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Characterization and Metrology for ULSI Technology 2000 International Conference

Spectroscopic Ellipsometry from the Vacuum Ultraviolet to the Far Infrared

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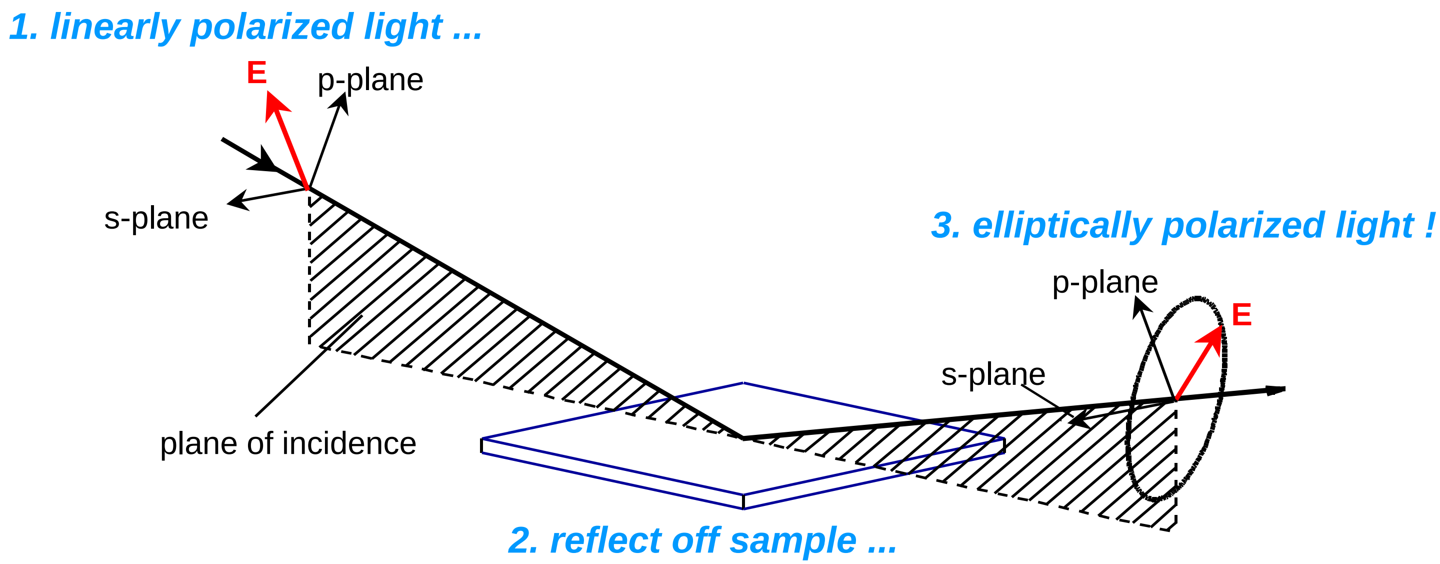
Presentation Outline

- Ellipsometry basics. Thin-films.
- Modern Instruments: VUV to far-IR.
- *Ex situ* examples.
- *In situ* examples.
- What's new?
  - Generalized ellipsometry: anisotropy
  - Depolarization: backside/roughness; Patterned wafers
  - Integrated metrology

Ellipsometry Overview

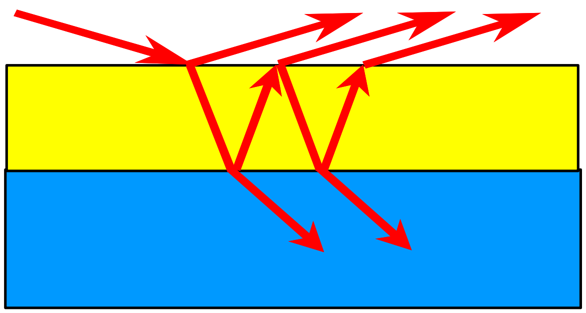


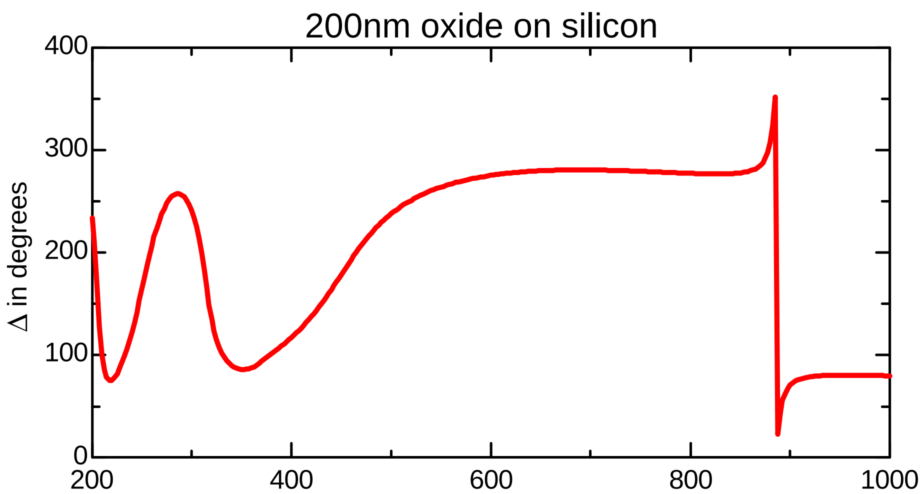
- Ellipsometry measures the change in polarization state of light reflected from a sample surface.

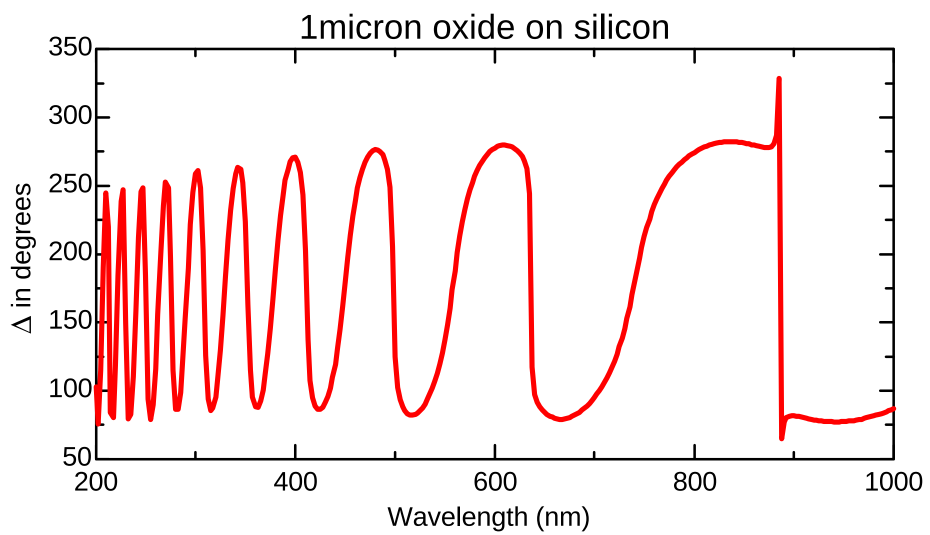
$$\rho = \tan(\Psi)e^{i\Delta} = \tan\left(\frac{R_p}{R_s}\right)e^{i(\delta_p - \delta_s)} = \frac{E_p^r / E_p^i}{E_s^r / E_s^i} = \frac{R_p}{R_s}$$

Interaction of Light with Thin Film

- Optical constants $N = n + ik$, or $\varepsilon = \varepsilon_1 + i\varepsilon_2 = N^2$ determine reflected/transmitted intensities, phase change, and angle change.







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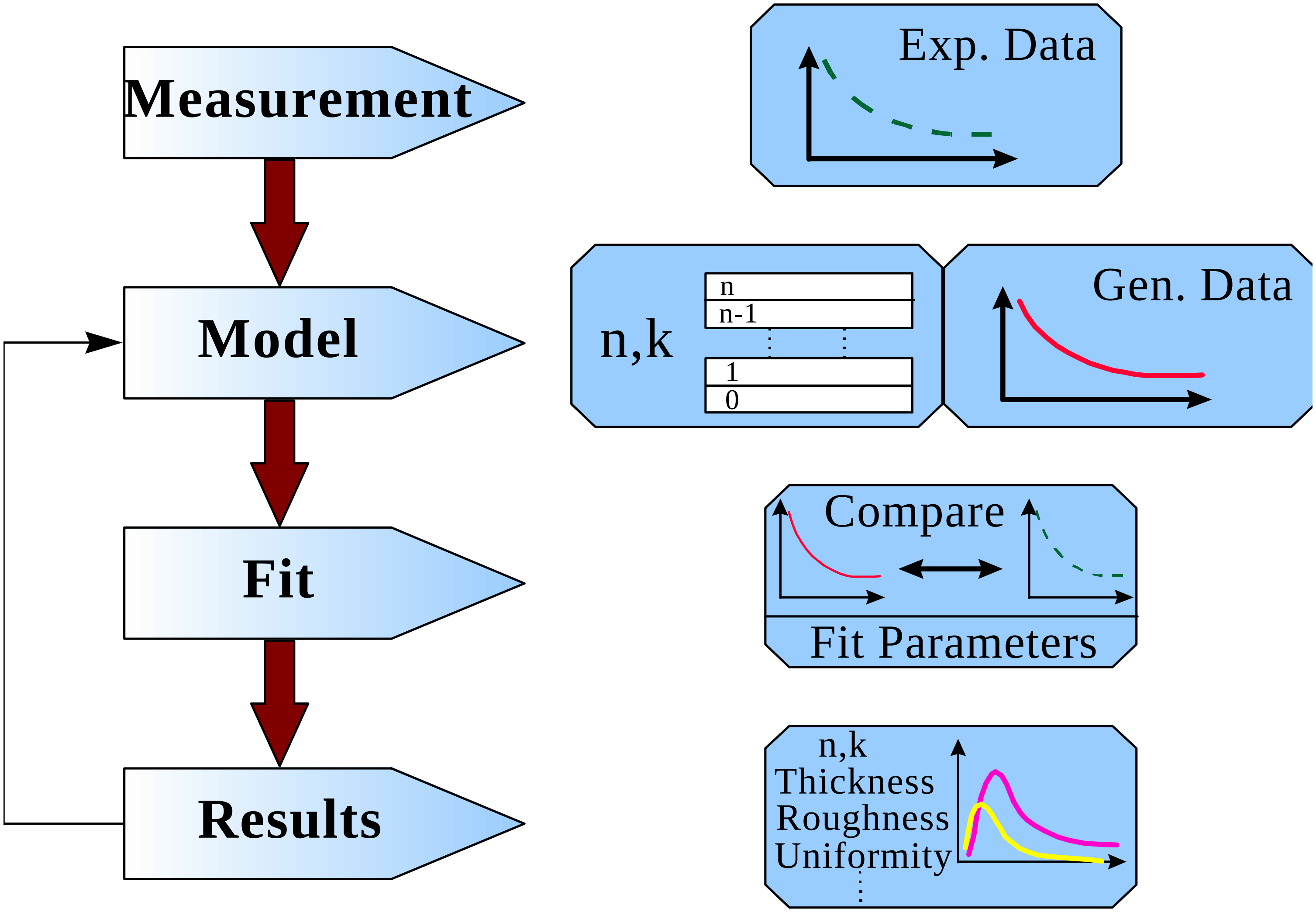
SE Data Analysis FlowChart



