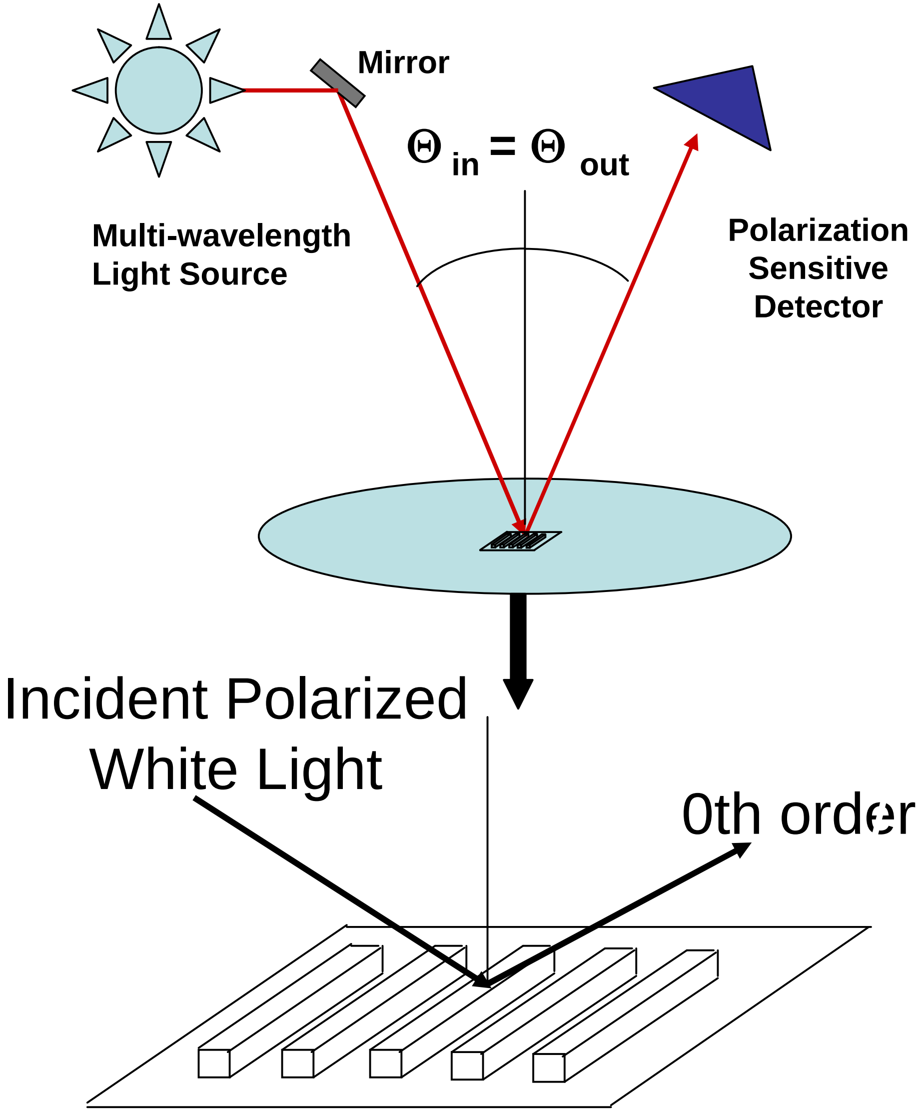
- **Transmission SAXS**
  - Non-destructive / no sample prep
  - Use 50-100μm scatterometry grating targets
- **Grazing incidence SAXS**
  - Somewhat faster, much larger spot

- **High precision measurements**
  - Sub-nm precision in pitch and linewidth
  - Sidewall angle & cross section
  - Corner rounding
  - linewidth distribution & roughness (LWR)

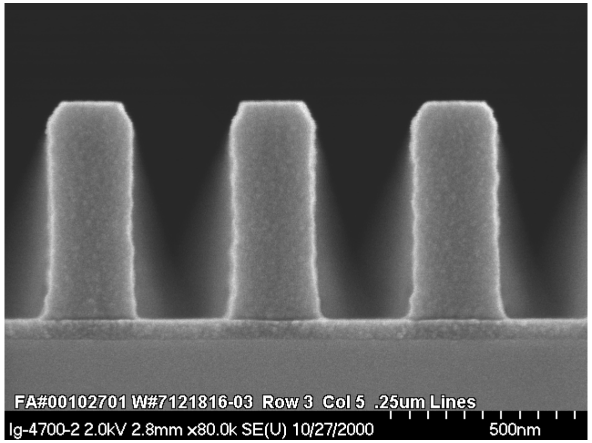
- **Assessments on-going for HAR structures & trenches**
- **Model fitting more straightforward than scatterometry**
  - No knowledge of material constants required

