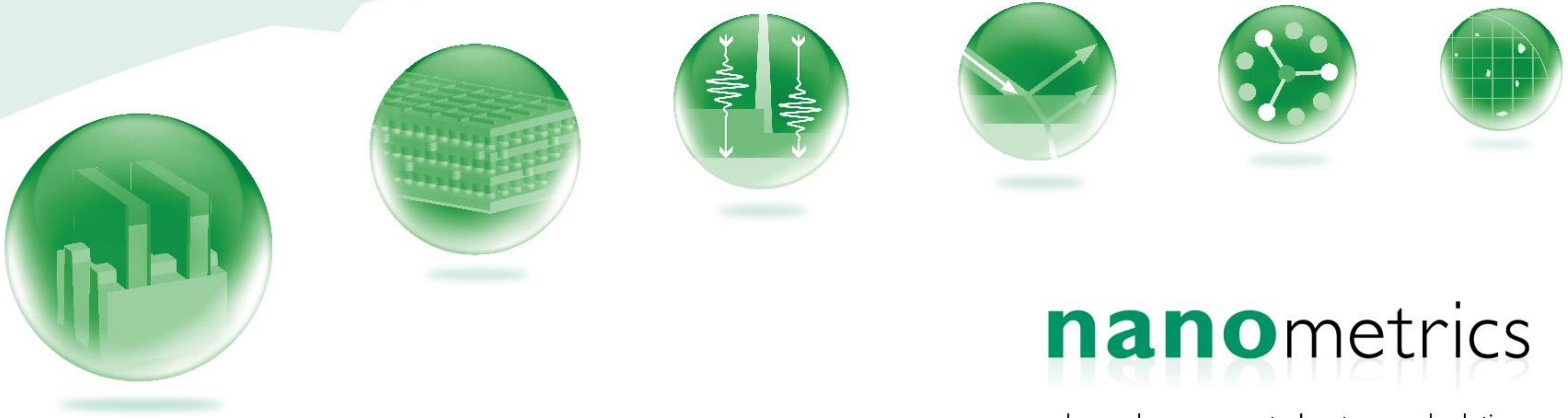


nanometrics

advanced process control systems and solutions

semiconductor | substrate | industrial

critical dimension | thin film | surface quality | composition | inspection

Optical Critical Dimension Metrology in Memory and Logic

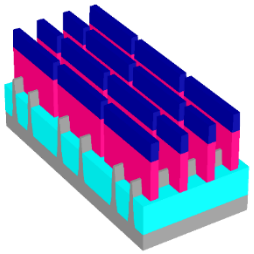
04/03/19

Andy Antonelli, Nick Keller, Nigel Smith

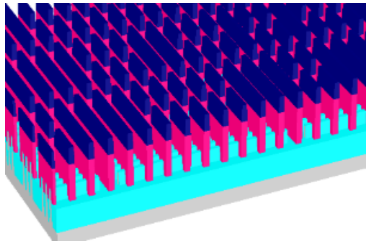
Vision: Measure Even More - Measure 3D Profile Everywhere

Thin film target

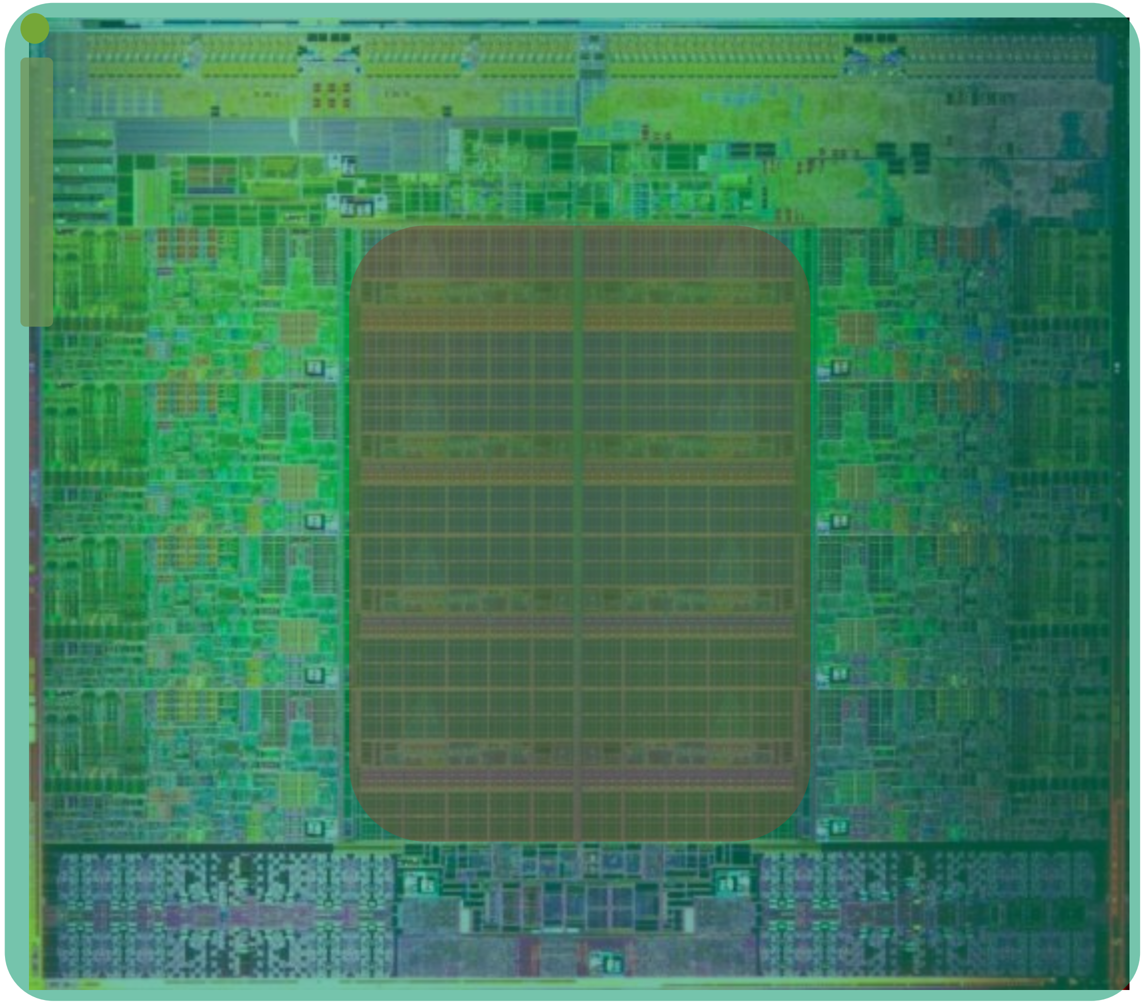
OCD target



SRAM region



“Random” logic



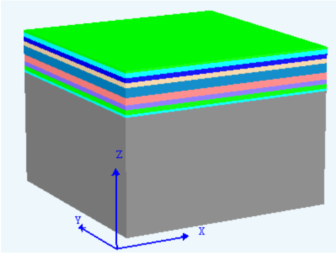
1990-2008 2009-2012 2011-2016

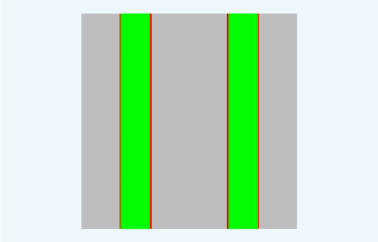
- **Enable broader types of measurements on more types of structures**
  - **Isolated & Random Logic**
  - **ASIC**
  - **Analog**
  - **Filler/Dummy**
  - **Complex Memory:**
    - **NAND over Periphery**
    - **SRAM**
    - **Emerging Memory over Active**

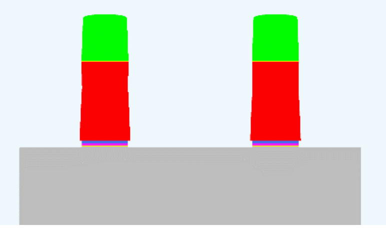
Measure anywhere: Isolated & Random Logic – ASIC – Analog – Filler/Dummy

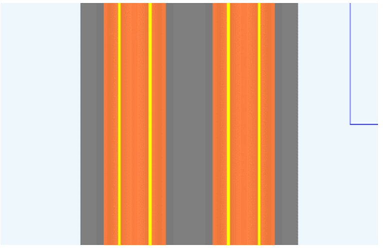
Logic Devices: Evolving Complexity demands Evolving Capability

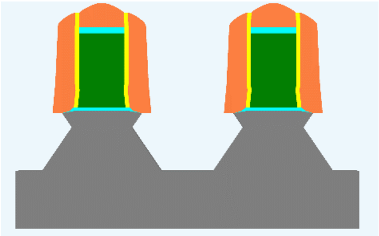
Thin Film	2D Grating - Planar	2D Grating – Complex	3D Grating	SRAM/On-Device
Thickness, Interface	Dimension	Profile Undercut/Re-Entrant	Complex Profile	Complete Profile

