TRANSPARENT MATERIALS

SESSION 2

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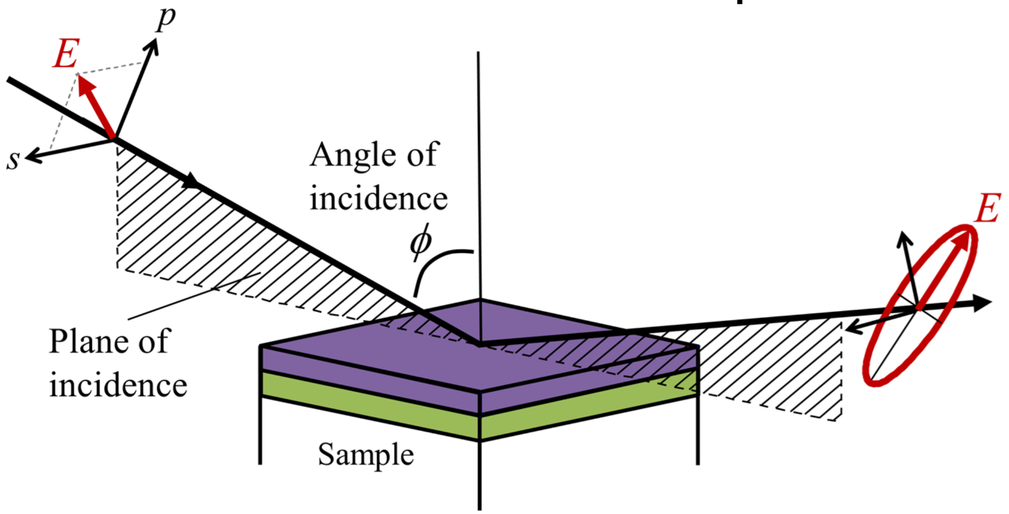
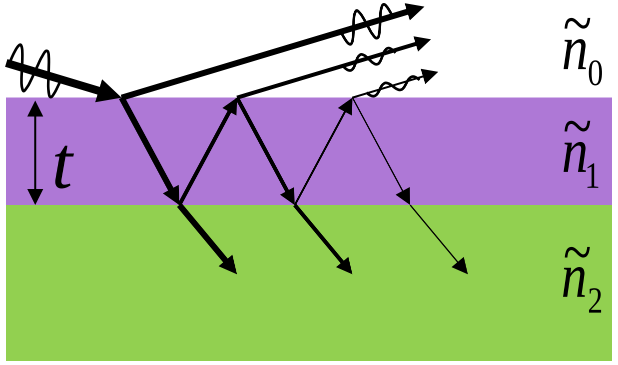
Course Outline

- Session 1: Introduction to Ellipsometry
- **Session 2: Transparent Materials**
- Session 3: Absorbing Materials using B-Spline
- Session 4: Semi-absorbing films using Gen-Osc
- Session 5: Thin Absorbing Films & Multi-Sample Analysis
- Session 6: Advanced Topics and Review





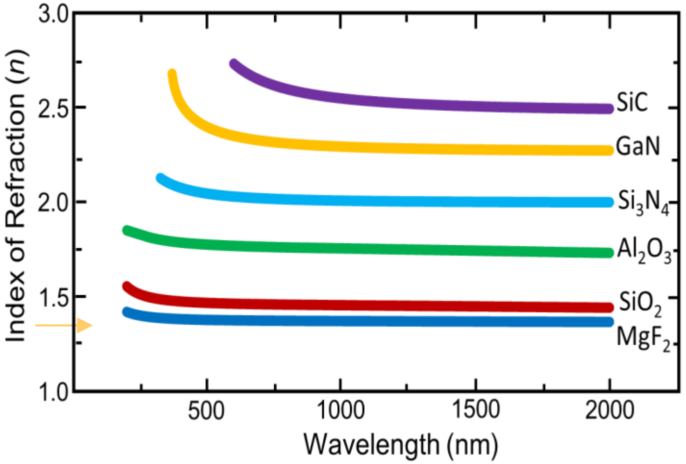
Material Optical Category

$$\tilde{n} = n - ik$$

$$\tilde{\varepsilon} = \varepsilon_1 - i\varepsilon_2$$

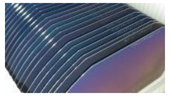
$$\tilde{\varepsilon} = \tilde{n}^2$$

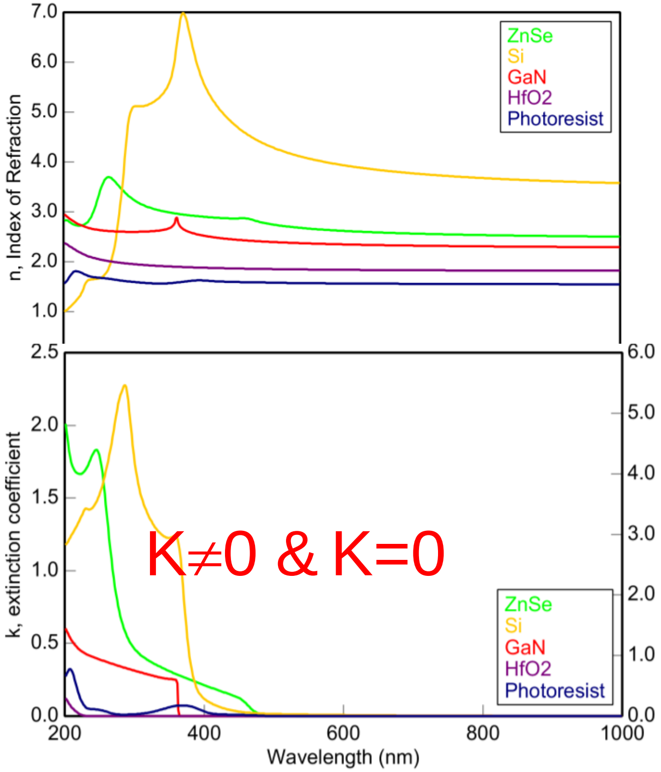
Transparent



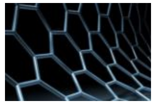
K=0

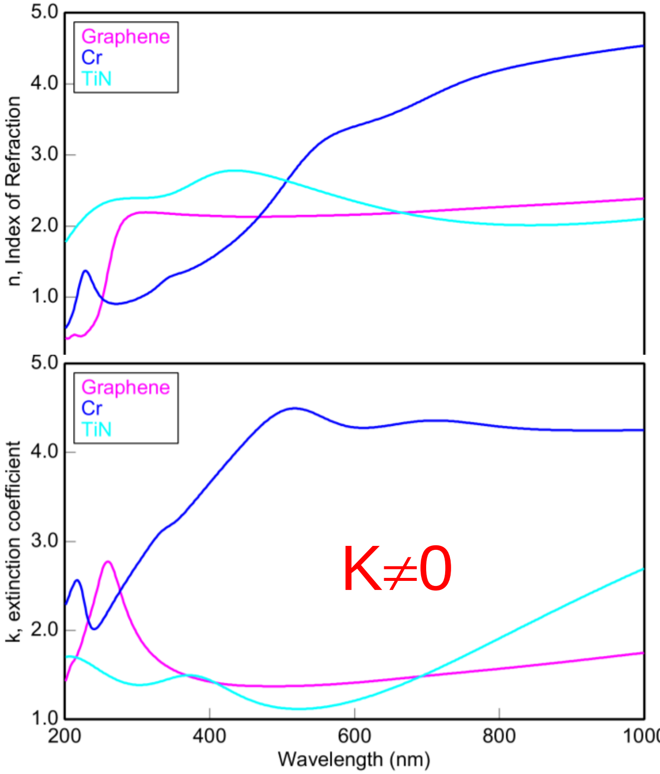
Semi-absorbing





Absorbing





Session 2: Transparent Films

A. Transparent Thin Films
   - Built-in Model
   - Ultra-thin films
   - Identify transparent region

B. Thin Film Complexities

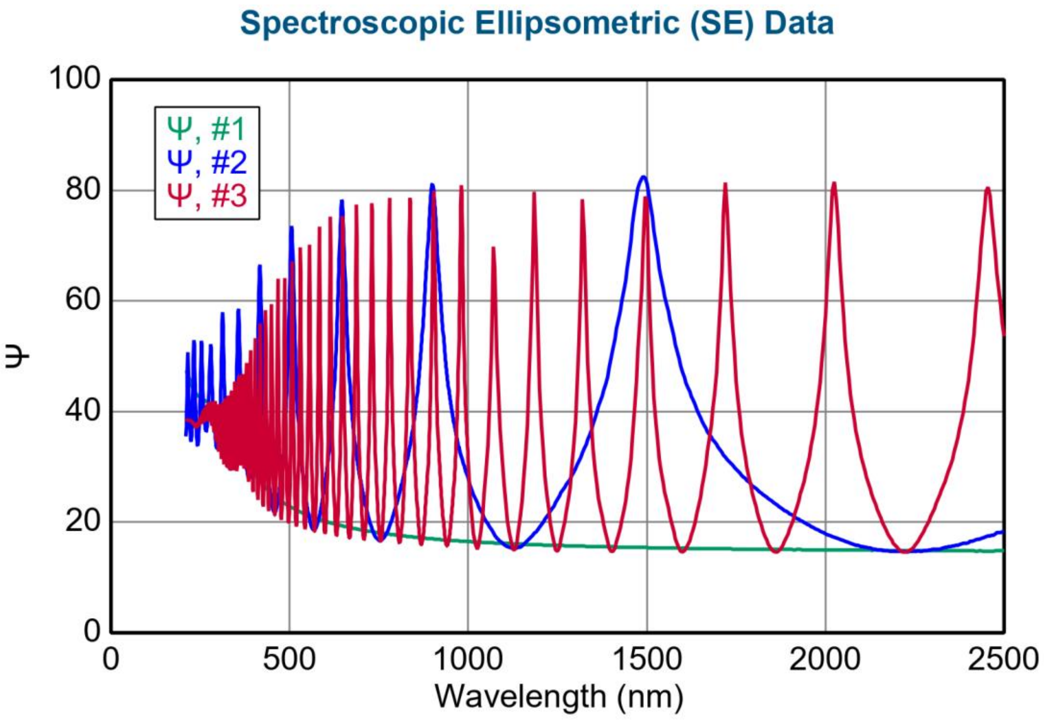
2A: Transparent Thin Films

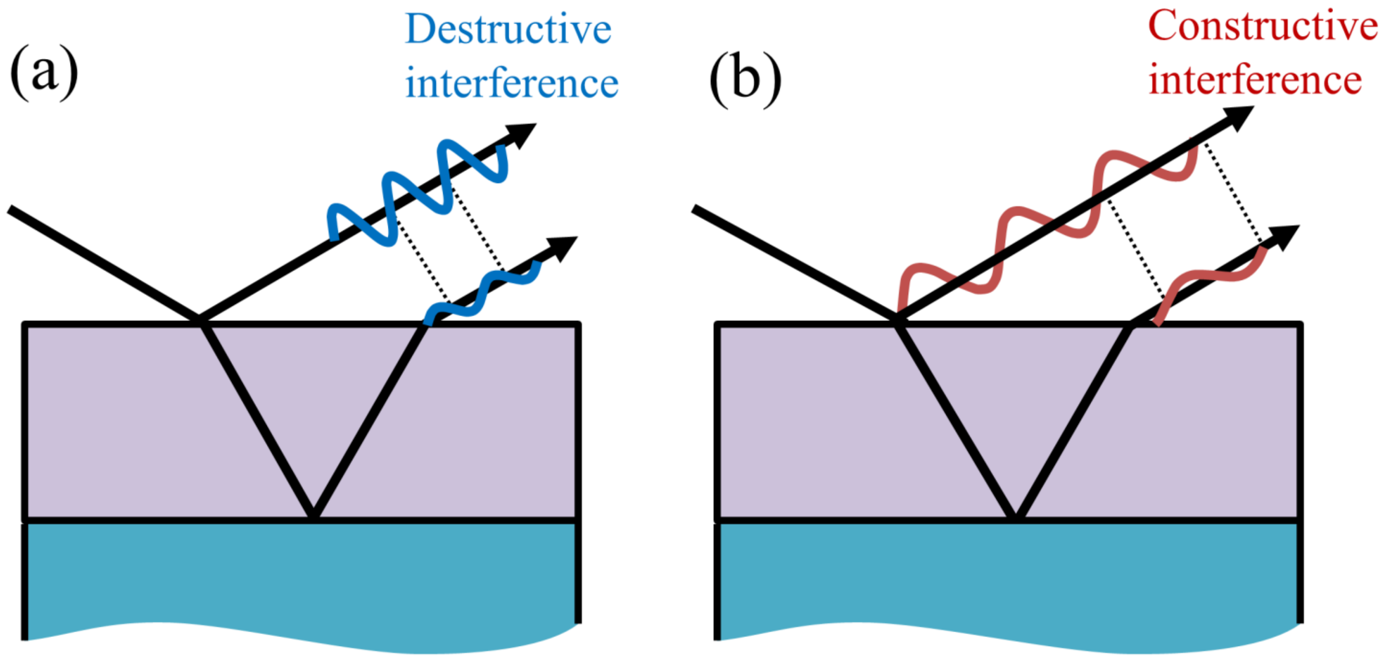
- Identify wavelengths where the film is transparent.
- Determine thickness and index (*n*) for any transparent film.
- Create model for similar samples.

- Data Features
- Modeling and Automation
  - Cauchy Dispersion Equation
  - Built-in model
- Saving Results

Data Features – Transparent Films

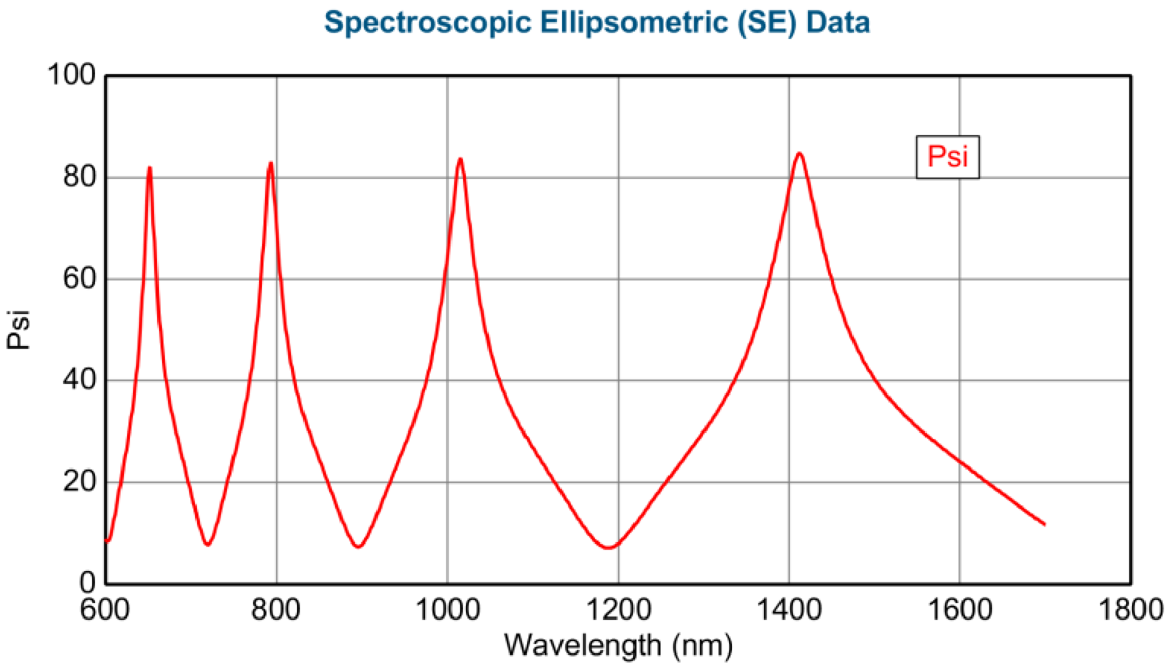
- Data curves oscillate resulting from interference effect.
  - The mixing of light from top and bottom of film with different path lengths causes interference that results in peaks and valleys in data.