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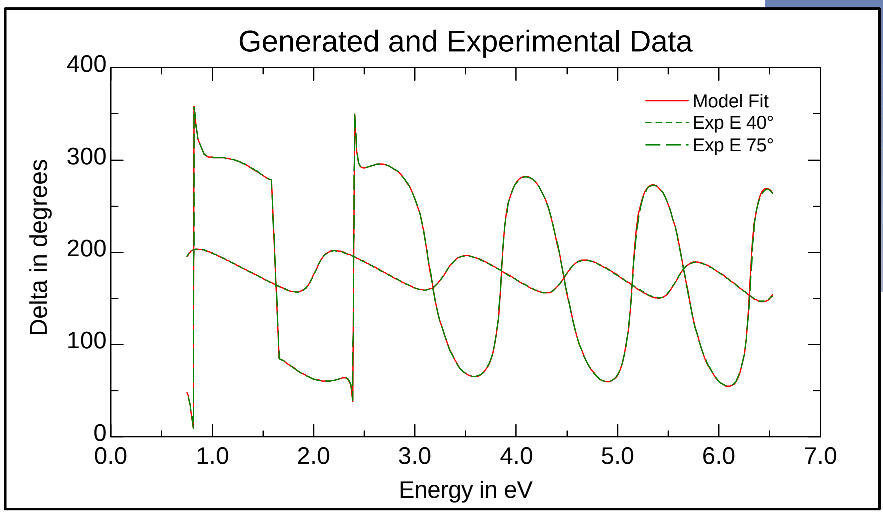
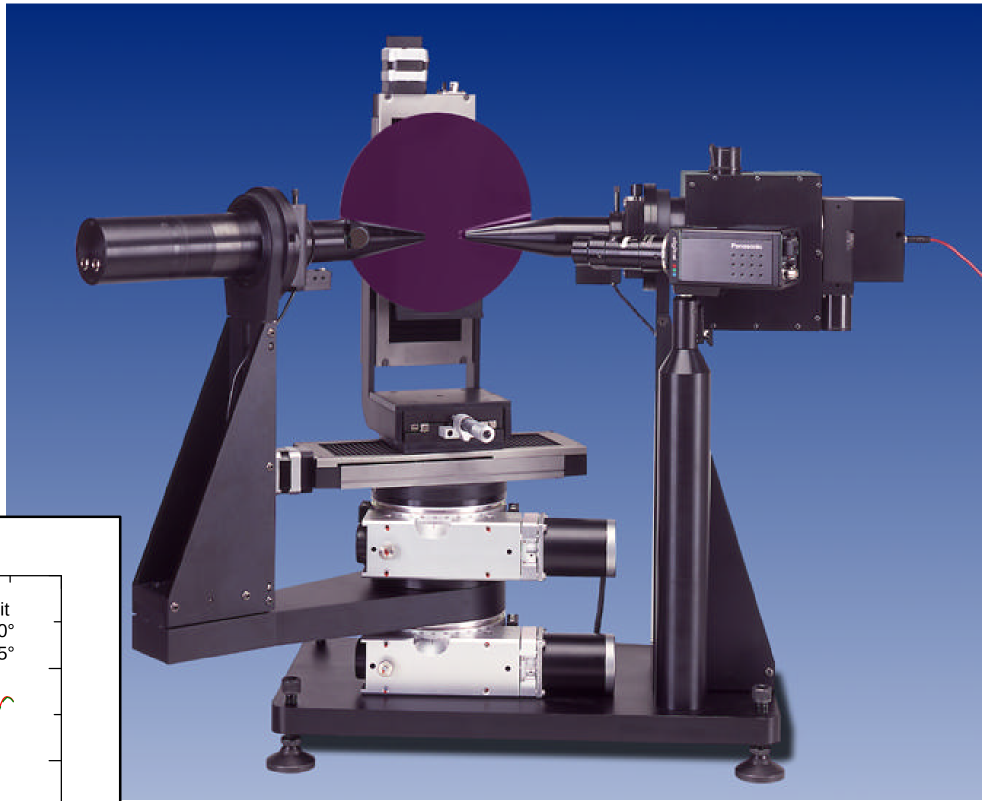
Ellipsometry Advantages

- Measures ratio of two values
  - Highly accurate & reproducible (even at low light levels)
  - No reference necessary
  - Not as susceptible to scatter, lamp or purge variation
- Measures a 'phase', 'Δ'
  - Very sensitive, especially to ultrathin films (<10 nm)
  - Provides TWO values at each wavelength
- Spectroscopic Ellipsometry (SE)
  - More Information – More Film Properties
  - Data at wavelength of interest (157nm,193nm,248nm…)

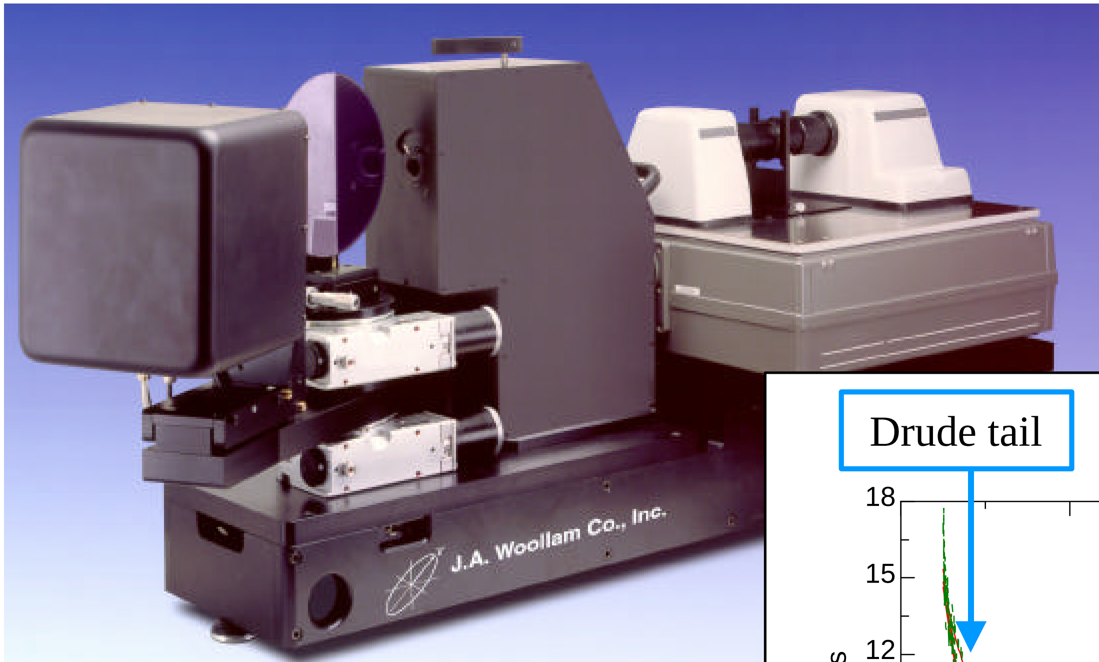
VASE®

- Spectral Range:
  - 193nm to 1700nm
- Automated Angle
- Variable Angle Spectroscopic Ellipsometry, Transmission and Reflection.



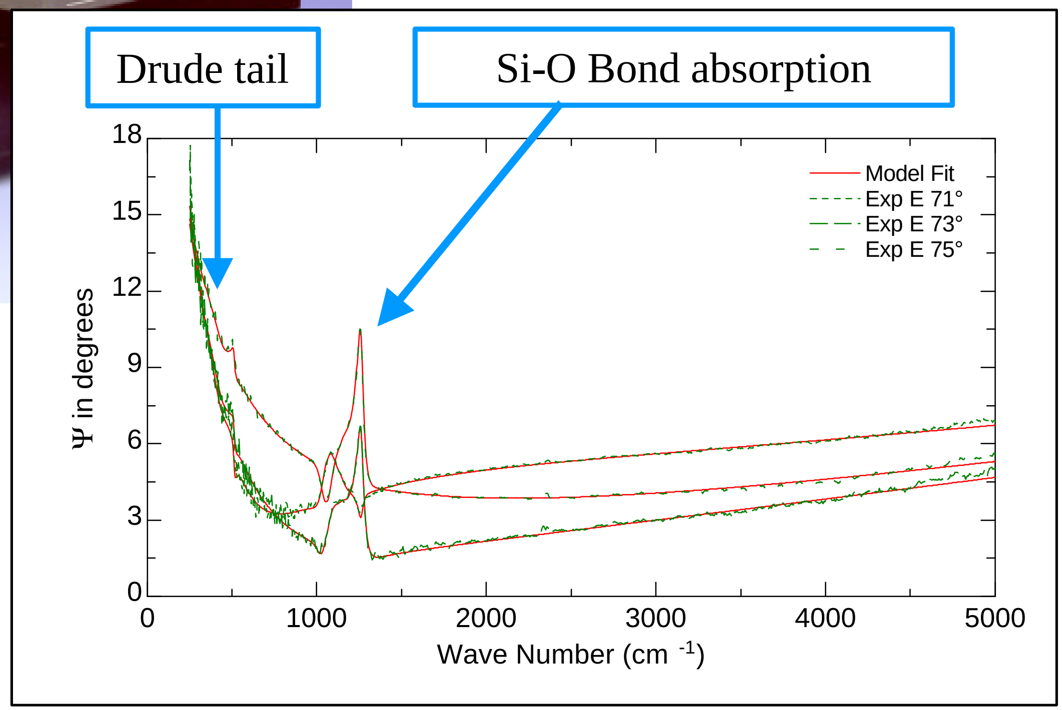


IR-VASE® Hardware



Spectral Range:

- 2 μm to 33 μm (300 to 5000 cm^{-1})



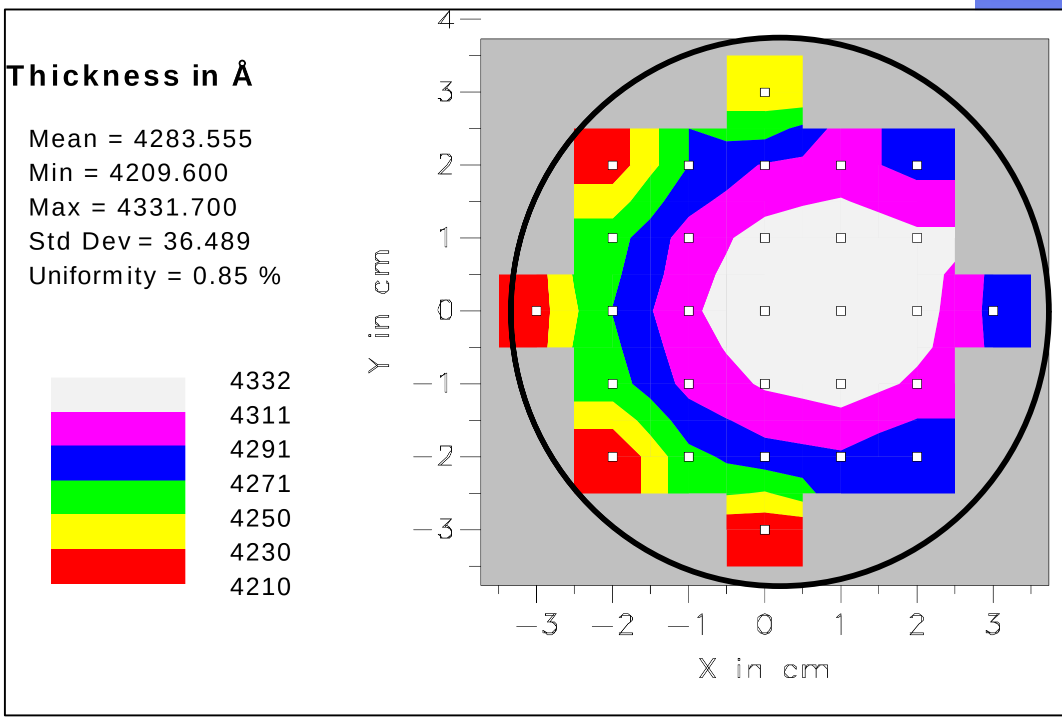
VUV-VASE^{TM} Instrumentation

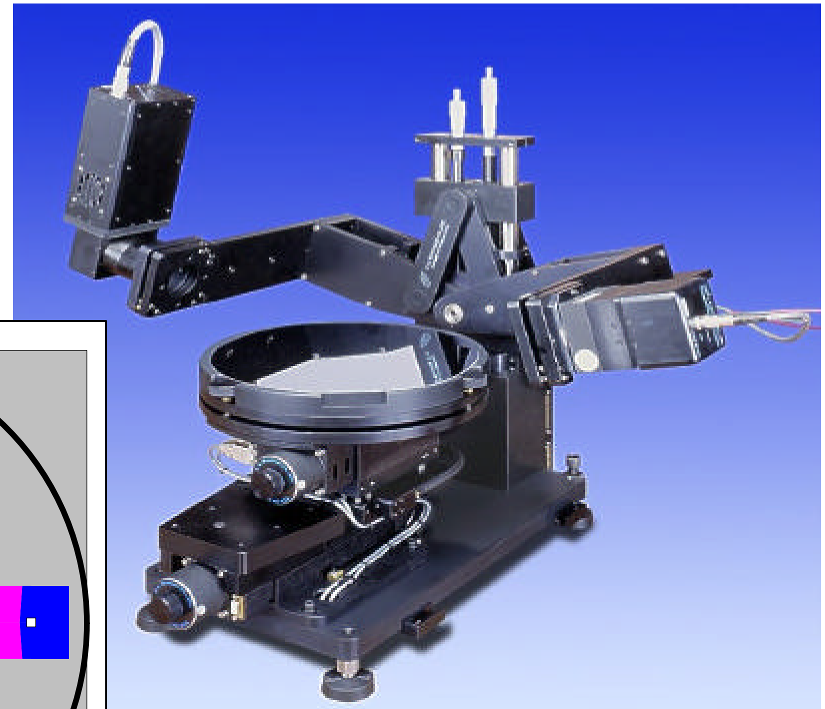
- Auto Angle:
  10°-90°
- Wavelength
  146nm-1100nm
- Nitrogen Purge
- AutoRetarder

