Spectroscopic Ellipsometry and Reflectometry from Gratings (Scatterometry) for Critical Dimension Measurement and *in situ*, Real-Time Process Monitoring

Fred L. Terry, Jr.

Dept of EECS / University of Michigan
+1-734-763-9764
+1- 734-763-9324 (fax)
fredty@umich.edu
http://www.eecs.umich.edu/~fredty

Outline

- Goals, Background, Theory
- Ex Situ Measurements for Topography Extraction
- In Situ Movies of Topography Evolution in Reactive Ion Etcher
- Limitations
- Conclusions, Challenges, Future Work

Goals & Background

- **Nondestructive, High Speed Extraction of Information from Patterned Structures**
  - **Critical Dimensions**
  - **Wall Shapes**
  - **Film Thicknesses**
- **Ideally Also Usable *in situ* for Real-Time Monitoring and Control of Fabrication Processes**
- **Exciting Work Present by H. Maynard at ICSE-2**
  - **Limited Applicability Due to Diffraction Effects**

$\Rightarrow$ **<u>Use Structures for which the Diffraction Problem Can Be Accurately Solved</u>**

Background I

- Basic Concept: Scattering (Diffraction) of Light from Features Produces Strong Structure in Reflected Optical Field
- Analyze Unique Data to Obtain Topography Information
- Periodic Structures (Gratings) Can Be Numerically Modeled "Exactly"
- Feature Resolutions Much Better than Rayleigh Limit Are Possible Since This Is Not A General Image Formation Problem
  - Periodicity of Structure Is Known
  - Dielectric Functions of Materials Are Known

Background II

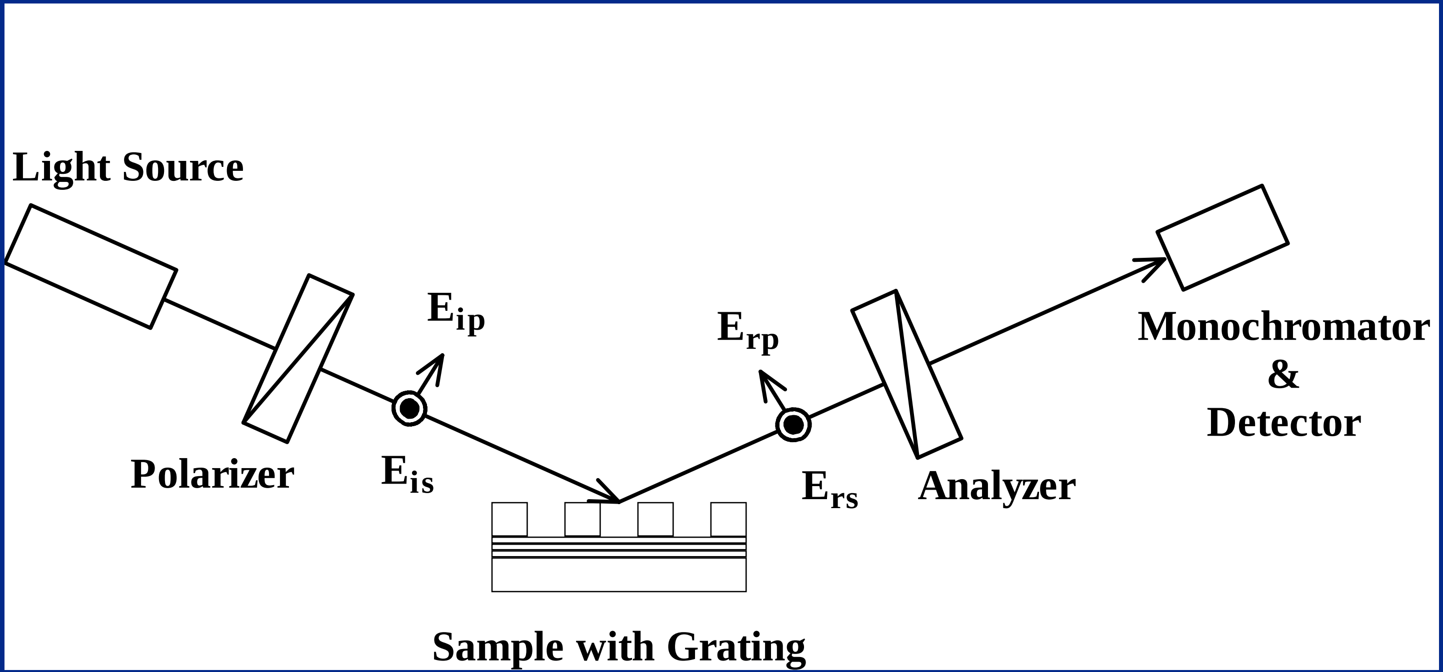
Single Wavelength Scatterometry

- **Examine Structure in Specular and/or Diffracted Modes vs. Angle of Incidence at a Single Wavelength**
  - Naqvi, McNeil, and Co-workers (UNM)
  - Elta, Terry, and Co-workers (U. Michigan)
  - Texas Instruments, Sandia Systems ⇒ Biorad ⇒ Accent

Spectroscopic Ellipsometry and Reflectometry

- **Examine Structure vs. Wavelength at Fixed AOI**
  - Terry and Co-workers (U. Michigan)
  - Spanos and Co-workers (UCB) ⇒ Timbre Technologies
  - IBM ⇒ Nanometrics
  - KLA-Tencor, ThermaWave/Sensys, Nova

Spectroscopic Ellipsometry



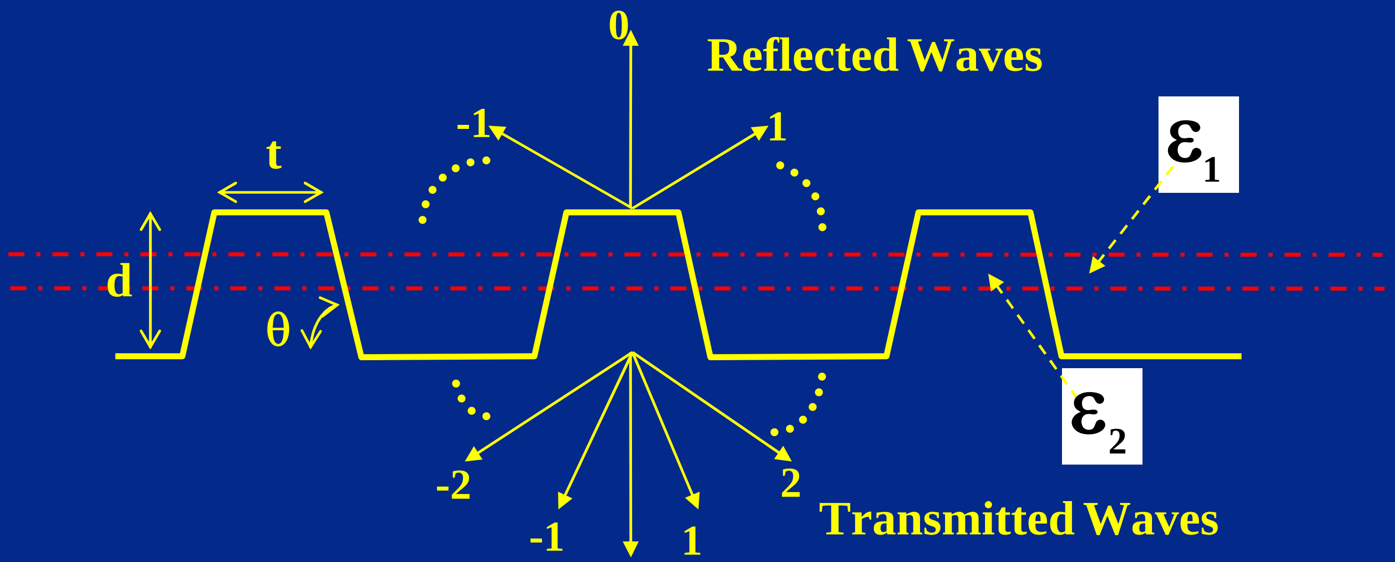
$$\rho = \frac{R_p}{R_s} = \frac{E_{rp}/E_{ip}}{E_{rs}/E_{is}} = \tan(\Psi)\cdot\exp(i\Delta)$$

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

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

Rigorous Coupled-Wave Analysis Method of Moharam and Gaylord

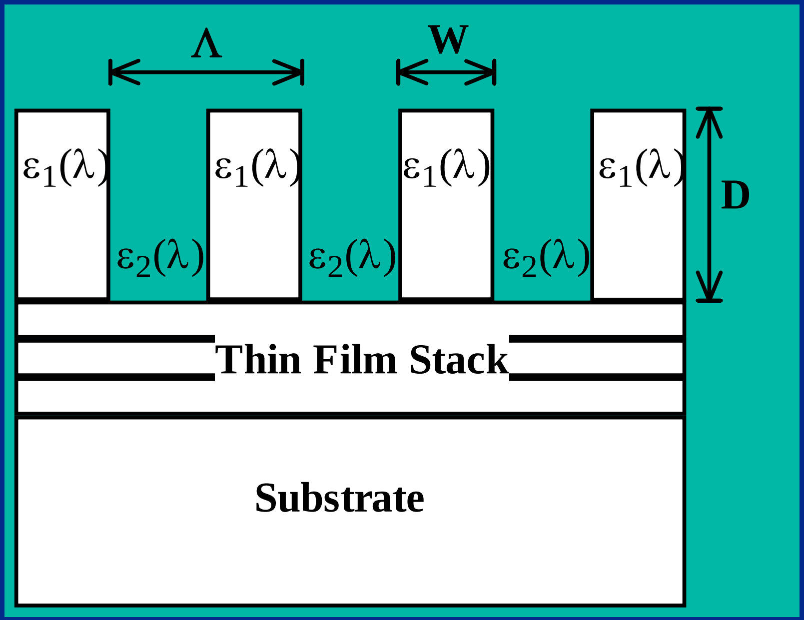
- **The Line is Sliced into a Number of Thin Layers**
- **Numerical Eigen-Matrix Solution for Maxwell's Equations**
- **Amplitudes & Phases of Different Diffraction Orders Are Obtained by Matching the EM Boundary Conditions**



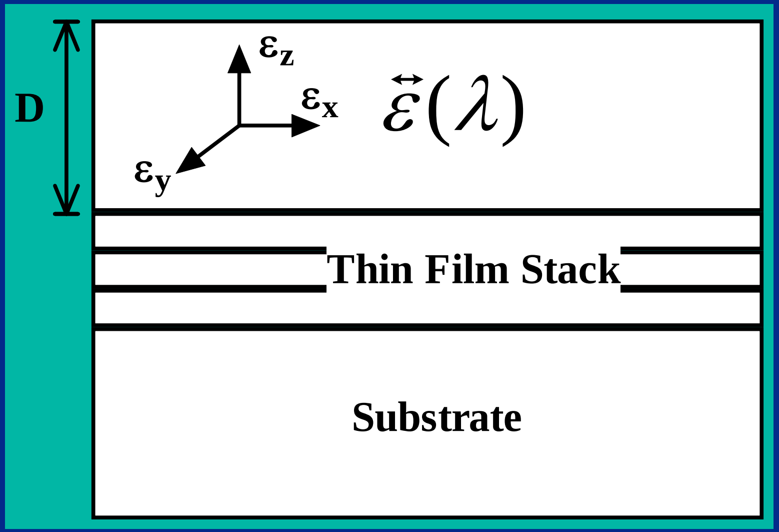
RCWA Computation Issues

- **Let *N* be the number of spatial harmonics retained for approximating the solution,**
- ***s* be the number of slices used for approximating grating profile,**
- **Then at each *wavelength* we need**
  - ***4Ns* linear equations for *p*-polarization**
  - **2(N+1)s linear equations for *s*-polarization**
- **Number of Required Slices (*s*) Depends on Shape of Line (typical 10-30)**
- **Number of Require Spatial Harmonics Depends on Λ/λ, ε of materials (typical 15-100)**
- **Large Scale Computation but Vectorizes Naturally for Parallel Processing (each λ independent)**
- **Continuing Advances by Computational E&M Theory Community**

Grating ⇔ Anisotropic Thin Film Analogy



1-D Grating



Anisotropic Thin Film

- **Line Height ⇔ Film Thickness**
- **Line Shape ⇔ Optical Dielectric Function**

Specular Spectroscopic Scatterometry

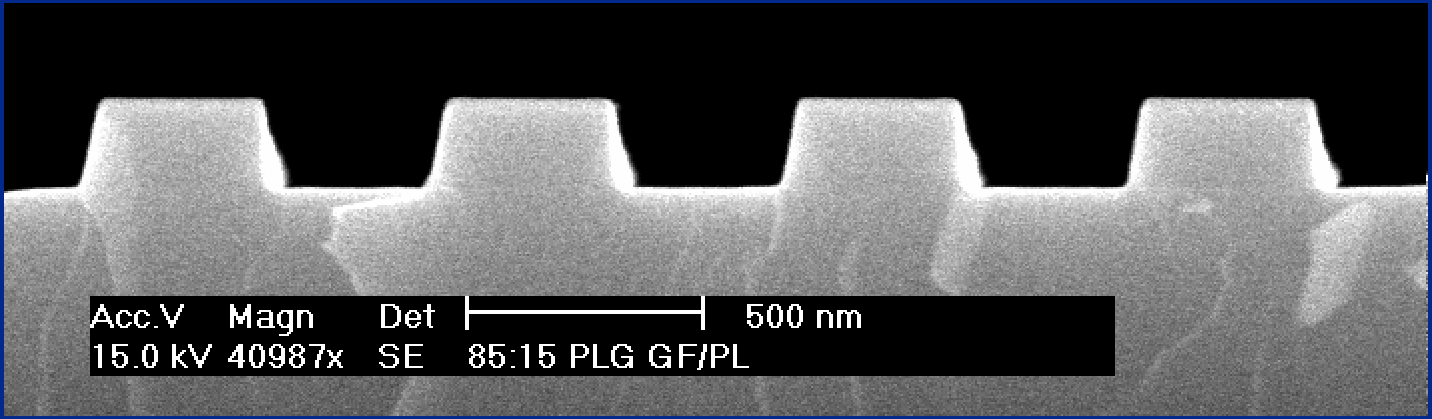
- Probes Wavelength Dependence of Scattering from a Given Line Size/Shape
- Grating Amplifies & Averages Single Line Effects
- Grating Periodicity Aids Accurate Diffraction Solution
- Result Sub-Wavelength Topography Sensitivity
- Extremely High Sensitivity to Line Height (D) $\Rightarrow$ Analogous 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)

Topography Extraction Example $W>\lambda_{min}$

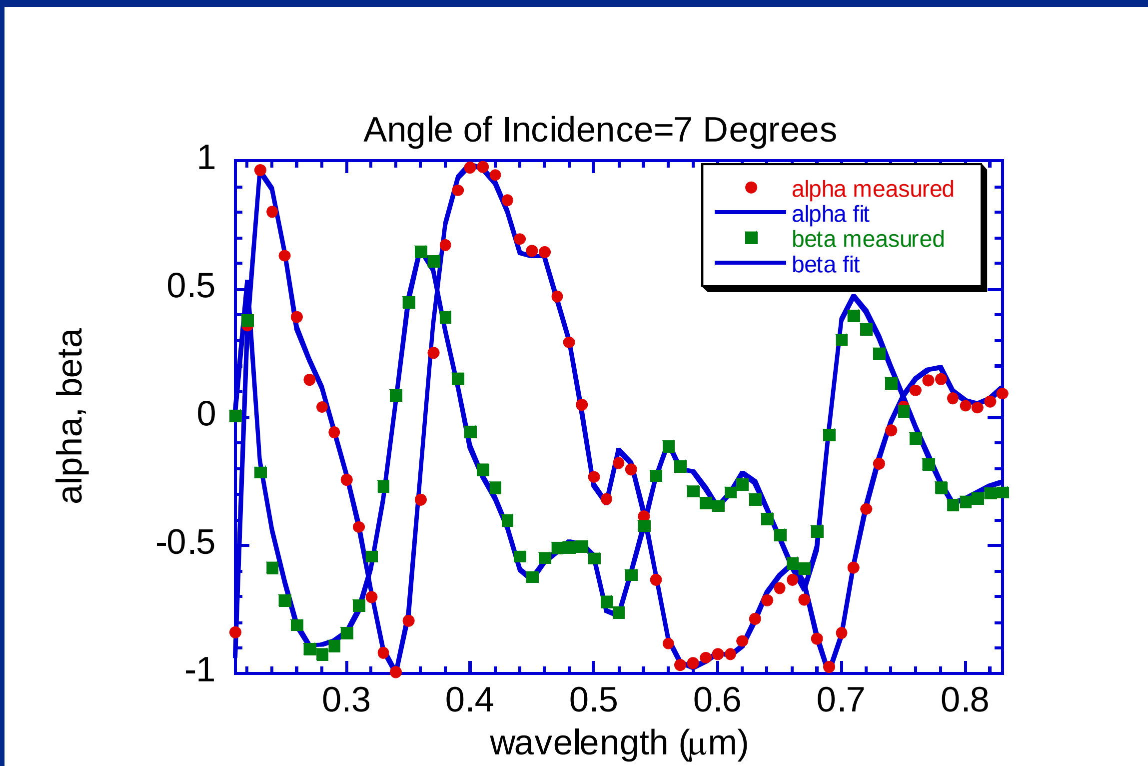
- Experimental Data Taken at 7° AOI with Sopra GESP-5 Ellipsometer
- 350 nm Line/ 700 nm Period Grating Etched in Single Crystal Si
- 350 nm Line/ 700 nm Period Photoresist on 31.7nm SiO_2 on Si
- Successively Improved Topography Estimations Using Levenberg-Marquardt Non-Linear Regression
  - Trapezoid (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)