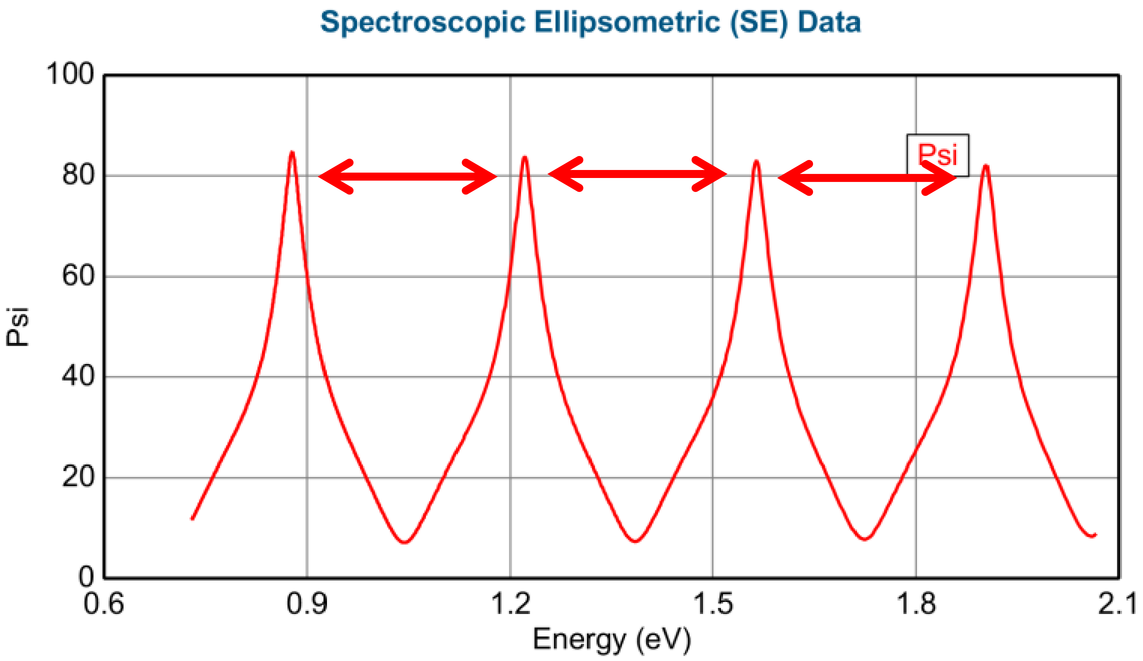




Thin Film Interference

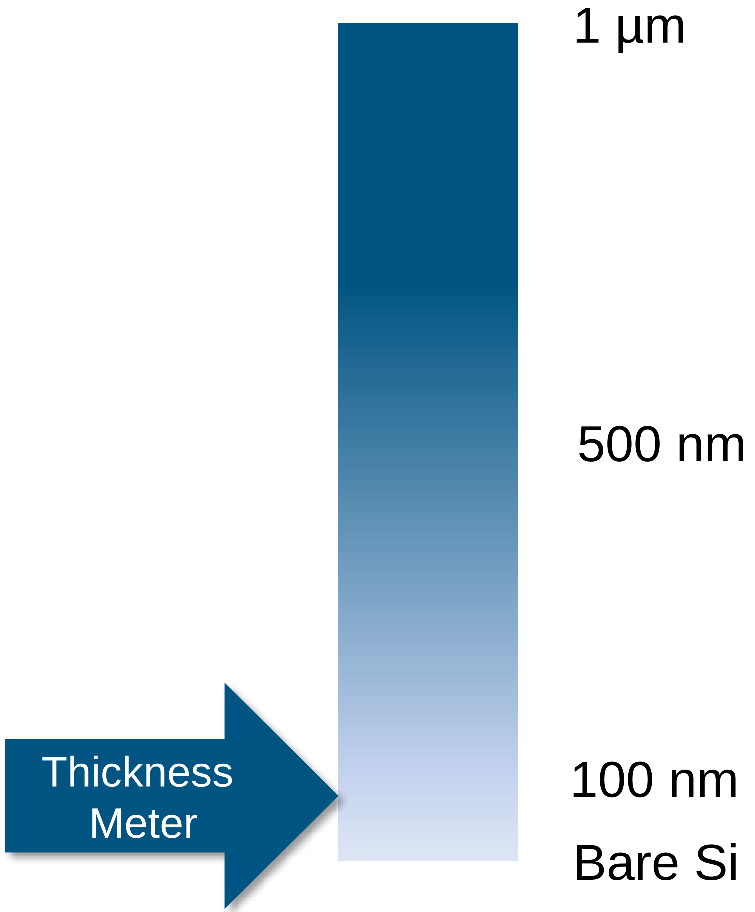
- Pattern affected by thickness <u>and</u> index of refraction (n).

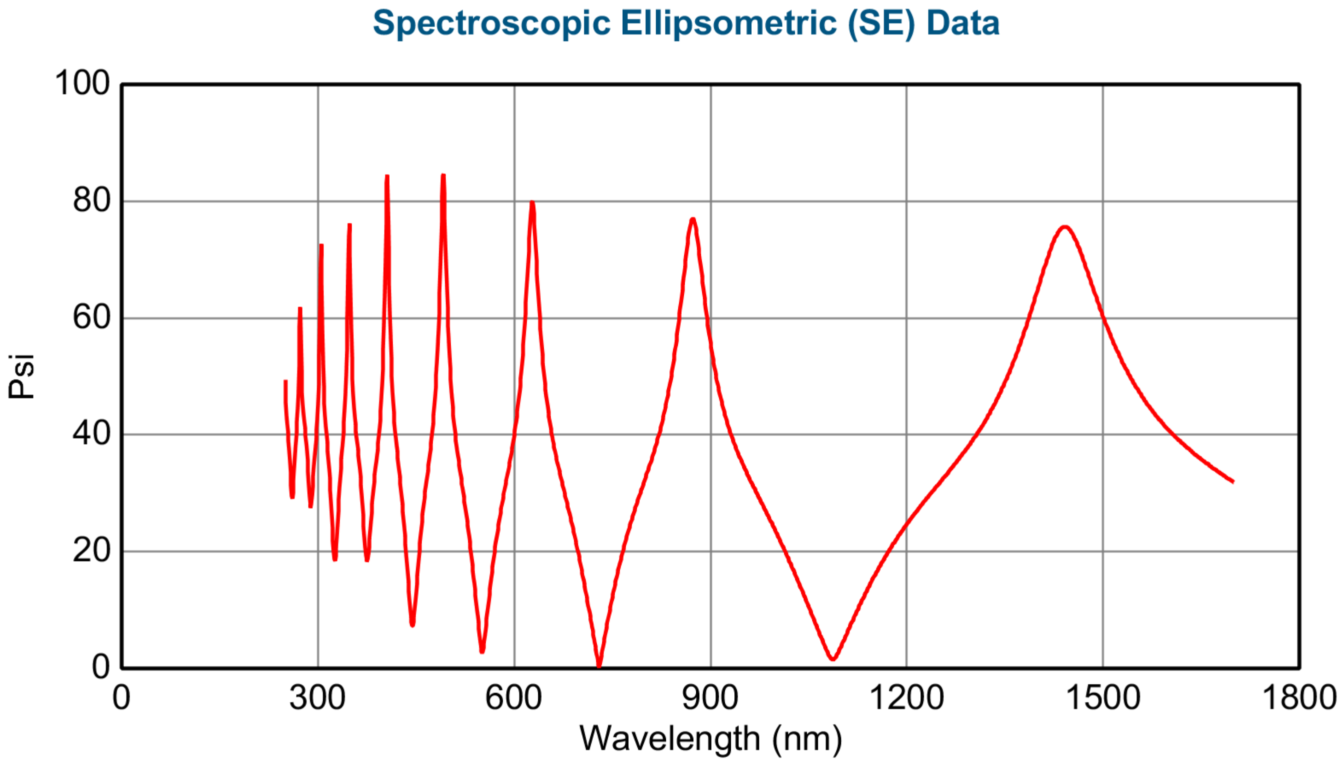




Thickness Effects

- # of oscillations ~ thickness
- Thicker films = more interference oscillations



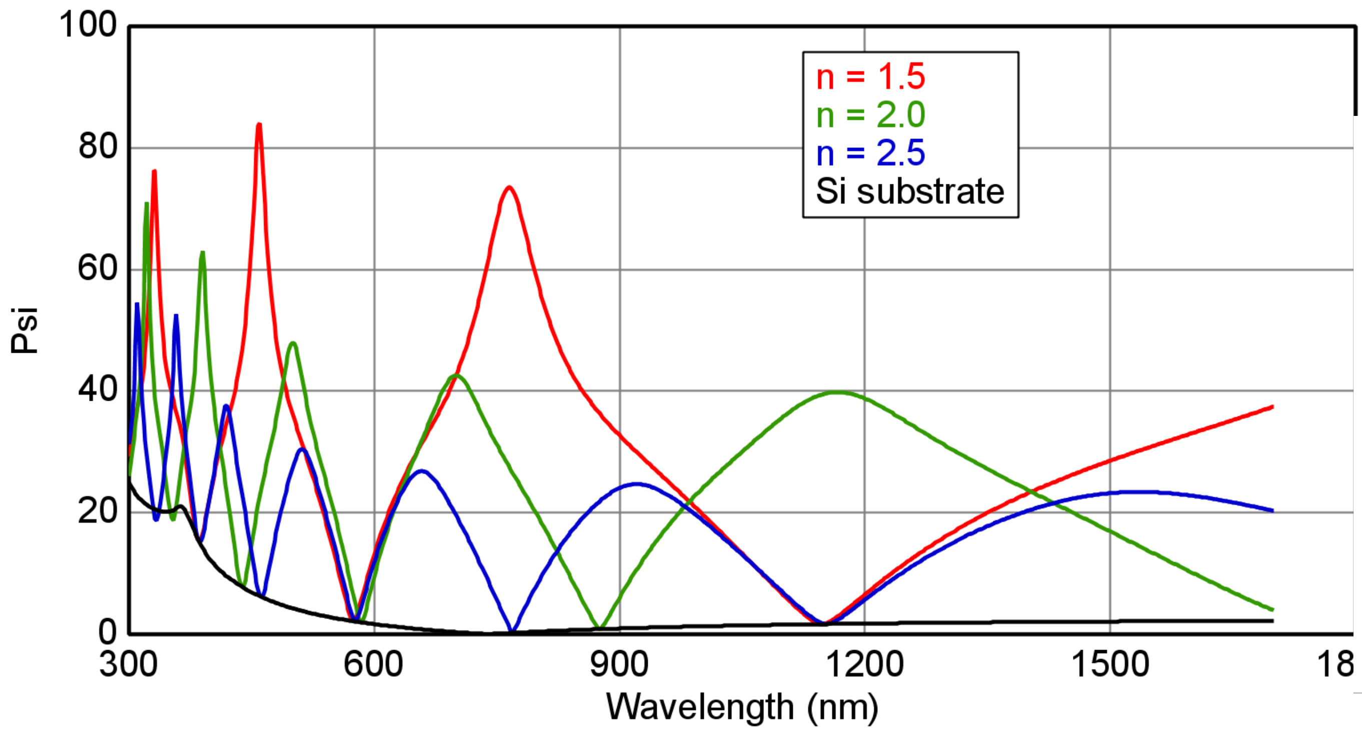


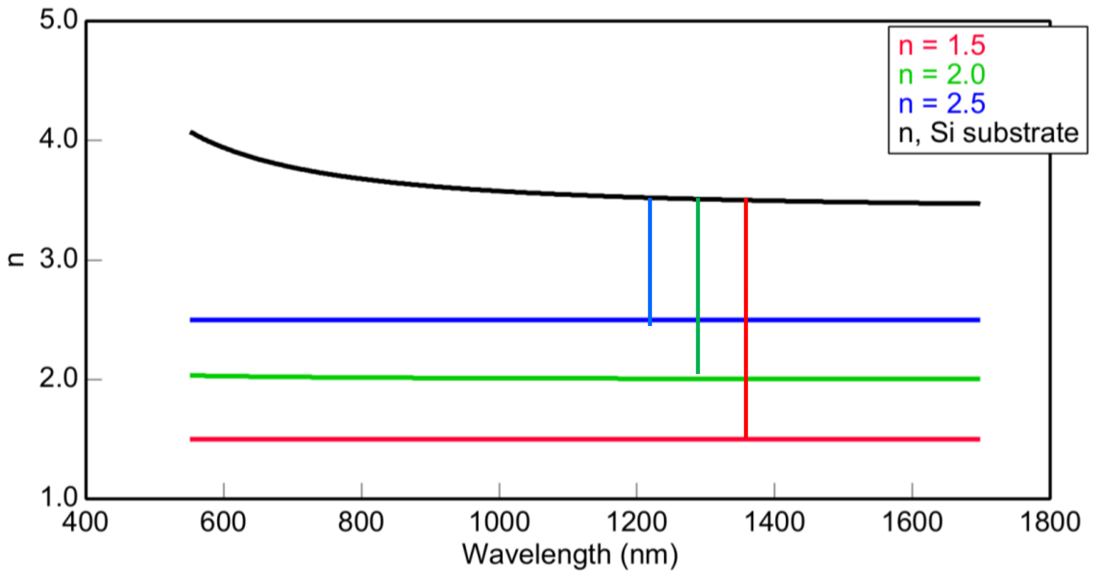
Index Effects

- Psi magnitude ~ index <u>difference</u> between film & substrate.
- Greater index difference = greater amplitude.
- Index also affects # of oscillation fringes.

Index changes phase velocity <u>and</u> reflected amplitudes at each interface

Spectroscopic Ellipsometric (SE) Data





Fitting Transparent Thin Films

I

Use Existing MATERIAL files

II

Use CAUCHY

III

Use AUTOMATED MODEL

Using Existing Mat files

- Refractive index of a film is fixed to predetermined values.
- Determine ONLY thickness.
- Works well when layer is stable and consistent, such as Si or silicon thermal oxide.
- Useful when ellipsometry lacks sensitivity to refractive index, such as ultra-thin films or in multi-layer stack.

I

Use Existing MATERIAL files

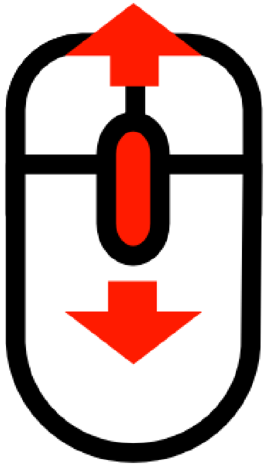
2-01 Thermal SiO_2 on Si

- **Determine thickness using existing optical constants.**

Use Existing MATERIAL files

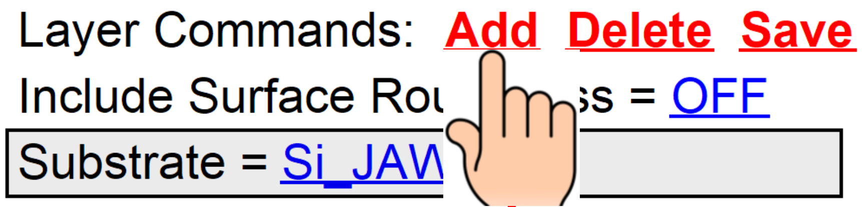
- Use “Si_JAW.mat” for substrate
- Add “SiO2_JAW.mat” for layer.
- Adjust thickness and fit.

