

Accuracy Limitations in Specular- Mode Optical Topography Extraction

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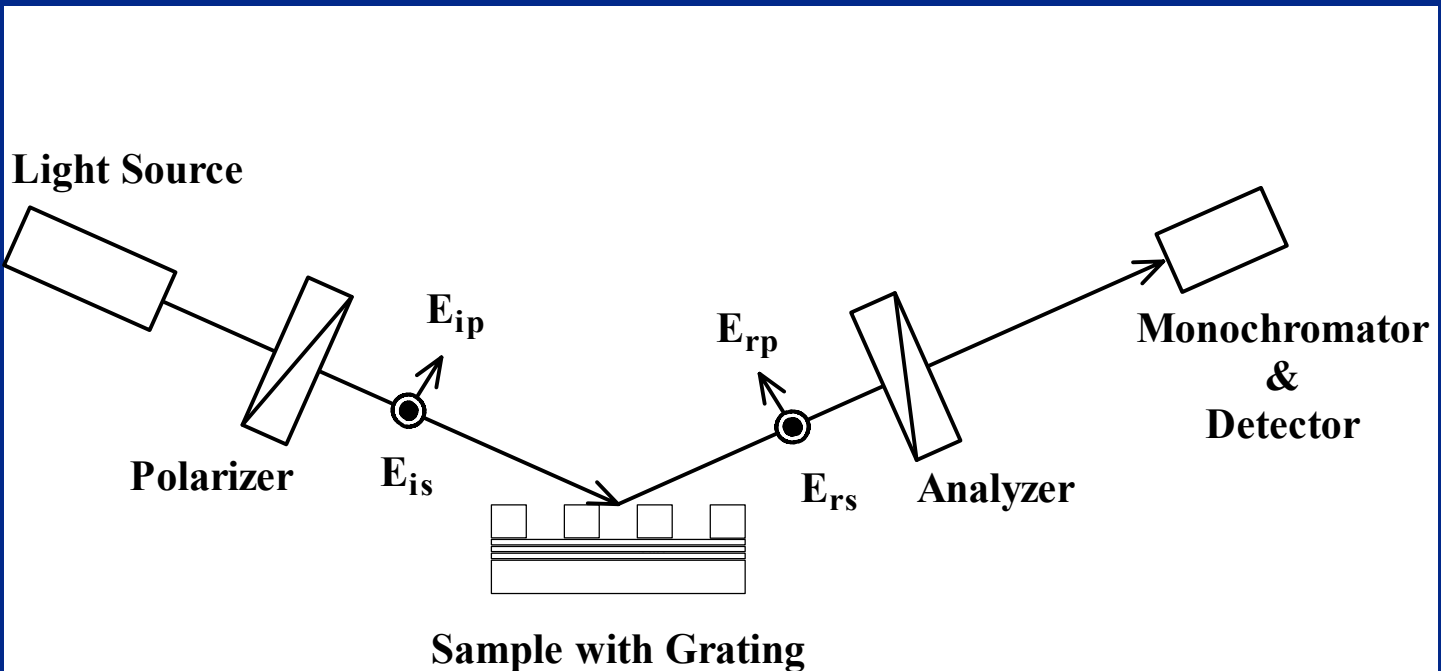
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Outline

- Goal: Use Specular Reflected Light Measurements from Gratings (Scatterometry) for Control of CD/Topography
- UofM Group: 1st Demos of Real-Time Monitoring and Endpoint Control of Photoresist CD in Etch Chambers
 - Ex Situ & In Situ Results
 - Demos on O₂ Plasma Trim-back of Photoresist for Gate
 - Requires Adaptation to Measurement Accuracy Limitations
- Simulations and Implications for Future of Scatterometry as Process Control Sensor

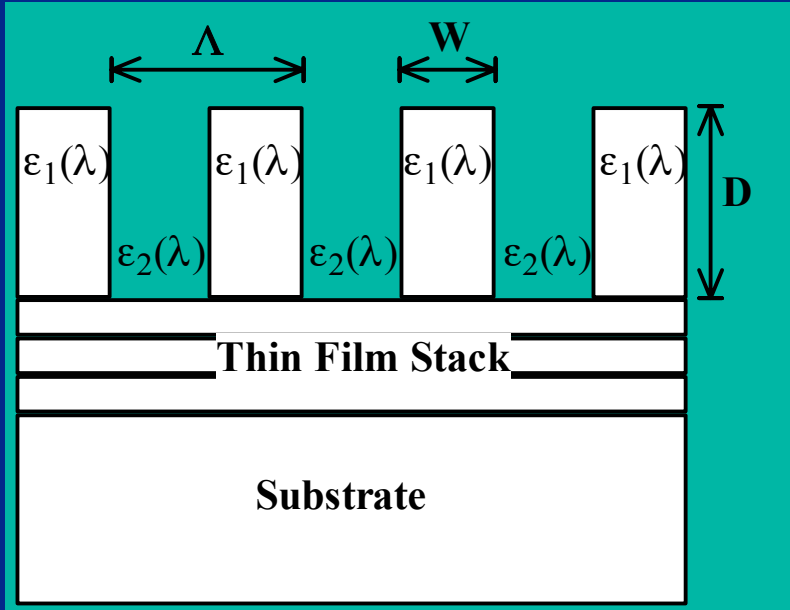
Spectroscopic Ellipsometry



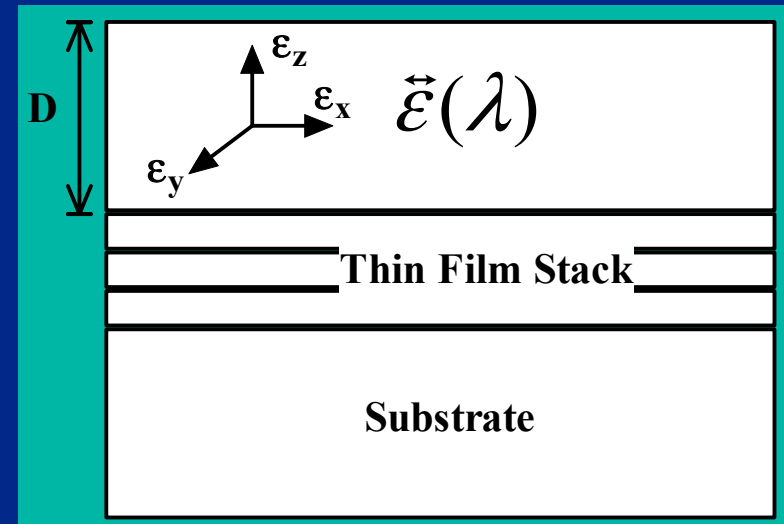
$$\rho = \frac{R_p}{R_s} = \frac{E_{rp} / E_{ip}}{E_{rs} / E_{is}} = \tan(\Psi) \cdot \exp(i\Delta)$$
$$\alpha = \cos(2\Psi), \quad \beta = \sin(2\Psi) \cdot \cos(\Delta)$$

- **Tan(Ψ) And Cos(Δ) Are Measured by Ellipsometry**
—Functions of wavelength and incident angle

Grating \Leftrightarrow Anisotropic Thin Film Analogy



1-D Photonic Crystal



Anisotropic Thin Film

- Line Height \Leftrightarrow Film Thickness
- Line Shape \Leftrightarrow Optical Dielectric Function

Specular Spectroscopic Scatterometry

- Probes Wavelength Dependence of Scattering from a Given Line Size/Shape
- Grating Amplifies & Averages Single Line Effects
- Grating Periodicity Aids Accurate Diffraction Solution
- Result Sub-Wavelength Topography Sensitivity
- Extremely High Sensitivity to Line Height (D) \Rightarrow Analogous to Thin Film Thickness
- Very Good Sensitivity to Linewidth (W) & Line-shape Under Proper Circumstances \Rightarrow Analogous to Parameterized Extraction of Optical Dielectric Function of Thin Film
- Accuracy of Topography Extraction Analogous to Accuracy of $\epsilon(\lambda)$ Extraction From Thin Films Using SE
 - Will Fail If Grating Is Too Shallow (Effective Optical Thickness Fails to Produce Thin Film Interference Effect)

Cruelty of Diffraction Physics:

$W/\lambda_{\min} + \varepsilon_{\text{line}}$ **Control Strength of Scattering**

$W \gtrsim \lambda_{\min} / 2$ to λ_{\min} **High Sensitivity to Detailed Shape in *Structure of Data* vs. λ**

