In Situ Measurements of Patterned Structures

Hsu-Ting Huang[1], Brooke Stutzman[2], Wei Kong[1], and Fred L. Terry, Jr.[1,2]

[1]Dept of EECS and [2]Applied Physics Program

734-763-9764

734-763-9324 (fax)

fredty@umich.edu

http://www.eecs.umich.edu/~fredty

Outline

- Motivation and Background
- Demonstration of Spectroscopic Ellipsometry for Analysis Patterned Wafers
- Two-Channel Spectral Reflectometry as a Lower Cost / Higher Reliability Alternative to Full Spectroscopic Ellipsometry
- In Situ Measurements of Grating Evolution (The Motion Picture)
- Advantages of Near-Normal Incidence SE (RDS) for Topography Measurements
- Conclusions and Future Efforts

Motivation

- High-Speed, Nondestructive, Critical Dimension (CD) Measurement in Deep Sub-μm Regime
    - Faster, More Accurate than CD-SEM
    - *Ex Situ* & *In Situ* Applications
- Depth, Wall Angle (Wall Shape)
    - *In Situ* Etch Monitoring
    - In Line Photolithography Characterization
- *In Situ* Applications Favor Fixed Position (Single Angle of Incidence) Instrumentation for High Speed
    - Spectral Methods

Background I

- Basic Concept: Scattering (Diffraction) of Light from Features Produces Strong Structure in Reflected Optical Field
- Analyze Structure to Obtain Topography Information
- Periodic Structures (Gratings) Can Be Numerically Modeled “Exactly”

Background II

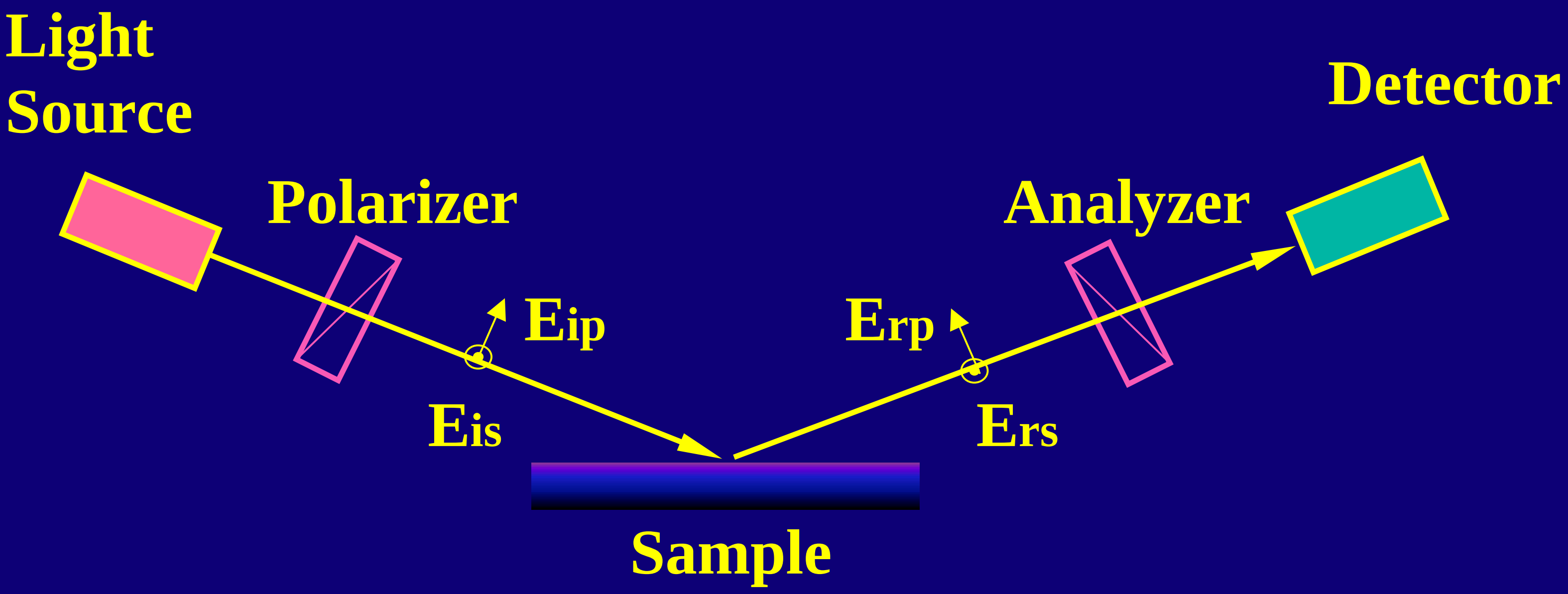
Single Wavelength Scatterometry

- 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

Spectroscopic Ellipsometry and Reflectometry

- Examine Structure vs. Wavelength at Fixed AOI
  - Terry and Co-workers (U. Michigan)
  - Spanos and Co-workers (UCB), Timbre Technologies

Ellipsometry



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

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

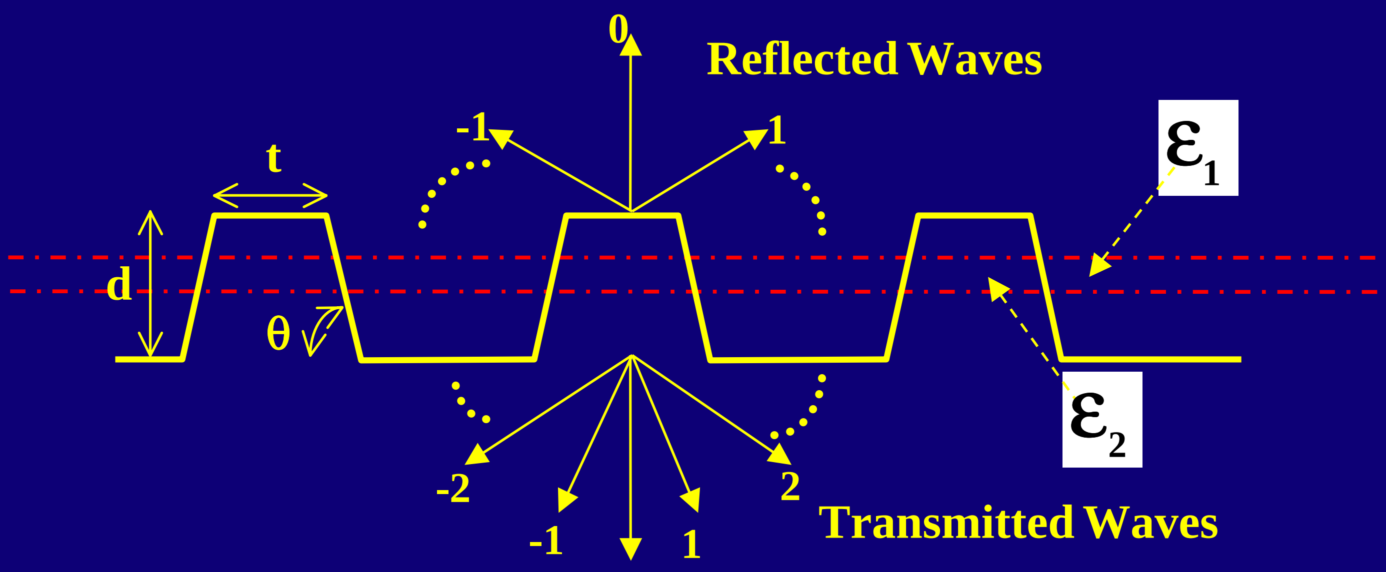
- **Tan(Ψ) And Cos(Δ) Are Measured by Ellipsometry**

  —Functions of wavelength and incident angle

Fred L. Terry, Jr., WISE-2000 Thin Film Metrology Workshop May 9, 2000

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

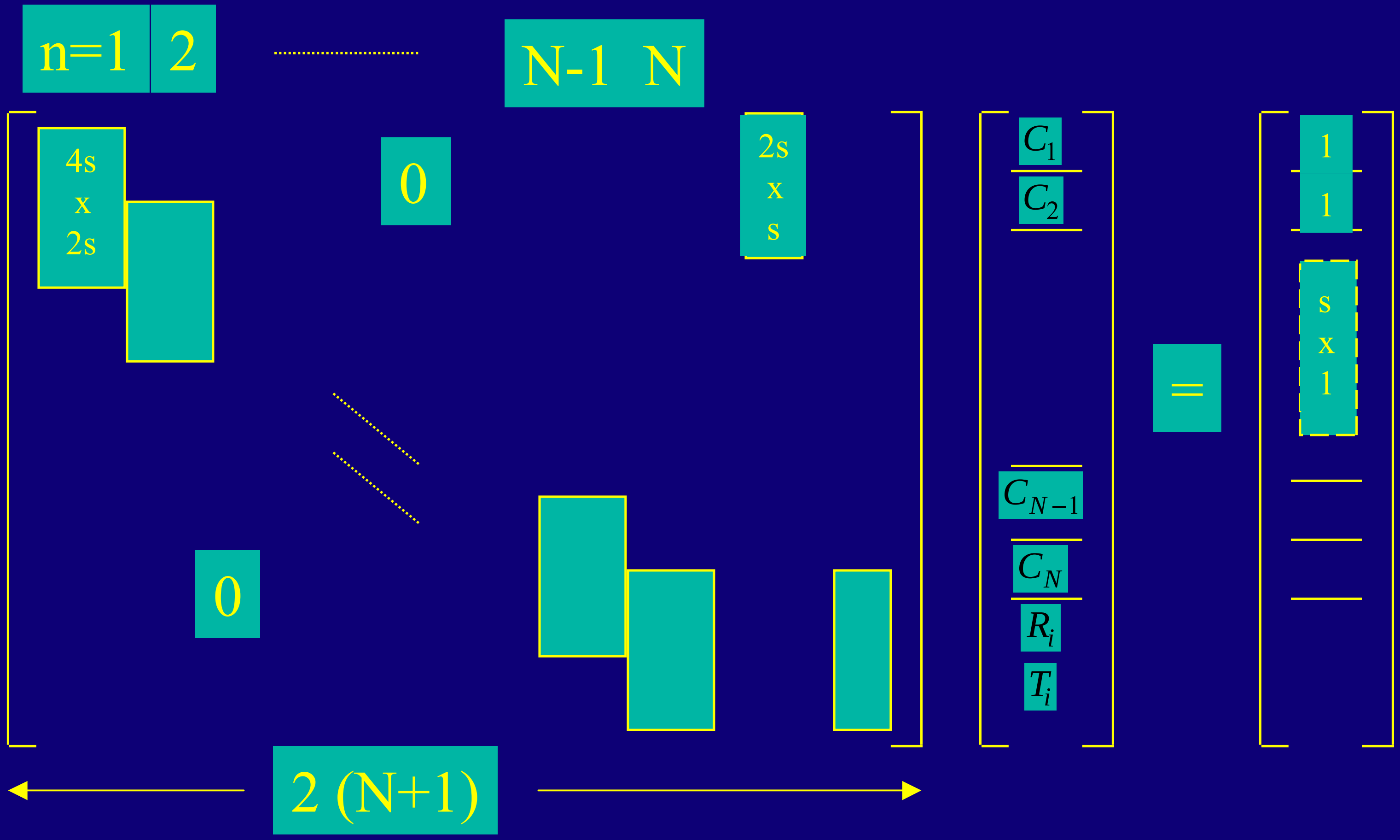


Fred L. Terry, Jr., WISE-2000 Thin Film Metrology Workshop May 9, 2000

RCWA Computation Issues

- Let *N* be the number of 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
- Typical: $s \geq 10$, $N \sim 45\text{-}65$

RCWA matrix considerations



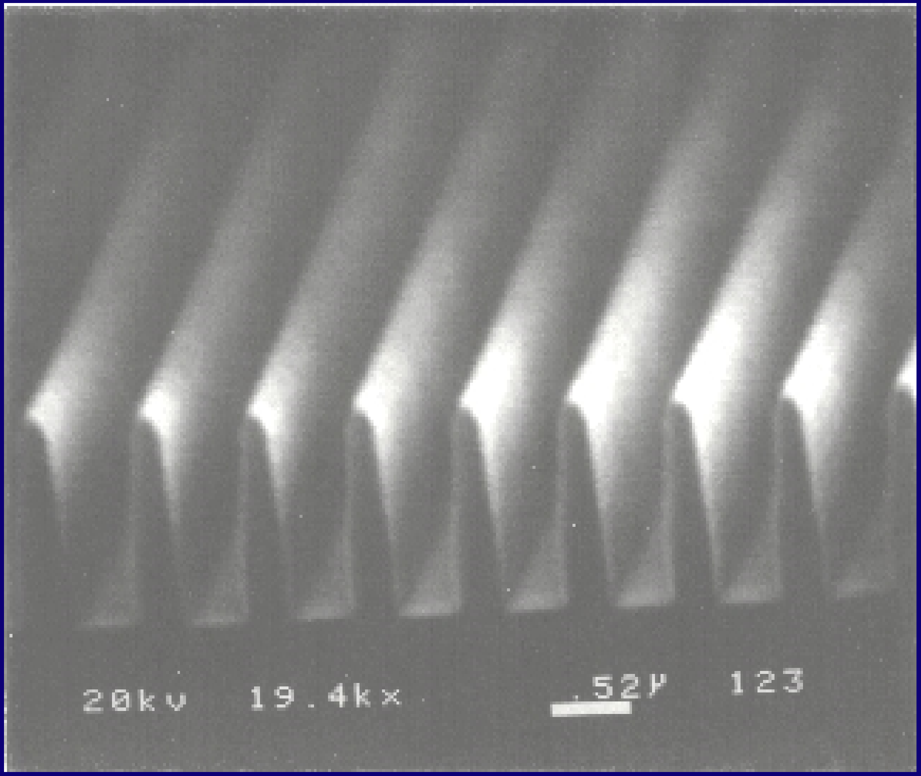
Typical N~45-65, S≈10

Solve separately for $\mathbf{E}_s$ and $\mathbf{E}_p$ to generate tan(ψ) and cos(Δ)

