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MULLER MATRIX SPECTROSCOPIC ELLIPSOMETRY BASED SCATTEROMETRY

Alain C. Diebold

AGENDA

- Introduction
- Mueller Matrix Spectroscopic Ellipsometry
- Simulation Methods
  - Rigorous Coupled Wave Analysis (RCWA)
- Scatterometry of Fins
- Scatterometry of DSA BCP
- Scatterometry of Copper Cross-Grating
- Conclusions

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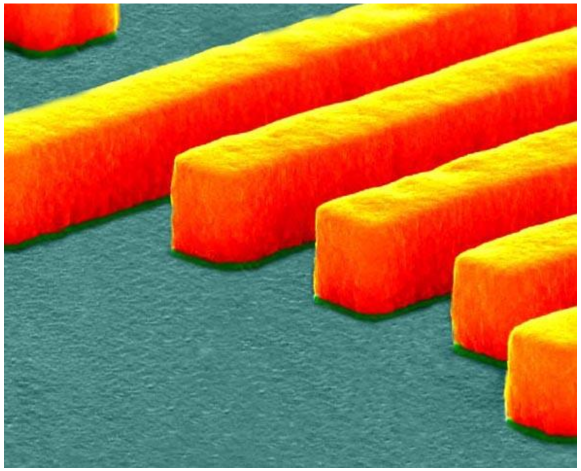
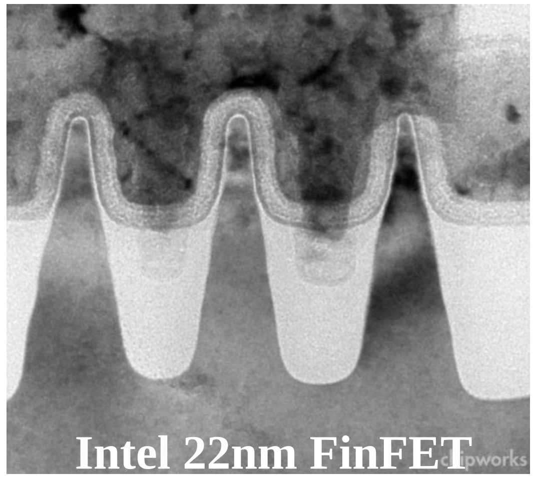
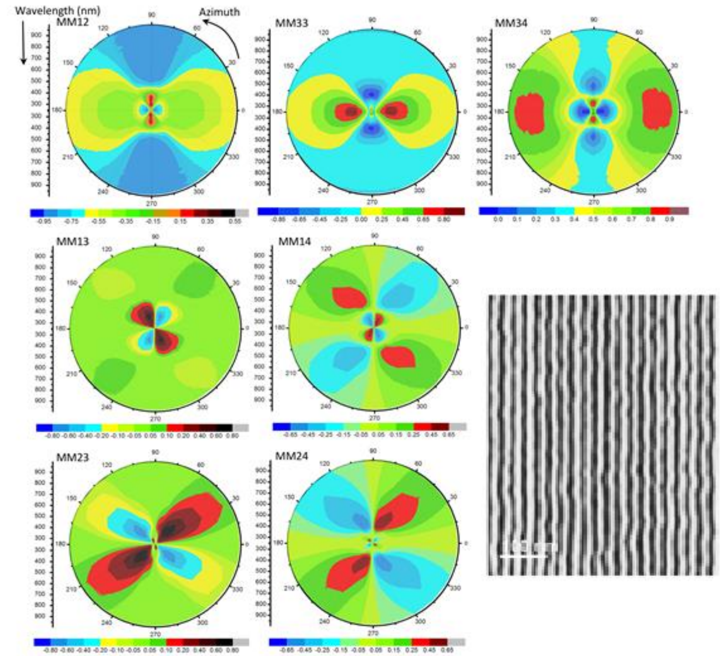
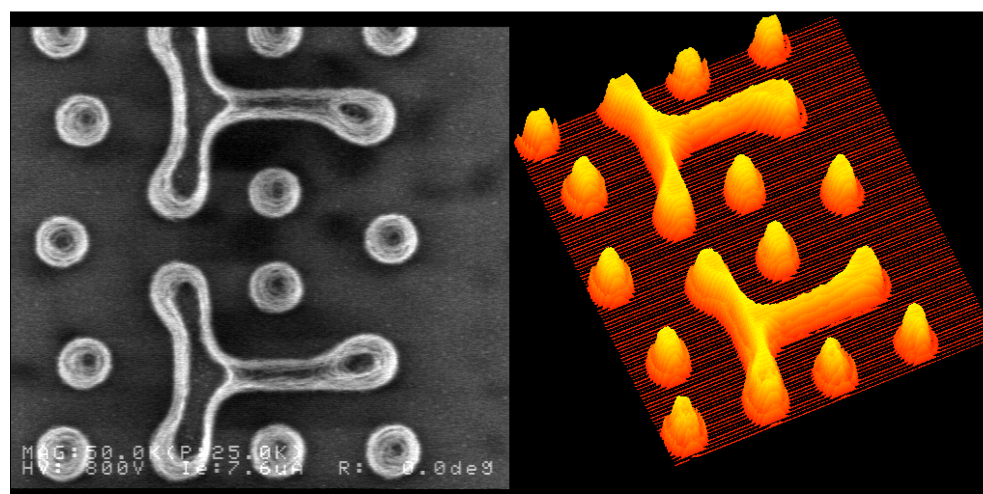
Optical Measurement of the Dimensions of 3D Features







Scatterometry measurement of of shape profile with dimensional Information
Is an alternative to CD-SEM



Figures : Andras Vladar (NIST) and Synopsys & A.C. Diebold – SPIE Key Note 2011

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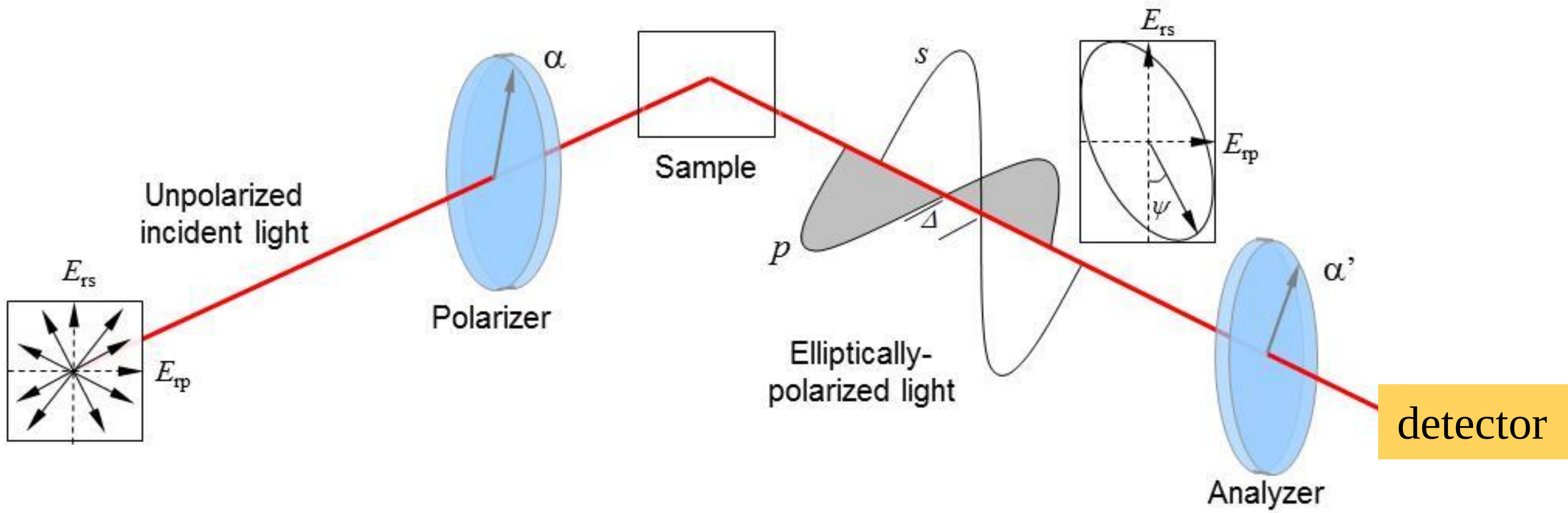
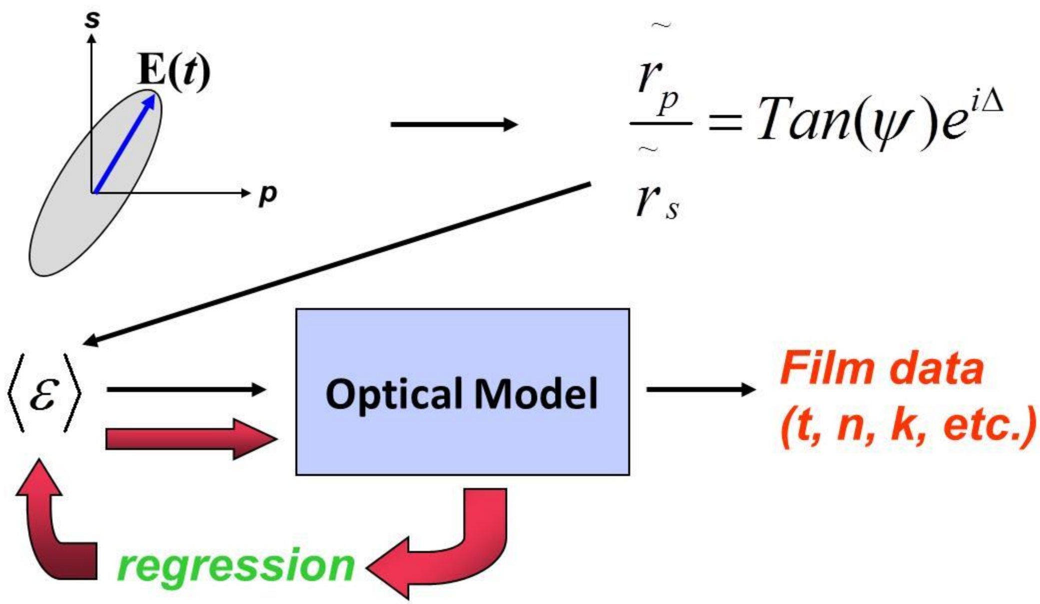
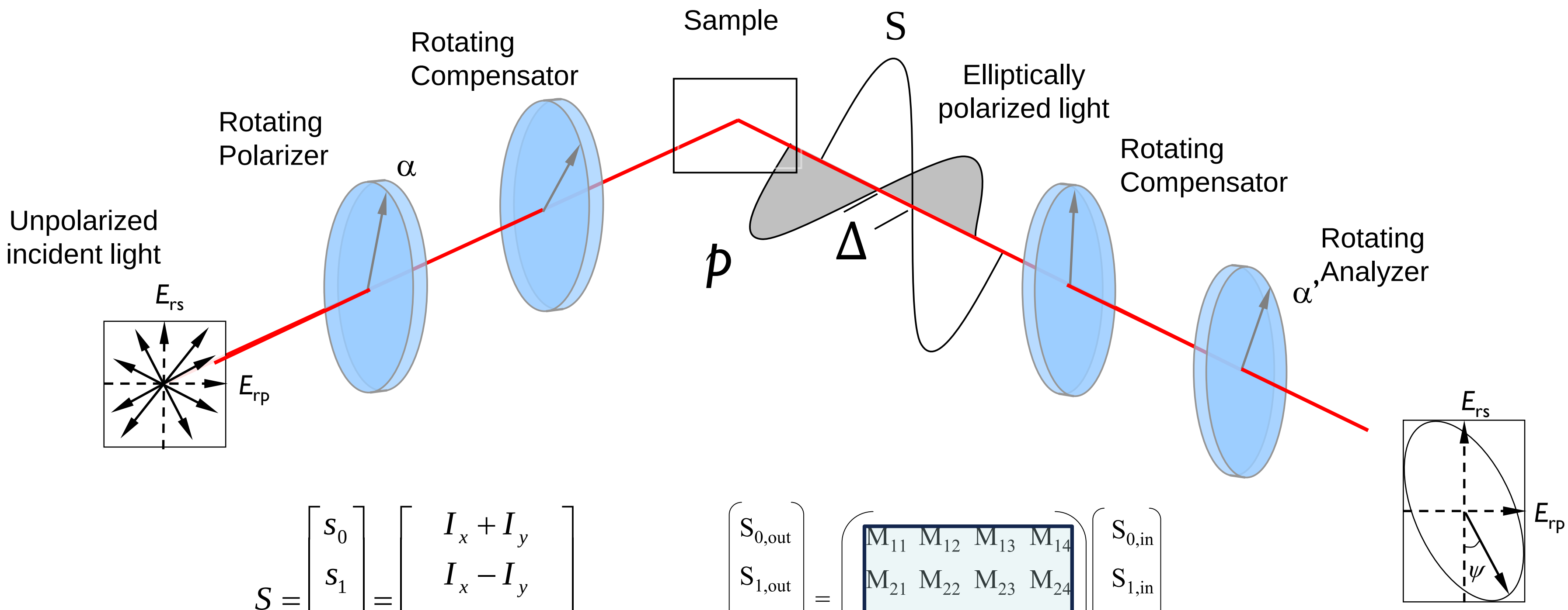
Ellipsometry





Dual Rotating Compensator Ellipsometer (RC2)