$W \approx \lambda_{\min} / 10$ to $\lambda_{\min} / 2$ **Sensitivity to Average CD, Diminishing Shape Information**

Most Shape Info in Magnitude not Fine Structure of Data

$W \ll \lambda_{\min}$ **Results Converge to EMA, No Real CD Info, Only Average Composition**

W
vs.
fixed
 λ_{\min}

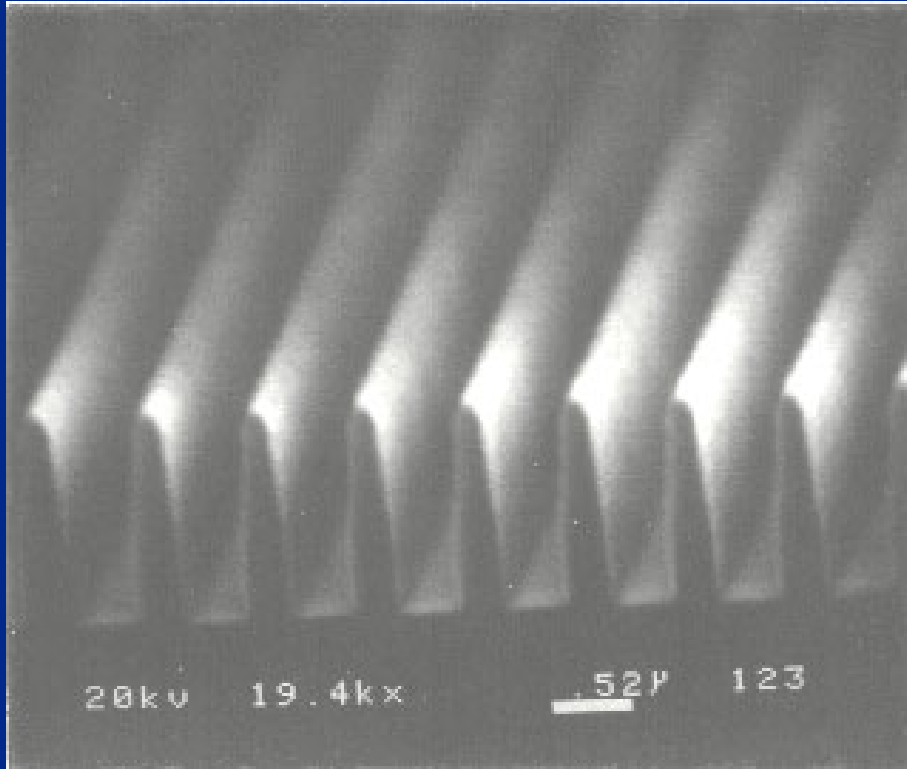


Topography Extraction

Example $W > \lambda_{\min}$

- Experimental Data Taken at 7° AOI with Sopra GESP-5 Ellipsometer
- 350 nm Line/ 700 nm Period Photoresist on 31.7nm SiO₂ on Si
- Successively Improved Topography Estimations Using Levenberg-Marquardt Non-Linear Regression
 - Trapezoid (3 parameters)
 - Trapezoid on Rectangular Base (4 parameters)
 - Triangular Top on Trapezoid on Rectangle (5 parameters)
 - 3 Quadratic Segments with Zero Top Width (Triangle-Trapezoid-Trapezoid with Curvature, 9 parameters)

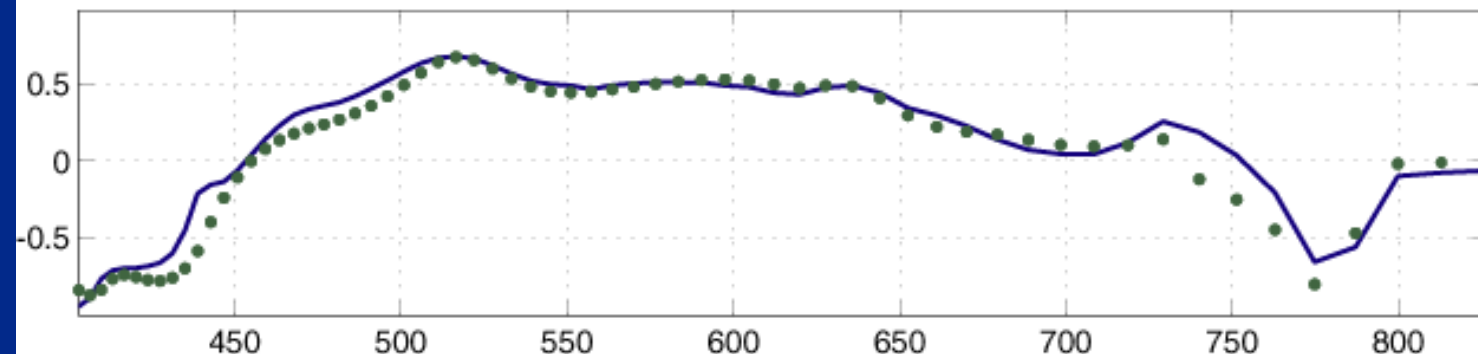
Submicron Grating



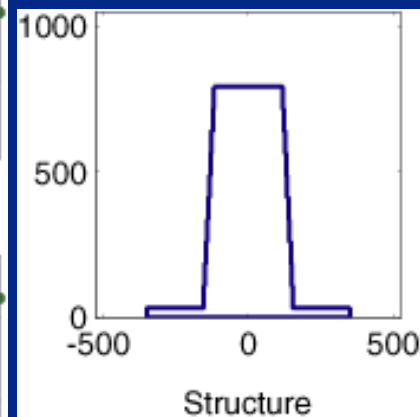
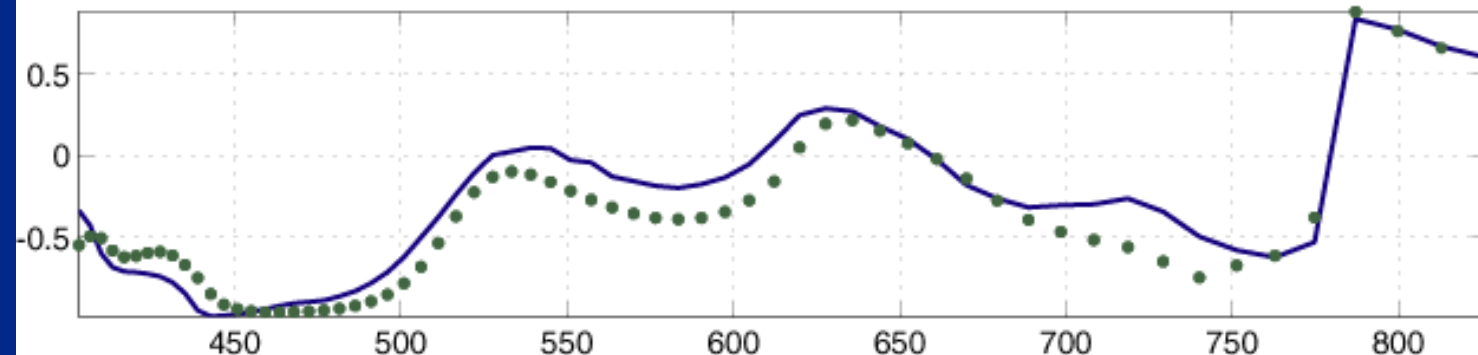
- $\sim 0.35\mu\text{m}$ Line/Space Grating In Photoresist/ 300\AA SiO_2/Si
- Accurate Photoresist $N(\lambda)$ Obtained by SE Measurement of Similarly Prepared Unpatterned Film
- Period Measured as $0.700\mu\text{m}$ Using 1st Order Diffraction Angle at Multiple λ 's

