Background

- *In Situ* Process Control Is Critical for the Future Factory.
- Wafer State Monitors (CD, Film Thickness and Profile) Are Important for the Advanced Semiconductor Process Control.
- Physical Metrology Is Challenged by the Shrinking Device Dimensions.

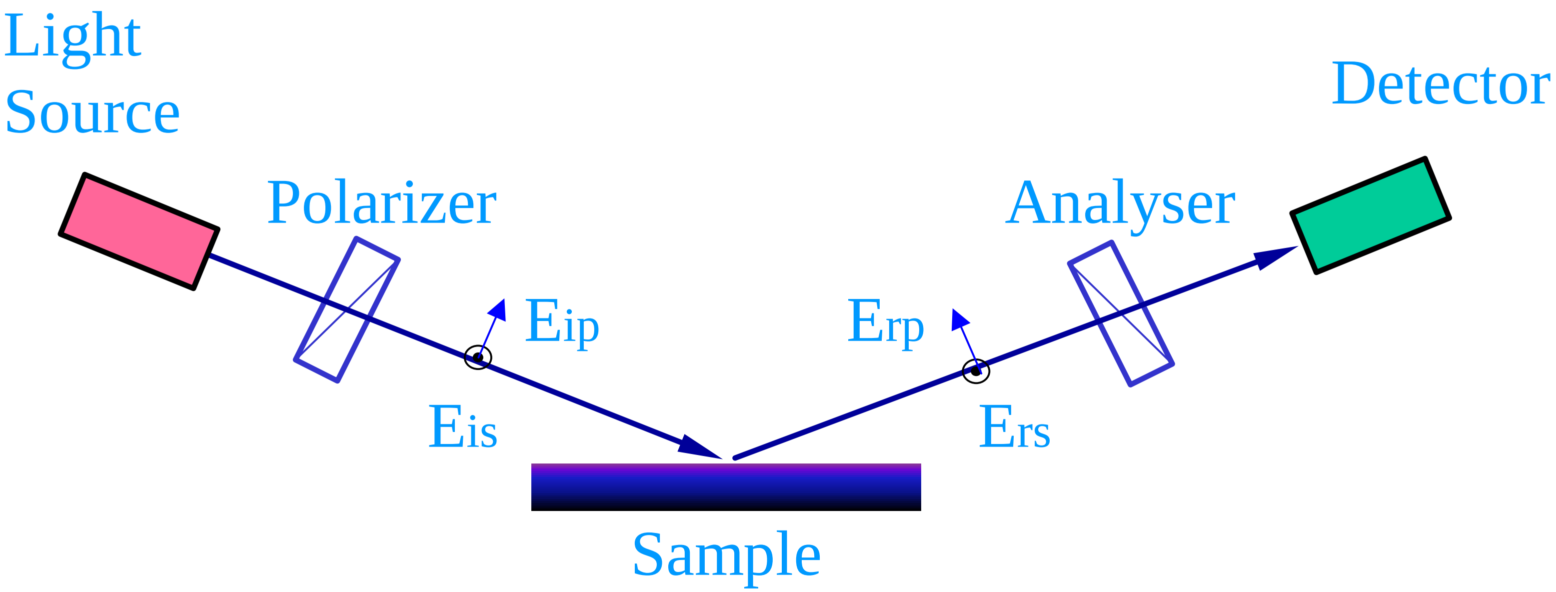
Overview

- **Specularly** Reflected Light Measurements (Ellipsometry, Reflectometry) Have Proven Accuracy in Monitoring **Blanket** Thin Film Thicknesses.
  - Limited applications to **patterned** wafers
- **Non-specular** Scattering (Diffraction) Measurements Can Yield Detailed Topography Information From Patterned Wafers.
  - Scatterometry , Fourier Imaging
  - Both require multiple-angle view of wafer (hard to implement for *in situ* monitoring)

Goals of Research

- Quantitative Analysis of Ellipsometry Data From Patterned Wafers → Extract Pattern Topography Information (Especially Depth)
  - Process control using product wafers
    - Reduction/elimination of test wafers
    - Reduced offline metrology
  - Increased knowledge of processes at real time level

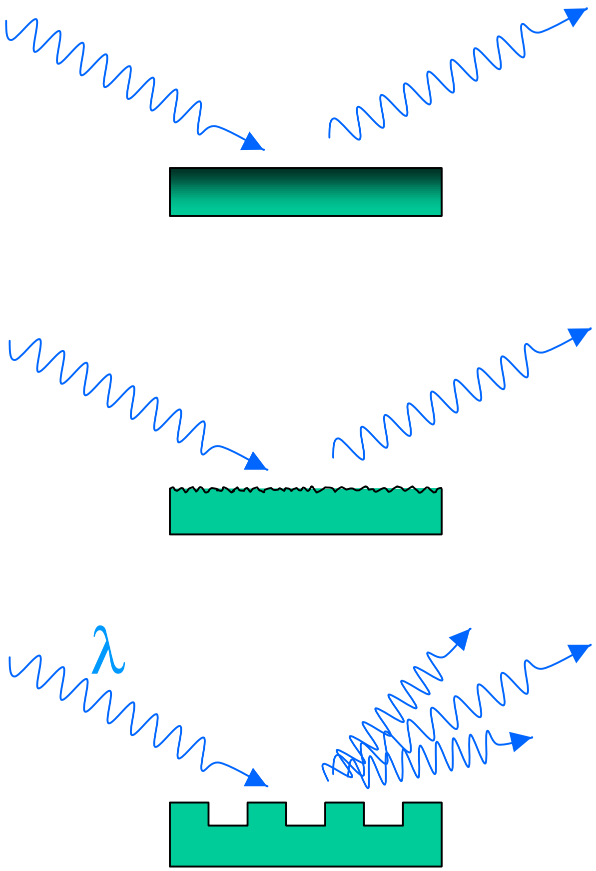
Ellipsometry



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

- Tan(Ψ) and Cos(Δ) are Measured by Ellipsometer.
  —Functions of λ

Scope of SE Applications



✓ Smooth Surface (d ~ 0)

- Thin film characterization

  d: feature size of uneveness

✓ Rough Surface (d << λ)

- Surface/interface characterization

? Patterned Surface (d ~ λ)