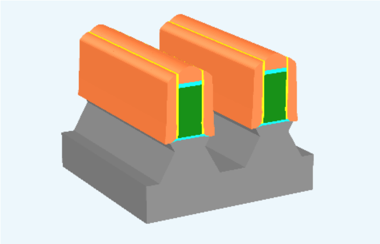


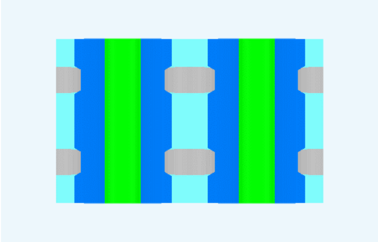


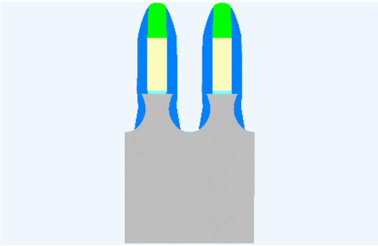


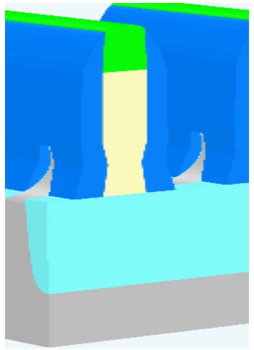


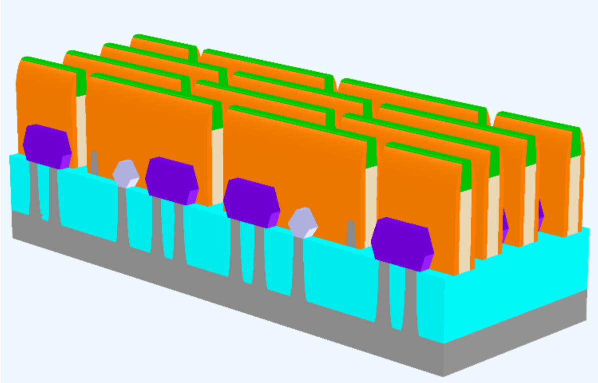










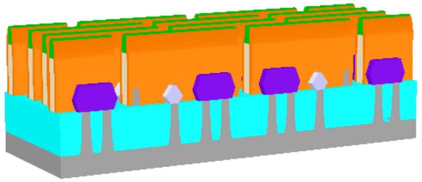


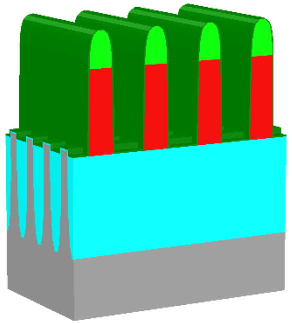
- **Motivations: Eliminate bias between Module, Process, Integration, Target and Device**

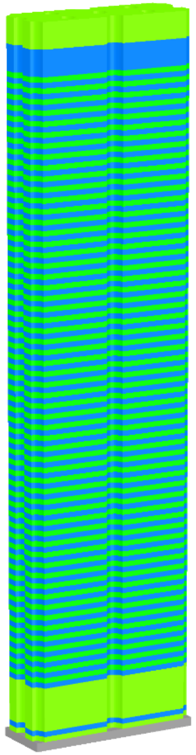
Memory Devices: Plenty of room in the Z Direction

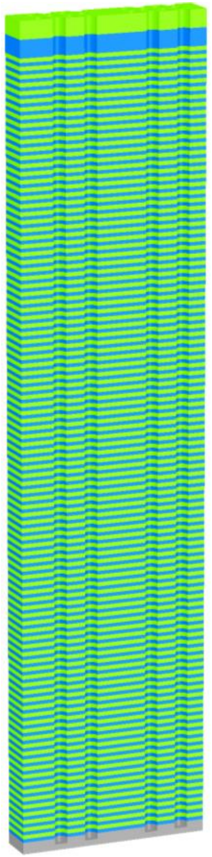
14nm SRAM Cell	Planar Flash -1xnm	64L 3D NAND	96L 3D NAND	2x 96L 3D NAND

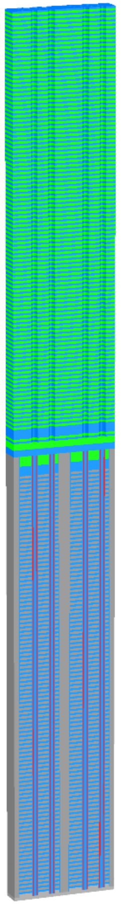
Technology Node











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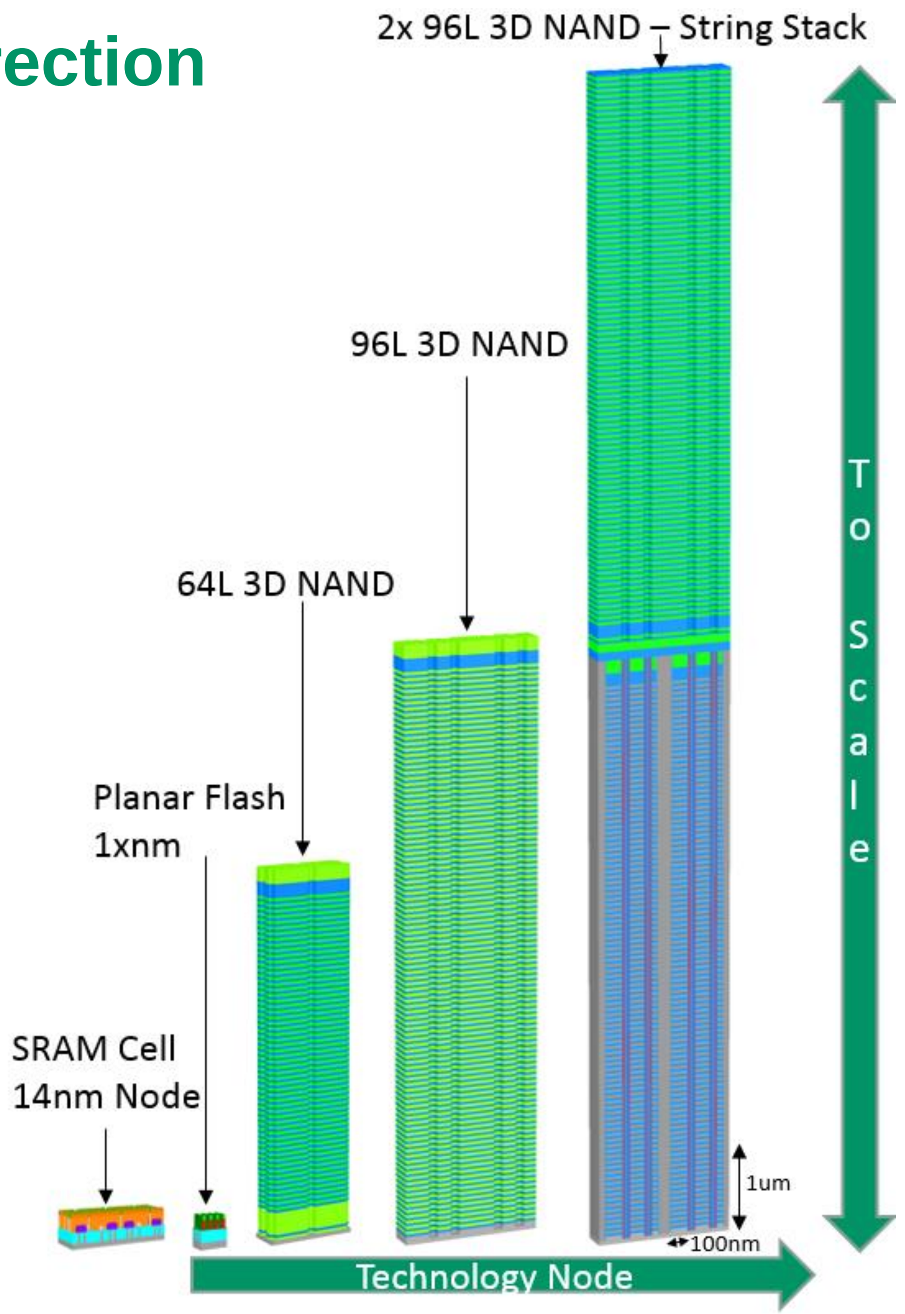
Memory Devices: Plenty of room in the Z Direction



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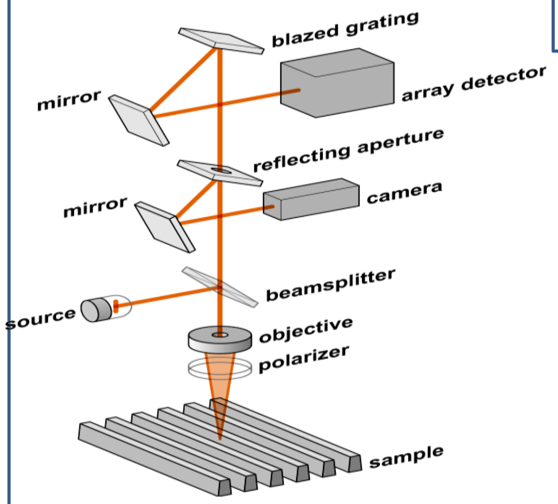
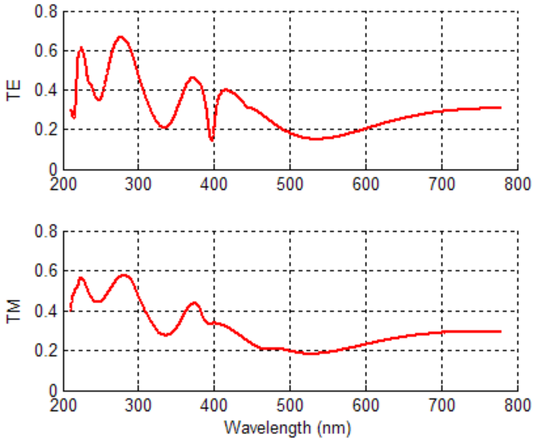
Optical Metrology Technique Overview

Spectroscopic Reflectometry

TE or s-polarization (normal to plane of incidence)
TM or p-polarization (parallel to plane of incidence)