Trapezoidal Fit 400-825 nm

Alpha= $\cos(2\Psi)$ iteration=10

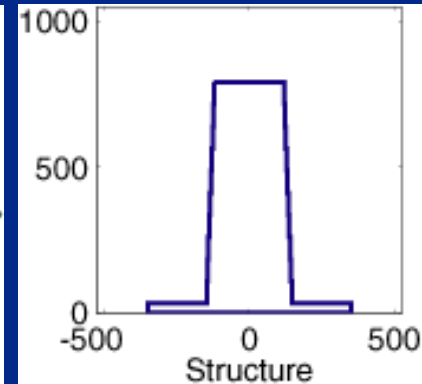
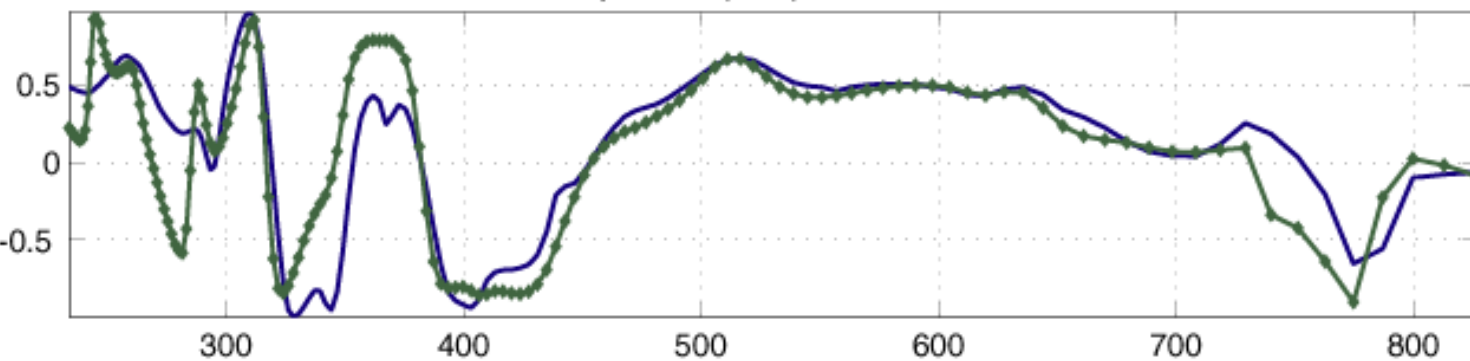


Beta= $\sin(2\Psi)\cos(\Delta)$ MSE=0.03099

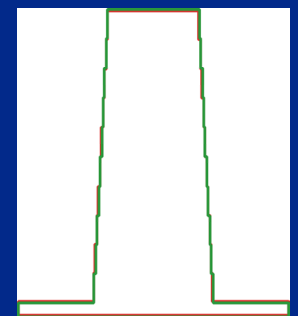
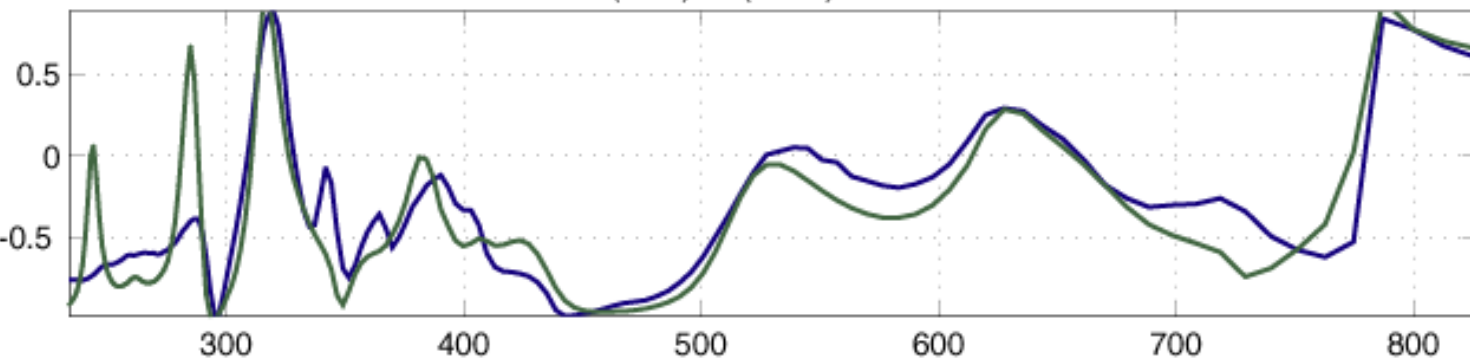


Trapezoidal Fit

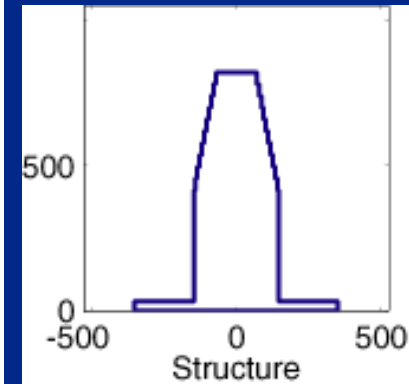
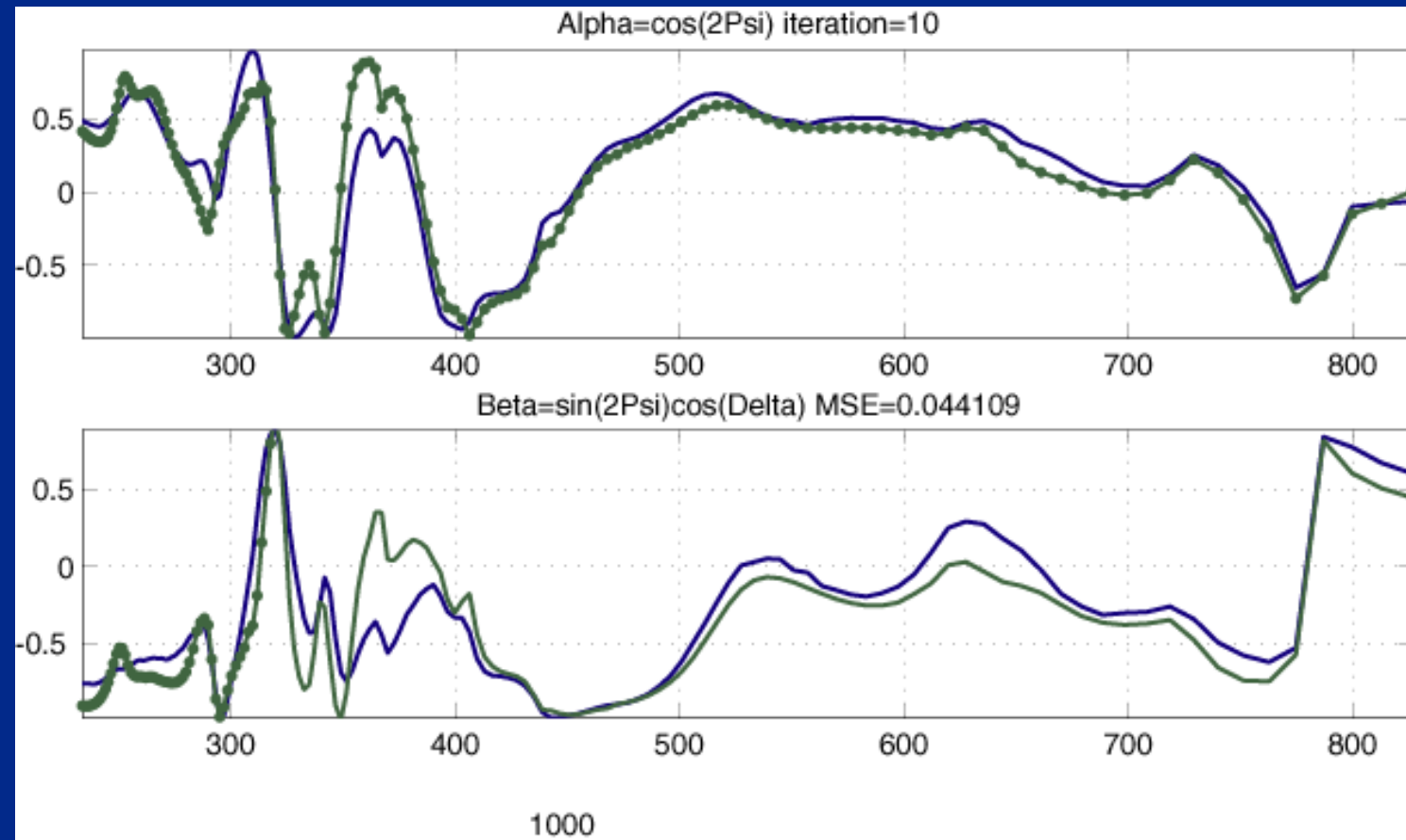
Alpha= $\cos(2\Psi)$ iteration=10