- Pattern profile characterization

  This Work

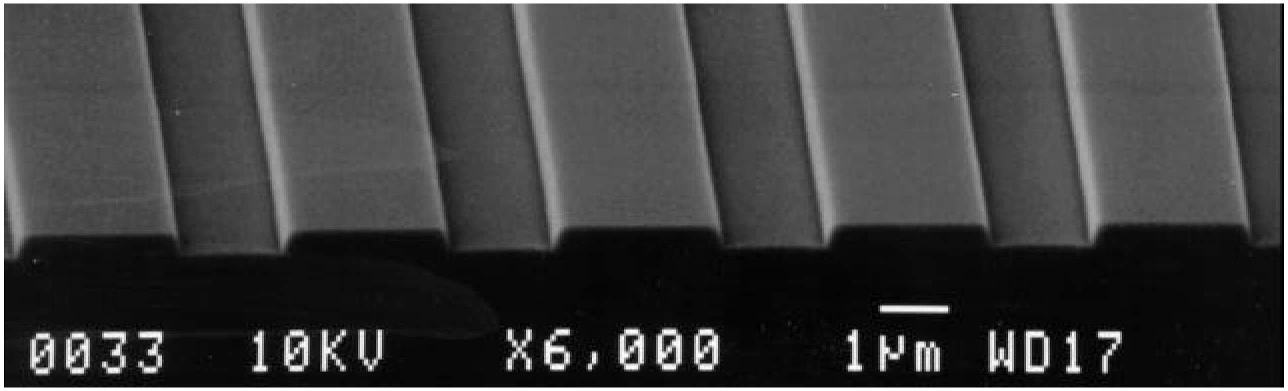
Models For This Work

- Three Approaches for Modeling Specular Reflection From Patterned Structures
  - Scalar approach of Heimann
  - Surface integral equation (SIE)
  - Rigorous coupled-wave analysis (RCWA)

Solving Maxwell's Equ Boundary Value Problem

Increasing Accuracy and Computation Time

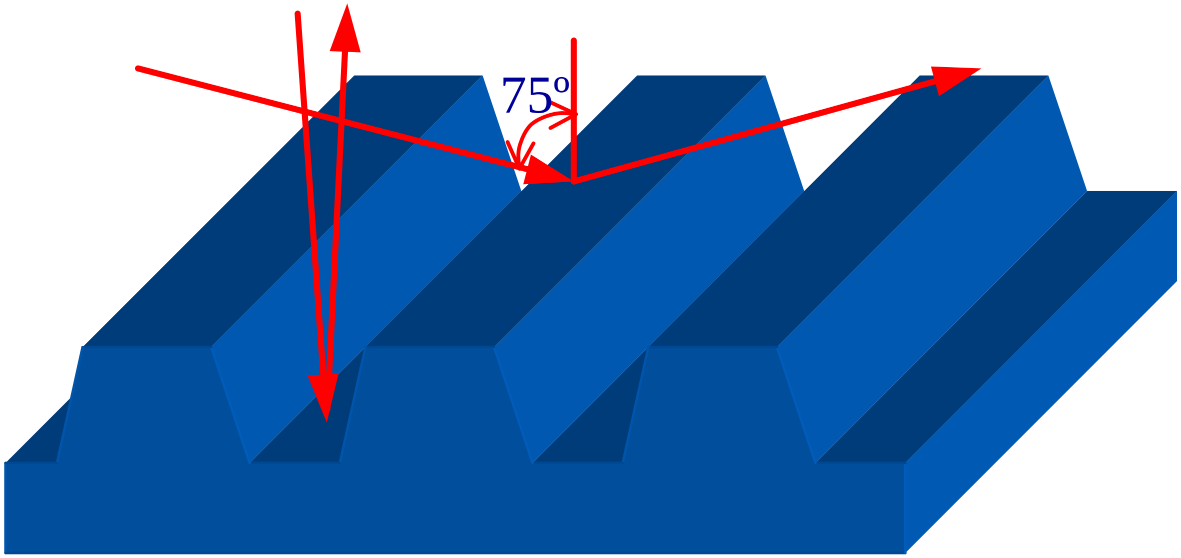
Sample: Si Relief Grating



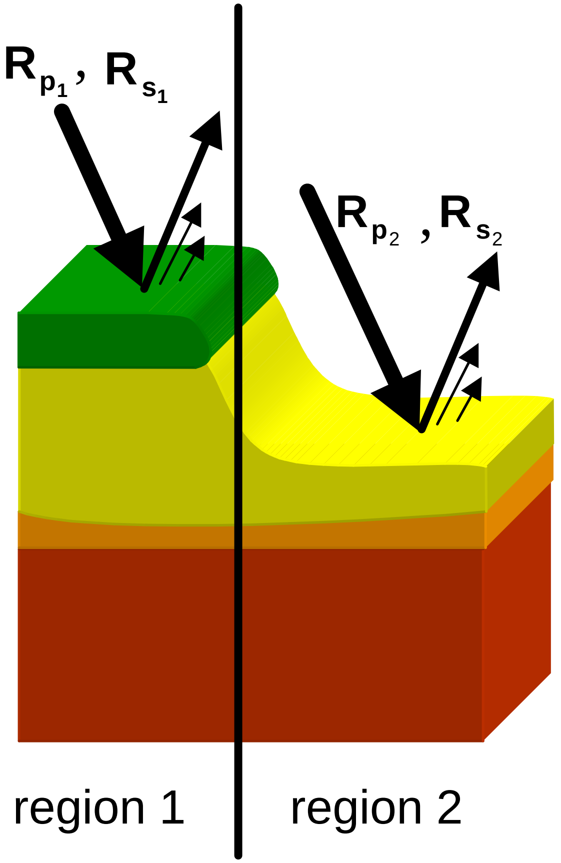
- Use Simple Structure to Minimize the Complexity in Initial Efforts
- The Lineshapes can be Modeled as Trapezoidal.
  - — Described by 4 parameters : period, top linewidth, depth, wall angle
- We Measure the Structure from SEM as: period=3.96 µm, top linewidth = 2.2 µm, depth = 0.52 µm, and wall angle = 73.9°.