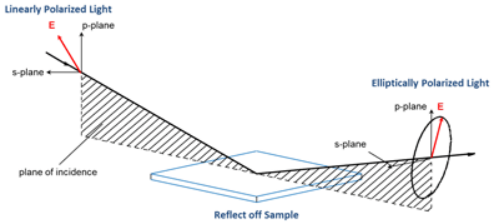




Schematic

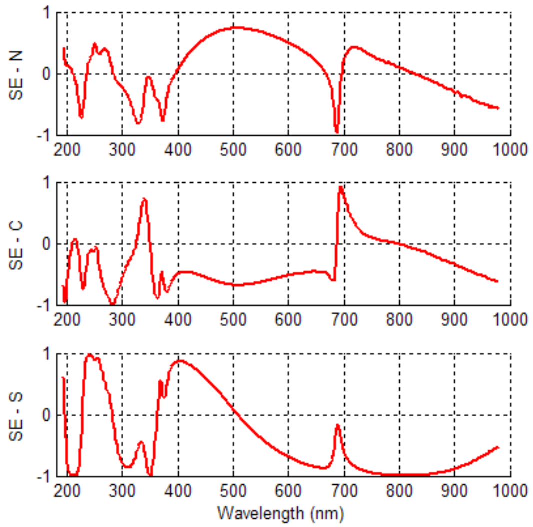
Spectra

Spectroscopic Ellipsometry



$$\frac{\tilde{E}_x}{\tilde{E}_y} = \frac{E_{xo}}{E_{yo}} e^{i(\delta_x - \delta_y)} = \boxed{\tan(\Psi) e^{i\Delta}}$$

$$N = \cos(2\Psi)$$
$$C = \sin(2\Psi)\cos\Delta$$
$$S = \sin(2\Psi)\sin\Delta$$



Schematic

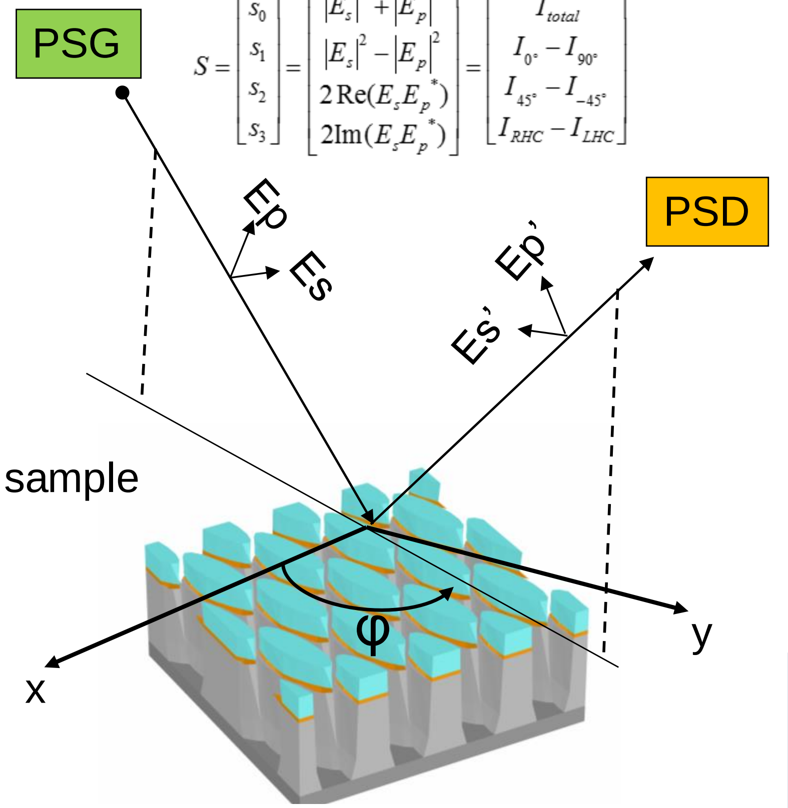
Spectra

- **Measures change in intensity**
- **Measures change in polarization**

Mueller Matrix OCD – Beyond Ellipsometry

Stokes vector

$$S=\begin{bmatrix}s_0\\ s_1\\ s_2\\ s_3\end{bmatrix}=\begin{bmatrix}|E_s|^2+|E_p|^2\\ |E_s|^2-|E_p|^2\\ 2\,\mathrm{Re}(E_sE_p^*)\\ 2\,\mathrm{Im}(E_sE_p^*)\end{bmatrix}=\begin{bmatrix}I_{total}\\ I_{0^\circ}-I_{90^\circ}\\ I_{45^\circ}-I_{-45^\circ}\\ I_{RHC}-I_{LHC}\end{bmatrix}$$



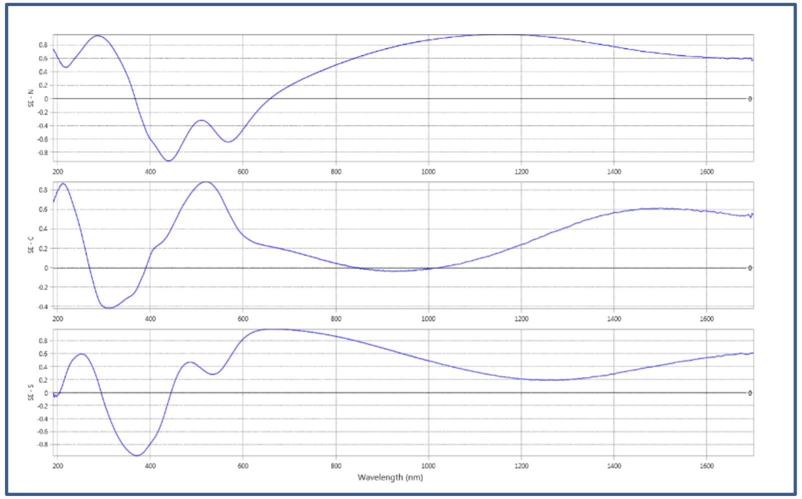
$$[S_{out}]=[MM]\times[S_{in}] \quad MM=\begin{bmatrix}M_{11}&M_{12}&M_{13}&M_{14}\\ M_{21}&M_{22}&M_{23}&M_{24}\\ M_{31}&M_{32}&M_{33}&M_{34}\\ M_{41}&M_{42}&M_{43}&M_{44}\end{bmatrix}$$

Mueller Matrix: Response of all possible polarization states induced by the sample

Standard SE

$$S_m=\begin{bmatrix}1&-N&0&0\\ -N&1&0&0\\ 0&0&C&S\\ 0&0&-S&C\end{bmatrix}$$

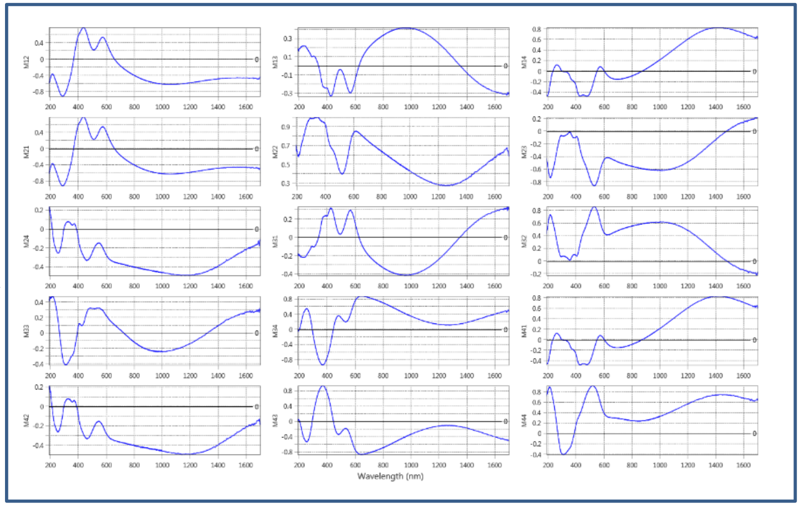
N, C, S spectra



Increased Spectral Information

Mueller Matrix

$$MM=\begin{bmatrix}M_{11}&M_{12}&M_{13}&M_{14}\\ M_{21}&M_{22}&M_{23}&M_{24}\\ M_{31}&M_{32}&M_{33}&M_{34}\\ M_{41}&M_{42}&M_{43}&M_{44}\end{bmatrix}$$



Symmetry of Mueller Matrix

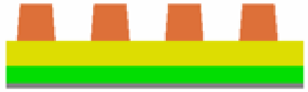
$$MM = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}$$

No cross-polarization

$$\begin{bmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{bmatrix}$$

- Off-diag. blocks vanish
- MM reduces to standard SE

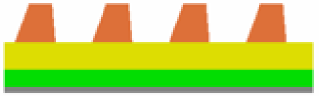
Azimuth = 0 ° or 90°



With cross-polarization

$$\begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}$$

- Off-diag. blocks non-zero
- Off-diag. blocks contain asym. info.



Azimuth = 90°

Cross polarization

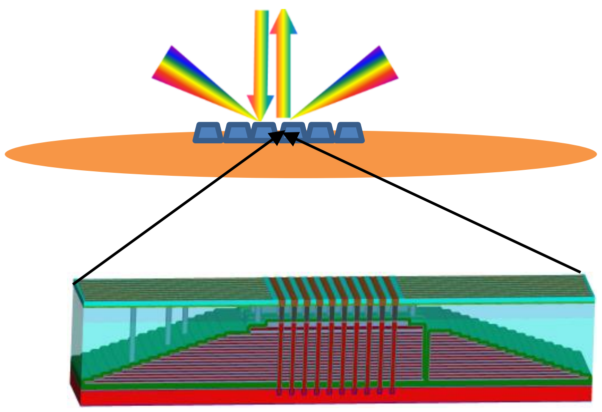
- "Off-diagonal" Mueller matrix elements add unique spectral information
- Key for parameter decorrelation

Asymmetric Structures

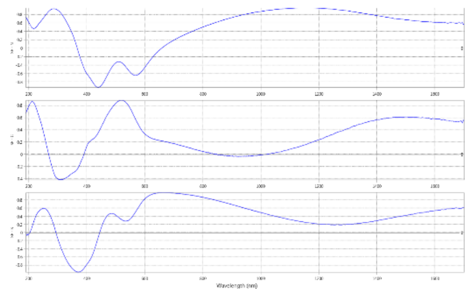
- If structures break mirror symmetry, off-diagonal element pairs are not equal
- Resulting differential holds unique information about the asymmetry (ex. Tilt, overlay shift, ect.)