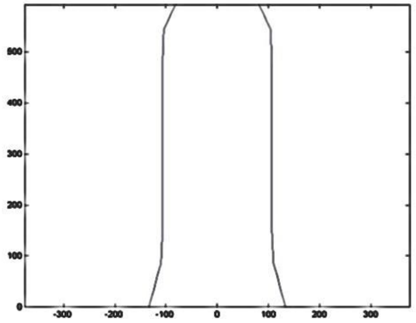
- **Chief drawback is throughput, but new lab/fab-scale high brightness sources are being developed.**
  - synchrotron: 1-5 s/measurement
  - cathode: >100 s/measurement

Optical Scatterometry (OCD)



Real Time Calculation of line width & shape & Libraries





See – Scatterometry by Chris Raymond in Handbook of Silicon Semiconductor Metrology

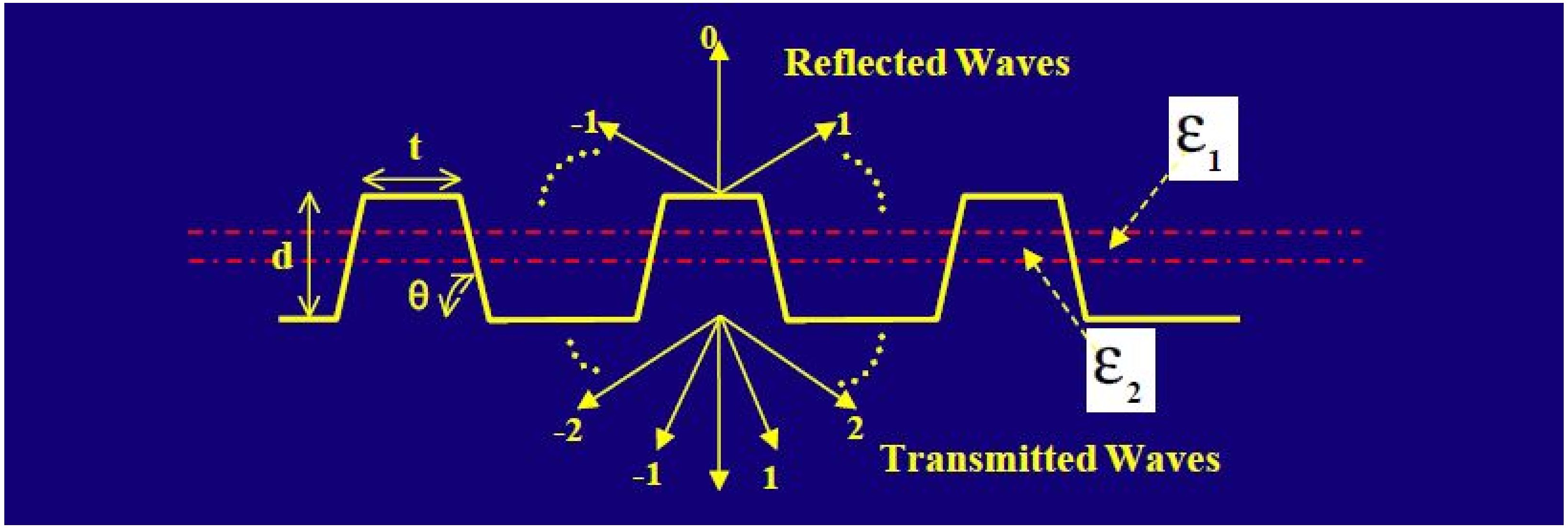
Rigorous Couple Wave Analysis

Grating - periodic in x direction

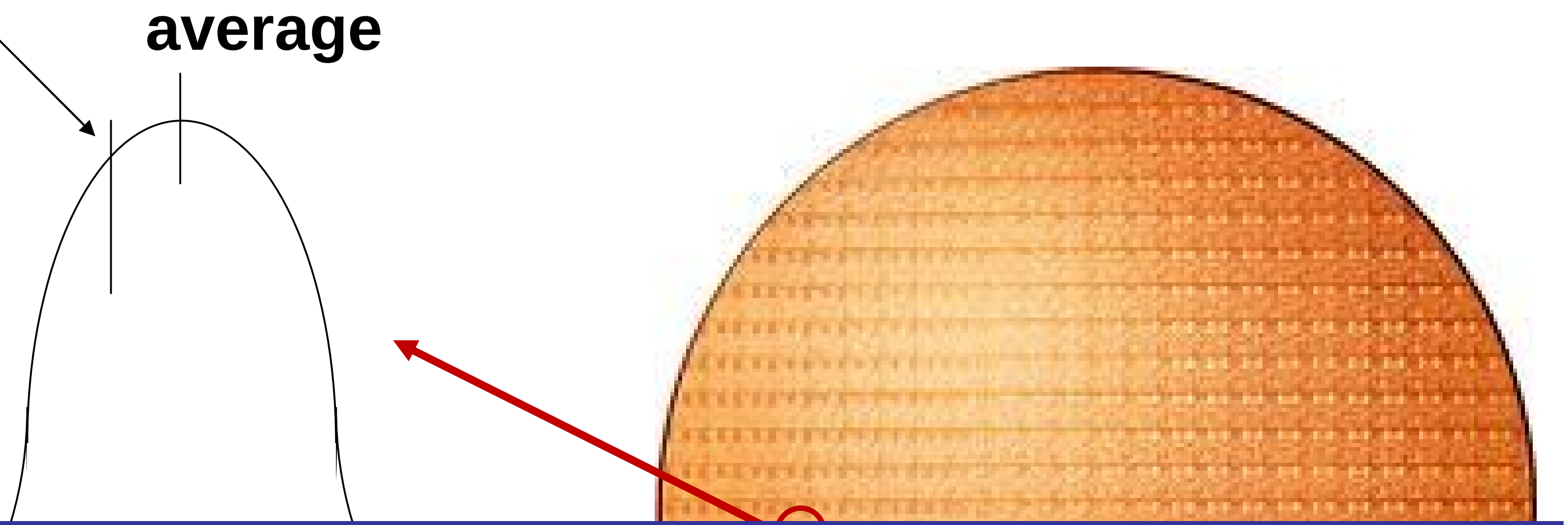
$$\varepsilon(x) = \sum_h \varepsilon_h \exp\left(j \frac{2\pi}{\Lambda} h x \right)$$

Solve coupled wave equations by ordinary matrix techniques with matched boundary conditions in the interface of air and substrate.

$$\frac{\partial S_{yi}}{\partial z} = k U_{xi} \qquad \frac{\partial U_{xi}}{\partial z} = \left(\frac{k_{xi}^2}{k} \right) S_{yi} - k \sum_p \varepsilon_{(i-p)} S_{yp}$$



What are you measuring?