Run time is approximately ~ 2-5 min/forward simulation

Demonstration of the Use of Spectroscopic Ellipsometry for Photoresist Topography Analysis: Photoresist Grating

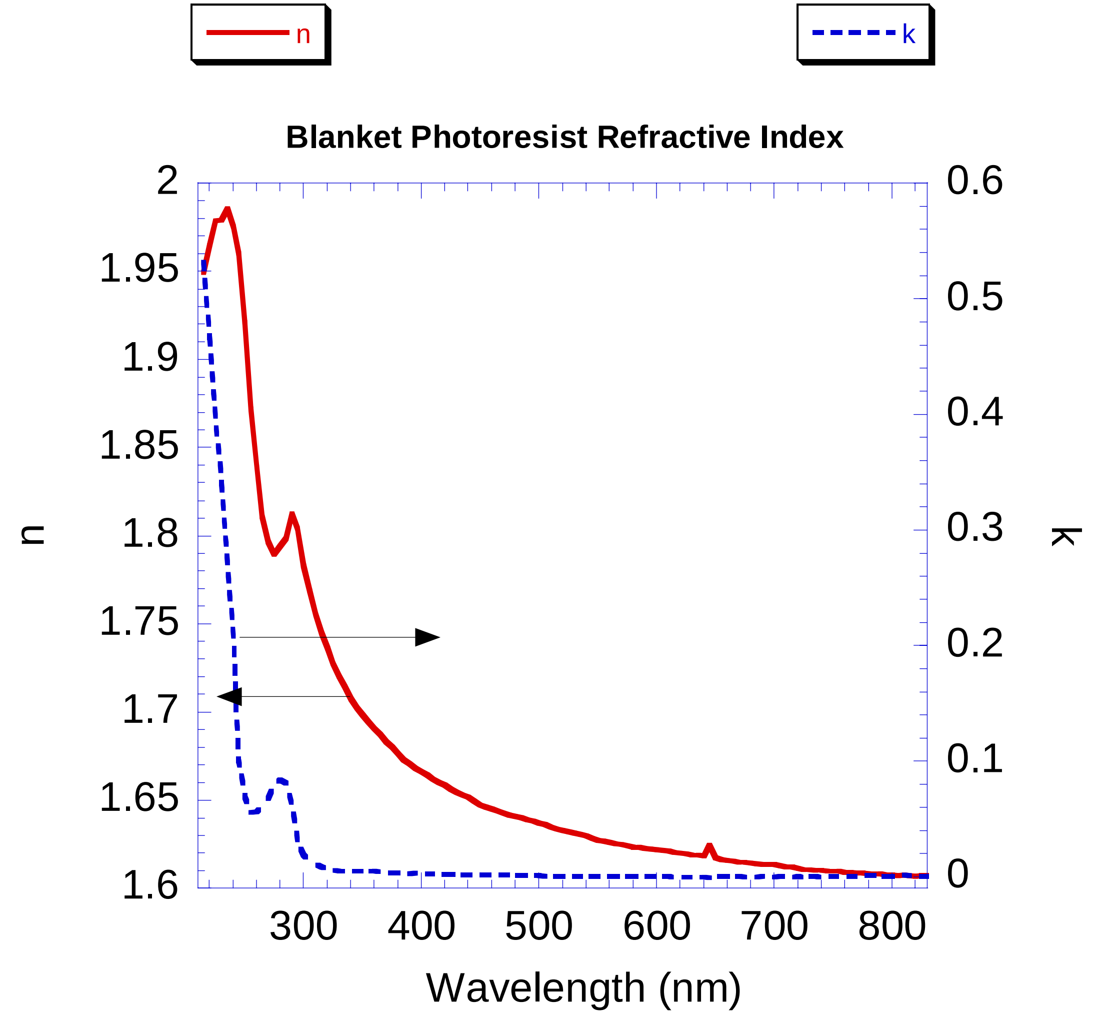
Submicron Grating



- ~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

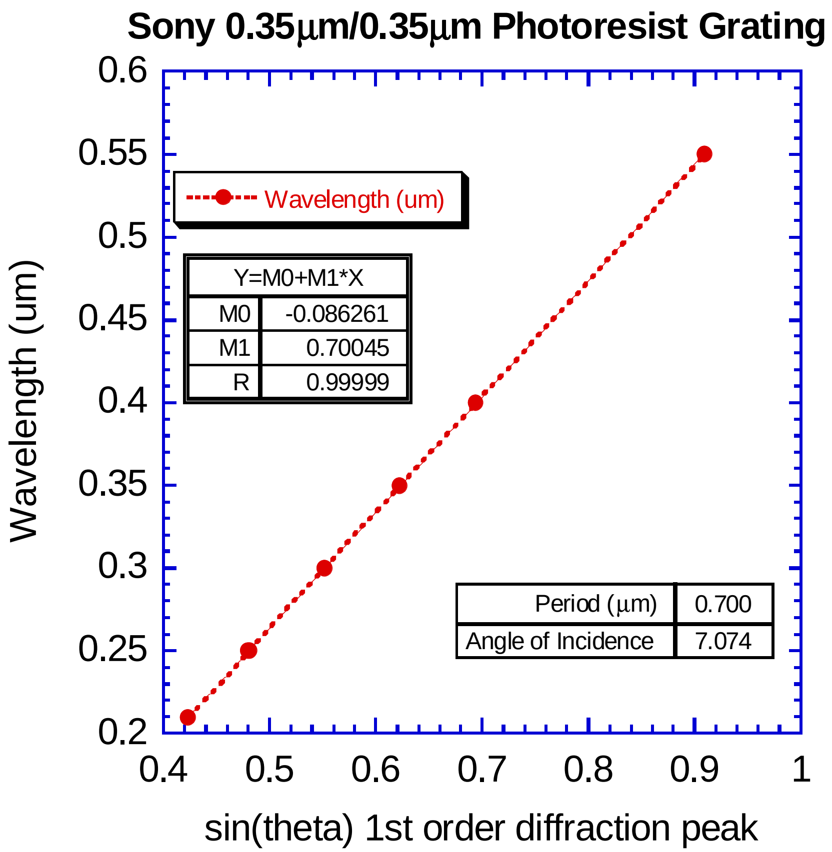
Photoresist Refractive Indices

- **Photoresist Refractive Index Extracted by 3-Angle SE Measurement (65, 70, 75º) of Similarly Prepared Blanket PR Film on Si**
- **Thickness Extracted from Transparent Region (500-830nm)**
- **(n,k) vs. λ Extracted by Direct Point by Point Fit**
- **Some Uncertainty Due to PR Changes During SE Measurements and Due to Vacuum Curing of PR Gratings**



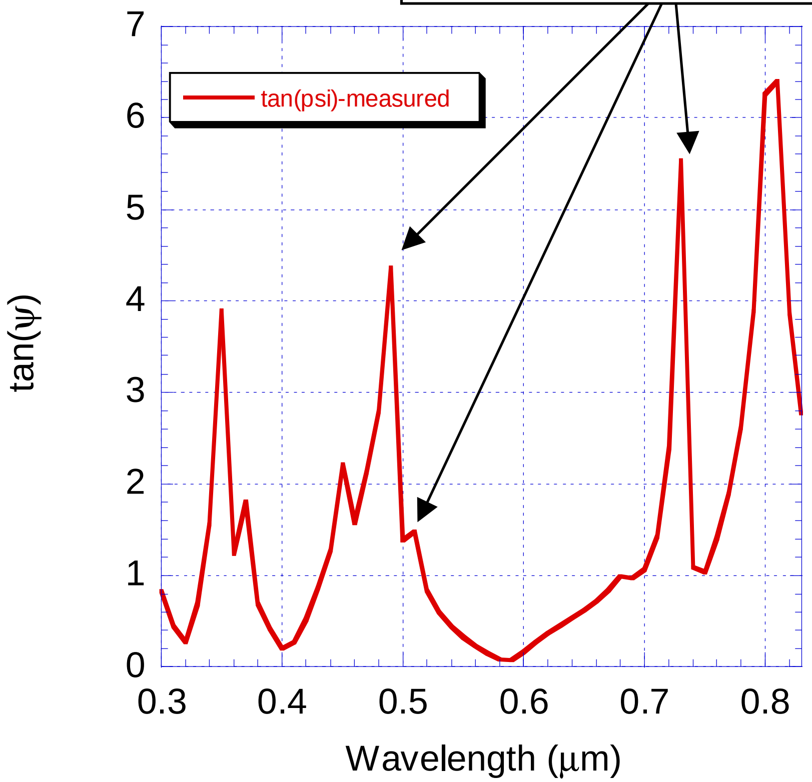
Extraction of Grating Period

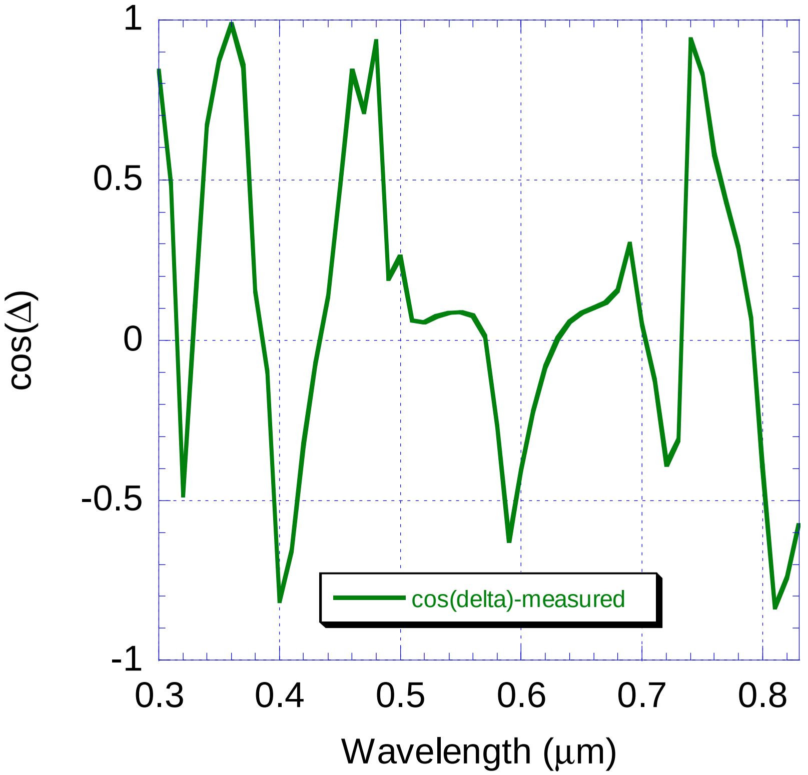
- Grating Equation:
  $\sin(\theta_D)= \sin(\theta_i)+m\lambda/P$
- For m=1 (1st Order Diffraction)
  $\lambda=P[\sin(\theta_D)- \sin(\theta_i)]$
- Measurements Done on Sopra GESP-5 in Scatterometry Mode at Nominal AOI=7°
- Sample Aligned to Plane of Incidence Using High Negative Order Diffracted Light (Backscattered Toward Polarizer Arm)
- Elimination of Period as a Free Variable Reduces Topography Extraction Problem



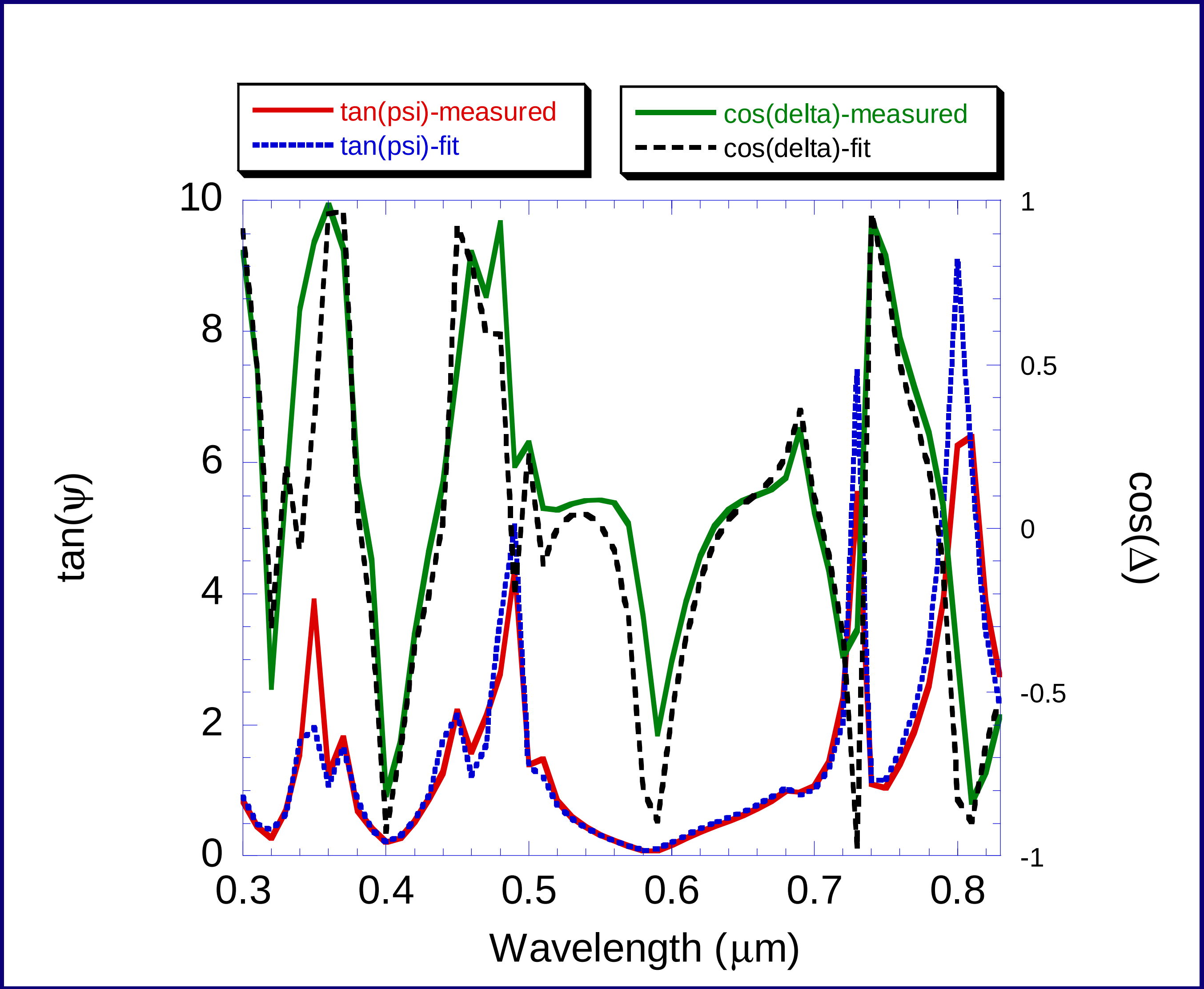
SE Data at 73º Angle of Incidence

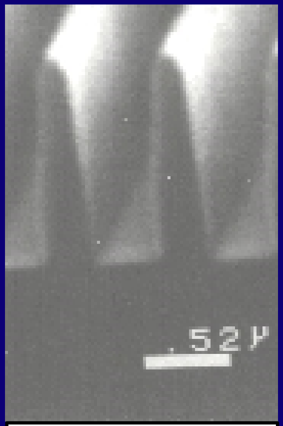
Sharp Reflection Resonances Change with Topography

