Accuracy Limitations in Specular-Mode Optical Topography Extraction

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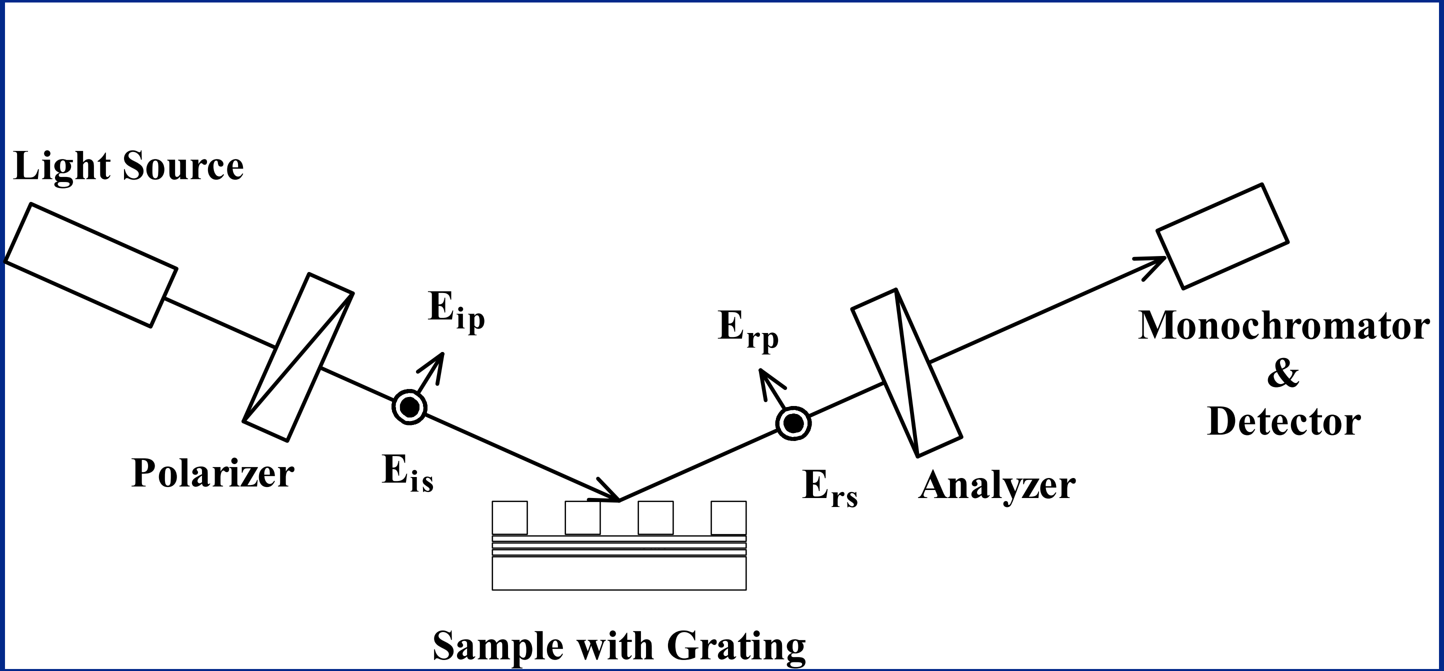
Outline

- 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 O_2 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



$$\rho = \frac{R_p}{R_s} = \frac{E_{rp} / E_{ip}}{E_{rs} / E_{is}} = \tan(\Psi) \cdot \exp(i\Delta)$$

$$\alpha = \cos(2\Psi), \qquad \beta = \sin(2\Psi) \cdot \cos(\Delta)$$

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

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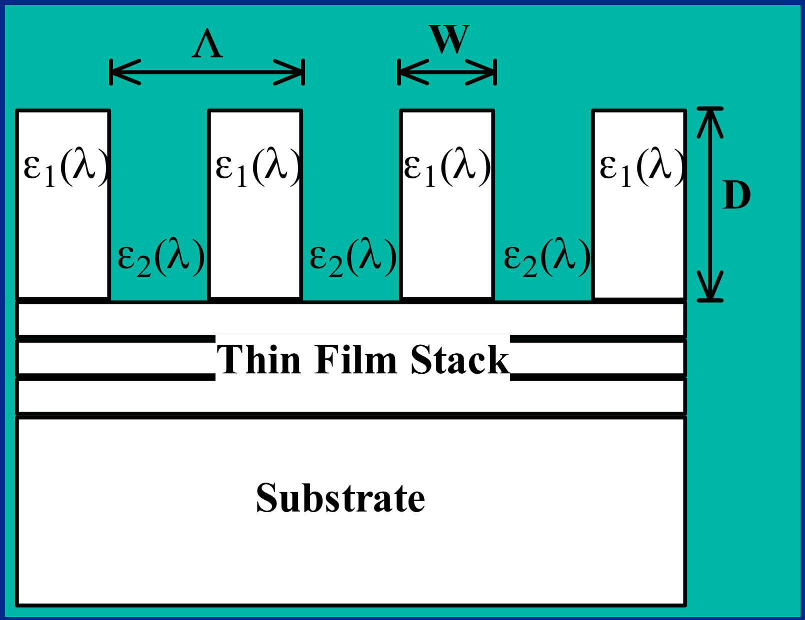
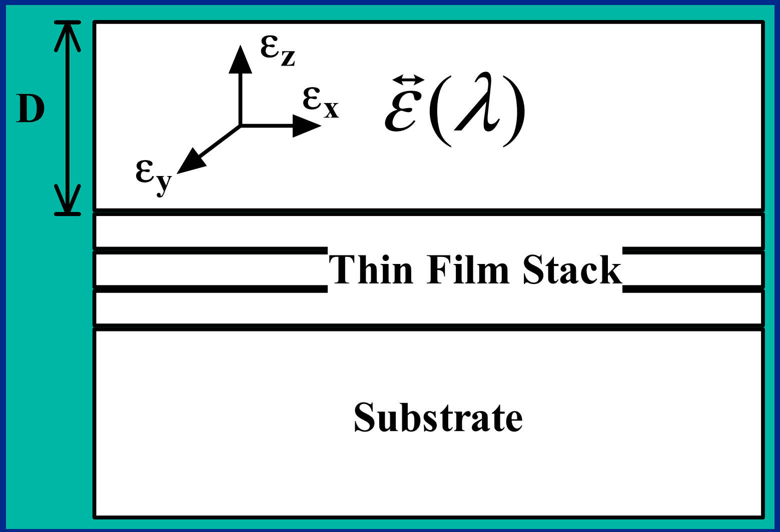
Grating ⇔ Anisotropic Thin Film Analogy



1-D Photonic Crystal



Anisotropic Thin Film

- **Line Height ⇔ Film Thickness**
- **Line Shape ⇔ 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 $\varepsilon(\lambda)$ 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/λ_{min} + ε_{line} Control Strength of Scattering

W vs. fixed λ_{min}

$W \gtrsim \lambda_{min}/2$ 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