Etch Experiment Description

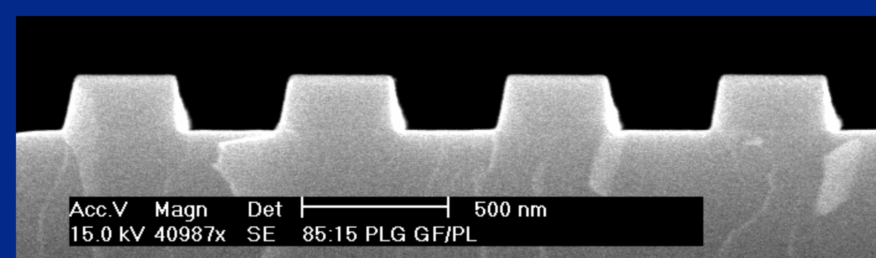
- Lam TCP9400SE Plasma Etching System
- Cl_2/HBr Si Main Etch Recipe
- Nominal Etching Rates:
  - Oxide 5.43Å/sec
  - Poly 52.1Å/sec
- Times: 60, 77, 97, 116, 135, 154, 174 sec



Near Normal SE for RIE Etched Si Grating



	SE & RCWA	SEM
CD (nm)	323±1.6	323±5
Depth (μm)	331±0.4	340±5
Wall Angle	83.2° ±0.29°	84.1° ±1.4°

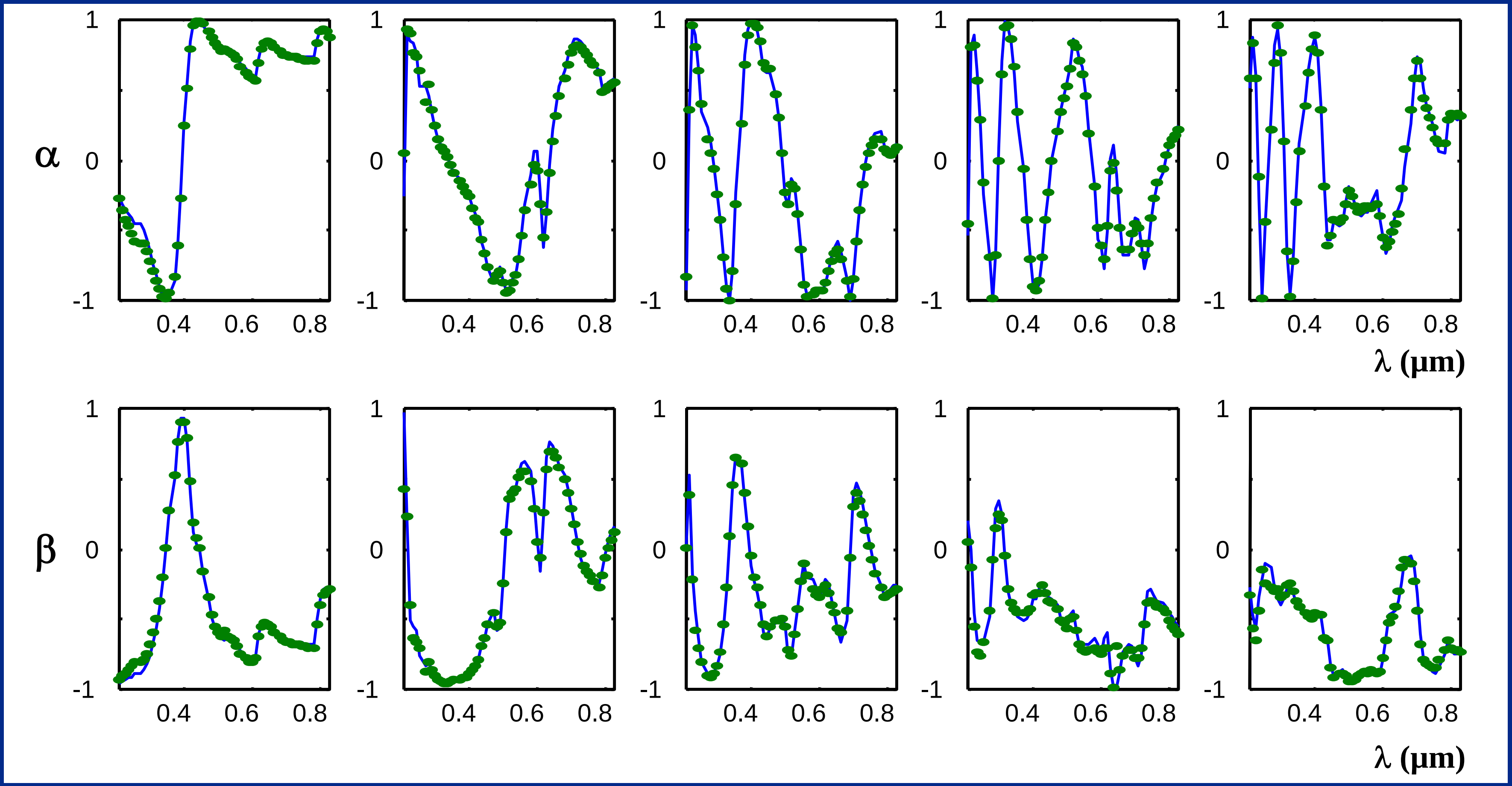


Time Evolved SE Data and Fitting

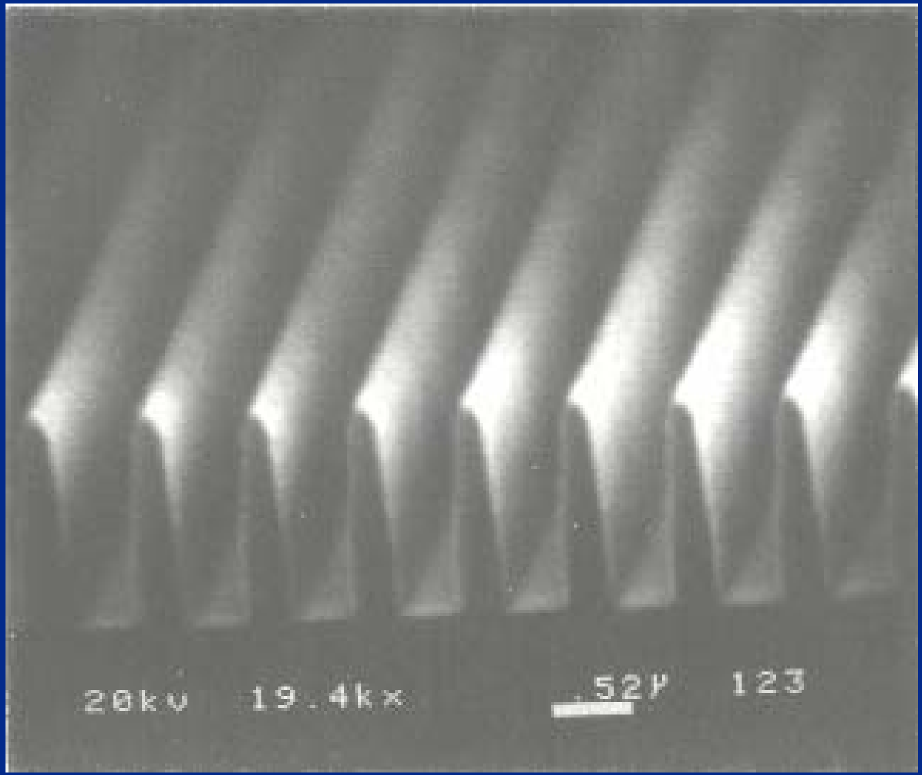
Incidence at 7°

● : Experiment
— : Theory

Etching Time →

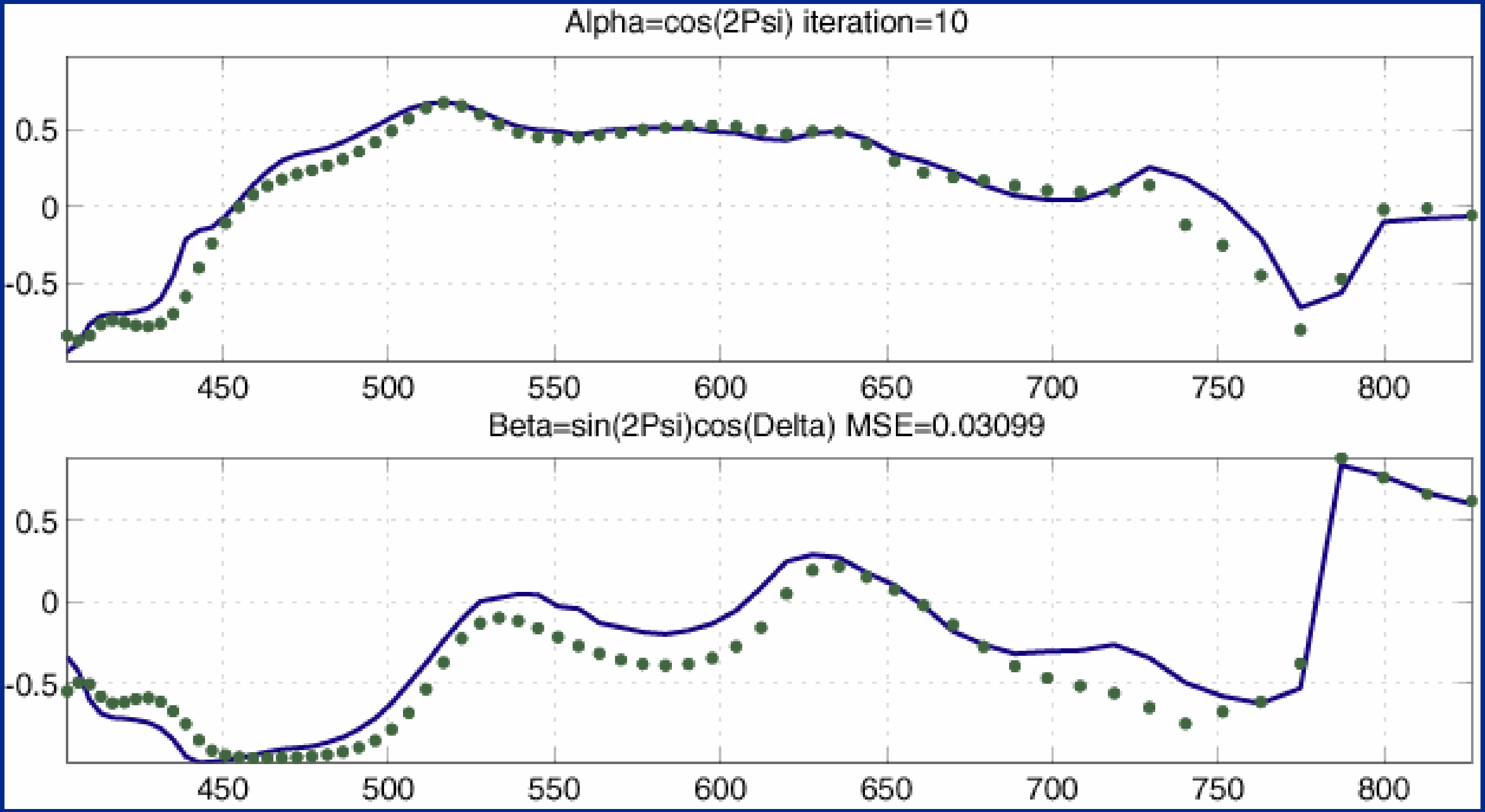


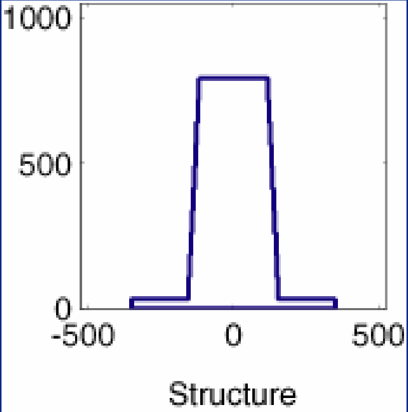
Submicron Grating



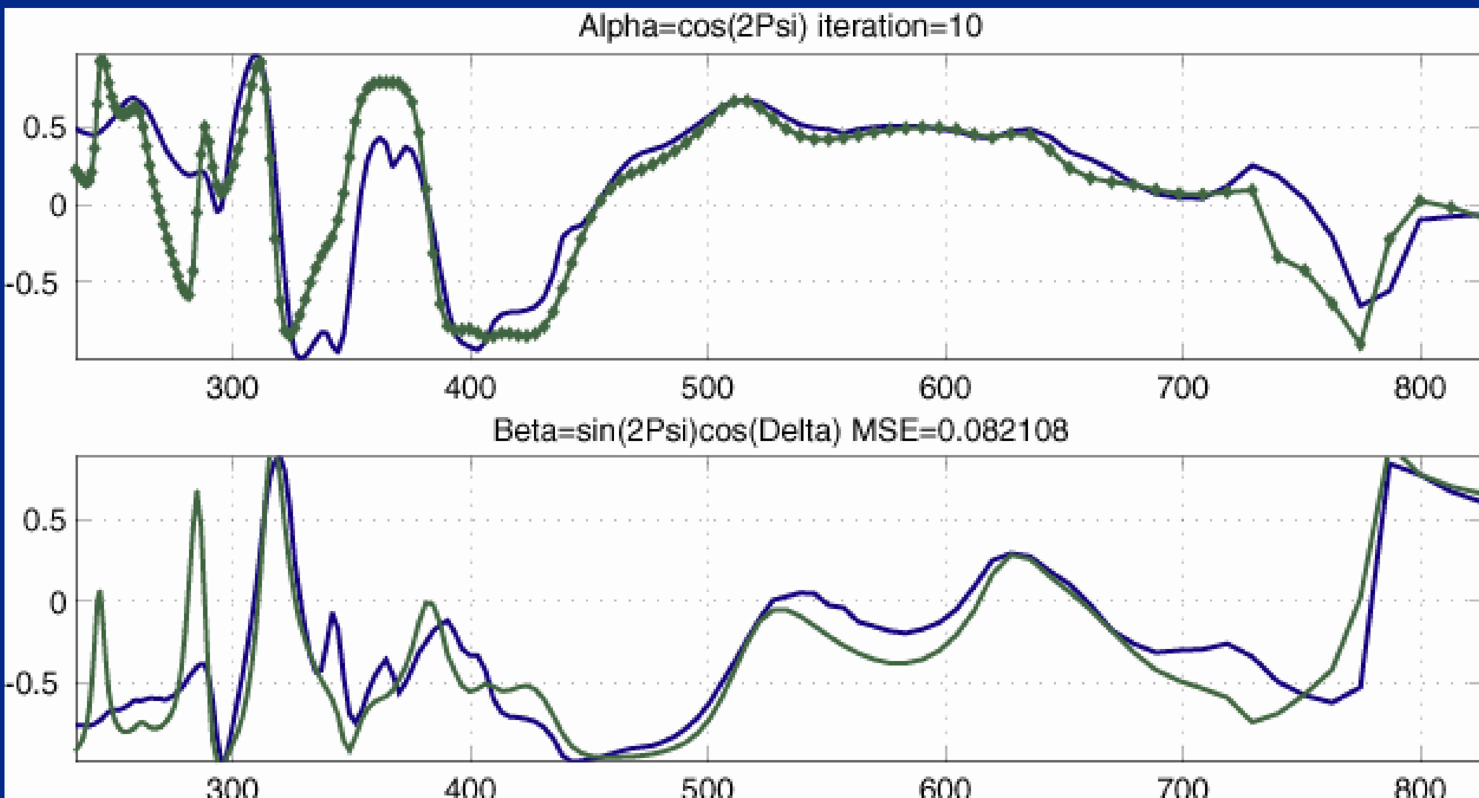
- ~0.35μm Line/Space Grating In Photoresist/300Å SiO_2/Si
- Accurate Photoresist N(λ) Obtained by SE Measurement of Similarly Prepared Unpatterned Film
- Period Measured as 0.700 μm Using 1st Order Diffraction Angle at Multiple λ's