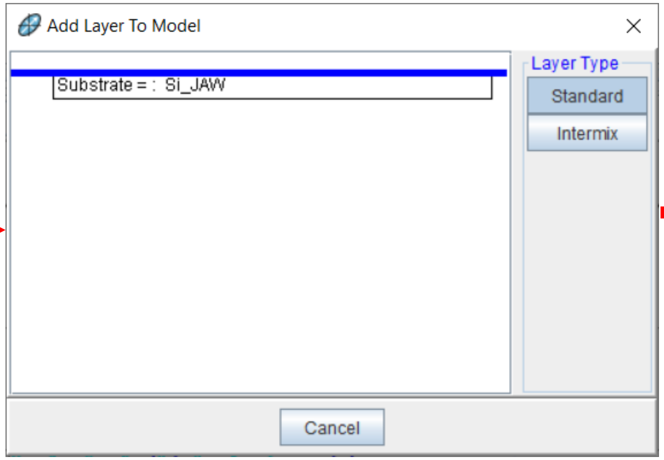
Use Roller-Wheel over the thickness
SHIFT X10
or
CTRL-SHIFT X1

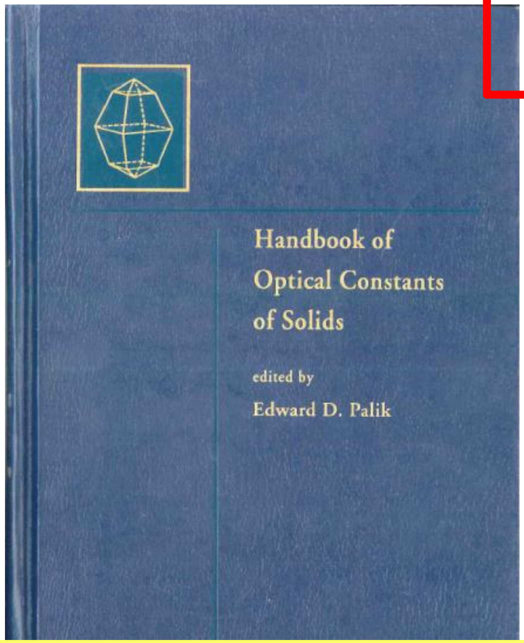


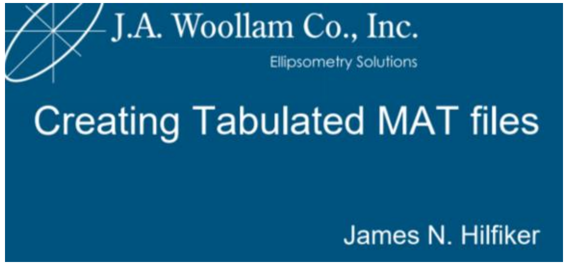
Existing Material Files

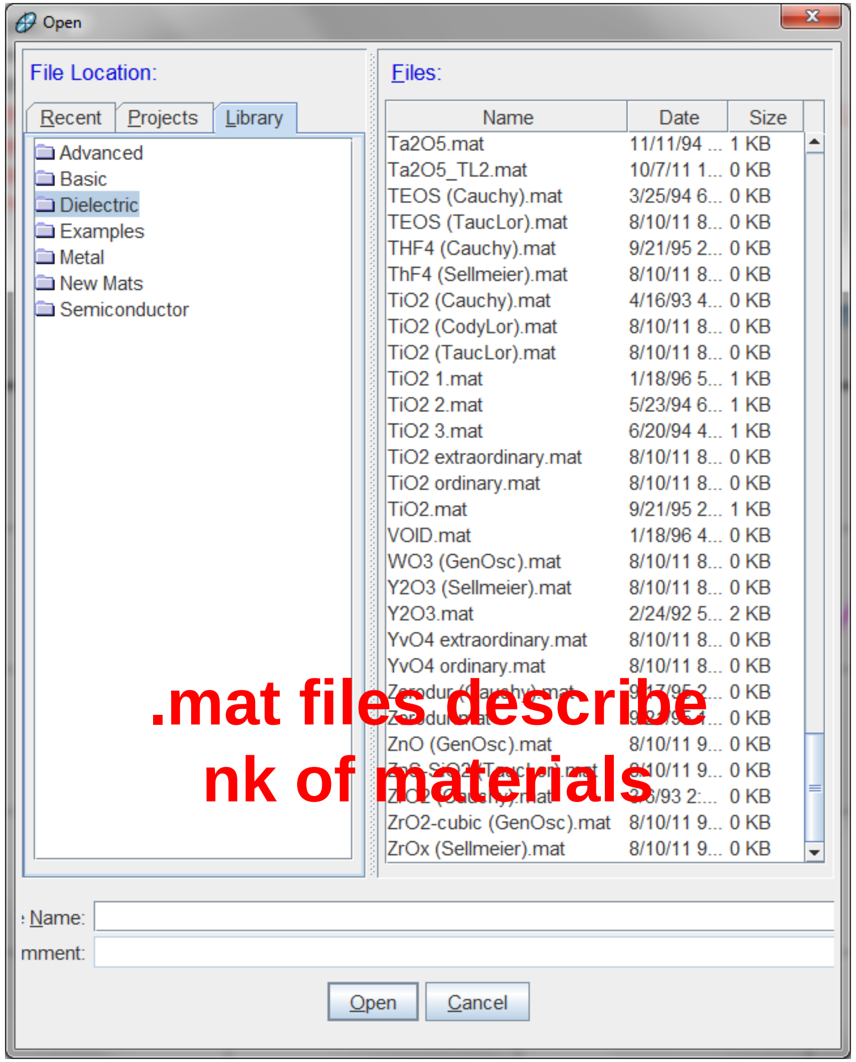
Use Existing MATERIAL files









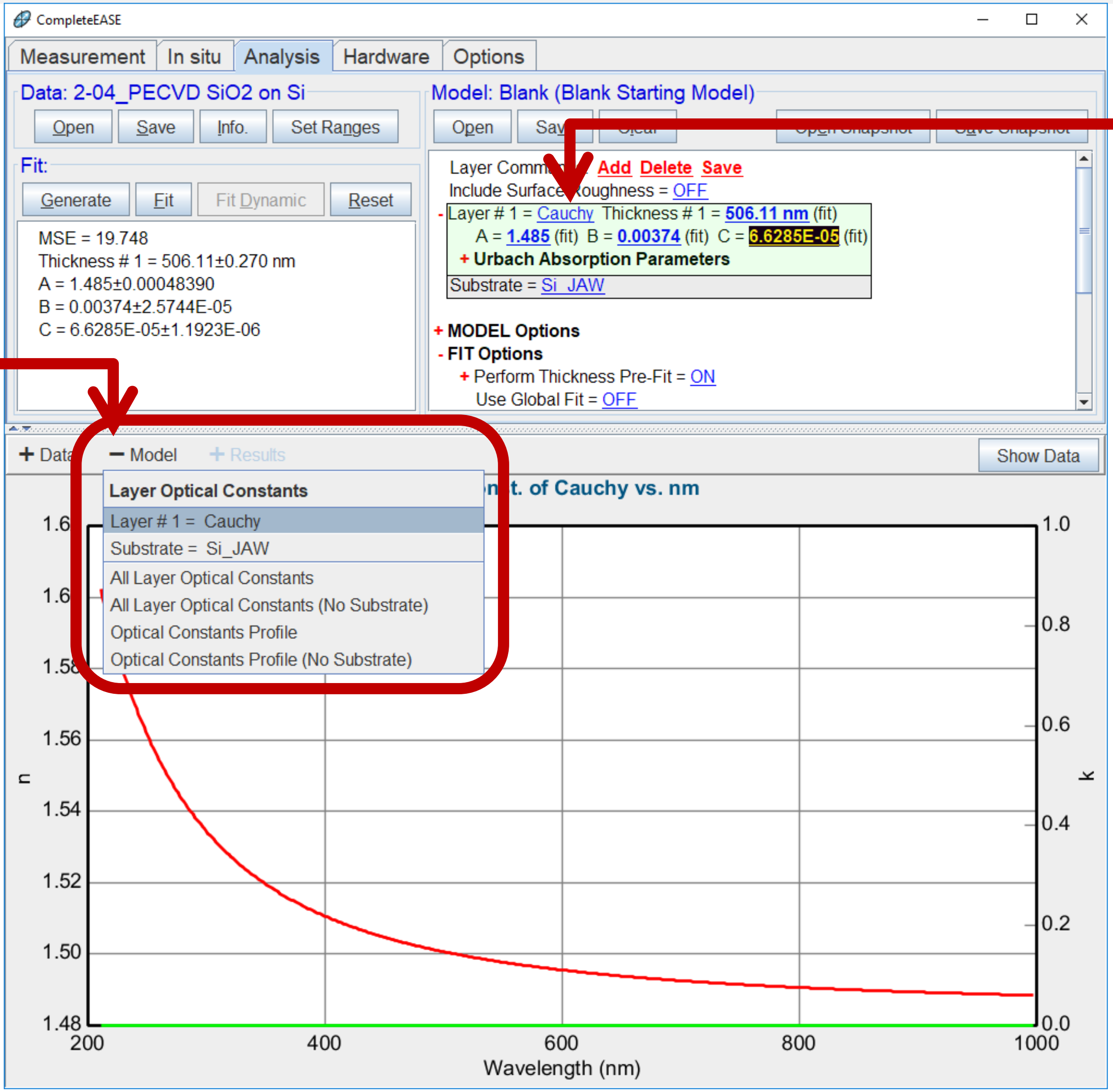


.mat files describe nk of materials

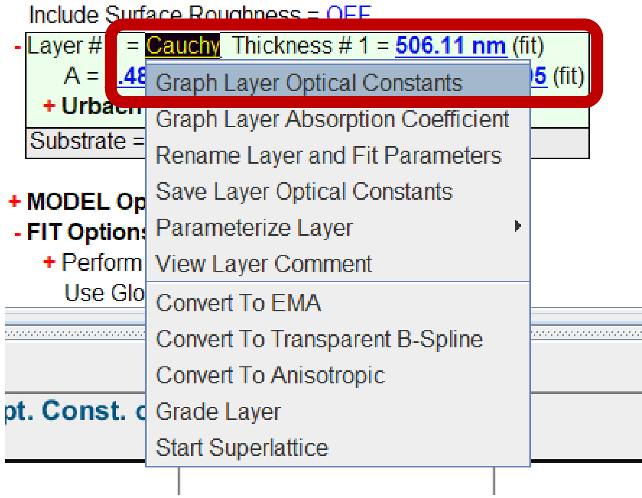
Palik, E. D. Handbook of Optical Constants of Solids (3 Volumes) Academic Press, San Diego, 1998.

Viewing Optical Constants

Left-Click on Model menu, choose Layer



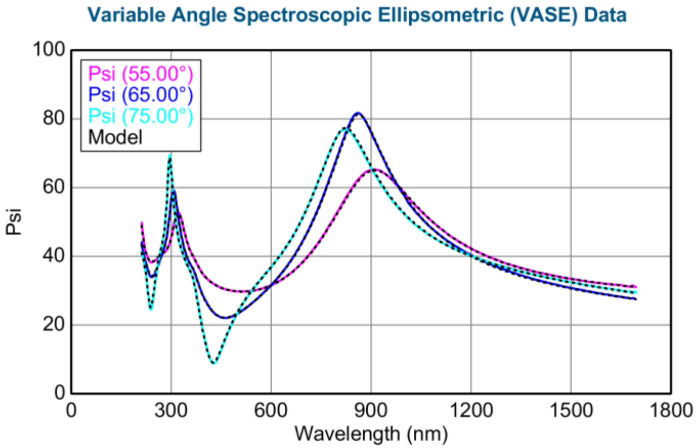
Right-Click on Layer Name

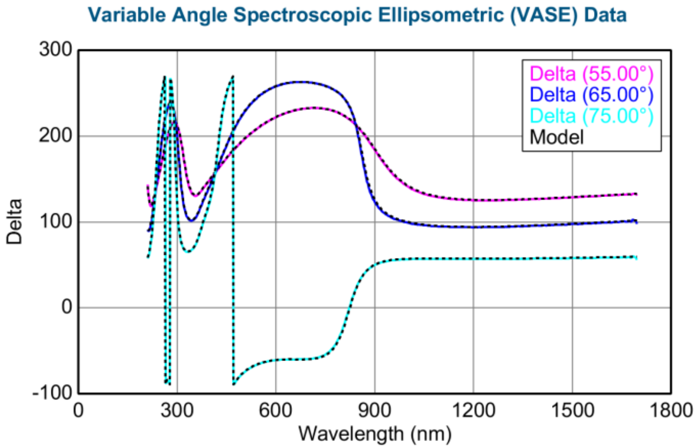


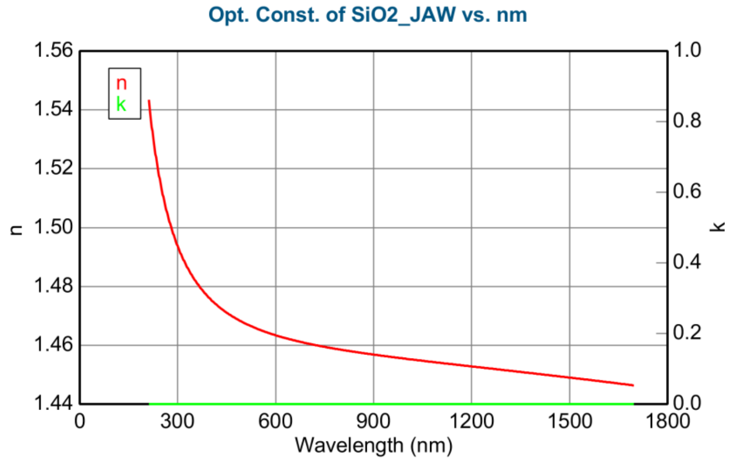
2-01 Thermal SiO_2 on Si: Results

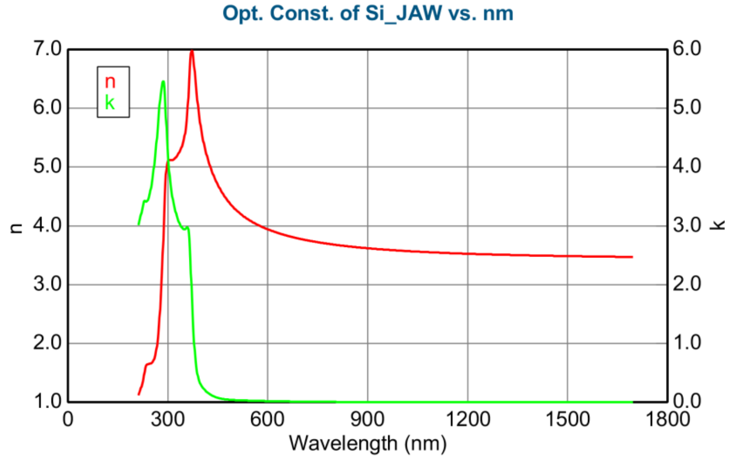
Fit Results	**Optical Model**
MSE = 9.439 Thickness # 1 = 188.72 ± 0.011 nm	Layer # 1 = SiO2_JAW Thickness # 1 = **188.72 nm** (fit) Substrate = Si_JAW

Experimental and Model Generated Data Fits









Si with Thermal Oxide Built-in Models

Systems with wvls up to 1700nm

Layer # 2 = SIO2_JAW Thickness # 2 = **100.00 nm** (fit)
Layer # 1 = INTR_JAW Thickness # 1 = 1.00 nm
Substrate = SI_JAW

- **MODEL Options**

  Angle Offset = **0.00** (fit)

RC2 XNIR Systems (wvls up to 2500nm)

+ Layer # 2 = SiO2_uniaxial_JAW3 Thickness # 2 = **1000.00 nm** (fit)
Layer # 1 = Intr_JAW3 Thickness # 1 = 1.00 nm
Substrate = Si_JAW3

- **MODEL Options**

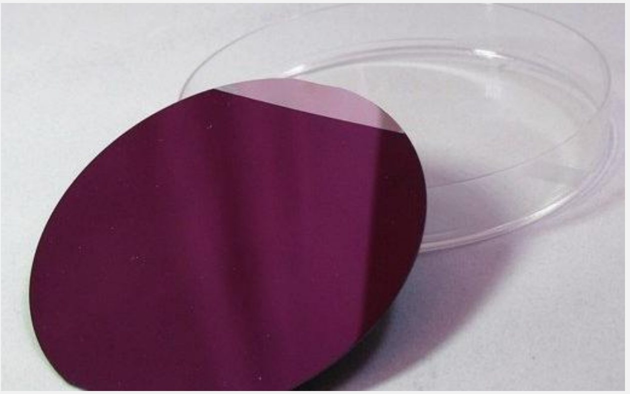
  Angle Offset = **0.00** (fit)

- Built for silicon with thermal oxide samples
  - Backside reflection not included.
- Recommend to use for system health check
- Angle offset is a hardware parameter and should not be sample-dependent for ex-situ systems
  - Only be validated with calibration wafers

*C. M. Herzinger et al, *Ellipsometric determination of optical constants for silicon and thermally grown silicon dioxide via a multi-sample, multi-wavelength, multi-angle investigation*, Journal of Applied Physics, 83,6,3323 (1998)