- Sample Load Lock
- Automated Sample Alignment

M-2000®

- Spectral Choices:
  - 193 nm to 1000 nm
  - 245 nm to 1000 nm
  - 370 nm to 1000 nm





- Hundreds of wavelengths

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Ex Situ Applications

Ellipsometry is Sensitive to:

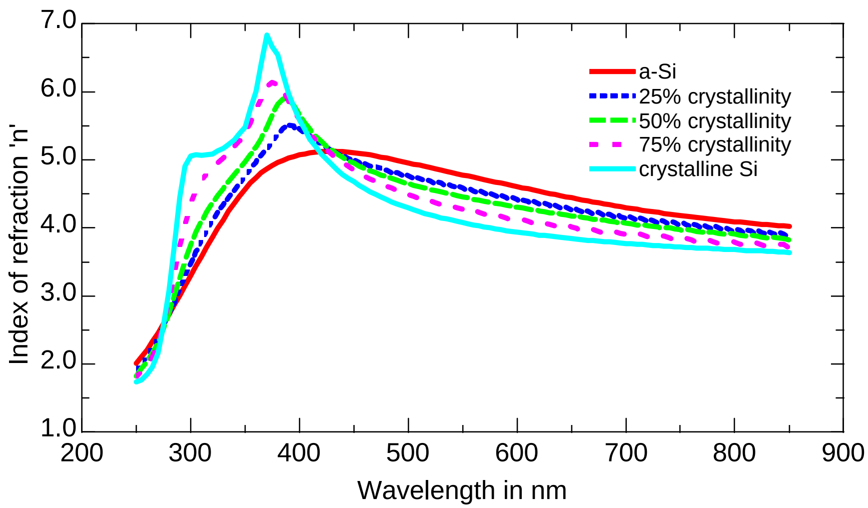
- Layer thickness
- Optical Constants
- Surface and Interfacial Roughness
- Composition / Crystallinity
- Optical Anisotropy
- Uniformity (over film area and depth)
- Any physical effect that induces changes in material optical properties

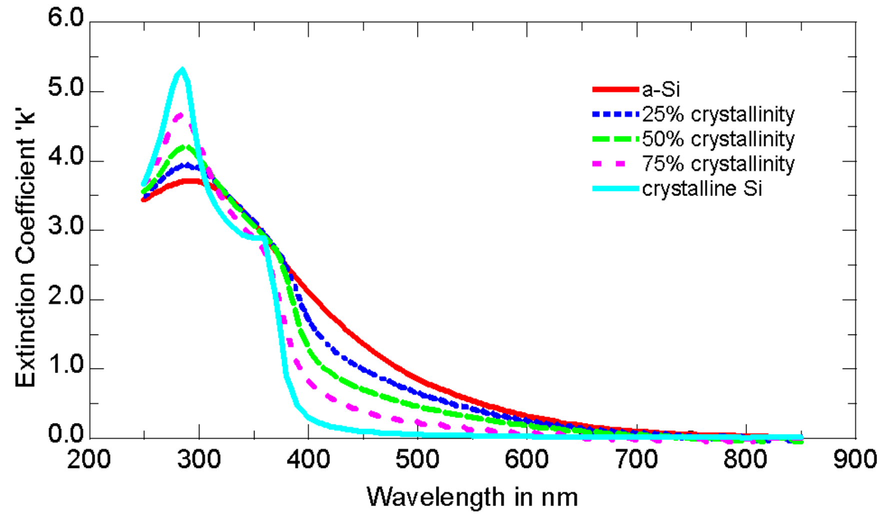
Semiconductor Industry

- Dielectrics (oxides, nitrides, carbides)
- Polymers (Low-Dielectric constant)
- Polysilicon
- Multilayers (ONOPO, SOI, ...)
- Lithography Applications
  - Photoresists
  - Antireflective coatings
  - Photomasks
- Compound Semiconductors

Crystallinity: Polysilicon

- Optical constants depend strongly on crystallinity, which can vary with process conditions.





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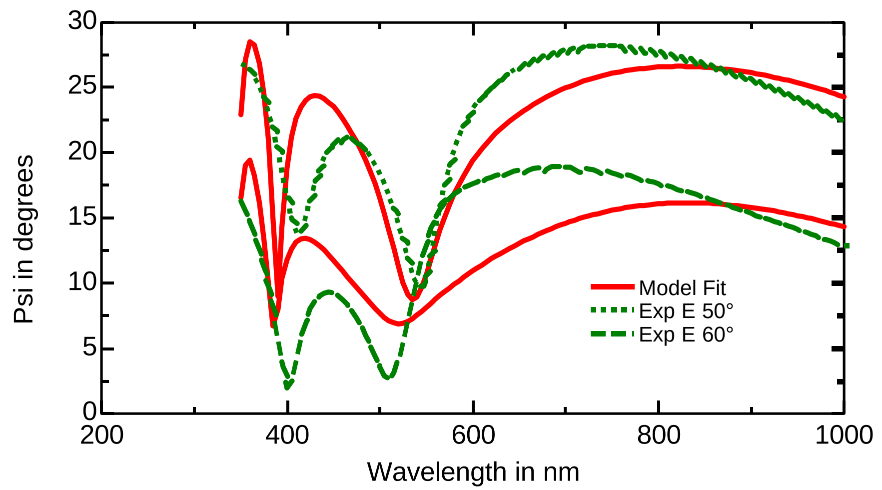
Si_3N_4 Film Thickness and Index
Initial Modeling Attempts

Optical Model #1

Cauchy Layer	2896.2 Å
Glass substrate	

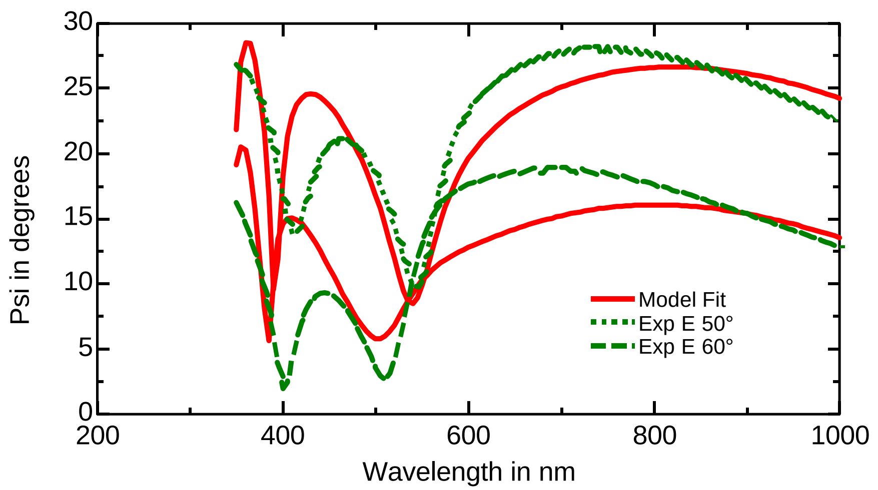
MSE = 176.6



Optical Model #2: Add Roughness

Surface Roughness	108.34 Å
Cauchy Layer	2878.1 Å
Glass substrate	

MSE = 165.7



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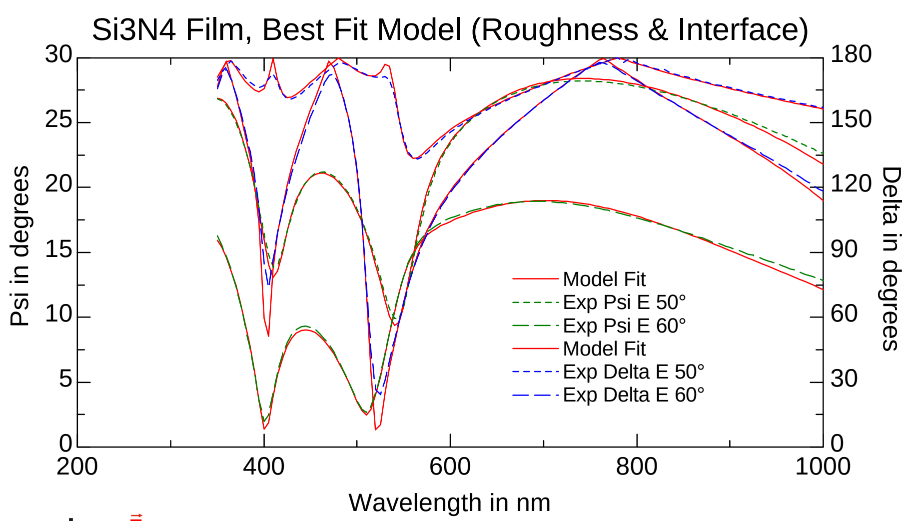
Si3N4 Film Thickness and Index
Best Fit Model

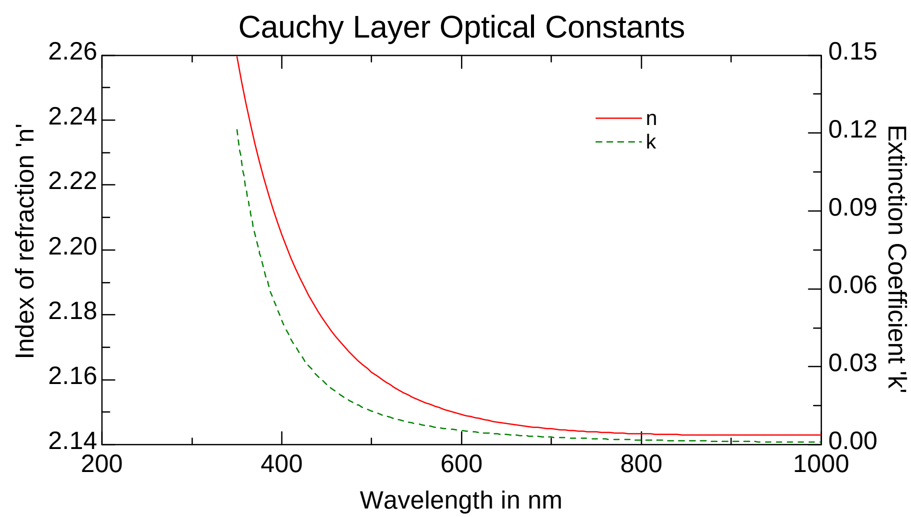
- After analysis, we found out film was deposited in two passes !

4	Surface Roughness	90.742 Å
3	Cauchy (same as #1)	1304.8 Å
2	'Interface' (50% void)	274.84 Å
1	Cauchy Layer	1324.6 Å
Glass Substrate		

Best Fit Optical Model

Final MSE = **10.31**





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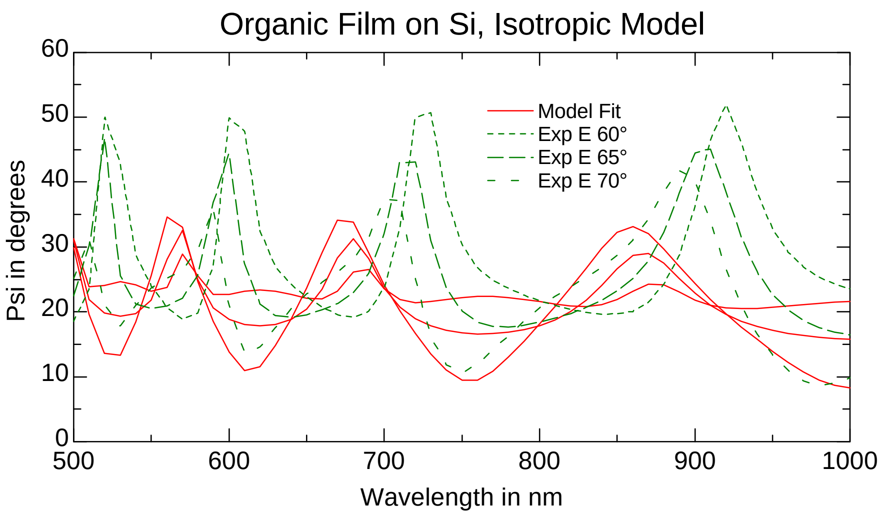
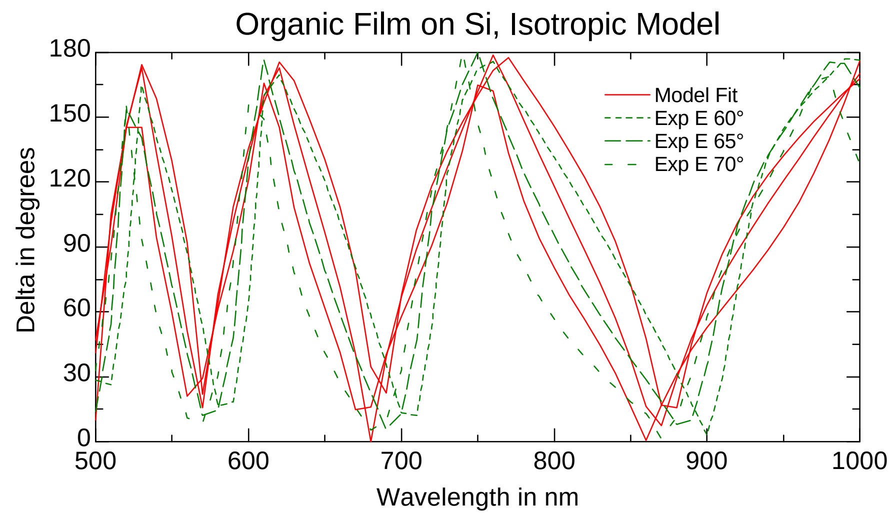
Organic Film on Si