Beta= $\sin(2\Psi)\cos(\Delta)$ MSE=0.082108

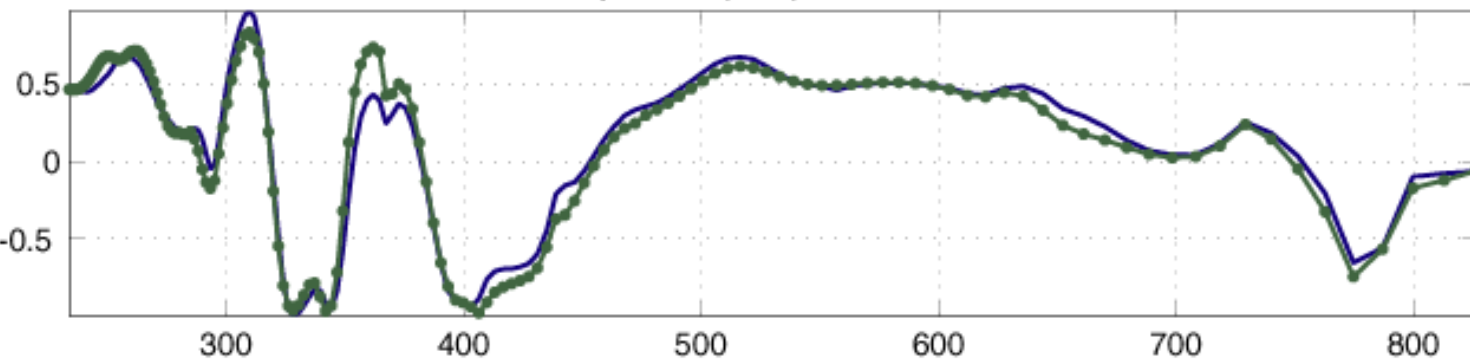


Trapezoid on Rectangle Fit

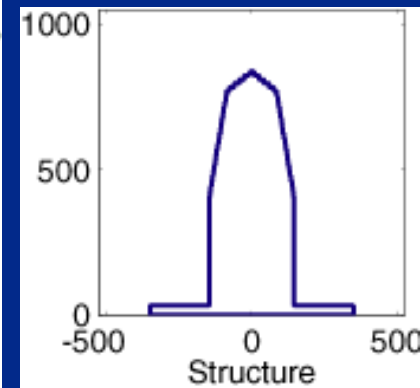
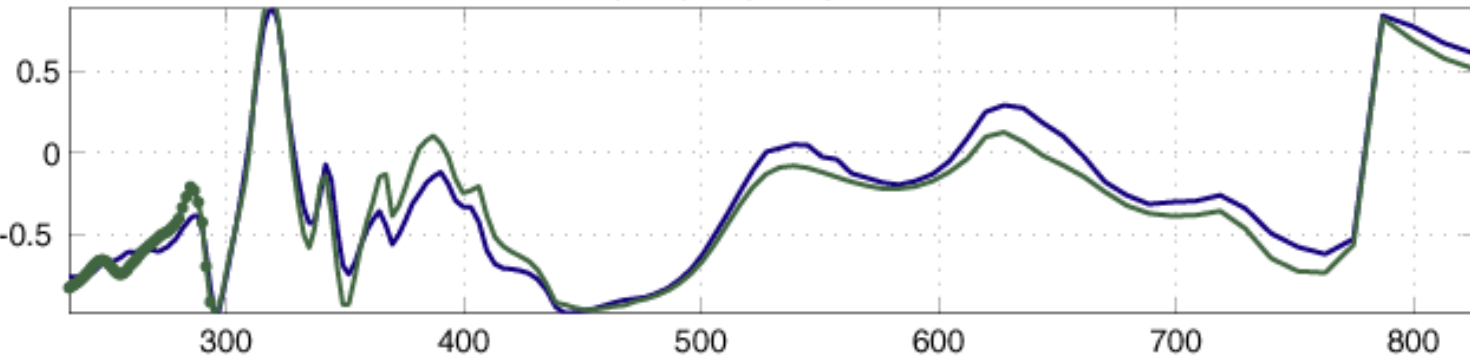


Triangle-Trapezoid-Rectangle Fit

Alpha= $\cos(2\Psi)$ iteration=10

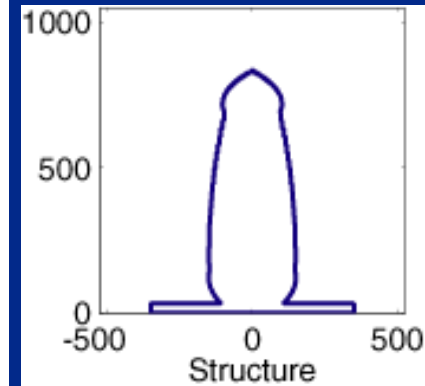
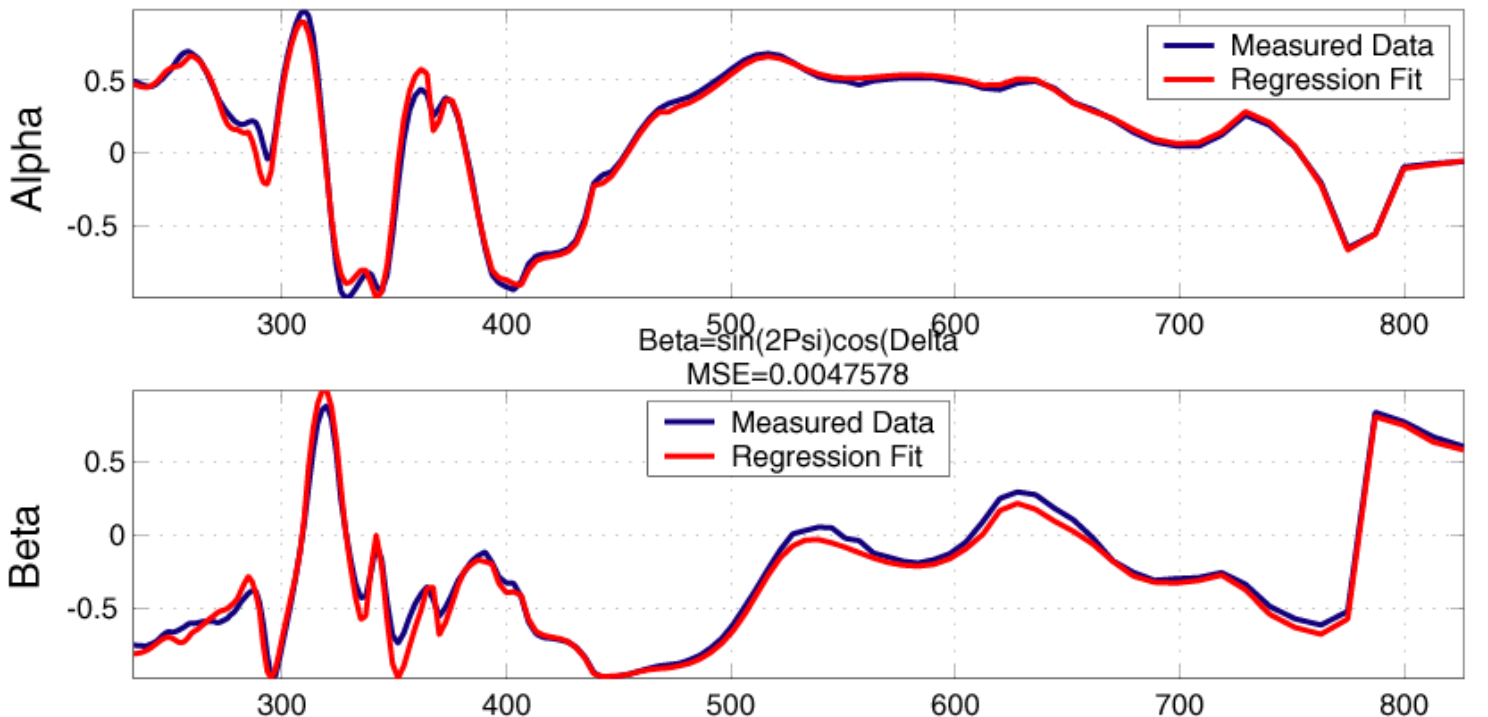