Configurations of SE Measurement

- Align The Grooves Normal to the Plane of Incidence
- Two Kinds of Measurements Conducted
  - —Near normal (6º) incidence
  - —Oblique (75º) incidence



Description of the Scalar Model



$$R_p = af_1.R_{p_1} + af_2.R_{p_2} \qquad R_s = af_1.R_{s_1} + af_2.R_{s_2}$$

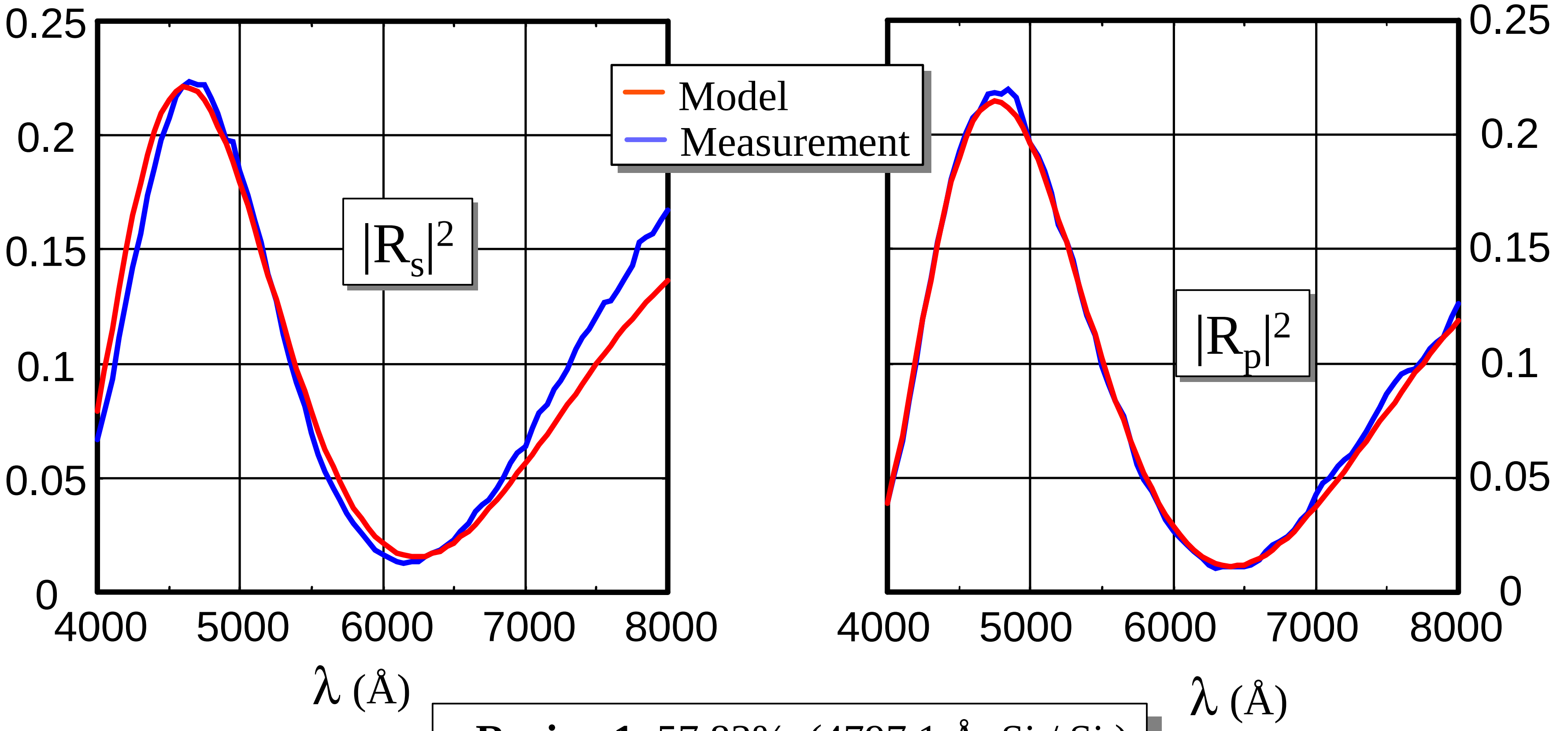
$$\rho = \frac{R_p}{R_s} = \tan(\Psi)e^{j\Delta}$$

af_1 , af_2 : Area Fractions

R_p , R_s : Reflectances in p and s polarizations

- Nominally, $af_1 + af_2 = 1$. But, af_1 and af_2 may be free parameters to consider unmodeled effects, e.g., Reflection from side walls.
- To obtain the reflectances, we add the corresponding complex fields, not their intensities.

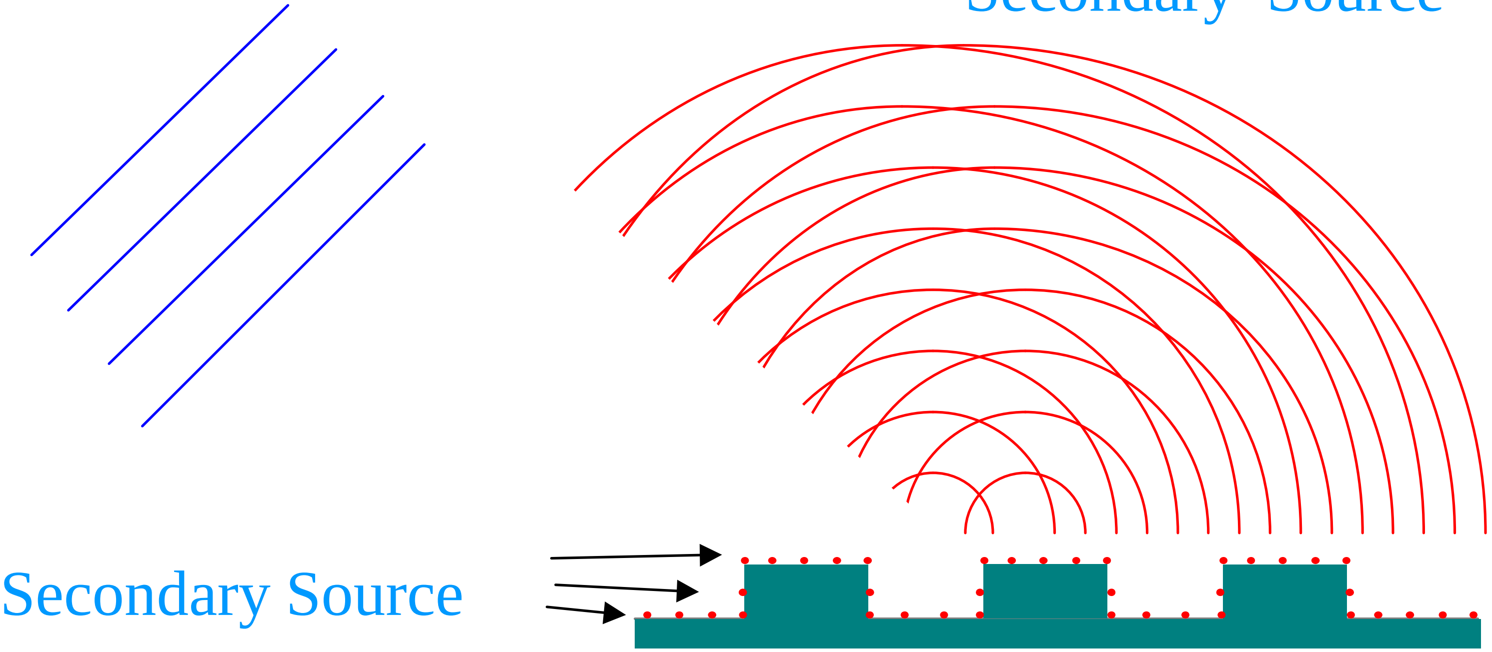
Scalar Model Applied to the Si Relief Grating