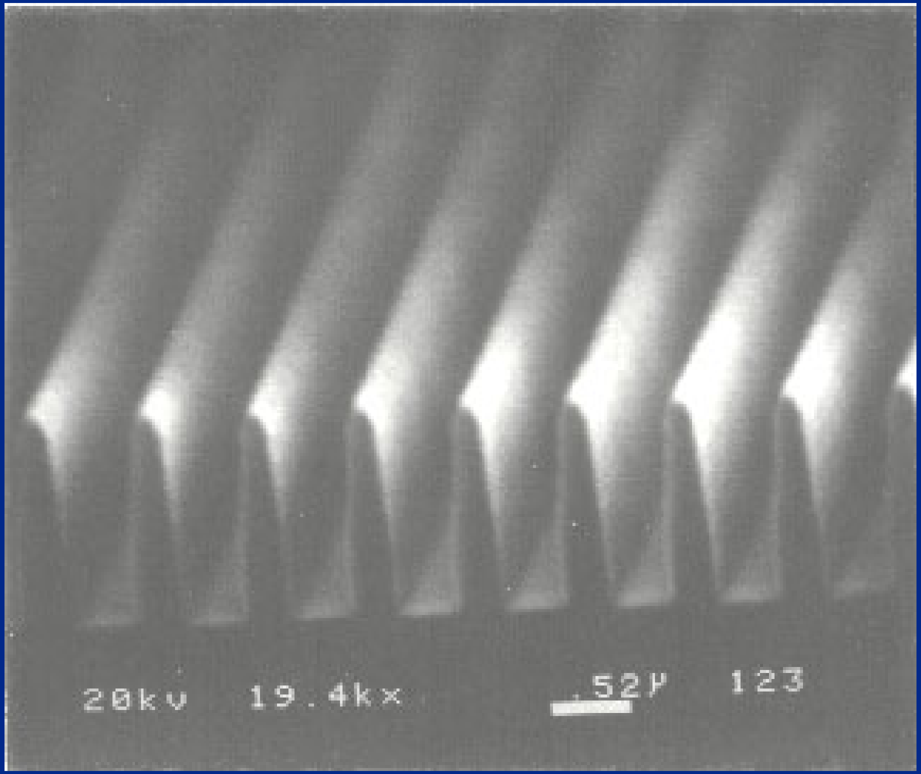
Most Shape Info in Magnitude not Fine Structure of Data

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

Topography Extraction Example W>λ_{min}

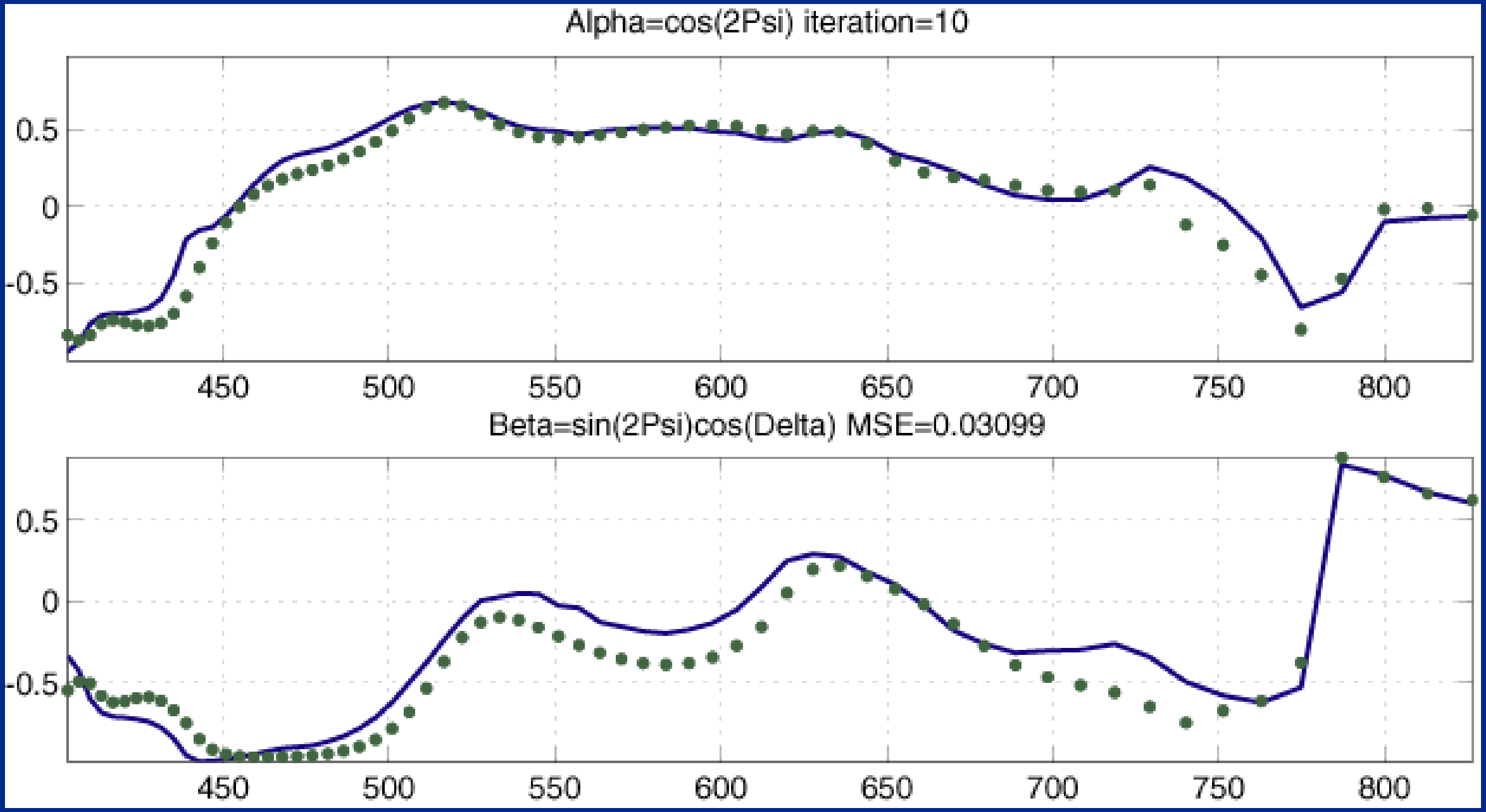
- Experimental Data Taken at 7° AOI with Sopra GESP-5 Ellipsometer
- 350 nm Line/ 700 nm Period Photoresist on 31.7nm SiO_2 on Si
- Successively Improved Topography Estimations Using Levenberg-Marquardt Non-Linear Regression
  - Trapezoid (3 parameters)
  - Trapezoid on Rectangular Base (4 parameters)
  - Triangular Top on Trapezoid on Rectangle (5 parameters)
  - 3 Quadratic Segments with Zero Top Width (Triangle-Trapezoid-Trapezoid with Curvature, 9 parameters)