Laboratory Ellipsometer
Great for All Types of Samples



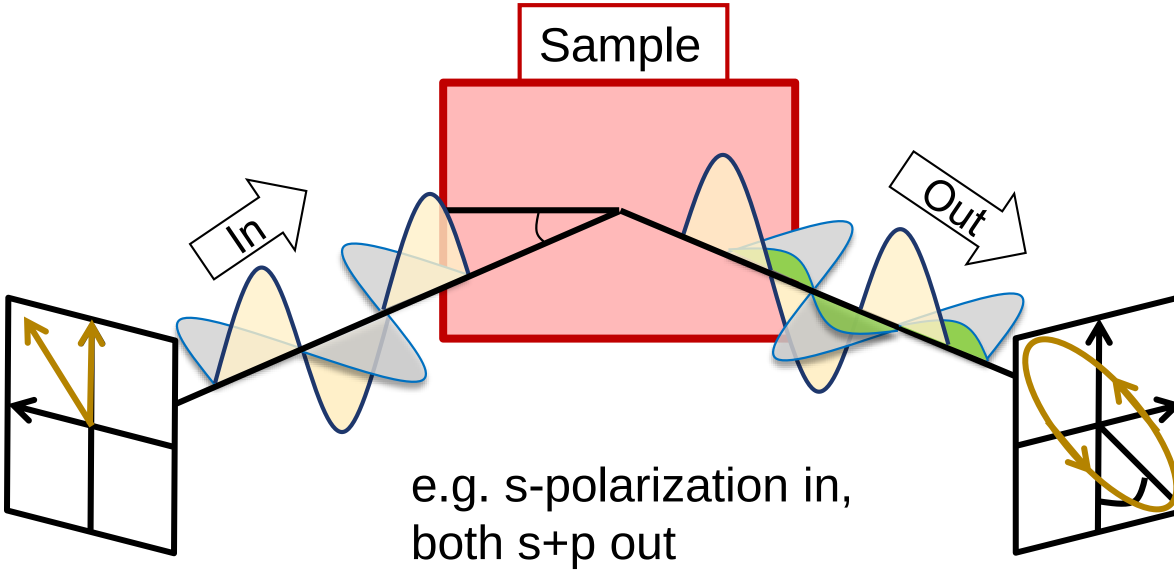
$$S = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I_x + I_y \\ I_x - I_y \\ I_{\pi/4} - I_{-\pi/4} \\ I_{LCP} - I_{RCP} \end{bmatrix}$$

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

Background optics



Cross / Standard
Polarization
Response

p ⟶ p+s

s ⟶ s+p

- Isotropic samples
  - Refractive indices of thin films lack spatial dependence
  - Thus, no azimuthal dependence or cross-polarization
- Anisotropic structures
  - Patterned surfaces result in spatially varying refractive indices
  - Thus, azimuthal dependence reflects sample symmetry

Mueller Matrix Basics

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Anisotropic, general grating

Post-normalization

$$M = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} = \begin{pmatrix} 1 & -N-\alpha_{sp} & C_{sp}+\zeta_1 & S_{sp}+\zeta_2 \\ -N-\alpha_{ps} & 1-\alpha_{sp}-\alpha_{ps} & -C_{sp}+\zeta_1 & -S_{sp}+\zeta_2 \\ C_{ps}+\xi_1 & -C_{ps}+\xi_1 & C_{pp}+\beta_1 & S_{pp}+\beta_2 \\ -S_{ps}+\xi_2 & S_{ps}+\xi_2 & -S_{pp}-\beta_2 & C_{pp}+\beta_1 \end{pmatrix}$$

- Matrix contains complete optical response of a sample
- Symmetry reduces number of independent elements
- 15 distinct elements in general

$$D = 1+\tan^2(\psi_{pp})+\tan^2(\psi_{ps})+\tan^2(\psi_{sp})$$

$$N = \frac{1-\tan^2(\psi_{pp})-\tan^2(\psi_{ps})-\tan^2(\psi_{sp})}{D}$$

$$C_{ij} = \frac{2\tan(\psi_{ij})\ \cos\Delta_{ij}}{D}$$

$$S_{ij} = \frac{2\tan(\psi_{ij})\ \sin\Delta_{ij}}{D}$$

$$\alpha_{ij} = \frac{2\tan^2(\psi_{ij})}{D}$$

$$\zeta_i = \frac{D\left(C_{ps}^2+S_{ps}^2(-1)^{i+1 \bmod 2}\right)}{2}$$

$$\xi_i = \frac{D\left(C_{sp}^2+S_{sp}^2(-1)^{i+1 \bmod 2}\right)}{2}$$

$$\beta_i = \frac{D\left(C_{sp}C_{ps}+S_{sp}S_{ps}(-1)^{i+1 \bmod 2}\right)}{2}$$

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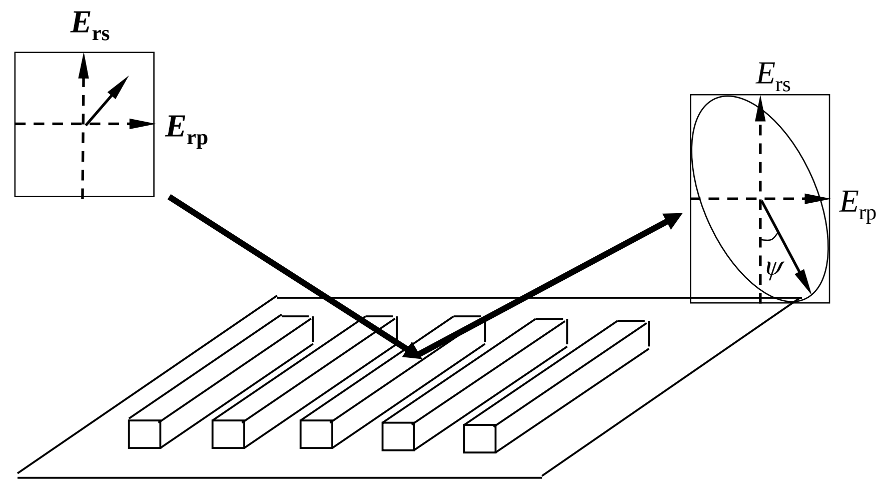
Scatterometry: 3D Metrology

- Inline optical metrology tool for critical dimension (CD) measurement for advanced process control.
- Fast, accurate & non-destructive.
- Diffraction from a periodic grating.

- **Optical simulator is used to generate the optical response for the structure of interest (Forward problem) and regression based or library based approach is used to extract the feature dimensions/additional information (Reverse problem).**



Ellipsometry of Grating Structures

Optical Response

$$\tan \Psi \, e^{j\Delta} = \frac{R^p}{R^s}$$

Ellipsometric Response

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

Mueller Response

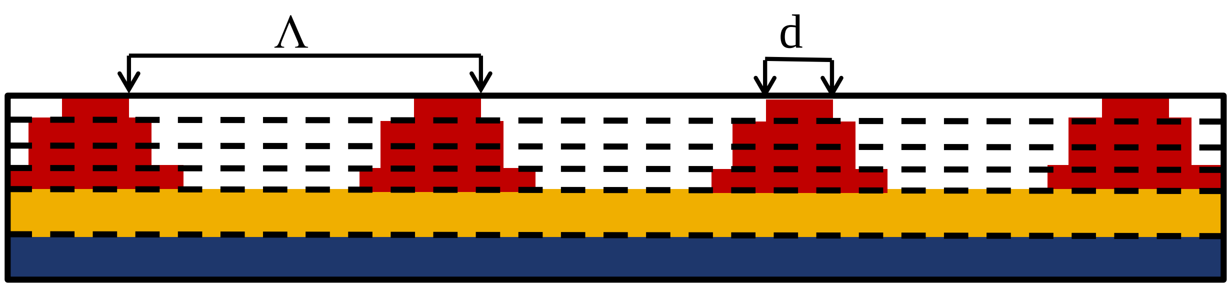
Rigorous coupled wave approximation (RCWA)

- Approximate full Fourier series for dielectric function

$$\varepsilon(x) = \sum_{n=-N}^{N} \varepsilon_n e^{i2\pi nx/\Lambda}$$

- Slice structure into stack of layers, coefficients determined:

$$\varepsilon_{n=0} = \varepsilon_{line} d/\Lambda + \varepsilon_{space}(1 - d/\Lambda) \qquad \varepsilon_{n\neq 0} = (\varepsilon_{line} - \varepsilon_{space})\sin(n\pi d/\Lambda)/n\pi$$



- Solve Maxwell's equations for incident TM polarized waves

$$\nabla^2 E_y(x,z) + k^2 \varepsilon(x) E_y(x,z) = 0 \qquad E_y(x,z) = \sum_{m=-\infty}^{\infty} E_{my} e^{(ik_{xm}x + ik_{zm}z)}$$

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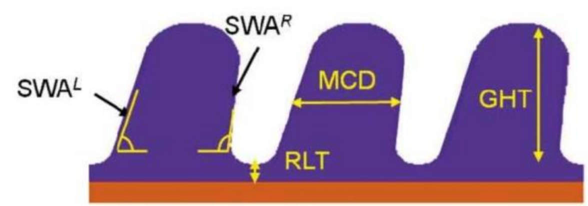
Mueller Matrix Basics

The interaction of light with the optical elements of the ellipsometer and the sample can be represented by the Mueller matrix (MM) Transformation.

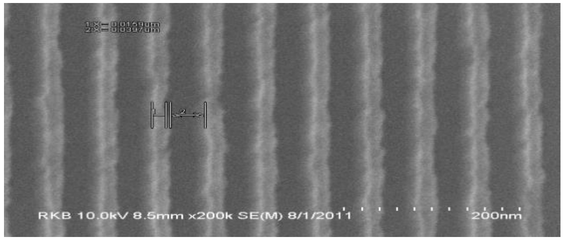
The intensity & polarization of the light can be represented by a Stokes vector

$$S = \begin{bmatrix} I_x + I_y \\ I_x - I_y \\ I_{45} - I_{-45} \\ I_L - I_R \end{bmatrix} \qquad \begin{pmatrix} S_{0,out} \\ S_{1,out} \\ S_{2,out} \\ S_{3,out} \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} S_{0,in} \\ S_{1,in} \\ S_{2,in} \\ S_{3,in} \end{pmatrix}$$

<u>Why does this matter</u>?
If you have samples with asymmetry/anisotropy
If you have samples that depolarize—roughness, systematic errors



The full generalized MM description gives complete information about the sample.



Anisotropy in off-diagonal elements and depolarization is distributed among the Mueller matrix elements

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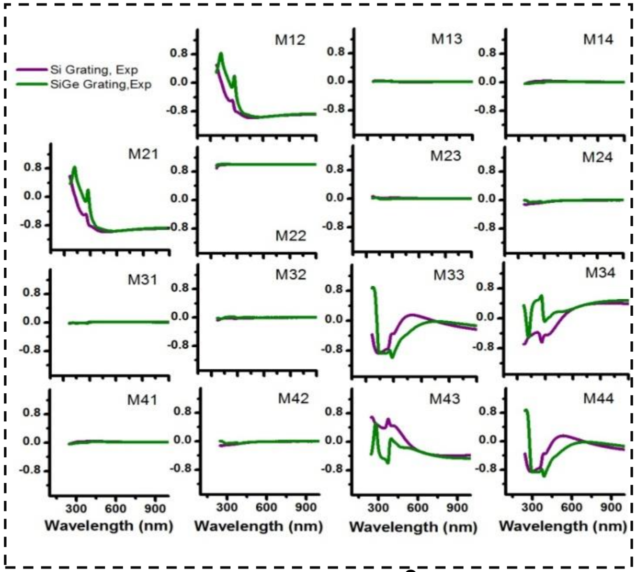
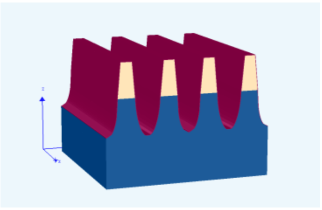
Si & SiGe Gratings