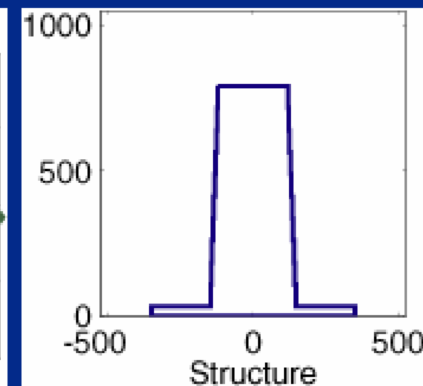
Trapezoidal Fit 400-825 nm

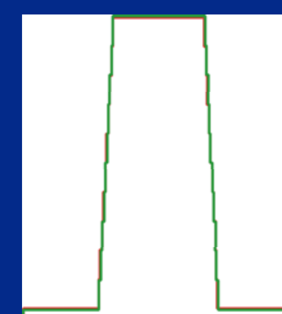




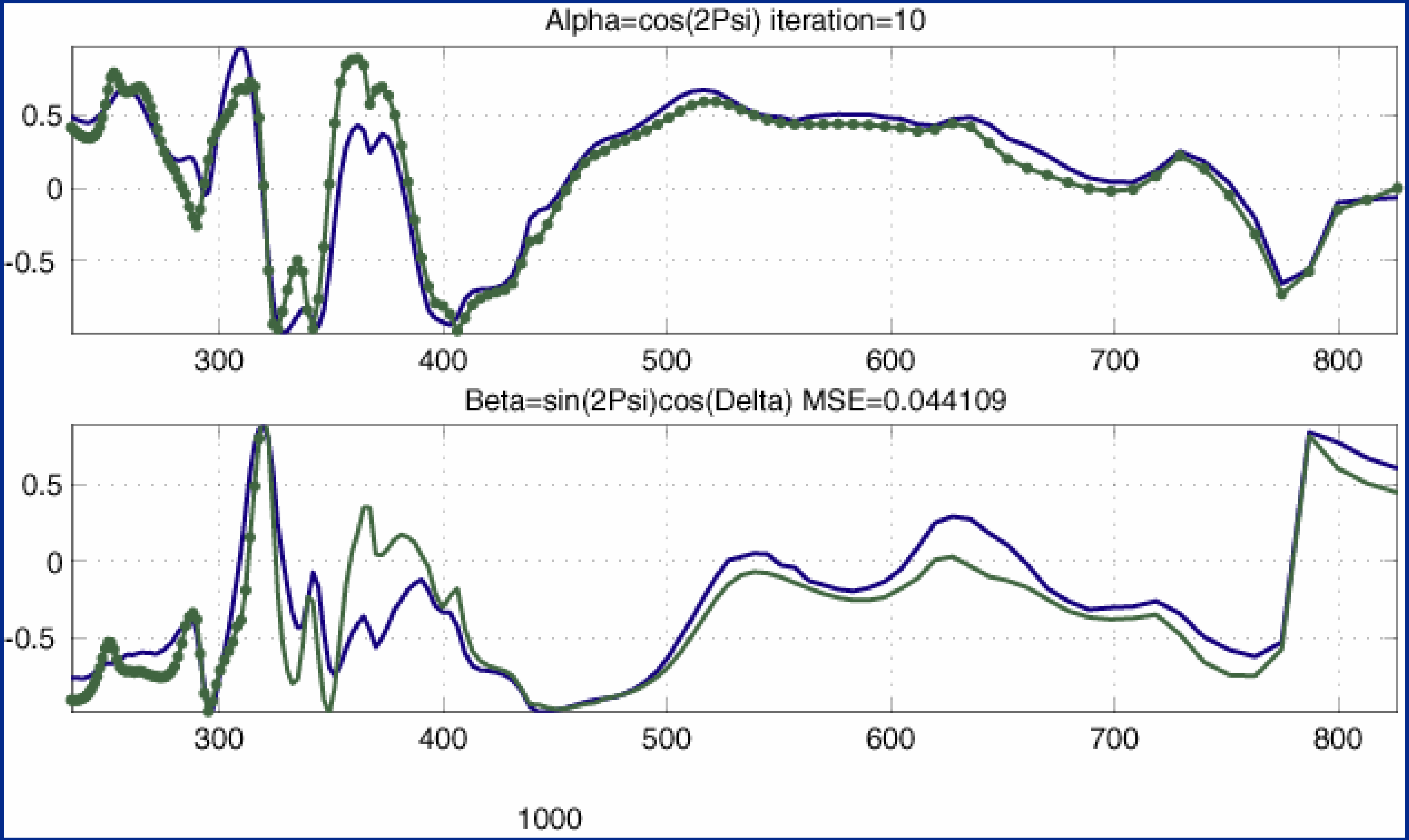
Trapezoidal Fit

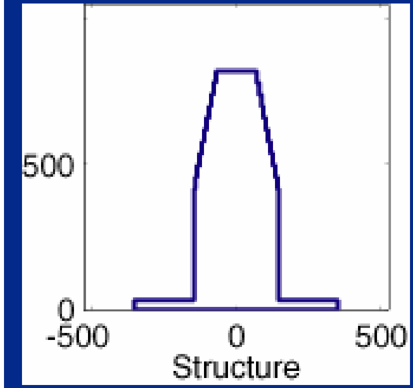




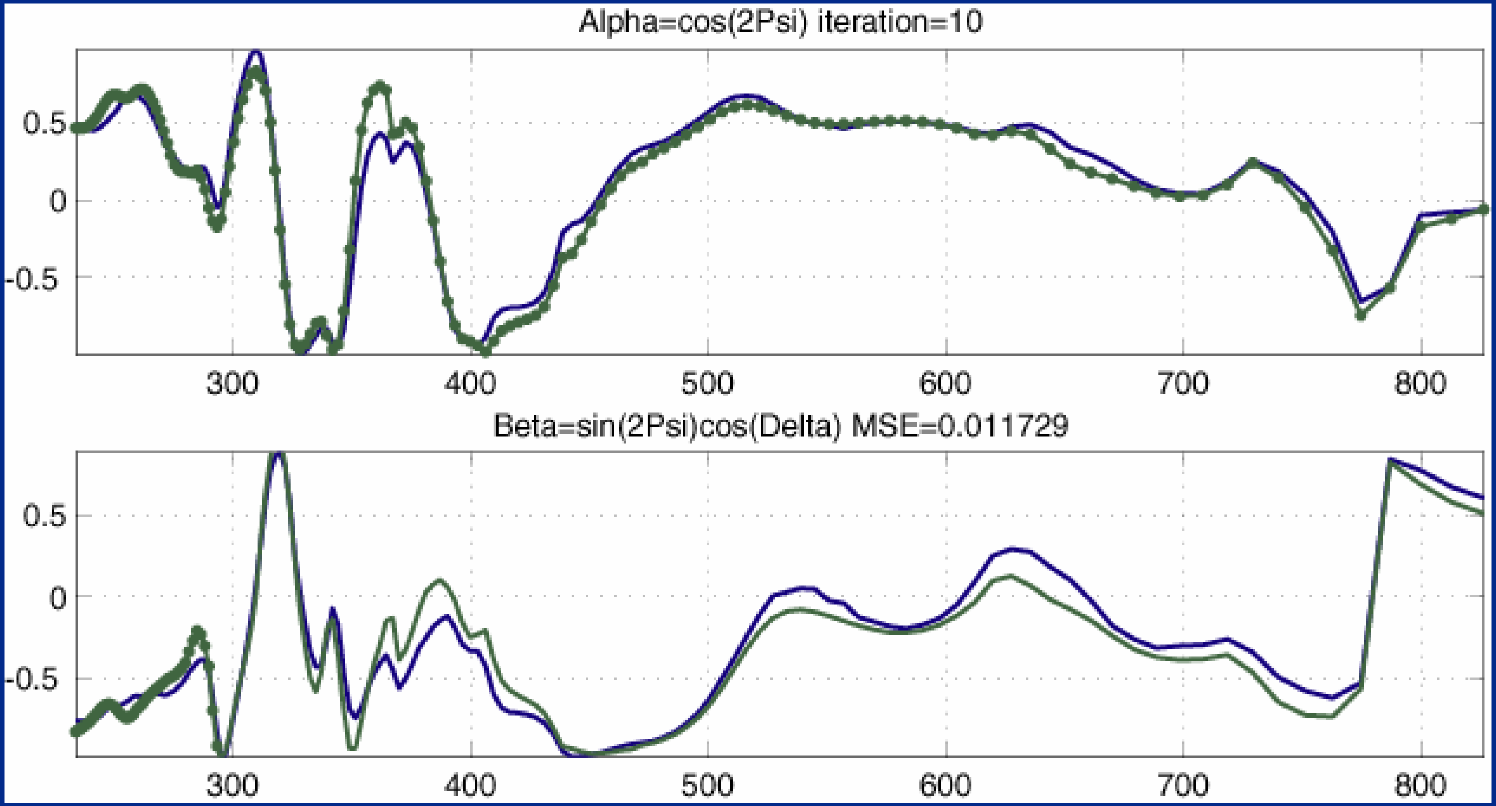


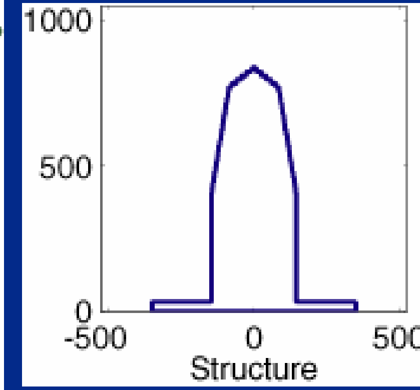
Trapezoid on Rectangle Fit



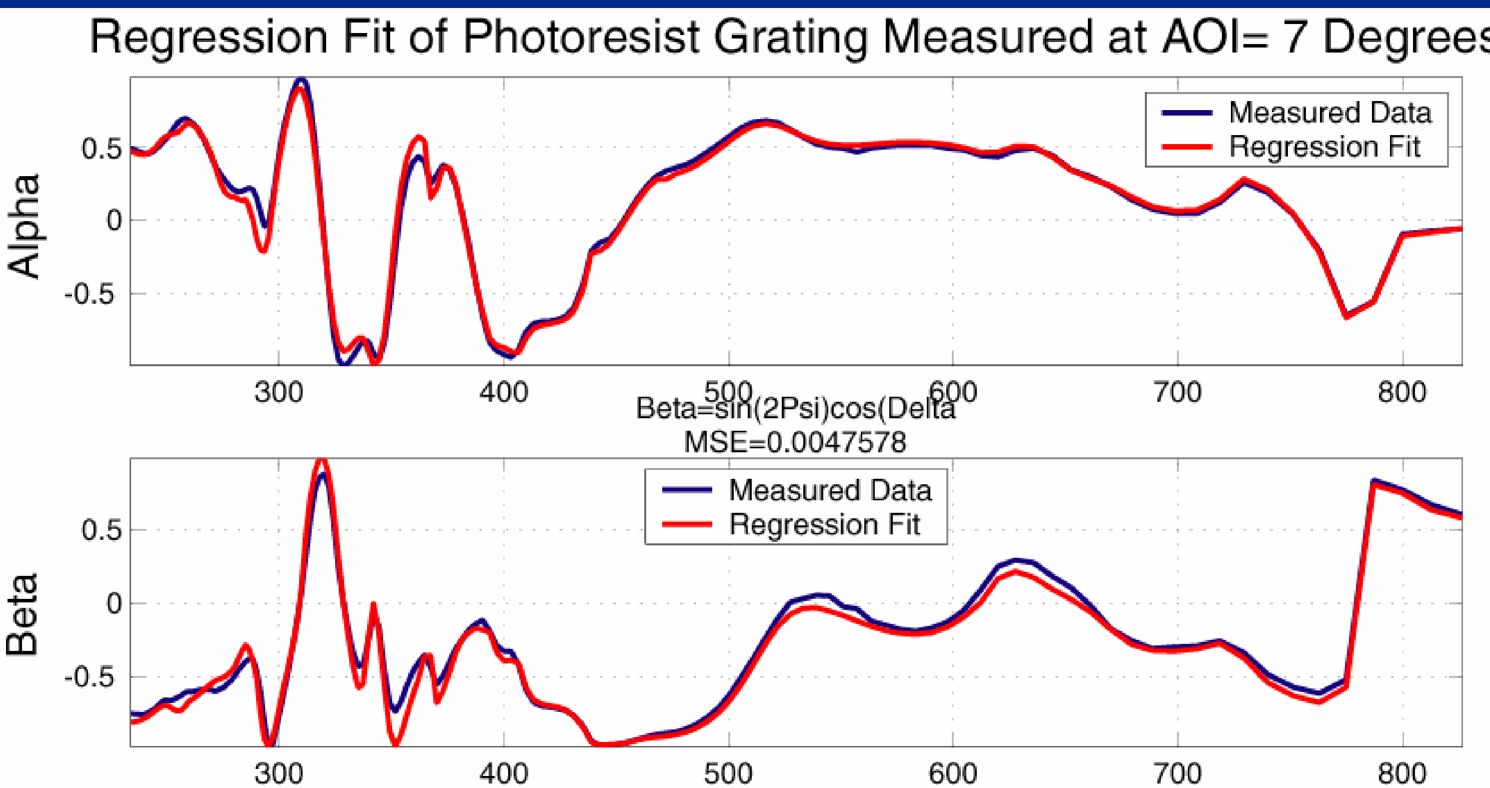


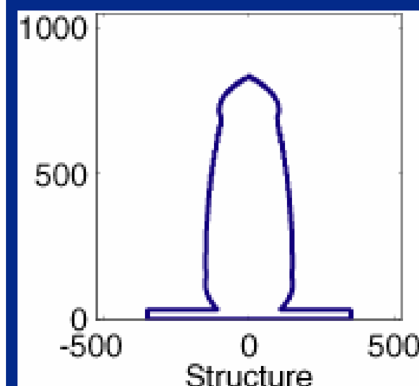
Triangle-Trapezoid-Rectangle Fit



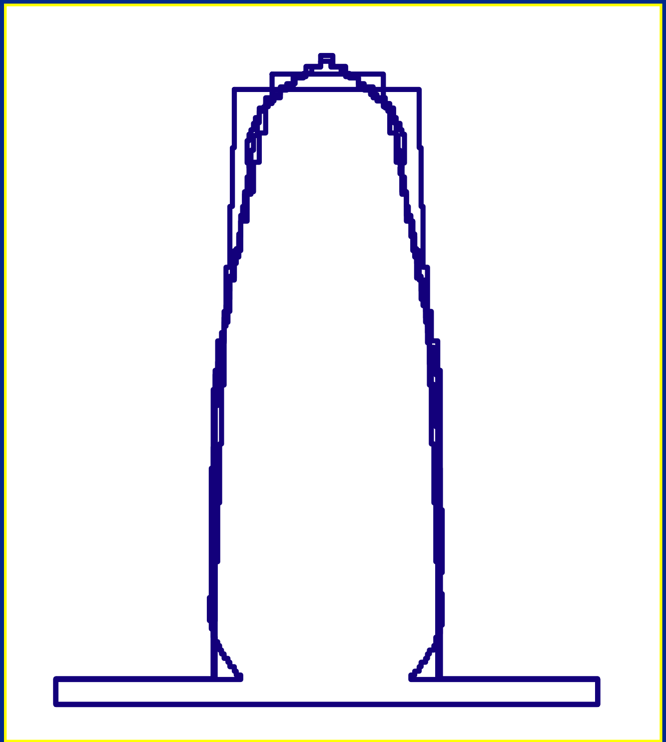


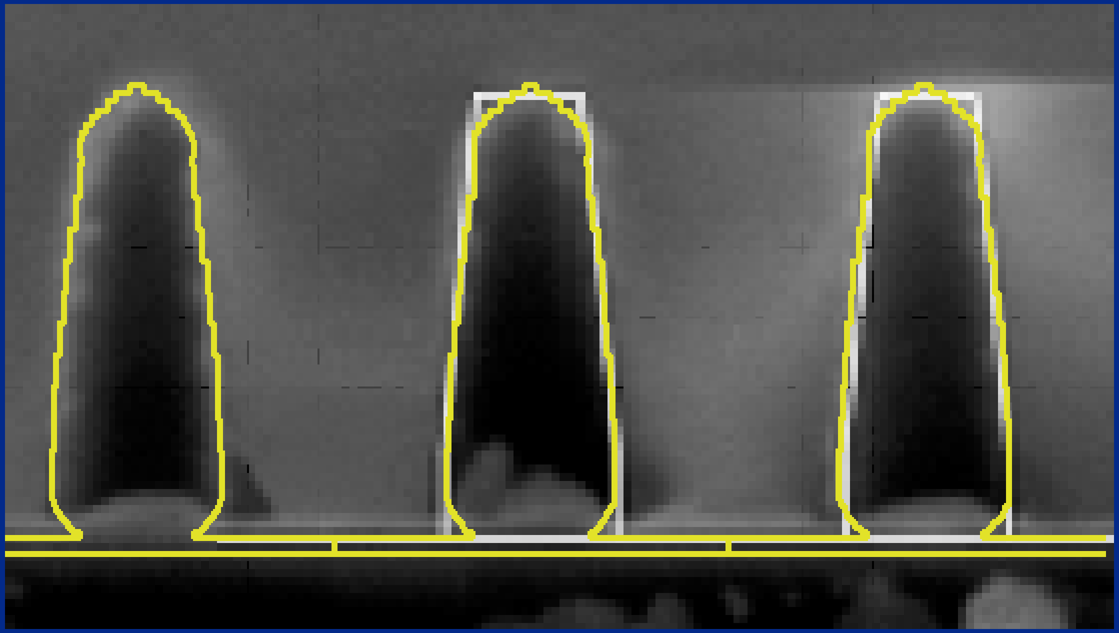
3-Segment Quadratic Fit





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

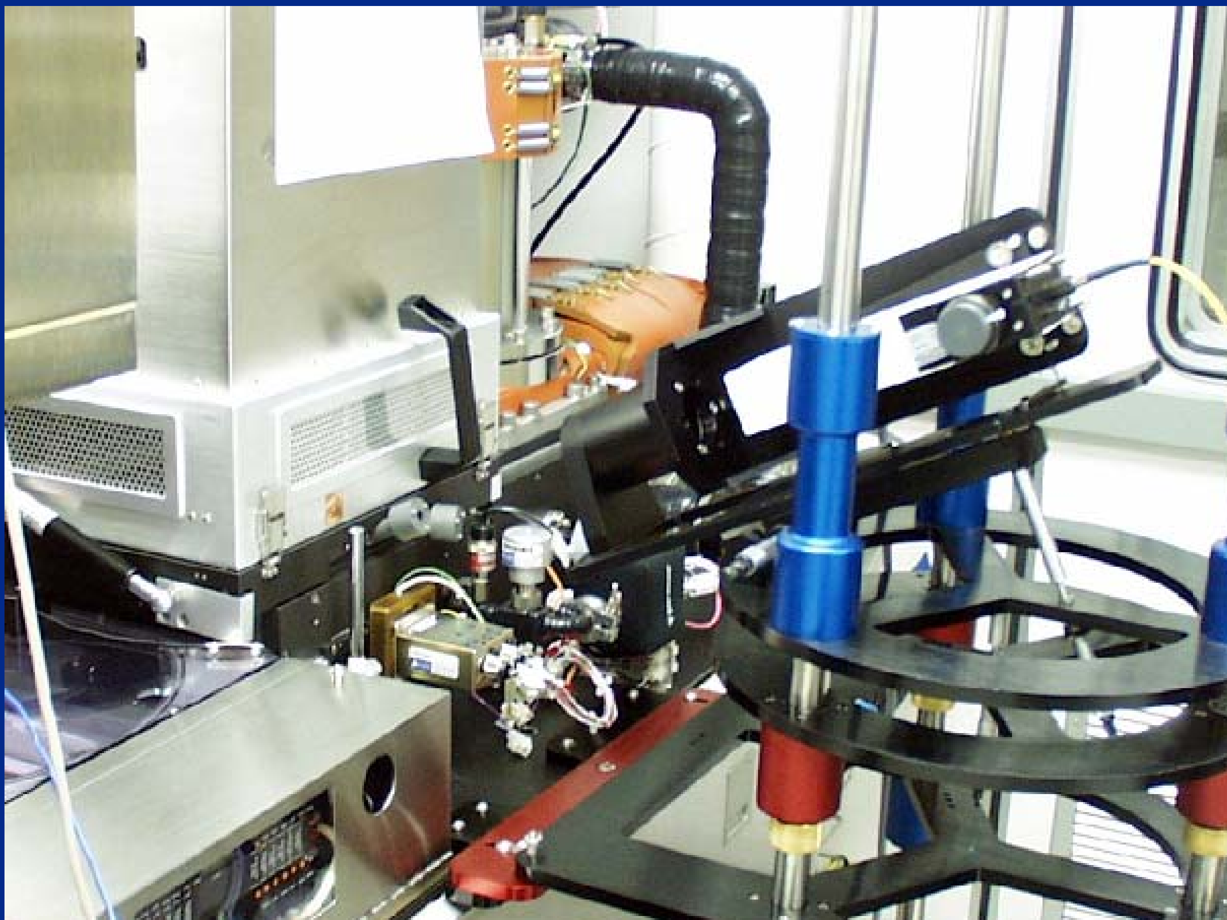
Fit Was Pushed to the Limits of Data

	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

In Situ Measurements: Real-Time Monitoring and Control

Movies

LAM TCP 9400 SE with SOPRA RTSE



Thanks to Dr. Helen Maynard, Lucent Bell Labs for Assistance with Port Layout

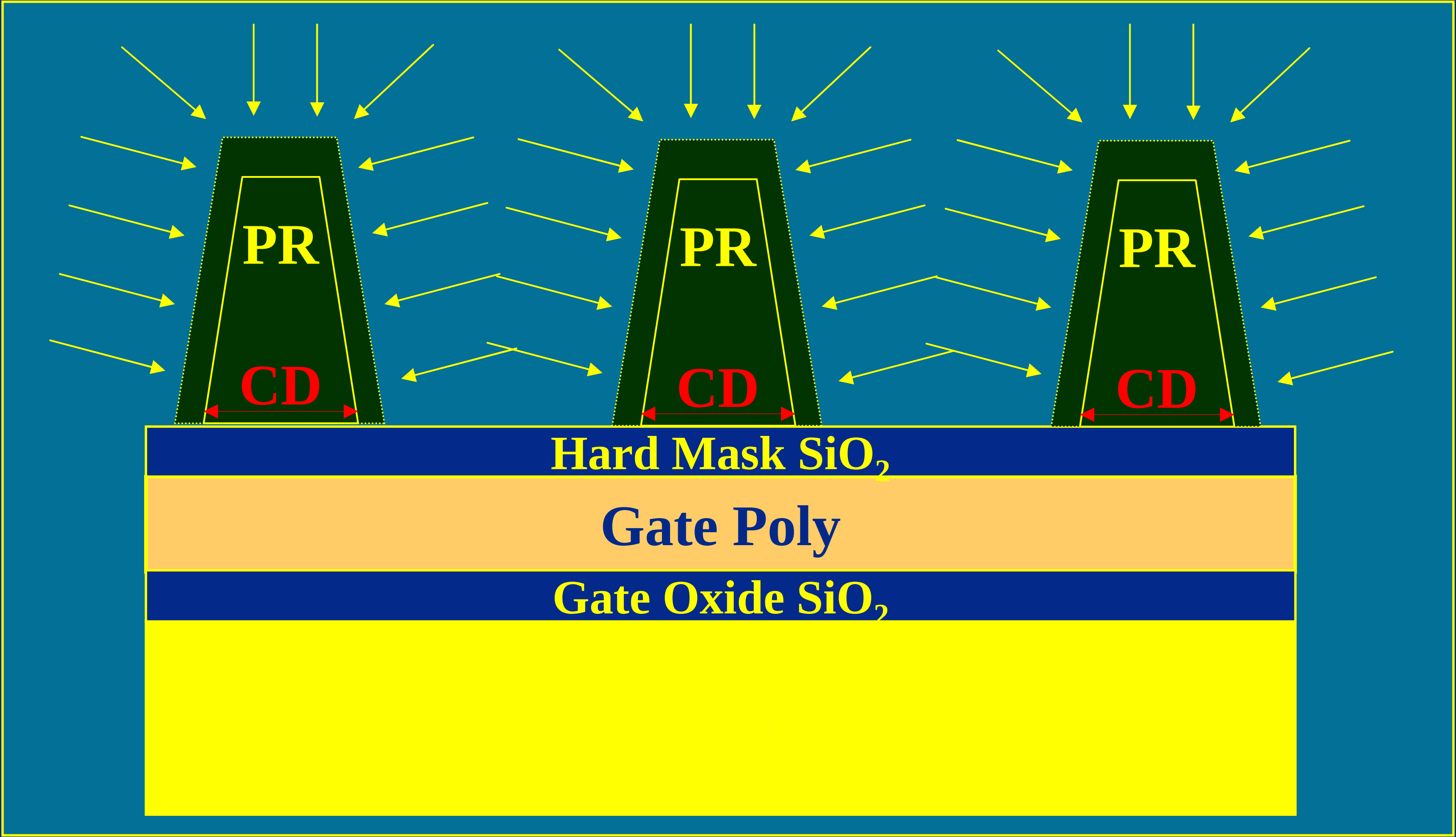
Real-Time Ellipsometry Pararmeters