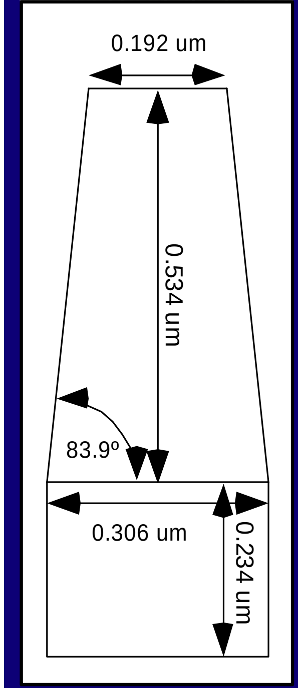




Approximate PR Topography







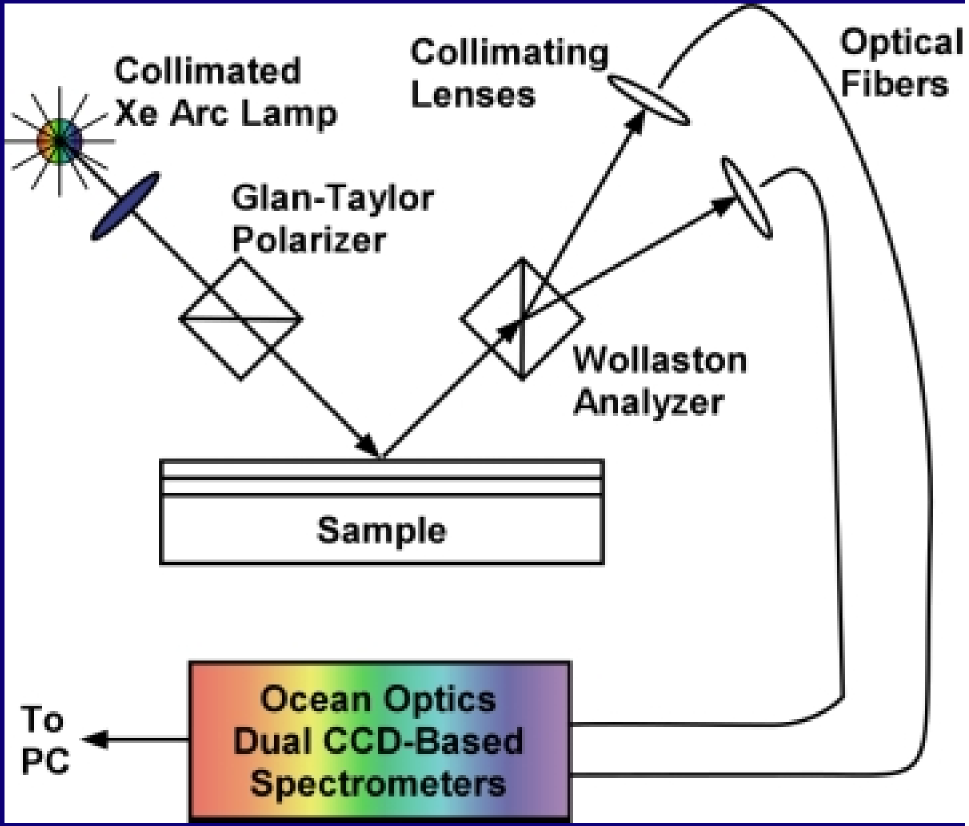
Key Points

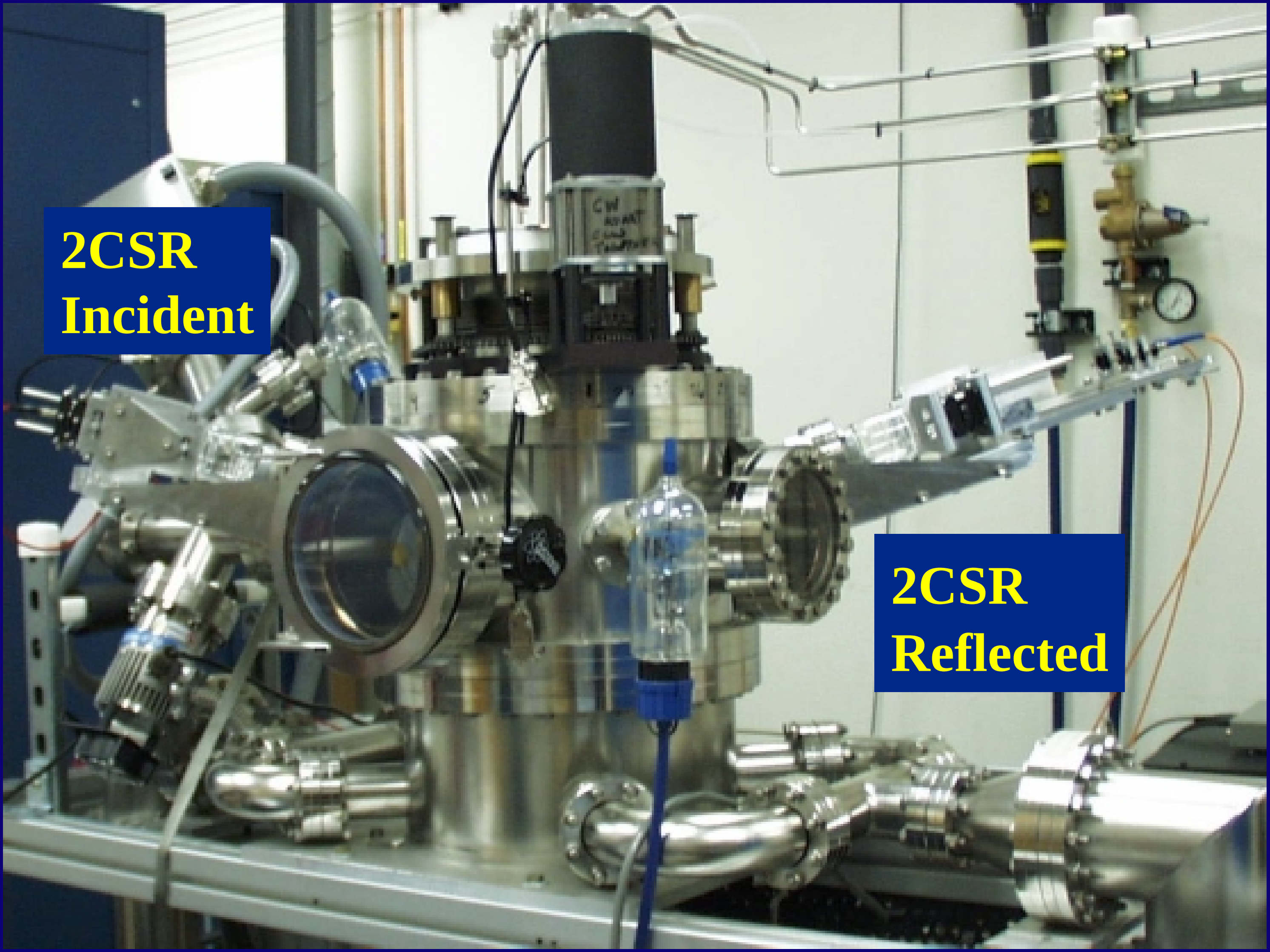
- Sharp Features in Spectroscopic Ellipsometry Data Are Very Sensitive to Detailed Shape of Lines in Grating
- These Sharp Features Are Known as Wood's Anomalies
  - R.W. Wood, Phys. Rev., p. 928 (1935) {further commenting on his observations from 1902-1912}
- Detailed Fitting Using Vector Diffraction Theory Can Yield Accurate Quantitative Information
- Some Important Questions:
  - Optimal Measurement Modes
  - Best Methods for Analysis (Inverse Problem) & Issues of Uniqueness

Alternative Measurement Tool for Production Applications: Two Channel Spectral Reflectometer

Two Channel Spectral Reflectometer

- Similar to Ellipsometer but Fixed Prisms (No Moving Parts)
- Measures $|R_s|^2$, $|R_p|^2 \Rightarrow \tan(\psi)$
- Key Is Availability of Adequate Low Cost, High Speed, Broad Wavelength Range Spectrometer
- 6ms Integration Time/20Hz Sampling Rate (Full Spectral) with Easy Upgrade to 3ms/40Hz
- Low Construction Cost (~$7K)
- Very Good Reproducibility and Near SE Level Accuracy Demonstrated