Beta= $\sin(2\Psi)\cos(\Delta)$ MSE=0.011729

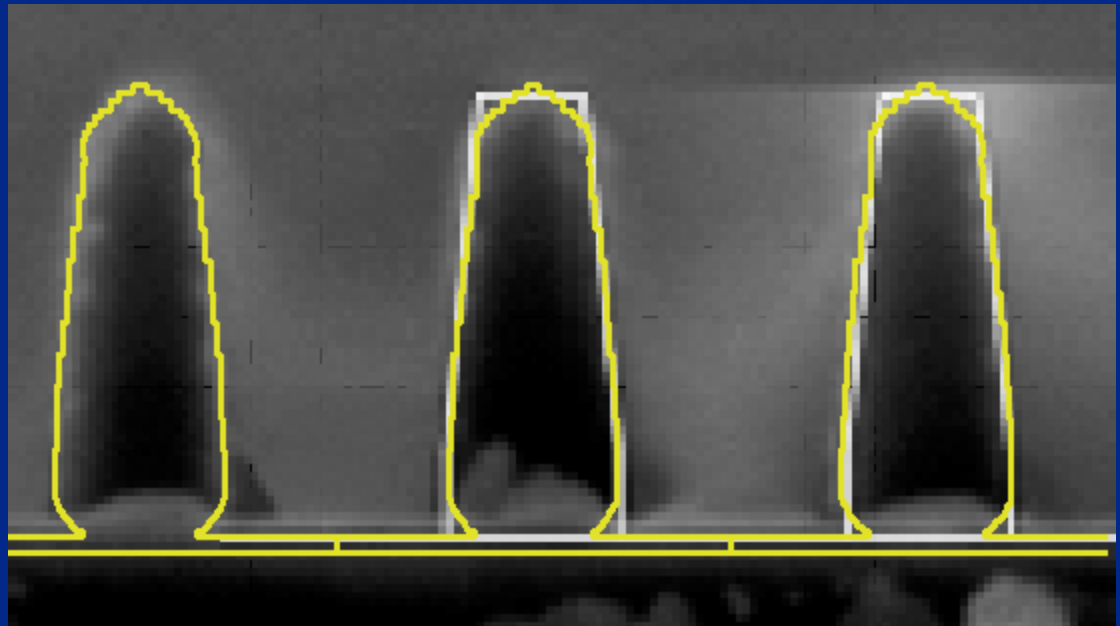
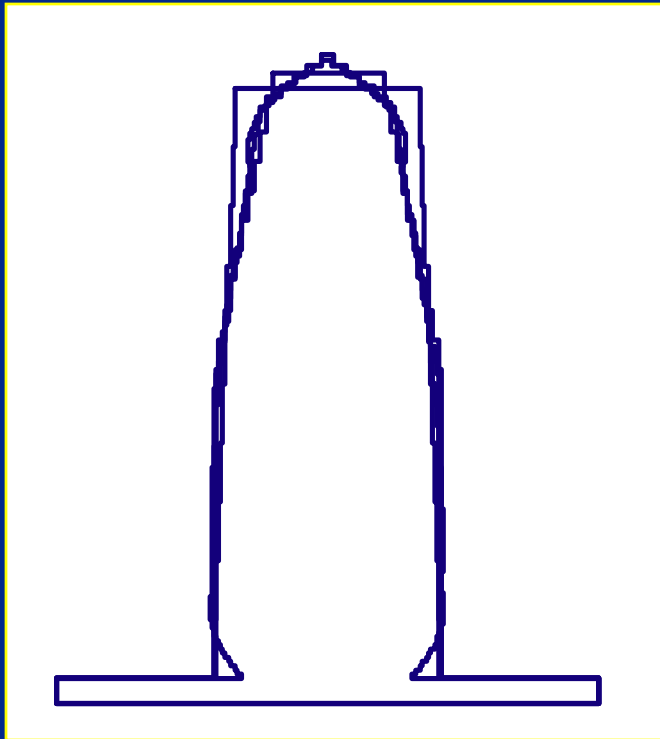


3-Segment Quadratic Fit

Regression Fit of Photoresist Grating Measured at AOI= 7 Degrees



Extracted Topography Comparison



3-Level Quadratic Fit Parameters, Confidence Limits, & Cross- Correlation Coefficients

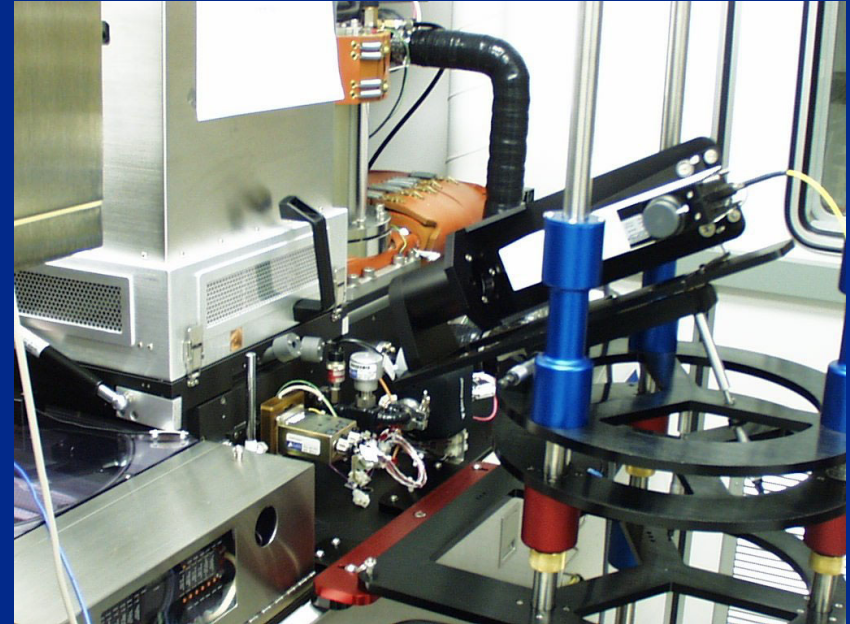
Term	Value	95.4% conf. Limit	Units
h1	146.51	4.55	nm
m11	0.7389	0.0097	slope
m12	-0.4698	0.011	quadratic curvature
h2	545.72	36.05	nm
m21	0.3461	0.0272	slope
m22	-0.1921	0.0282	quadratic curvature
h3	112.35	34.79	nm
m31	0.0803	0.0529	slope
m32	-0.1933	0.0659	quadratic curvature

Fit Was
Pushed to
the Limits
of Data

	h1	m11	m12	h2	m21	m22	h3	m31	m32
h1	1	0.356	-0.217	-0.369	-0.176	0.121	0.267	0.101	0.04
m11	0.356	1	-0.88	-0.34	-0.31	0.354	0.301	-0.098	0.219
m12	-0.217	-0.88	1	0.373	-0.02	-0.08	-0.363	-0.146	-0.009
h2	-0.369	-0.34	0.373	1	0.512	-0.527	-0.993	-0.369	-0.108
m21	-0.176	-0.31	-0.02	0.512	1	-0.981	-0.493	0.286	-0.474
m22	0.121	0.354	-0.08	-0.527	-0.981	1	0.517	-0.31	0.501
h3	0.267	0.301	-0.363	-0.993	-0.493	0.517	1	0.394	0.082
m31	0.101	-0.098	-0.146	-0.369	0.286	-0.31	0.394	1	-0.866
m32	0.04	0.219	-0.009	-0.108	-0.474	0.501	0.082	-0.866	1

RTSE Etch Movie

- In Situ Sopra Real-Time Spectroscopic Ellipsometry Monitoring of Photoresist Trim-Back in Lam 9400 TCP
- Data Collect at 63.5° AOI
- Non-Linear Filter Method to Detect Endpoint
- This Experiment Stopped at 200nm
- Work of Drs. Hsu-Ting Huang, Ji-Woong Lee, Pramod Khargonekar, and Fred Terry