- 63.5° AOI Dictated by Geometry of Etch System
- RTSE System Run at Maximum Data Collection Rates Due to Fast Time Scale of Industrial Etch Processes (~100 s total times, Etch Rates ~3-5 nm/s)
- Single-Turn of Polarizer Data Sampling Time (0.1 s)
  - Capture Data with Only few 0.1's nm Thickness Change During Samplin
- Minimum Data Acquistion Time ~1 sample/0.18s
- Usable Data for λ=300-780 nm
- Fixed Analyzer Angle 45°

Example Process Critical Dimension Control: Etch to Target

Reactive Ion Etch to Shrink CD to a Desired Dimension

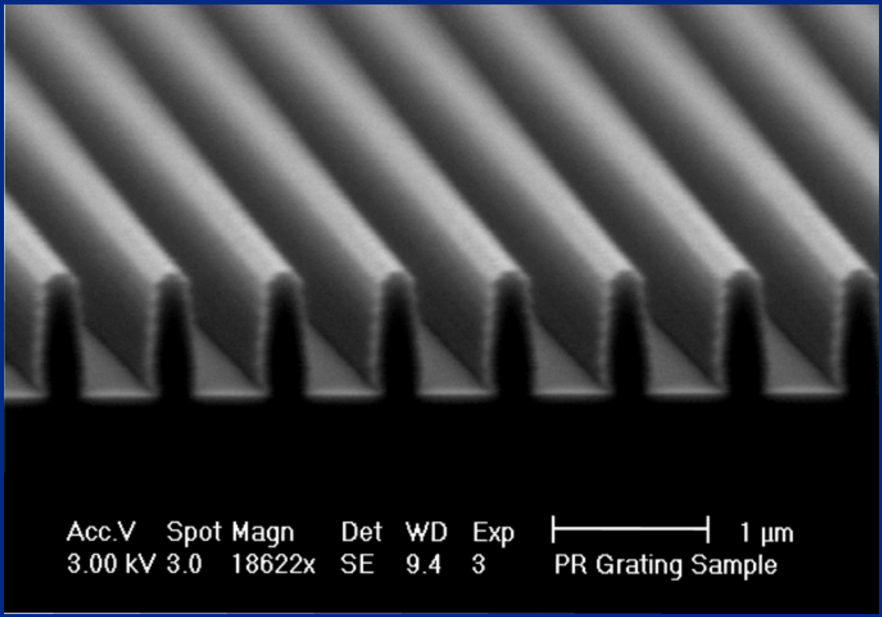
Goal: Achieving Same Final CD regardless of Incoming CD & RIE Process Variation

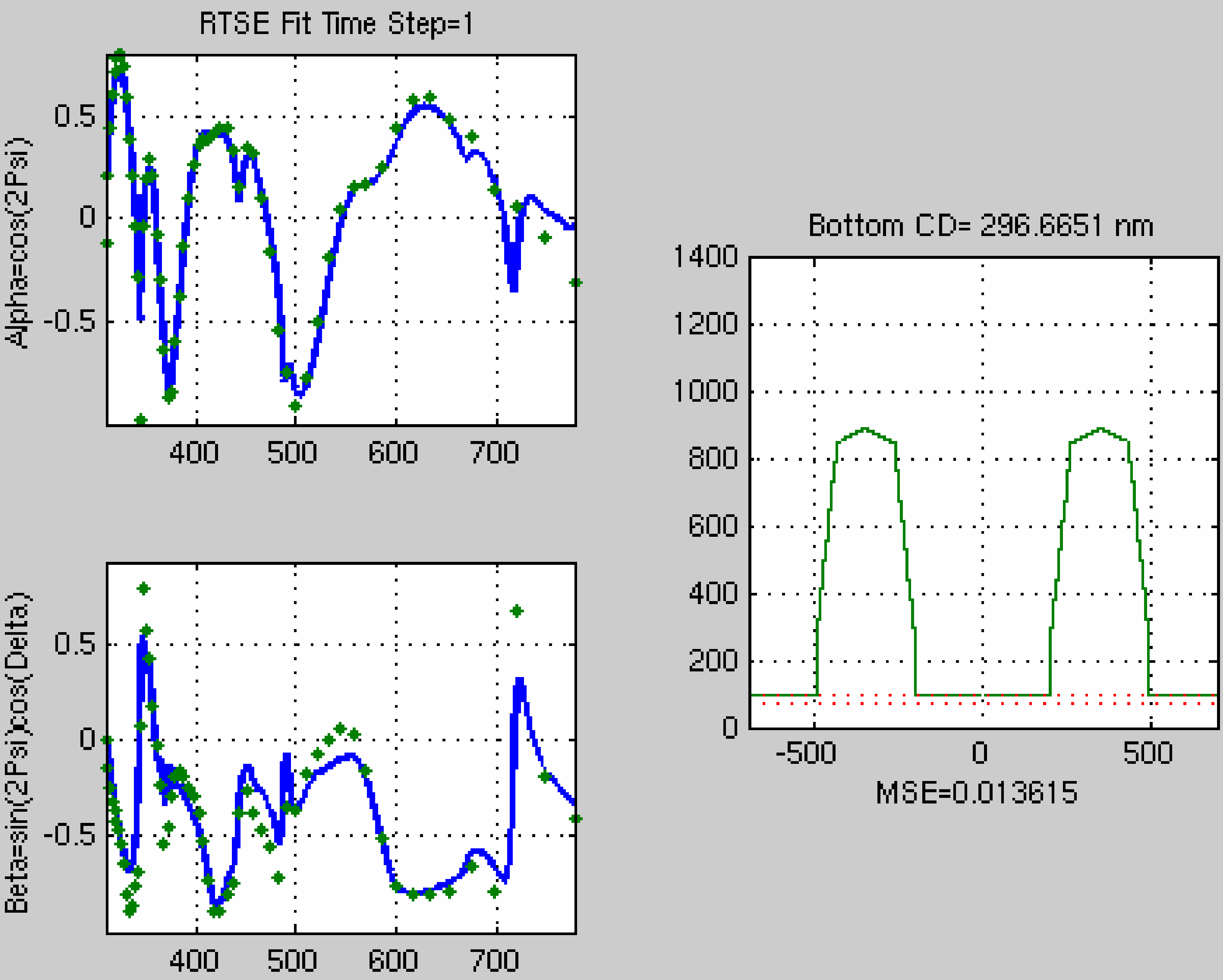


Experiment Description

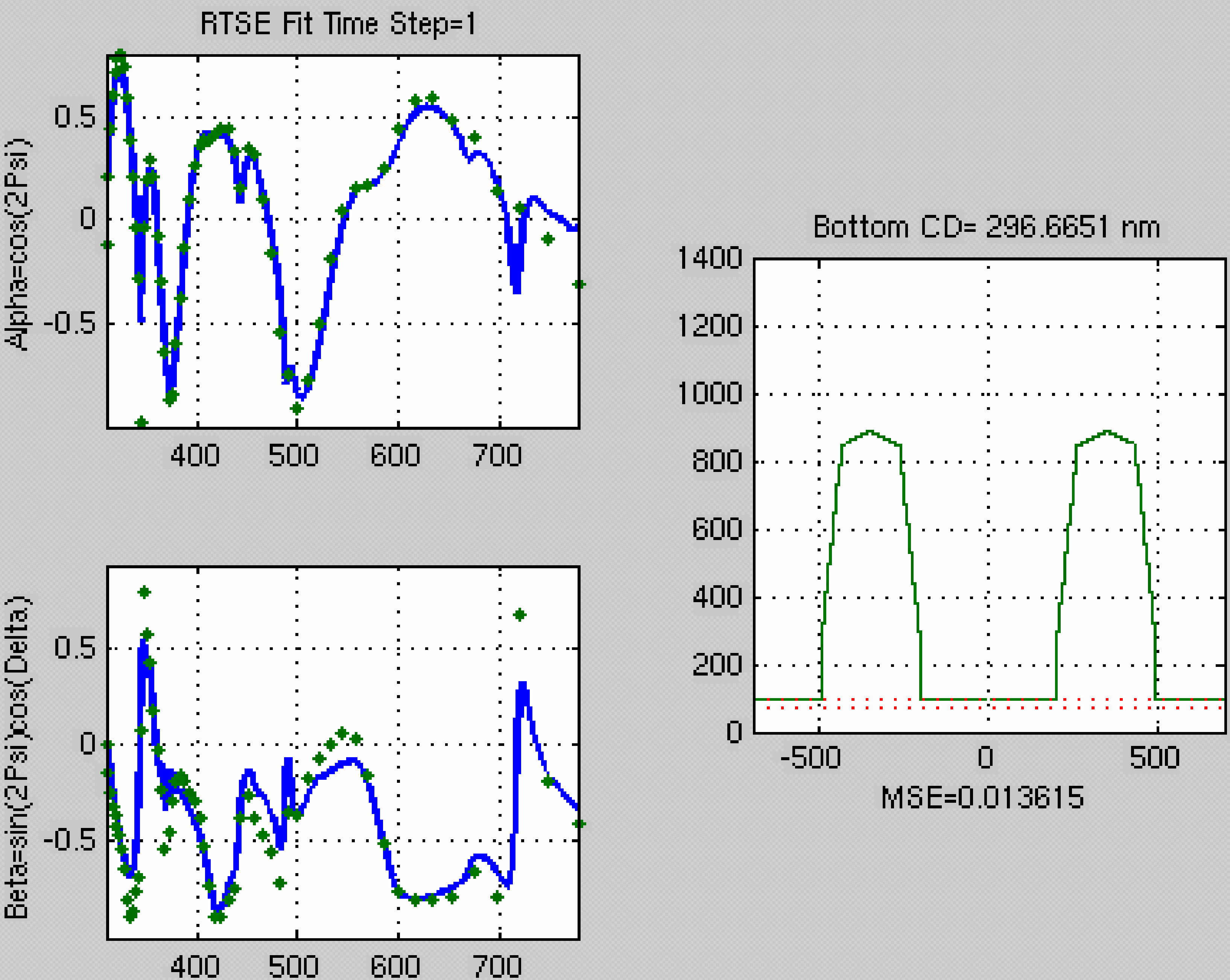
- Lam 9400 TCP Etcher
- O_2 Plasma Gas
- Target: Trim Bottom CD to 200nm
- Non-Linear Filter Method to Detect Endpoint and Shut-Off Plasma
- This Experiment Stopped at 200nm
- Work of Drs. Hsu-Ting Huang, Ji-Woong Lee, Pramod Khargonekar, and Fred Terry