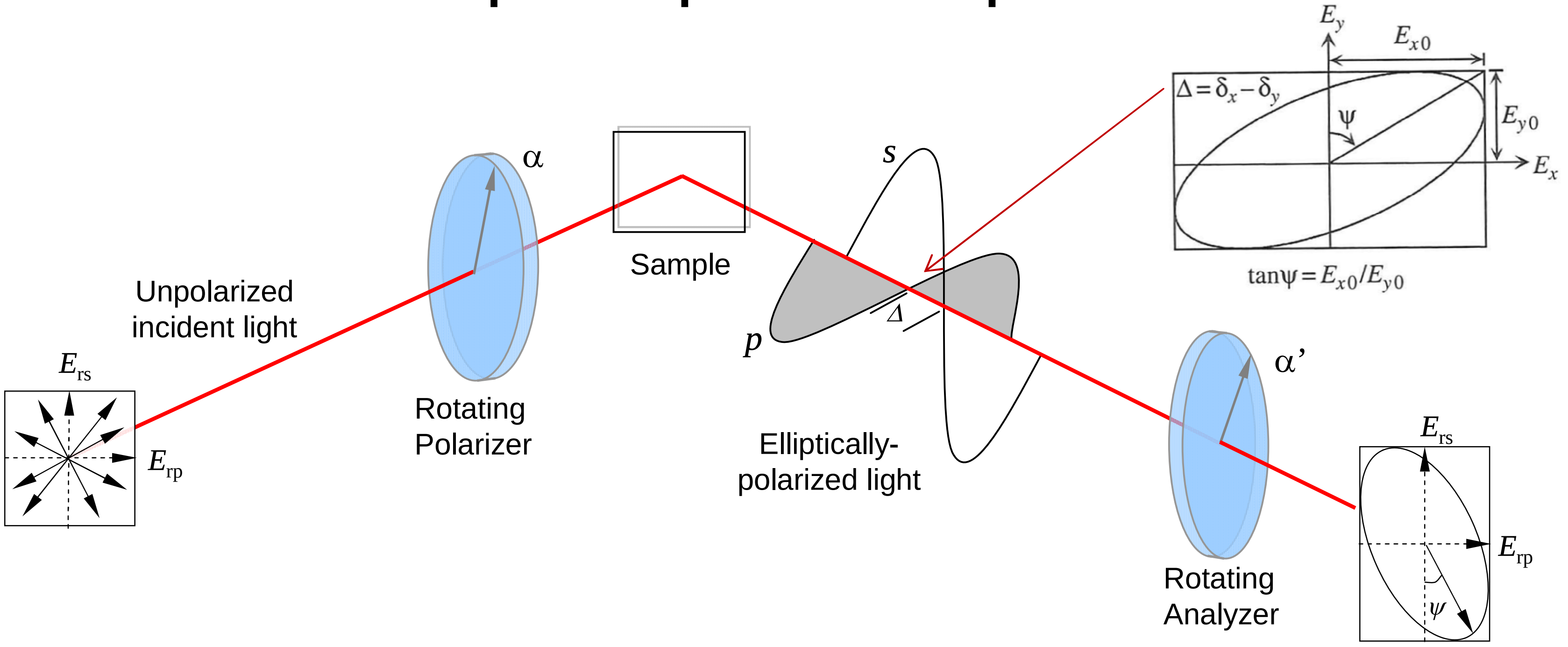
single value from distribution

average

Measurement Convergence -
CD-SEM measurement of multiple lines in same image
and Scatterometry determined Average Value

Rotating-polarizer ellipsometry (P_RSA)

One example from many types of ellipsometers
Great for Isotropic Samples & No Depolarization