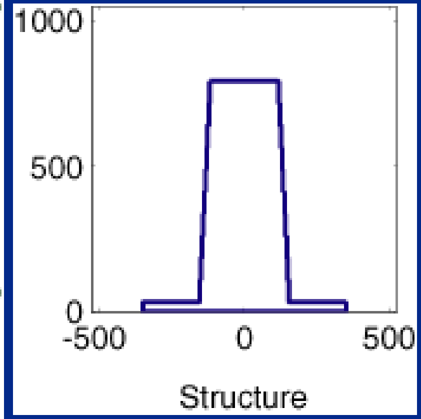
Submicron Grating



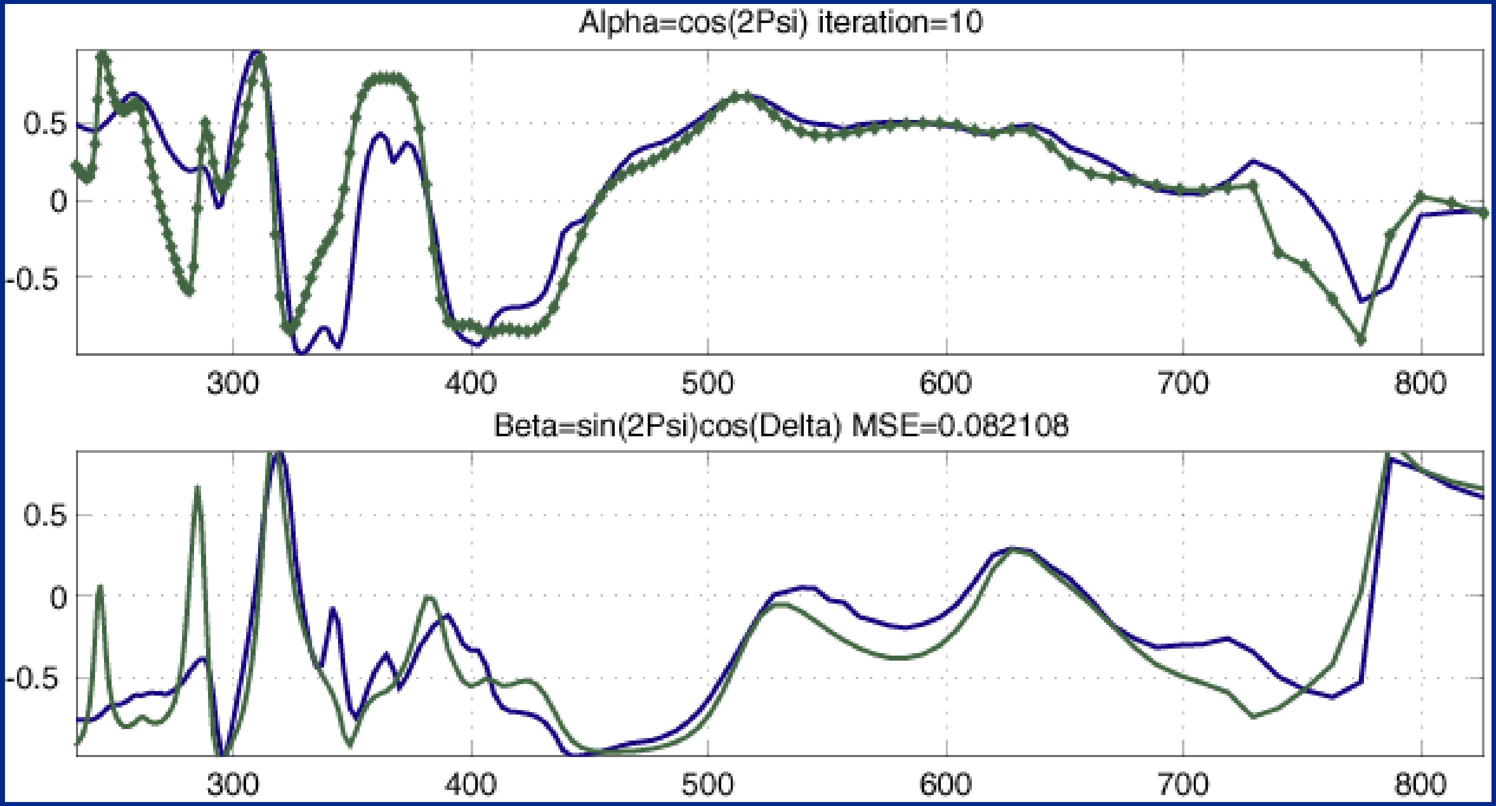
- ~0.35µm Line/Space Grating In Photoresist/300Å SiO_2/Si
- Accurate Photoresist N(λ) Obtained by SE Measurement of Similarly Prepared Unpatterned Film
- Period Measured as 0.700 µm Using 1st Order Diffraction Angle at Multiple λ's