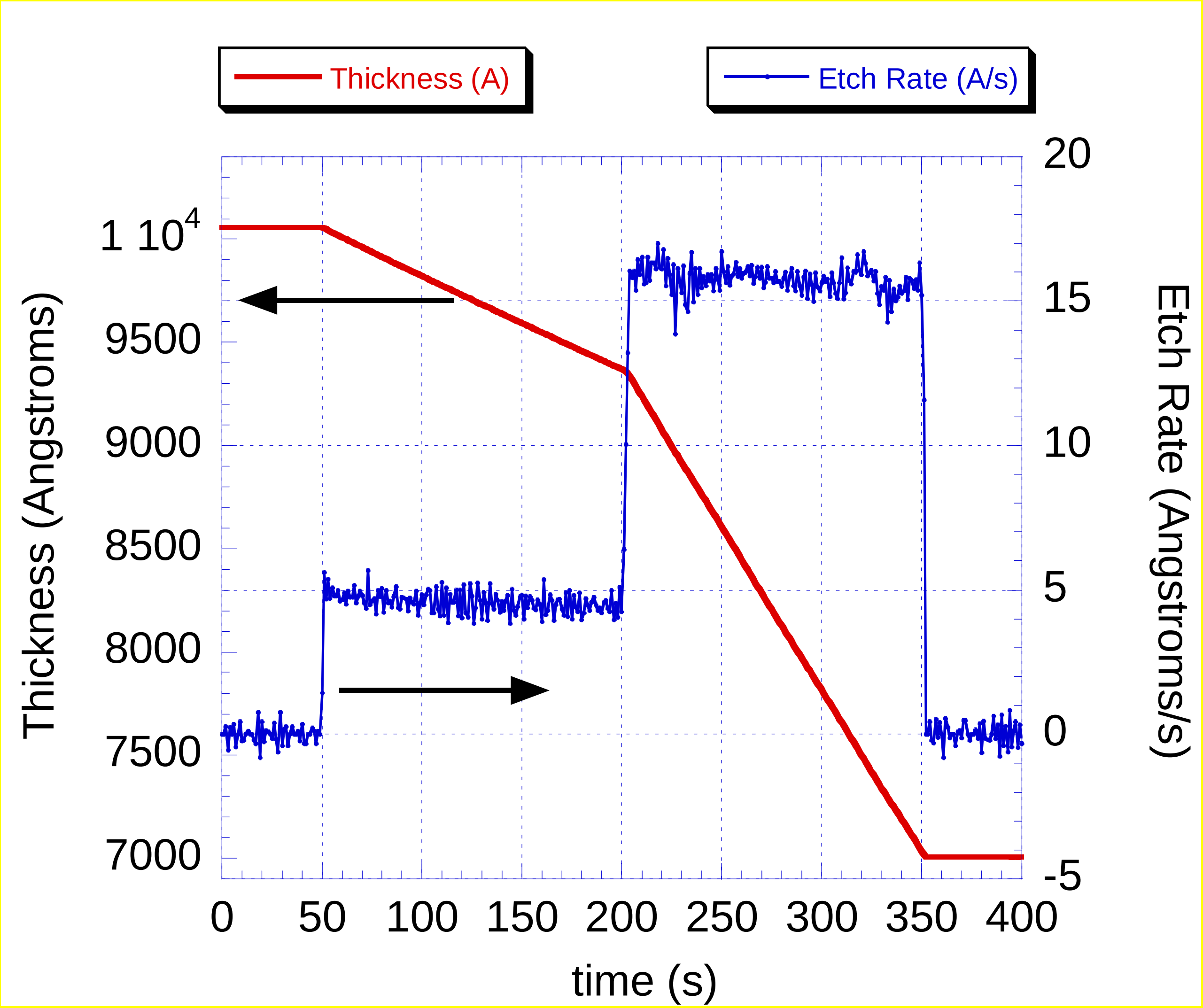


2CSR Incident

2CSR Reflected

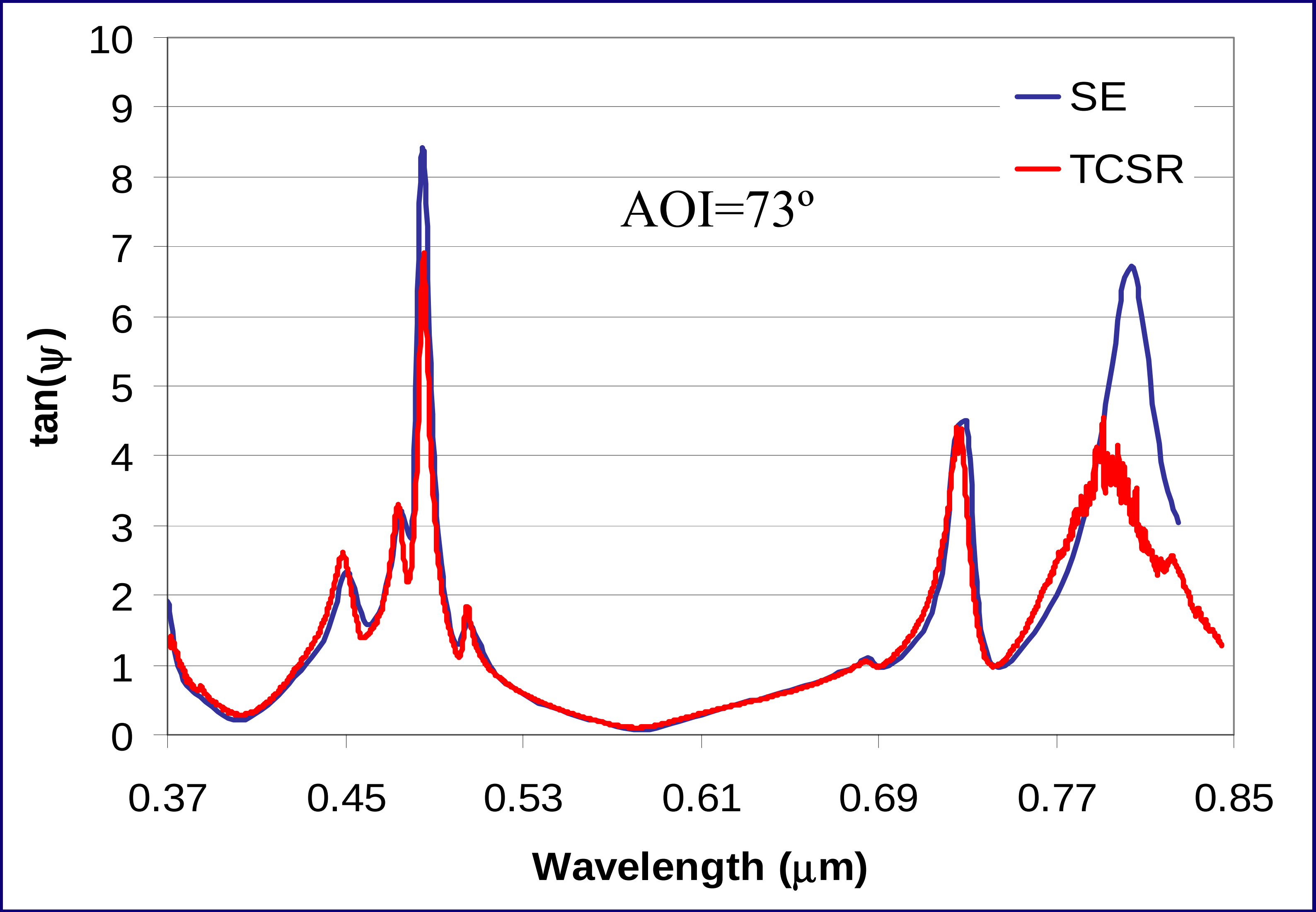
Real-Time Etch Monitoring: Blanket Film

- SiO_2 Etched in CF_4 at 50 & 100W
- Thickness from Fit to Both $|R_p|^2$&$|R_s|^2$
- 6ms Integration Time, 1s Sampling Time
- Thickness Repeatability σ_d=0.22Å
- Etch Rate Standard Deviation σ_e=0.37Å/s

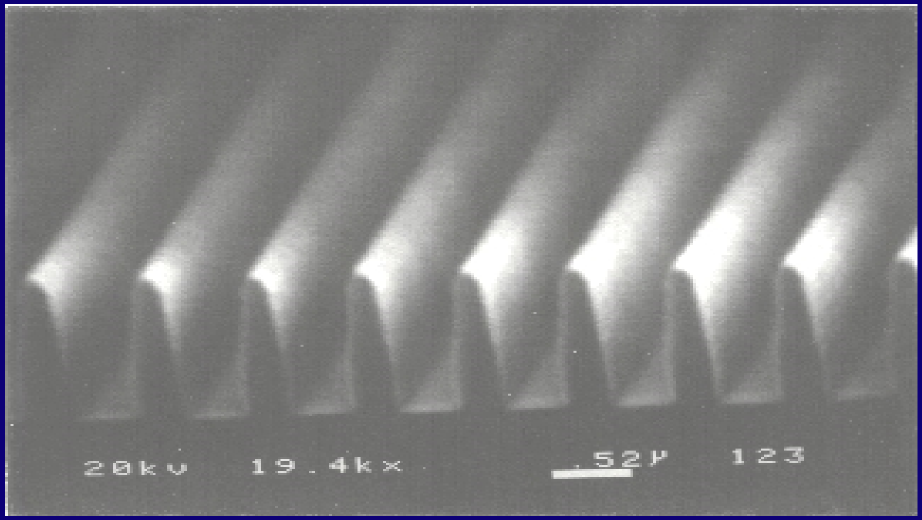


Fred L. Terry, Jr., WISE-2000 Thin Film Metrology Workshop May 9, 2000

Tan(ψ) Vs wavelength, SE and TCSR



In Situ Topography Evolution: The Motion Picture

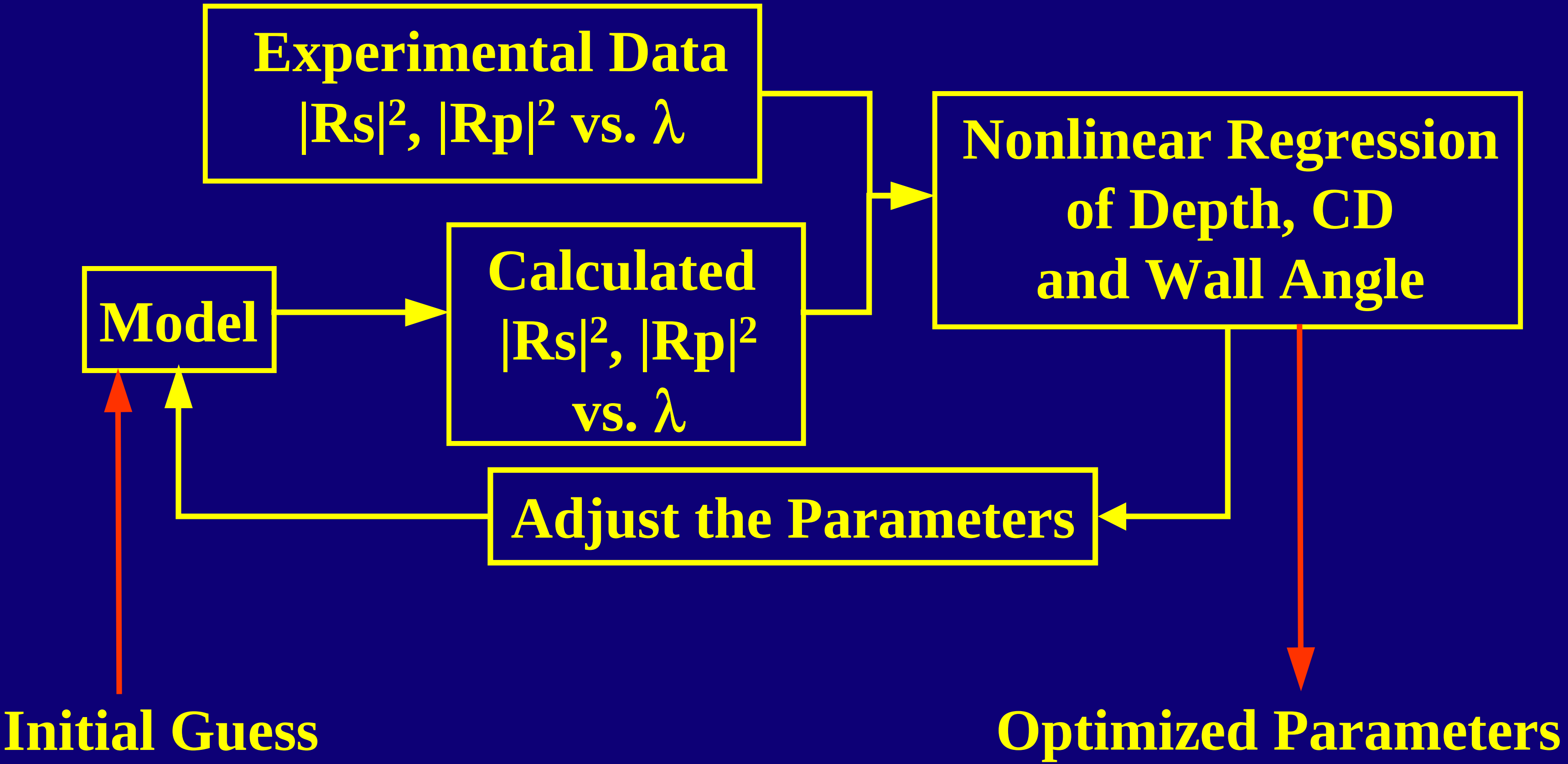


- **Grating with 0.35 μm line/space width**
- **Grating In Photoresist/ 317Å SiO_2Si**
- **Period Measured as 0.700 μm Using 1st Order Diffraction Angle at Multiple λ's**

Etch experiment

- Modified GEC Etching Chamber
- 100 mTorr, 100 sccm O_2,15 W 13.56 MHz RF
- Blanket PR Etch Rate ~0.5 nm/s
- Simple Test Case / Photoresist Trim Process Used to Reduce Gate CD Below Photo Limitations