- **Region 1**: 57.83% (4797.1 Å Si / Si)
- **Region 2**: 25.11% (Si)

SIE Model of Vector Diffraction

- Based on the Surface Equivalence Theorem (Generalization of Huygens' Principle)



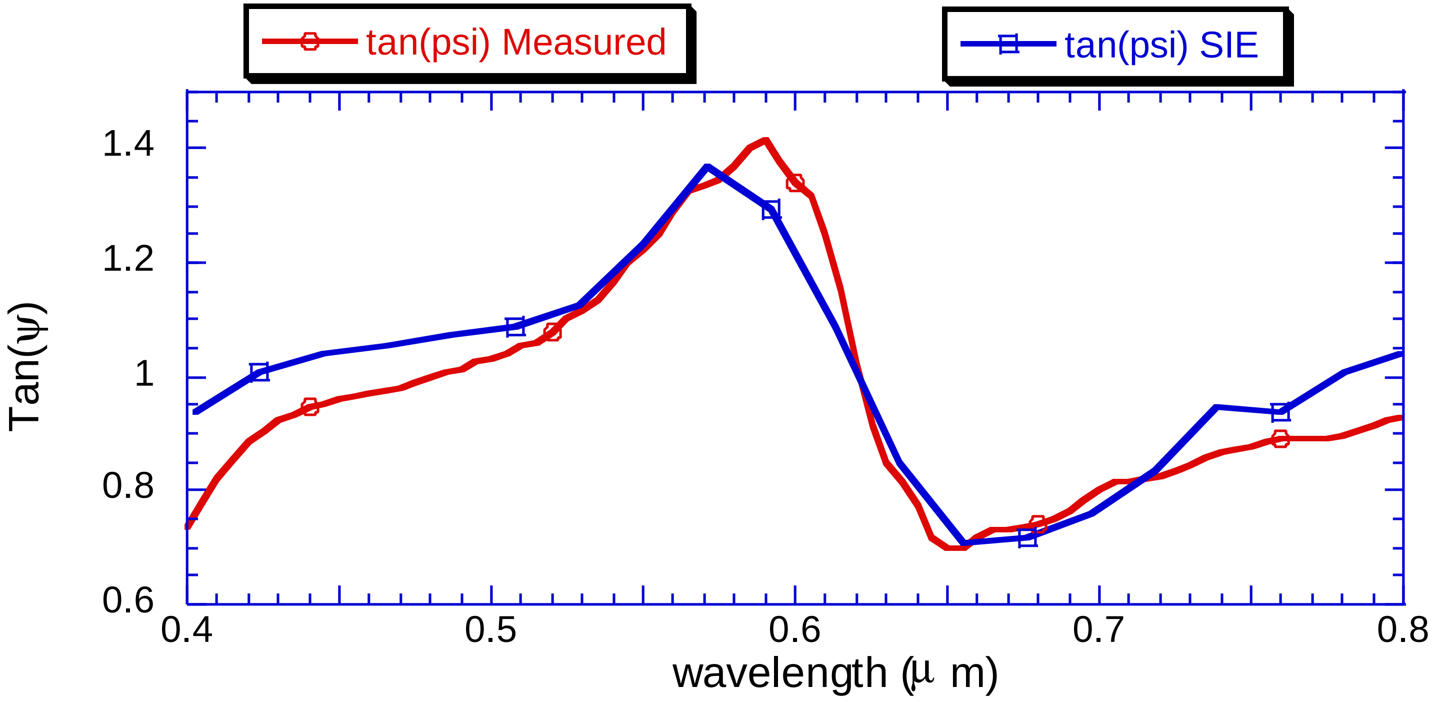
Incident Wave

Interference from Secondary Source

Secondary Source

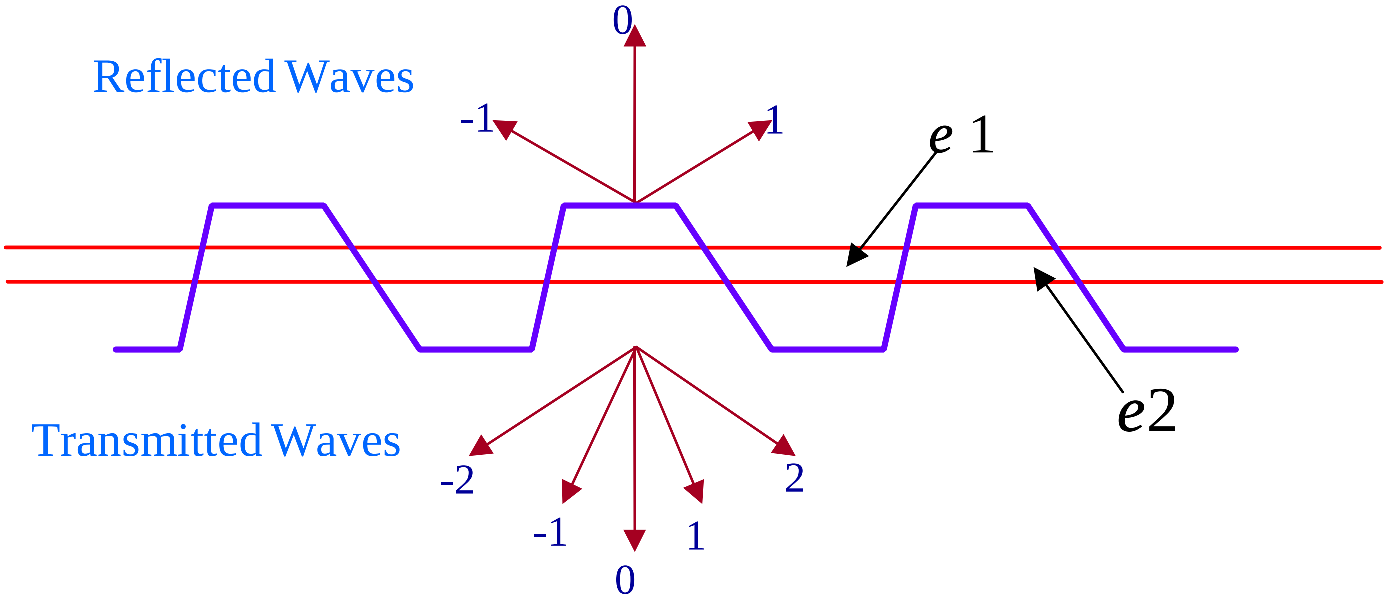
Patterned Wafer

SIE Simulation of Near-normal Ellipsometry