Optical Critical Dimension (OCD) Measurement Flow

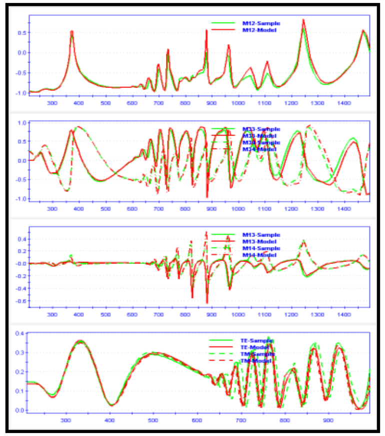
Measurement



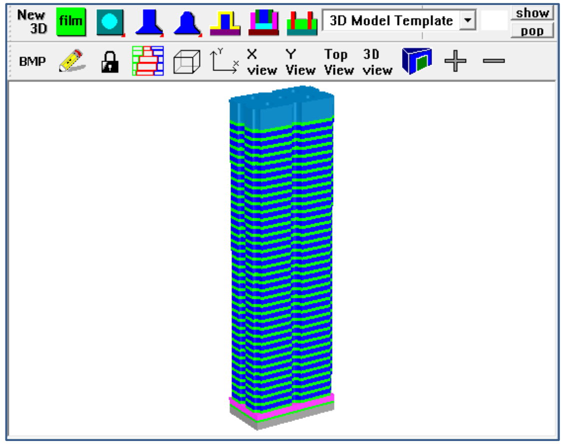
Spectra



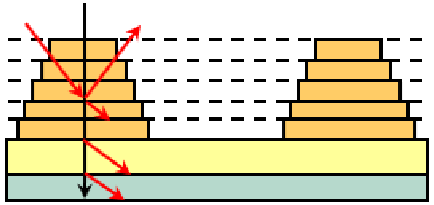
Regression



OCD Model



RCWA Engine



Results

Thickness of layers

Grating layers/thin film layers

Grating parameters

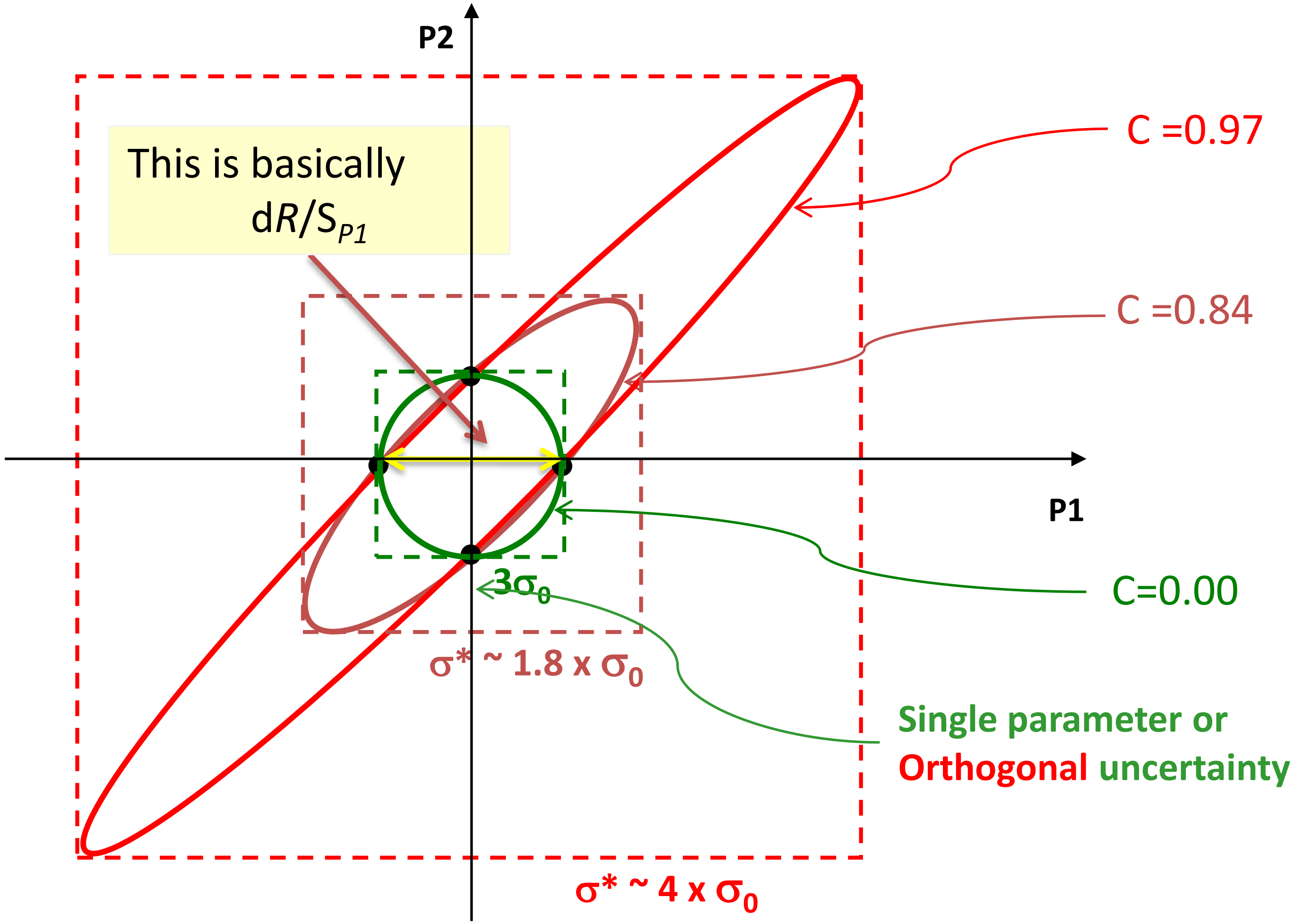
CDs: Bottom, Mid and Top; Side wall angles; Footing, rounding, bowing, notch, spacer CD, conformal coating, shoulder, trench fill, recess, 3D shape, overlay shift

OCD Case Studies

- Gate-All-Around field effect transistors
- Plasmons & Interconnects
- High Aspect Ratio 3D Memory

OCD Background – Parameter Sensitivity & Uncertainty Analysis

- **Parameter Uncertainty**
  - **Sigma** – Estimated standard deviation of the parameter output resulting from measurement noise and parameter correlation
  - **Osigma** – Single parameter uncertainty or "Orthogonal Uncertainty". Estimated standard deviation of a parameter's output resulting from measurement noise alone
  - **Sigma/Osigma** – "Correlation Penalty" is a measure of the impact of parameter correlation on precision



- **Correlation "amplifies" measurement uncertainty**
  - Orthogonal uncertainty is determined by sensitivity (d*R*/*S*)
  - Correlation does not affect orthogonal uncertainty

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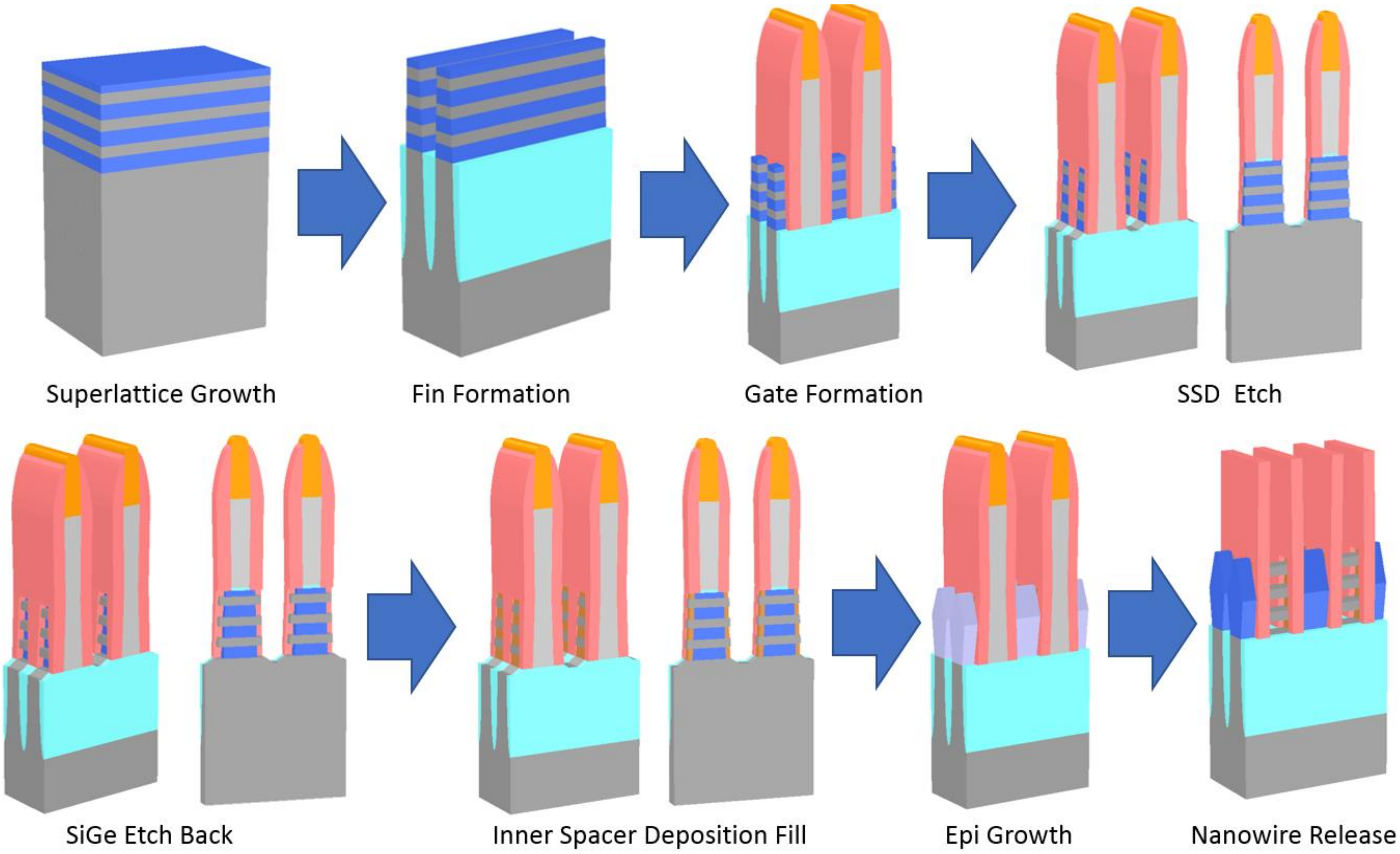
Horizontal Gate-All-Around Process Flow