~350nm Line/Space Grating

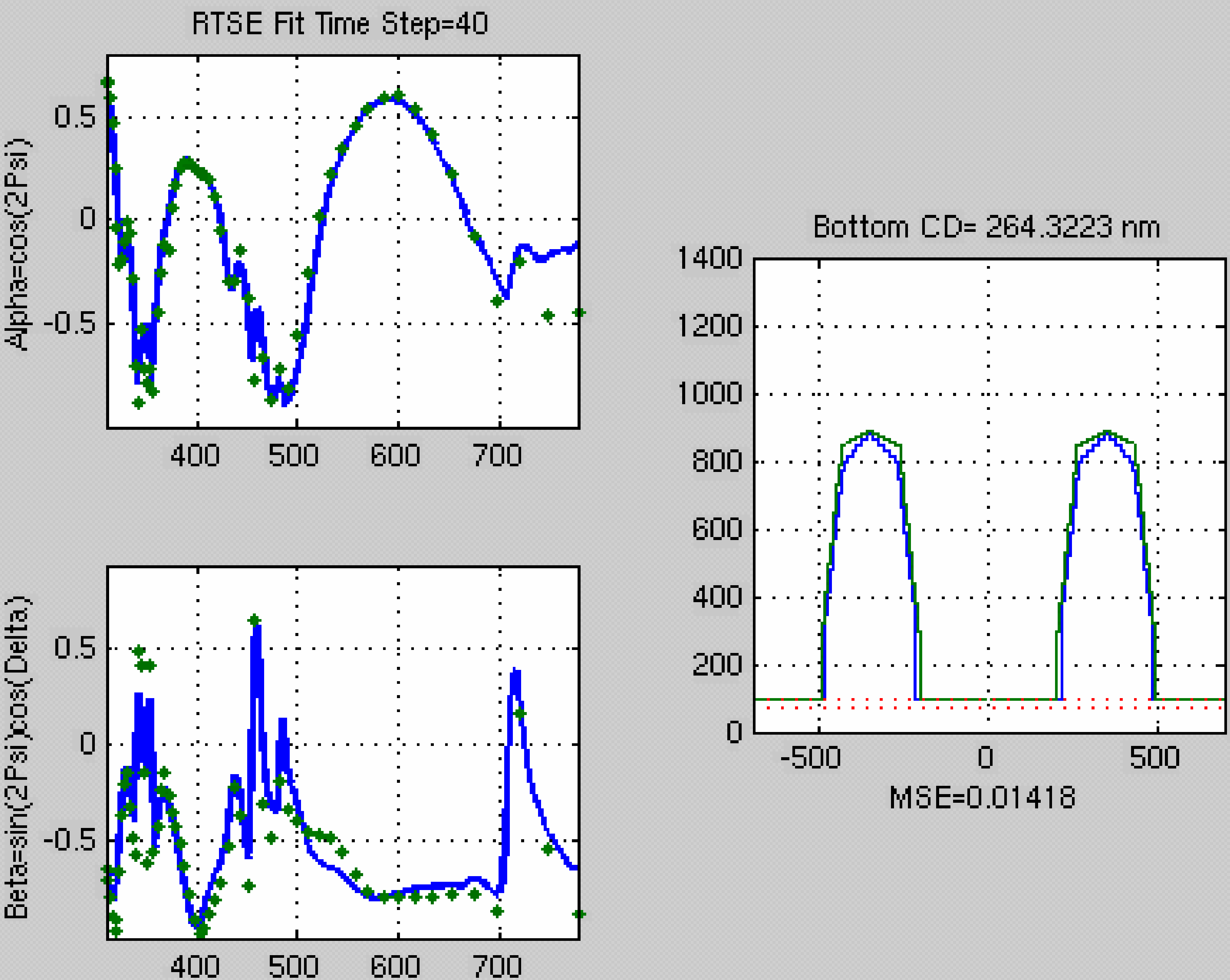


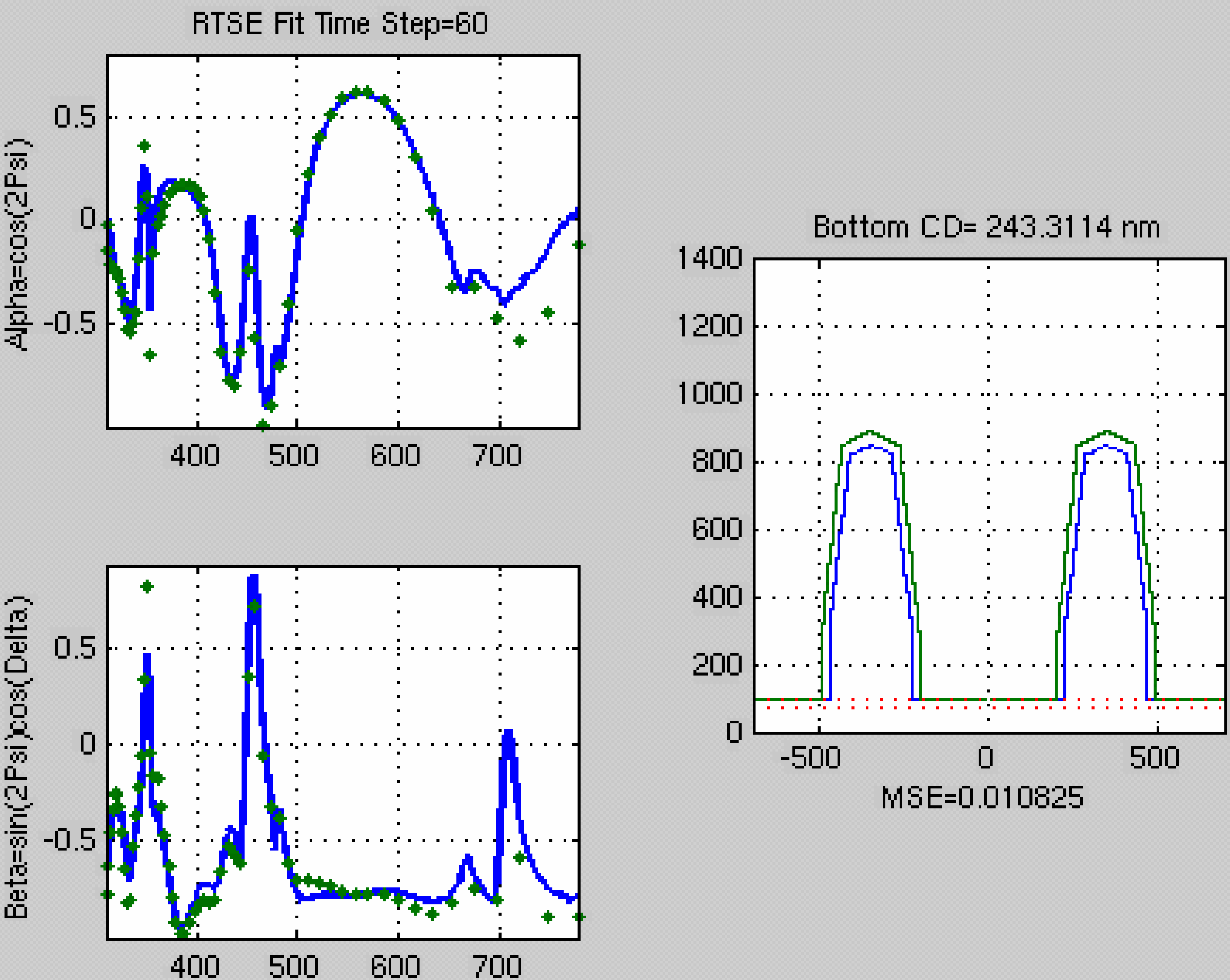


RTSE Fit Time Step=1
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Bottom CD= 296.6651 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.013615

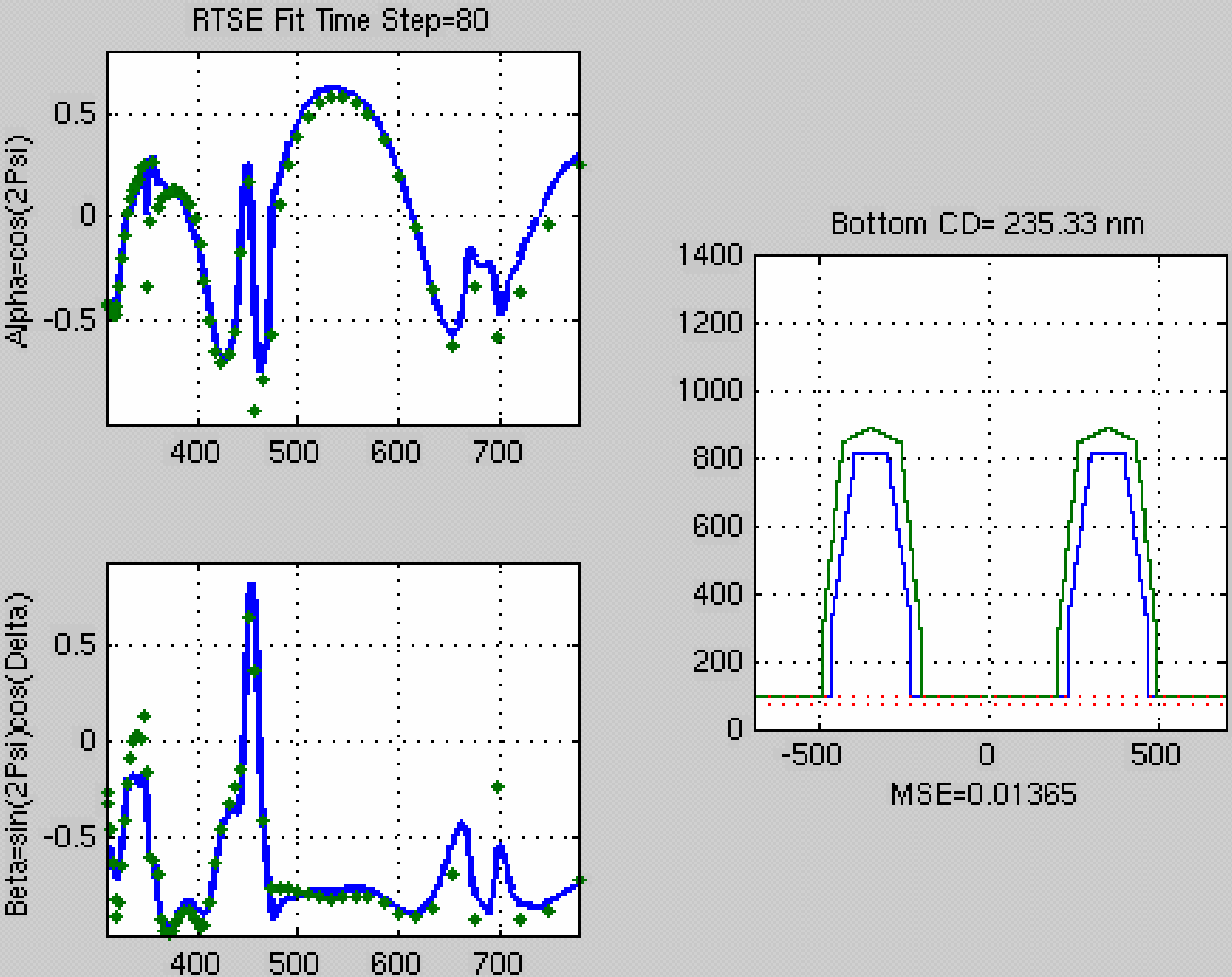


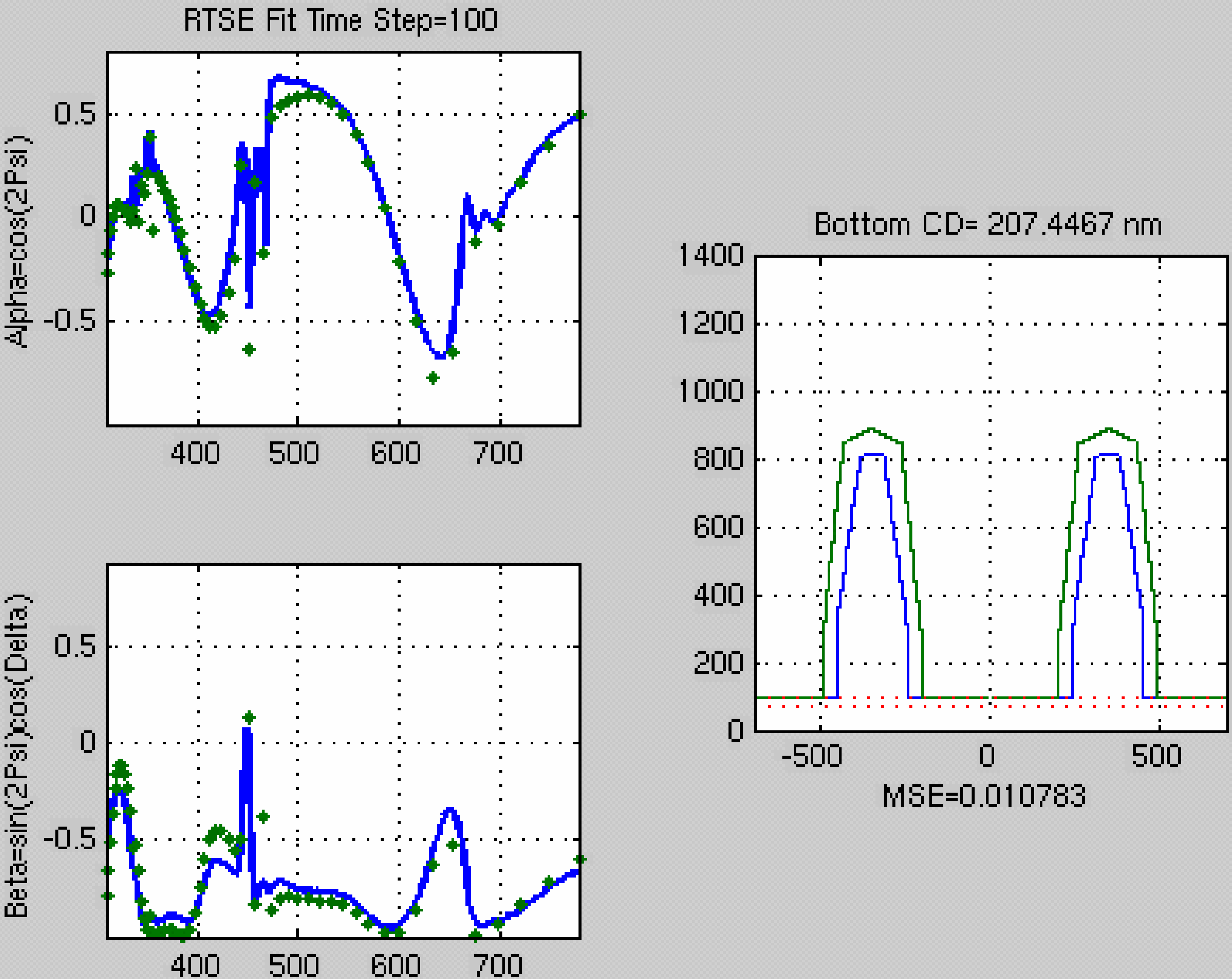
RTSE Fit Time Step=1
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Bottom CD= 296.6651 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.013615

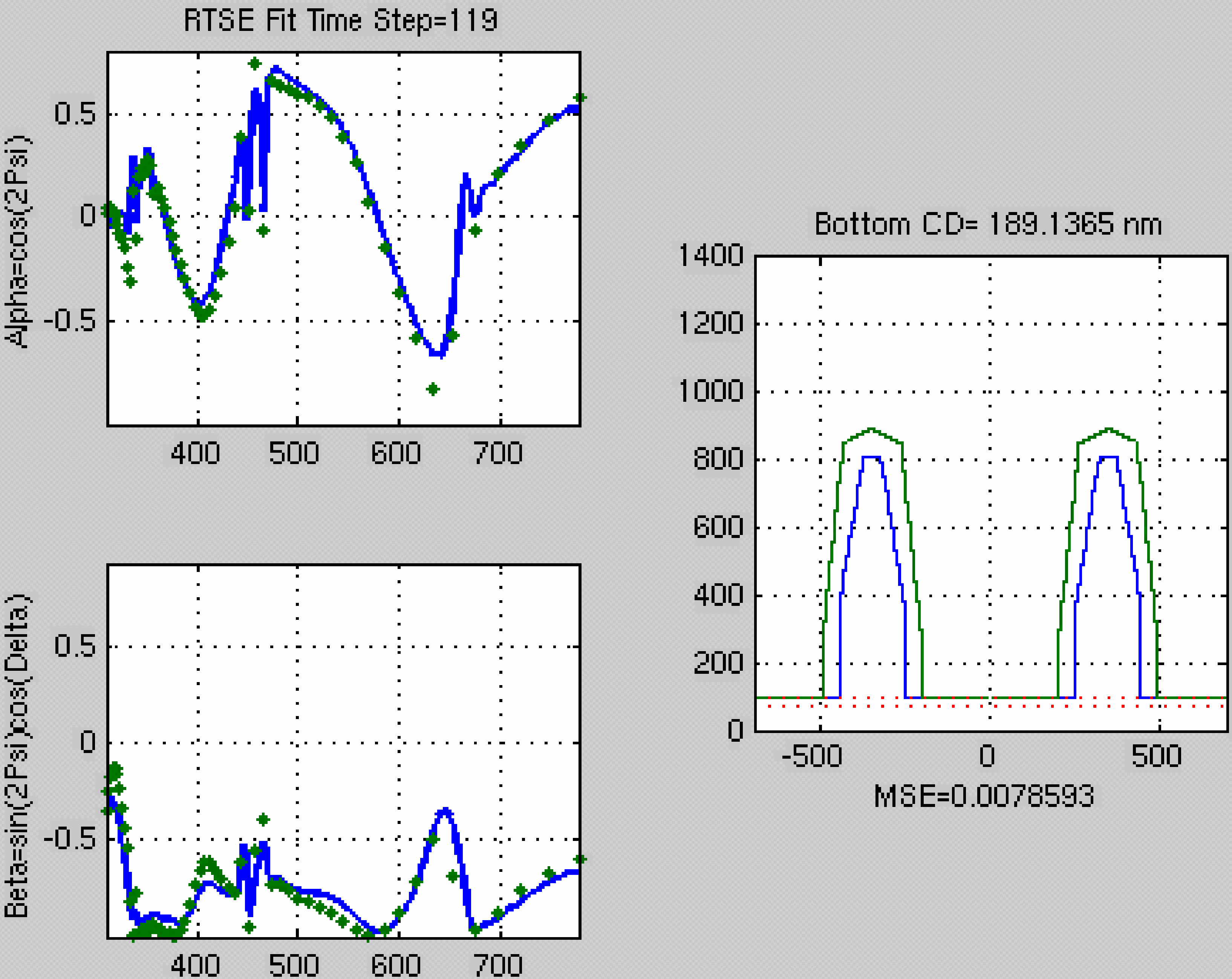

RTSE Fit Time Step=40
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Bottom CD= 264.3223 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.01418