$$S = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I_x + I_y \\ I_x - I_y \\ I_{\pi/4} - I_{-\pi/4} \\ I_{LCP} - I_{RCP} \end{bmatrix}$$

Stokes Vector

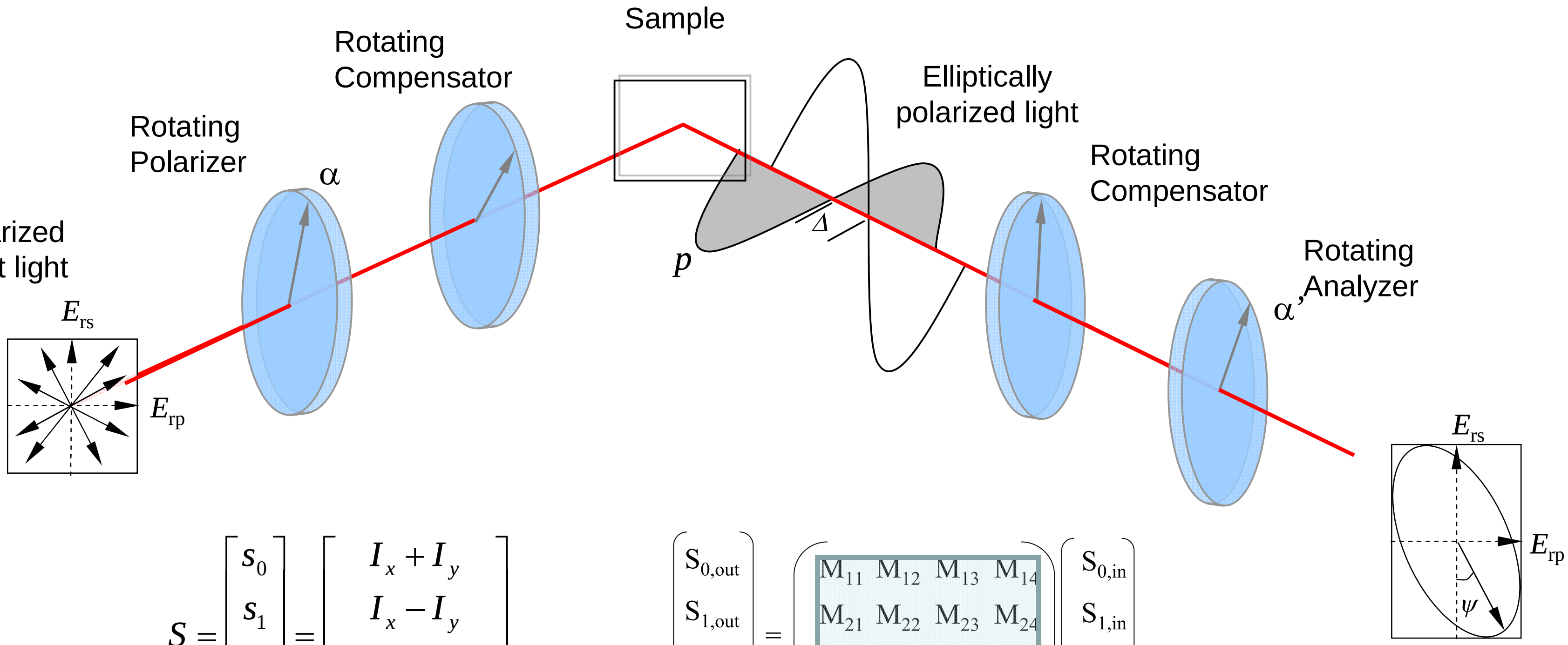
$$\begin{pmatrix} S_{0,\text{out}} \\ S_{1,\text{out}} \\ S_{2,\text{out}} \\ S_{3,\text{out}} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} S_{0,\text{in}} \\ S_{1,\text{in}} \\ S_{2,\text{in}} \\ S_{3,\text{in}} \end{pmatrix}$$