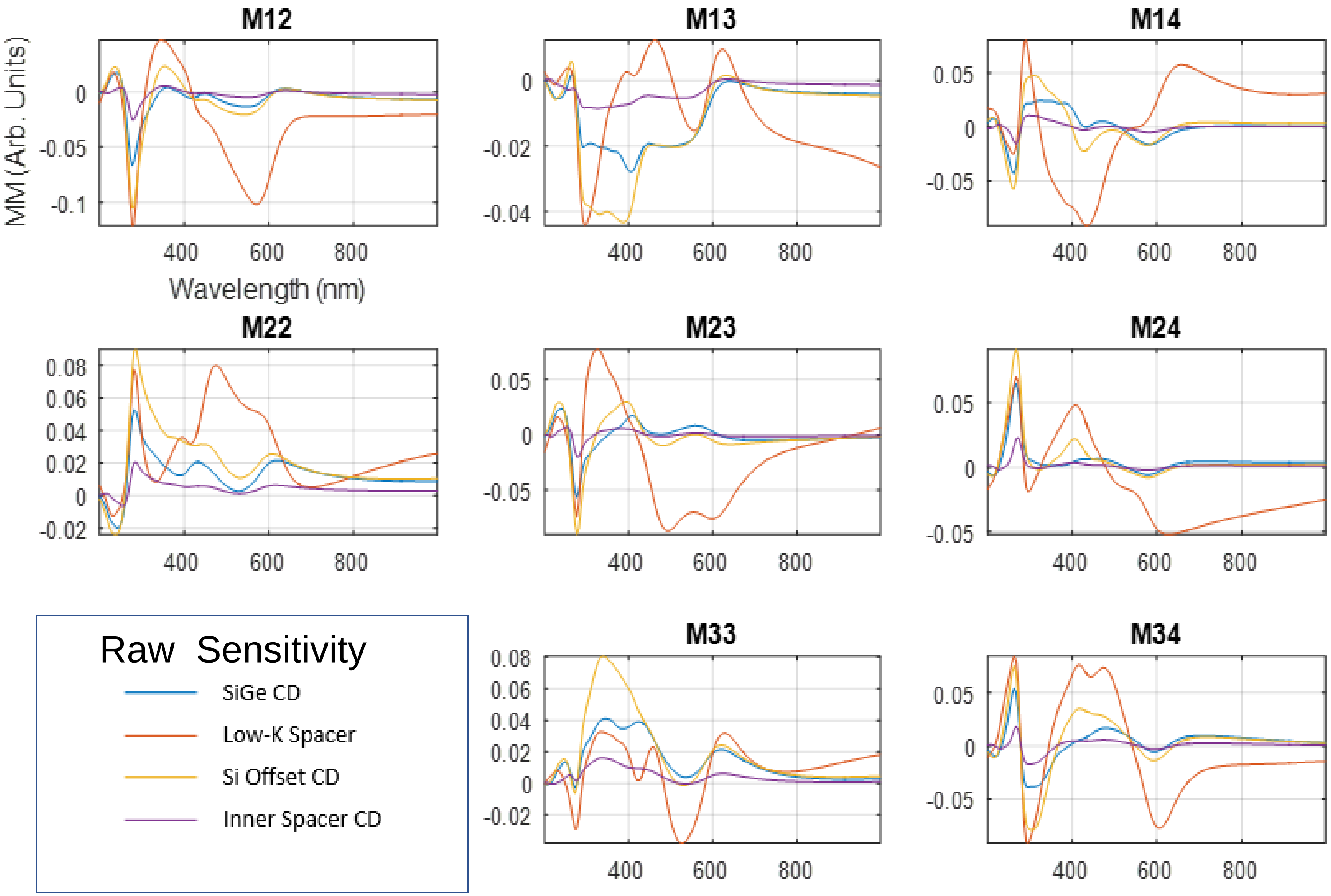


Source: “Perspective: Optical measurement of feature dimensions and shapes by scatterometry,” A.C. Diebold, A. Antonelli, and N. Keller, APL Materials 6 058201 (2018).

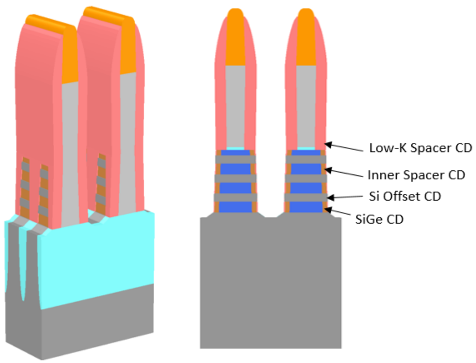
Horizontal Gate-All-Around Feature Simulation

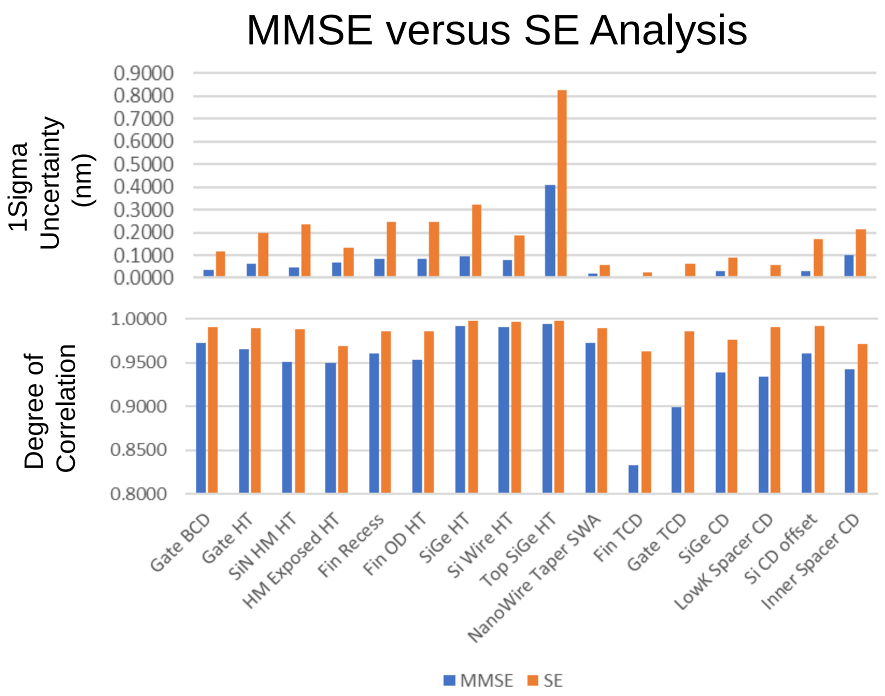
Inner Spacer Etch Back

Wavelength Range: 200 – 1000 nm
Azimuth Angle: 45 °



Parameter	Dimension (nm)
Gate Pitch	64
Fin Pitch	30
Wire Diameter	8
Inner Spacer	4
Gate Spacer	10





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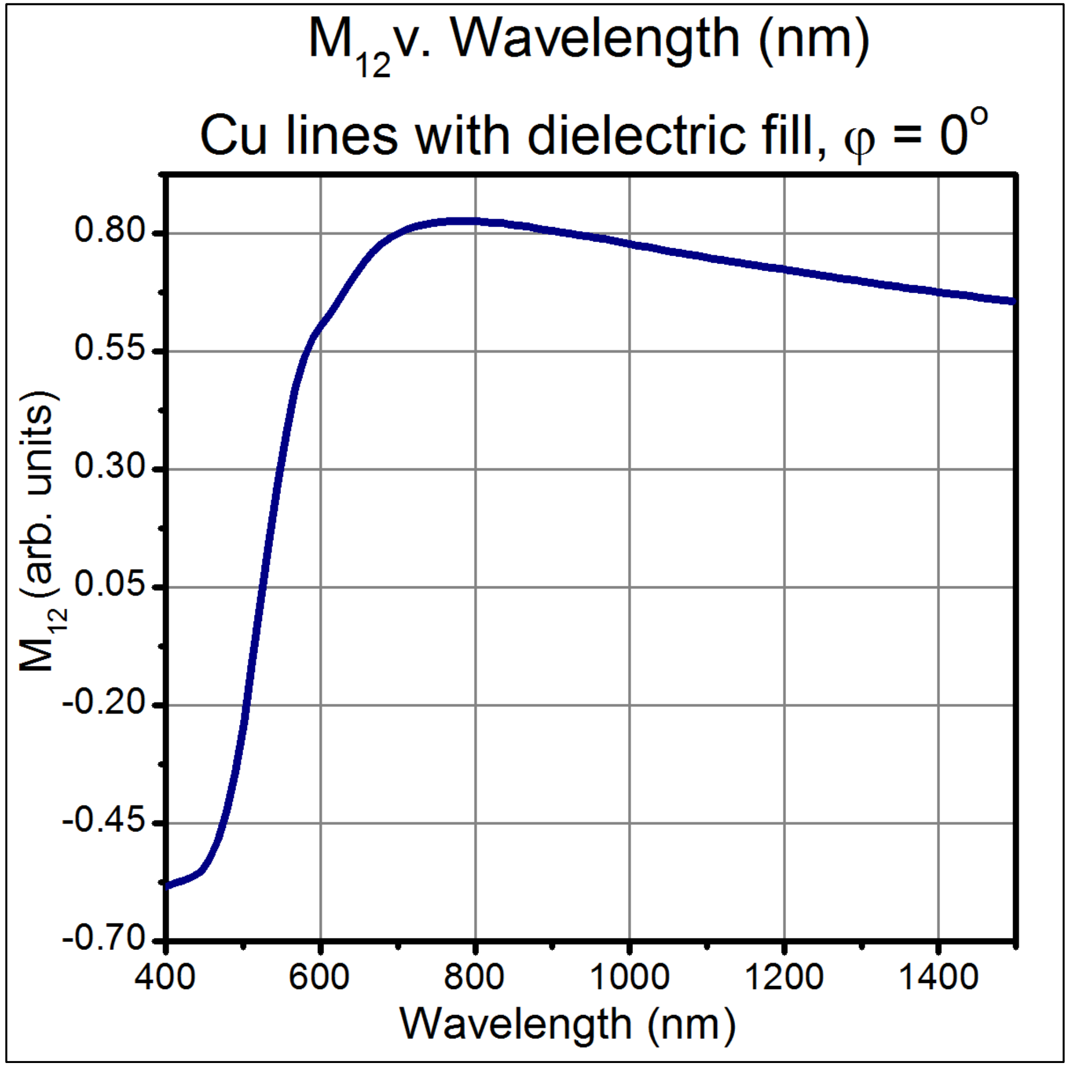
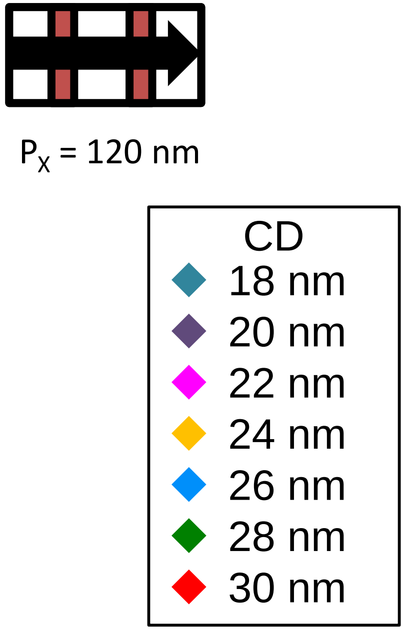
OCD Case Studies