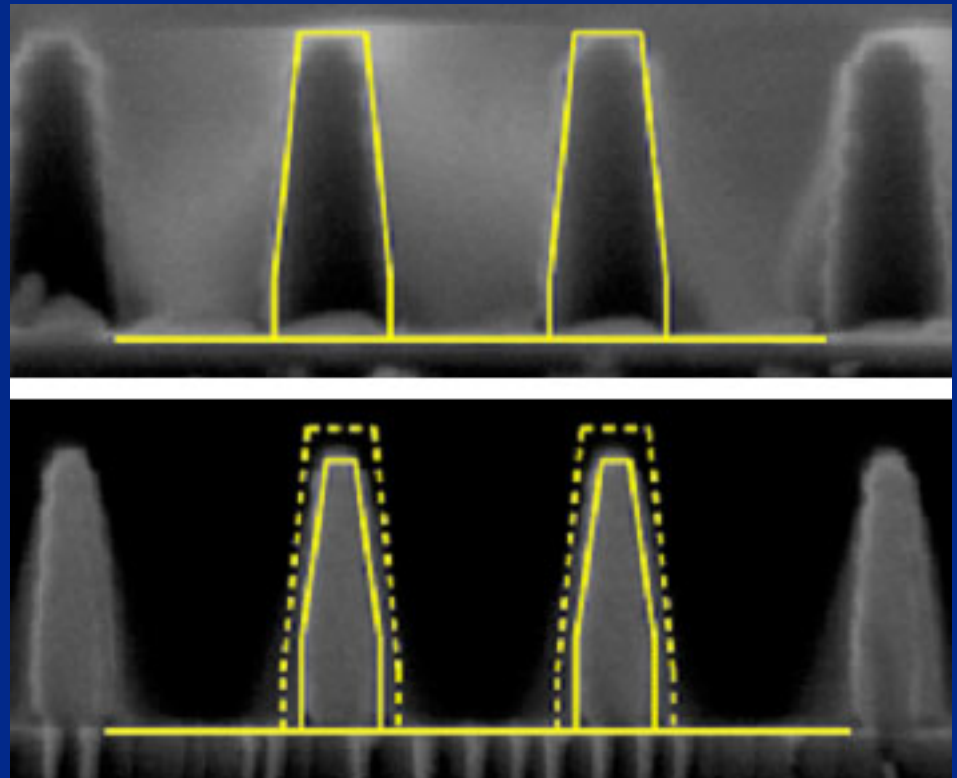


Trim to Target CD Movie

sprt7_tritraprect.mov

In Situ Optical CD/Automated Etch to Target CD

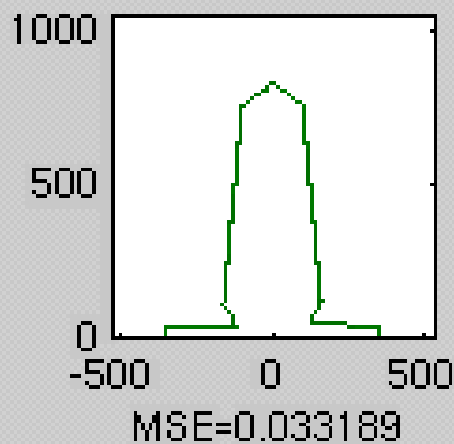
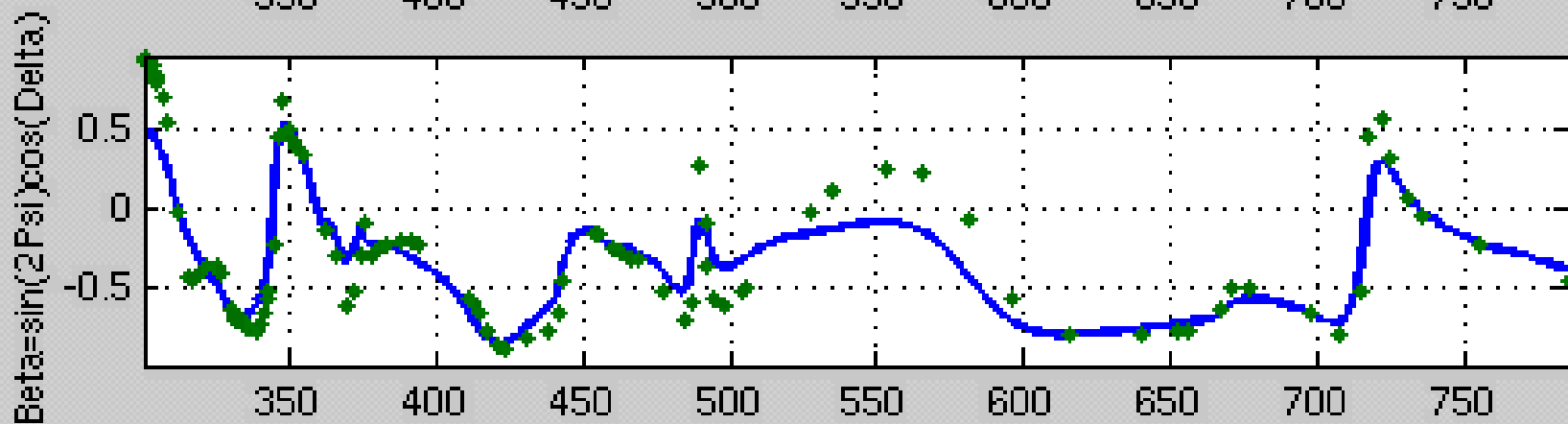
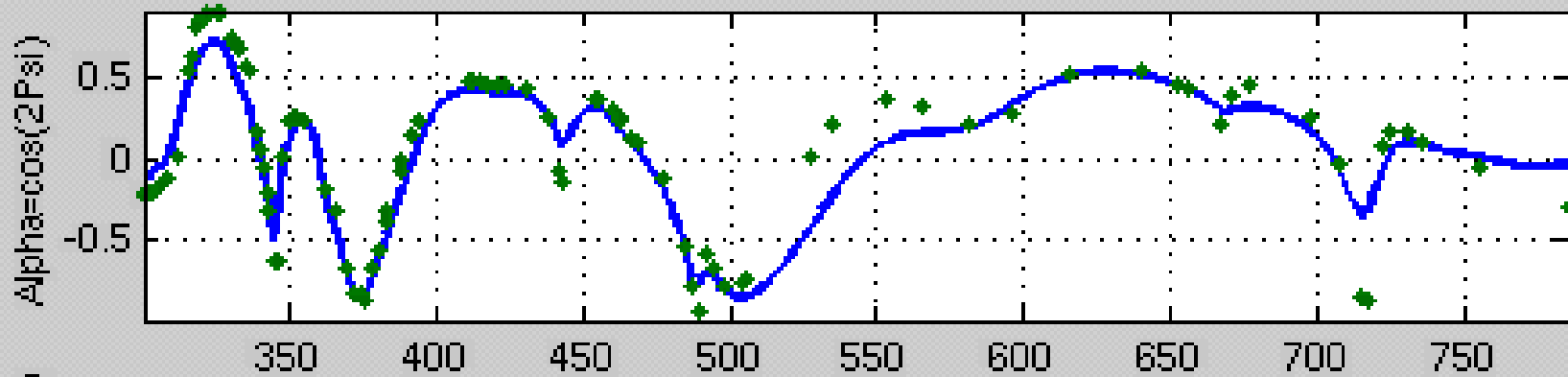
- O₂ Plasma Photoresist Trim in Lam 9400 TCP
- *In Situ* Real-Time Spectroscopic Ellipsometry Monitoring of Photoresist Grating Structure
- Off-Line RCWA Analysis of Grating Diffraction Problem
- Nonlinear Filtering Algorithm for Real-Time Data Analysis
 - *Completely Hands-off Automated Etch to Target CD*
- **Before Etching (top):**
 - Bottom CD: 296 nm
 - Feature Height: 777 nm
- **After Trim-back (bottom):**
 - Bottom CD: 200 nm (target)
 - Feature Height: 697 nm