Mueller Matrix

$$\tan \Psi e^{i\Delta} = \frac{r^P}{r^S}$$

Dual Rotating Compensator Ellipsometer (RC2)

Laboratory Ellipsometer
Great for All Types of Samples



$$S = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I_x + I_y \\ I_x - I_y \\ I_{\pi/4} - I_{-\pi/4} \\ I_{LCP} - I_{RCP} \end{bmatrix}$$

Stokes Vector

$$\begin{pmatrix} S_{0,out} \\ S_{1,out} \\ S_{2,out} \\ S_{3,out} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} S_{0,in} \\ S_{1,in} \\ S_{2,in} \\ S_{3,in} \end{pmatrix}$$

Mueller Matrix

Optical Scatterometry Summary

- **Diffraction-Based Tool - Ellipsometers / Reflectometers**
  - Optical scattering→ average grating CD/profile
  - Software/model-dependent solution of CD/profile
  - Not imaging tool like CD-SEM, less localized info

- **Pros**
  - Fast, non-destructive, cheap CD/profile metrology
  - Non-vacuum → small size → standalone or integrated
  - High confidence measurement of average process

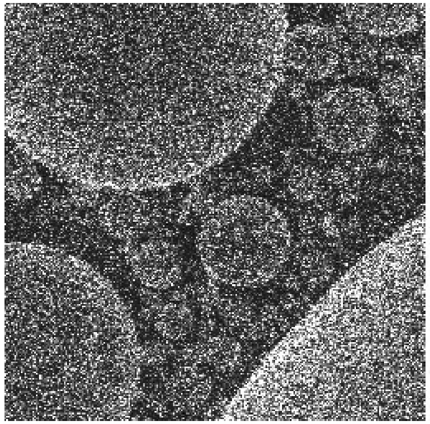
- **Cons**
  - Accuracy known only after verification to reference
  - No variation information
  - Grating target only, not applicable in-circuit, cannot measure discrete features
  - Model solution vulnerable to shift in optical properties

CD-SEM Life Extension

- The useful life of CD-SEM may be extended through improved alignment and calibrations.
  - Drift corrected frame averaging (NIST)
  - Tool matching and performance monitoring using the Contrast Transfer Function

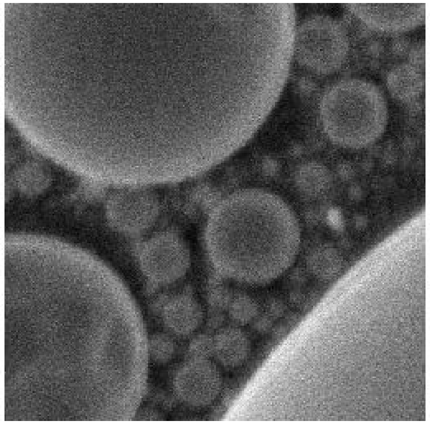
Frame averaging with drift correction

Contour metrology can be improved through frame average if successive frames are aligned using information from interferometer based stage tracking.