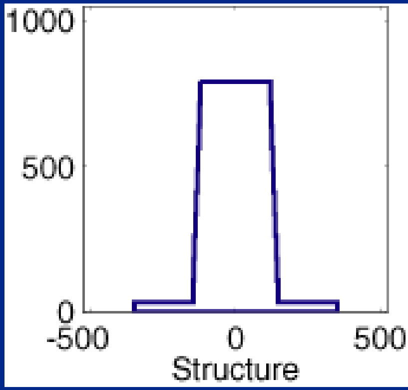
Trapezoidal Fit 400-825 nm

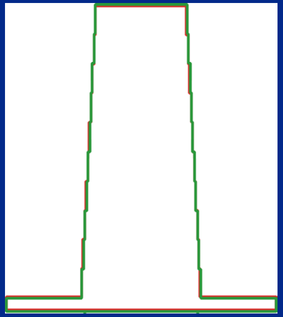




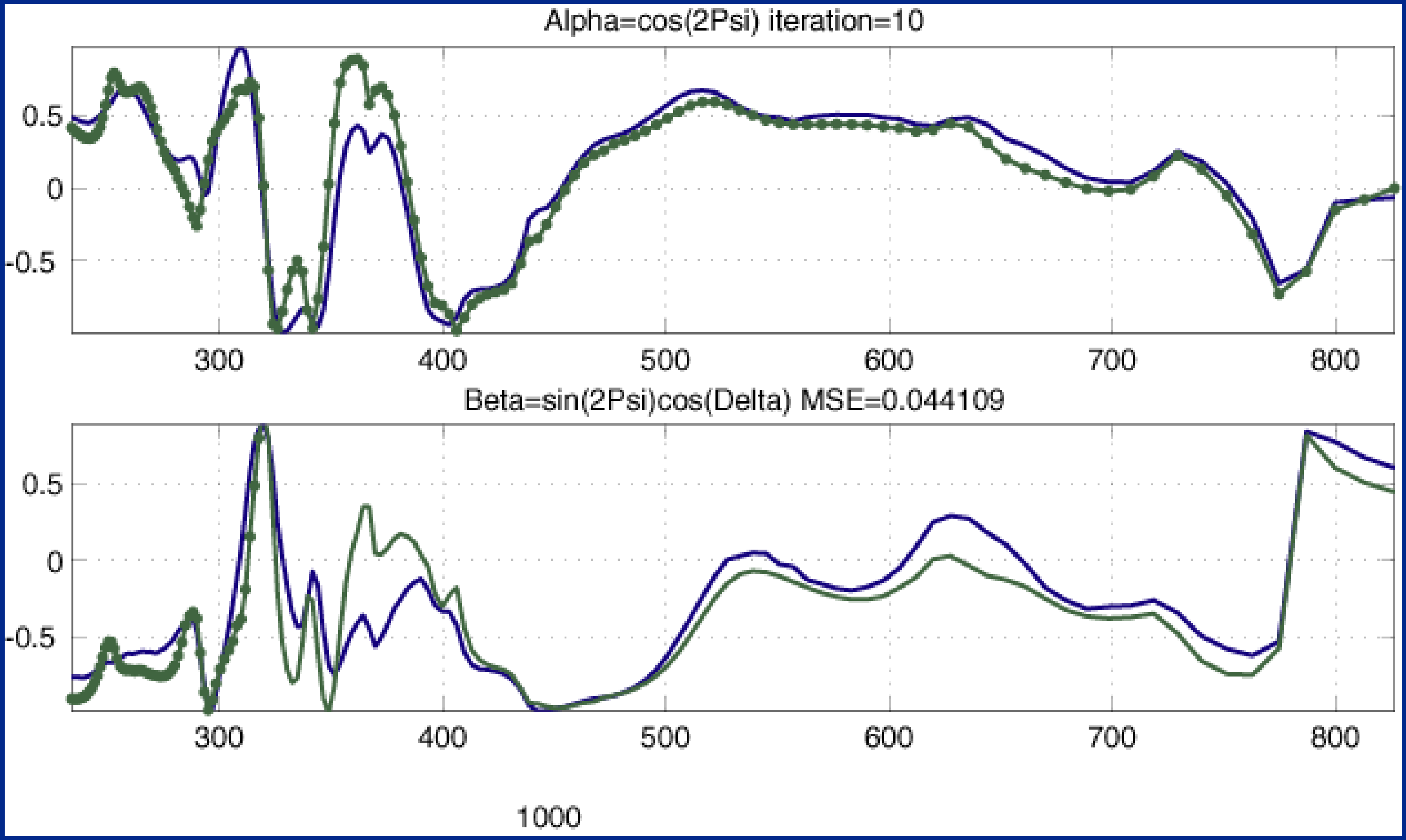
Trapezoidal Fit

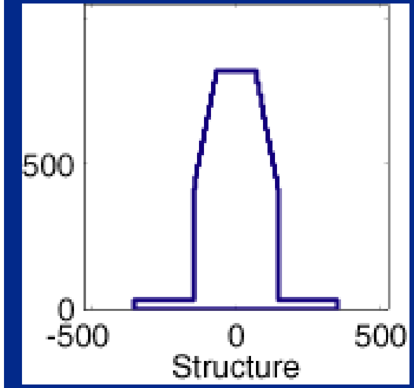






Trapezoid on Rectangle Fit





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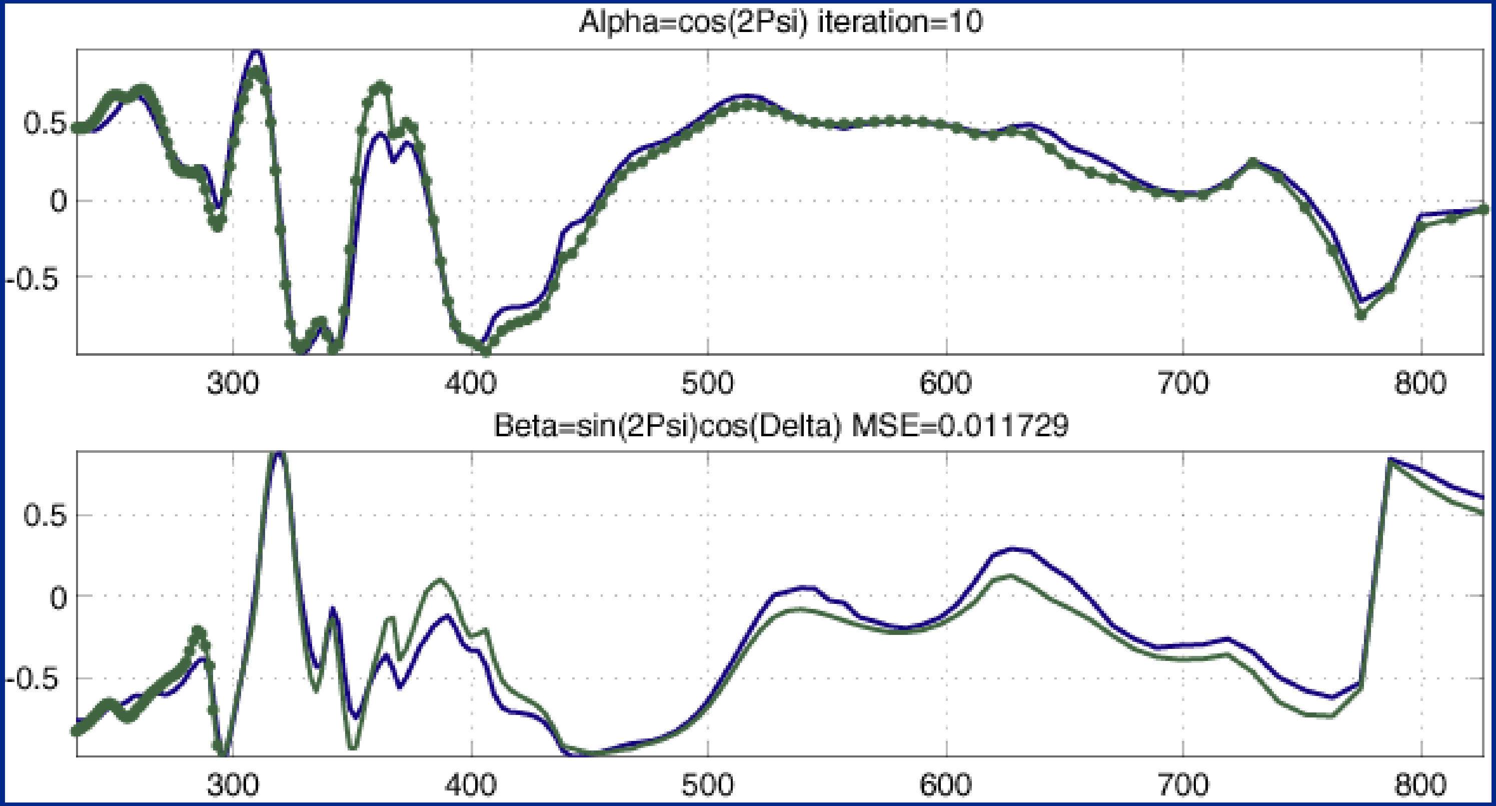
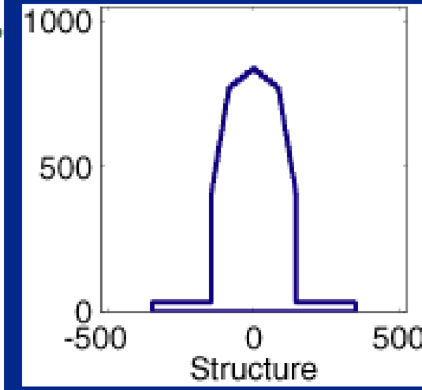
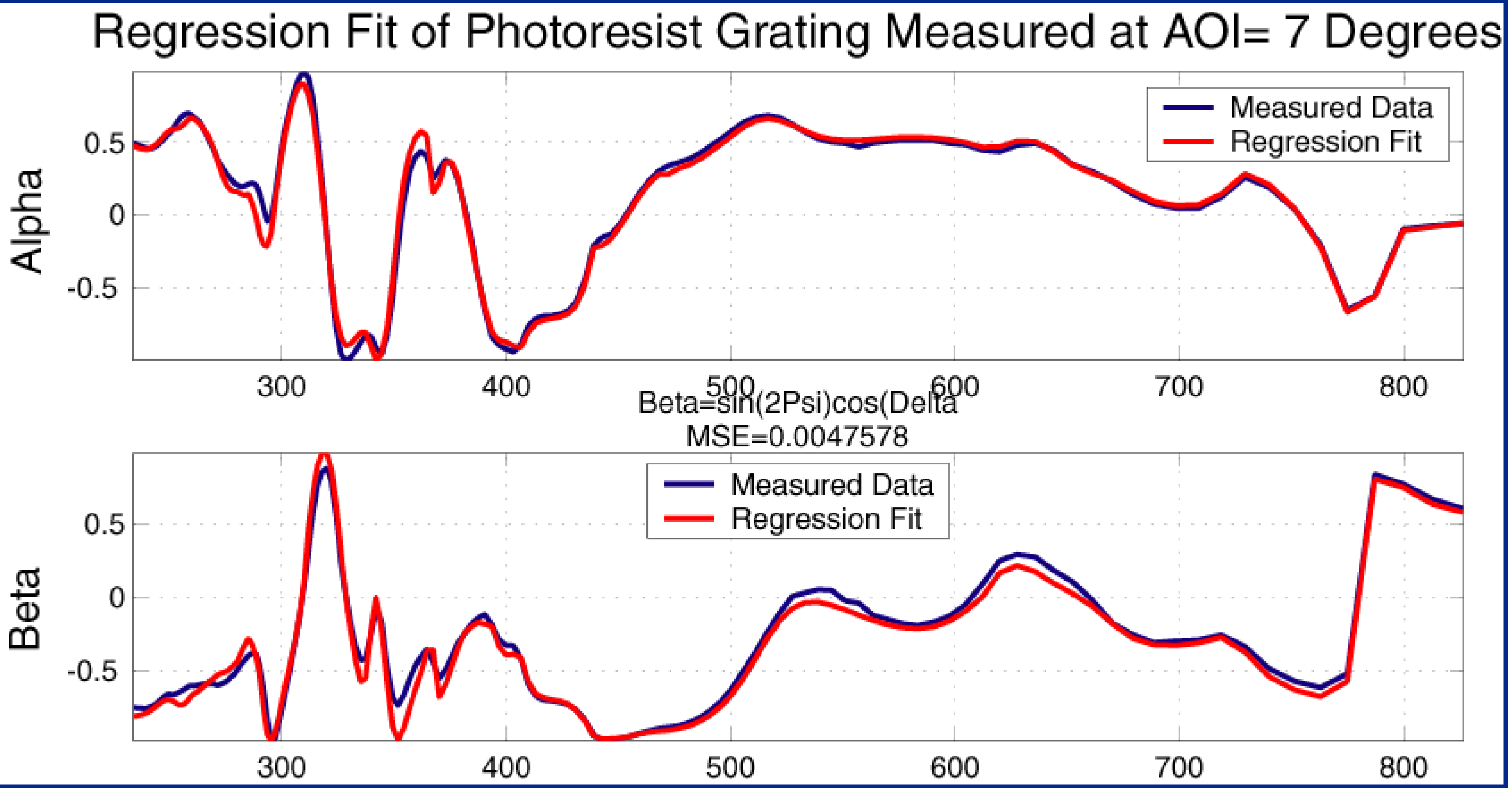
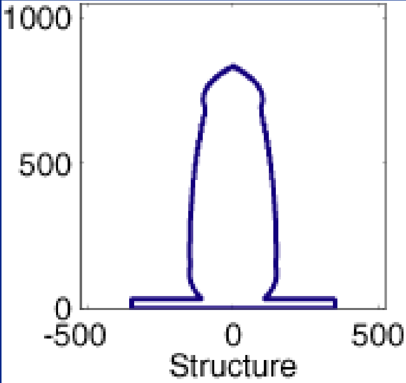
Triangle-Trapezoid-Rectangle Fit