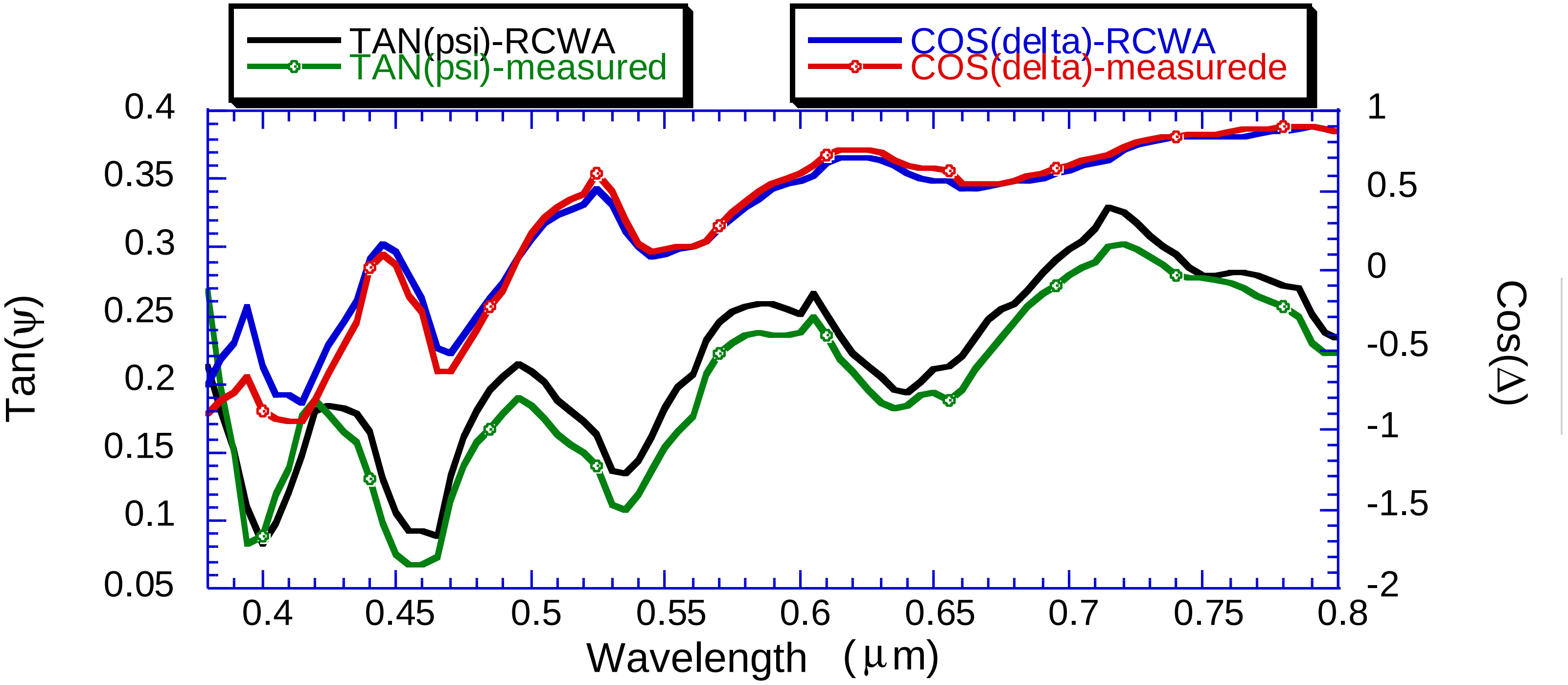
Measured and SIE Fitted Ellipsometry Data at 6° for the Nominal 500 nm Deep, 4 μm Period Structure

Rigorous Coupled-Wave Analysis (RCWA)



- Numerical Eigen-matrix Solution for Maxwell’s Equation
- Groove Is Sliced Into a Number of Thin Layers
- Amplitudes of Different Diffraction Orders Are Obtained by Solving Coupled-wave Equations