(2-02) Ta_2O_5 on Si

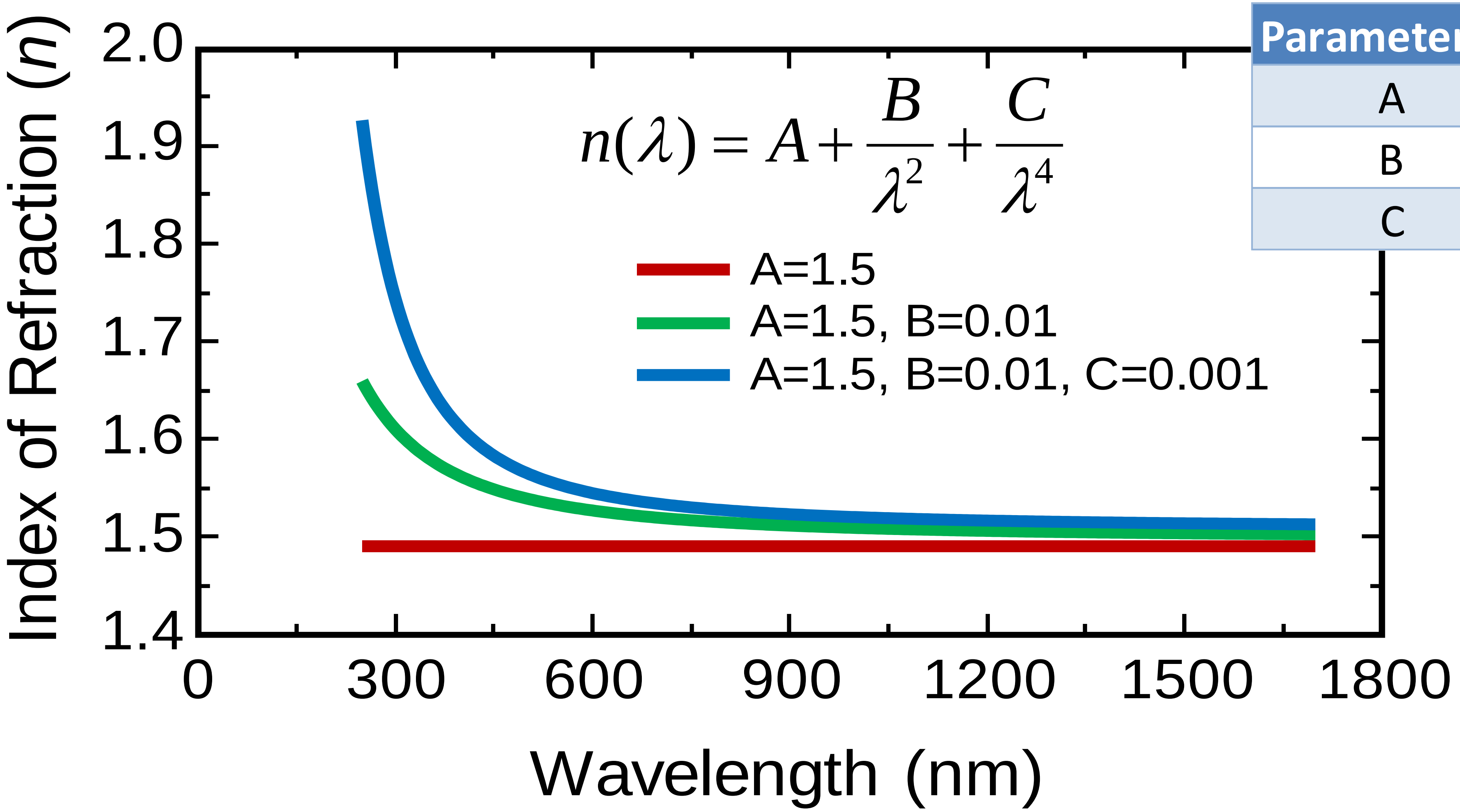
- **Fit data using Ta2O5.mat**



Use Existing MATERIAL files

- Copy index of refraction to Graph Scratchpad
- What can be done to further improve the fit?

Cauchy Parameters



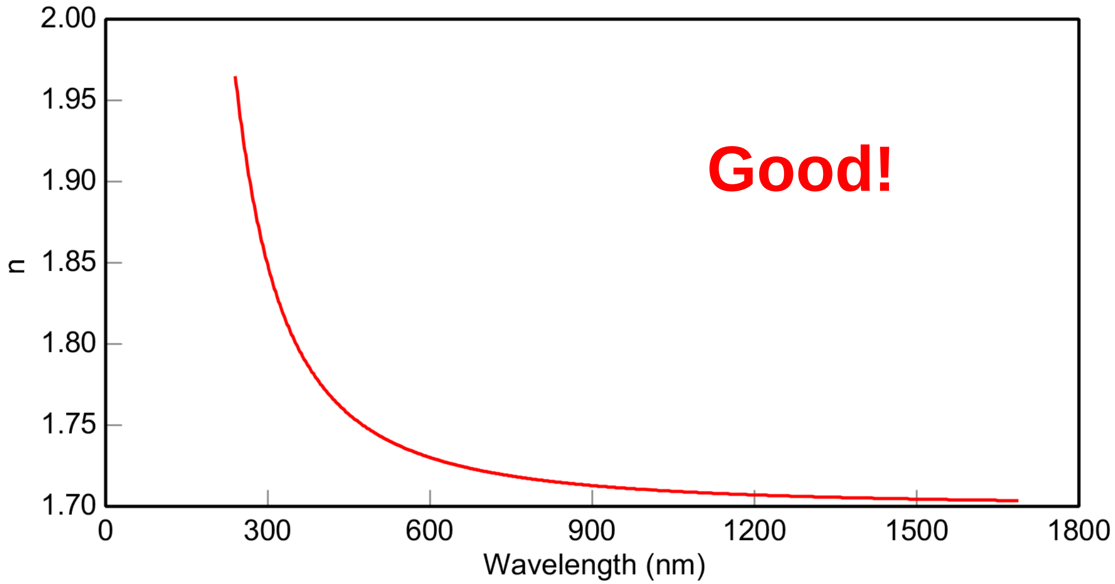
Parameter	Typical Range
A	1.3-2.5
B	0.005-0.05
C	0.0000-0.005

Physicality of Cauchy Dispersion

Physical

- Transparent index of refraction <u>must</u> increase with decreasing wavelengths (referred to as **normal dispersion**)

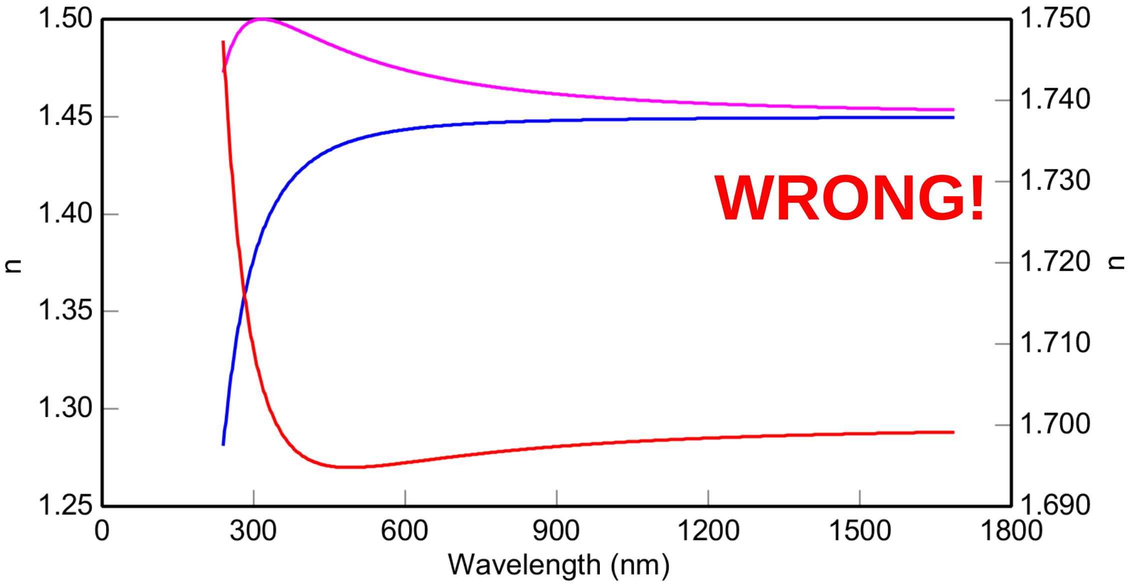
Physical Cauchy Index of Refraction



Unphysical

- If transparent index of refraction (n) decreases towards shorter wavelengths.
- <u>Possible solutions</u>
  – Reset C=0
  – Reduce the wavelength range
  – Add absorption

Unphysical Cauchy Index of Refraction



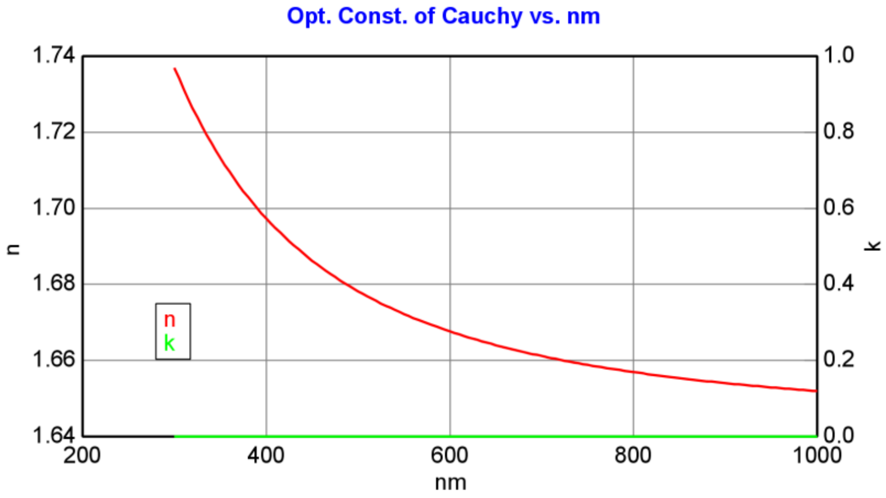
Which results are physical?

A

A= 1.643

B= 0.009

C= -4.8600E-05

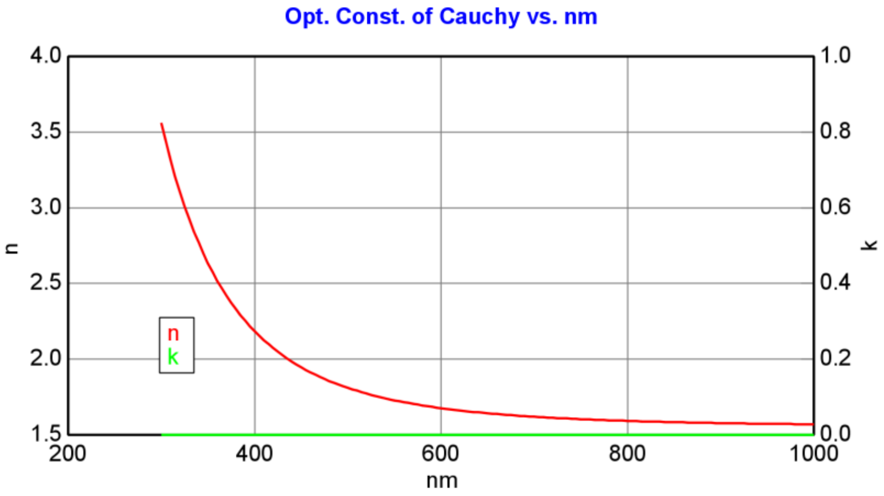


B

A= 1.555

B= -0.00177

C= 0.01640

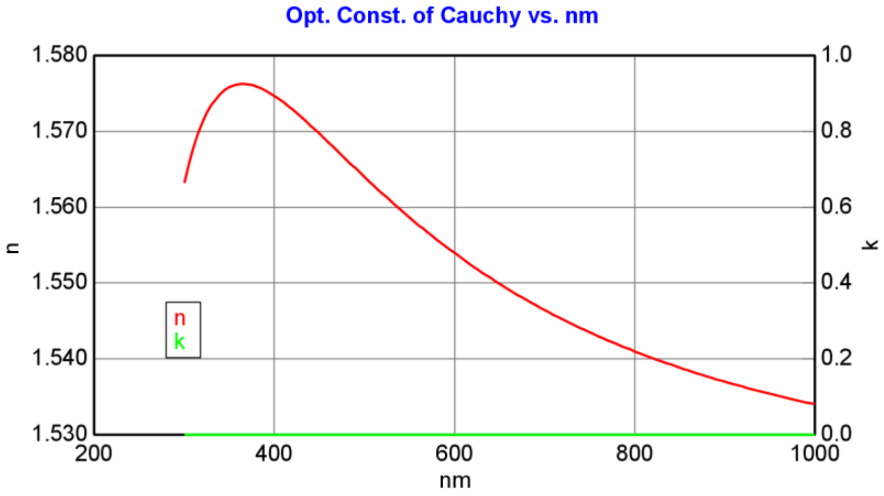


C

A= 1.520

B= 0.015

C= -0.001

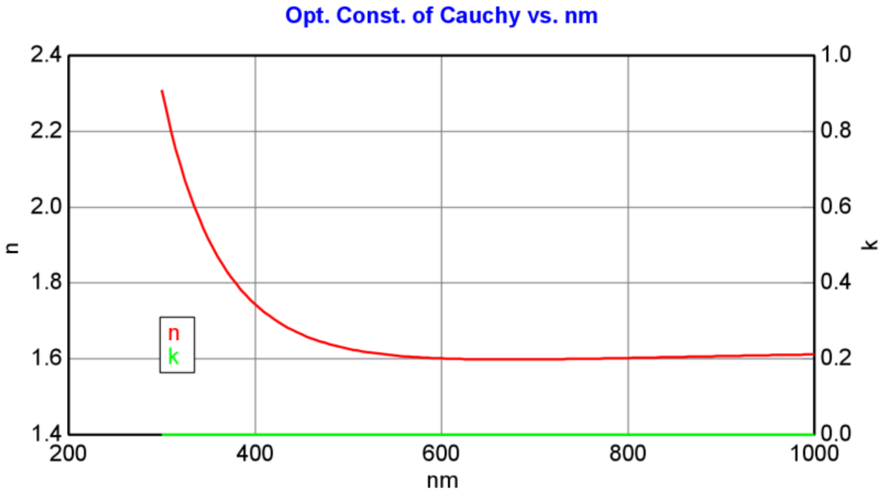


D

A= 1.643

B= -0.04009

C= 0.009



Cauchy Procedure

II

Use CAUCHY

Estimate Index
(Cauchy-A)