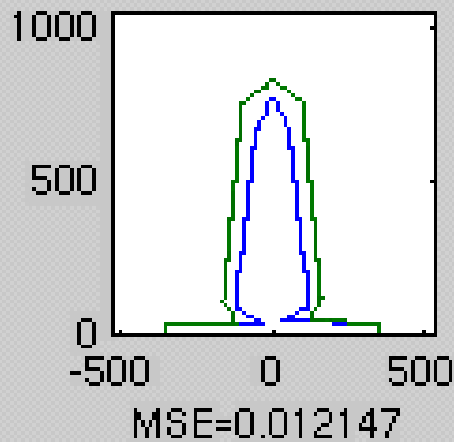
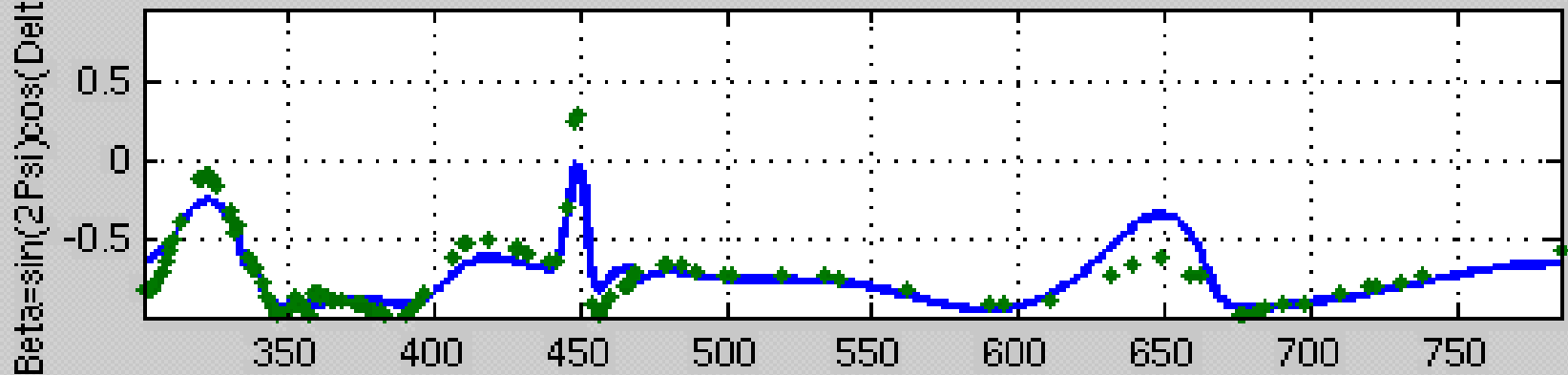
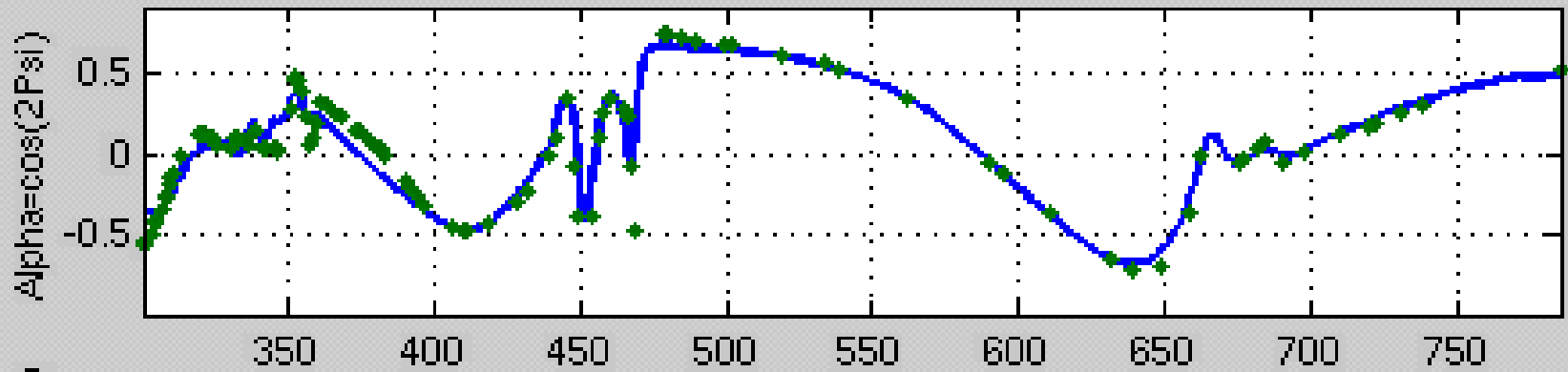
RTSE Etch Monitoring: Over-Fitting

- **Attempt to Fit for Under-Cut of Resist**
- **Over-Parameterization Due to Limited Absolute Accuracy of Measurement**
- **In This Case, Accuracy is Limited by Stray Light, Lower UV Photon Counts**
 - Usable Minimum Wavelength ~300nm
 - **Some Distortion of Peak/Valley Shapes**

RTSE Fit Time Step=1



RTSE Fit Time Step=101

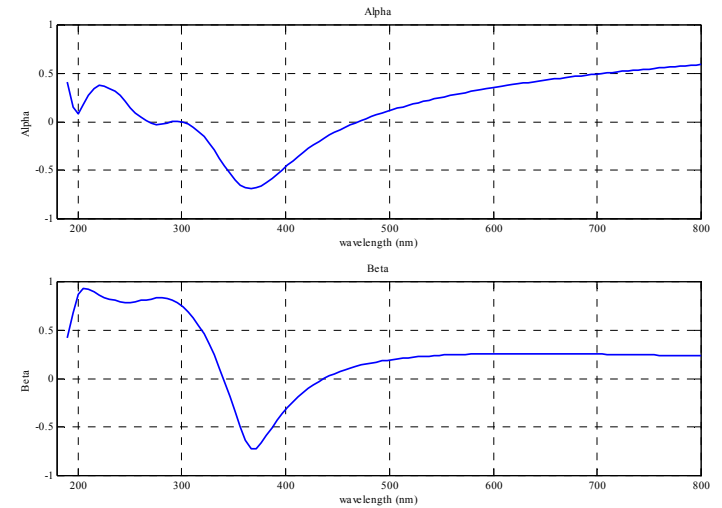
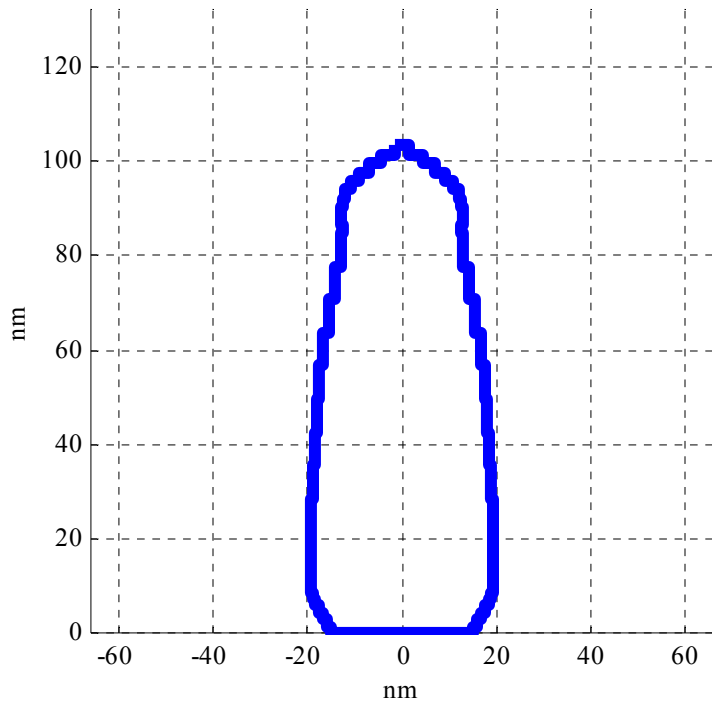


Simulations of ITRS Photoresist Milestones

- Simulated Data using Model DUV Photoresist at 2010, 2013, and 2016 Technology Nodes
- Rectangular Profiles Assumed with:
 - $\Lambda=90\text{nm}$ $W=25\pm 1.5\text{nm}$ Thick=100nm
 - $\Lambda=64\text{nm}$ $W=18 \pm 1.1\text{nm}$ Thick=80nm
 - $\Lambda=44\text{nm}$ $W=13 \pm 0.7\text{nm}$ Thick=50nm
- Assumed 190-800nm Spectroscopic Ellipsometry Measurements
- *Good News: Diminishing but Usable CD Sensitivity to 2016*
- *Bad News: Loss of Detailed Shape Sensitivity even at 2010*