RTSE Fit Time Step=60
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Bottom CD= 243.3114 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.010825


RTSE Fit Time Step=80
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Bottom CD= 235.33 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.01365

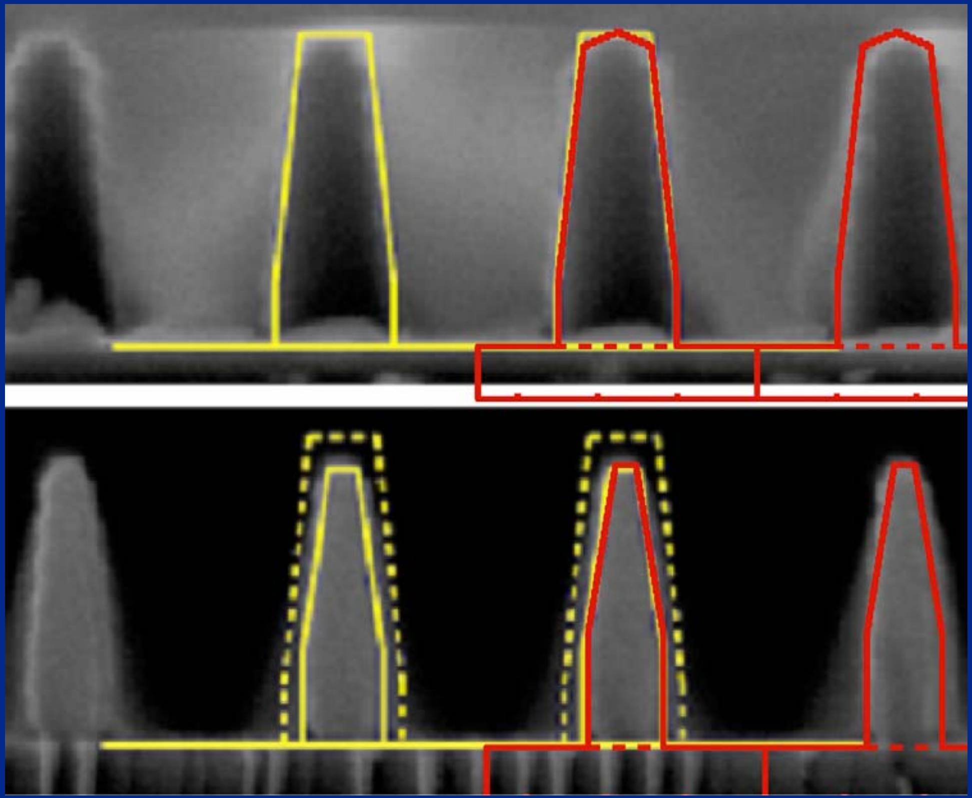

RTSE Fit Time Step=100
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Bottom CD= 207.4467 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.010783



RTSE Fit Time Step=119
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Bottom CD= 189.1365 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.0078593

In Situ Optical CD/Automated Etch to Target CD

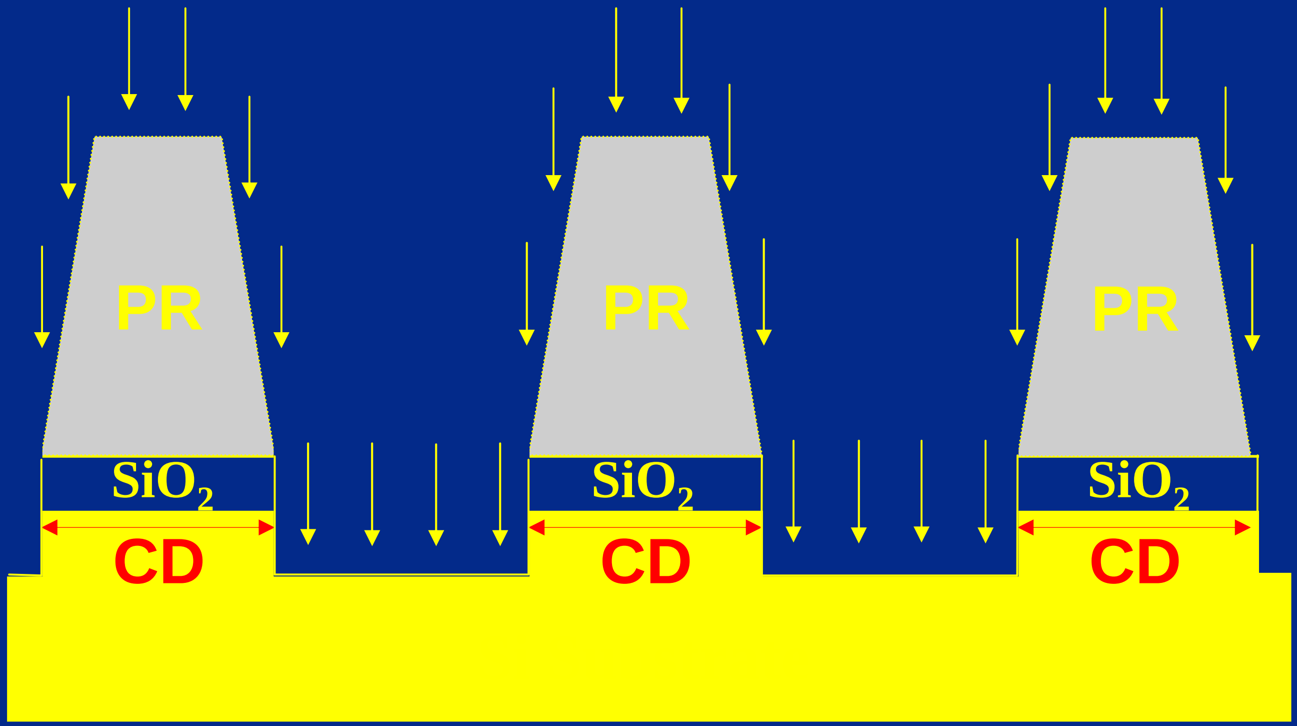
- O_2 Plasma Photoresist Trim in Lam 9400 TCP
- *In Situ* Real-Time Spectroscopic Ellipsometry Monitoring of Photoresist Grating Structure
- Off-Line RCWA Analysis of Grating Diffraction Problem
- Nonlinear Filtering Algorithm for Real-Time Data Analysis
  - *Completely Hands-off Automated Etch to Target 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

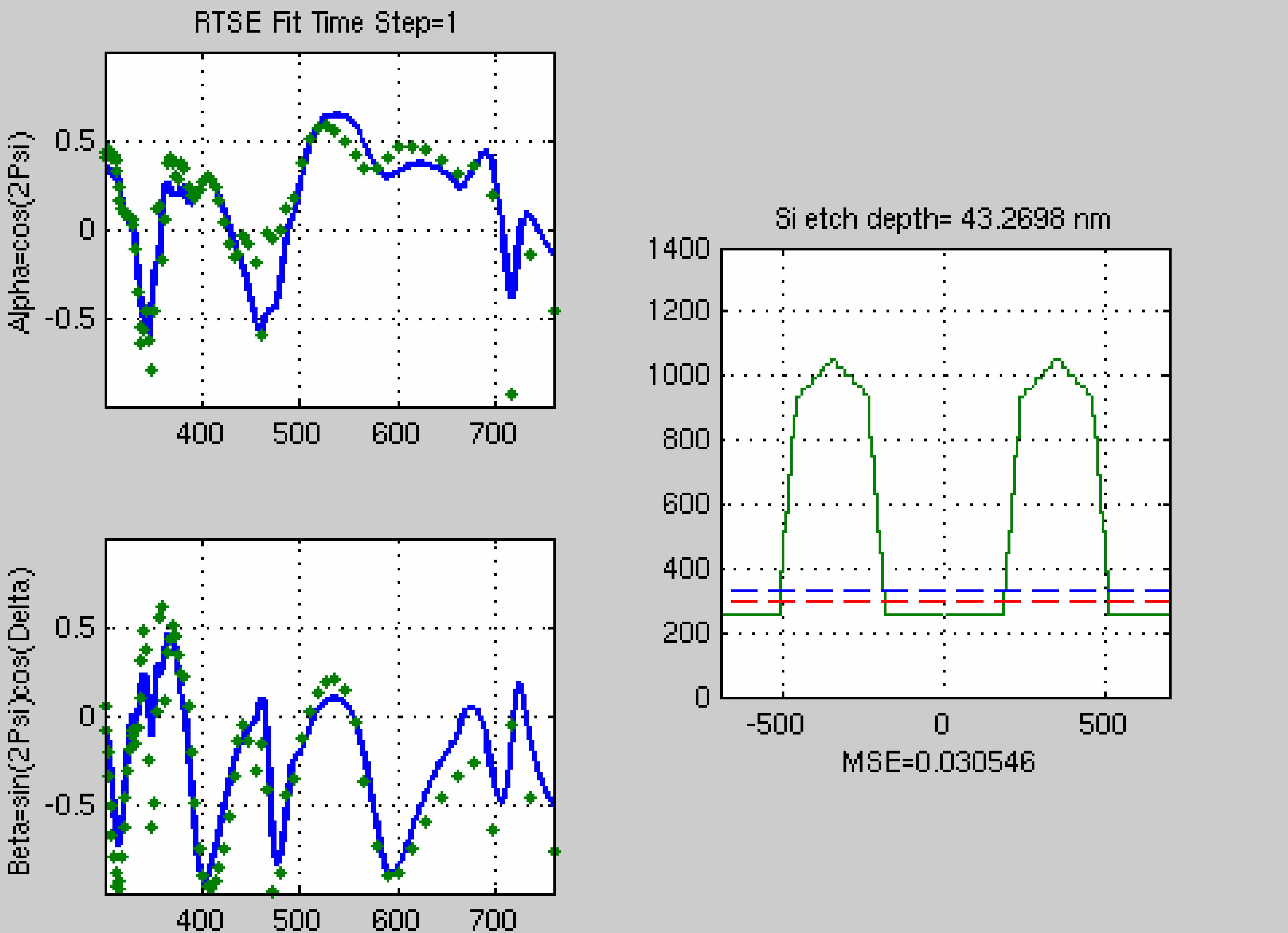


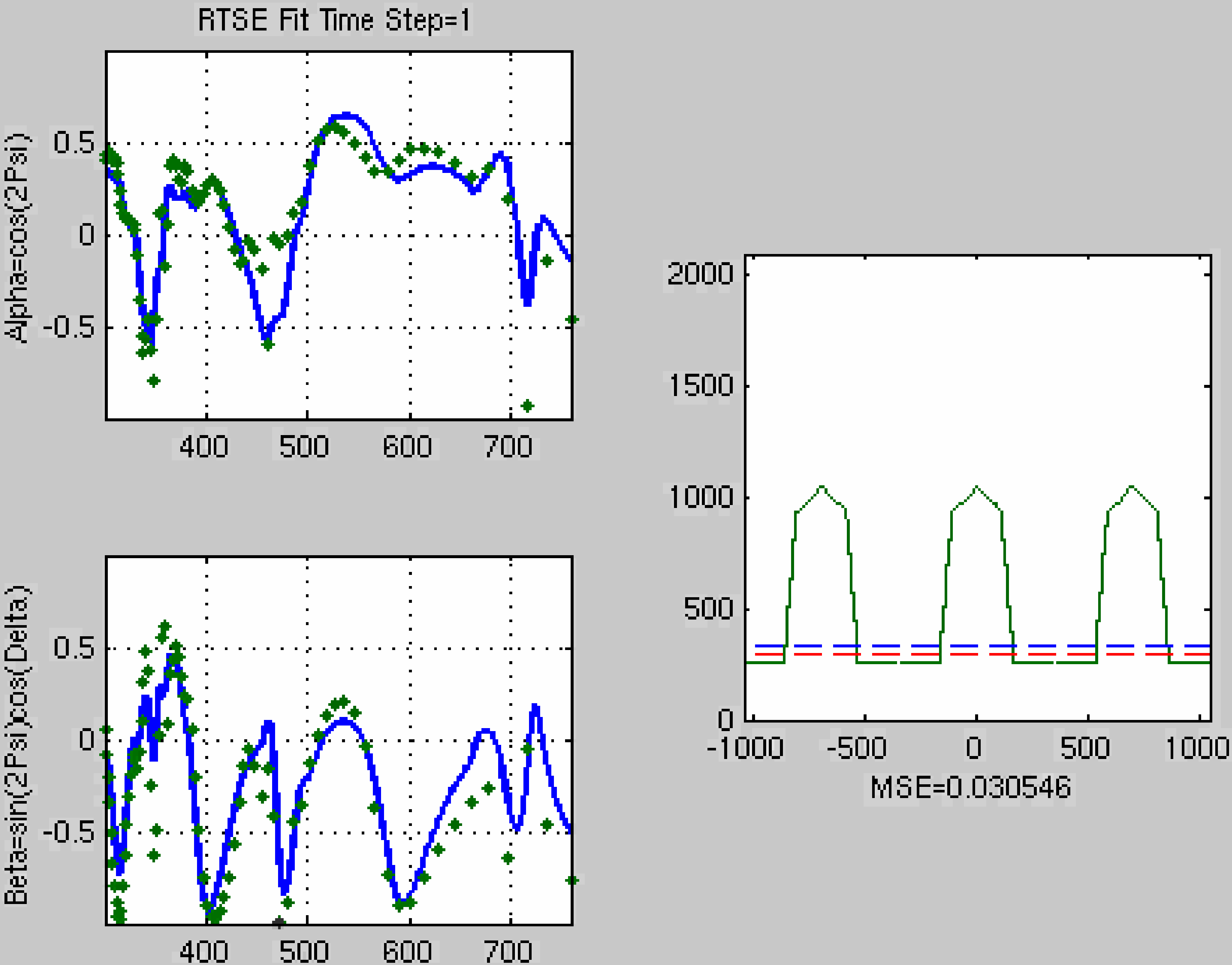
Start:	Trimmed:
CD 296.7±9.1nm	CD 189.1±29.3nm
Height 790.0 ±63.4nm	Height 710.9 ±67.6nm

Experimental Description

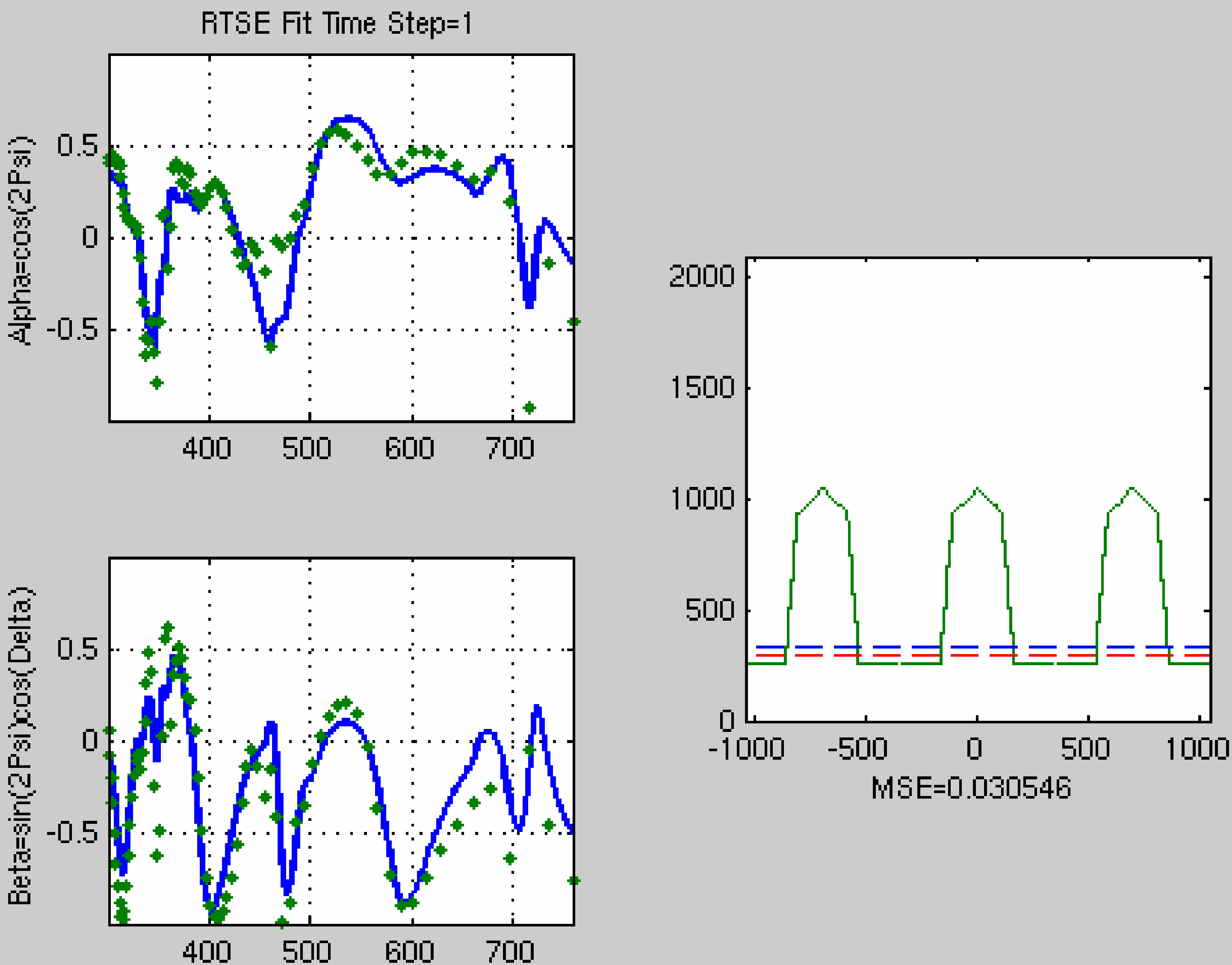
- Lam TCP9400SE Plasma Etching System
- Plasma Gas: HBr 100 sccm & Cl_2 15 sccm
- Nominal Etching Rate: PR 5Å/sec, Oxide 3.6Å/sec, and Poly 30Å/sec