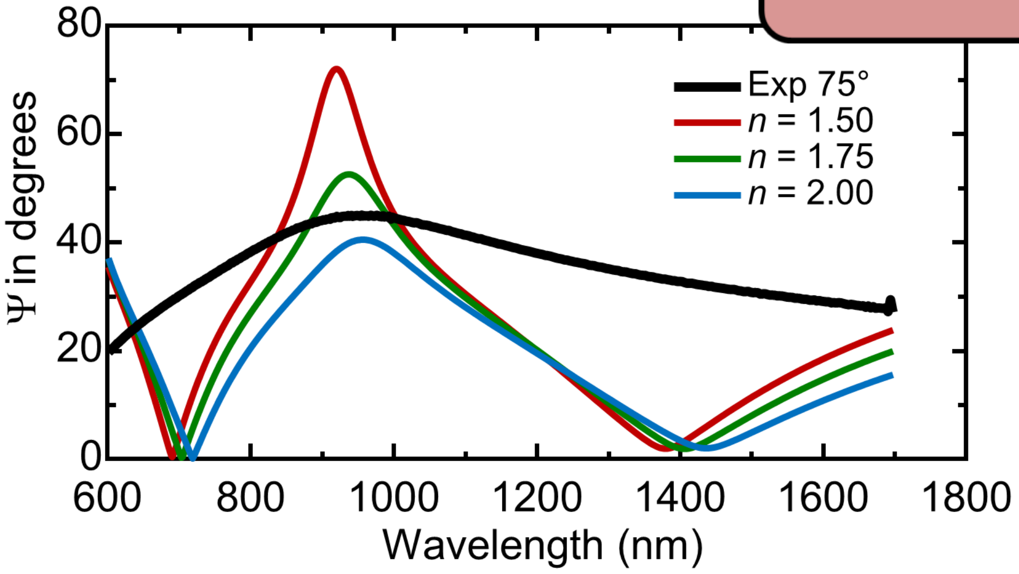
⇩

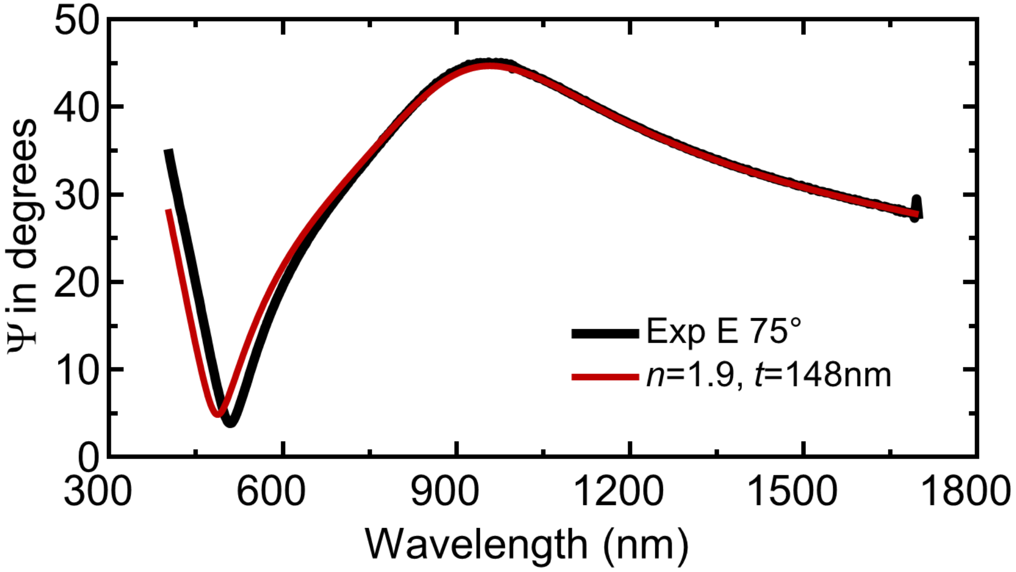
Estimate Thickness

⇩

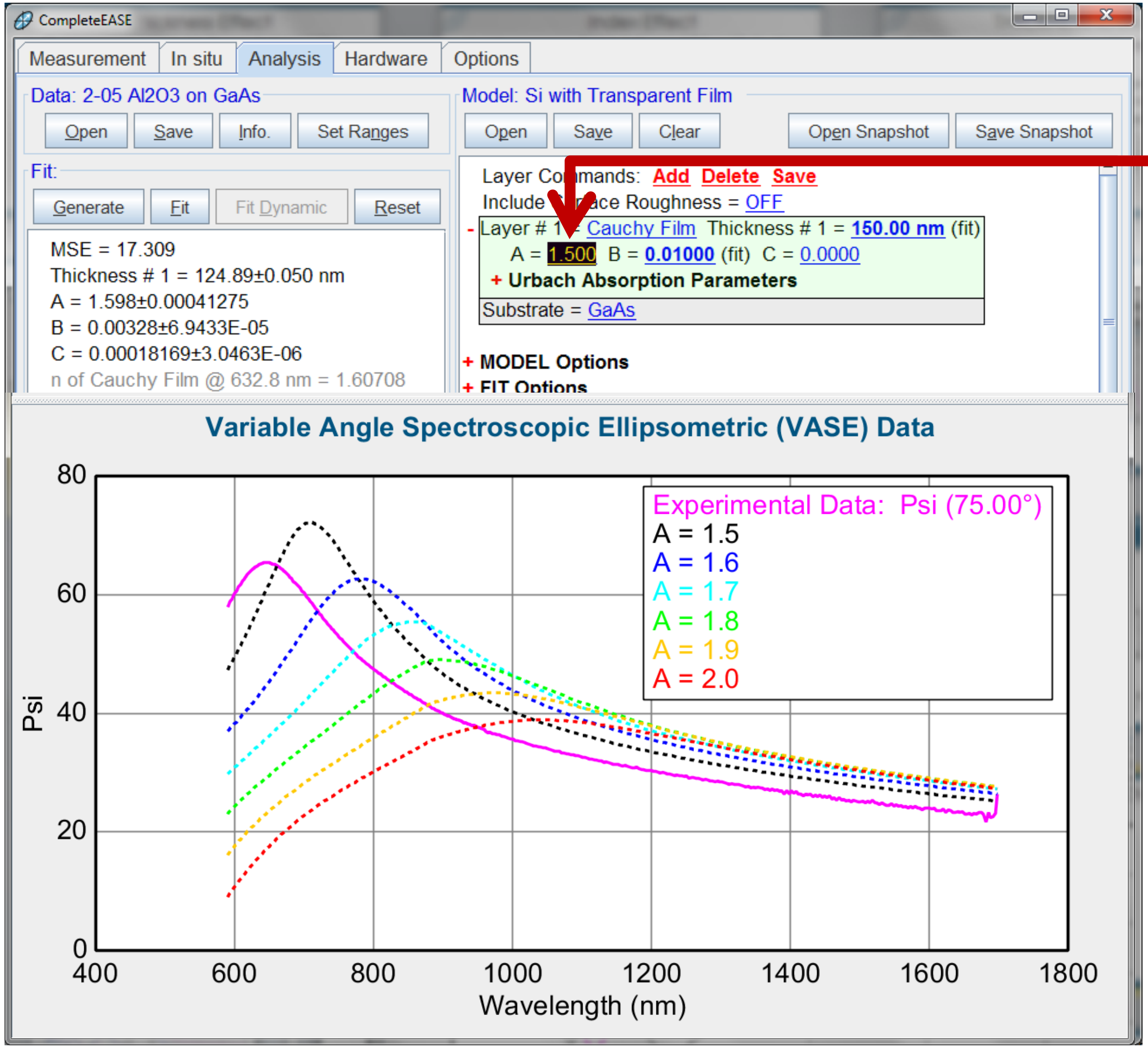
Fit Thickness & Cauchy Parameters

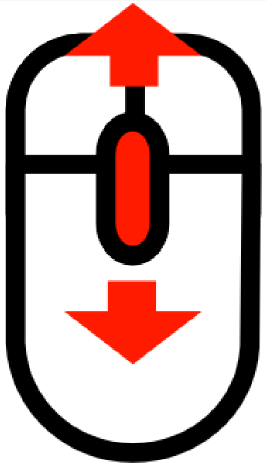
Start with B = 0.01 and C=0, only add at end if needed





Estimating the Index





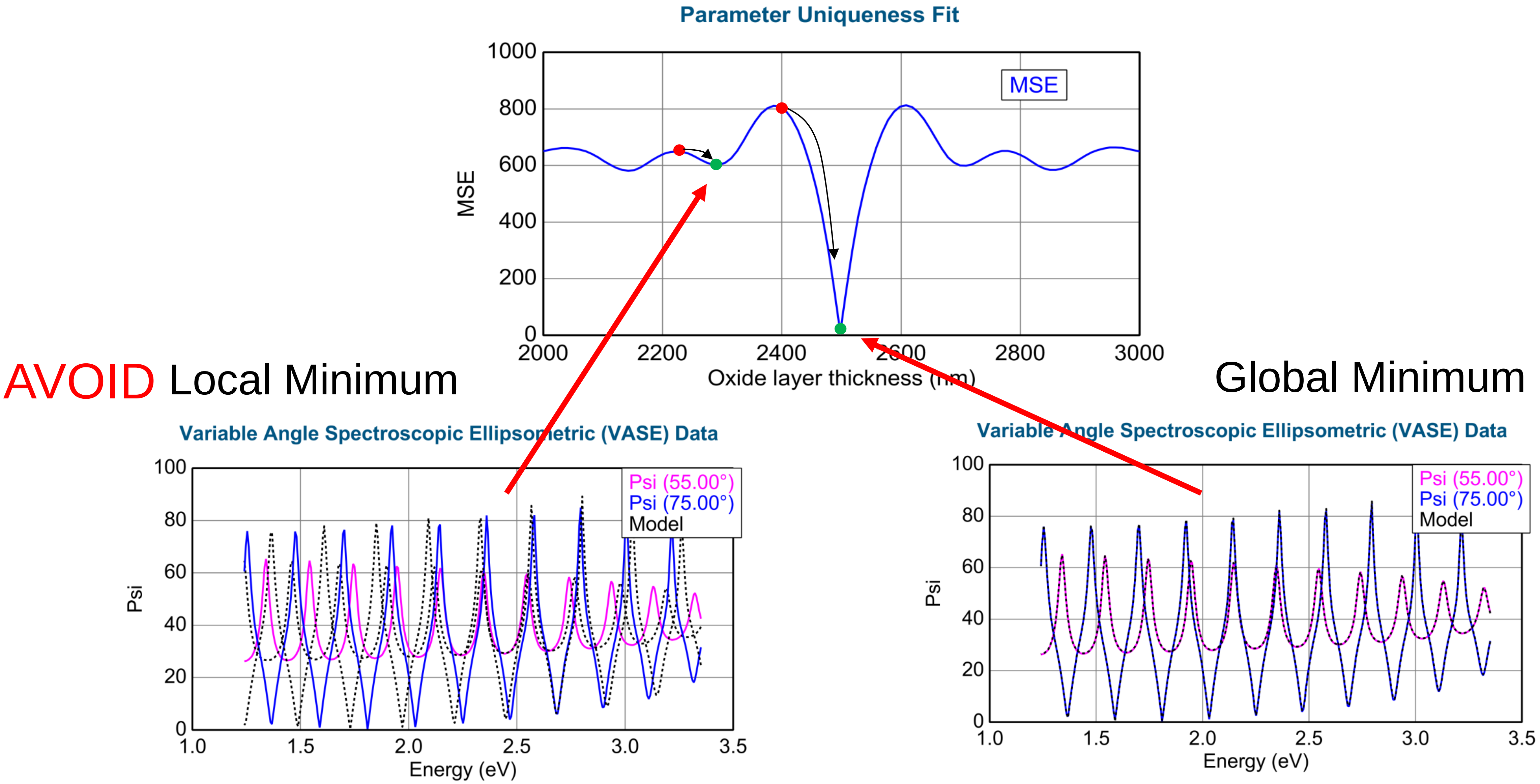
SHIFT
or
CTRL-SHIFT

Roll the ‘A’ parameter until Psi peaks / valleys have same amplitude as data curves.

Keep B = 0.01, C=0

Range of ‘A’ between 1.3 and 2.5

Start Values Matter



“Auto” Cauchy Procedure

III

Use AUTOMATED MODEL

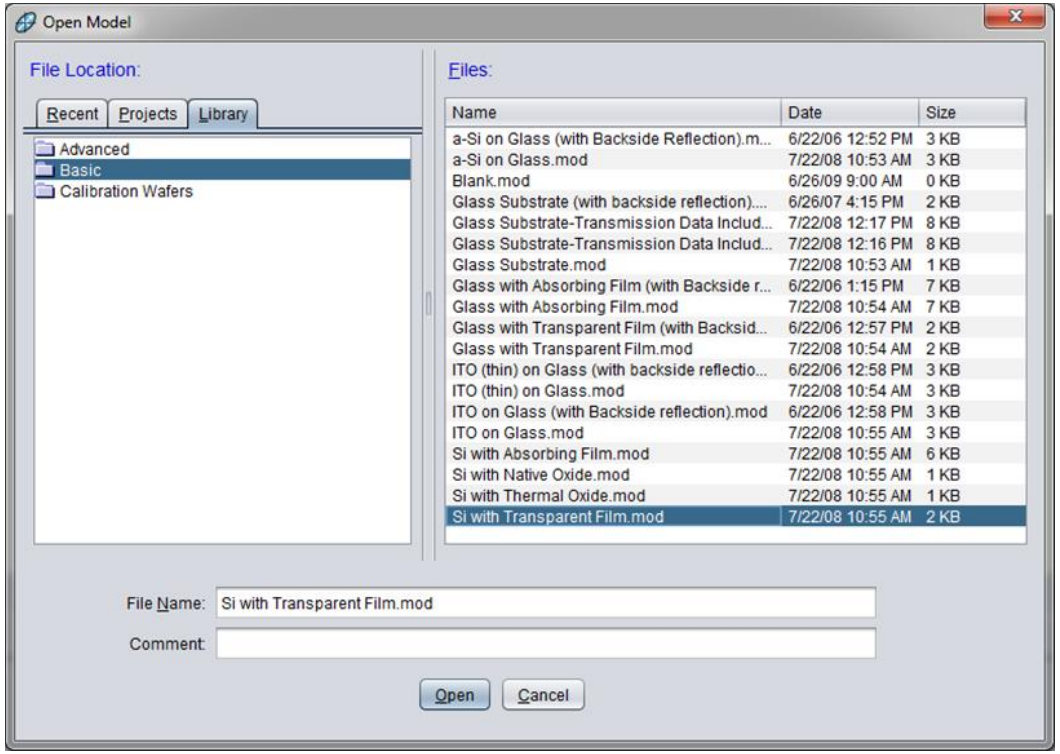
Estimate Thickness & Index

⇩

Fit Thickness & Cauchy Parameters

Si with Transparent Film.mod

(uses Thickness Pre-Fit & Global Fit)



Si with Transparent Film.mod

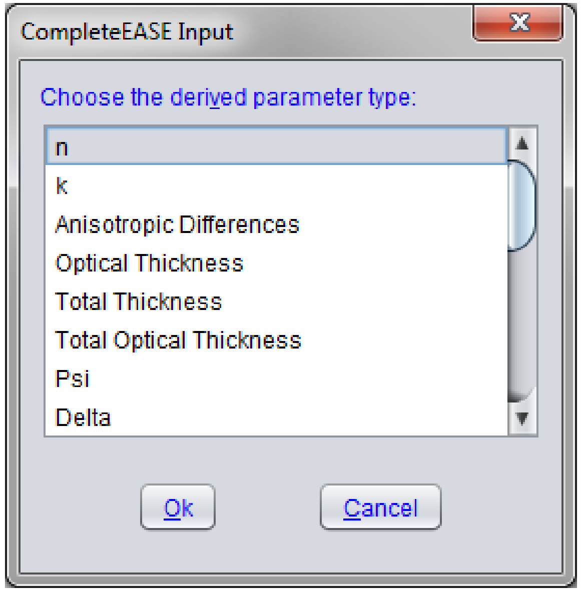
Include Surface Roughness = OFF
- Layer # 1 = Cauchy Film Thickness # 1 = 100.00 nm (fit)
  A = 1.500 (fit) B = 0.0000 (fit) C = 0.0000 (fit)
  + Urbach Absorption Parameters
Substrate = SI_JAW

+ **MODEL Options**
- **FIT Options**
  + Perform Thickness Pre-Fit = ON
  - Use Global Fit = ON
    # of Data Points = 20 # of Iterations = 5
    Parm #1 = A
      Min. = 1.300 Max. = 3.000 # Guesses = 30
    Parm #2 = (none)
    Parm #3 = (none)
    Include Wvl. Range Expansion Fits = OFF
  Fit Weight = N,C,S
  Limit Wvl. for Fit = OFF
  Limit Angles for Fit = OFF
  Max. Acceptable MSE = 100.000
  - Include Derived Parameters = ON
    Add Derived Parameter
    1: Type = n Layer # = 1 Wavelength = 632.8 nm Name = n @ 632.8 nm Hide = OFF
      # of Decimal Places = 5
      Low Spec. = 0.00 High Spec. = 0.00
+ **OTHER Options**

Configure Options
Turn Off All Fit Parameters

- Valid for Si substrate with transparent film, NO backside reflections
- Cauchy A, B, C and thickness already ON
- Includes Thickness Pre-Fit, Global Fit for Cauchy A, derived parameter n@632.8nm