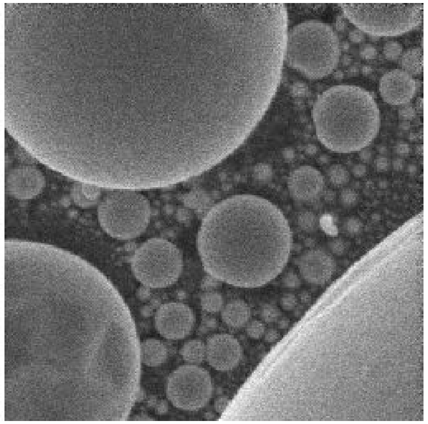
Single frame

11ms frame time



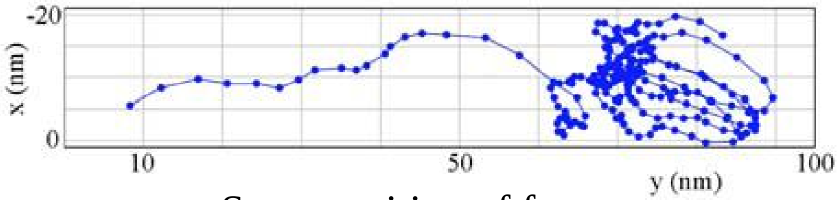
70 frames

Standard frame averaging



70 frames

NIST averaging

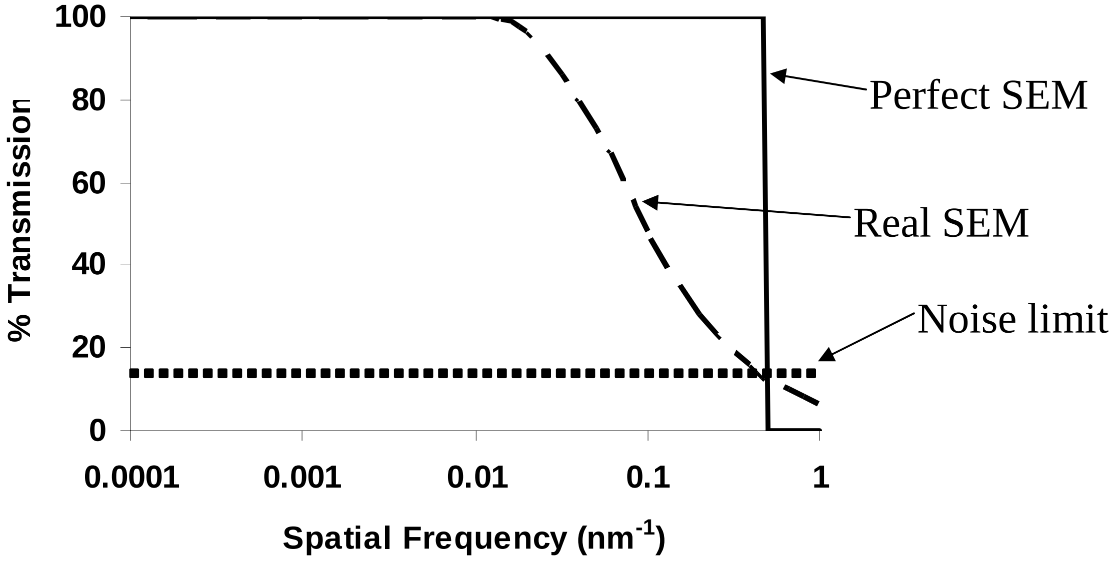


Stage position of frames

Andras Vladar (NIST)

Contrast Transfer Function

- The Contrast Transfer Function (CTF) of a tool provides a measure of the fidelity with which sample information is transferred to the final image, as a function of spatial frequency.
  - Resolution limit is when the CTF falls below the noise floor.



D.C. Joy, J. Michael, B. Griffin, *Evaluating SEM Performance from the Contrast Transfer Function*. Proc. SPIE **7638**, 76383J (2010)