- Isotropic Model

Cauchy Layer	7919.3 Å
Si substrate	

MSE = 316.2



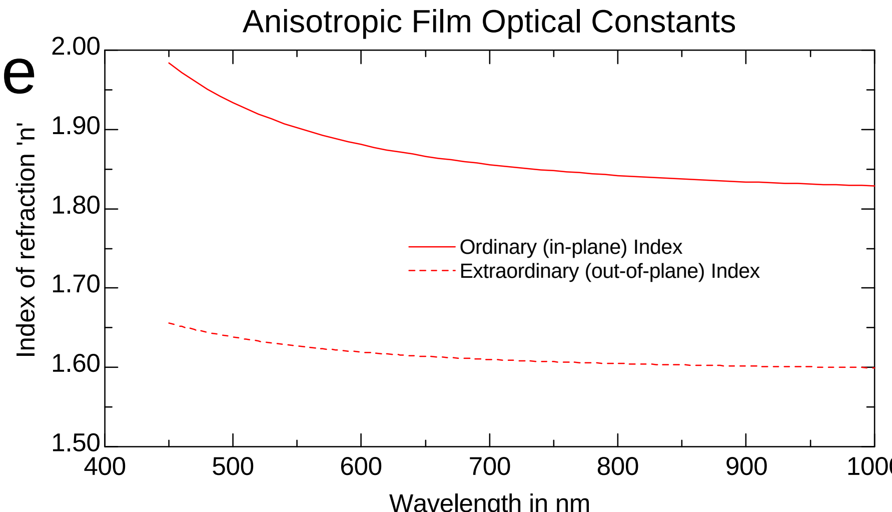


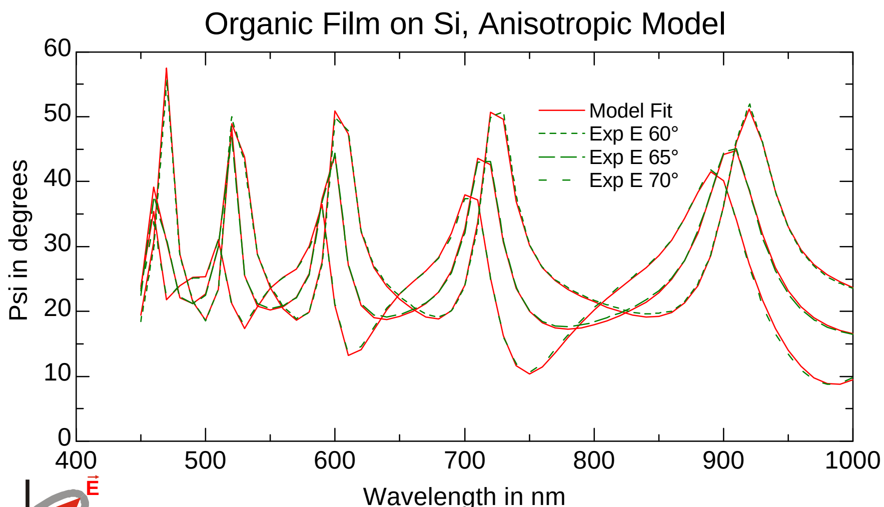
Spin-Cast Organic Film on Si

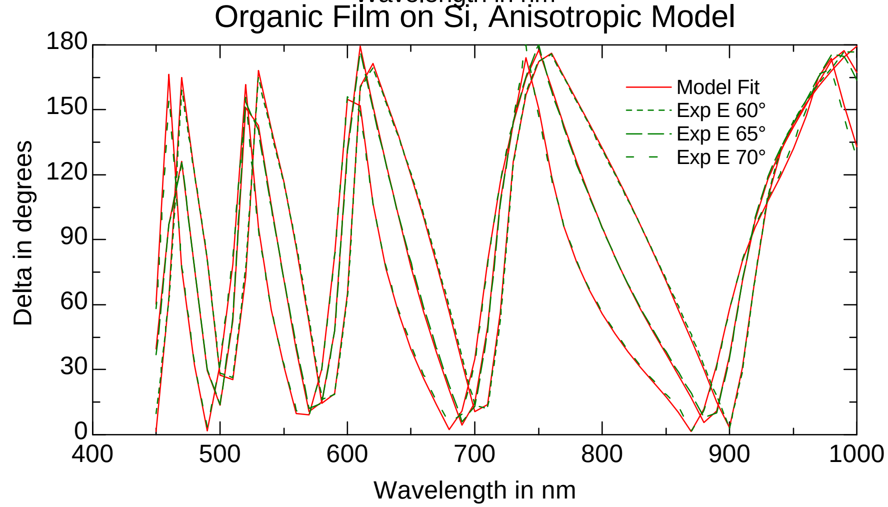
- Uniaxial anisotropy model, optical axis normal to surface

MSE = 16.9

aniso-Cauchy	9951.8 Å
Si substrate	







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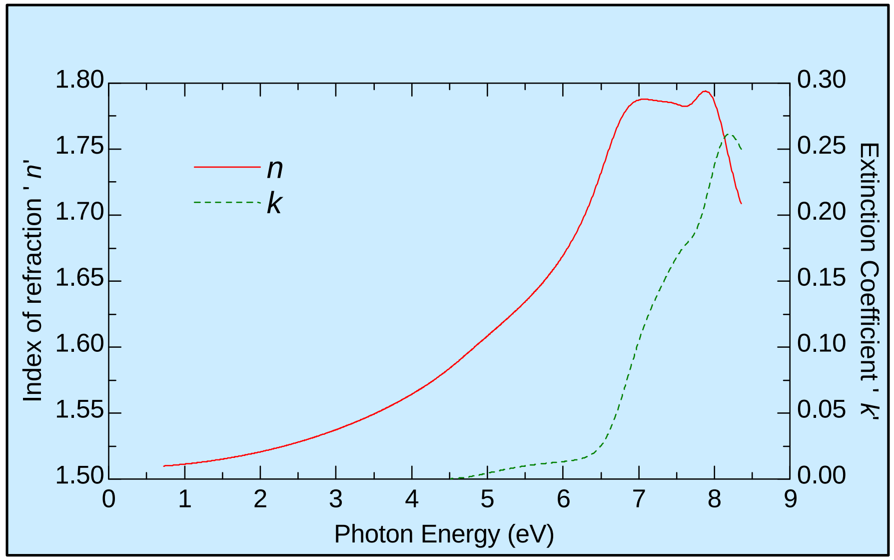
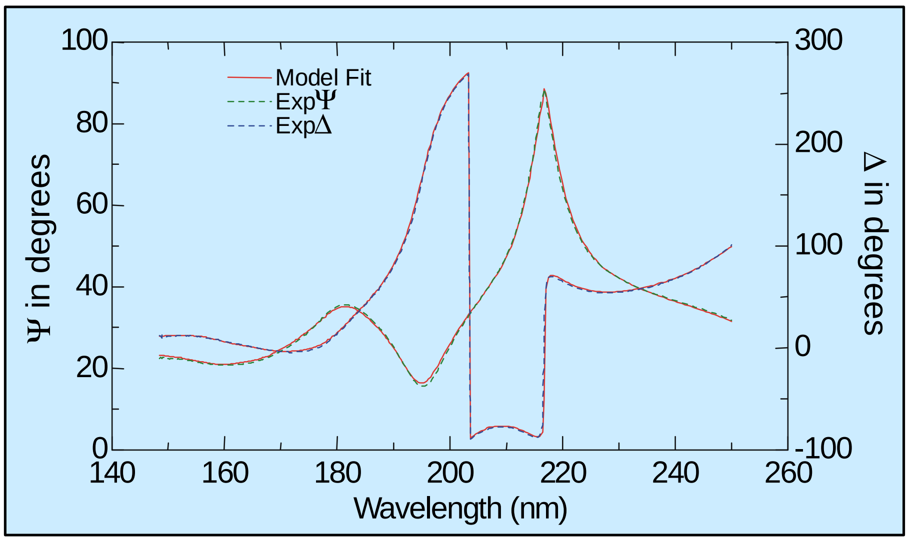
Photoresists

- Measure refractive index at each lithography line
  - 248 nm, 193 nm, 157 nm…





- Monochromator before sample allows accurate optical characterization of resists in UV without exposing.

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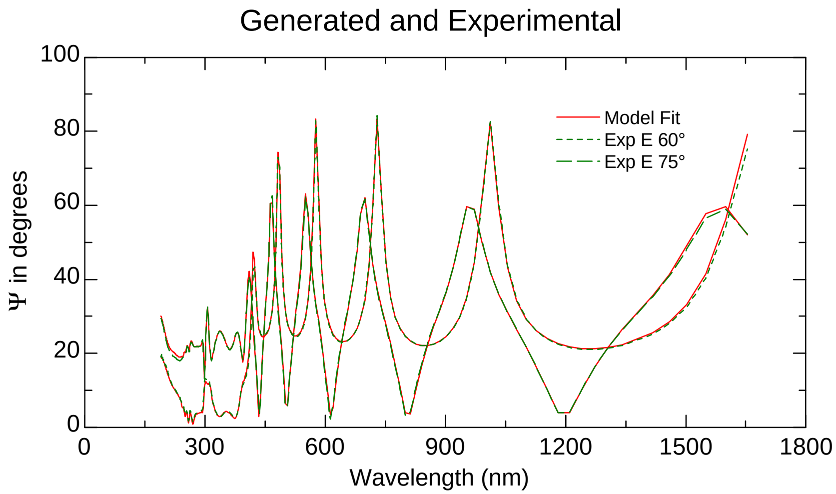
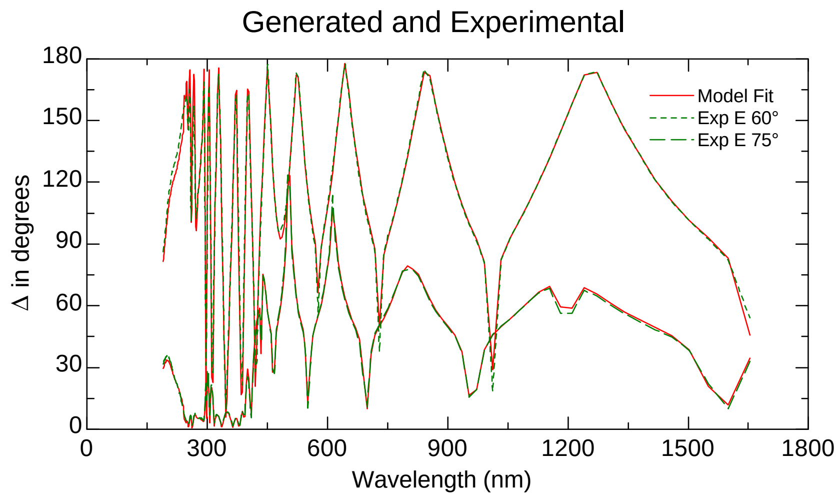
Multilayer: Resist on ARC

- Both layer thicknesses can be determined because of the DUV data where there is high optical contrast between layers.