Use for Preliminary Search. Turn OFF when close to answer

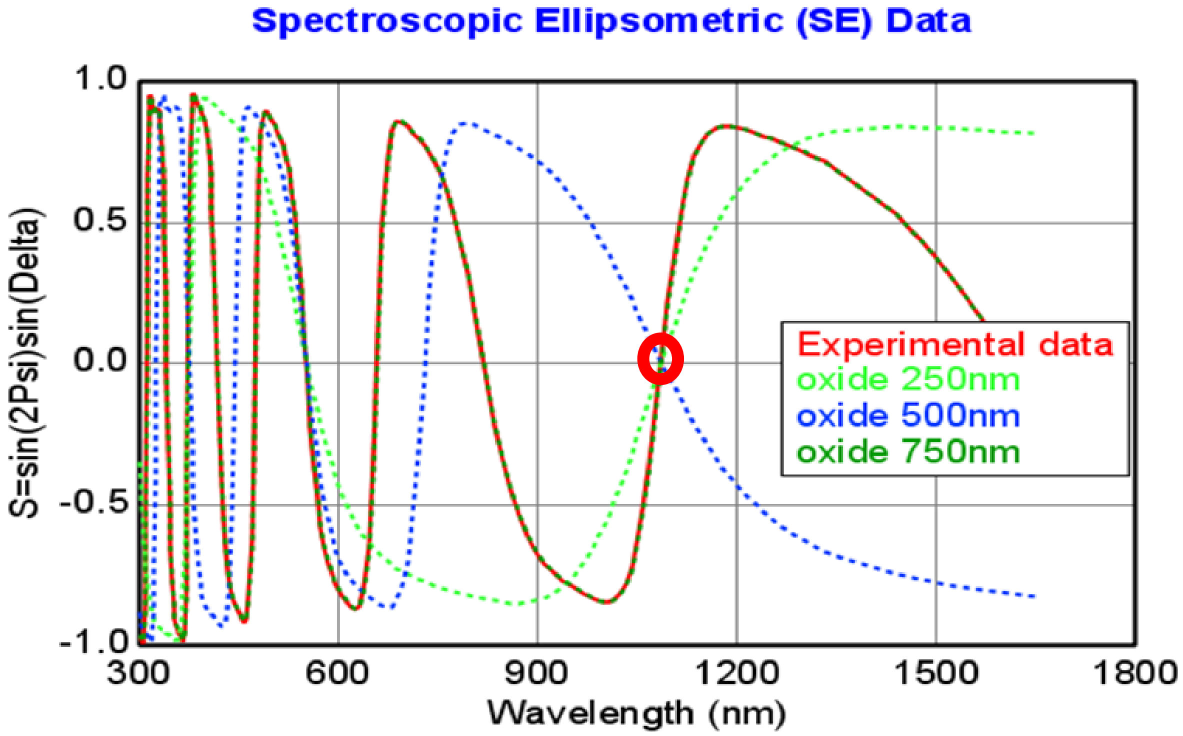


Always remember to check if the refractive index is physical!

Thickness Prefit

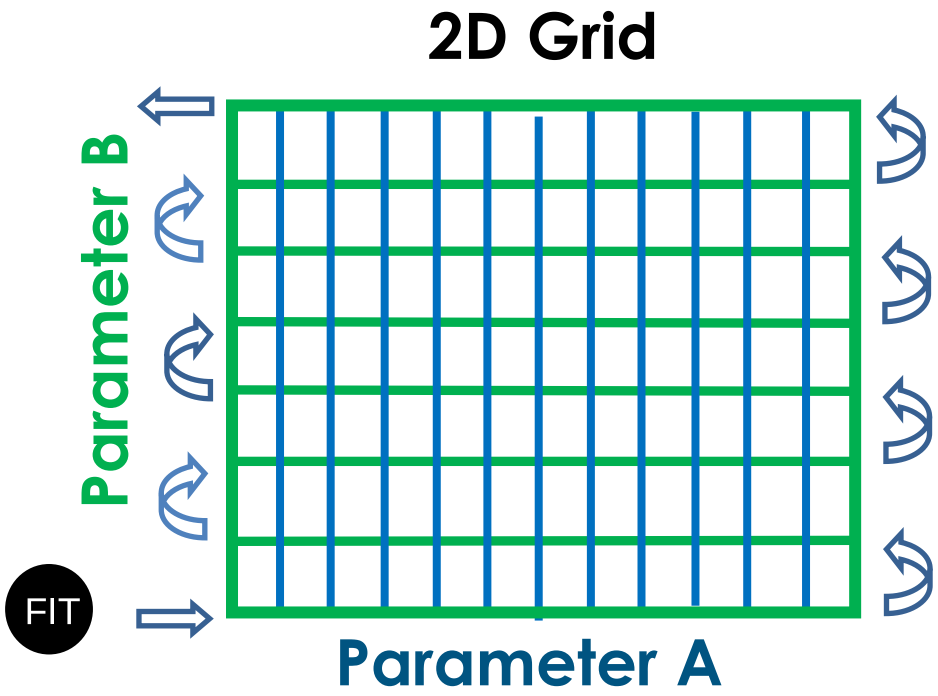
- **Very Fast** algorithm to identify possible thickness values
  - Useful in built-in model, unknown start values, thick films and mapping data
  - Need correct index, since index also affects interference.

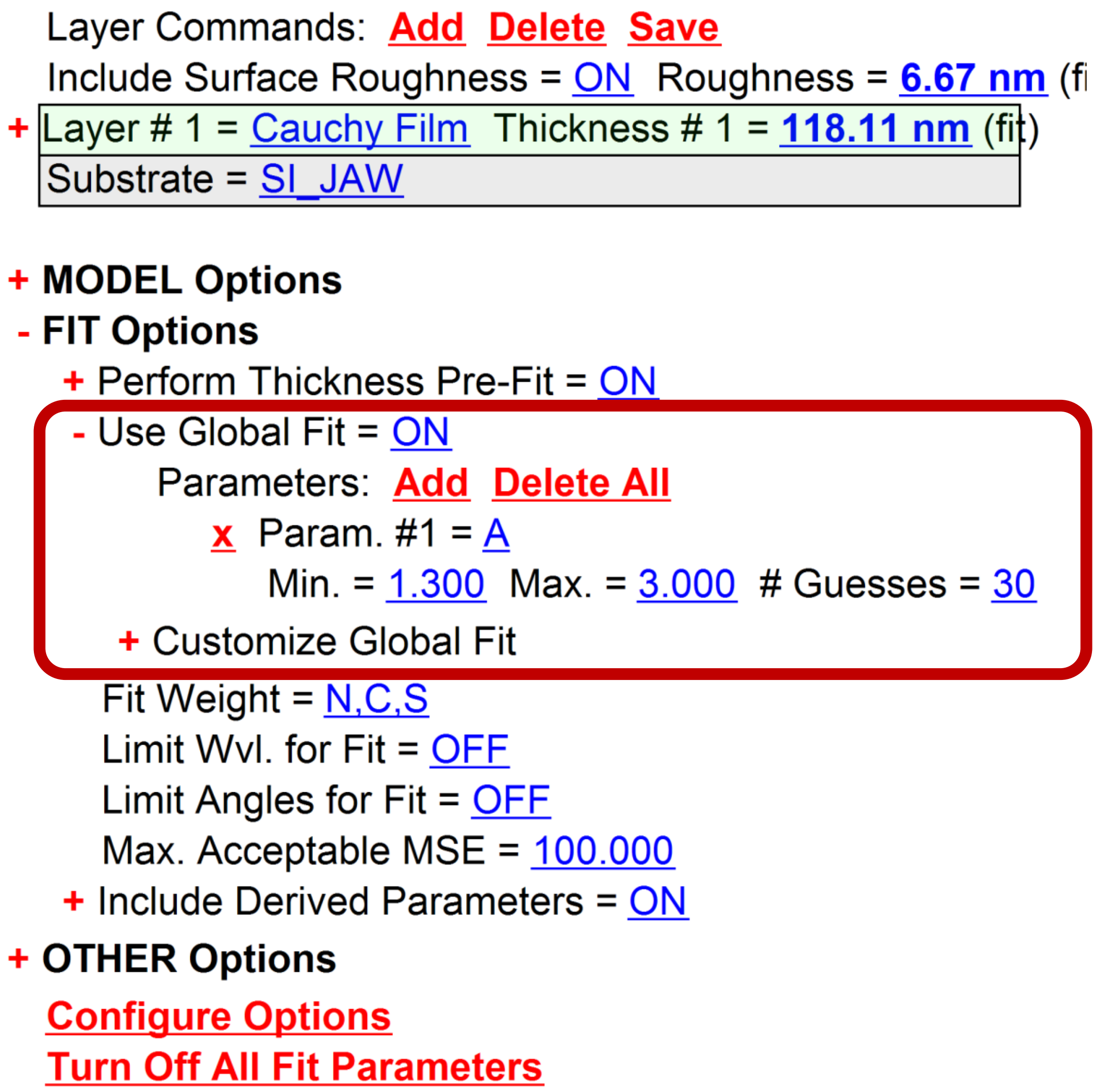
Combine with Global Fit for Index to improve search.



Global Fit

- Search *any* fit parameter using a grid of possible values
- Helps avoid “local” MSE minimums

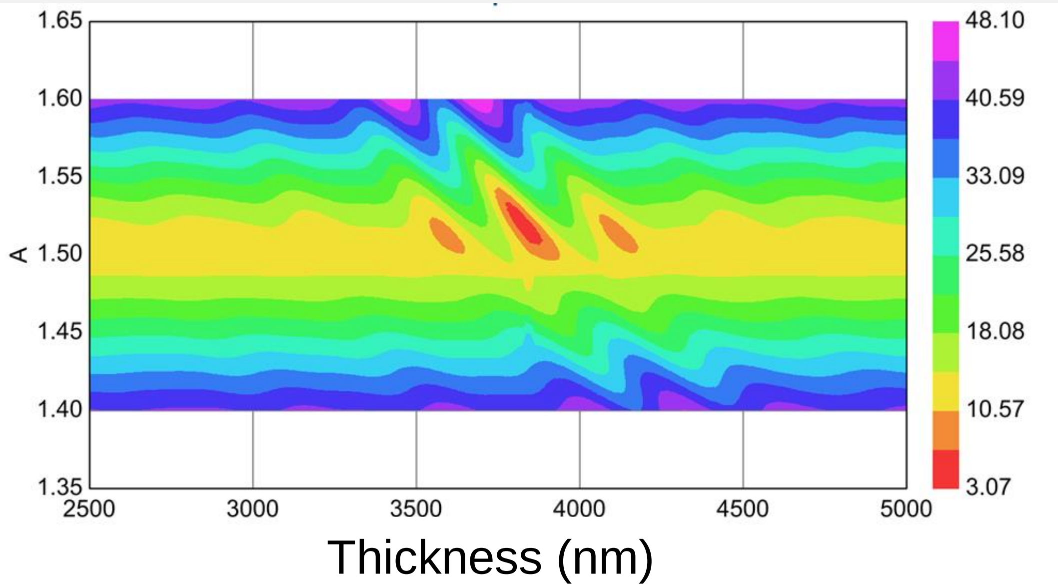


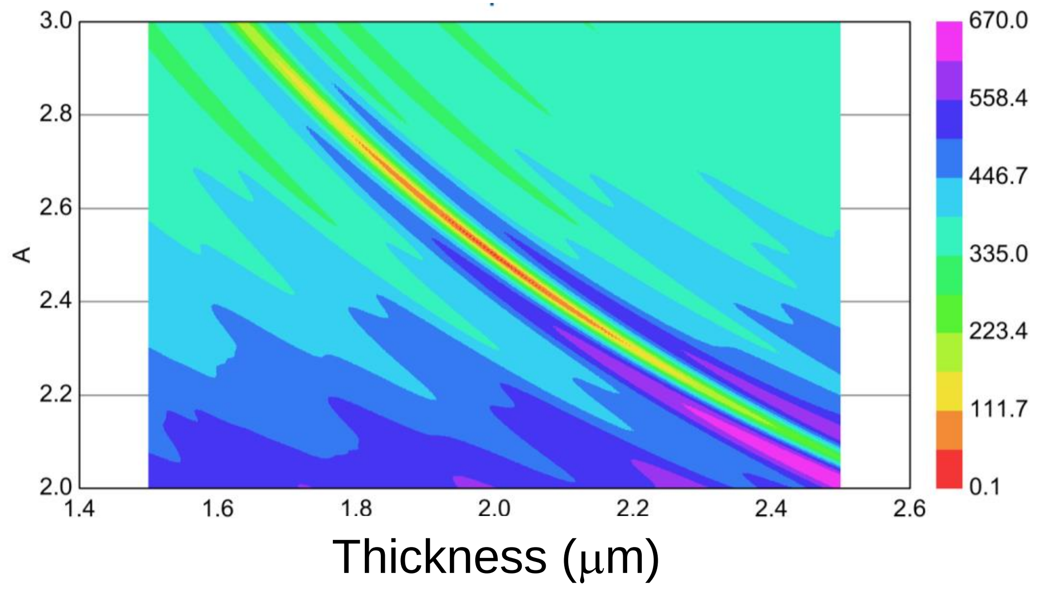


Global Fit "Guidelines"

- Search every 50 nm thickness.
  - 20 guesses for every 1 micron.
- Search every 0.05 index.
  - 20 guesses for every *n* range of 1.

- Limit total "# guesses" to avoid long fitting times.
  - Avoid fitting Cauchy "B" and "C"