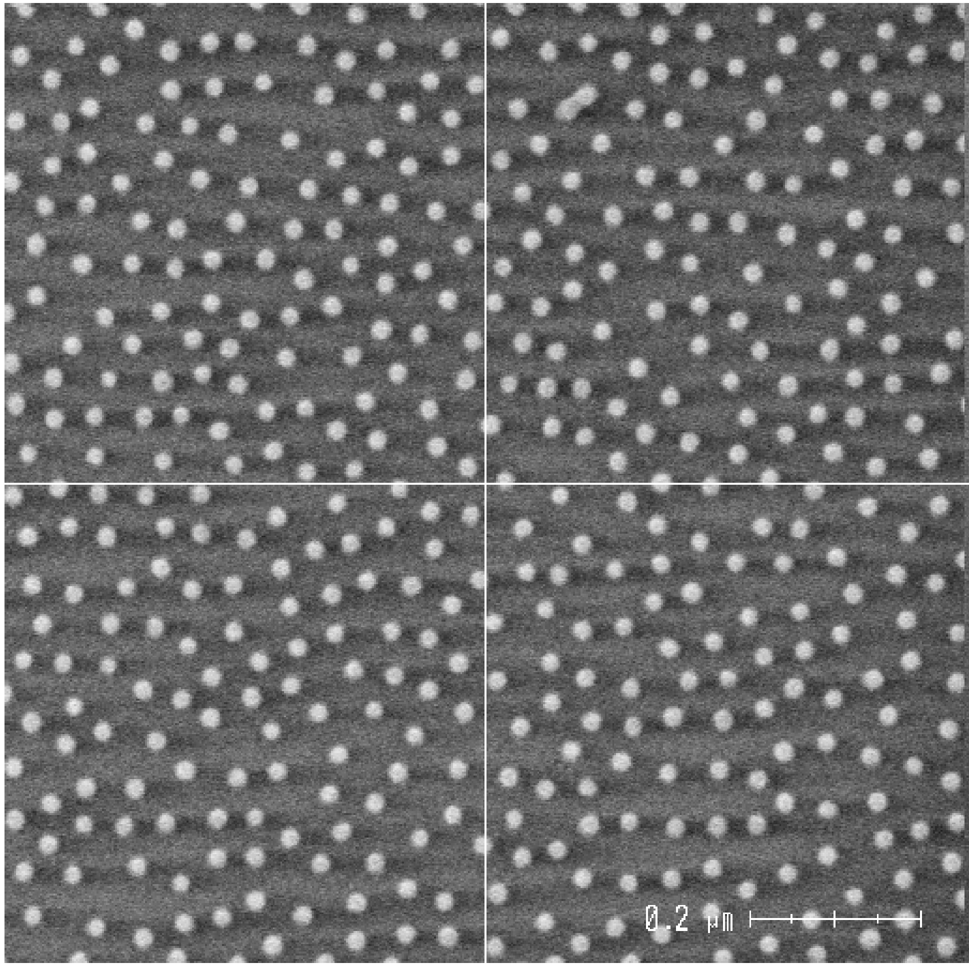
Obtaining the CTF

- The CTF can be obtained from the Fourier transformed image of a specimen with uniform power across all spatial frequencies.
  - Impossible to produce perfectly, but can use
    - Fresnel Zone Plates
    - Pseudo-random dot arrays
  - Quality of transform depends on precision of specimen

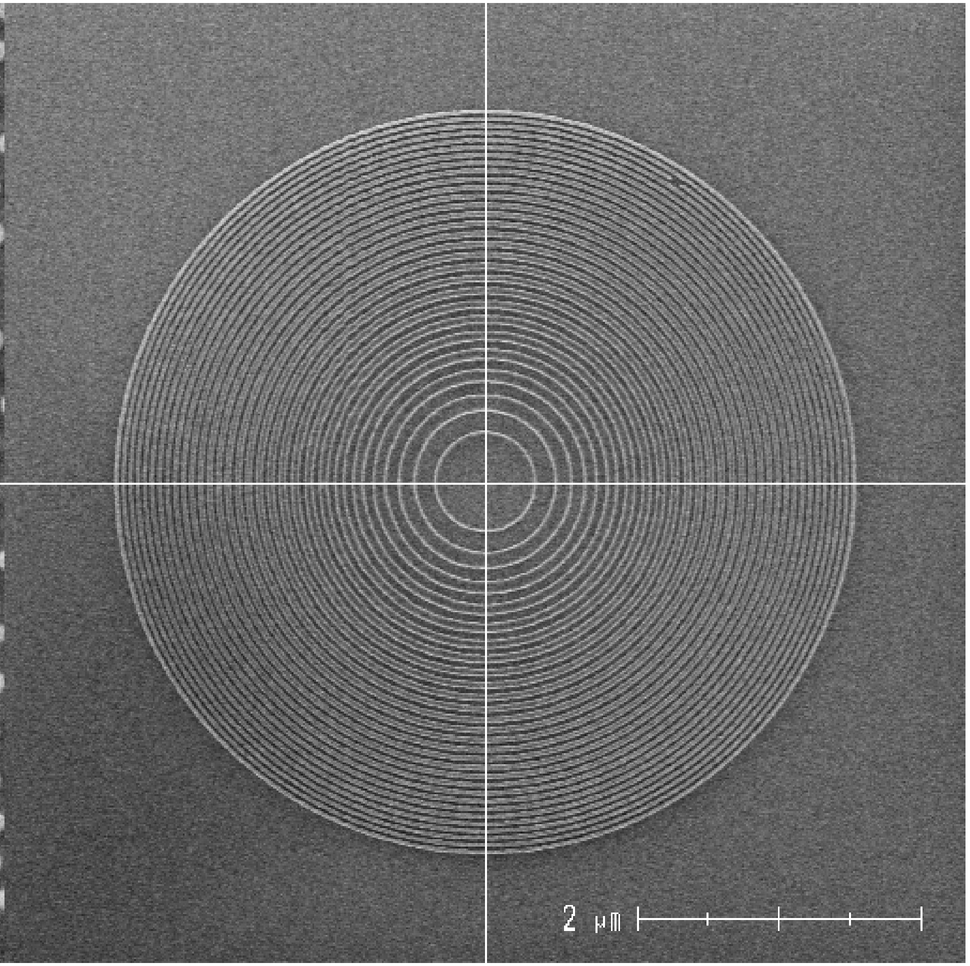
- Notes:
  - CTF is a simplification of the Optical Transfer function appropriate for digital images
  - CFT = Fourier Transform of the Point Spread Function

CTF Targets

CTF test structures: photoresist on silicon, prepared with e-beam written template and nano-imprint lithography with a 22 nm process.