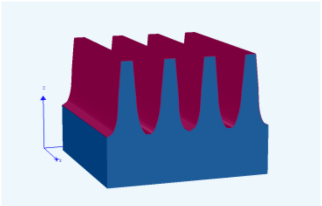


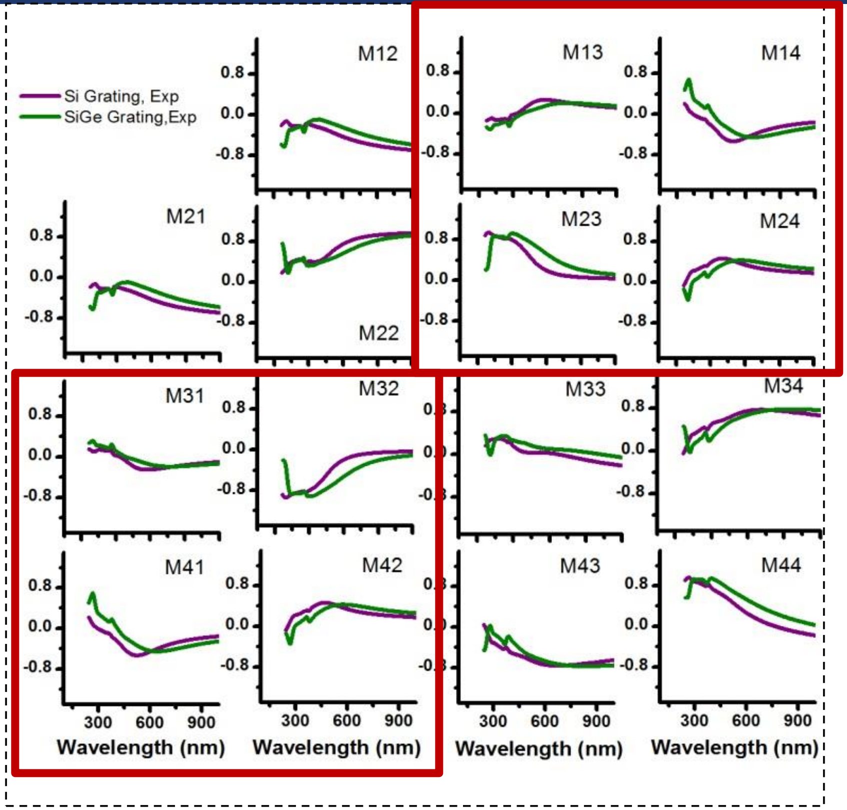
Azimuth = 0^0

SiGe Grating

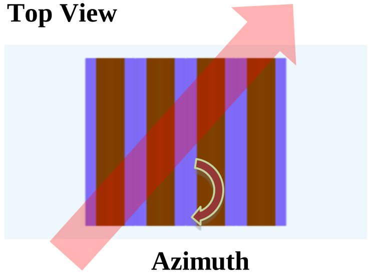


Si Grating

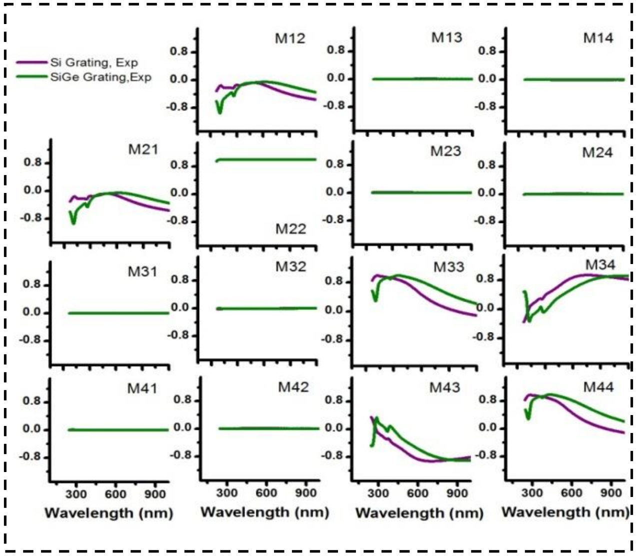




Azimuth = 45^0



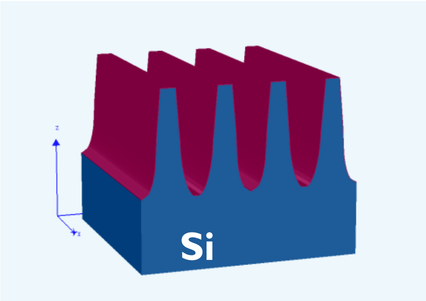
Non-zero off-diagonal Mueller response



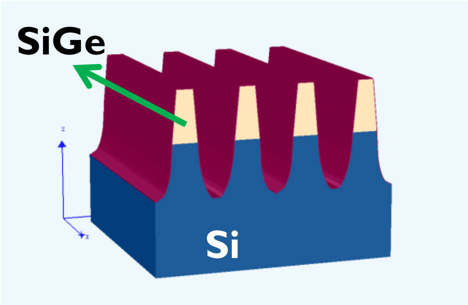
Azimuth = 90^0

Results: Si & SiGe Gratings

Wafer ID	Si Fins			
Mean OCD values	Azimuth			Coupled Multi-azimuth Regression
	0^0	45^0	90^0	
Bottom CD (nm)	29.3 1σ=0.01	32.4 1σ=0.01	31.3 1σ=0.03	30.9
Top CD (nm)	11.7 1σ=0.01	12.7 1σ=0.01	12.3 1σ=0.01	11.4
Height (nm)	65.5 1σ=0.07	66.3 1σ=0.02	67.5 1σ=0.01	65.9
MSE	0.03	0.06	0.04	0.04



Wafer ID	SiGe Fins			
Mean OCD values	Azimuth			Coupled Multi-azimuth Regression
	0^0	45^0	90^0	
Bottom CD (nm)	24.2 1σ=0.03	29.2 1σ=0.03	26.2 1σ=0.02	24.5 1σ=0.03
Top CD (nm)	11.8 1σ=0.01	14.6 1σ=0.01	12.1 1σ=0.01	14.8 1σ=0.01
SiGe Height (nm)	35.1 1σ=0.02	35.3 1σ=0.03	36.2 1σ=0.03	36.7 1σ=0.02
MSE	0.09	0.18	0.06	0.15



Fully Biaxially strained SiGe Optical properties were used in the analysis. *G.R. Muthinti et al J. Appl. Phys. 112, 053519 (2012).*

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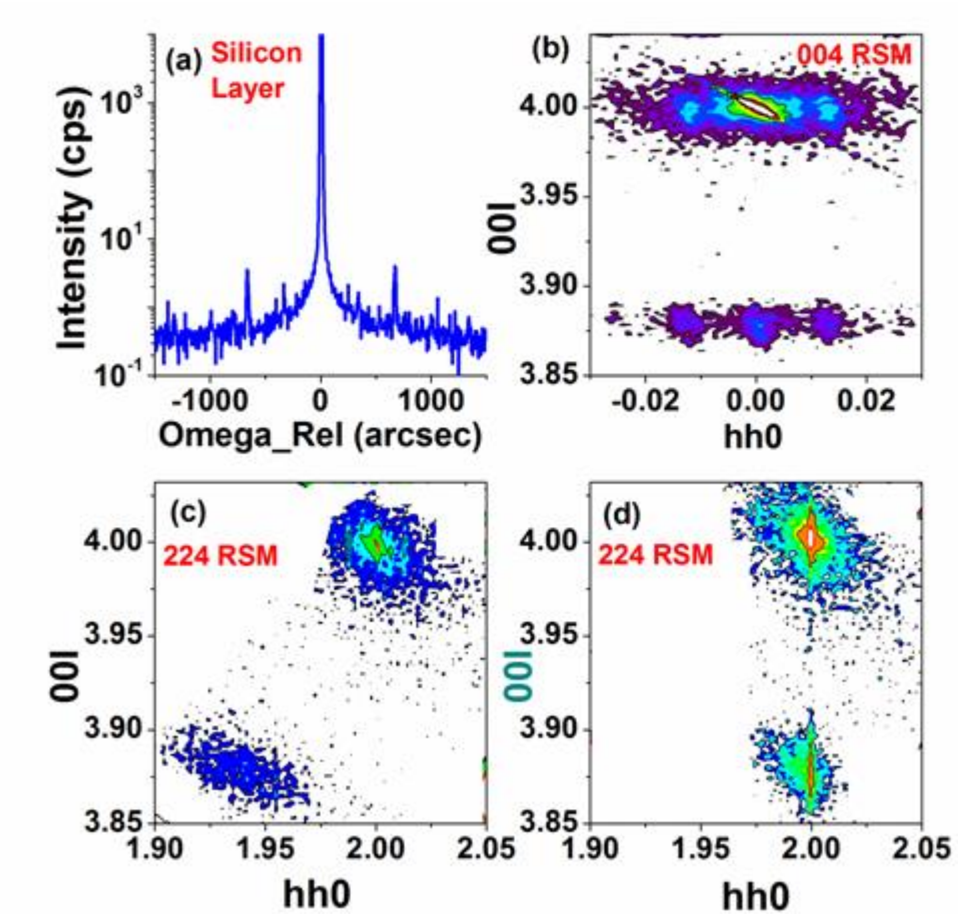
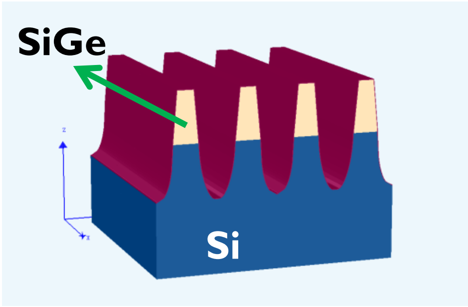
SiGe Grating –RSM HRXRD

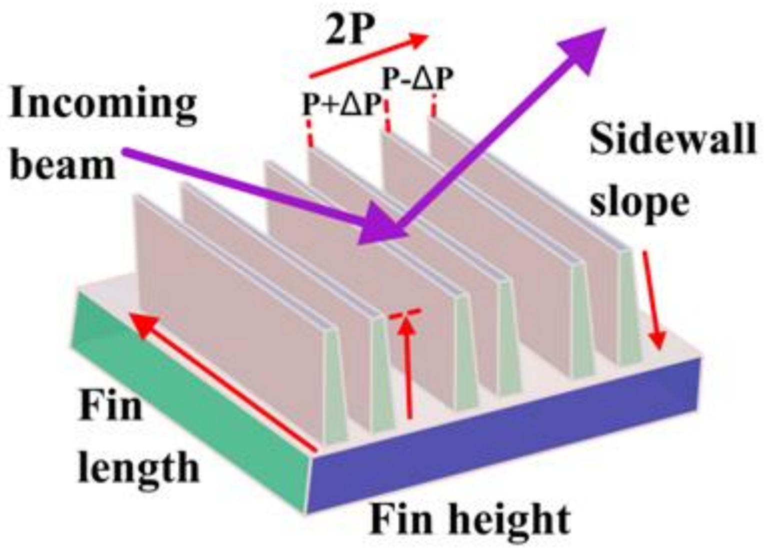


Beam ⊥ to Fins

Beam ‖ to Fins



SiGe Grating



SiGe layer strained along the length of the fin and partially relaxed perpendicular to it.

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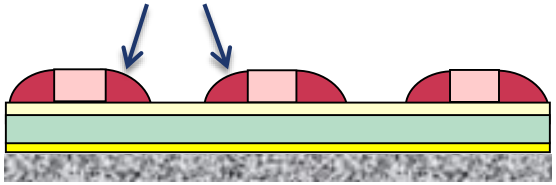
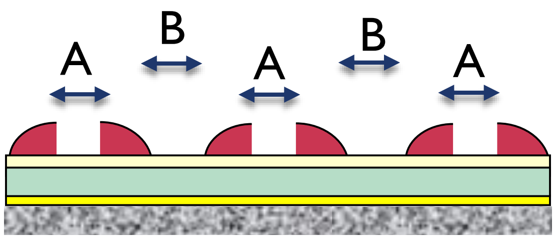
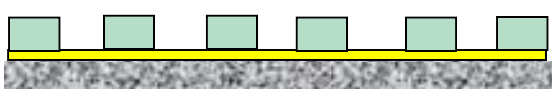
Dual Patterning Spacer Lithography