RCWA Simulation of 75º Spectroscopic Ellipsometry

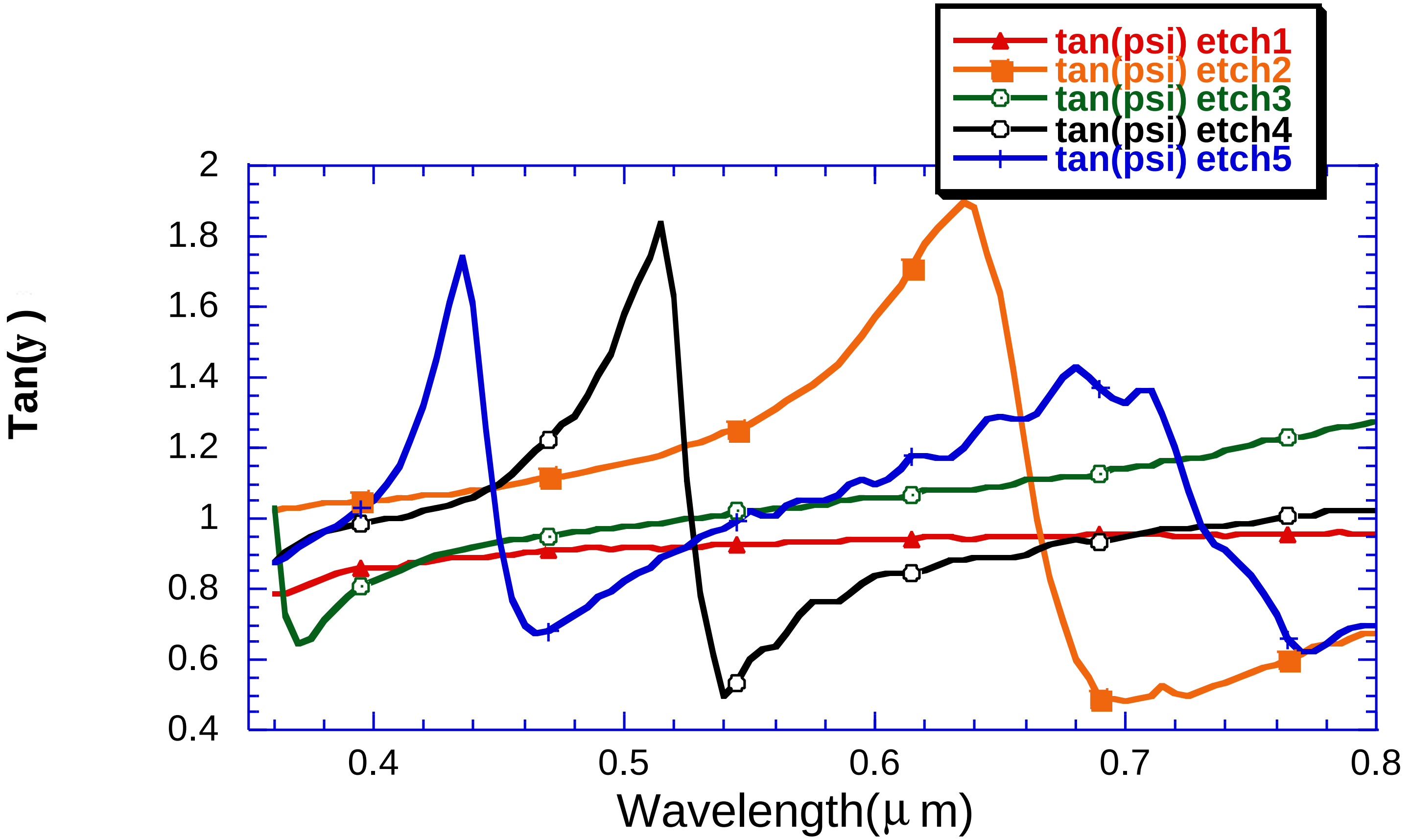


Measured SE Data From the 500 nm Depth, 4 μm Period Sample. The RCWA Simulation Yielded a Period of 4.0 μm, a Top Linewidth of 2.2 μm, a Sidewall Angle of 72.95º, and a Depth of 480 nm.

Grating Analysis Approach

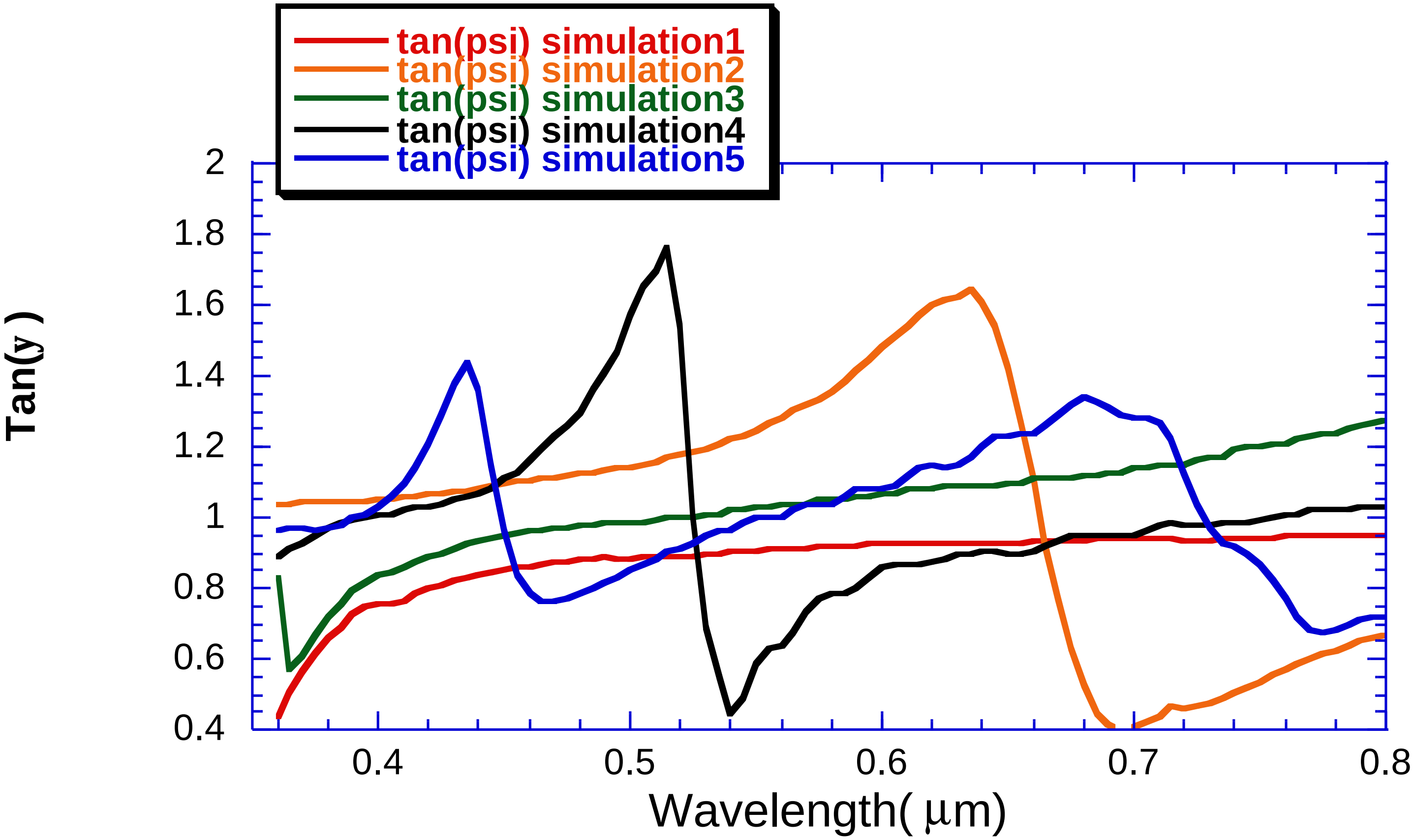
- Successively Better Approximations
  - Estimate Etch Depth From Near-normal Incidence Spectral **Reflectometry** in p-polarized Mode (Fast)
  - Extract the Grating Period From the **Diffraction** Experiment
  - Refine Depth Estimate and Estimate Period, Linewidth, and Wall Angle Using **SIE** Analysis of s- and p-polarized Reflectances (~1 min/λ)
  - Refine Topography Esitmates Using **RCWA** on Spectroscopic Ellipsometry Data (~5 min/λ)