2	Photoresist	6117.9 Å
1	i-line AR Coating	3107.7 Å
0	Silicon substrate	1 mm





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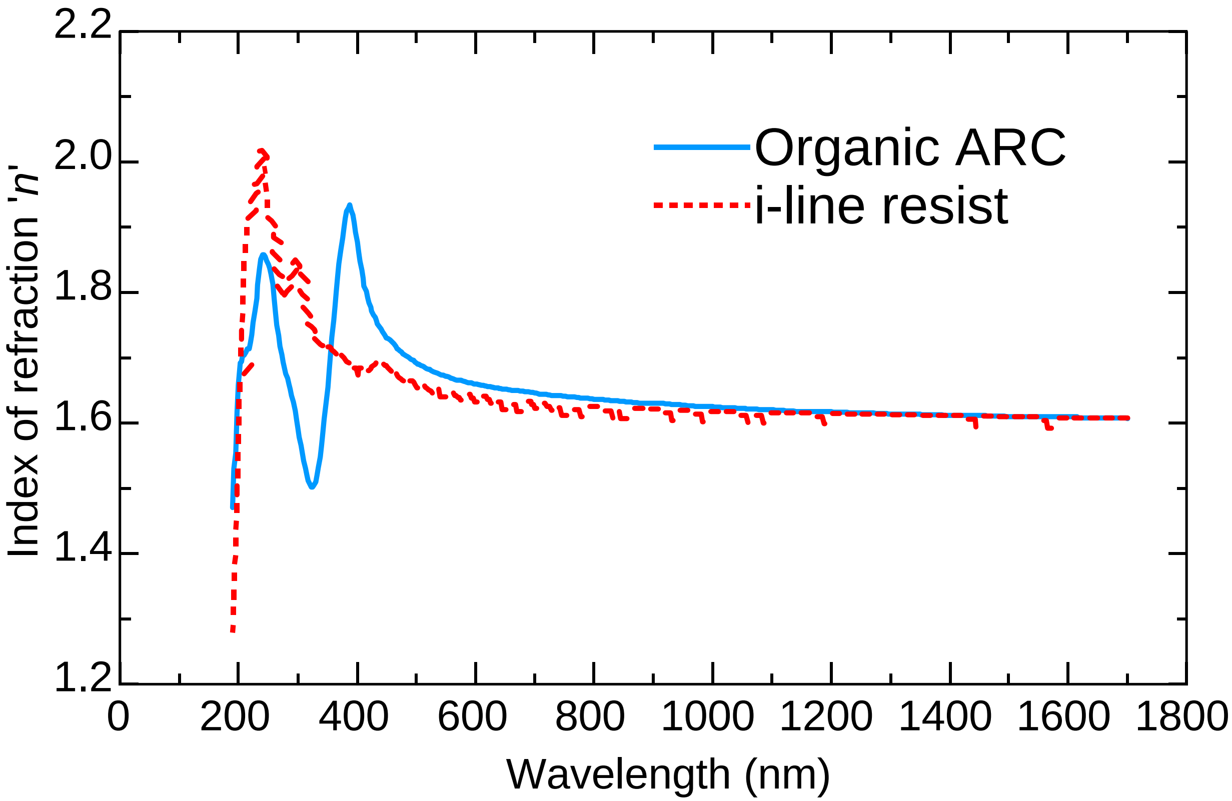
Resist and ARC Optical Constants

- Similar Dispersion except at shorter wavelengths where both films become absorbing.



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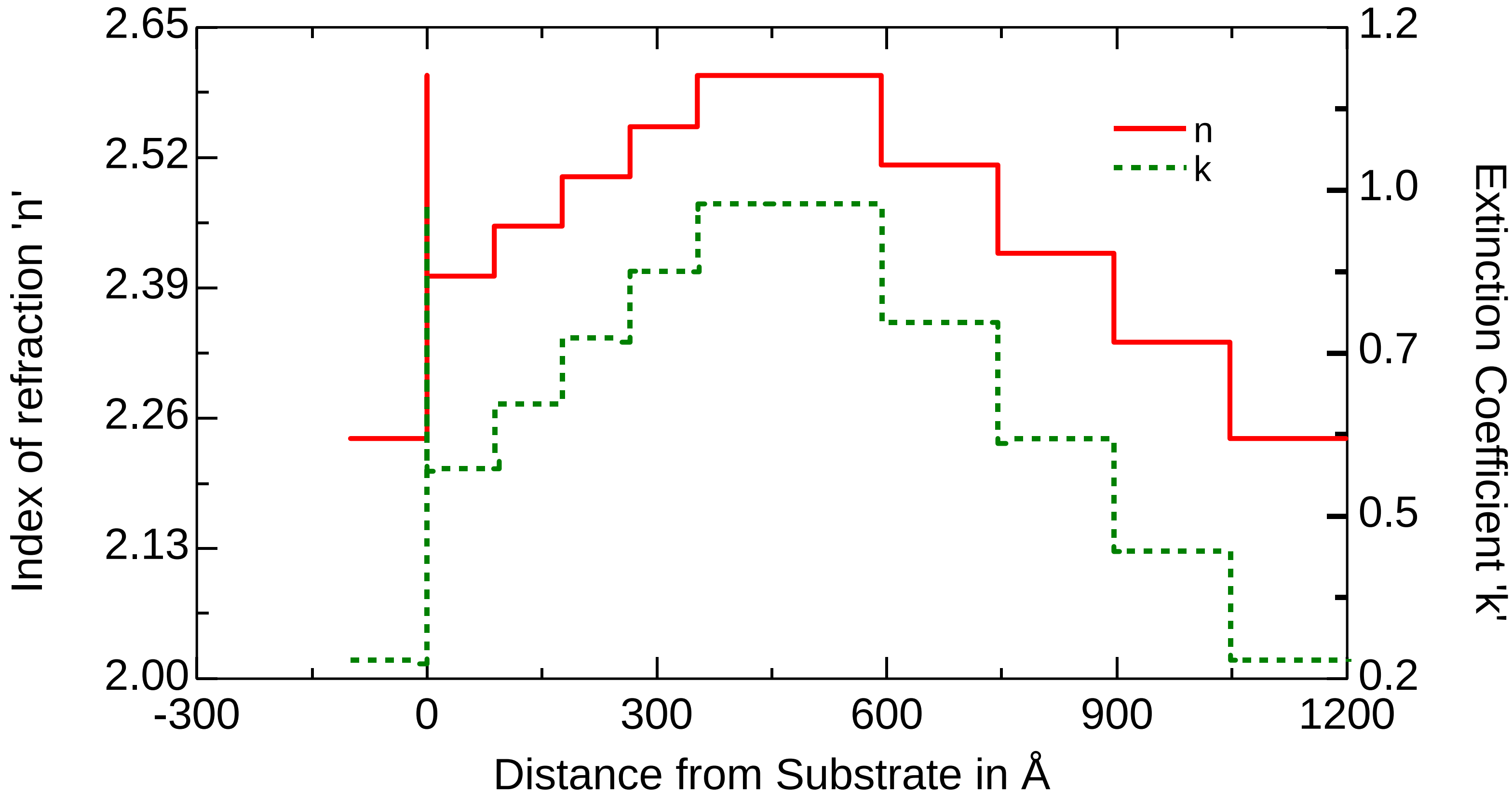
Phase Shifting Photomasks

- Complex material structures (index grading)



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IR-VASE® Advantages

- **High Sensitivity to Ultra-thin films**

  The "phase" information of Spectroscopic ellipsometry (not available from FTIR reflectance or absorptance) is highly sensitive to ultrathin films.

- **Directly measure accurate Optical Constants**

  No Kramers-Kronig analysis with extrapolation required, as in FTIR.

- **Non-destructive Characterization**

  Measurements do not require vacuum; can study liquid-solid interfaces, e.g. wet-etch, biological, or medical applications.

- **No Baseline or Reference sample required**

  Samples smaller than the beam diameter can be measured because the entire beam does not need to be collected. Ellipsometric measurements are accurate and quantitative. FTIR reflectivity and absorbance measurements are relative.

Silicon Epitaxial Layers on Silicon

- Drude equation used to model free carrier optical absorption

Measured:

- Epitaxial Si Layer Thickness (t_{epi}) = 273nm
- Native Oxide Thickness (t_{ox}) = 1.2nm
- Epitaxial Layer Resistivity (ρ_{epi}) = 5.13 Ω-cm
- Substrate Resistivity (ρ_{sub}) = 0.0175 Ω-cm

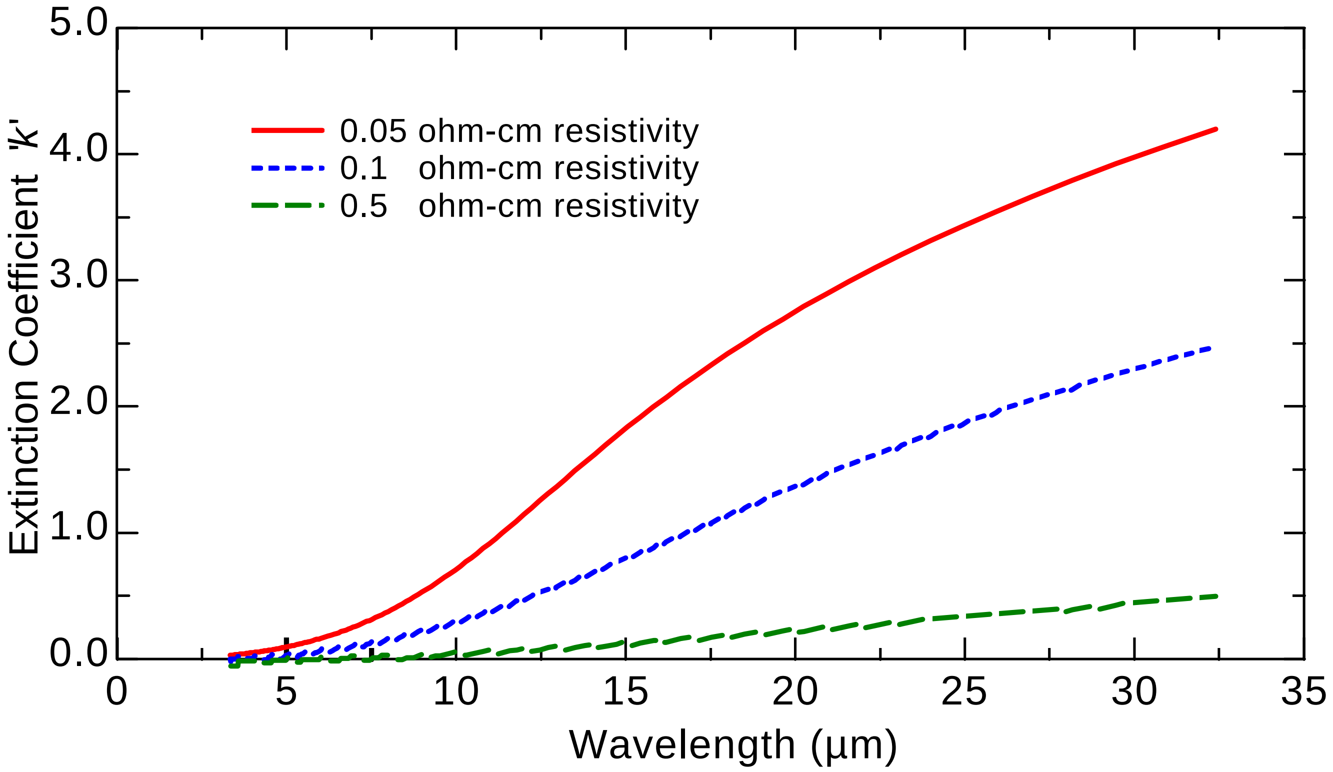
Model

2	native oxide (ir oscillator model)	t_{ox}
1	silicon with free carriers	t_{epi}
0	silicon with free carriers	0.6 mm

$$e_{Drude}\left(E_{ph} = \ w\right) = \frac{- \ ^2}{e_0\, r\, 10^{-2}\left(t \cdot 10^{-15} E_{ph}^{\ 2} + i\ E_{ph}\right)} \quad \text{and} \quad r = \frac{m^*}{Nq^2\, t} = \frac{1}{q\, m N}$$

Doping Concentration (resistivity)

- Dopants introduce free-carrier absorption in the Infrared.