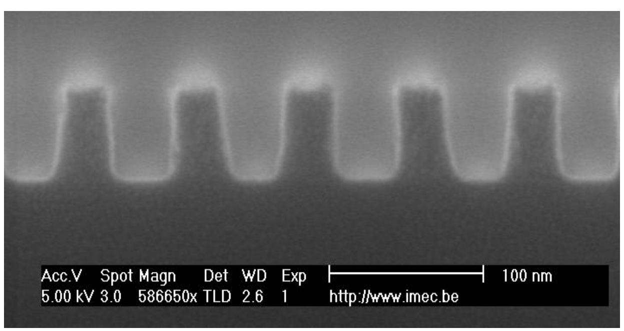
Spacer Pattern



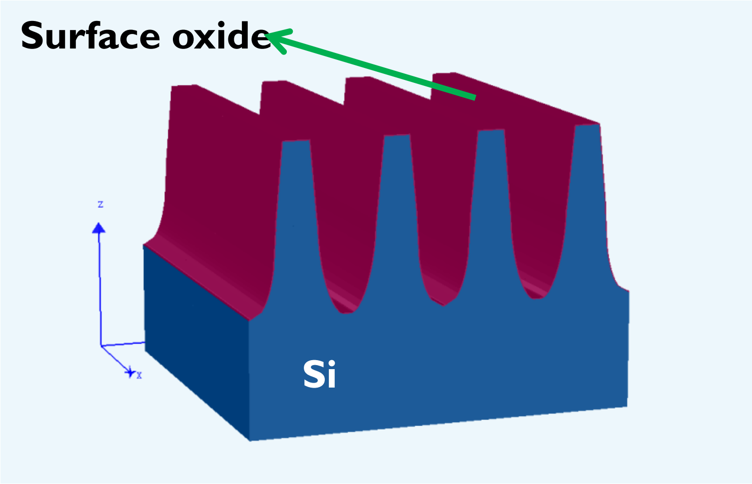
Two space distances = pitch walking



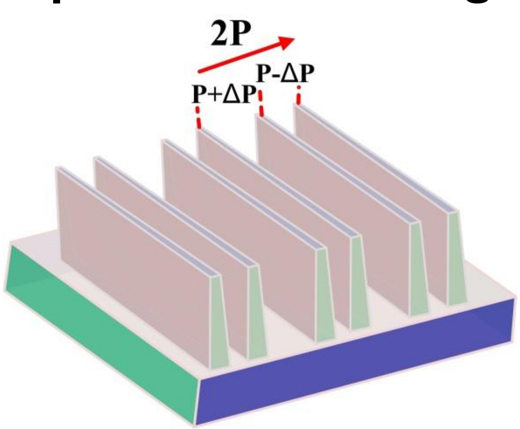




No Pitch Walking

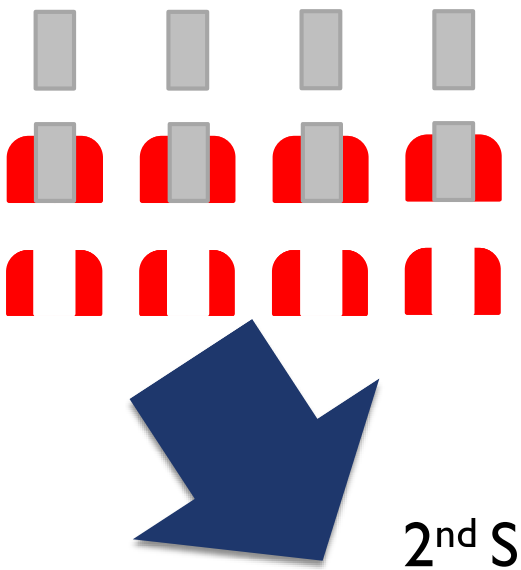


Pitch Walking
~ 1nm pitch difference plus uneven etching



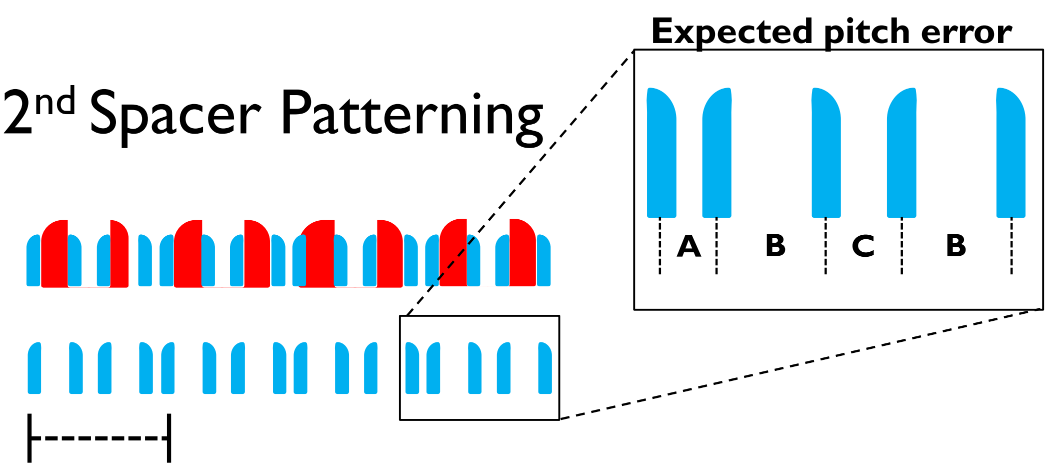
Quadruple Patterning Spacer Lithography

1st Spacer Patterning



3 Space Values instead of 2

2nd Spacer Patterning



Pitch Walking in Quadruple Patterning

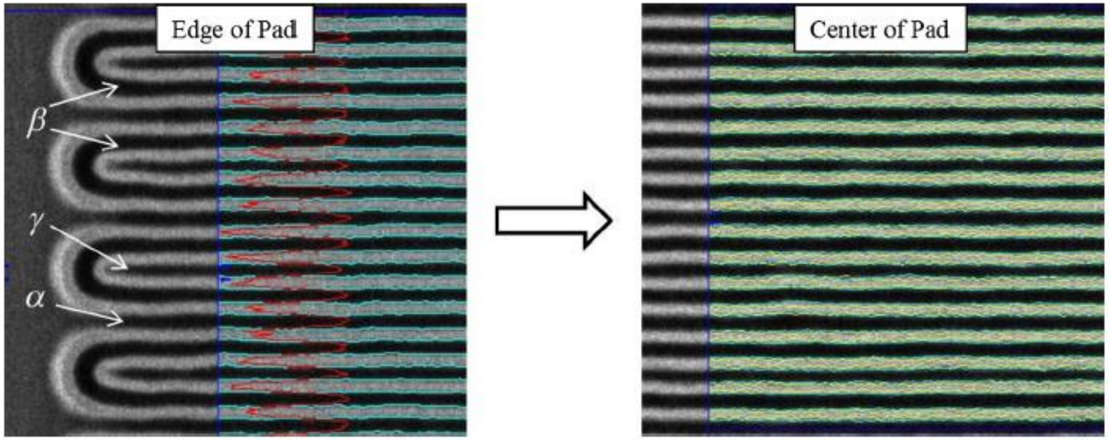


Fig. 4 The CD-SEM would locate α, β, and γ on the edge of OCD measurement pad and jump to center of pad.

2 nm Improvement in measurement in Stability
of Measurement of Pitch Walking using Virtual Referencing

Taher Kagalwala, Alok Vaid, et al, J. Micro/Nanolith. MEMS MOEMS 15(4), 044004 (2016)

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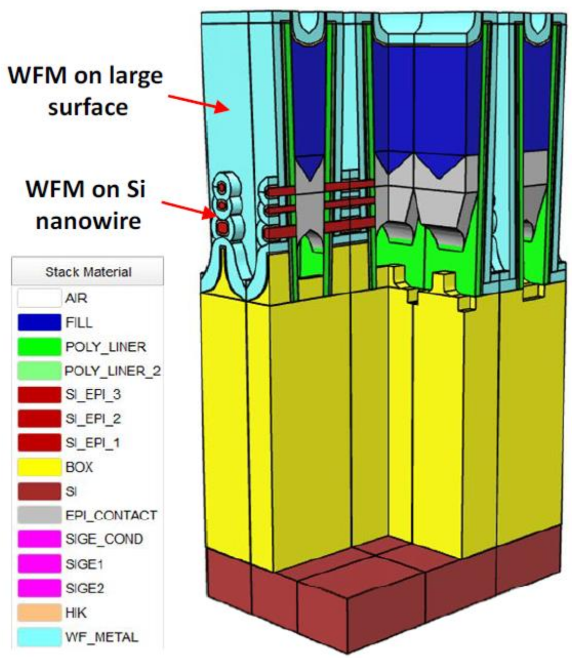
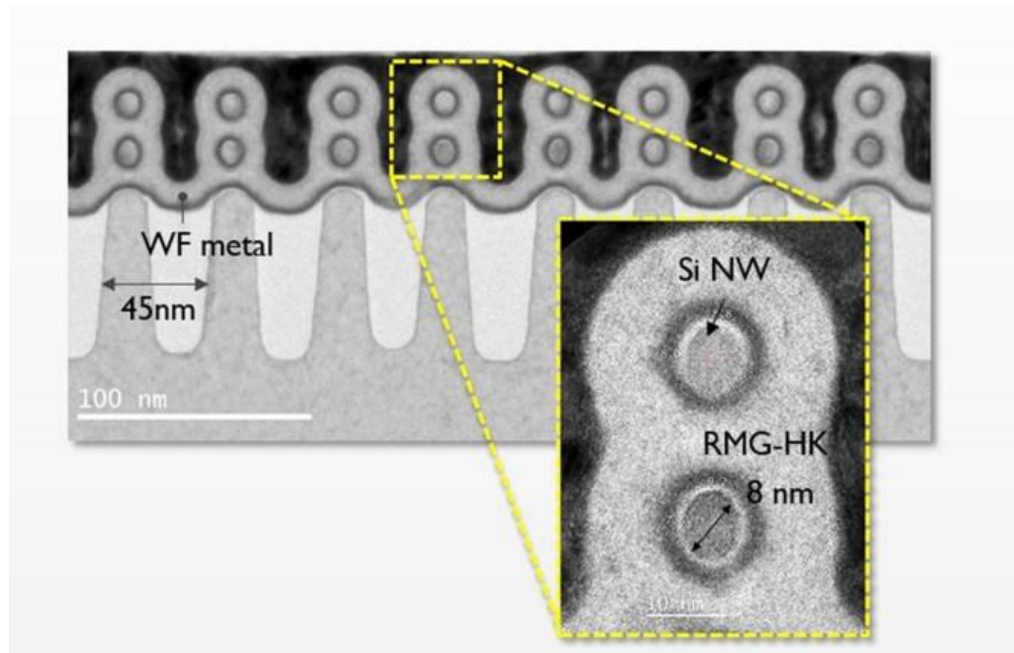
Vertical Nanowire Transistors





- Advanced in-line optical metrology of sub-10nm structures for gate all around devices (GAA), R. Muthinti, SPIE 2016 – Scatterometry
- Vertically Stacked Gate-All-Around Si Nanowire CMOS Transistors with Dual Work Function Metal Gates, H. Mertens, et al, (IEDM 2016)

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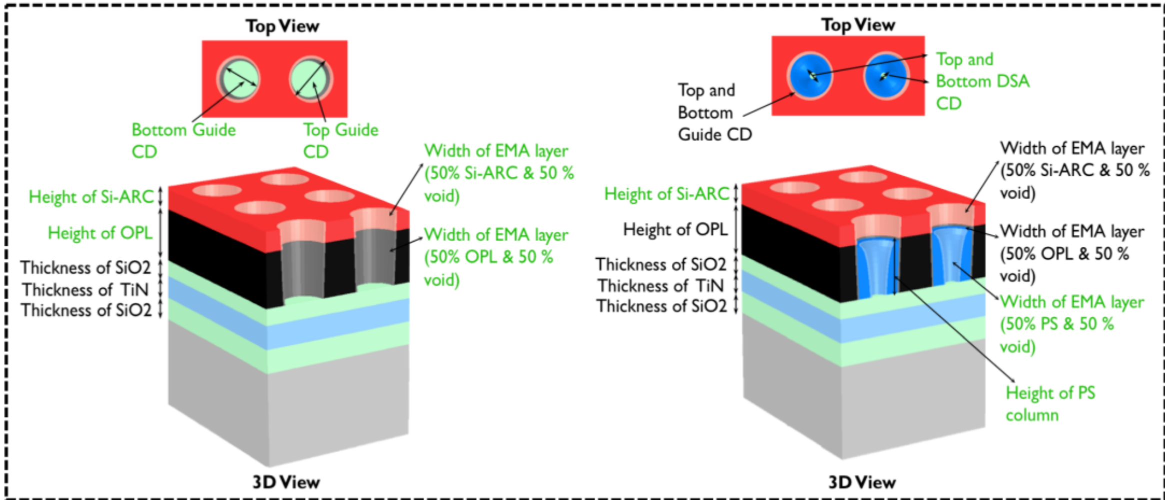
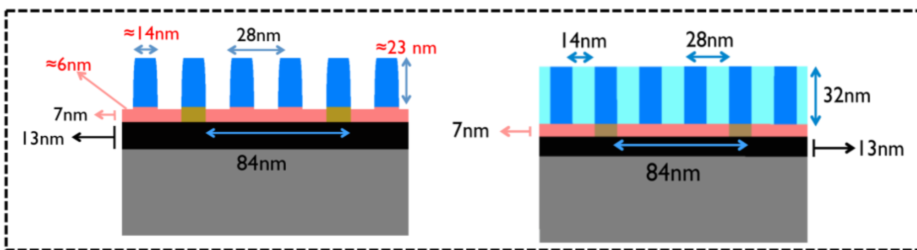
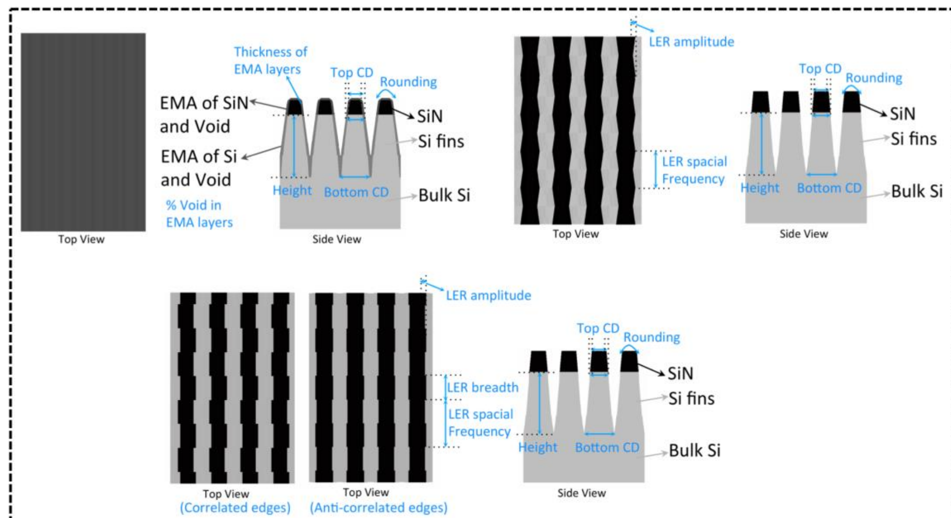
DSA of Block Co-Polymers