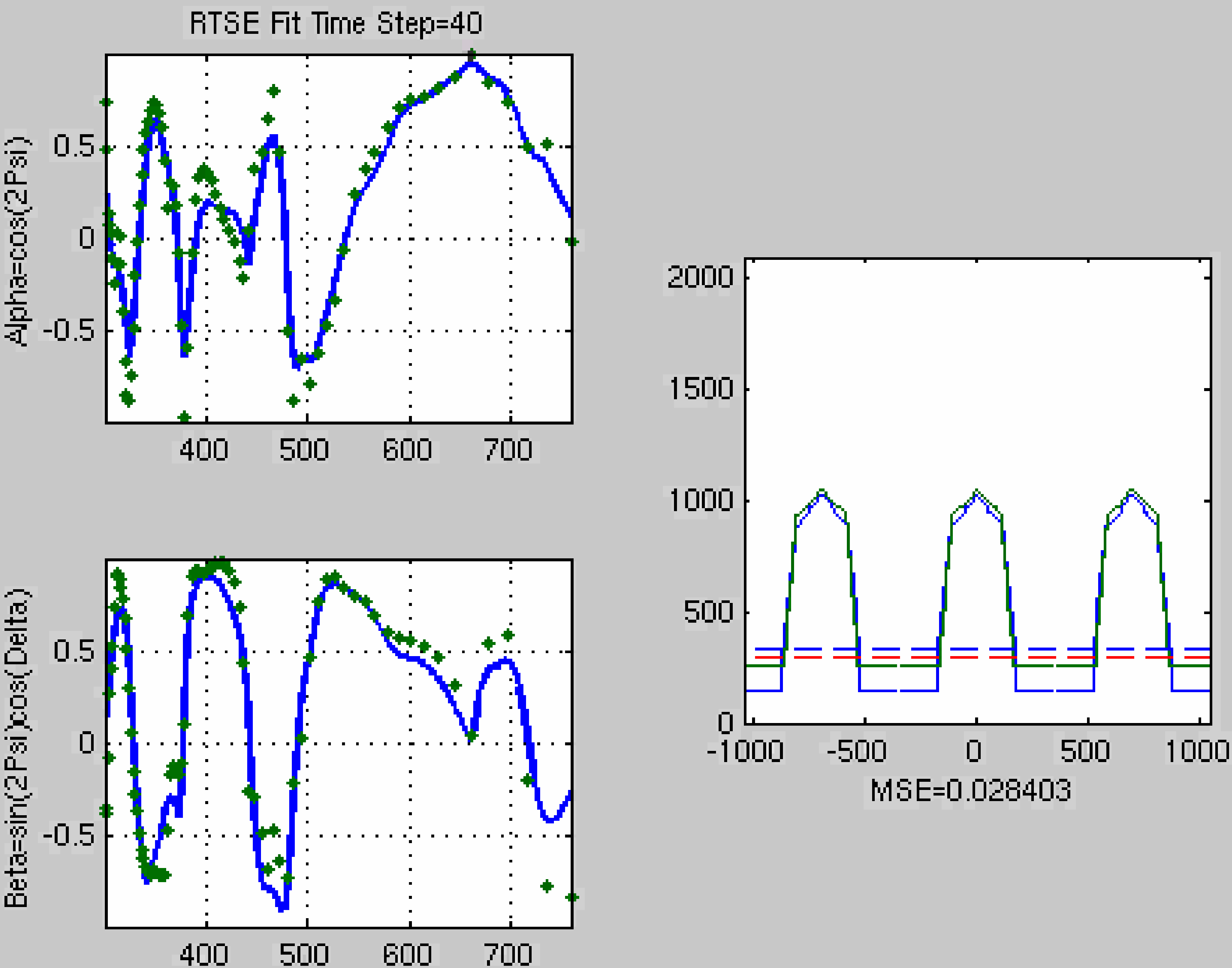

RTSE Fit Time Step=1
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
Si etch depth= 43.2698 nm
1400
1200
1000
800
600
400
200
0
-500
0
500
MSE=0.030546



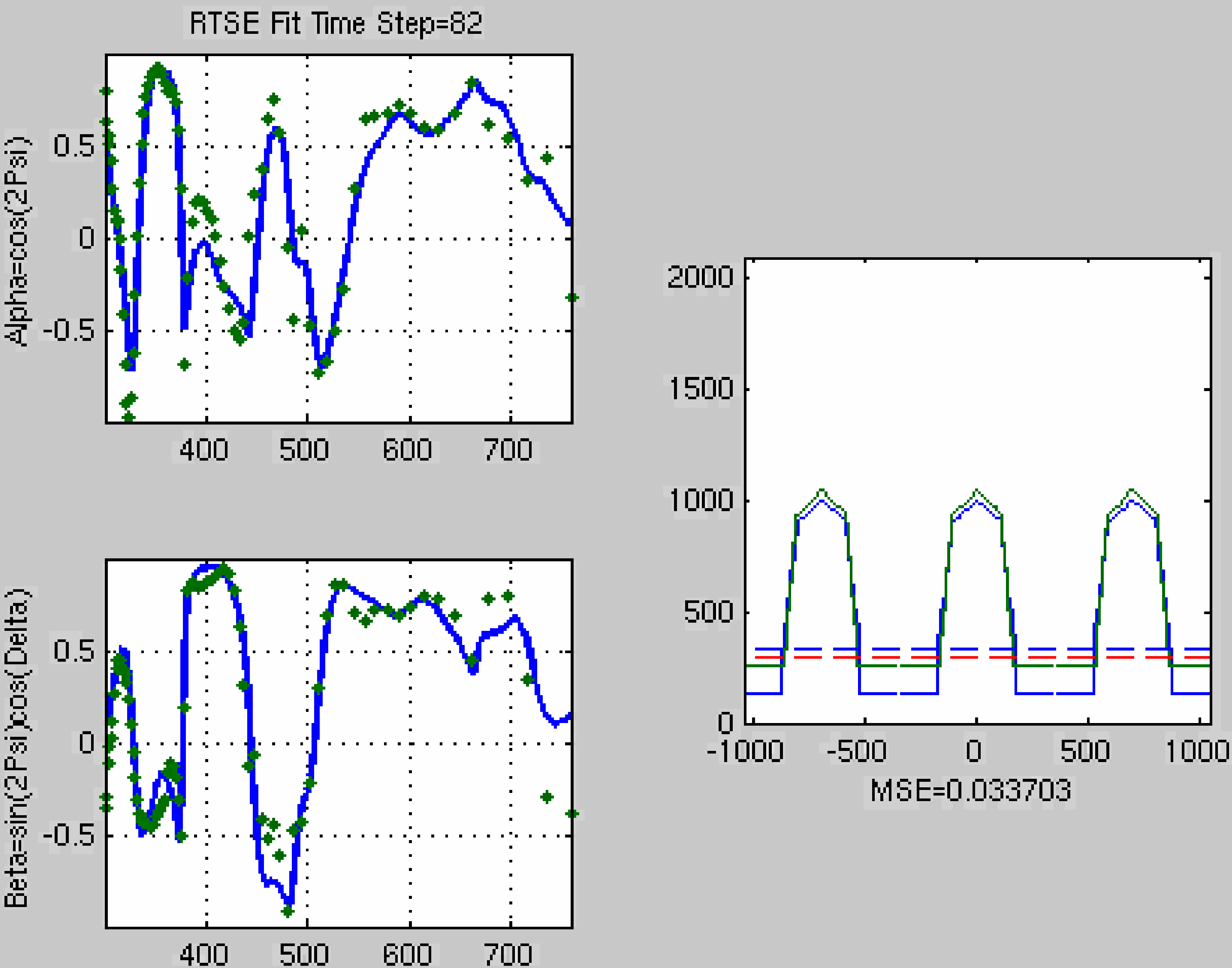
RTSE Fit Time Step=1
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
2000
1500
1000
500
0
-1000
-500
0
500
1000
MSE=0.030546



RTSE Fit Time Step=1
Alpha=cos(2Psi)
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
2000
1500
1000
500
0
-1000
-500
0
500
1000
MSE=0.030546

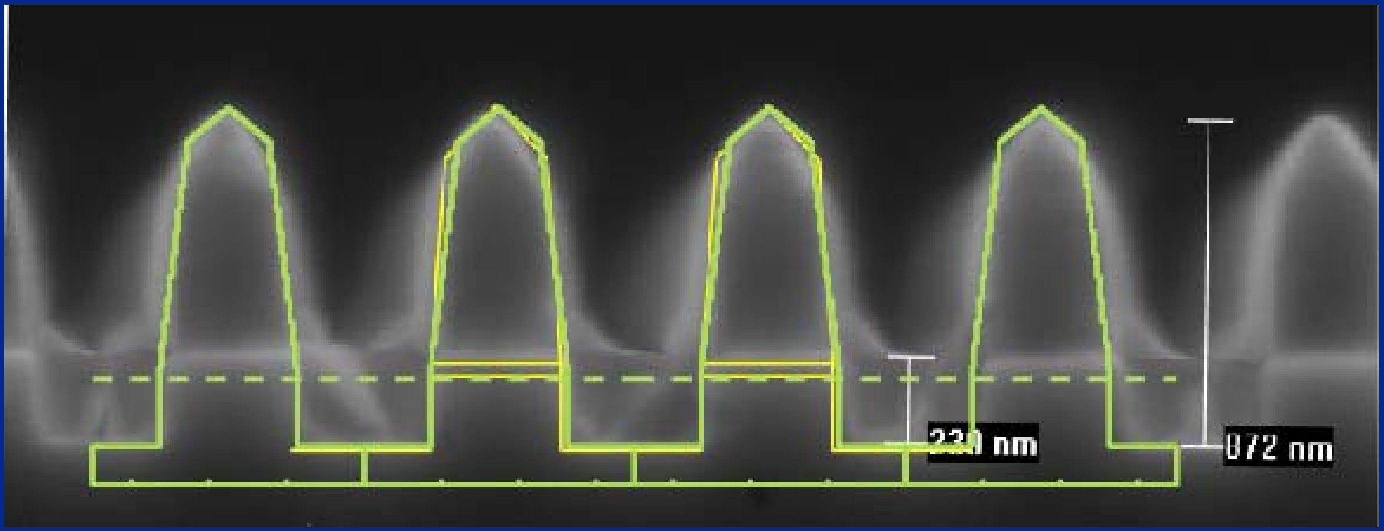


RTSE Fit Time Step=40
Alpha=cos(2Psi)
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
2000
1500
1000
500
0
-1000
-500
0
500
1000
MSE=0.028403



RTSE Fit Time Step=82
Alpha=cos(2Psi)
0.5
0
-0.5
400
500
600
700
Beta=sin(2Psi)cos(Delta)
0.5
0
-0.5
400
500
600
700
2000
1500
1000
500
0
-1000
-500
0
500
1000
MSE=0.033703