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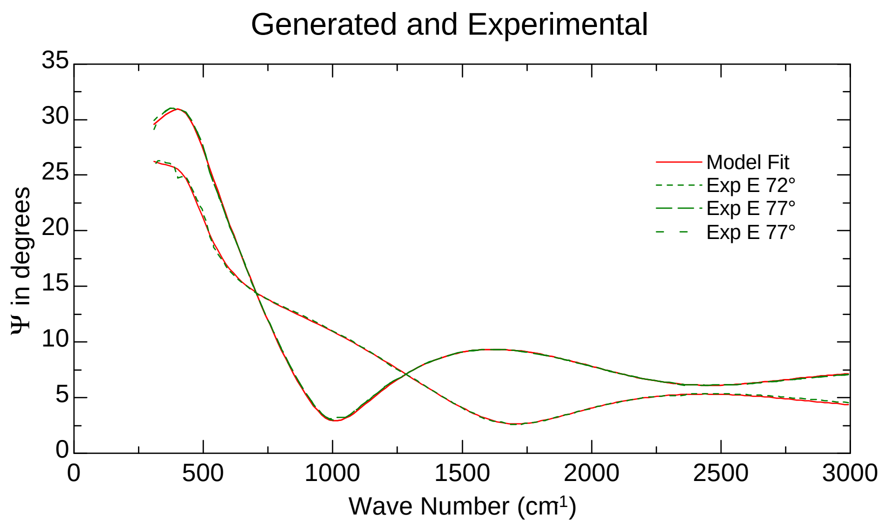
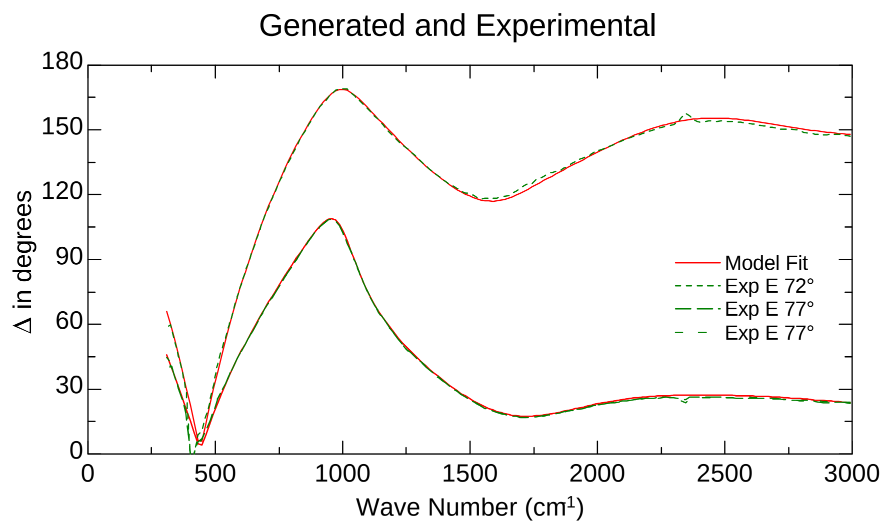
THIN EPI-LAYER

- Measure epi-layer thickness and substrate resistivity

1	Epitaxial Silicon	0.95435 µm
0	Silicon Substrate	1 mm





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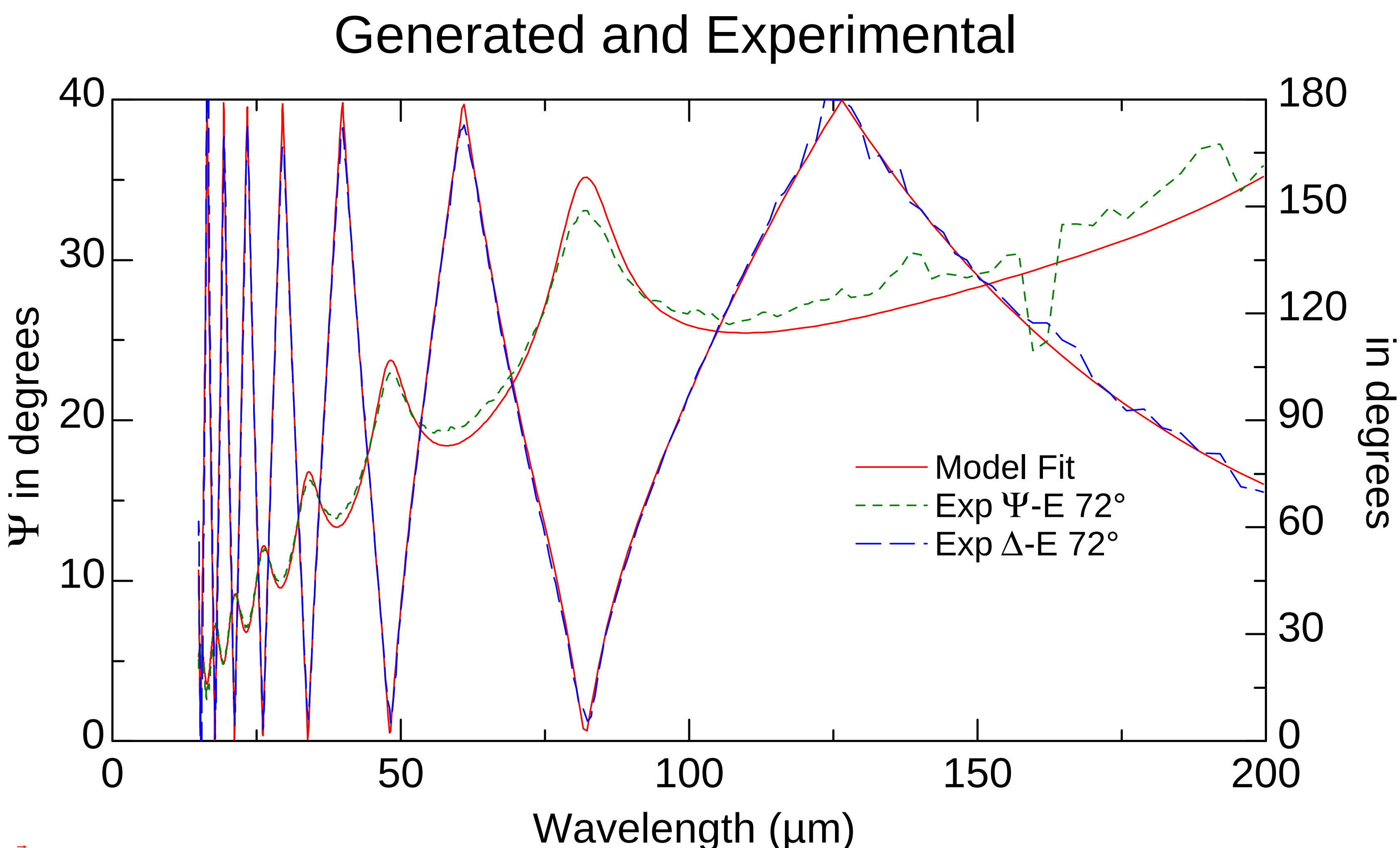
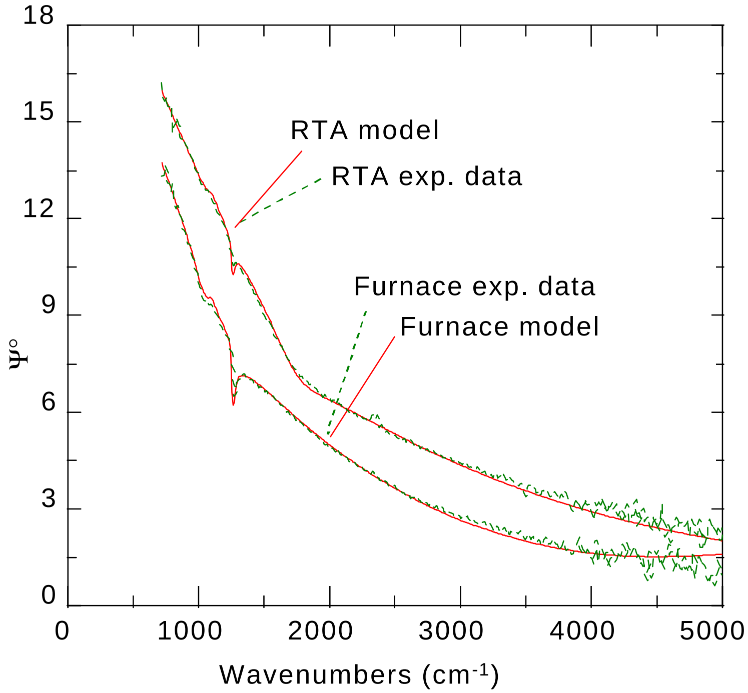
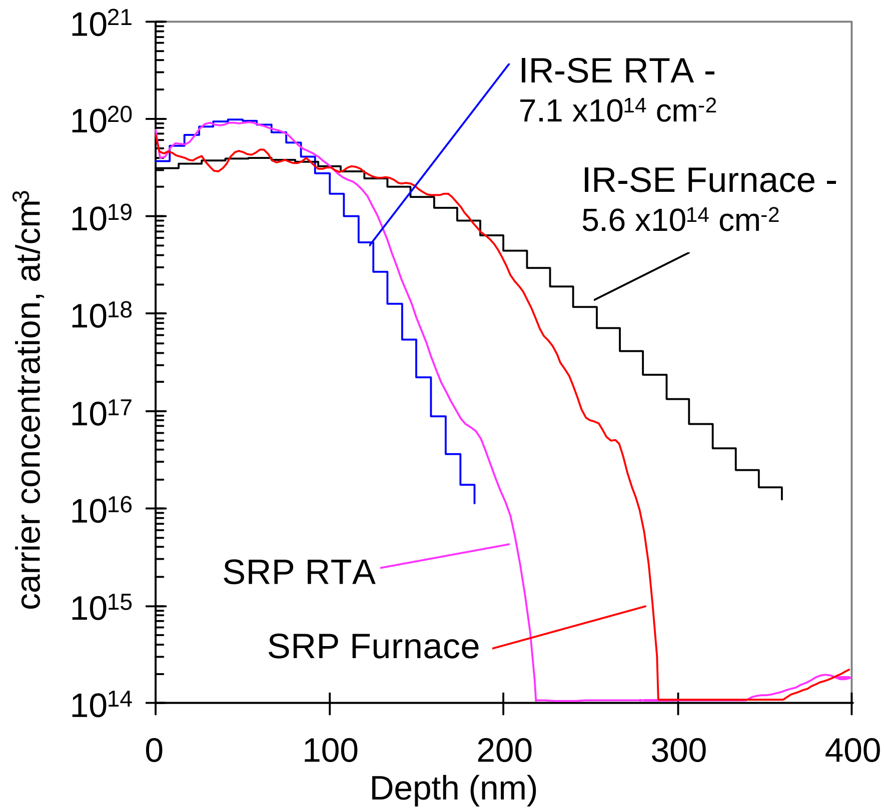
Epi-silicon: Far-IR data & fit



Ion-implanted doping profiles

- Implant-dose: 10^{15} As-cm^{-2} @ 80 keV



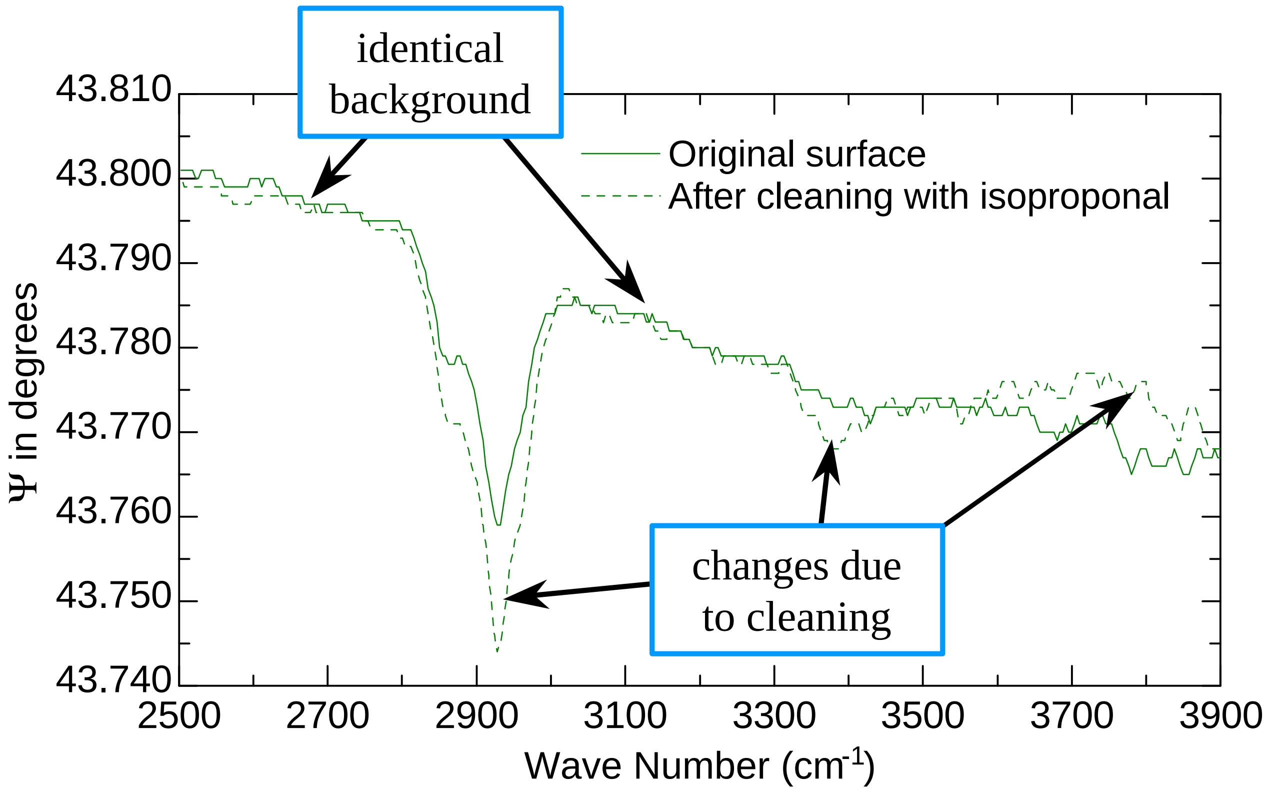


T.E. Tiwald, D.W. Thompson, J.A. Woollam, W. Paulson, and R. Hance, *Thin Solid Films*, **313-314** (1998) pp. 662-667.