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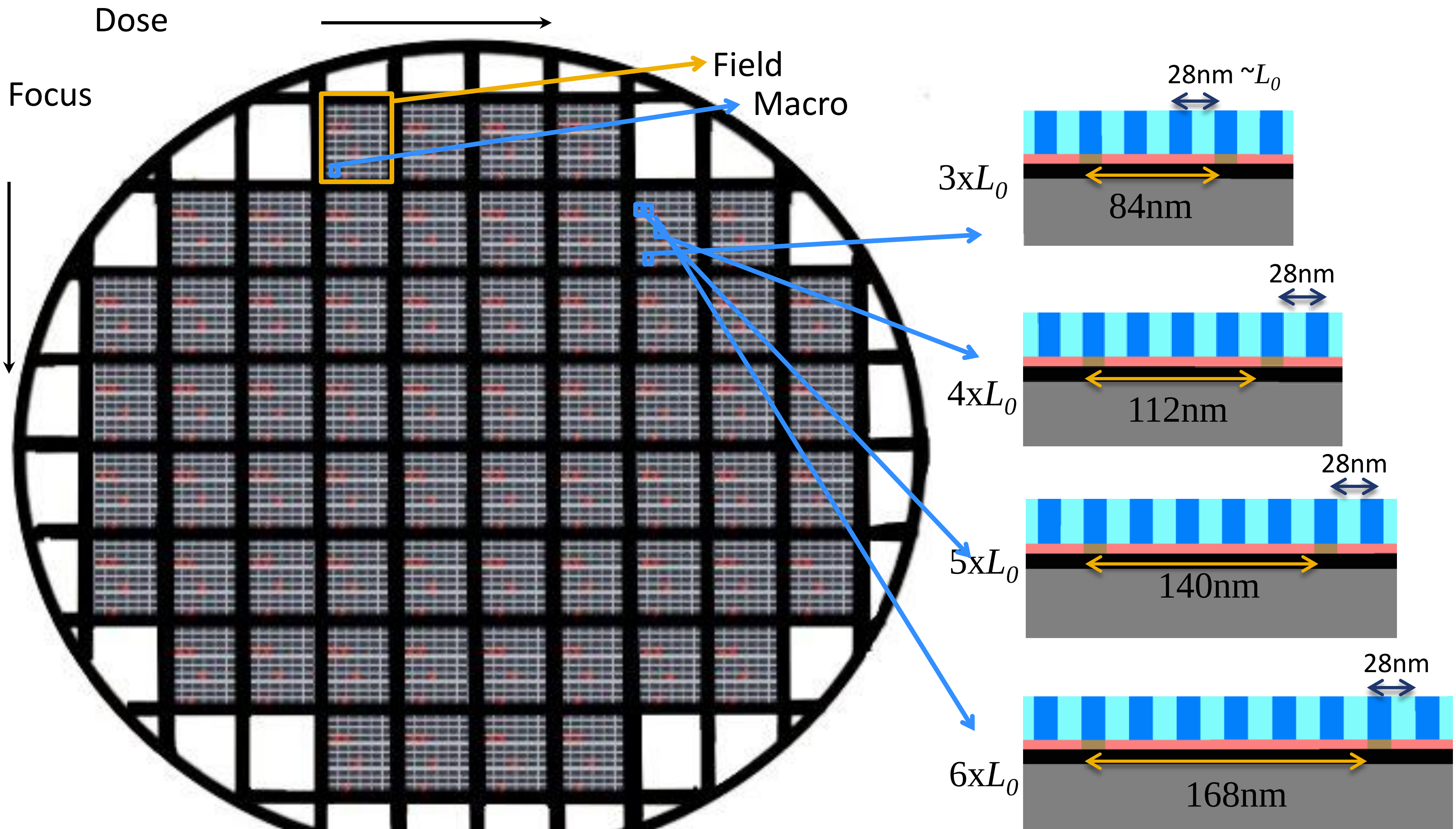
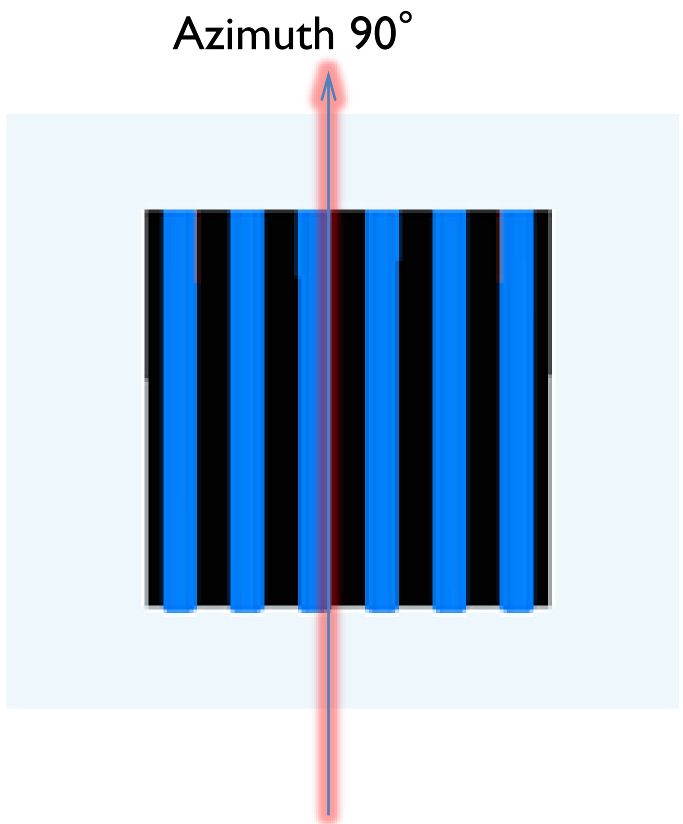
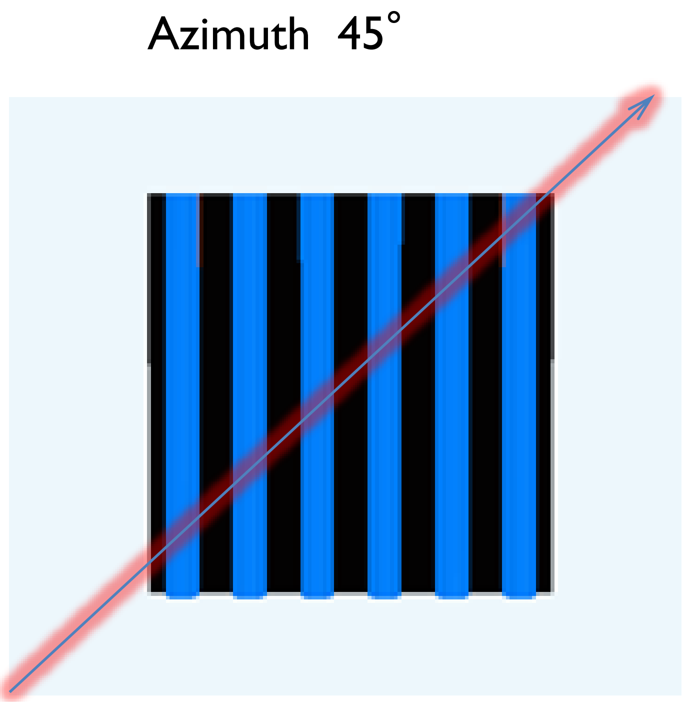
FEM Wafer layout



L_0 : Intrinsic lamellae period of PS-b-PMMA

Useful Definitions





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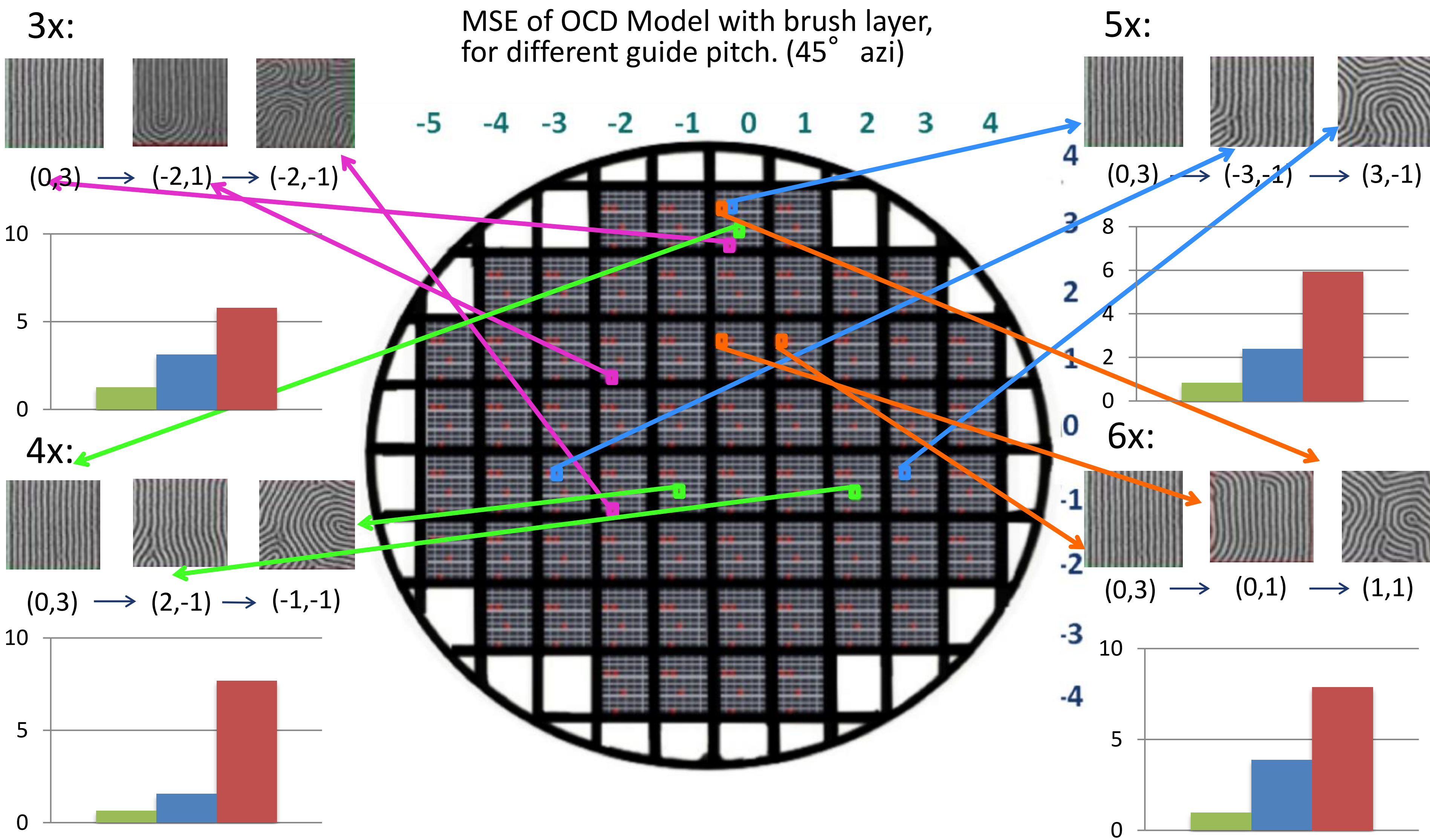
Guide Comparison

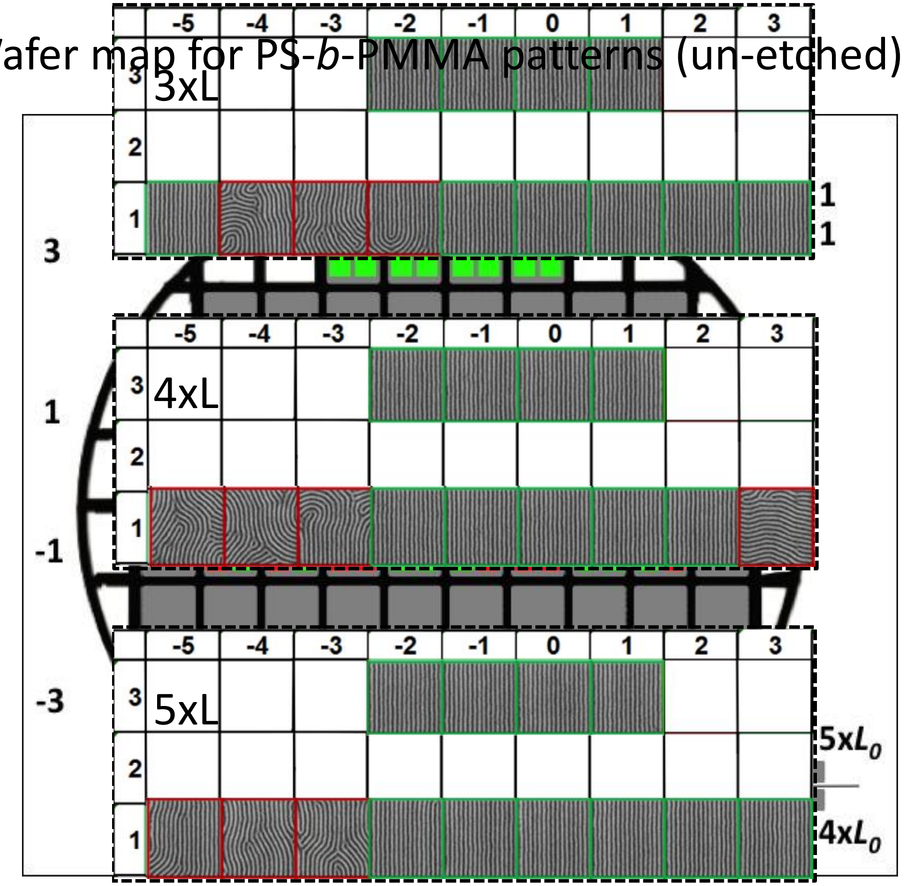
MSE of OCD Model with brush layer, for different guide pitch. (45° azi)



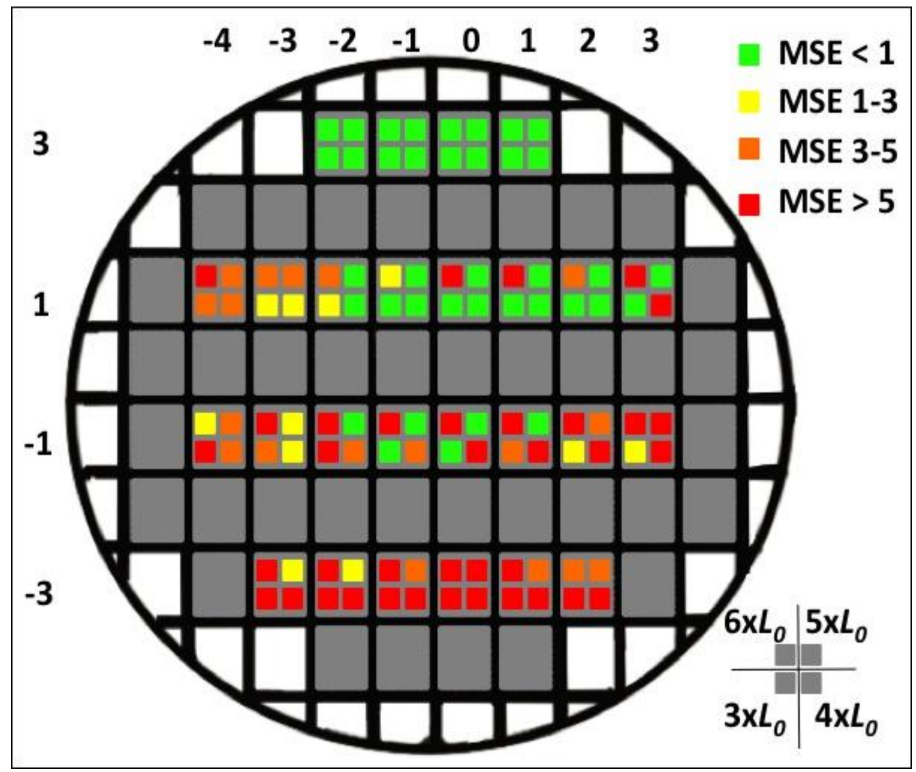
MSE value increases for all different guide pitch samples with increase in disorientation

Wafer Map: Etched Samples

Wafer map for PS-*b*-PMMA patterns (un-etched)

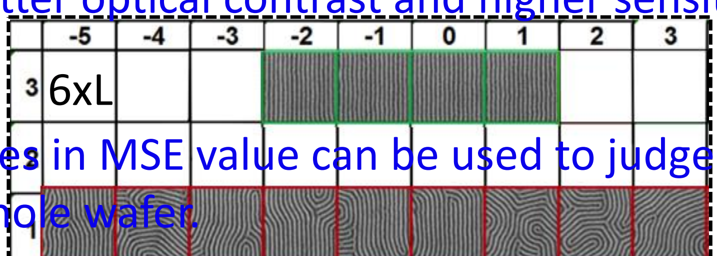


Wafer map for PS line space patterns (etched)



Better optical contrast and higher sensitivity for MMSE was obtained for etched samples.