3-Segment Quadratic Fit





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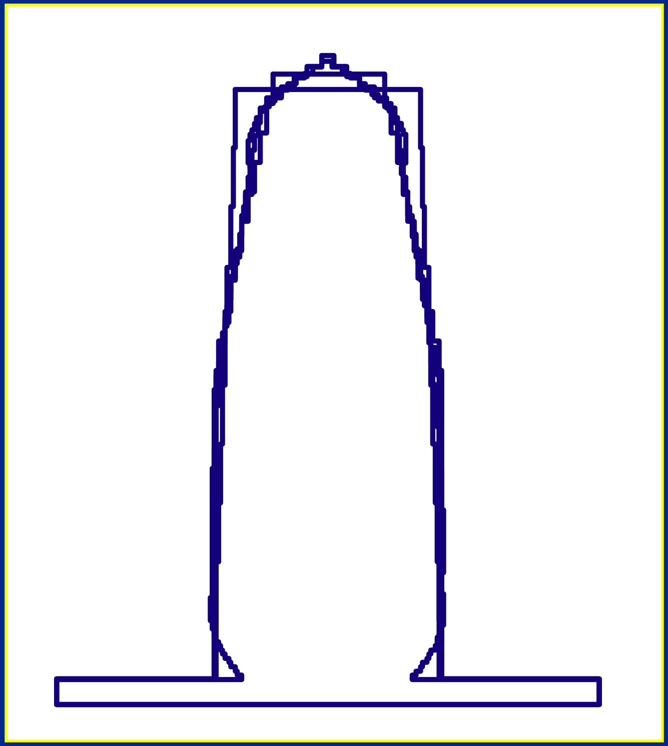
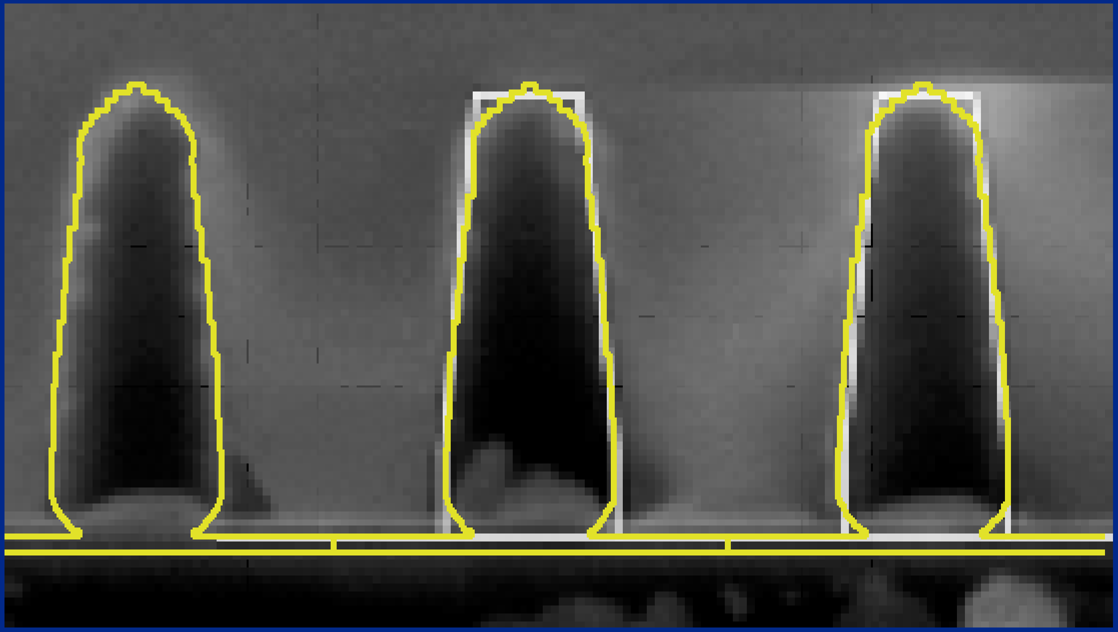
Extracted Topography Comparison





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

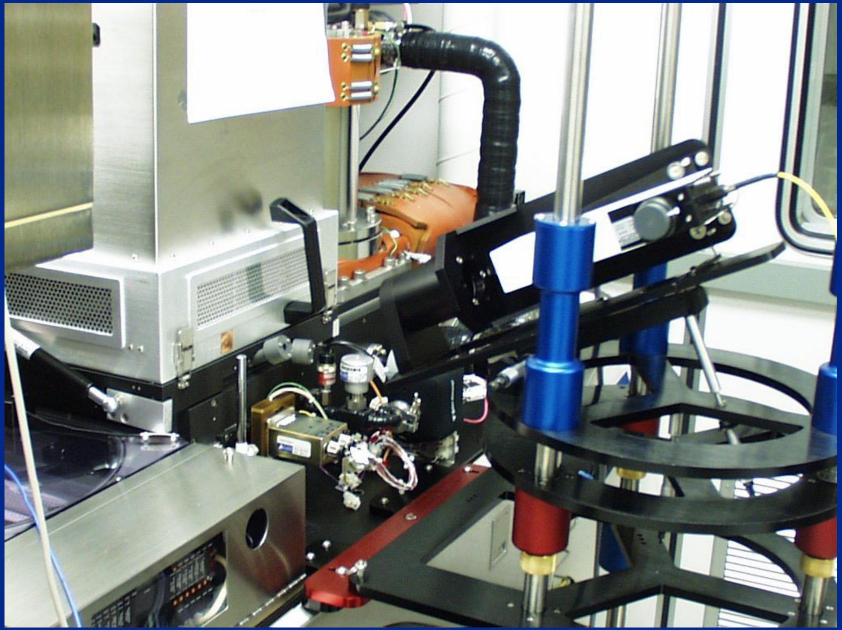
Term	Value	95.4% conf. Limit	Units
h1	146.51	4.55	nm
m11	0.7389	0.0097	slope
m12	-0.4698	0.011	quadratic curvature
h2	545.72	36.05	nm
m21	0.3461	0.0272	slope
m22	-0.1921	0.0282	quadratic curvature
h3	112.35	34.79	nm
m31	0.0803	0.0529	slope
m32	-0.1933	0.0659	quadratic curvature