Data Analysis



Experimental Data
$|Rs|^2$, $|Rp|^2$ vs. λ

Nonlinear Regression of Depth, CD and Wall Angle

Model

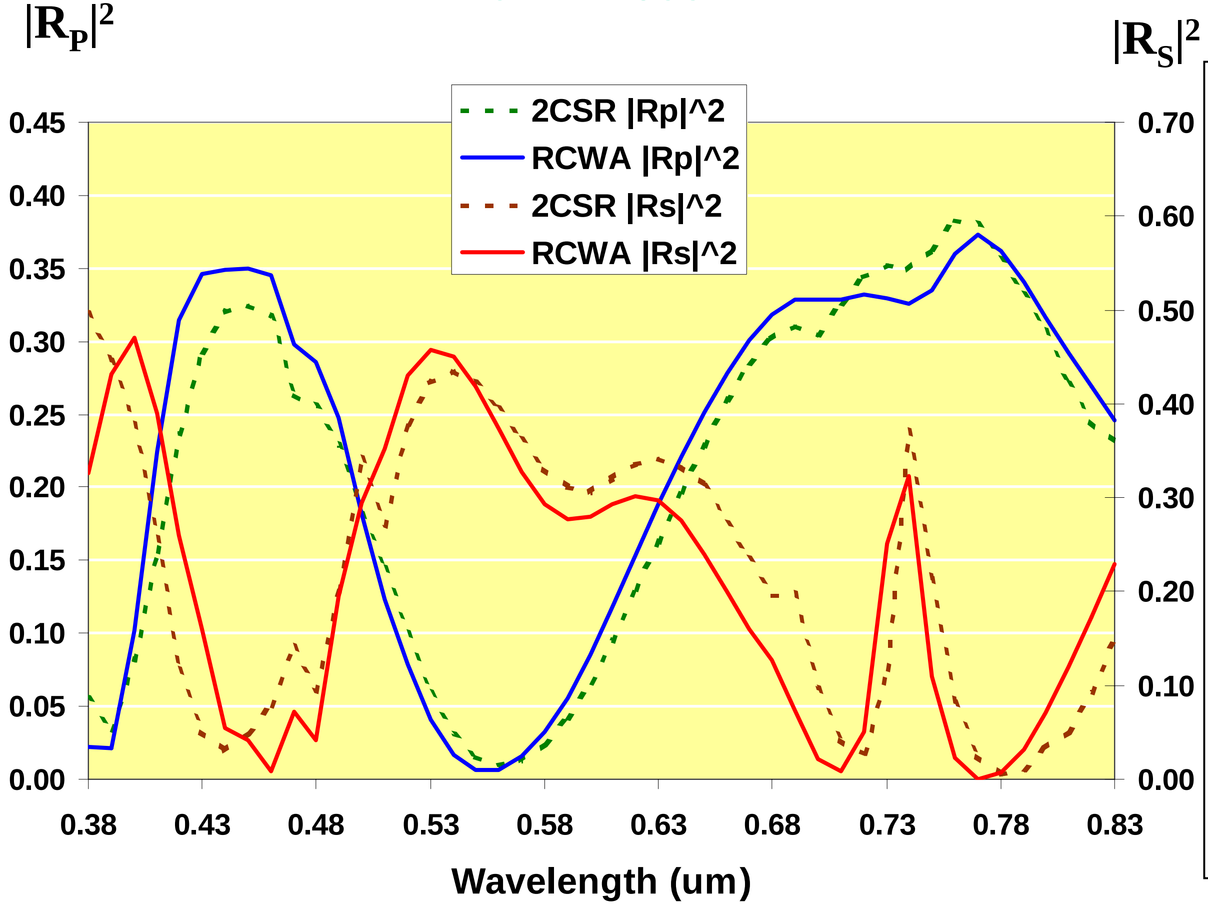
Calculated
$|Rs|^2$, $|Rp|^2$ vs. λ

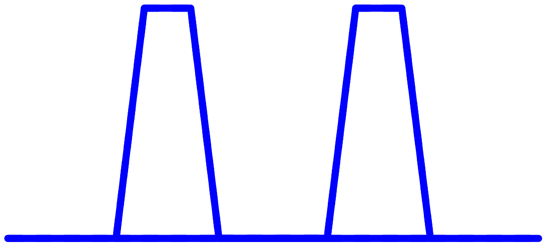
Adjust the Parameters

Initial Guess

Optimized Parameters

Time = 7 sec





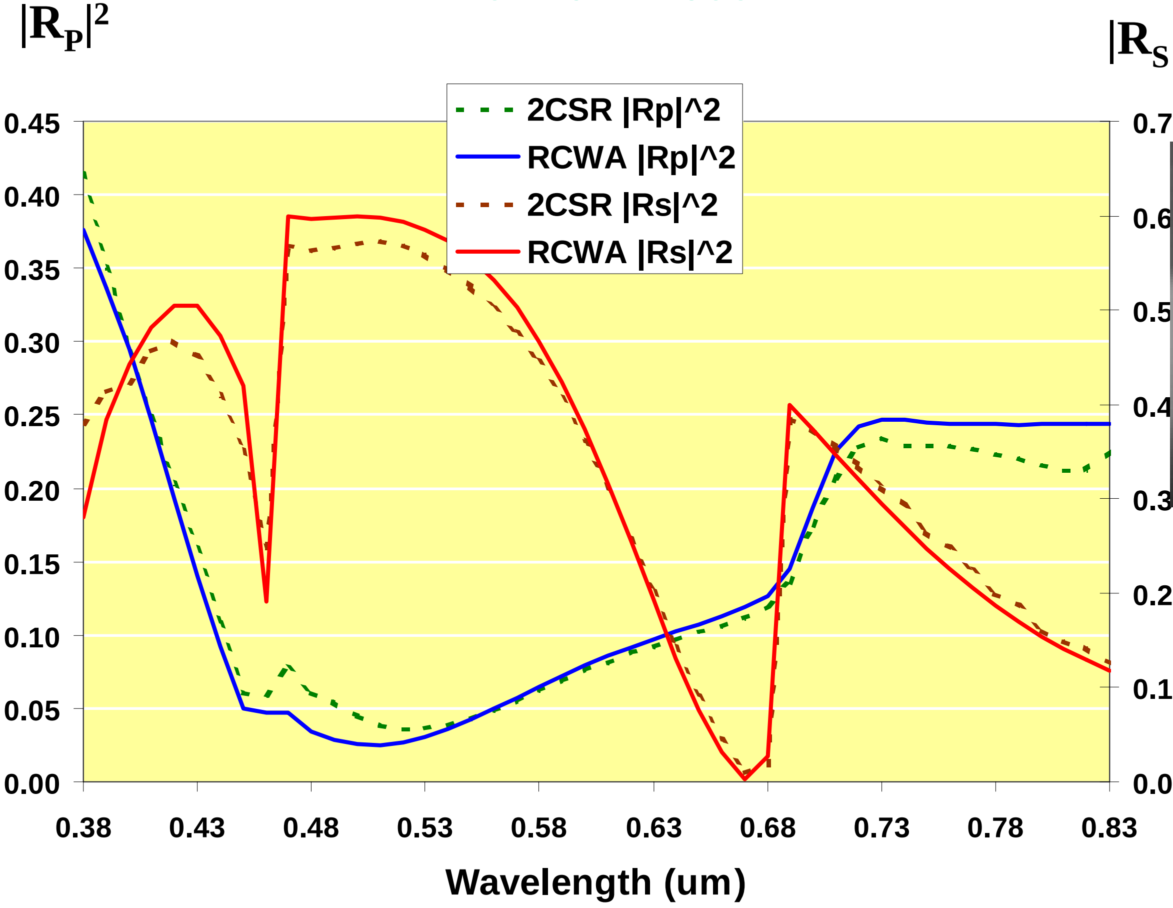
Height: 0.757 µm

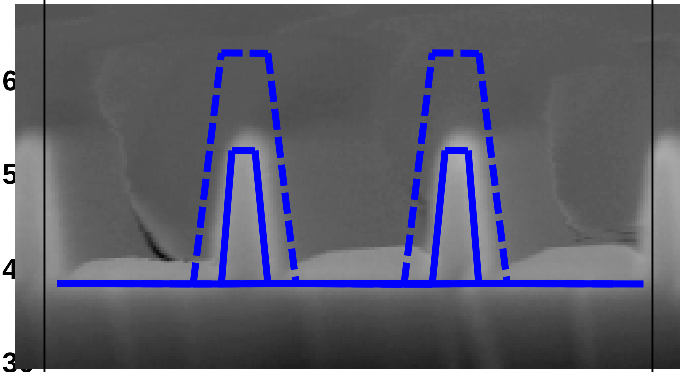
TopWidth: 0.154 µm

Bottom: 0.343 µm

WallAngle: 82.9º

Time = 617 sec

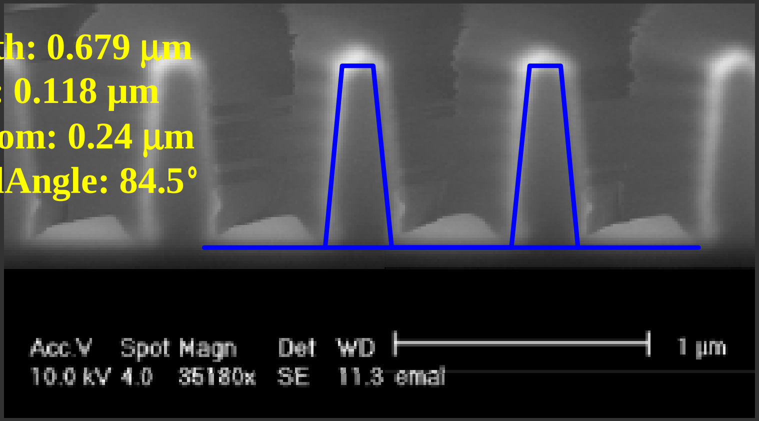




Height: 0.436 μm
TopWidth: 0.076 μm
Bottom: 0.154 μm
WallAngle: 84.9º

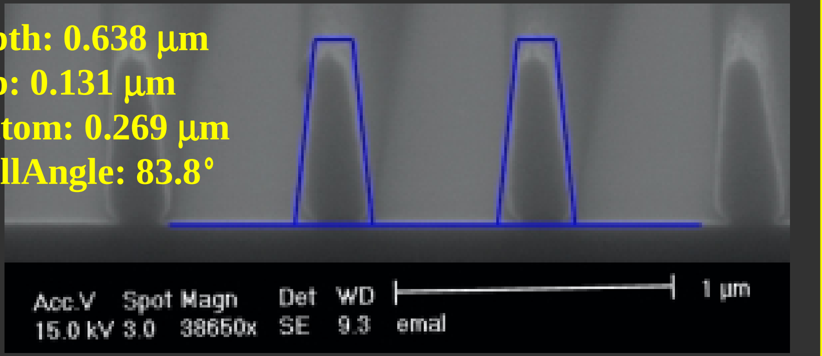
RCWA Result vs. SEM Photo

Etch Time: 120 sec



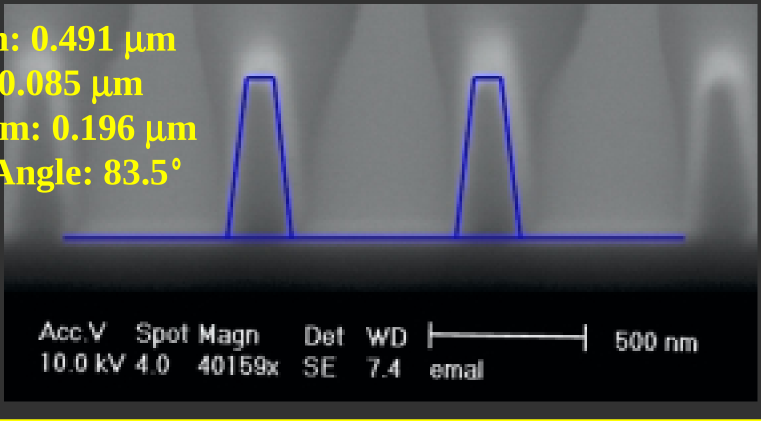
Depth: 0.679 µm
Top: 0.118 µm
Bottom: 0.24 µm
WallAngle: 84.5°

Etch Time: 240 sec



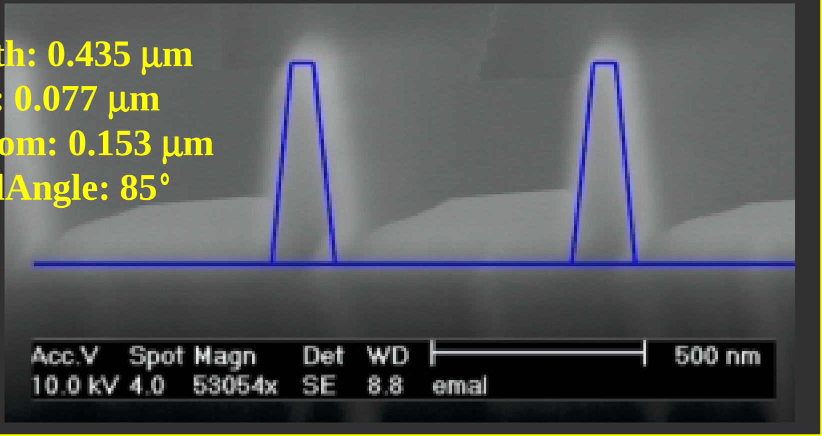
Depth: 0.638 µm
Top: 0.131 µm
Bottom: 0.269 µm
WallAngle: 83.8°

Etch Time: 450 sec



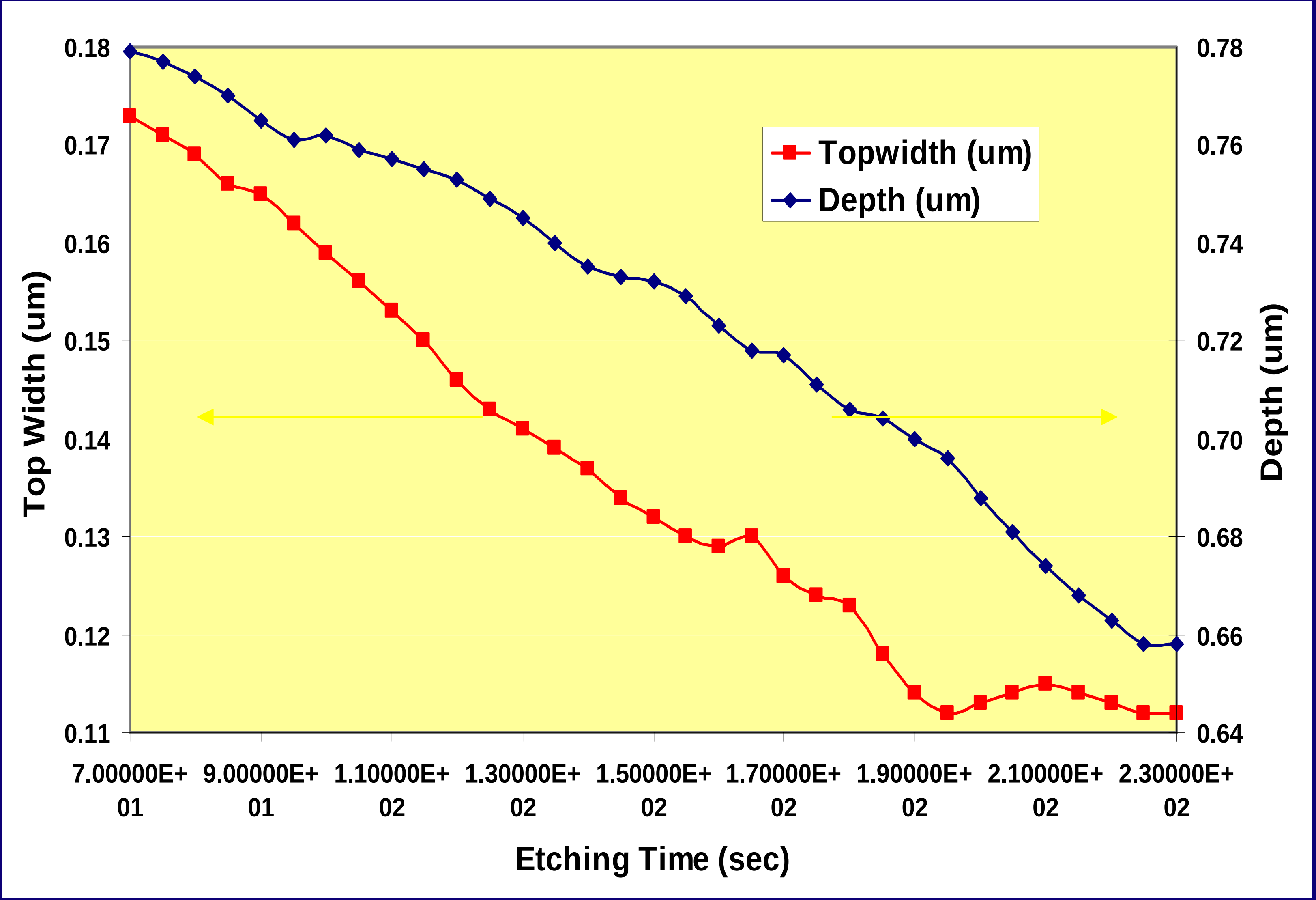
Depth: 0.491 µm
Top: 0.085 µm
Bottom: 0.196 µm
WallAngle: 83.5°