Si Grating Etched to Different Depths



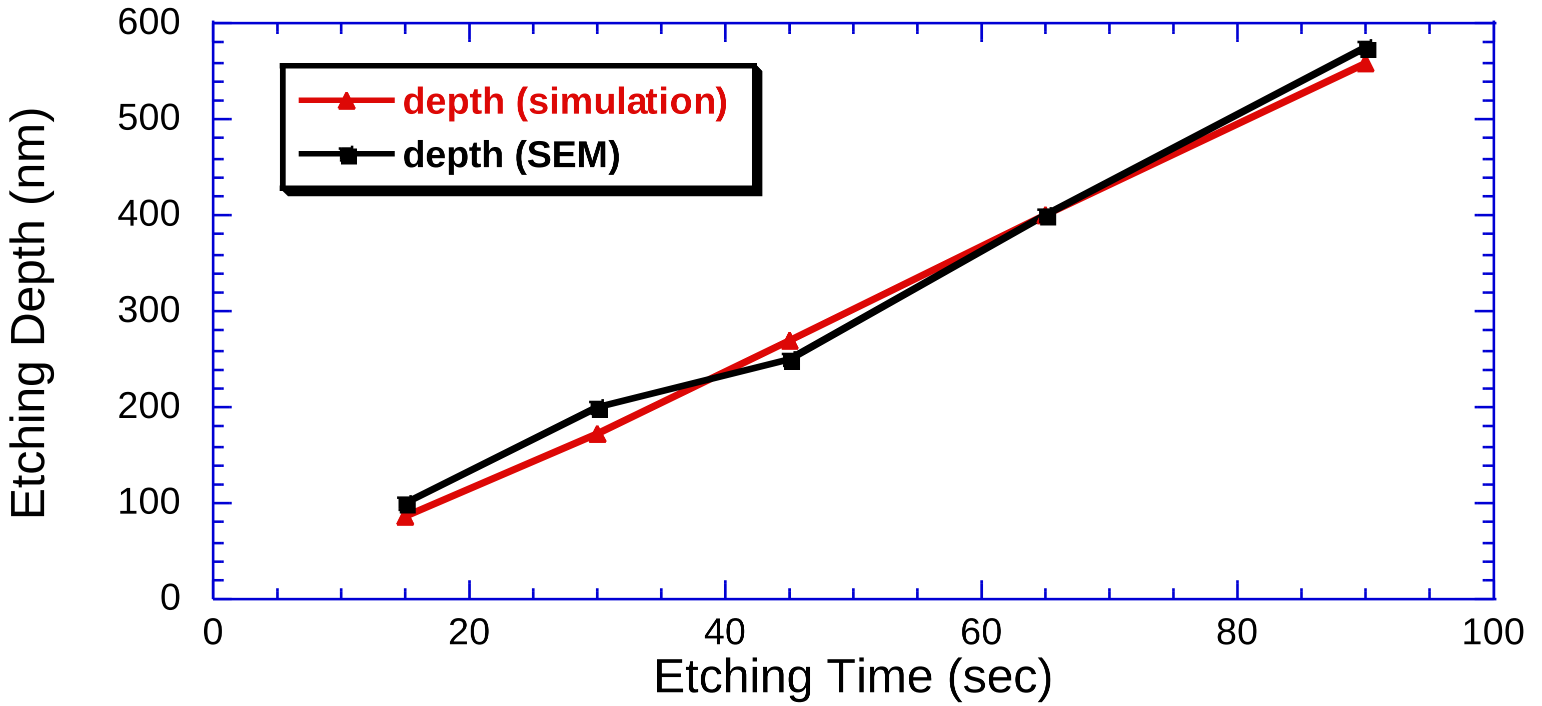
Si Relief Gratings with Nominal 2μm Lines and Spaces Etched to Depths of Approximately 100, 200, 300, 400, and 600 nm.

Simulation of Grating Etch



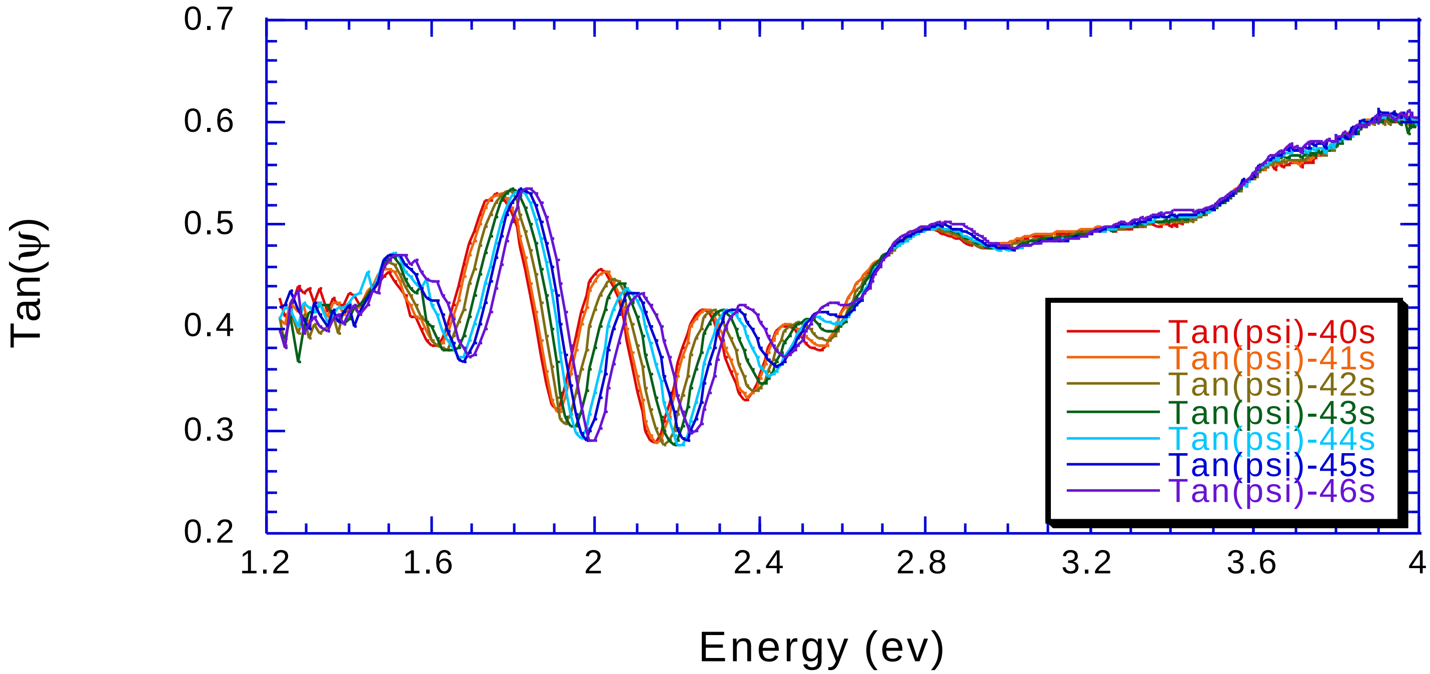
Approximate Simulation of Si Relief Grating Etch. Note That the Trends of the Spectroscopic Ellipsometry Data Are Captured.