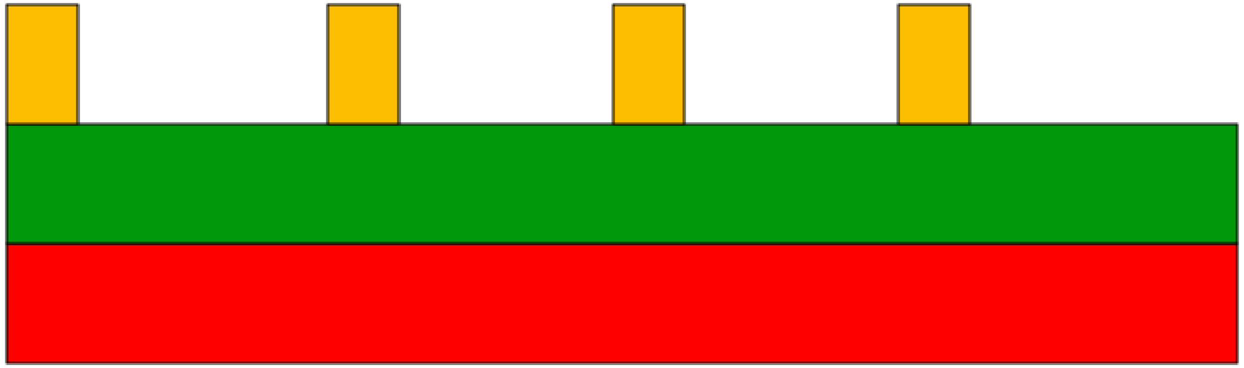
- Gate-All-Around Field Effect transistors
- Plasmons & Interconnects
- High Aspect Ratio 3D Memory

Conventional Cu Grating Structures





- 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



Source: "Plasmonic Enhancement of the Ellipsometric Measurement of Thin Metal Lines", Sam O'Mullane, Ph.D. Dissertation (2015).

Plasmons: Surface vs Localized Effects

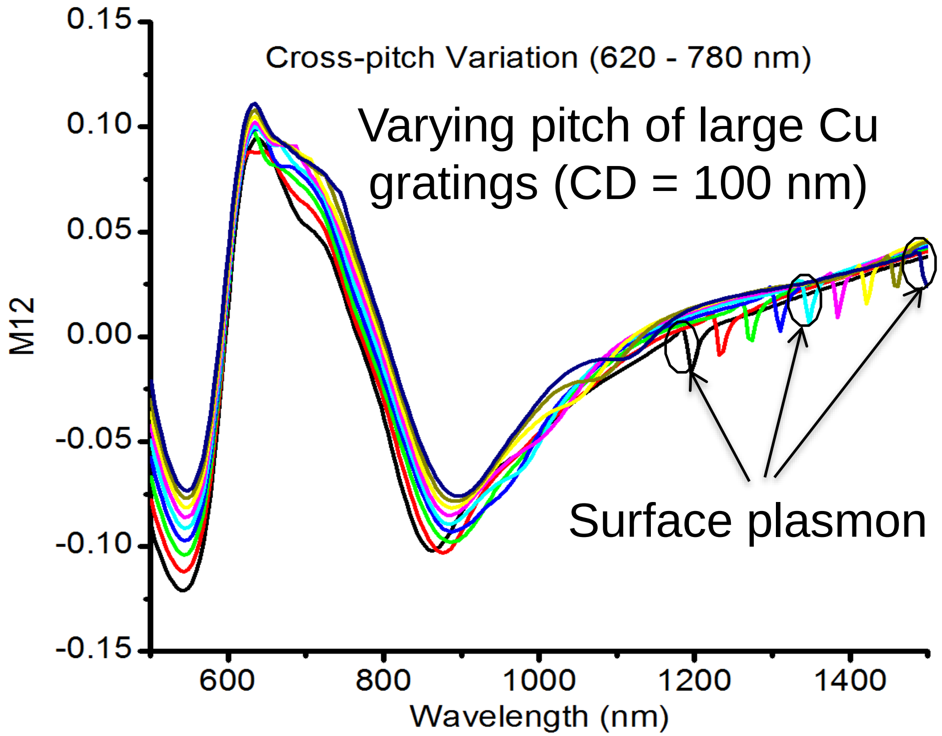
- **Surface plasmons**
  - Propagate parallel to metal-insulator surface
  - Only couple to p-polarization (TM)
  - Require some form of coupling, e.g., grating or prism

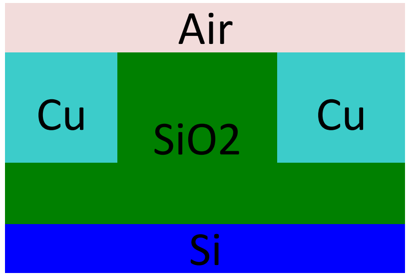
$$k_{in}\sqrt{\frac{\epsilon_m \epsilon_i}{\epsilon_m + \epsilon_i}} = k_{SP} = k_{in} + mk_P$$

- **Localized plasmons**
  - Most confined to nanostructures

$$\alpha = 4\pi r^3 \frac{\epsilon_p - \epsilon_d}{\epsilon_p + 2\epsilon_d}$$

  - Often due to resonance in polarizability (α) of particle
  - Exemplar: cavity modes which couple through sandwiched dielectric





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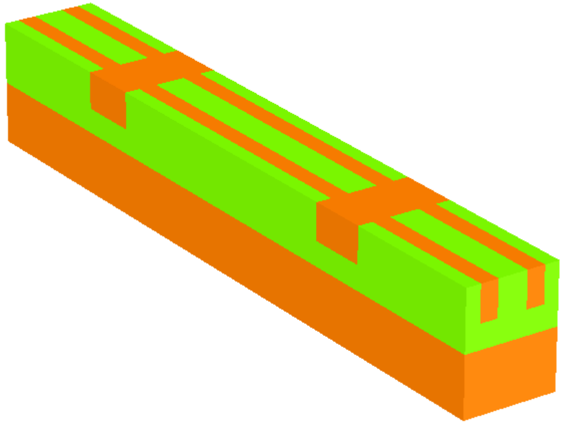
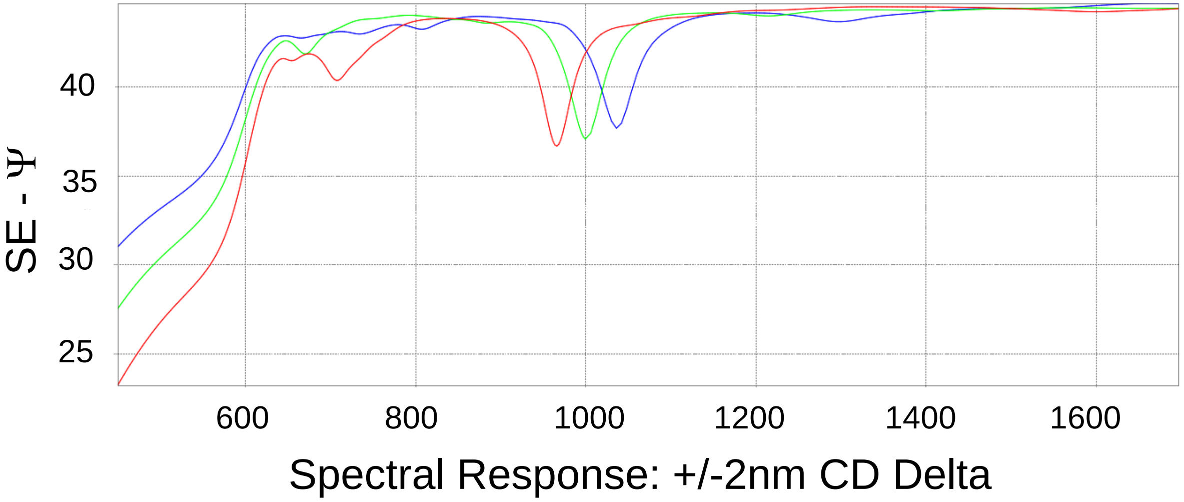
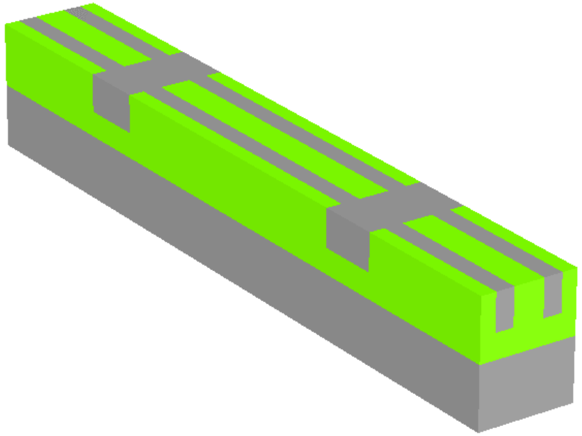
Plasmonic Active Cu X-Grating vs Plasmon Inactive Si X-Grating