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

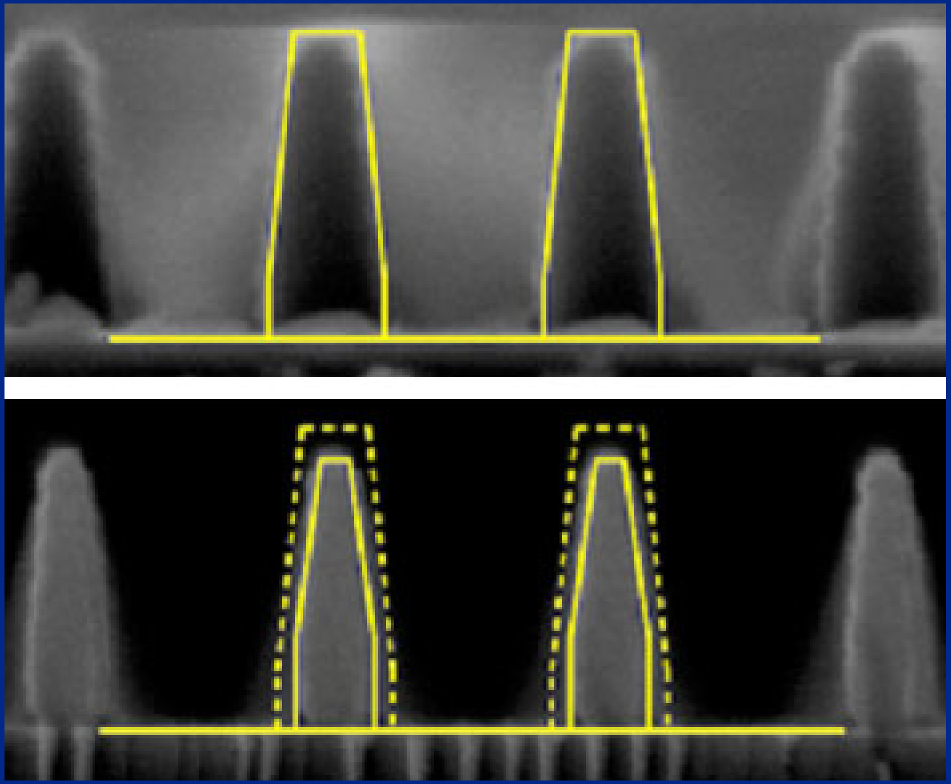
Click on image to run movie
Data - line
Fit - Dots

It may take a few seconds to run depending on your connection speed

sprt7_tritraprect.mov

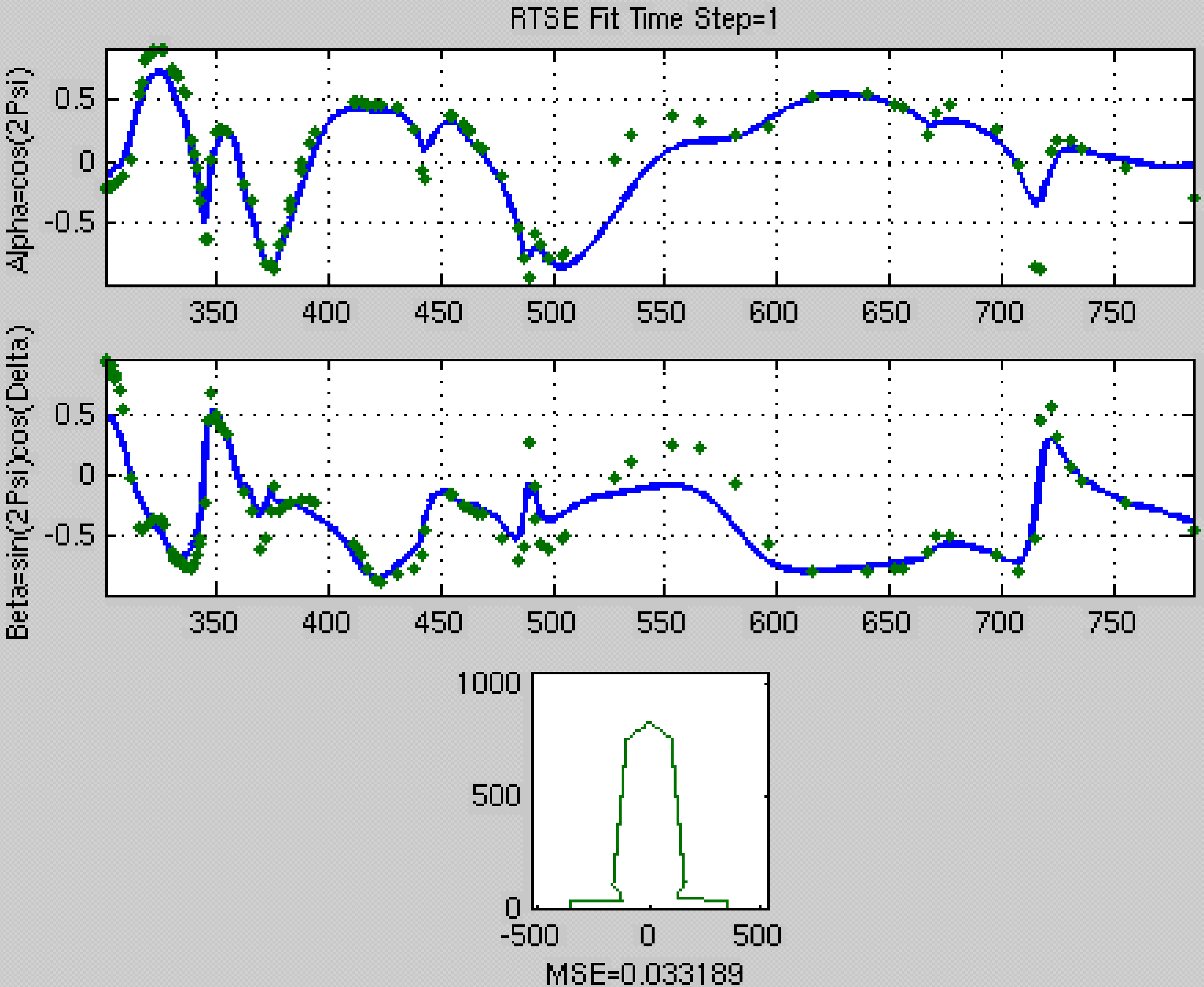
In Situ Optical CD/Automated Etch to Target CD