SRP: Spreading Resistance Probe

Au Before and After Cleaning

- Sample was removed for cleaning, and remounted for measurement
- Note the high level of both precision and reproducibility in the data



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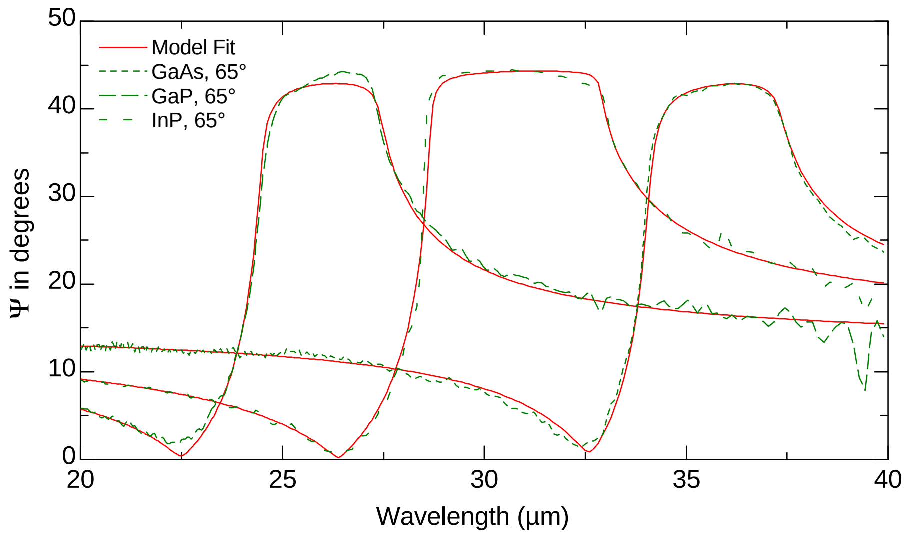
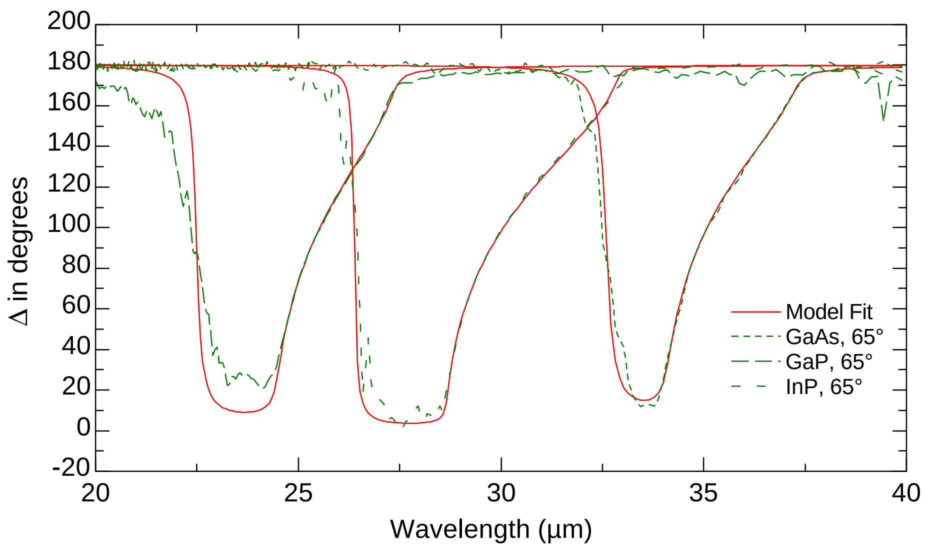
Optical Measurement of Phonon Structure in III-V Semiconductors

- IR-VASE® determined phonon spectra in agreement with published values
- Data fit with simple Restrahlen model; without free-carrier effects
- RCE provides much better data than RAE





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In Situ Spectroscopic Ellipsometry

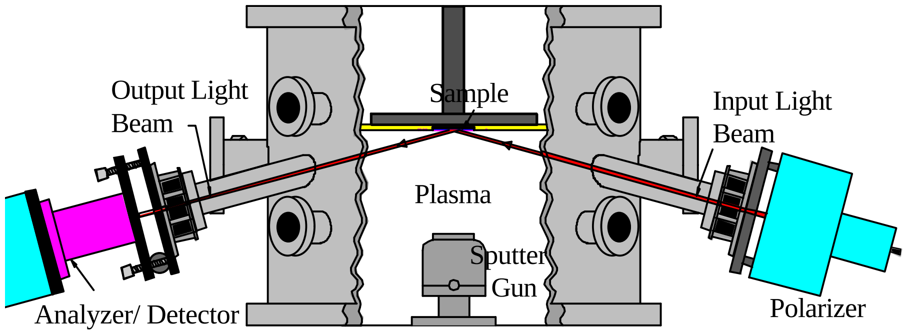
- *In situ* Spectroscopic Ellipsometry has been used in a wide variety of applications:
  - Sputter Deposition
  - Etching (RIE, ECR, …)
  - Electrodeposition
  - e-Beam Evaporation
  - and more...
  - Annealing
  - MBE
  - PVD
  - CVD

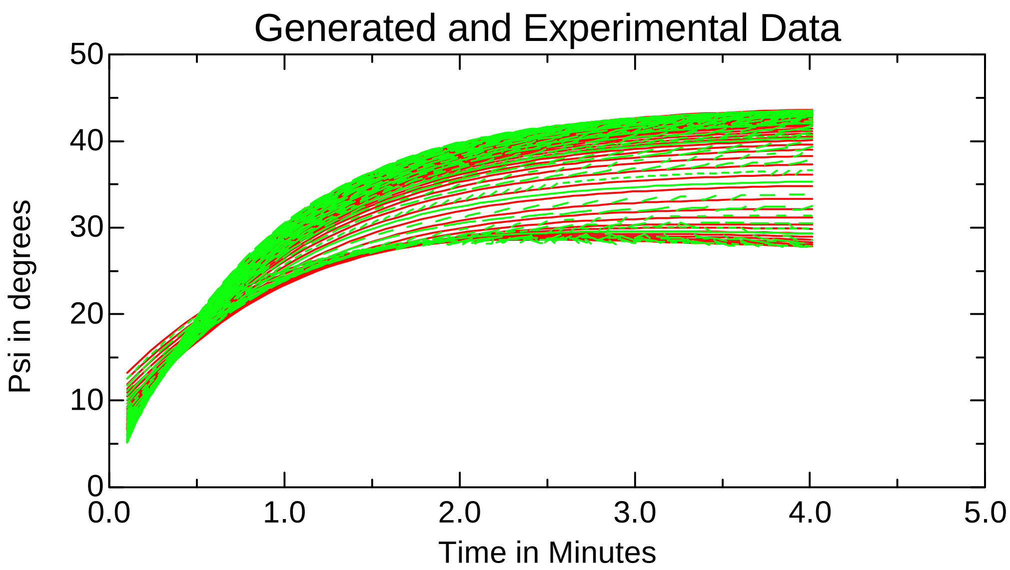
What Can We Measure *In Situ*?

- Substrate Temperature
- Substrate Surface Quality
- Oxide Thickness and Desorption
- Interfacial regions
- Growth Rates
- Substrate and film optical constants
  - (without surface oxide)
- Alloy Composition
- Multi-layer Thickness

UNL Sputter Chamber

- Sputter chamber retrofit with optical ports for *in-situ* ellipsometry.





- Measure growth rate and optical constants for thin films.

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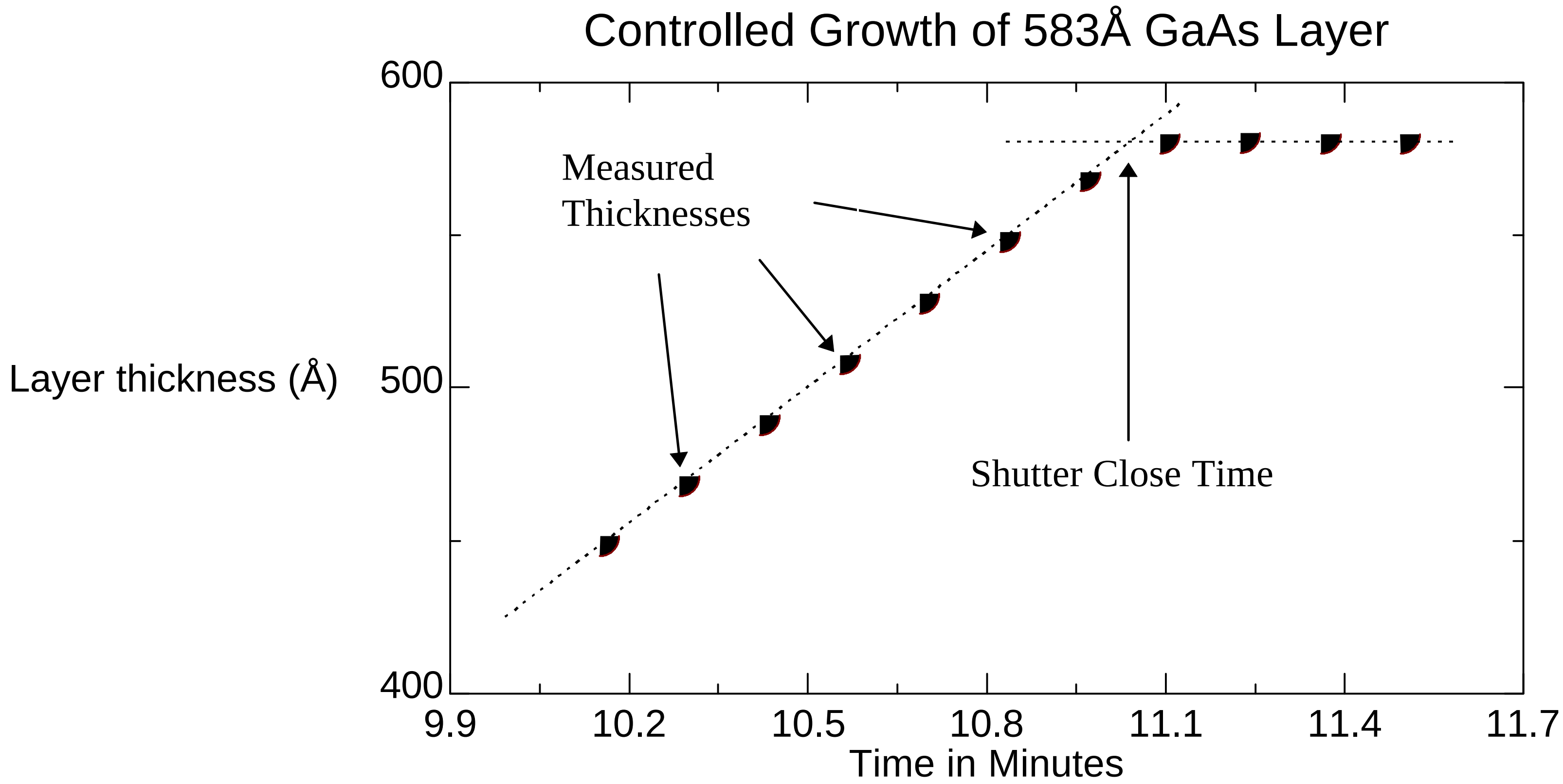
Real-time Thickness Prediction based on last ‘n’ points

- Predict when to turn off process with high precision



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Hg1-xCdxTe (MCT) grown by MBE

Purpose / Goals of *in situ* Ellipsometry:

- Monitor Substrate **Temperature** before growth
  - good quality MCT will grow only in a 10° temperature window

- Monitor Substrate **Surface Quality** before growth
  - the substrate is heated to desorb the oxide

- Monitor and *Control* the MCT **Composition**
  - IR devices *require* a composition accuracy of ±0.001!