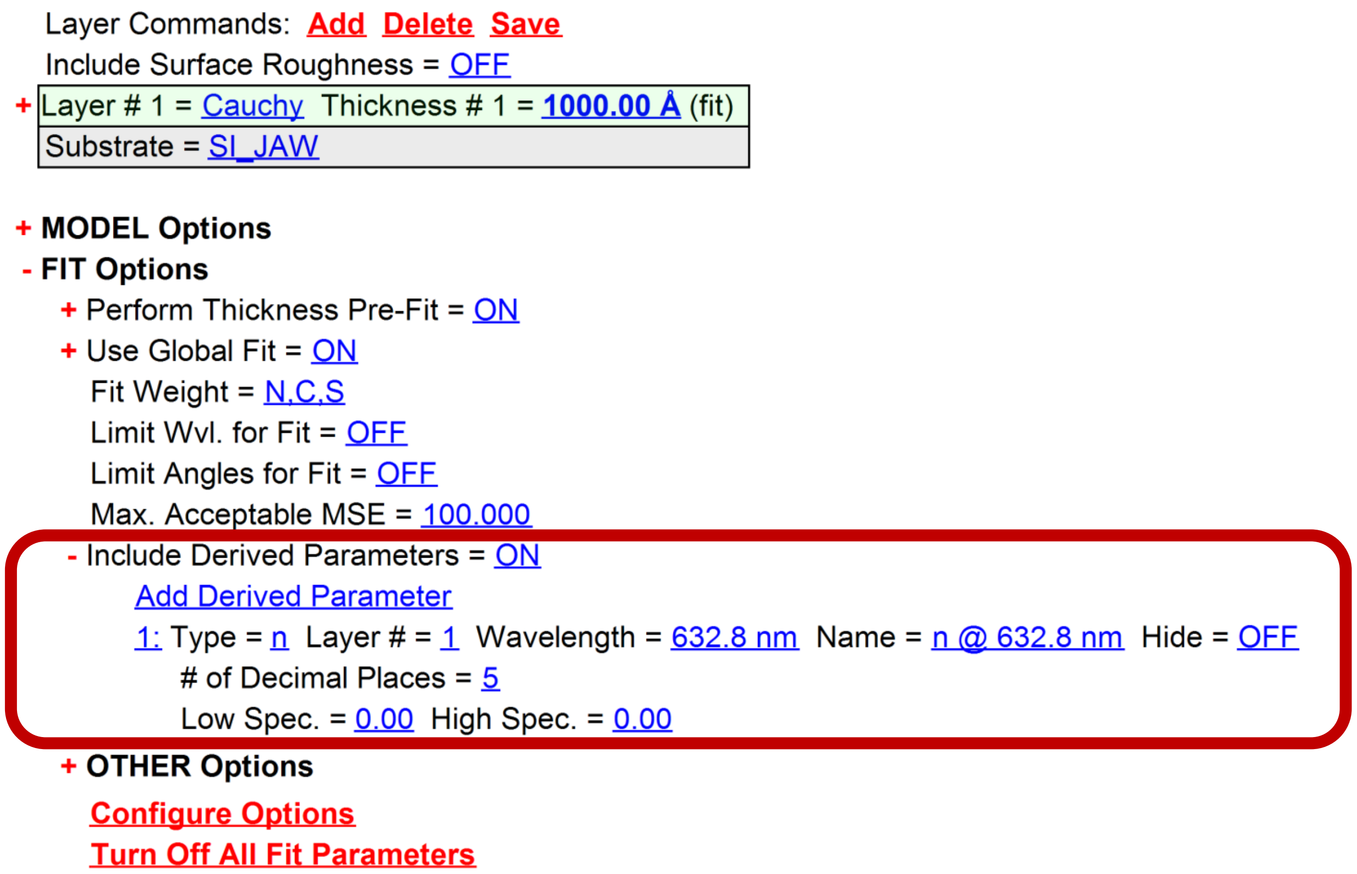


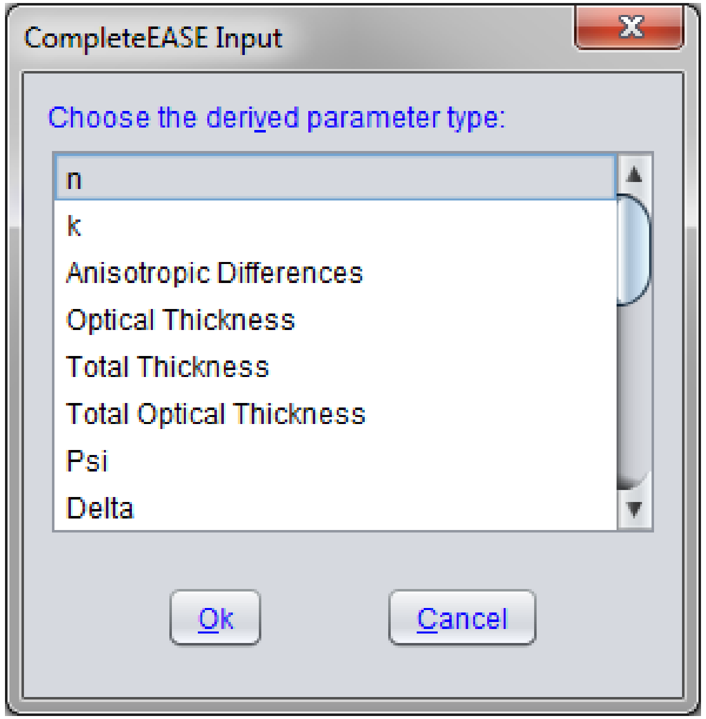


Global minimum is narrower for larger index

Derived Parameters

Calculates or reports user-selected values based on Fit Results



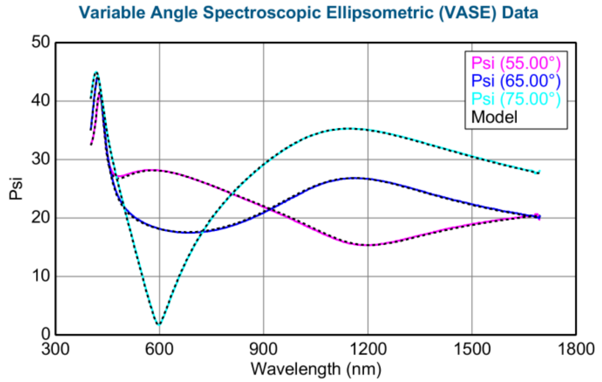


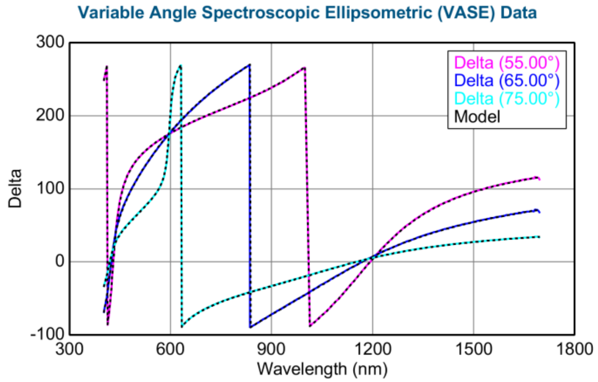
2-02 Ta_2O_5 on Si: Results

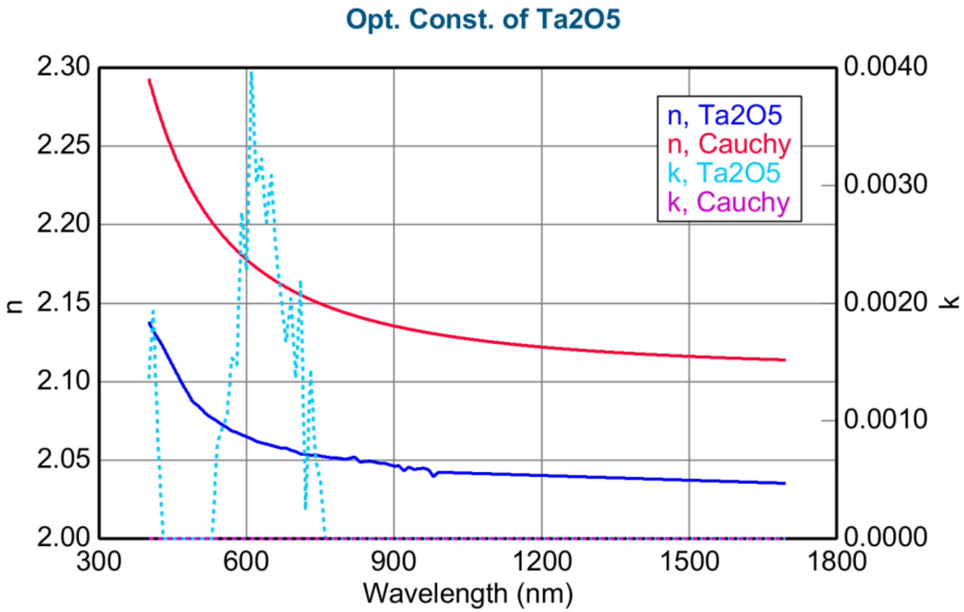
Fit Results	Optical Model
MSE = 5.117 Thickness # 1 = 152.34 ± 0.019 nm A = 2.106 ± 0.00024121 B = 0.02241 ± 0.00023662 C = 0.00124 ± 3.4986E-05	- Layer # 1 = Cauchy Thickness # 1 = **152.34 nm** (fit) A = **2.106** (fit) B = **0.02241** (fit) C = **0.00124** (fit) + **Urbach Absorption Parameters** Substrate = Si_JAW

	MSE	Ta2O5 Thickness (nm)	n @ 632.8 nm
Ta2O5	77.416	163.64	2.061
Cauchy	5.117	152.34	2.170

Experimental and Model Generated Data Fits

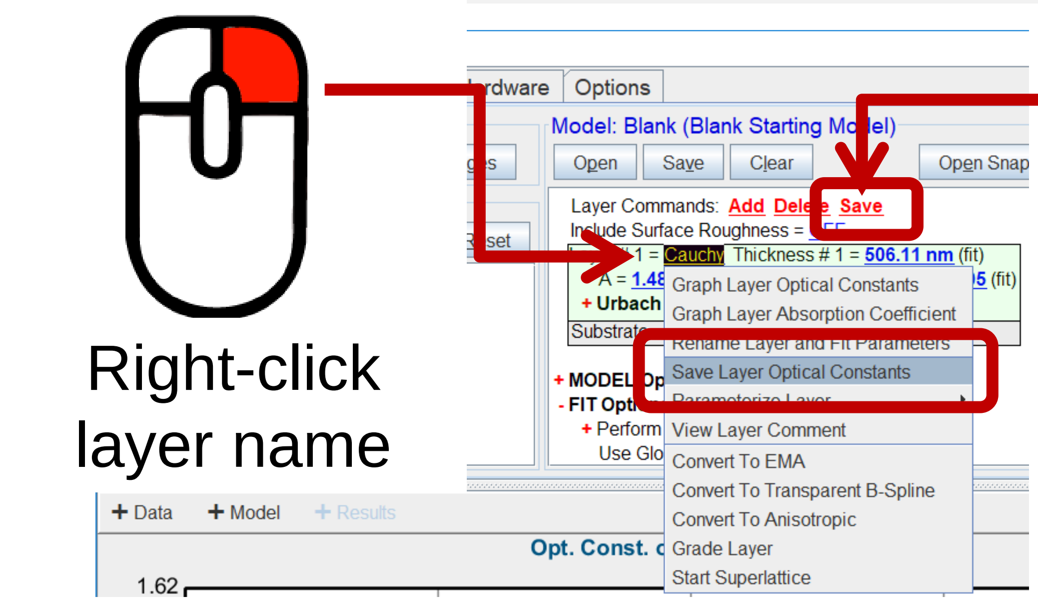


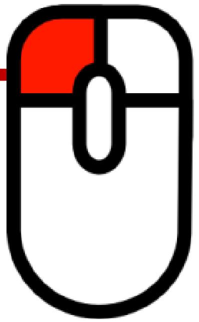




Saving Material Files

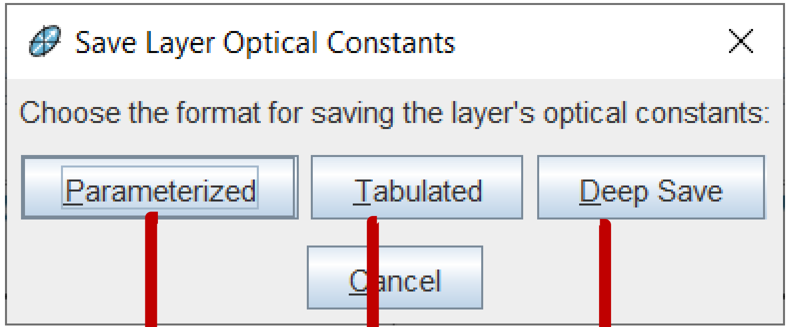
Right-click layer name





Left-click Save Layer Command

Choose Format



Save parameters

Fixed table

Save parameters, range and will be default as fit parms

- Layer # 3 = MgF2_Parm_c Thickness # 3 = 0.00 nm
  A = 1.378 B = 0.00309 C = -7.6324E-06
  + Urbach Absorption Parameters

Layer # 2 = MgF2_Tab Thickness # 2 = 0.00 nm

- Layer # 1 = MgF2_Deep_c Thickness # 1 = **0.00 nm** (fit)
  A = **1.378** (fit) B = **0.00309** (fit) C = **-7.6329E-06** (fit)
  + Urbach Absorption Parameters

Substrate = SI_JAW

MgF2_Tab.mat - Notepad

File Edit Format View Help

ANGSTROMS
E1E2

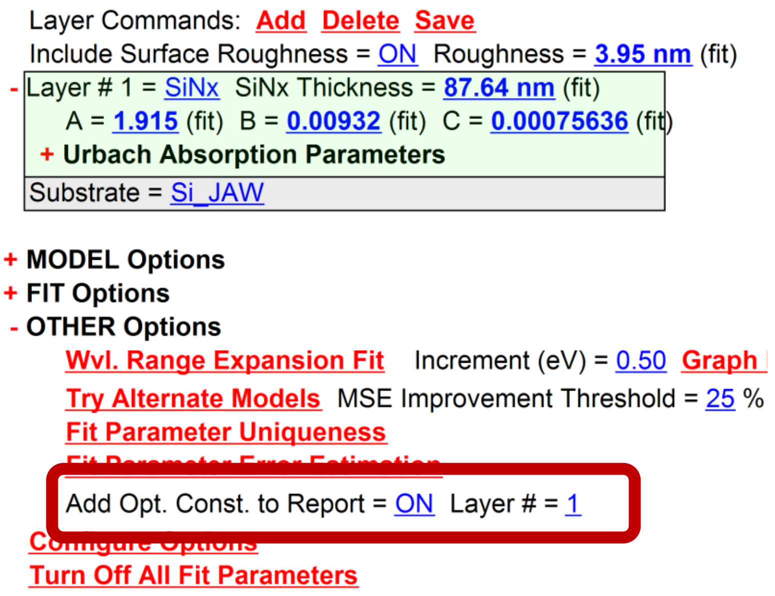
1900.0000	2.1254433	0.0000000
1910.0000	2.1231935	0.0000000
1920.0000	2.1209763	0.0000000
1930.0000	2.1187910	0.0000000
1940.0000	2.1166372	0.0000000
1950.0000	2.1145141	0.0000000
1960.0000	2.1124213	0.0000000
[illegible]	2.1103582	0.0000000
1980.0000	2.1083243	0.0000000
1990.0000	2.1063190	0.0000000
2000.0000	2.1043418	0.0000000

Quick “Analysis Report”

- Copy data analysis details to clipboard.

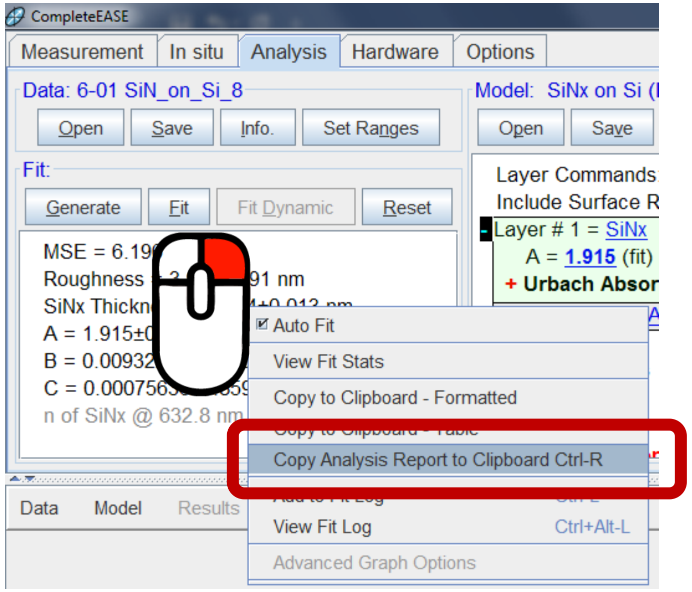
1. Get model ready

OTHER Options:
“Add Opt. Const. to Report”

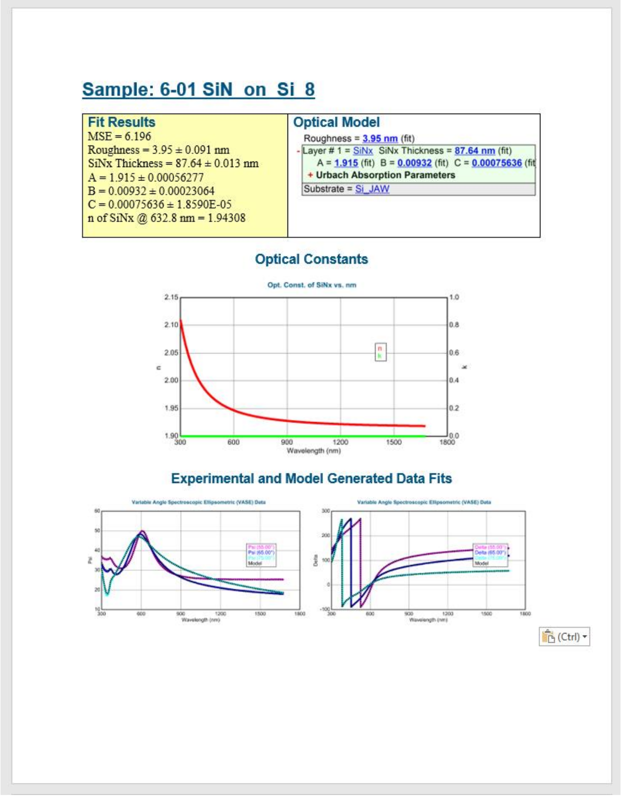


2. Right-click in Fit panel:

“Copy Analysis Report to Clipboard”