Etch Time: 600 sec



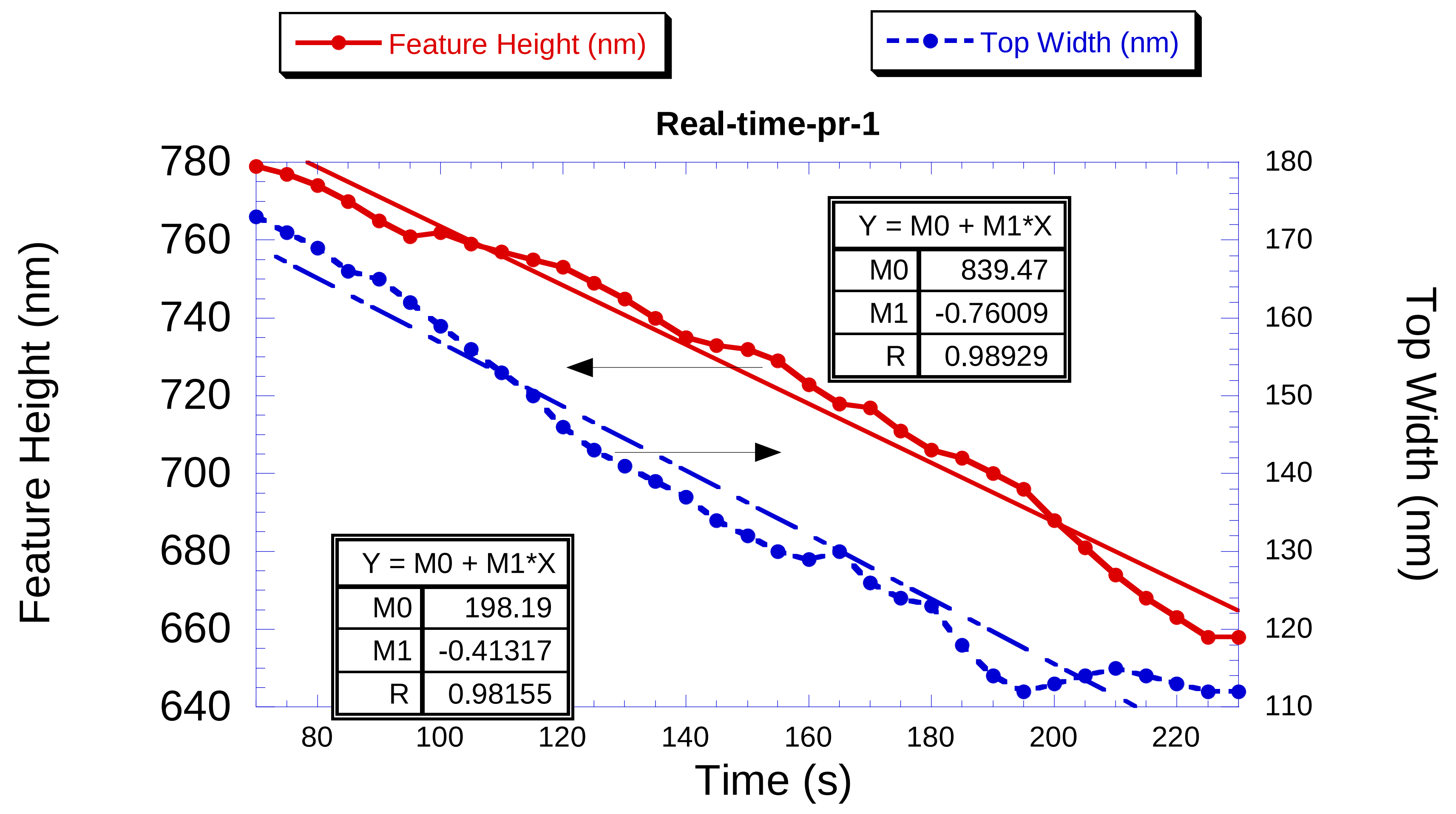
Depth: 0.435 µm
Top: 0.077 µm
Bottom: 0.153 µm
WallAngle: 85°

Grating Profile Evolution vs. Etching time



Fred L. Terry, Jr., WISE-2000 Thin Film Metrology Workshop May 9, 2000

Grating Profile Evolution vs. Etching time



Y = M0 + M1*X	
M0	839.47
M1	-0.76009
R	0.98929

Y = M0 + M1*X	
M0	198.19
M1	-0.41317
R	0.98155

Fred L. Terry, Jr., WISE-2000 Thin Film Metrology Workshop May 9, 2000

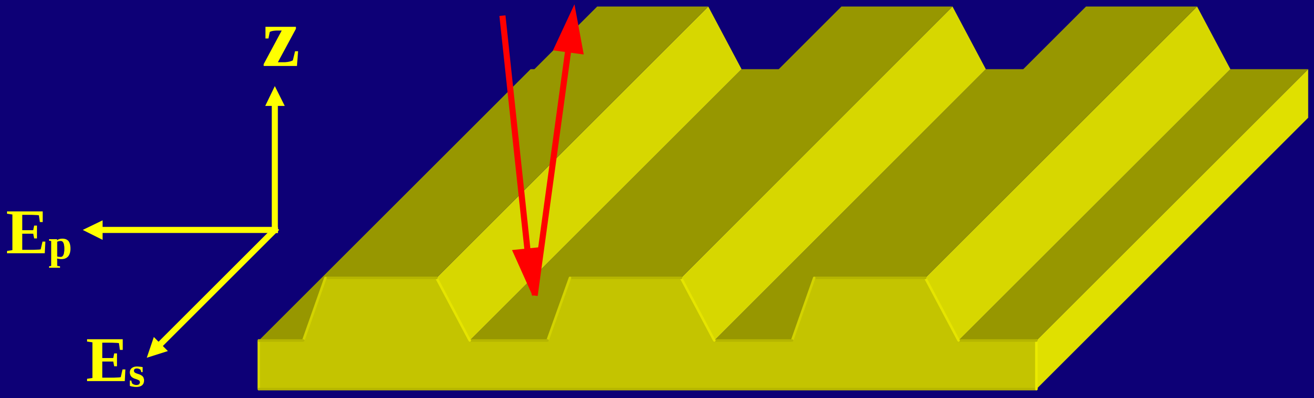
Real-Time In Situ CD Monitoring/Control Status

- Kernel Based Learning Algorithm Interpolation Scheme Fully Automated on Modified GEC Reactor
- 1st Demonstration of Fully Automated Endpoint-On-Target-CD Accomplished on 2/4/00 in GEC Reactor with ms Level Execution Speeds
- Further Tests Found that the KBL Approach is too Sensitive to Noise and Systematic Experimental Error
- New Algorithm Developed and Tested Using a Nonlinear Convex Hull Estimation Technique
  - Initial Testing is Highly Successful
  - Speed Optimization Underway
  - Further Tests and Theoretical Analysis is Underway
- Joint Effort with Ji-Woong Lee and Prof. Pramod Khargonekar

Near-Normal Incidence Spectroscopic Ellipsometry/Reflectance Difference Spectroscopy

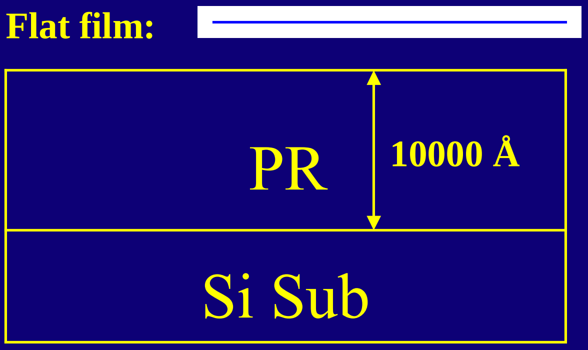
Advantages of Near-Normal SE/RDS vs. Conventional Oblique Angle SE

- **Maximizes Sensitivity to the Pattern**
  - **$\Delta R = (R_p - R_s) = 0$ at Normal Incidence on Unpatterned Wafers**
- **Maximizes the Illumination of Sidewalls**
- **Reflectance Difference Spectroscopy (RDS)**
  - **Established III-V Epi Growth Monitor / Detects Oriented Surface Molecular Bonds (Dimmers)**
  - **Detection Limit of $\Delta R/R \approx 5 \cdot 10^{-5}$**

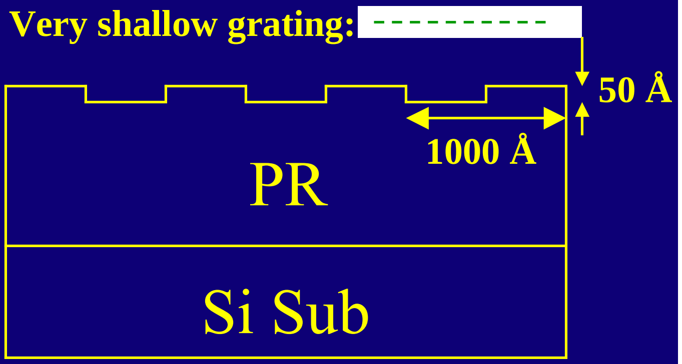


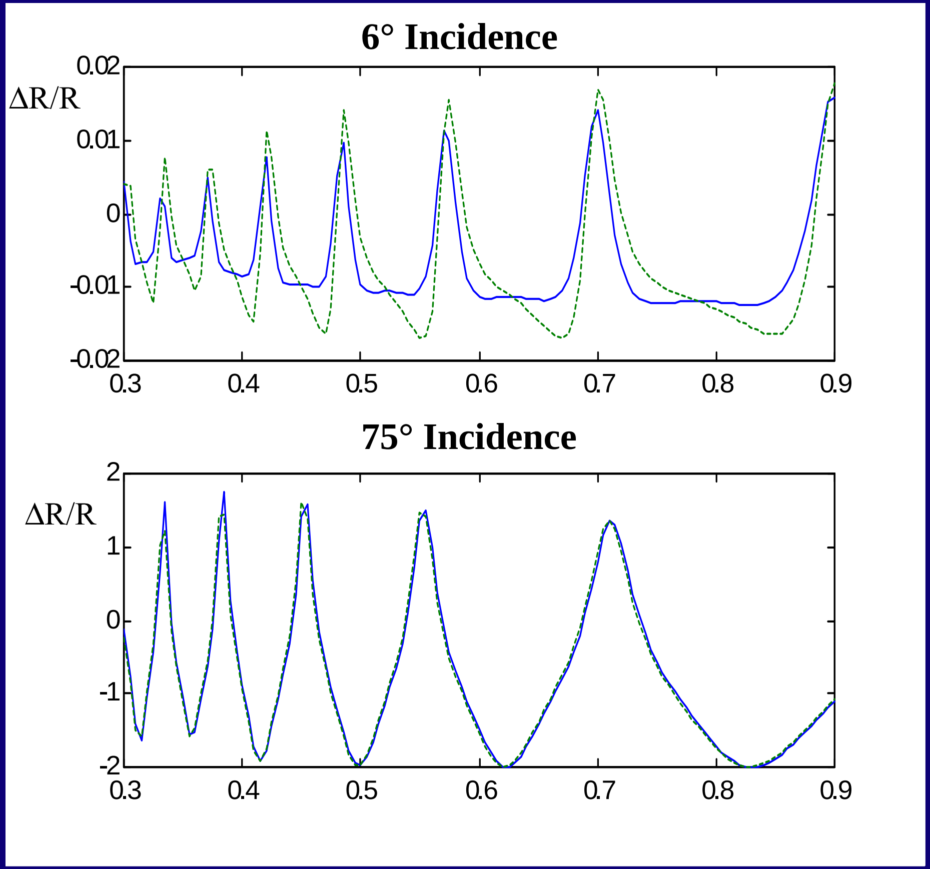
Simulation Study: Normal vs. Oblique Incidence for Slightly Modulated PR Gratings