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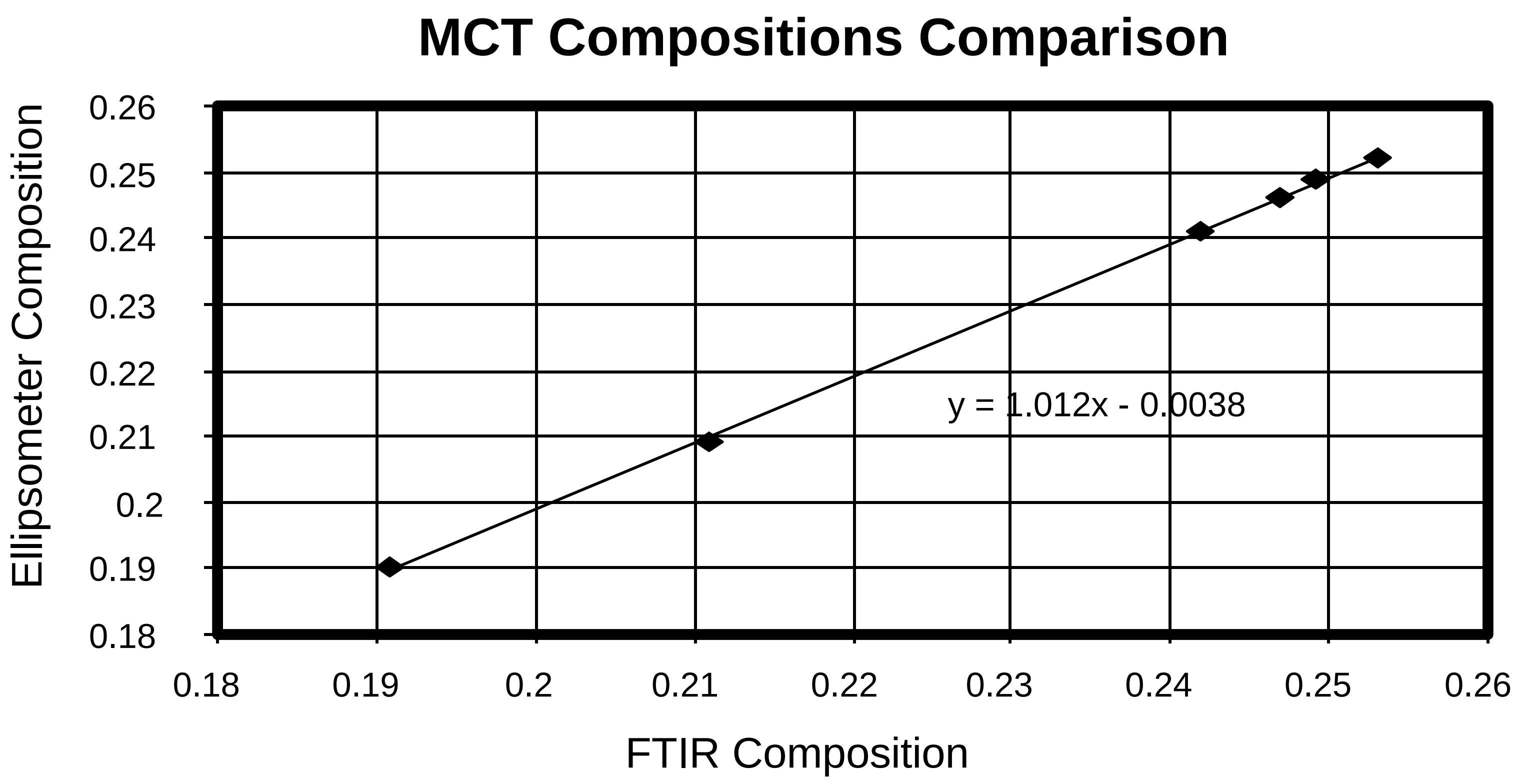
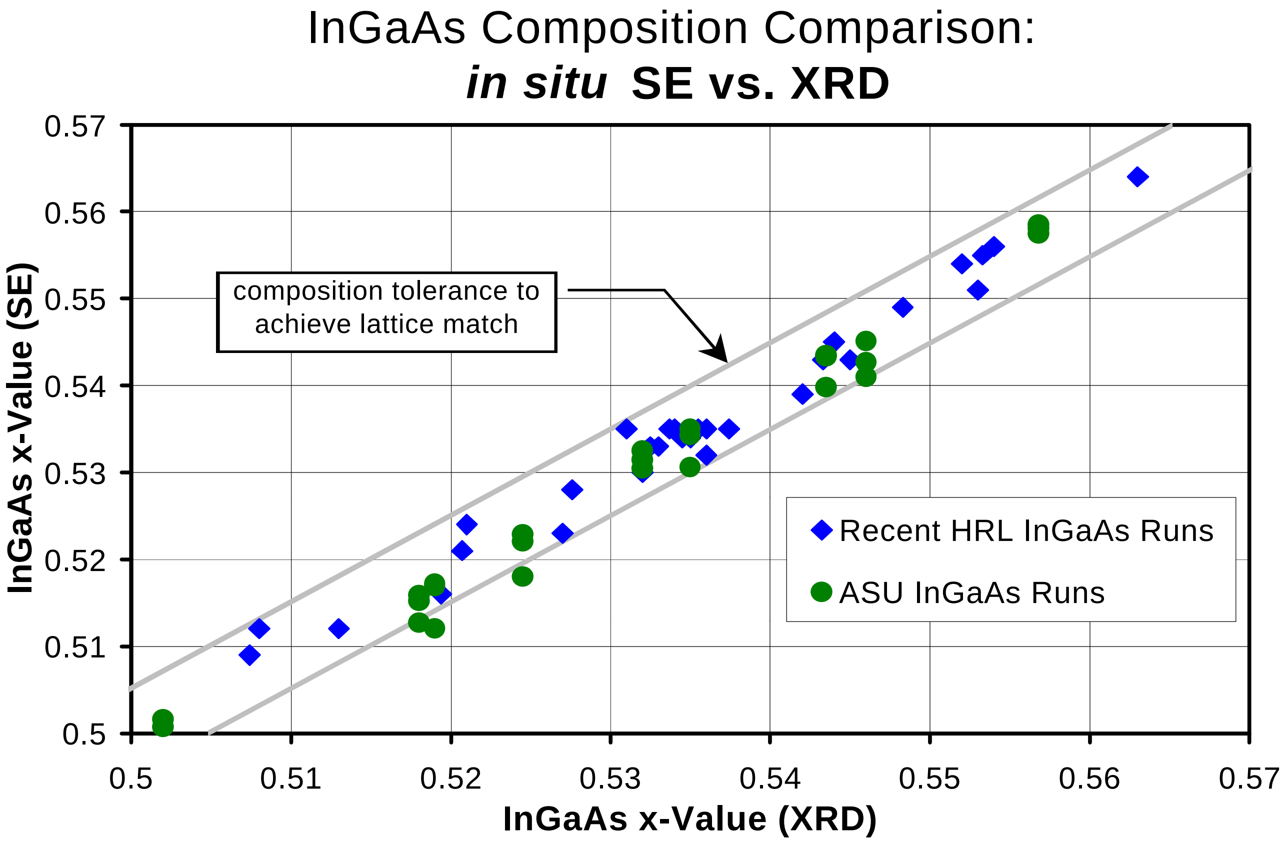
Composition Accuracy

- 6 independent MCT growth runs (without control)
  - post-deposition *in situ* ellipsometry analysis



Long Term Run-to-Run InGaAs Composition Accuracy

- Std. Dev. in SE composition error of ±0.002 achieved over a 6 month period (at ASU)



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Generalized Ellipsometry...

- Does not assume zero off-diagonal components for the Jones matrix. Uses the following relationship…

$$\begin{bmatrix} p_{out} \\ s_{out} \end{bmatrix} = \begin{bmatrix} r_{pp} & r_{sp} \\ r_{ps} & r_{ss} \end{bmatrix} \cdot \begin{bmatrix} p_{in} \\ s_{in} \end{bmatrix}$$

- Thus, a generalized sample is described by…
  - AnE $\tan(\Psi) \cdot e^{i\Delta} = \dfrac{r_{pp}}{r_{ss}}$
  - Aps $\tan(\Psi_{ps}) \cdot e^{i\Delta_{ps}} = \dfrac{r_{ps}}{r_{pp}}$
  - Asp $\tan(\Psi_{sp}) \cdot e^{i\Delta_{sp}} = \dfrac{r_{sp}}{r_{ss}}$

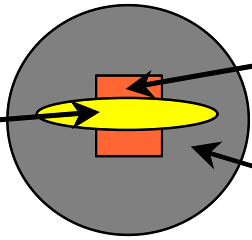
Depolarization Measurements

- Requires AutoRetarder™ or Rotating Compensator (e.g. M-2000®)

- Potential Applications
  - transparent substrates (back-side effects)
  - patterned samples
  - layer thickness non-uniformity
  - finite spectral bandwidth

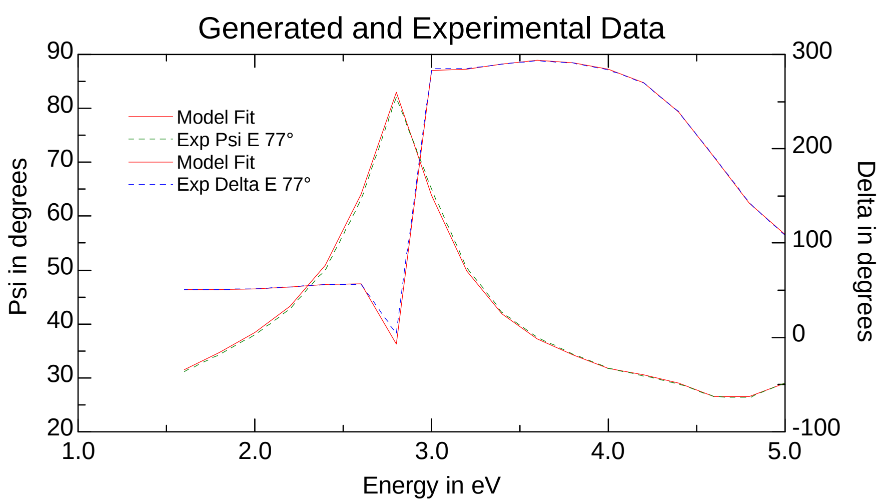
Patterened Samples (depolarization)

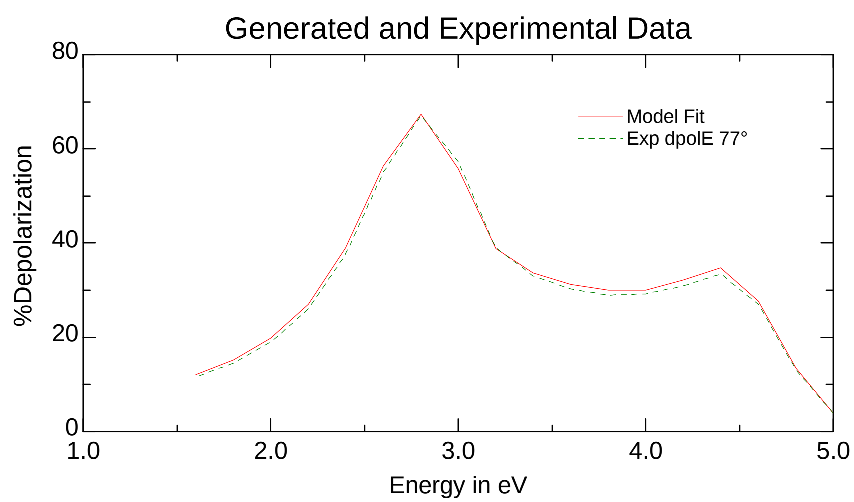
2	oxide_final	98.752 nm
1	oxide_final	1.8176 nm
0	si_final_tabulated	1 mm



MSE=4.605

ThkUni 14.03 (% of unetched area in beam)





B. Johs, et al., "Overview of Variable Angle Spectroscopic Ellipsometry (VASE), Part II: Advanced Applications" SPIE Proc. Vol CR72, (1999) pp. 50-51.

Conclusions

- 142 nm to 200 micron spectral range.
- Variable angle; focusing; mapping; monochromator or diode-based; polarization control: autoretarder.
- Ex situ applications:
  - oxides, poly-silicon, stacks, photoresists, surface contamination/cleaning, optical constants.
  - Advanced applications: graded layers, anisotropy, depolarization, patterned material.
- In situ monitor/control of:
  - Growth/etch, thickness, temperature, composition