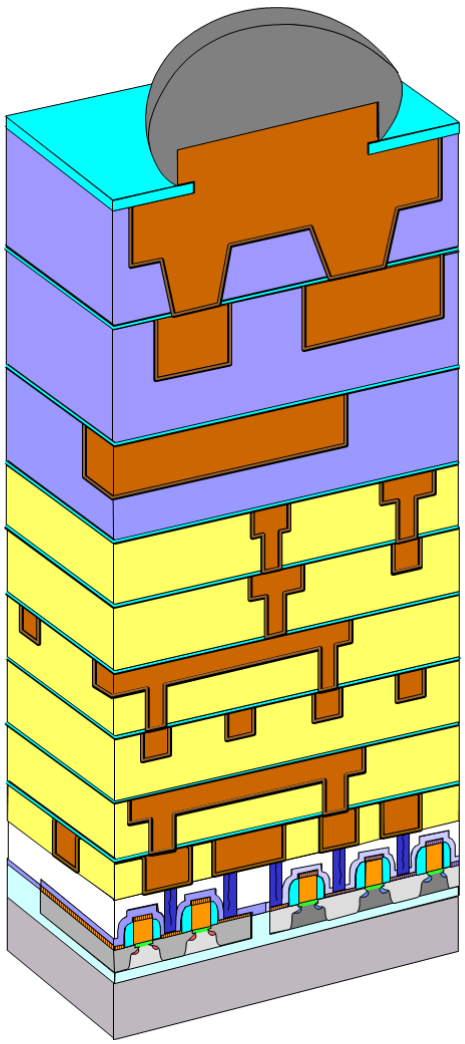
Wafer map with respect to MSE value.



Changes in MSE value can be used to judge degree of alignment of PS line space patterns across the whole wafer.

Motivation

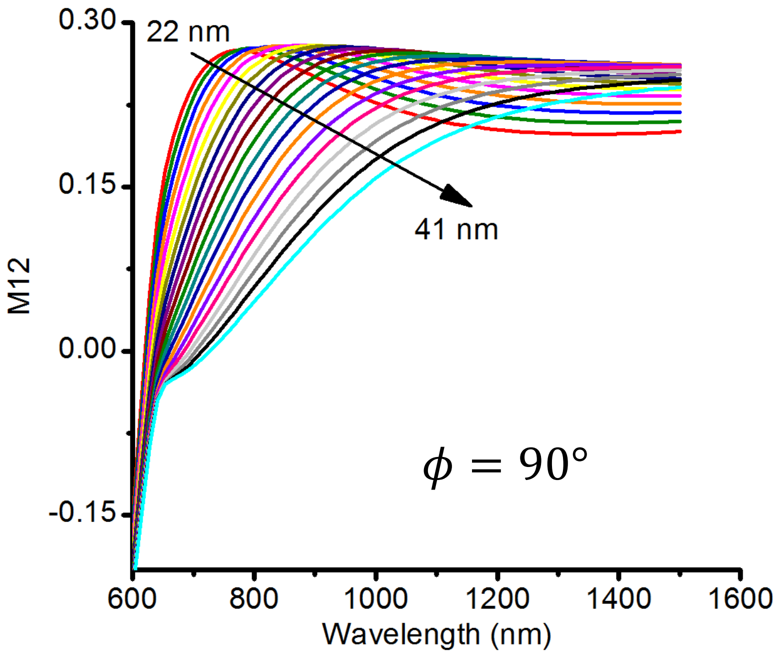
- Challenges for interconnect technology according to ITRS:
  - Trench depth and profile
  - Via shape
  - Measure lines < 25 nm wide
  - 14 nm node in production → Metal lines ~ (25 nm width, ie ½ pitch)
  - Line edge roughness
- **Enhance OCD methods to overcome insensitivety to changes in metal line CD and shape**



Images from Prof. E. Levine, SUNY Poly

1D Cu grating test structure

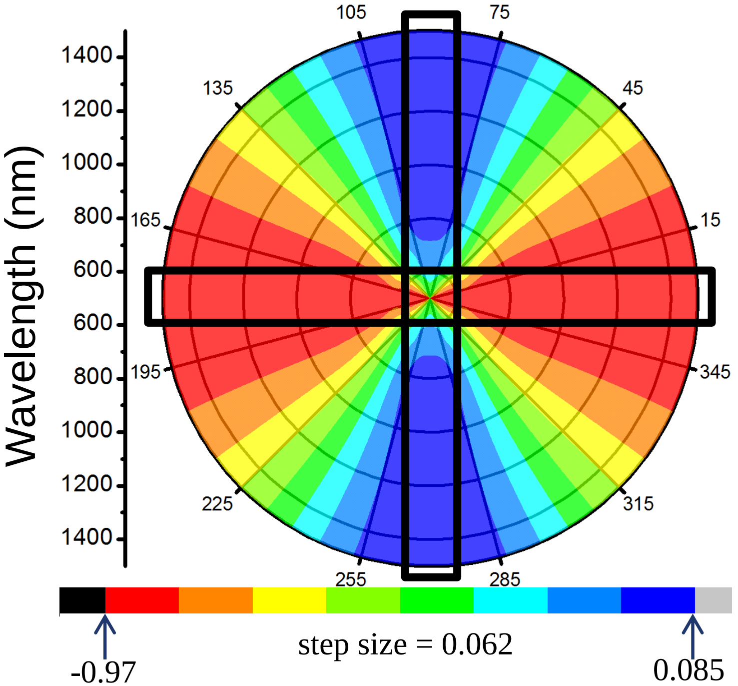
M12: CD variation 1D Cu lines AOI = 65°

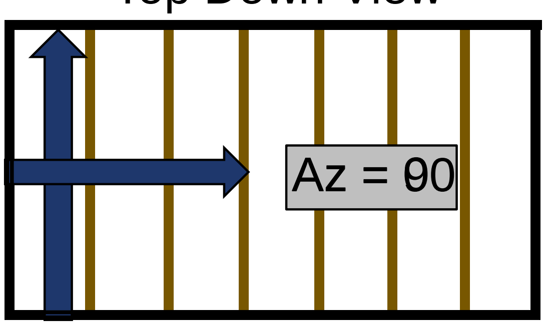


$$M_{12} = -\cos(2y)$$

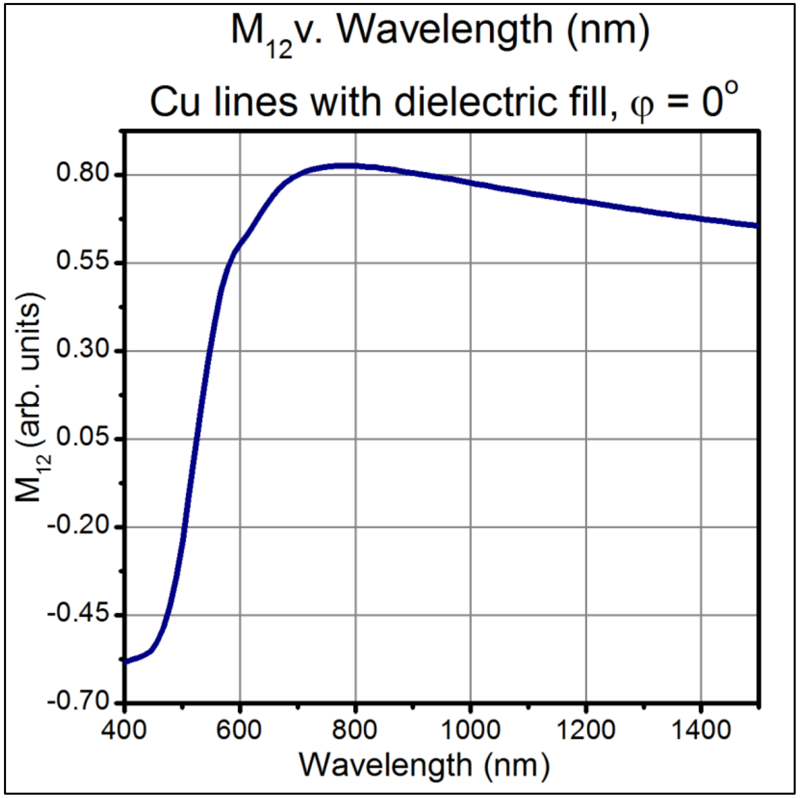
- Poor sensitivity to CD / No characteristic minima
- No Plasmons for small CD grating at $\phi = 0°$
- **~1 nm CD sensitivity**
- Pitch is 64 nm in left plot

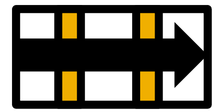
M12: Azimuthal rotation v. wavelength





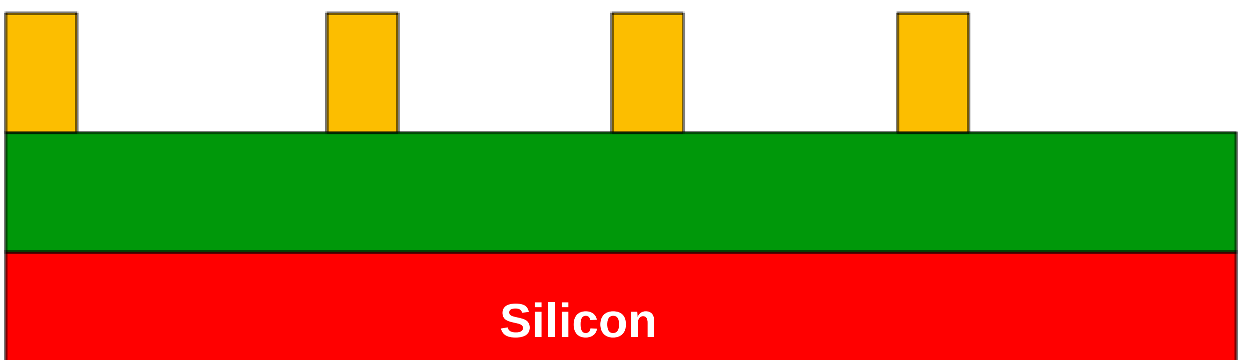
Problem: standard Cu lines and lack of sensitivity





P_X = 120 nm

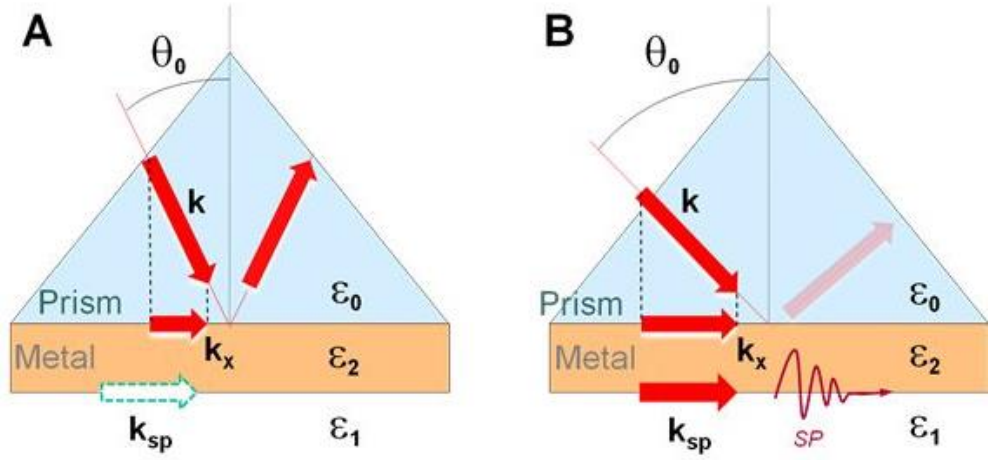
Azimuthal angle relative to small Cu lines



- Left: minimally distinguishable curves for CD_Y = 18 – 30 nm with a 2 nm step size
- Largely featureless in IR-visible wavelength range
- Azimuthal angle change has minimal effect on CD sensitivity