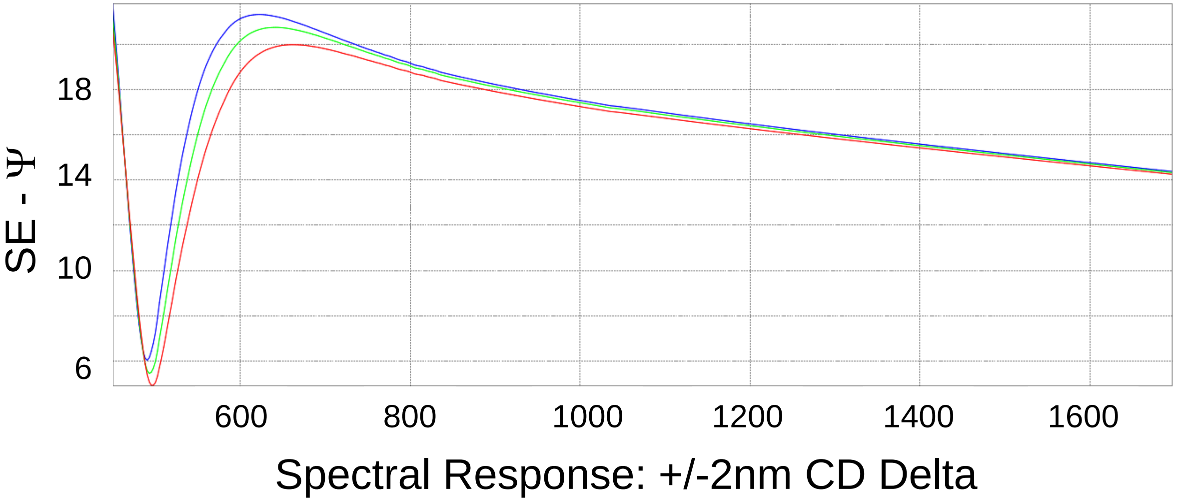
Cu X-Grating





Si X-Grating





OCD Case Studies

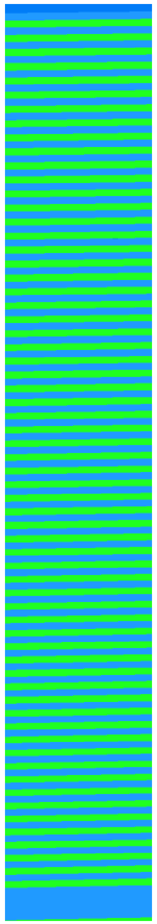
- Gate-All-Around Field Effect transistors
- Plasmons & Interconnects
- High Aspect Ratio 3D Memory

Challenges in 3D Memory Optical Metrology

Thin Film

Tier Stack Deposition

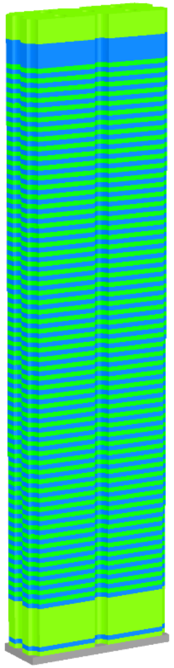
Challenge:
- Sensitivity to Å-level changes in tier thickness
- Sensitivity to individual layer excursions

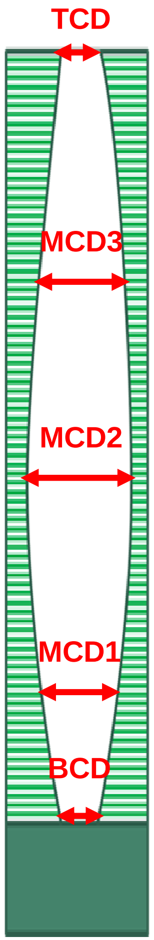


Patterned

Channel Hole Etch

Challenge:
- Sensitivity to the CD as function of channel height
- Sensitivity to etch depth

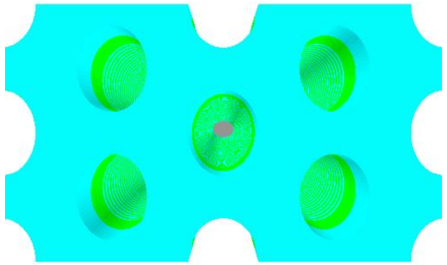


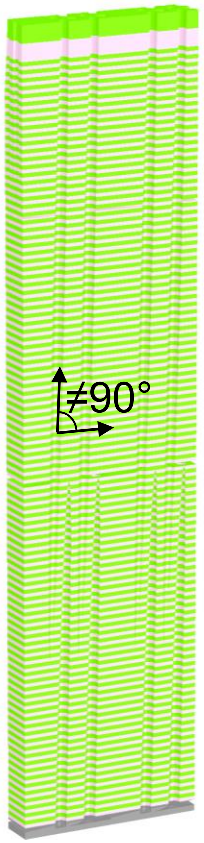


Advanced Patterned

Channel Hole Etch Tilt

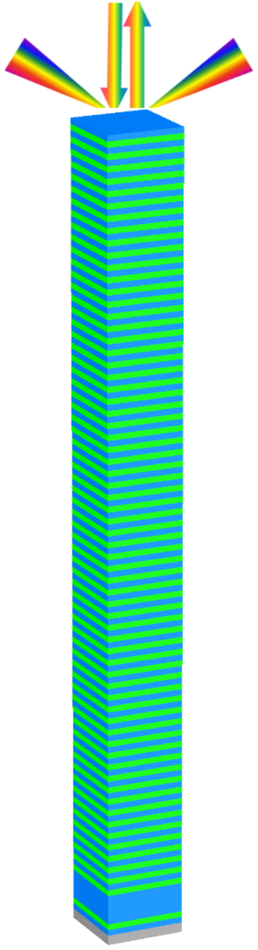
Challenge:
- Sensitivity to tilt
- Sensitivity to hole shape



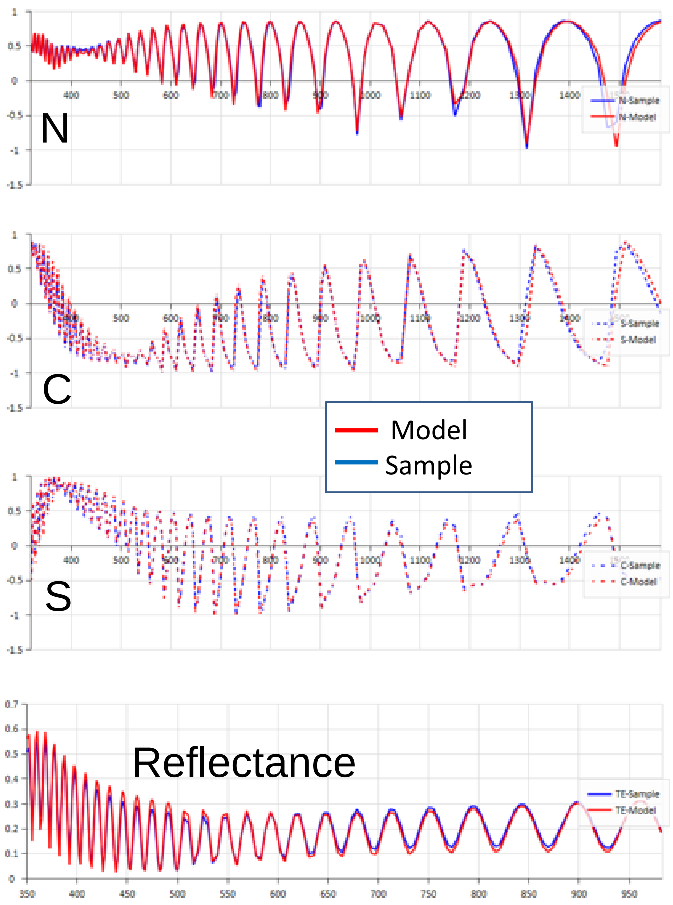


Tier Stack Thickness Measurement

Measure & Analyze

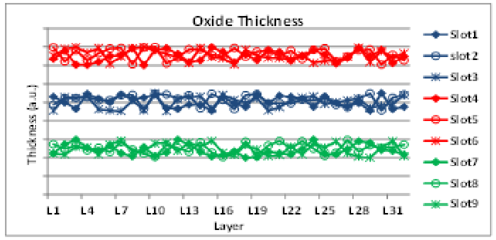


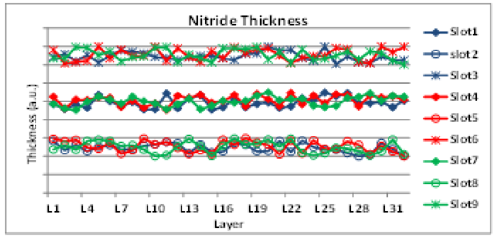
Spectra and Model Fit



Tier THK Skew Sensitivity

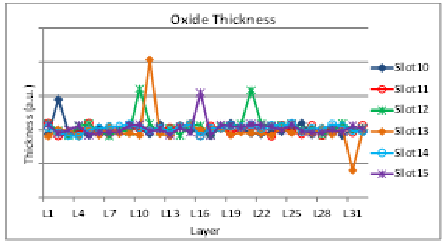
Slot	SiO2 Tier THK	SiN Tier THK
1	POR	POR
2	POR	-
3	POR	+
4	+	POR
5	+	-
6	+	+
7	-	POR
8	-	-
9	-	+