- O_2 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

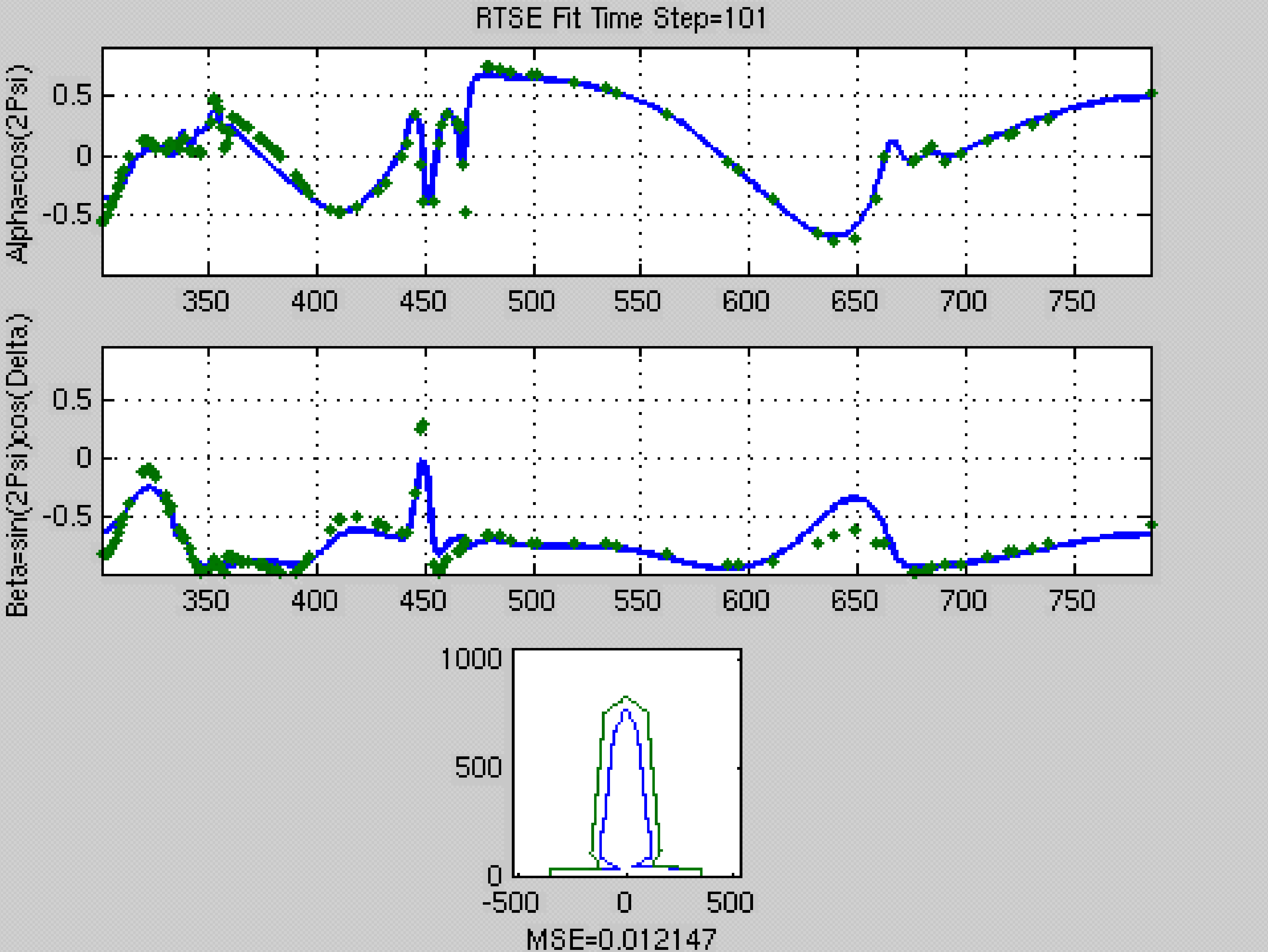


RTSE Etch Monitoring: Over-Fitting

- 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



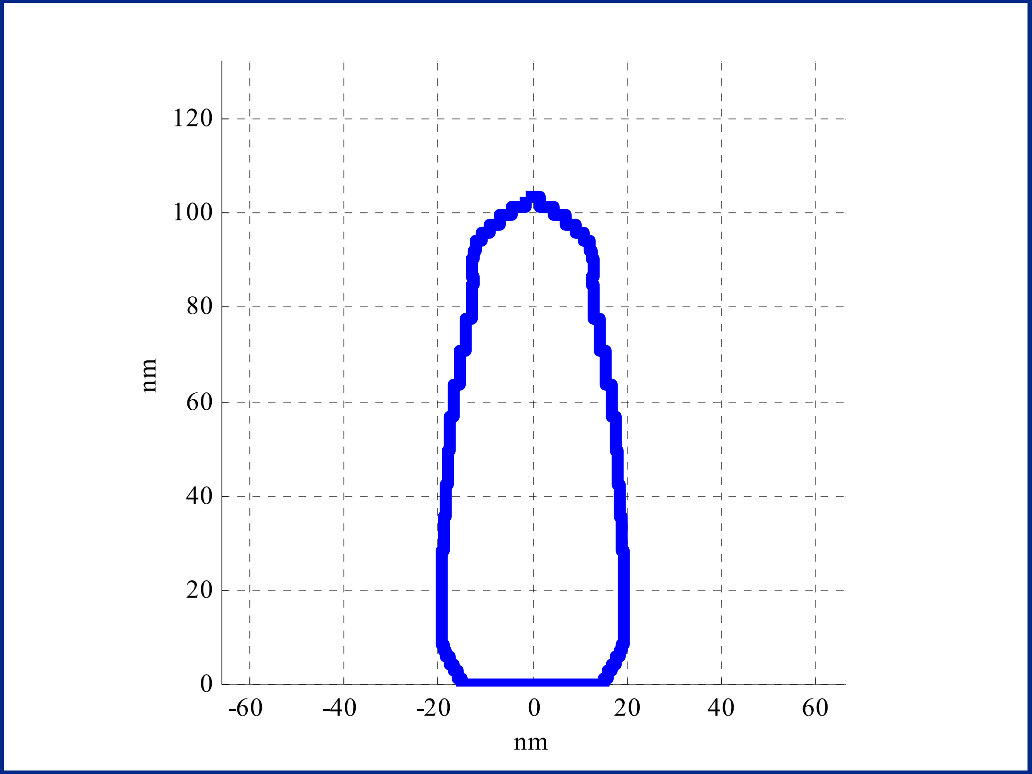
RTSE Fit Time Step=1
Alpha=cos(2Psi)
0.5
0
-0.5
350
400
450
500
550
600
650
700
750
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
350
400
450
500
550
600
650
700
750
1000
500
0
-500
0
500
MSE=0.033189

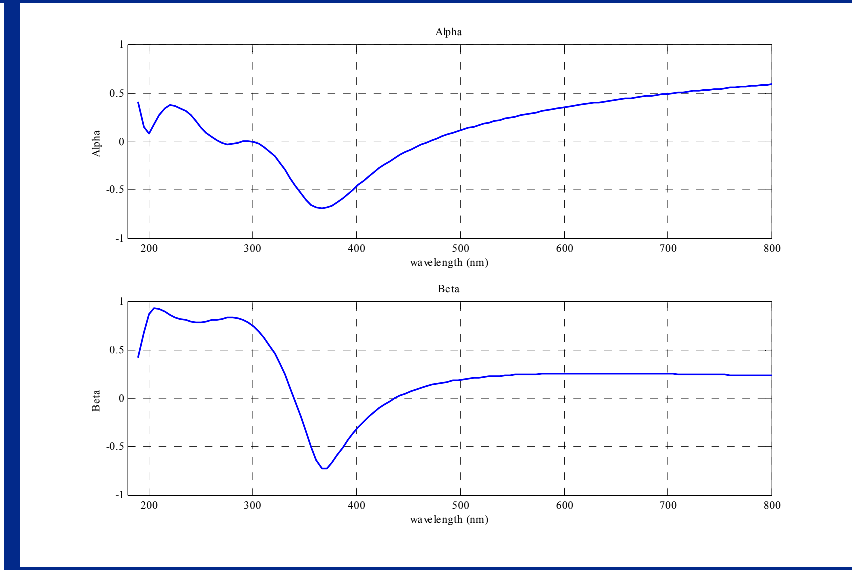

RTSE Fit Time Step=101
Alpha=cos(2Psi)
0.5
0
-0.5
350
400
450
500
550
600
650
700
750
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
350
400
450
500
550
600
650
700
750
1000
500
0
-500
0
500
MSE=0.012147

Simulations of ITRS Photoresist Milestones

- **Simulated Data using Model DUV Photoresist at 2010, 2013, and 2016 Technology Nodes**
- **Rectangular Profiles Assumed with:**
  - $\Lambda=90$**nm W=25±1.5nm Thick=100nm**
  - $\Lambda=64$**nm W=18 ± 1.1nm Thick=80nm**
  - $\Lambda=44$**nm W=13 ± 0.7nm 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***