Flat film: —

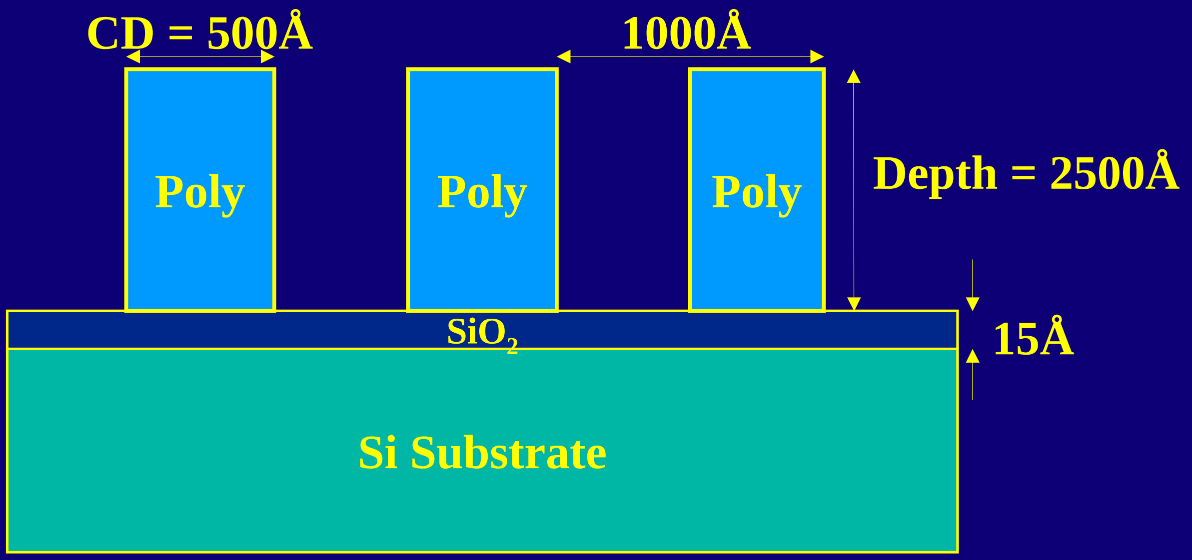


Very shallow grating: - - - - - -





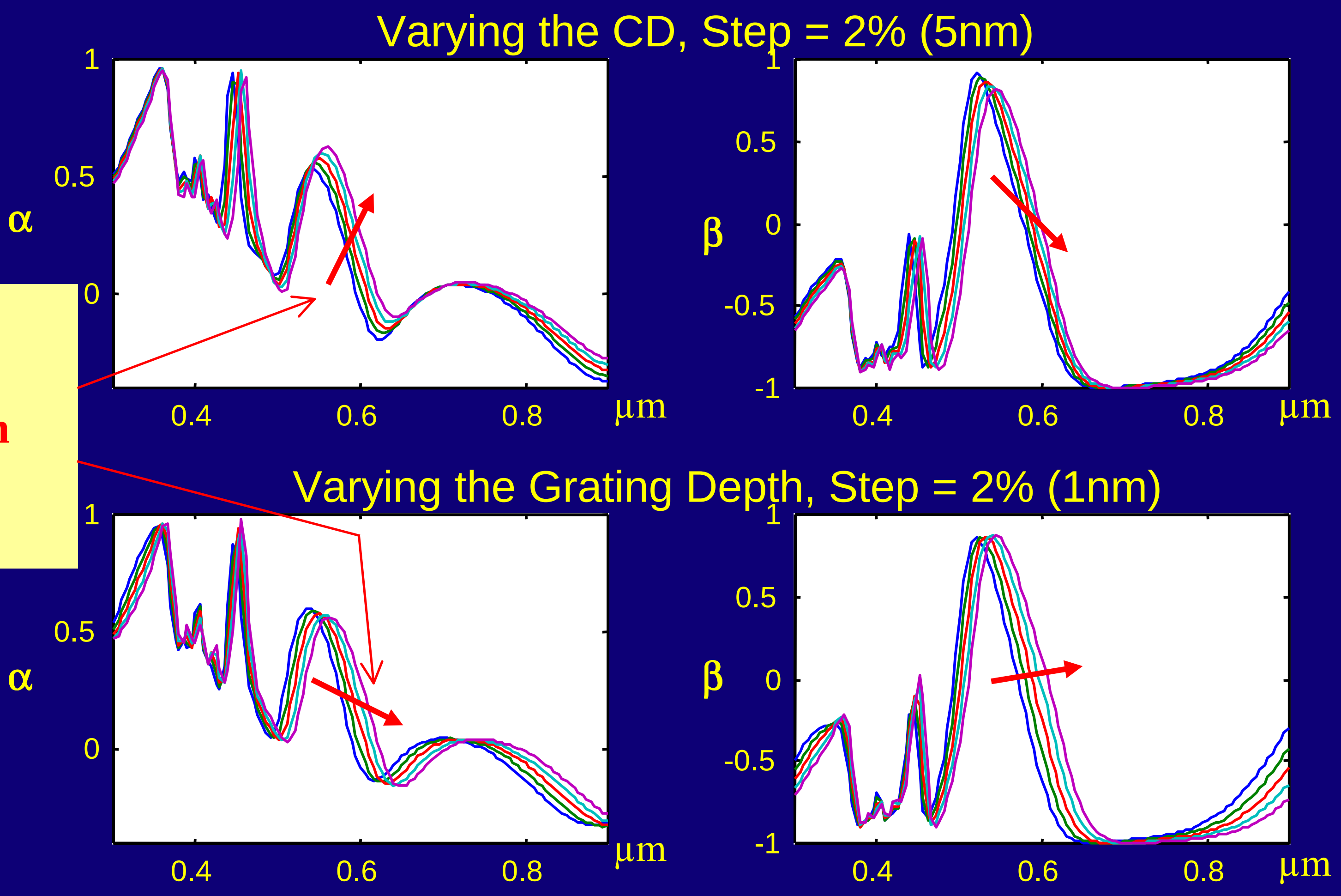
Simulation Study:
Sub-µm Semiconductor Gate Profile



- **Target: To extract CD & depth separately from SE measurement.**
- **$\alpha = \cos(2\Psi)$, $[\alpha = -(\Delta R/R)/2]$**

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

SE Simulation at Near Normal Incidence (CD vs. Depth)



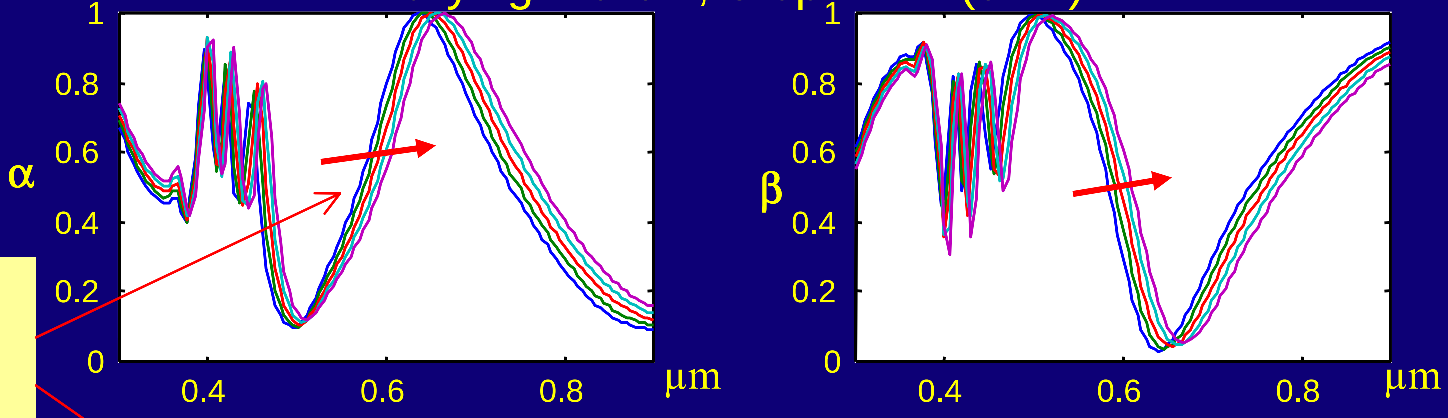
Varying the CD, Step = 2% (5nm)

Varying the Grating Depth, Step = 2% (1nm)

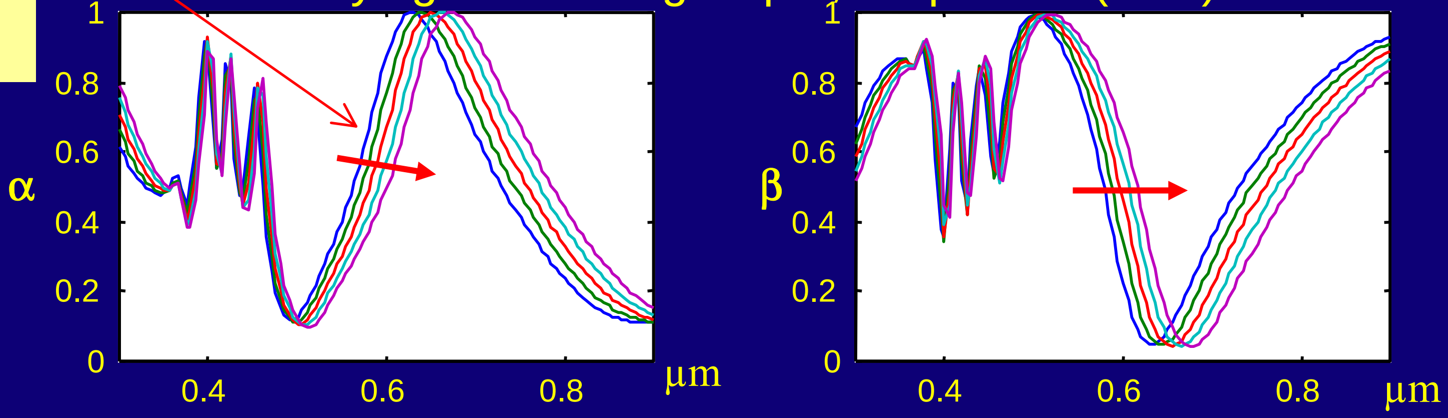
Nearly Orthogonal CD & Depth Variation Separated

SE Simulation at Off-Normal 75° Incidence (CD vs. Depth)

Varying the CD, Step = 2% (5nm)



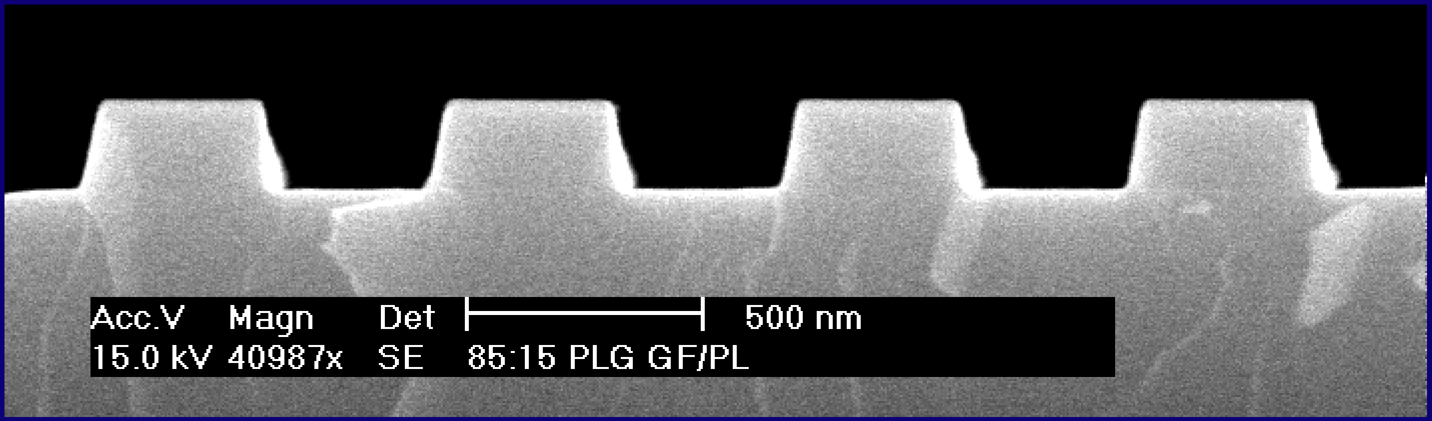
Varying the Grating Depth, Step = 2% (1nm)



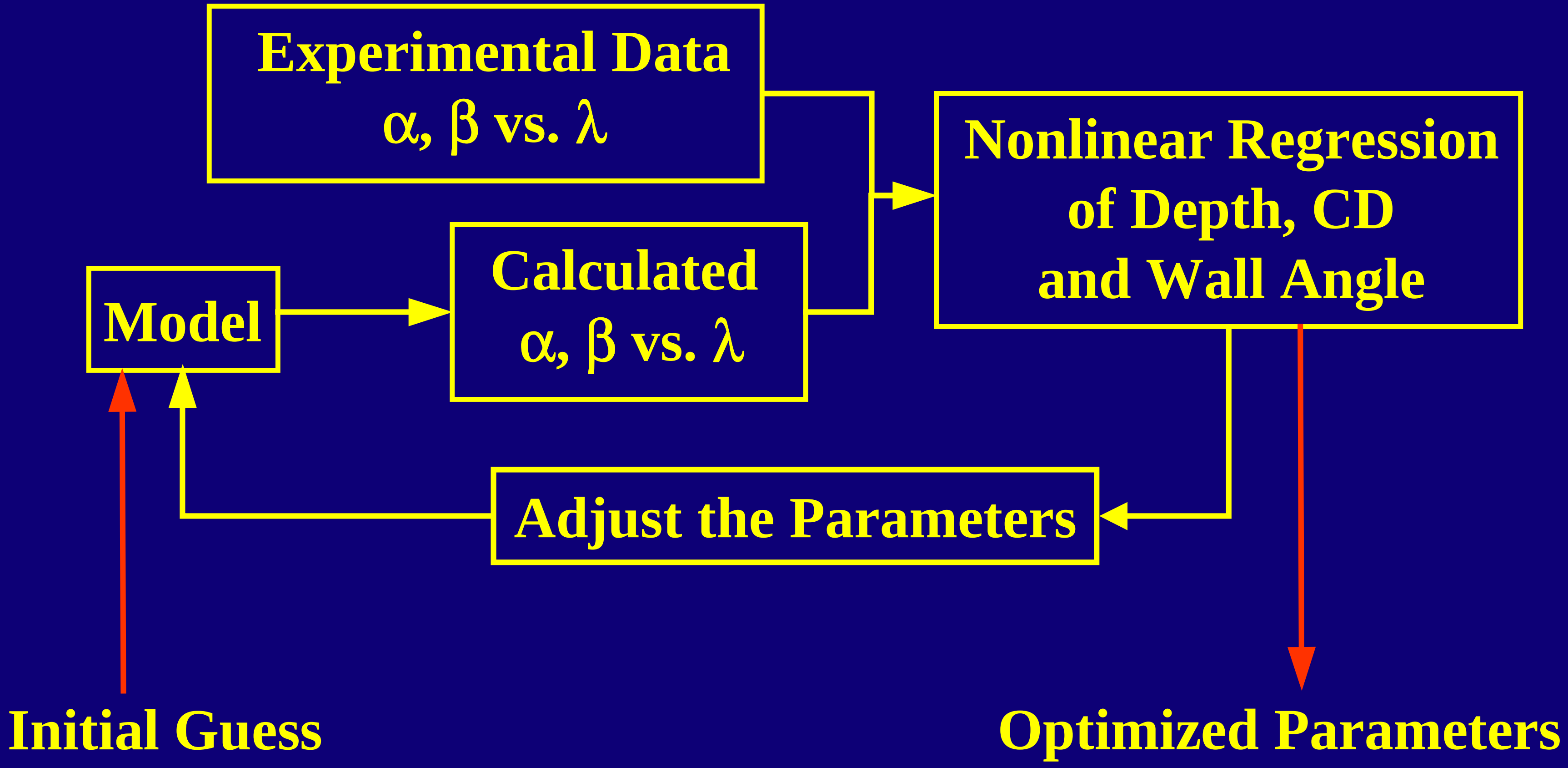
Nearly Parallel CD & Depth Strongly Correlated