CD
- ◆ 18 nm
- ◆ 20 nm
- ◆ 22 nm
- ◆ 24 nm
- ◆ 26 nm
- ◆ 28 nm
- ◆ 30 nm

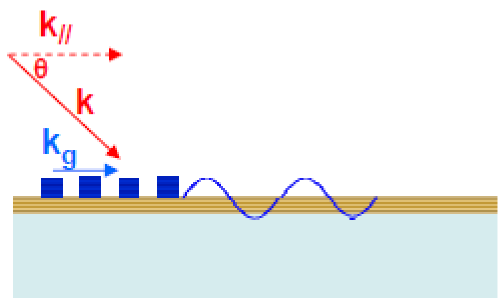
Surface Plasmon Polaritons

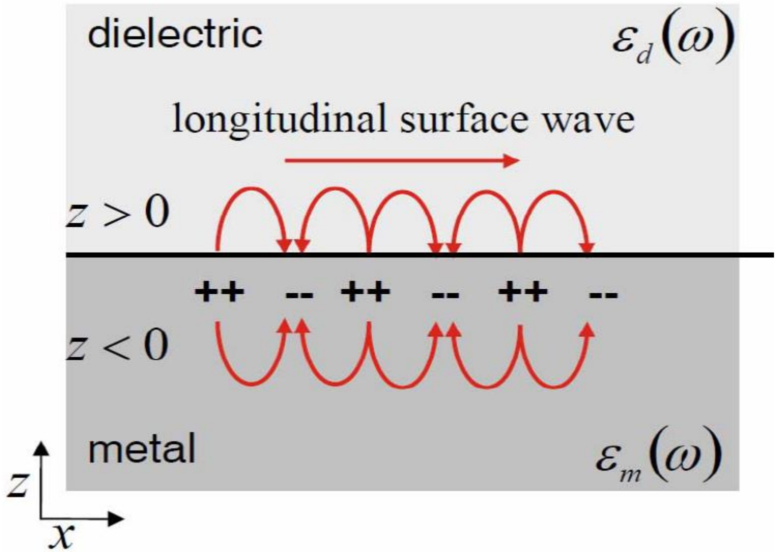


$k_x \neq k_{sp}$ → No plasmon excitation

$k_x = k_{sp}$ → Plasmon excitation

Coupling to a grating



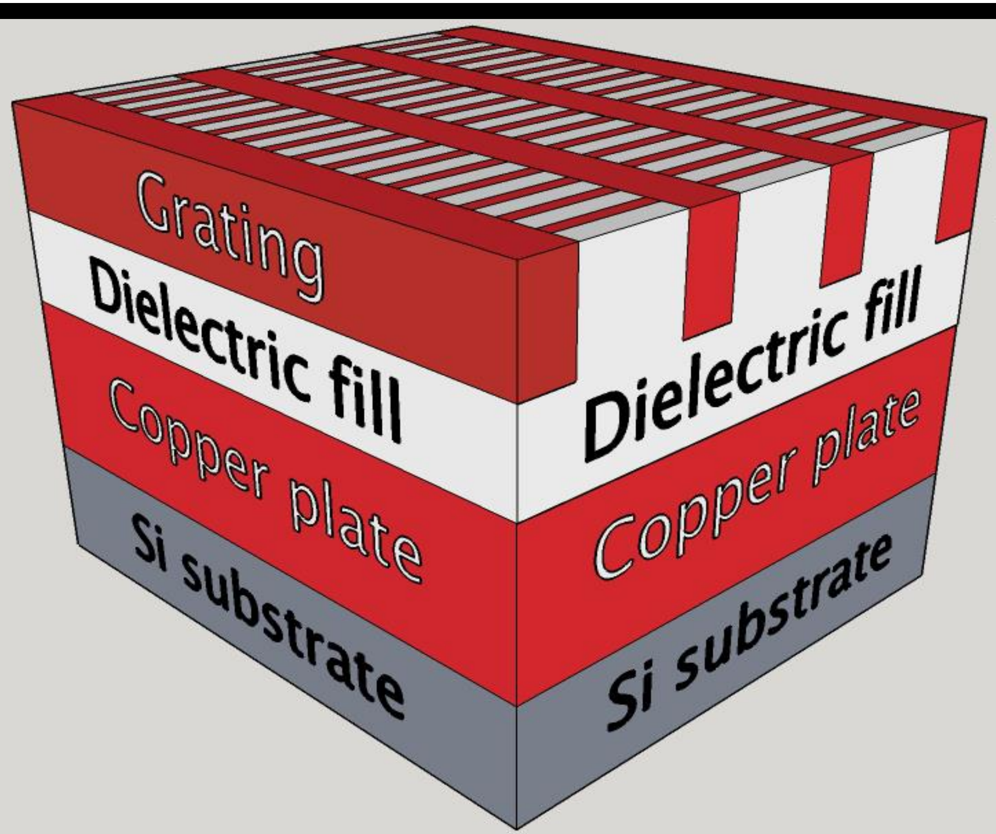


Surface Plasmon Polariton Transverse Magnetic Mode Also called p mode

https://www.photonics.ethz.ch/fileadmin/user_upload/Courses/NanoOptics/plasmons2.pdf

Cross-gratings

- Picture below: 3D views of structure
- Use larger features to launch plasmons that enhance sensitivity to smaller features



Simulation challenges

- Convergence difficulty for RCWA simulation of metallic cross-grating
  - Requires more computational power than local computer provides
  - Solved with new NanoDiffract engine and cloud based computing
  - Many publications on plasmonic-sample ellipsometry attempt to model only key spectral features with RCWA, often poorly due to above considerations
  - Our work can model entire spectra with RCWA+FEM approach

- FEM time constraints
  - 1 simulation = 1-10 minutes comp. time, 1 spectra = 2-10 hours
  - Depends on sample parameters (mesh, sample volume) and wavelength step size
  - All simulations run locally, no cluster computing

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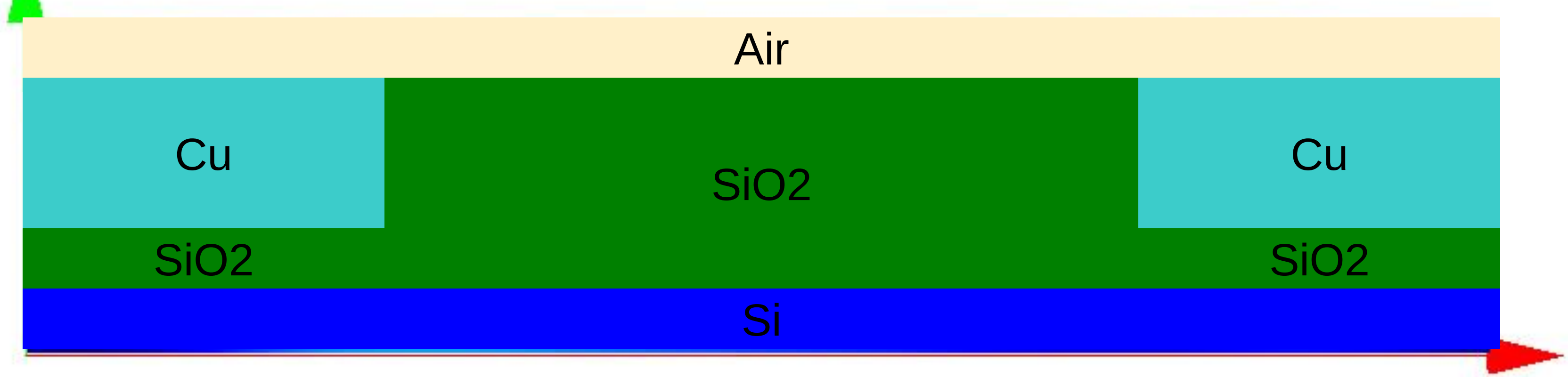
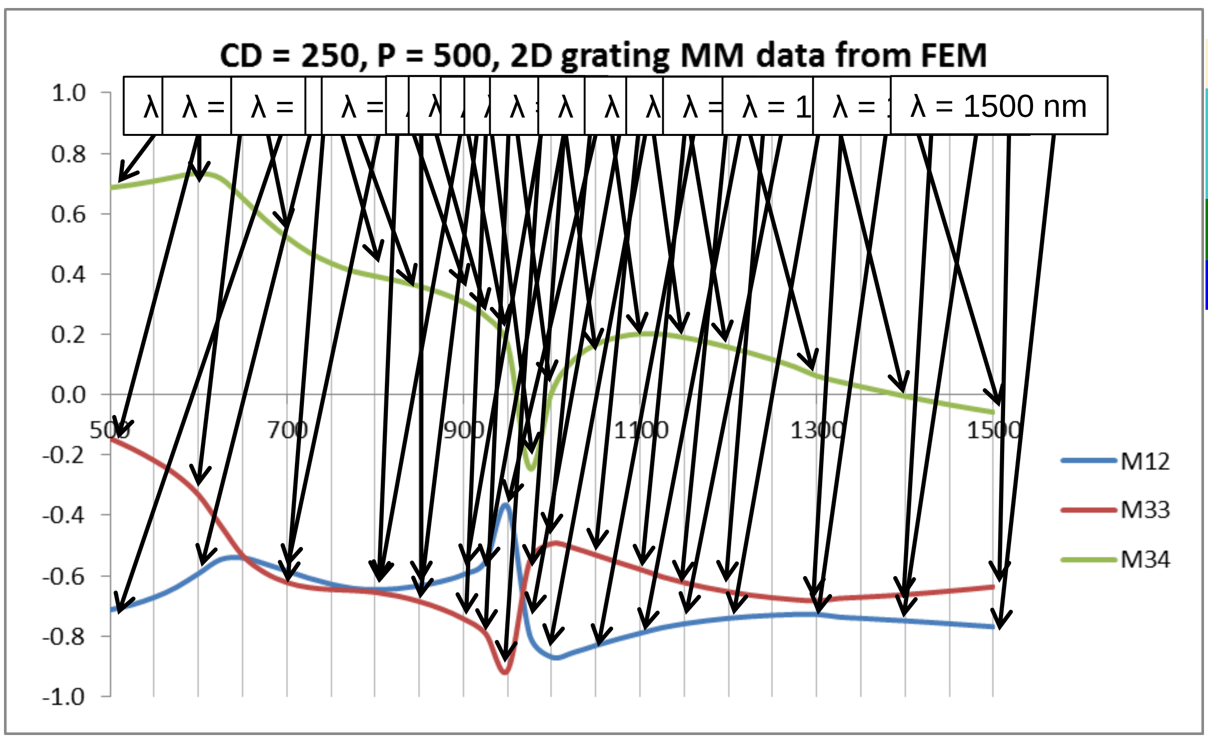
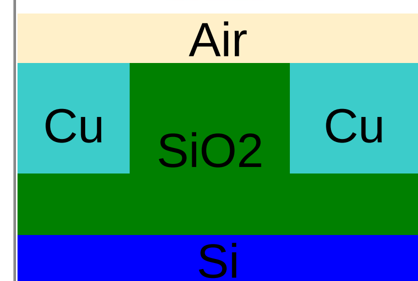
MM Spectra v. H field from FEM

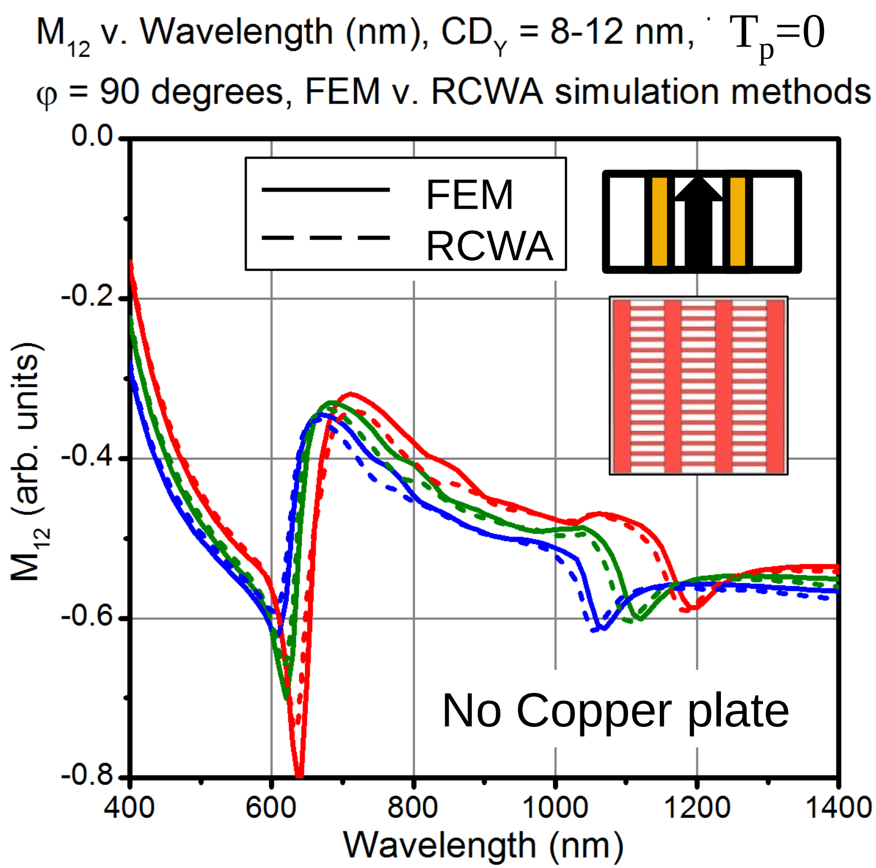
H field color range: red = 50 μA/m, blue = 0 μA/m