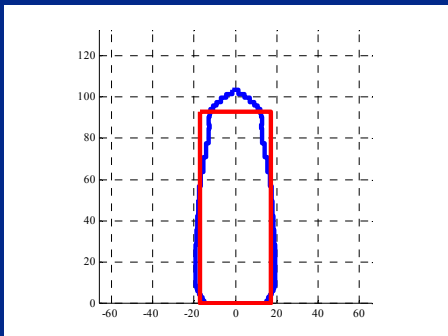
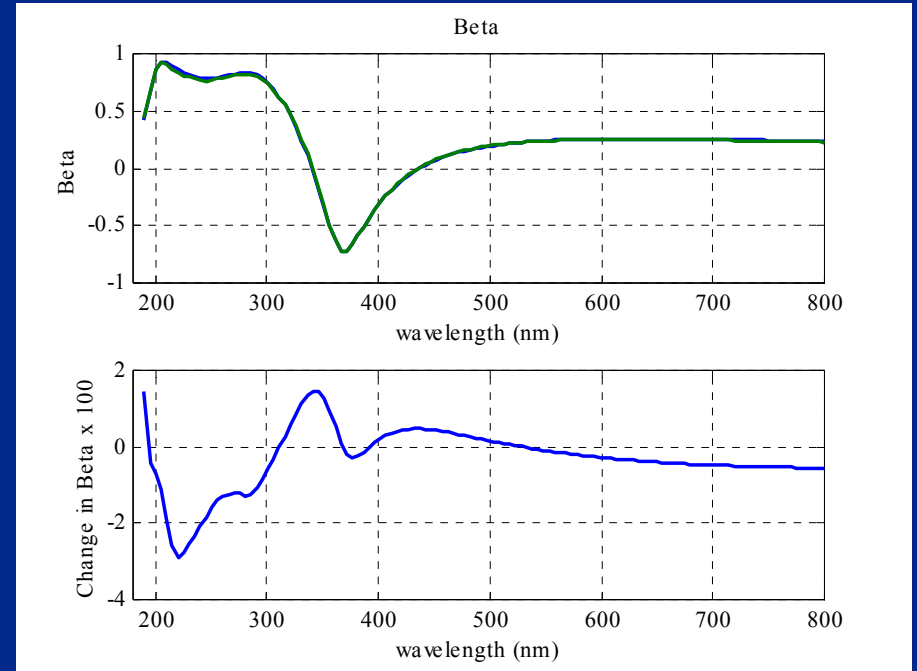
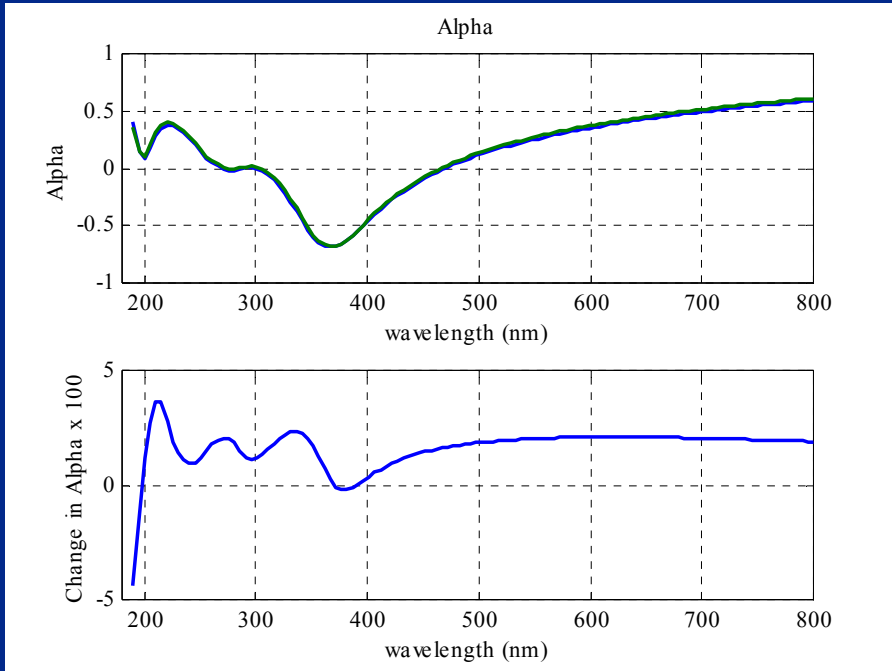
Simulated ~40nm PR Line

$\Lambda=90\text{nm}$



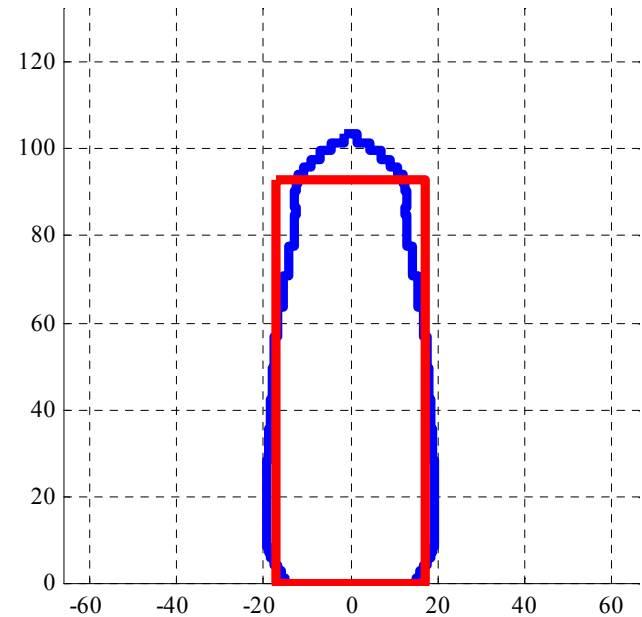
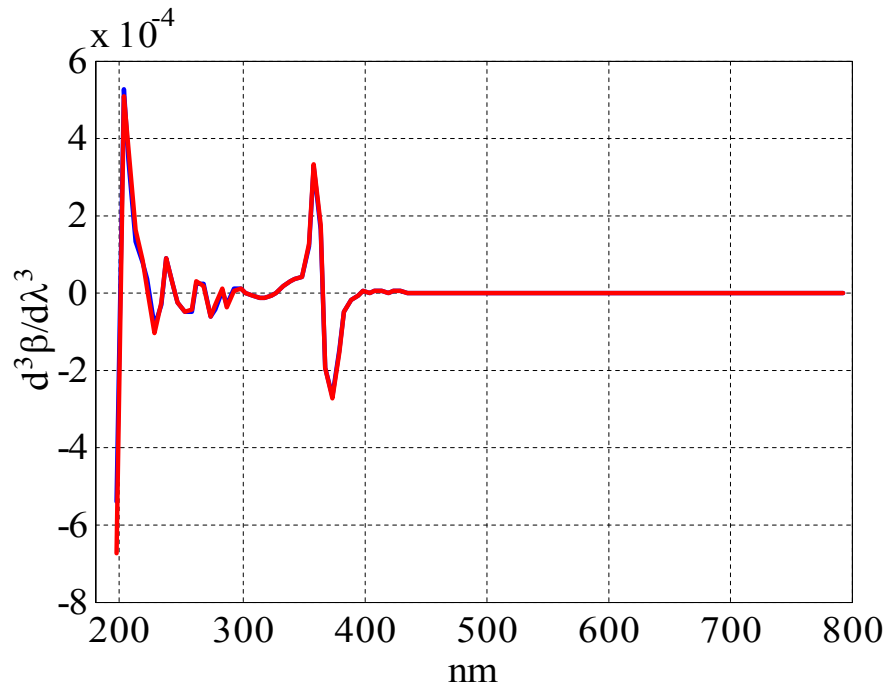
Can Detailed Shape Information Be Extracted?

Fit Using Rectangular Only Model



- **Rectangle Fit Averages More Complex Structure**
- **Examine Structure Differences in Data Through Derivatives vs. λ**

$d^3\beta/d\lambda^3$ For Complex Line & Rectangular Fit



No Structural Difference in Data Vs. Fit, All Information Concerning the More Complex Shape is in the Small Absolute Differences

Structure of Data and Fit

- **Fitting with a Rectangle-Only Geometry Yields NO Structure Differences, Only Magnitude Differences**
- **Examining Derivatives of Data and Fit Illustrates Complete Lack of Structural Differences**
- **VERY High Instrument Accuracy Needed For Detailed Topography Extraction Without Resorting to VUV Measurements**
- **High Accuracy RCWA Calculations Required for Simulation/Regression**

Conclusions

- Extraction of Topography Using Specular-Mode Spectroscopic Ellipsometry and Related Techniques Provides Outstanding Height and Average CD Capabilities to the End of the ITRS
- Detailed Lineshape Extraction Ability Exists But Gets Worse As W/λ_{\min} Decreases
- Situation Better for Gate Materials vs. Photoresist (ϵ)
- Possibly Achievable but Very High Accuracy Measurements Are Required for Detailed Shape Extraction
 - Instrumentation, Alignment, and Simulation Accuracy Must All be Very Good
- VUV & EUV Scatterometry Needed for the Future
- Unanswered Questions on Line-Edge Roughness, Line Material Variations, etc.

Acknowledgements

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 - Project Ended August, 1999
- **Research funded in part by: AFOSR/DARPA MURI Center for Intelligent Electronics Manufacturing (AFOSR F49620-95-1-0524)**
 - Projected Ended August, 2001
- **Research funded in part by: NIST Intelligent Control of the Semiconductor Patterning Process (70NANB8H4067)**
 - Project Ended June, 2002
- **Industry Support Badly Needed for Continued University Efforts in this Area**