Comparison of PR-Masked Si Etch to SEM Cross-Section

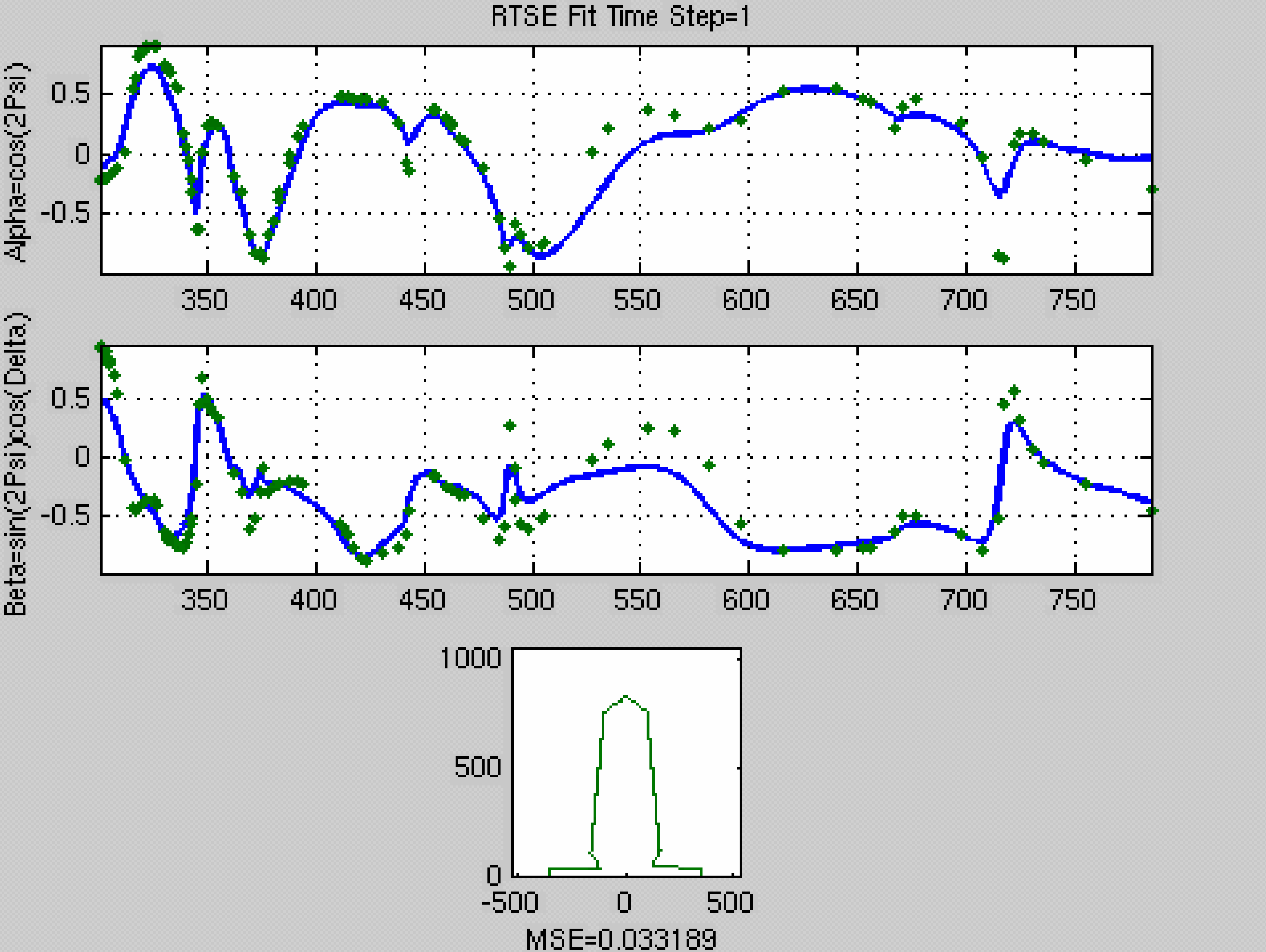


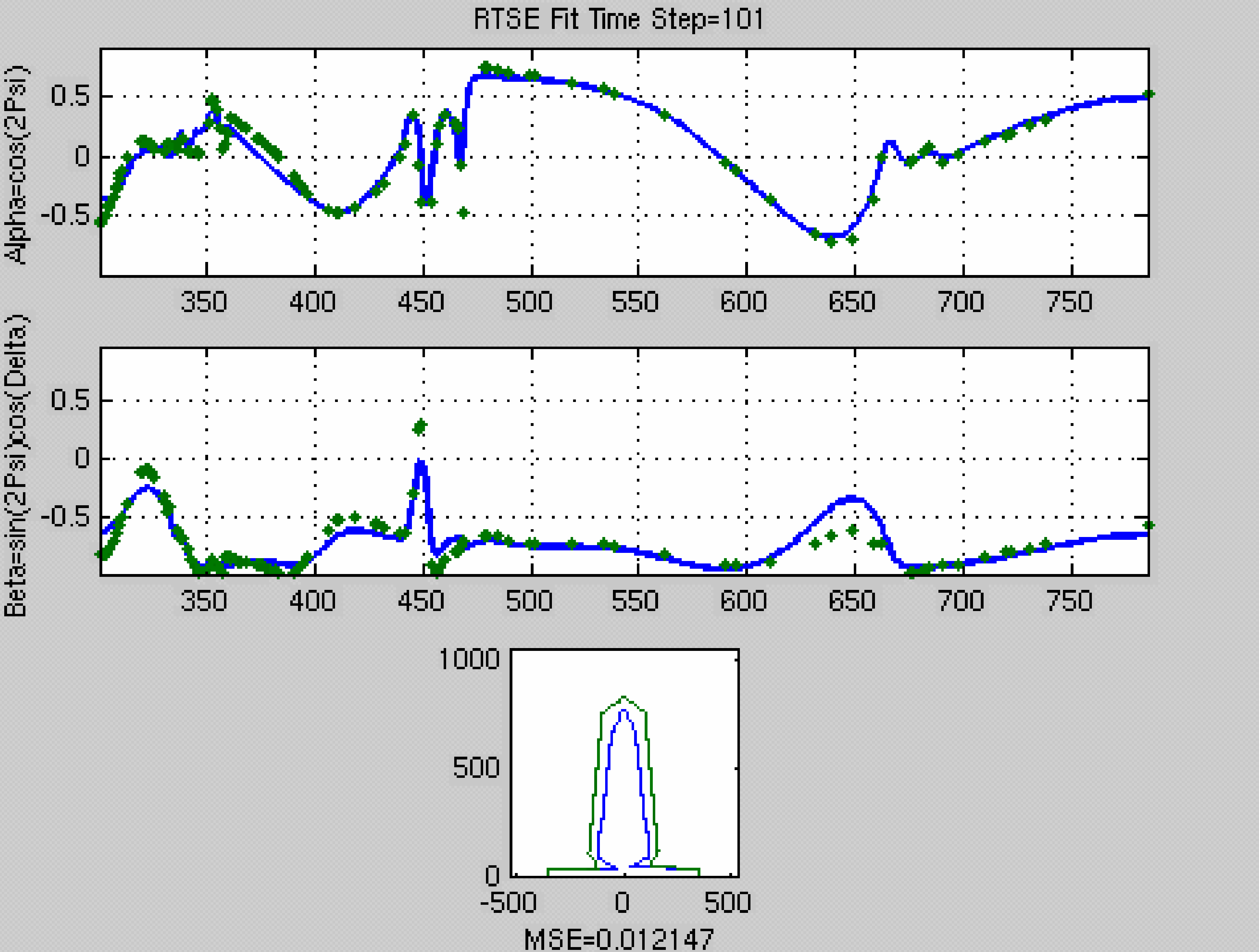
- **Si Trench Depth 173.32 ± 0.26 nm**
- **Si CD 354.62 ± 11.37 nm**

Limitations & Challenges

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

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

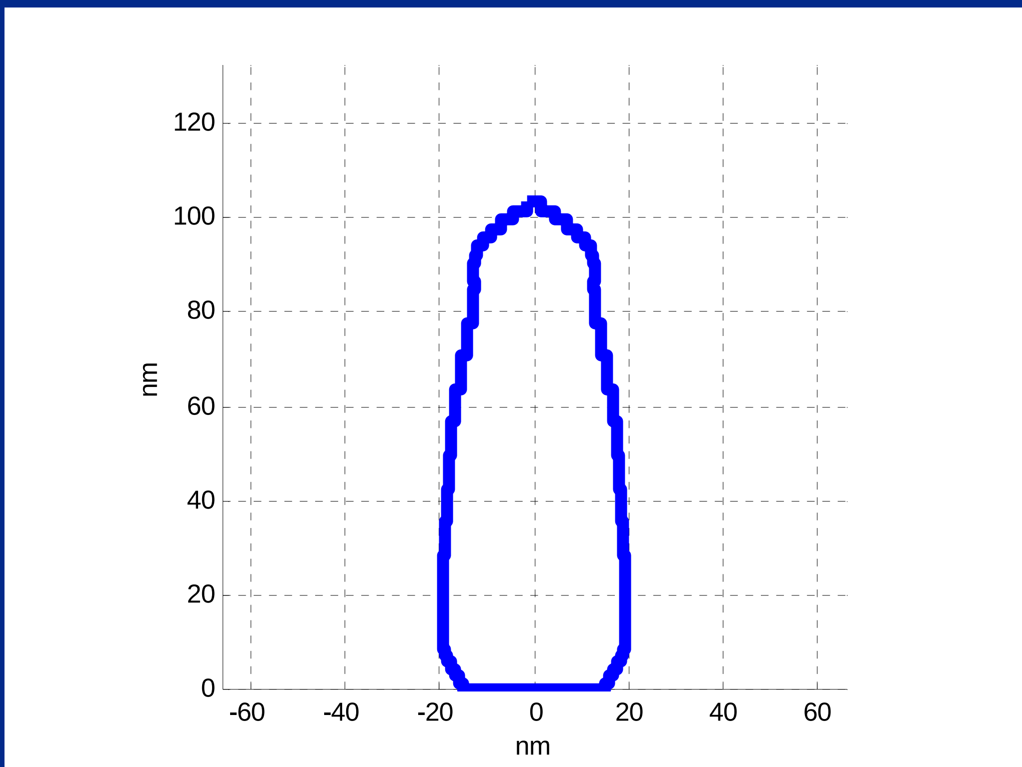
Most Shape Info in Magnitude not Fine Structure of Data

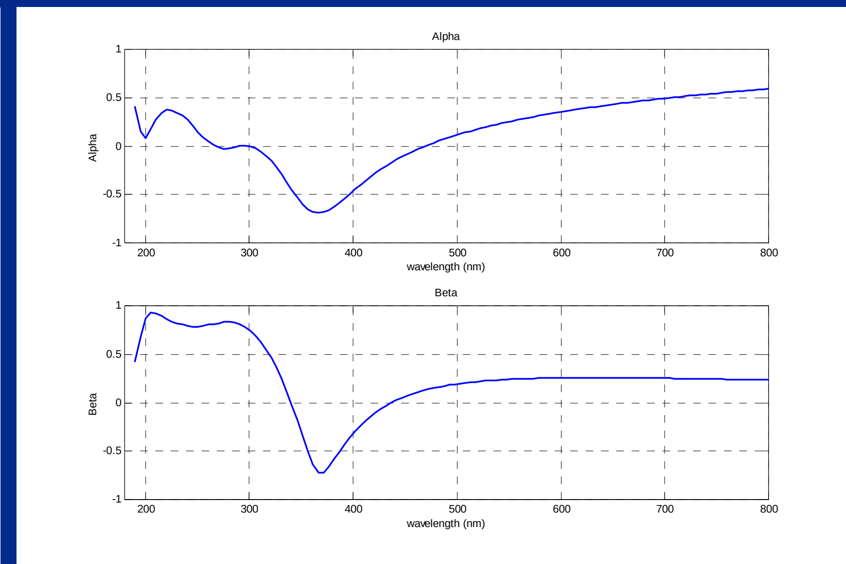
$W \lll \lambda_{min}$ Results Converge to EMA, No Real CD Info, Only Average Composition

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***

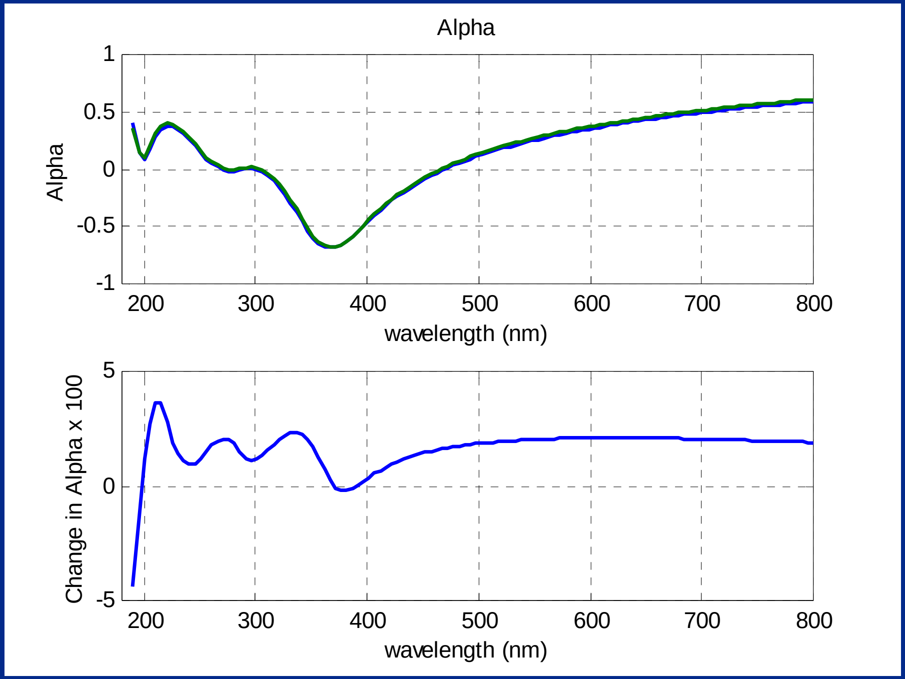
Simulated ~40nm PR Line
Λ=90nm

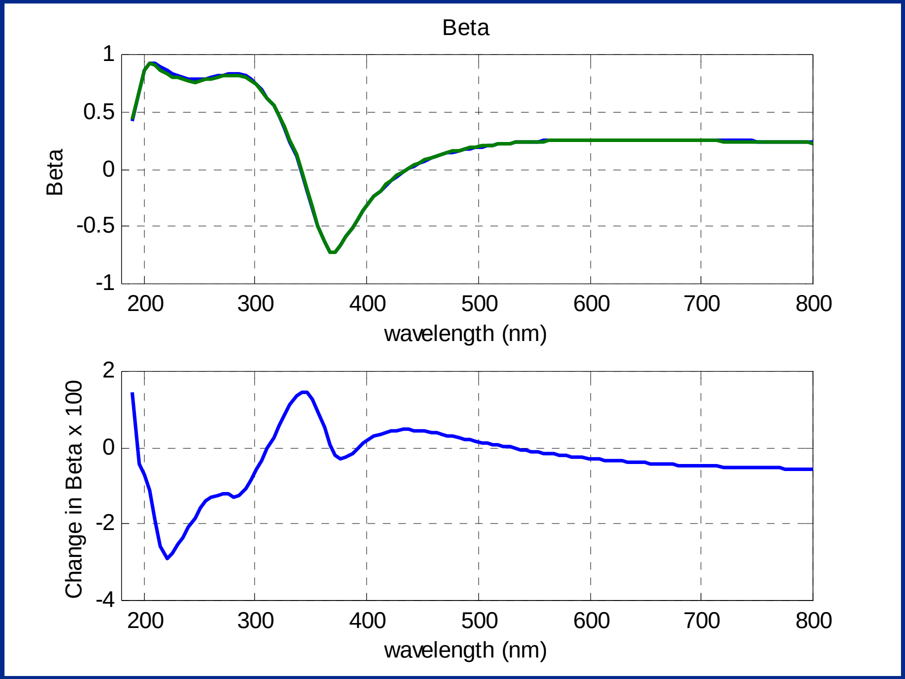


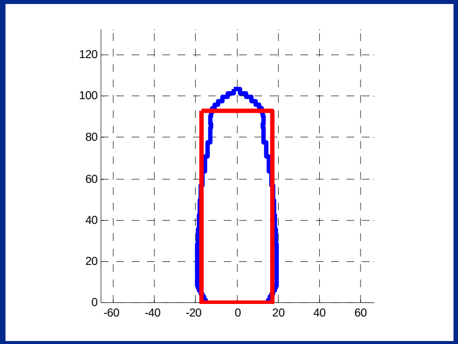


Can Detailed Shape Information Be Extracted?

Fit Using Rectangular Only Model

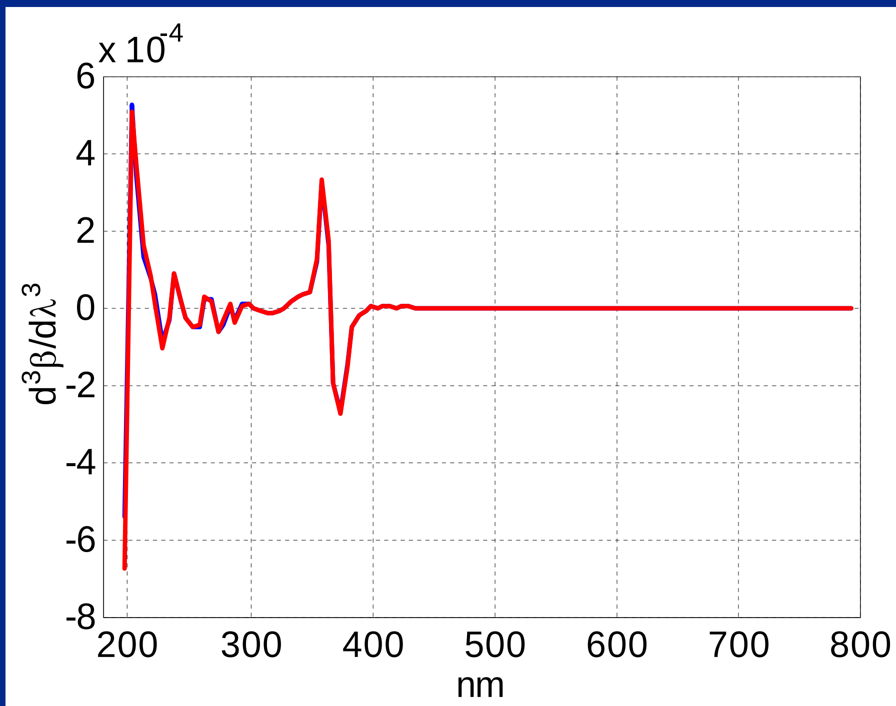


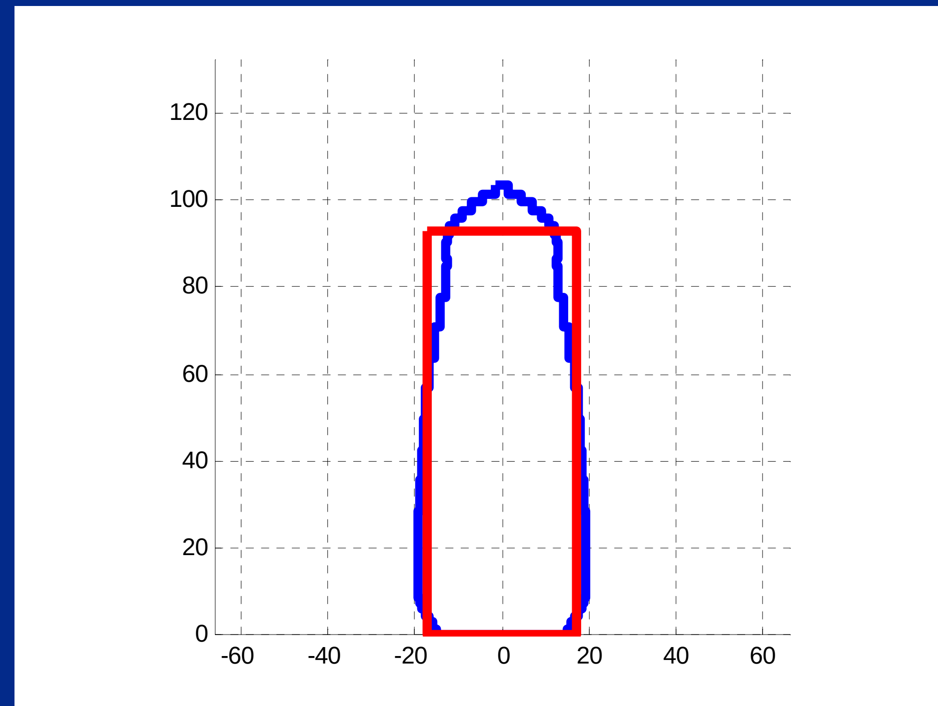




- **Rectangle Fit Averages More Complex Structure**
- **<u>Examine *Structure* Differences in Data Through Derivatives vs. λ</u>**

$d^3\beta/d\lambda^3$ 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**
- **VUV & EUV Scatterometry Needed for the Future**

Conclusions & Challenges

- Spectroscopic Ellipsometry + Accurate Diffraction Modeling Allows Topography Extraction with Resolution $\ll \lambda$
- *in situ* Applications Allow Fabrication Processes to be Studied and Controlled in New Ways
- Wide-Spread Deployment in IC Industry
- 2-D Arrays Under Development by Several Companies
- Exploratory Line-Edge Roughness Extraction Work Underway

Conclusions & Challenges

- Diffraction Modeling for Non-Periodic Structures
  - Process Control on Real Product IC's
  - Applications in Biology and other "Messy" Fields
- Instrumentation and Measurement Schemes for Isolated or Sparse Structures
- Detailed Understanding of Accuracy Limitations, Parameter Correlation Effects, etc.

Acknowledgements

- Collabators:
  - Drs. Hsu-Ting Huang, Pete Klimecky, Wei Kong, Ji_Woong Lee, Meng-En Lee, Brooke Stutzman
  - Prof. Pramod Khargonekar
  - Dr. Dennis Grimard, Mr. Dennis Swieger, and Mr. Jeff Fournier
- 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