Pseudo-random dot array

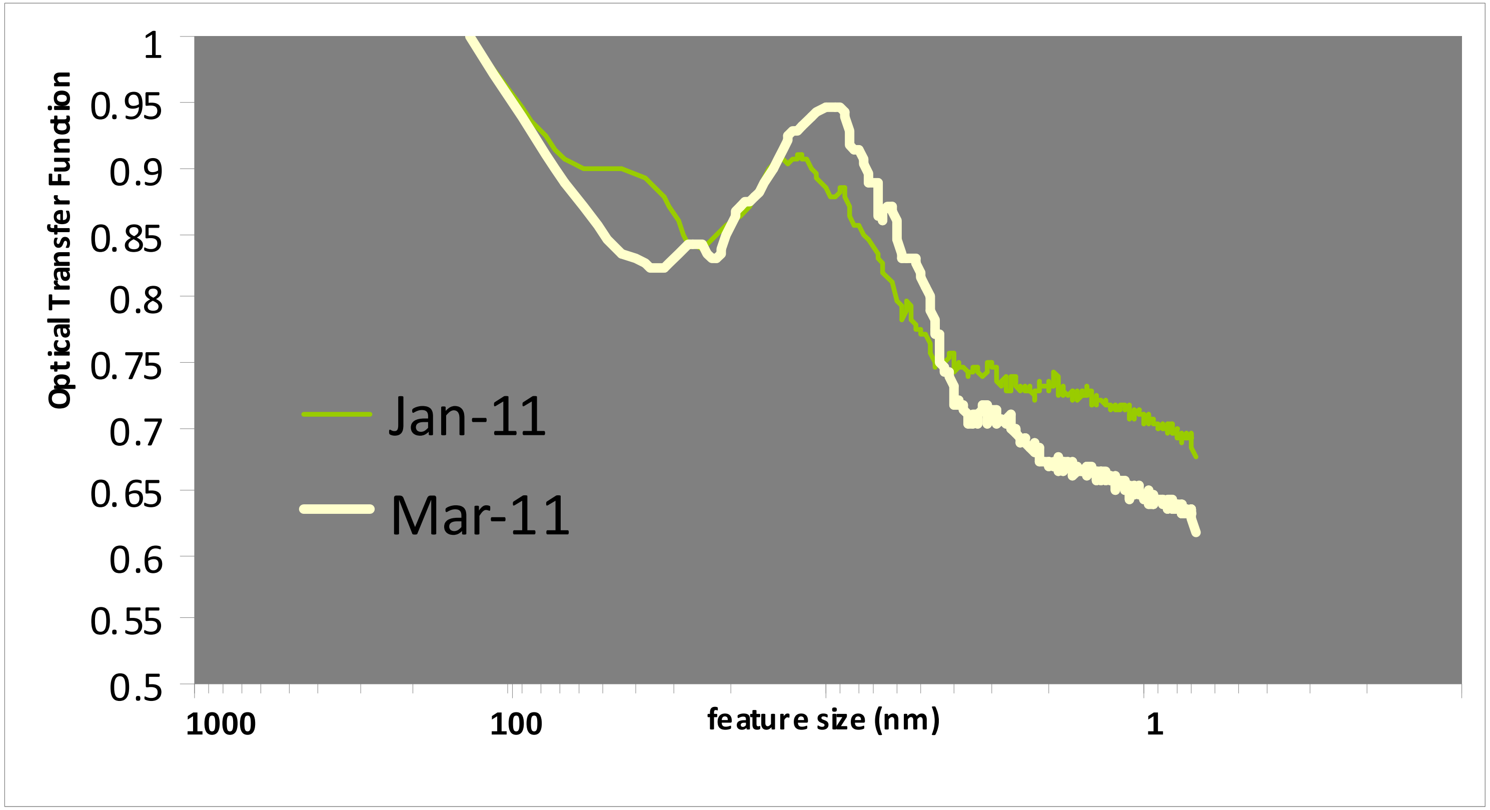


Fresnel Zone Plate

Performance Defects

- Tool performance defects have signatures in the CTF.
  - Defocus
  - Astigmatism
  - Aberrations
  - Vibrations
  - Detector efficiency
  - External fields

Tracking Tool Performance



- Data corresponding to the larger feature sizes appears unchanged
- Data taken in March shows a noise floor with less magnitude, which begins at smaller feature sizes

Conclusions

- Candidate solutions exist for replacing CD-SEM, but there is no clear leader.
  - More development is necessary
- Optical Scatterometry is currently feasible, but:
  - Results are strongly model & material dependent
  - Does not provide information on variance
- X-ray Scatterometry is not currently practical, but:
  - Synchrotron-based results are impressive
  - Significant amount of information can be extracted
  - Models are robust
- Fortunately, a little more life can be squeezed out of CD-SEMs