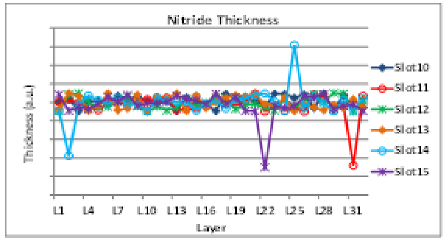




Tier Layer THK Excursion Sensitivity

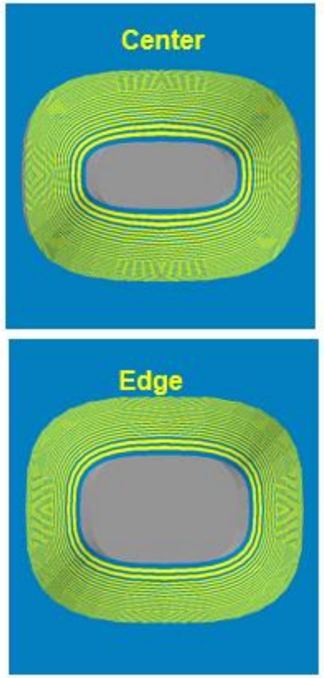
Slot	SiO2 Tier THK	SiN Tier THK
10	L2 +	POR
11	POR	L31 -
12	L10 + L21 +	POR
13	L11 + L31 -	POR
14	POR	L2 – L25 +
15	L16 +	L22 -

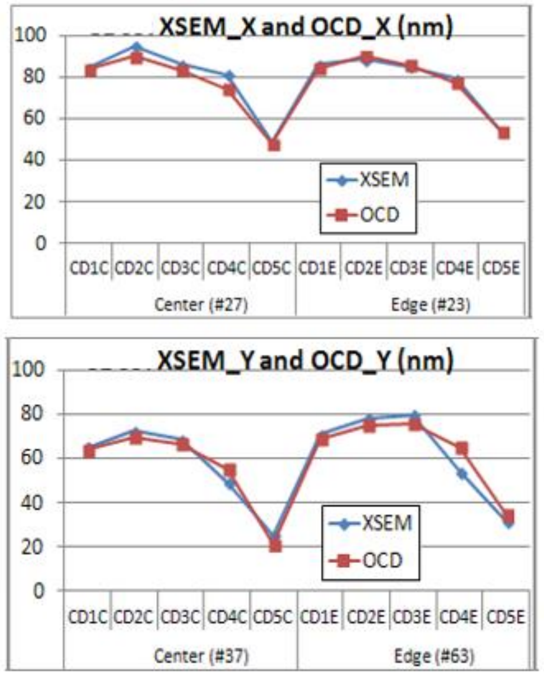




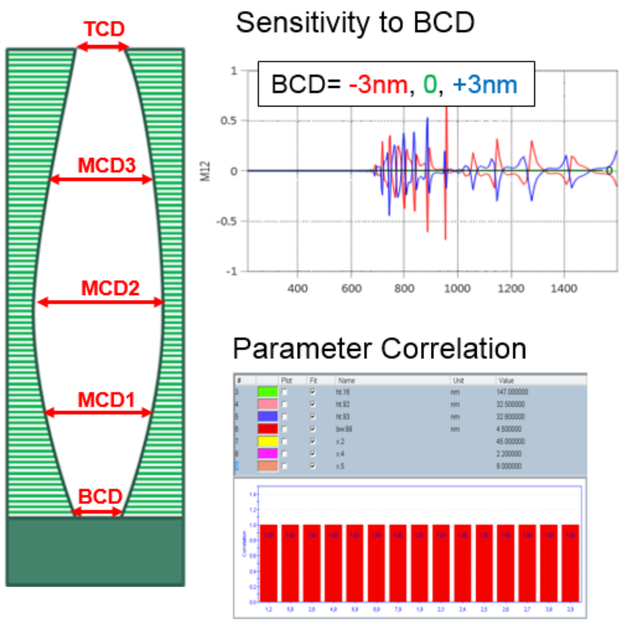
OCD – Channel Hole Etch – Measurement Validation

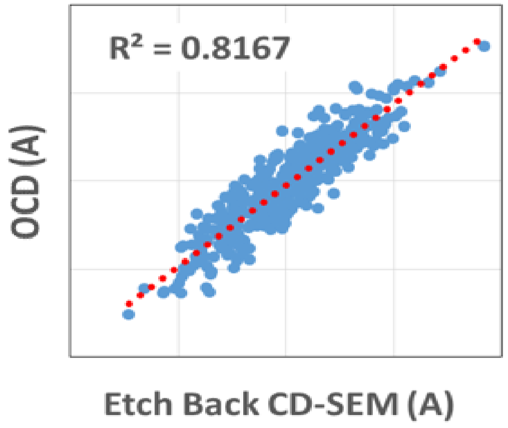
Channel Hole Profile – Site to Site Trend





Channel Hole Profile Measurement Strategy





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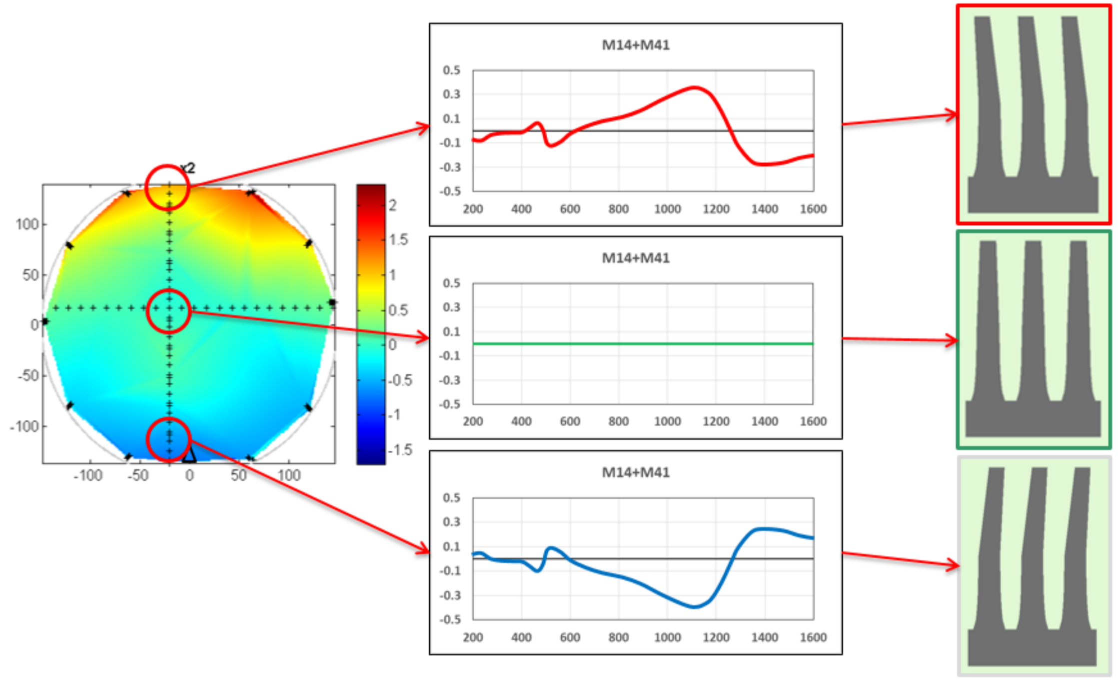
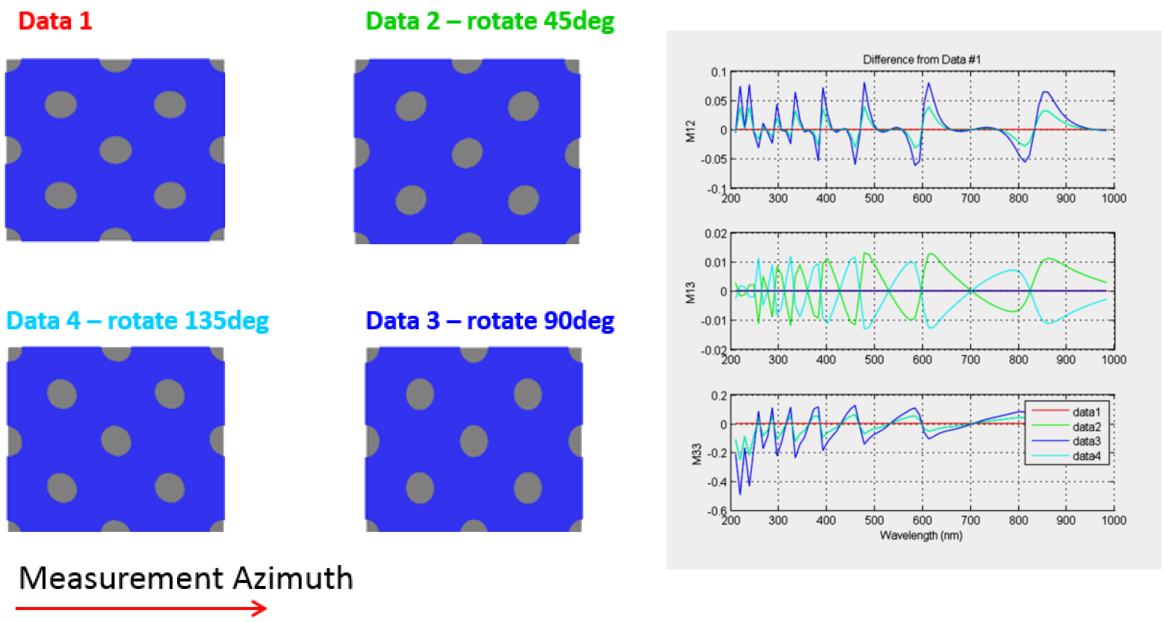
Advanced OCD Applications Enabled by Mueller Matrix OCD

MM Off-Diagonal Response to Structure Tilt



MM Off-Diagonal Response to non-orthogonal Hole Orientation



Summary

- **Logic and 3D memory have a wide variety of challenging metrology problems**
- **Optical metrology offers a fast and non-destructive way of addressing some**
- **But physics demands more sophisticated models and methodologies**
- **Do not count out optical metrology any time soon**

Thank you!

nanometrics

advanced **process control** systems and solutions

semiconductor | substrate | industrial

critical dimension | thin film | surface quality | composition | inspection