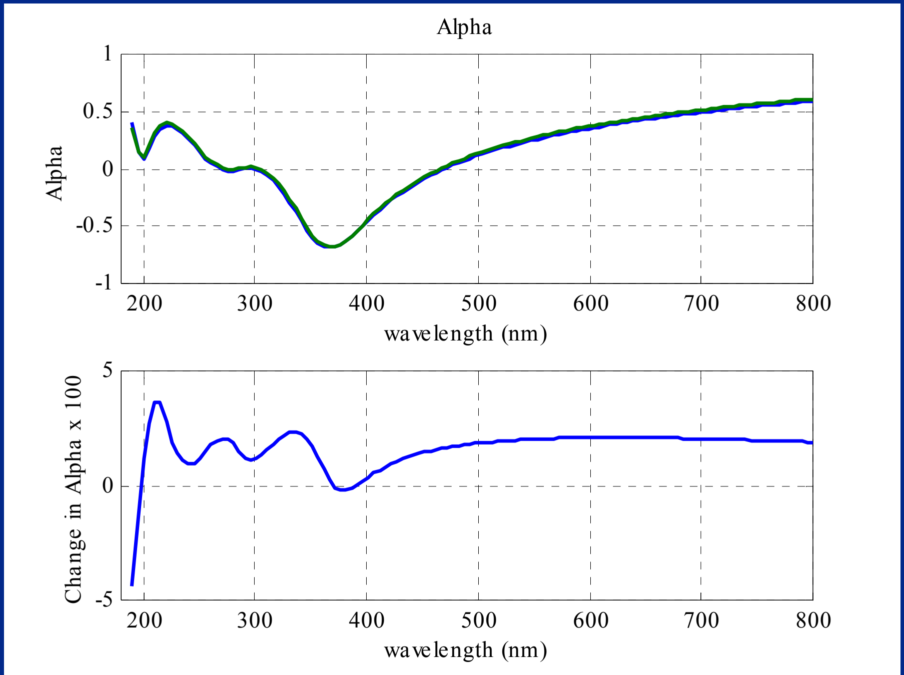
Simulated ~40nm PR Line
Λ=90nm

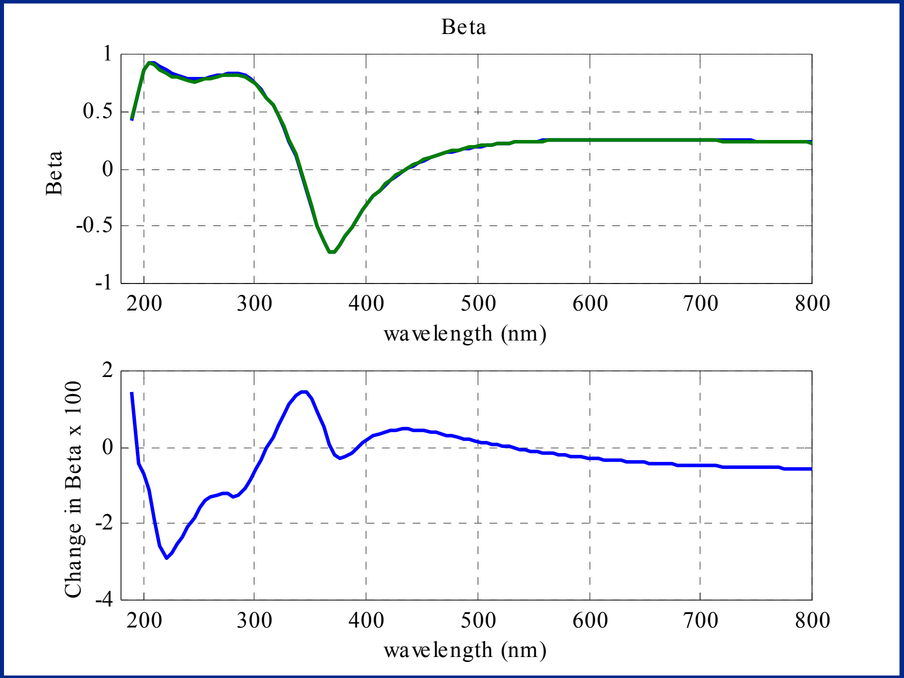


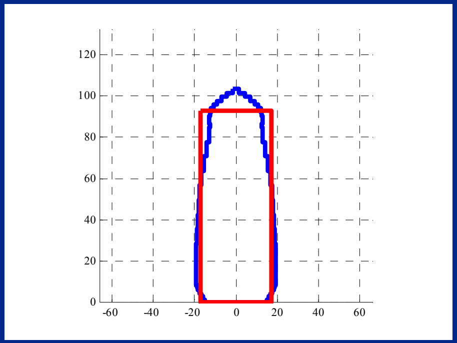


Can Detailed Shape Information Be Extracted?

Fit Using Rectangular Only Model

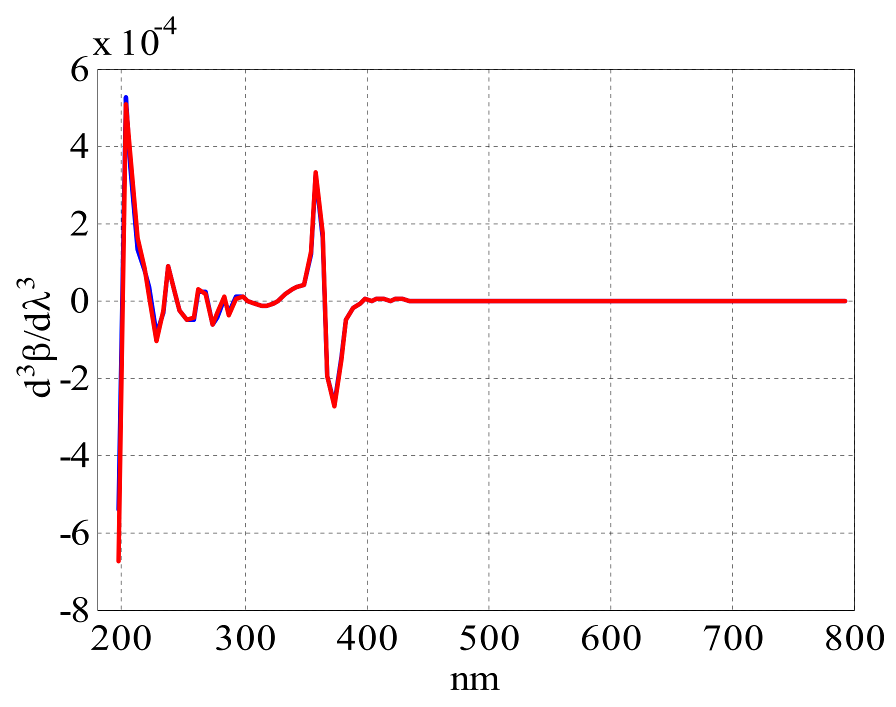


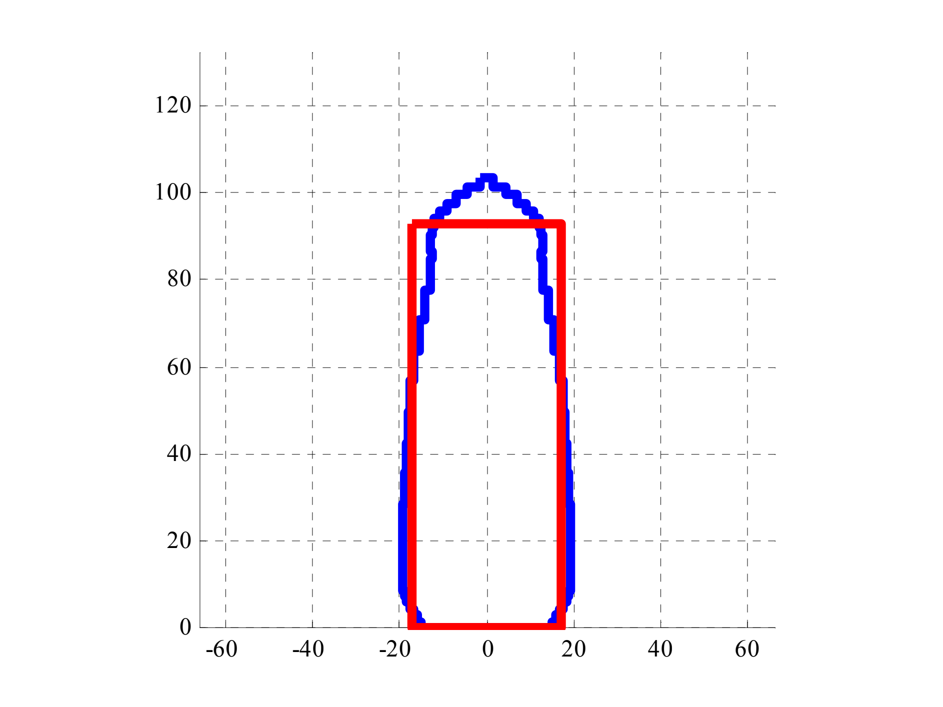




- **Rectangle Fit Averages More Complex Structure**
- **<u>Examine *Structure* Differences in Data Through Derivatives vs. λ</u>**

$d^3\beta/d\lambda^3$ 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

- Initial Work Funded by SRC Center of Excellence for Automated Semiconductor Manufacturing
  - 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
- <u>Industry Support Badly Needed for Continued University Efforts in this Area</u>