Comparison With SEM



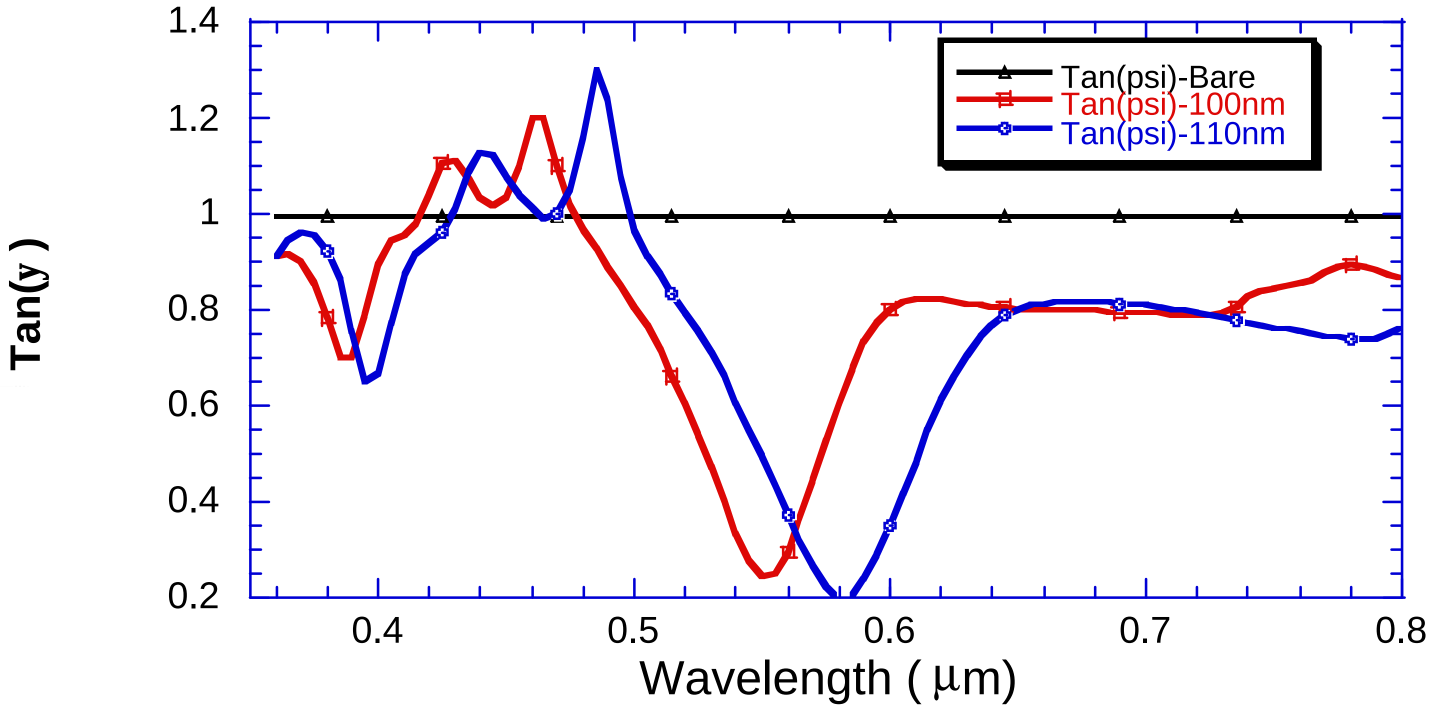
The Depths Extracted From the Simulation Are in Very Good Agreement With Those Measured From SEM. The Non-uniformity Among Different Die May Be Responsible for the Small Difference.

Real Time Data Collection



- Part of SE Data During the Etch of Patterned PR/4800Å Poly/300Å Sio2/si (6 sec in Total With 1 sec Intervals)
- The RTSE Possesses a Data Collection Capability of <0.5 sec With a Whole Visible Light Spectral Range.

Deep Sub-micrometer Regime



- Simulations Shows That for 100nm Features, the Near-normal SE Curves Still Exhibits Strong Structures, As Opposed to Even Smaller Structures and Blanket Wafers.
- The 100nm and 110nm Curves **IS** Different.
- Conclusion: Can “See” 100nm and Resolute 10nm.

Conclusions

- Spectroscopic Ellipsometry Can Give Accurate Depth and Topography Information From Patterned Structures.
- Quantitative Analysis of Diffraction Effects Is Computationally Time-intensive.
- *In Situ* Rapid Data Acquisition Is Possible With RTSE.

Future Efforts

- Improved Algorithms for Higher Speed Vector Diffraction Analysis
- Quantitative Analysis of Topography Parameter Sensitivities and Optimal Measurement Conditions
- Non-linear Regression Method for Topography Parameter Extraction

Technology Transfer Possibilities

- Working With National Semiconductor Mentors on Applications to Gate Linewidth Control
- Analysis Methods Easily Transferable/no New Instrumentation Required
  - Exist SE's for Blanket Measurements Can Be Used for Patterned Wafer Metrology

Acknowledgements

- This Work Was Supported in Part by
  - Semiconductor Research Corporation (Contract 97-FC085)
  - AFOSR/DARPA MURI Center for Intelligent Electronics Manufacturing (AFOSR F49620-95-1-0524)
  - State of Michigan Center for Display Technology and Manufacturing
- The Authors Would Also Like to Thank Dr. D. S. Grimard and Ms. M. Gulari for Assistance With Sample Fabrication