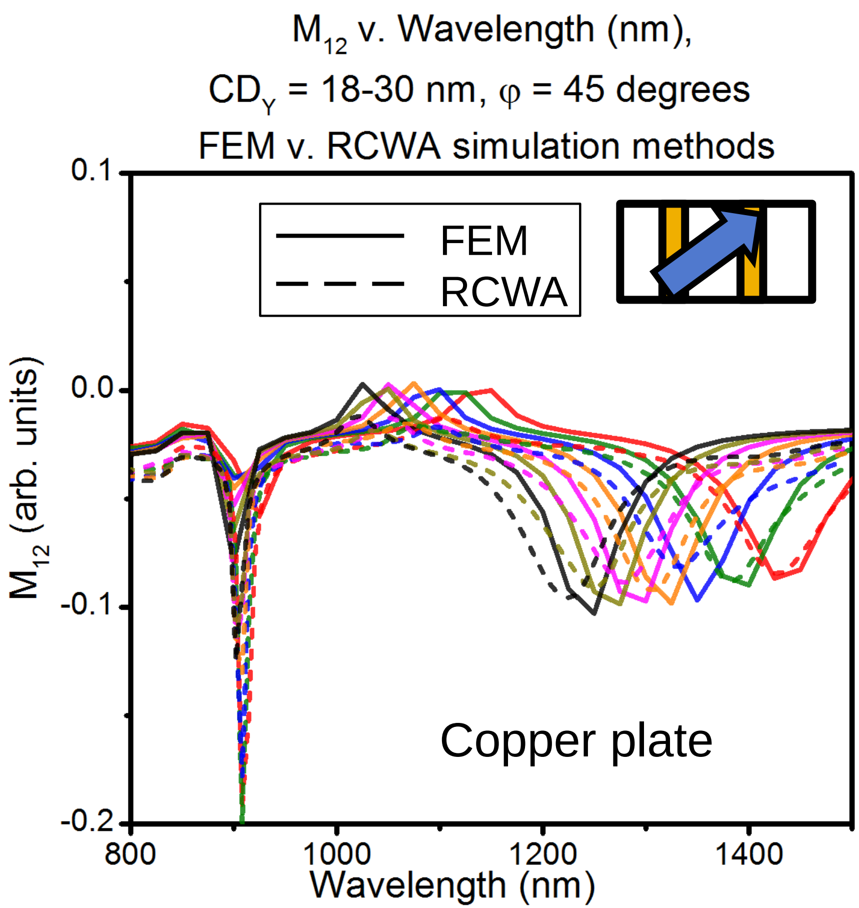






FEM vs. RCWA





- Left: original cross-grating, red CD_Y = 8 nm to blue CD_Y = 12 nm
- Right: new cross-grating (w/Cu plate), red CD_Y = 18 nm to blue CD_Y = 30 nm

Cross-gratings

- Picture below: 3D and top-down views of structure
- Use larger features to launch plasmons that enhance sensitivity to smaller features

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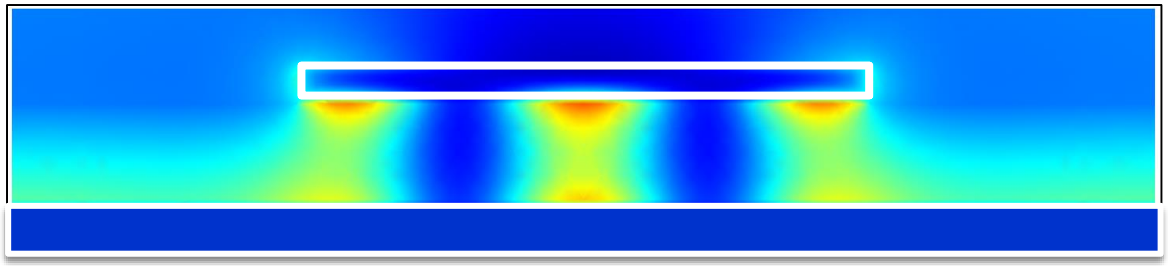
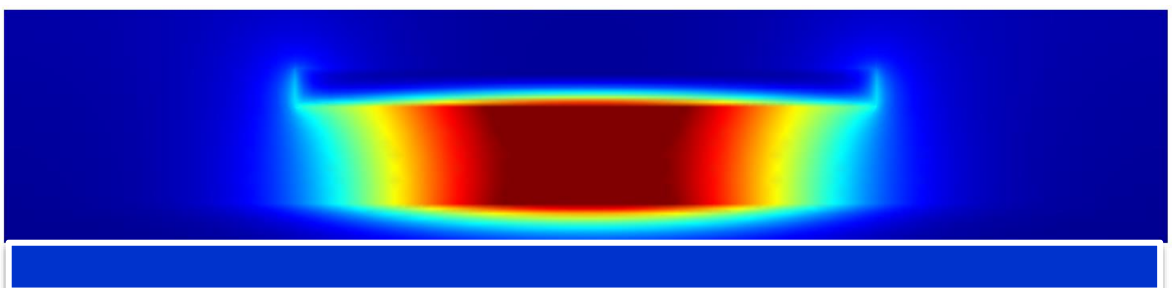
Cavity Modes

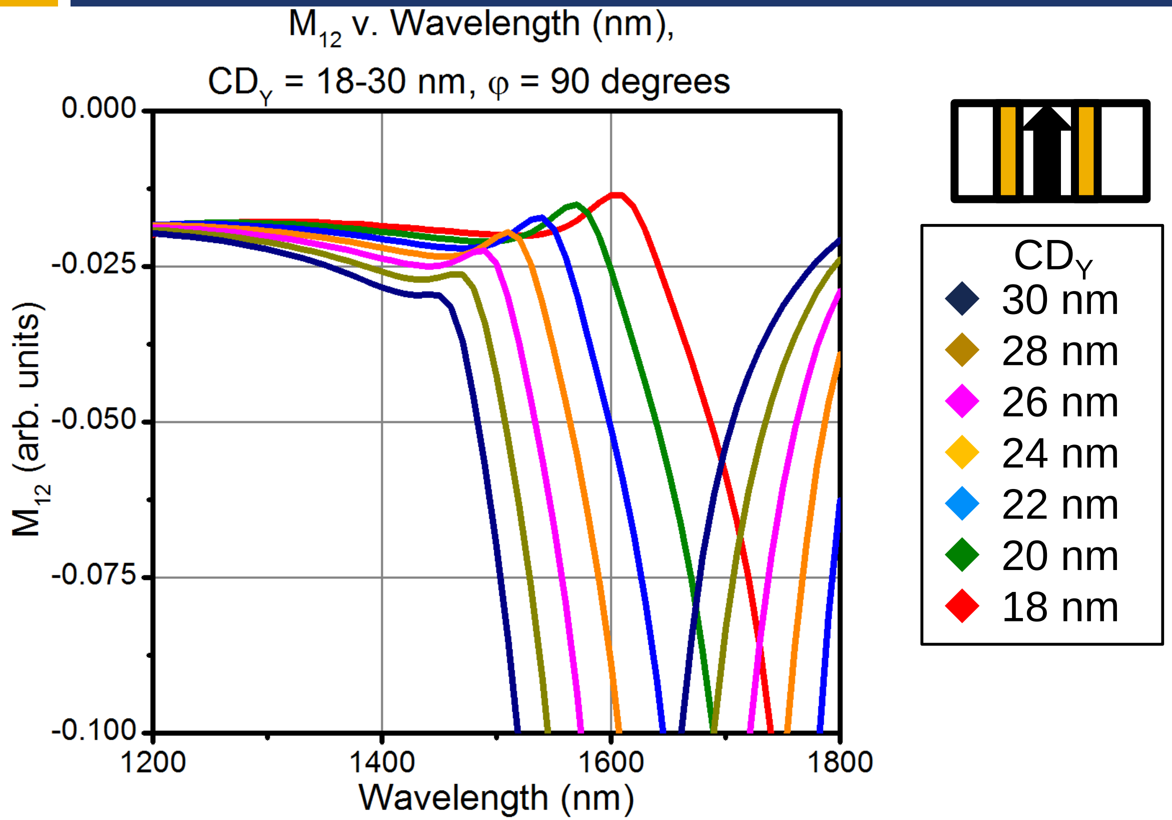


H field for cross-grating structure, φ = 0, λ = 700 nm. Dark blue H = 0 μA/m, red H = 50 μA/m. Localized plasmon activity in between copper grating (white outlined rectangle) and copper plate (substrate seen).



H field for cross-grating structure, φ = 0, λ = 1450 nm. Dark blue H = 0 μA/m, red H = 50 μA/m. Localized plasmon activity in between copper grating and copper plate.

M_{12} v. Wavelength (nm)
CD_Y variation seen at φ = 90



- CD_Y variation from 18 to 30 nm with a 2 nm step size
- M_{12} spectra shown
- Two distinct minima: first between 1600-1800 nm and second between 900-1100 nm
- Maxima from 850-950 nm and 1450-1600 nm
- SPR at 700 nm
- P_Y = 120 nm;
  CD_X = 100, P_X = 600 nm

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Fill-factor vs Relative-CD

- Fill-factor (old assumption)
  - Localized minima location highly dependent on the area ratio $\frac{A_{grating}}{A_{total}}$
  - Result: increasing CD leads to higher order localized plasmons (left)

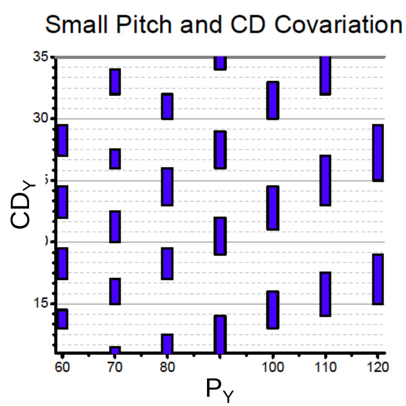
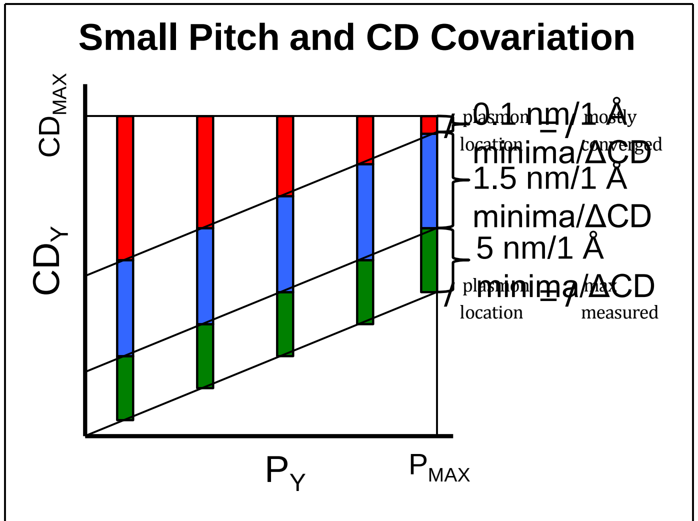


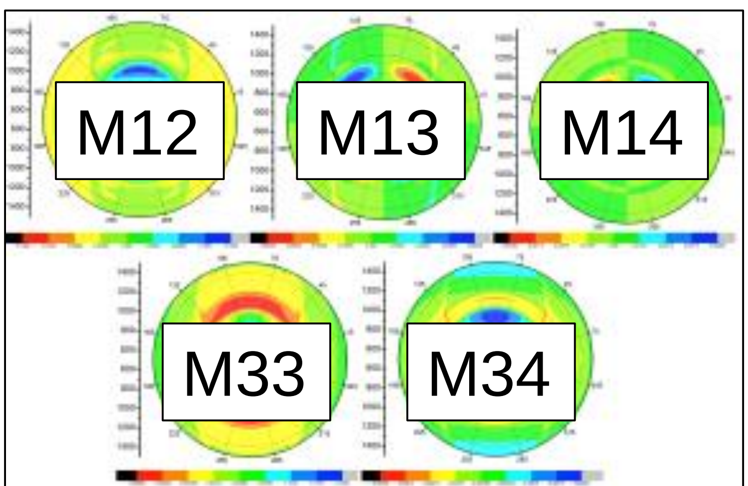
Fig. 4. Each bar represents the window in which a plasmonic resonance is visible in the spectra above 800 nm resulting in CD sensitivity. Infinite cross-grating, P_y = 875 nm, L_y = 100 nm, ΔP_x = 10 nm, Δ CD = 0.5 nm.



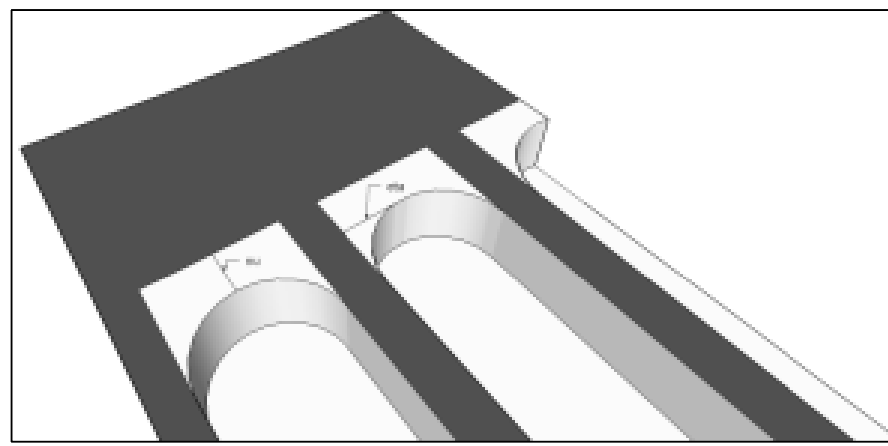
- Relative-CD (new observed behavior) $\frac{\mathrm{DCD}}{\mathrm{CD}_{nominal}}$
  - Localized minima location highly dependent on the change
  - Result: increasing CD leads to convergence towards single minima (right)
  - Higher orders normally present in visible spectra, coexist with primary minima

Conclusions

- Using FEM for initial analysis important for accurate modeling of resonant structures
- Combined FEM+RCWA method guarantees quick modeling capabilities with accurate results
- **Fabricated Samples will have rounded edges**



Difference between rectangular and rounded



Prolith Simulation

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