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**



Data Analysis



Experimental Data
α, β vs. λ

Model

Calculated
α, β vs. λ

Nonlinear Regression
of Depth, CD
and Wall Angle

Adjust the Parameters

Initial Guess

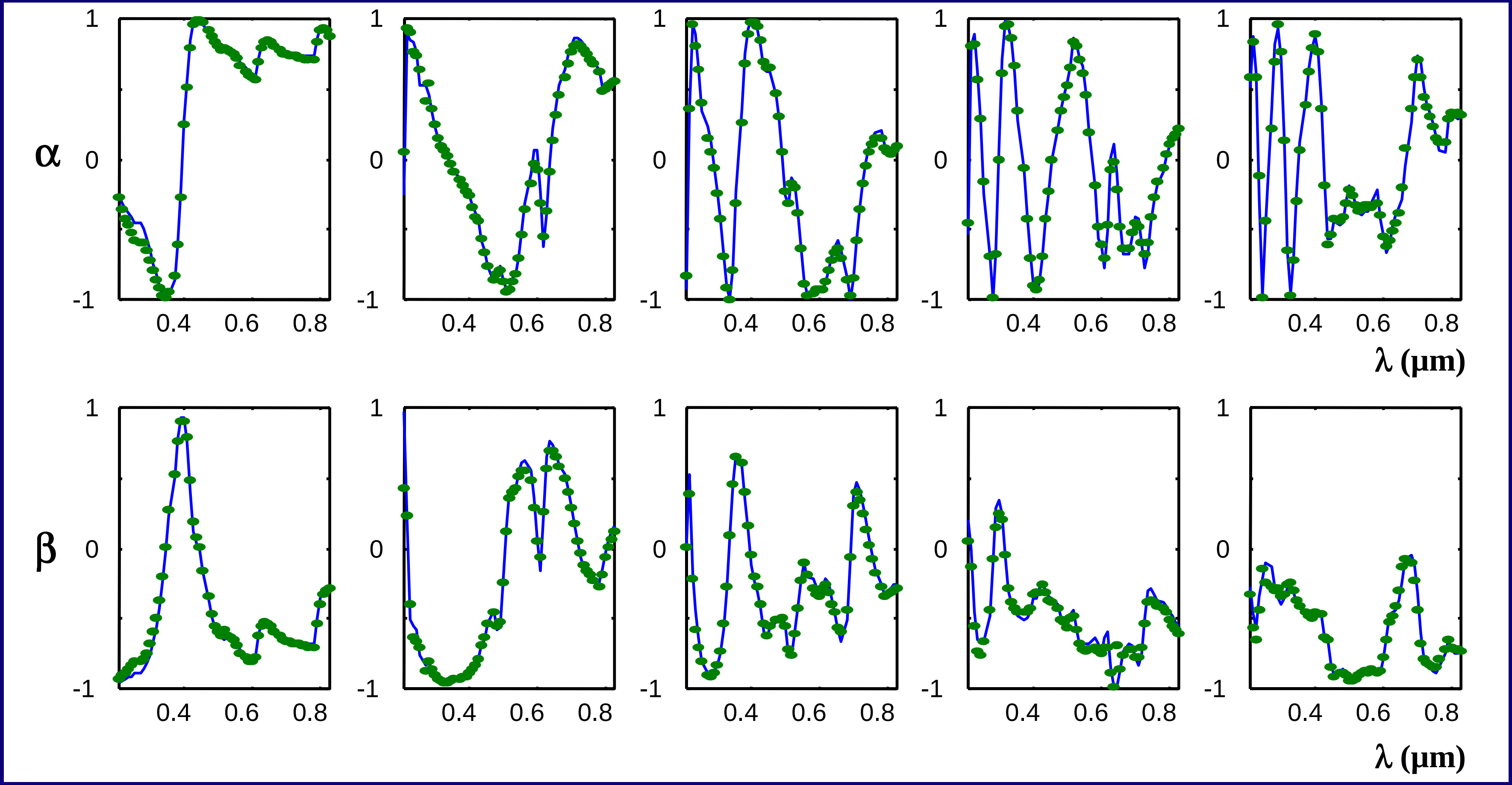
Optimized Parameters

Time Evolved SE Data and Fitting

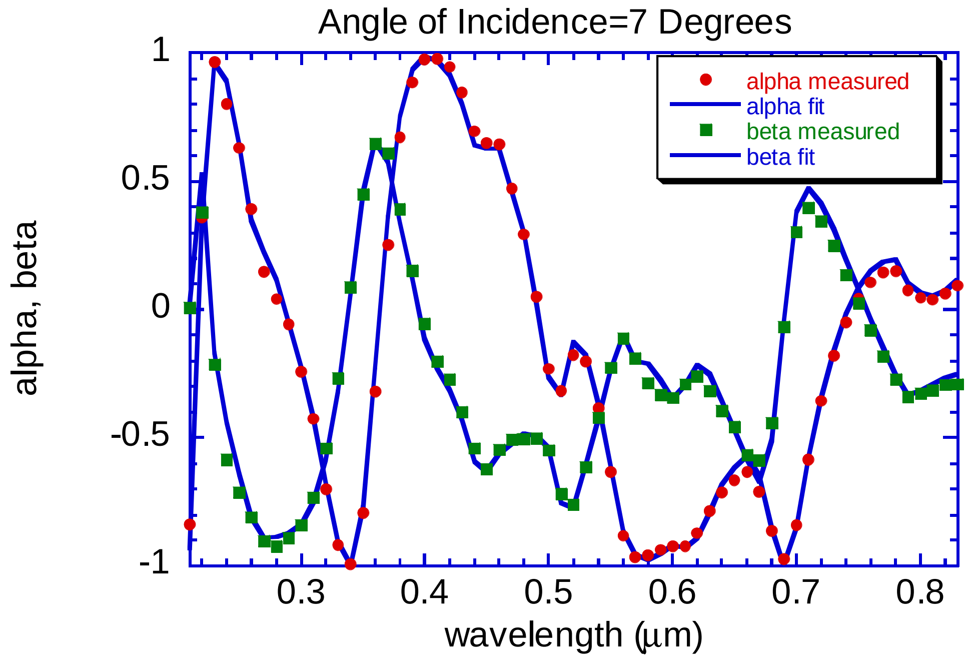
Incidence at 7°

● : Experiment
— : Theory

Etching Time



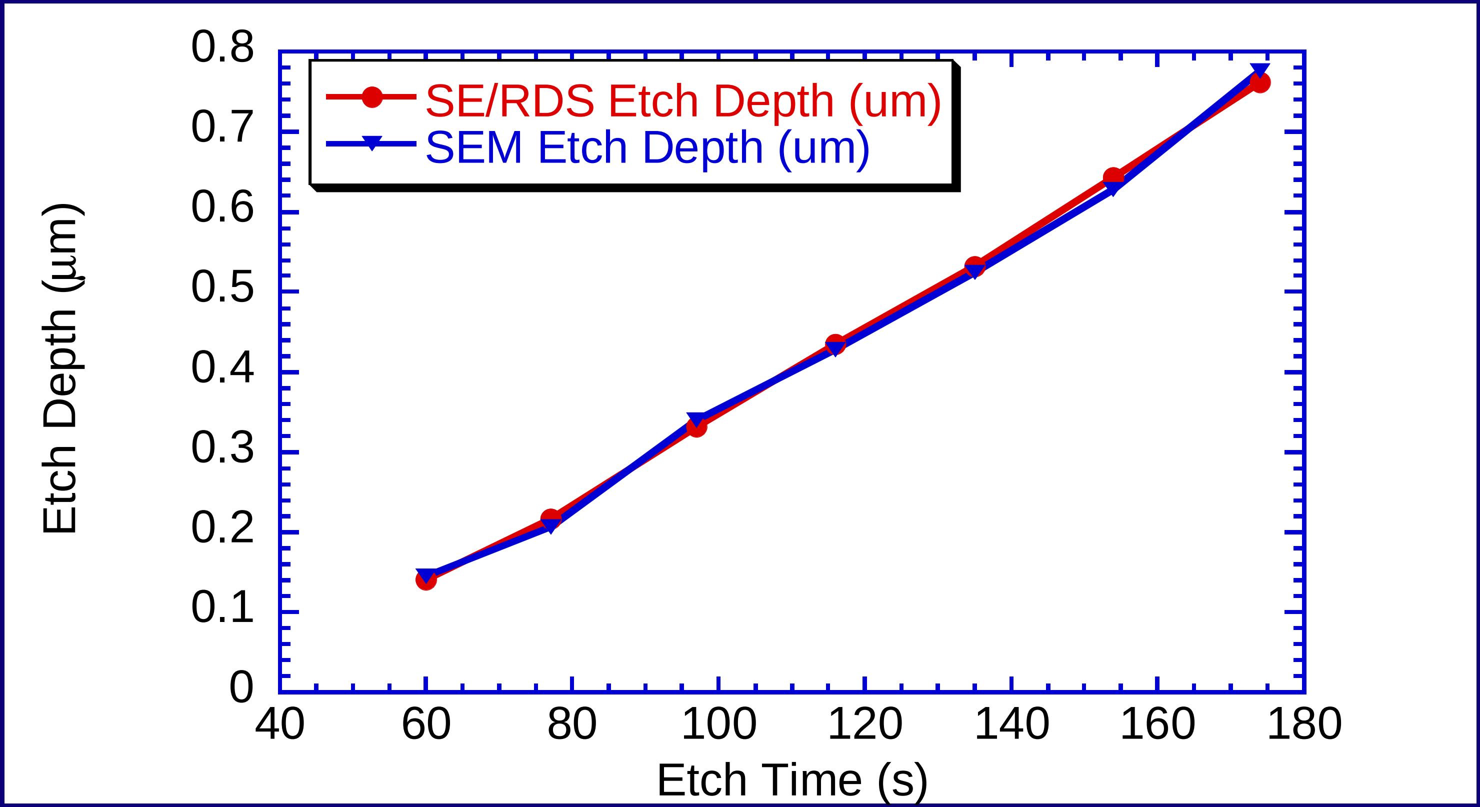
Near Normal SE for RIE Etched Si Grating



	SE & RCWA	SEM
CD (µm)	0.323 ±0.0016	0.323 ±0.005
Depth (µm)	0.331 ±0.0004	0.340 ±0.005
Wall Angle	83.2° ±0.29°	84.1° ±1.4°

Fred L. Terry, Jr., WISE-2000 Thin Film Metrology Workshop May 9, 2000

Time-Evolved Data



- The depths extracted from the SE measurement are in very good agreement with those measured from SEM.
- The time evolved data shows strong potential for *In Situ* etch monitoring.

Conclusions

- Single Angle of Incidence Spectroscopic Ellipsometry is Highly Sensitive to CDs in Deep Sub-µm Regime
- Operation in Near-Normal (RDS) Mode Improves the Ability to Separately Extract Topography Parameters (Depth, CD, and Wall Angle)
- Experimentally Demonstrated Capability on 0.35µm Line/Space Structures
- Simulations Show Potential to Resolve CDs of 50nm and Below
- Easy to Implement with Existing Commercial SEs
- Alternative Implementation with Two-Channel Spectral Reflectometer

Future Work

- Improving Ease & Speed of Analysis
- Understanding Error Limits
  - Errors Induced By Parameterization of Shapes
  - Variations in Lines
  - Uniqueness Issues
- Overlap of Grating/Non-Grating Patterns – NIST ULSI Metrology Conference (Kong, Huang, Terry)
- Demonstration in Process Control Applications
  - Real Time RIE Endpoint Control – Etch to Target CD
- Use with RTSE on Lam 9400
- Near Normal 2CSR on Lam 9400
- Experimental Demonstrations on Smaller Structures
- More Complex Test Patterns

Acknowledgements

- Funding from
  - – DARPA/AFOSR MURI Center for Intelligent Electronics Manufacturing (AFOSR GRANT NO. F49620-95-1-052)
  - – Semiconductor Research Corporation (Contract 97-FC085) {project ended}
  - – NIST-ATP: Intelligent Control of the Semiconductor Patterning Process
- Valuable Technical Assistance
  - – Jeff Fournier
  - – Pete Klimecky
  - – Dennis Schwieger