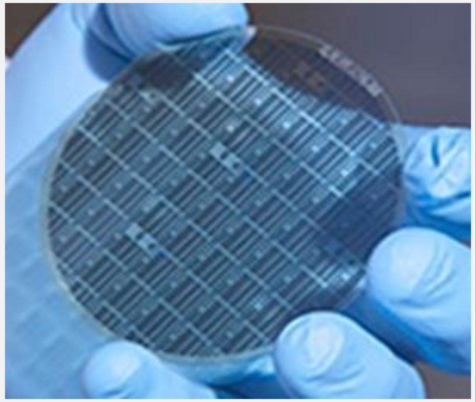
3. Paste



Built-in Models

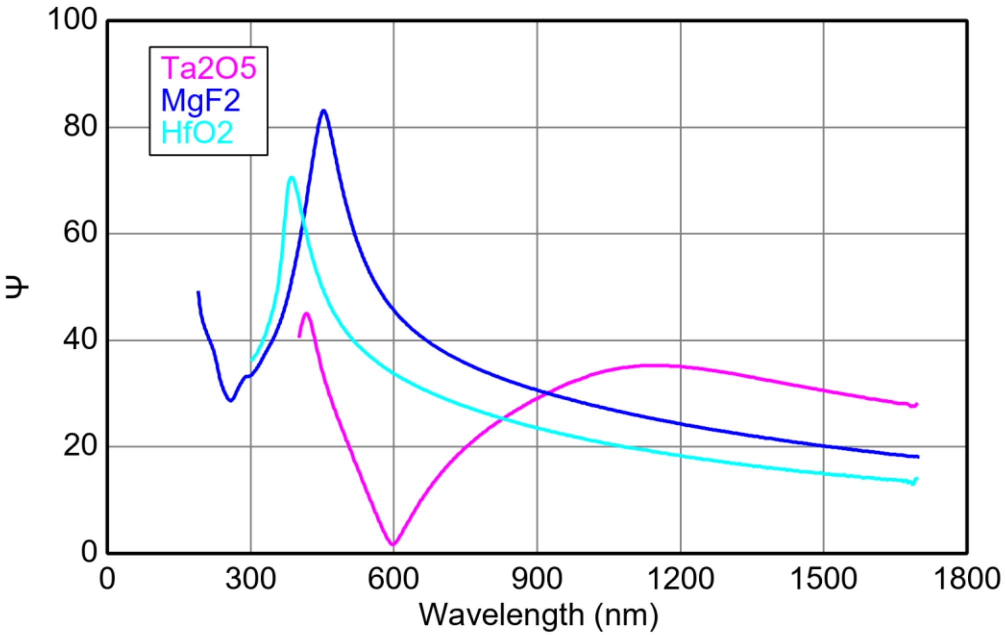
- **Ta_2O_5 on Si**
- **MgF_2 on Si**
- **HfO_2 on Si**

Use
AUTOMATED
MODEL



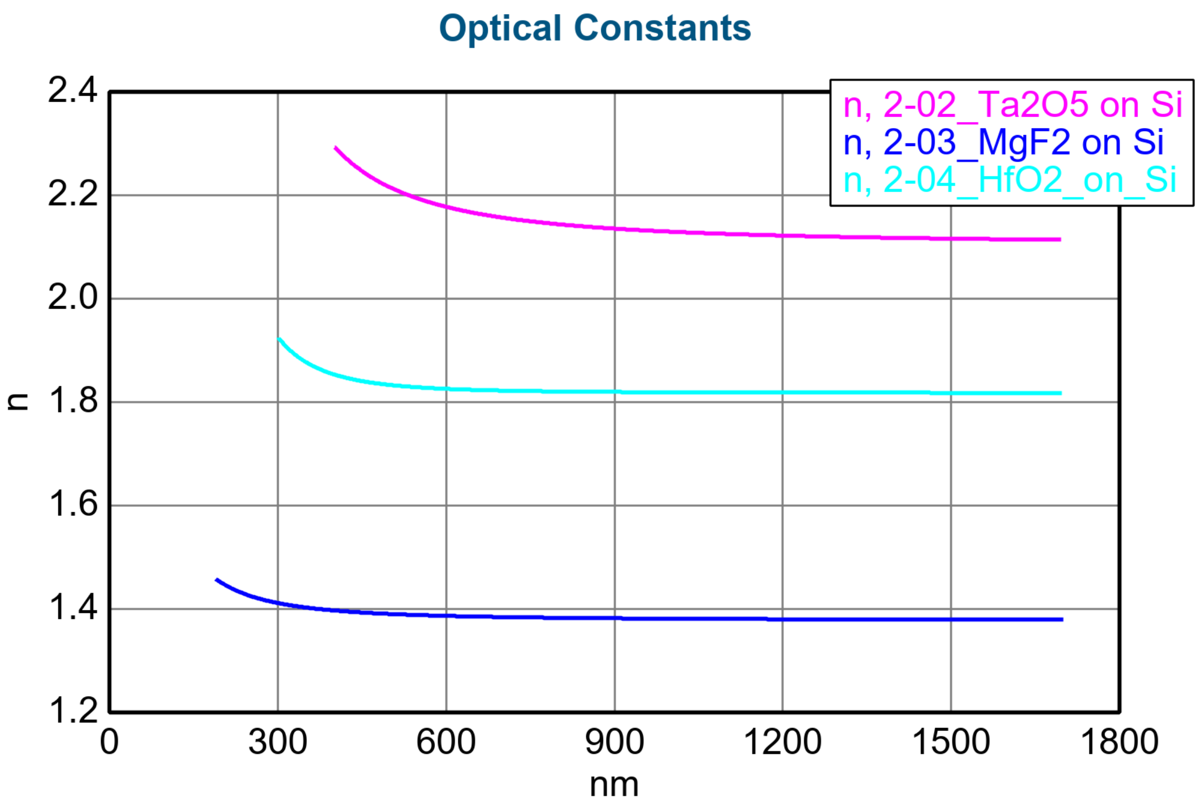
- Practice Built-in Model
- Save refractive index and snapshots

Variable Angle Spectroscopic Ellipsometric (VASE) Data



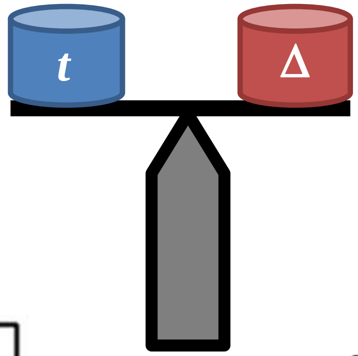
Built-in Model Practice Data Results

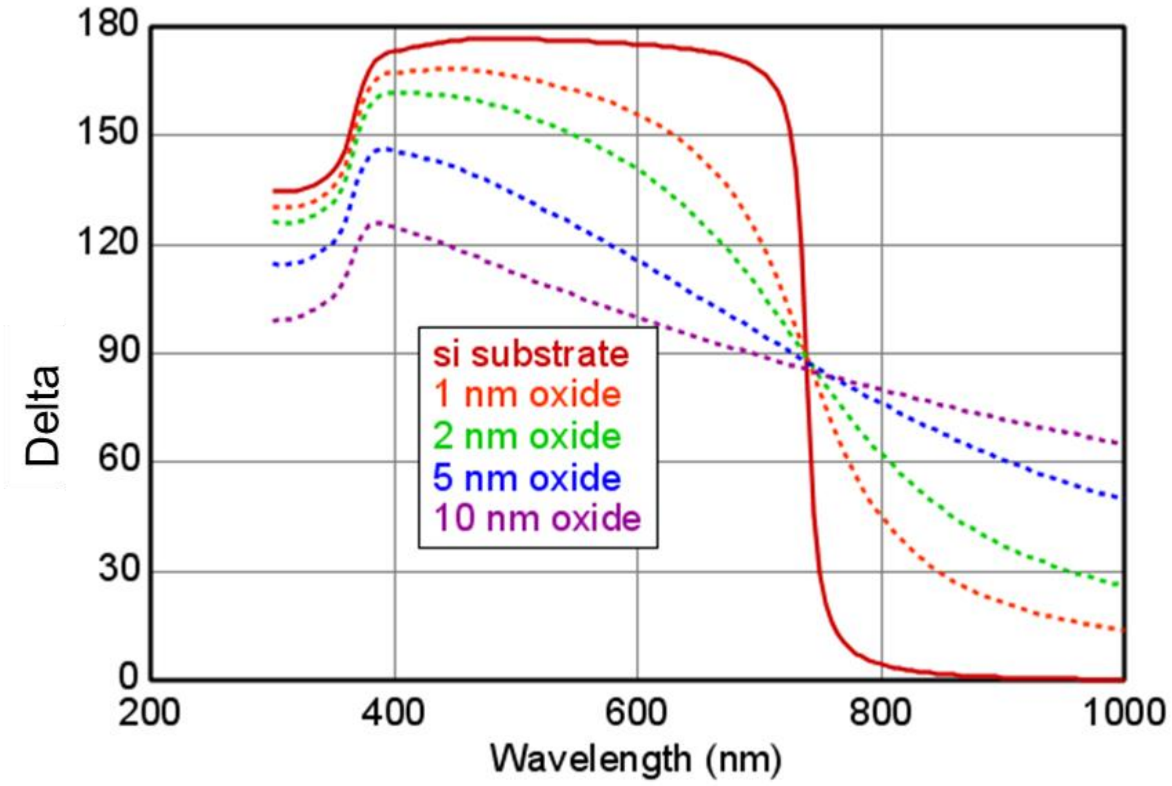
	MSE	Thickness	A	B	C	n @ 632.8 nm
2-02_Ta2O5 on Si	5.117	152.34	2.106	0.02242	0.00124	2.16961
2-03_MgF2 on Si	5.442	112.12	1.378	0.00309	-7.63E-06	1.38586
2-04_HfO2_on_Si	6.375	61.29	1.818	0.000604	0.000824	1.8243

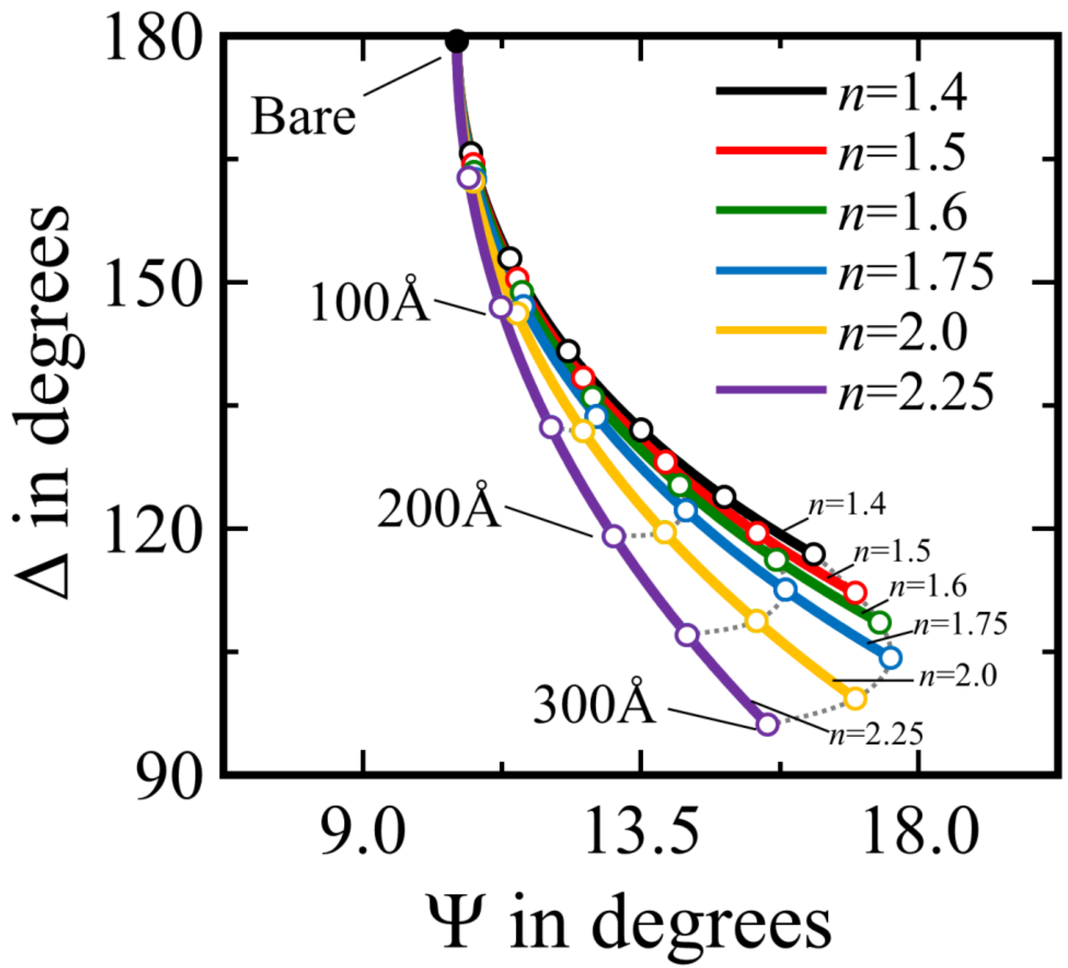


Ultra-Thin Films

- Only Δ changes significantly with thickness.
- Can't determine index.





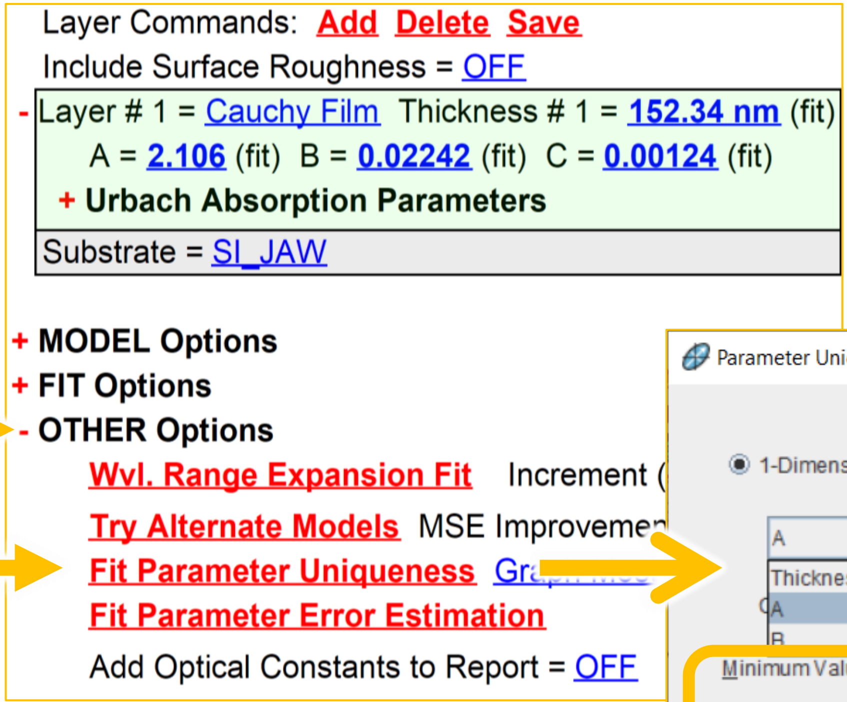


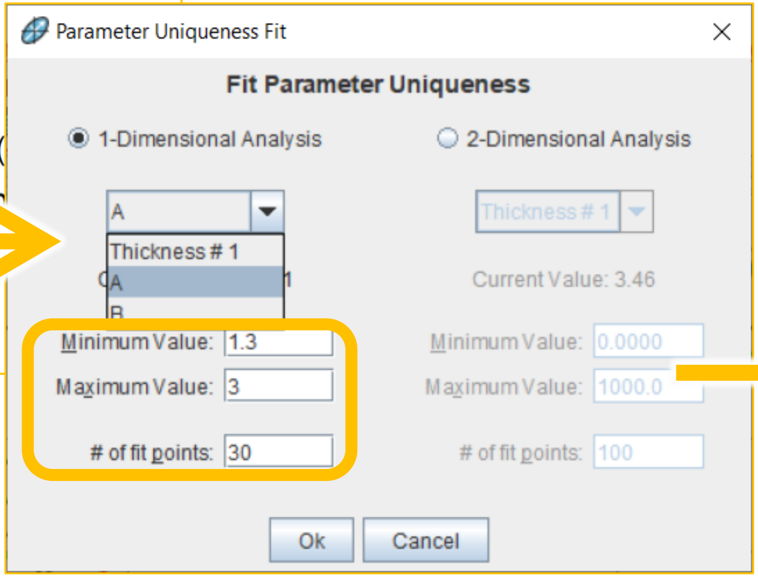
[2-05] SAM film on Si_A_post

- **Use “Si with transparent film.mod”**
- **Test sensitivity to Cauchy A parameter**

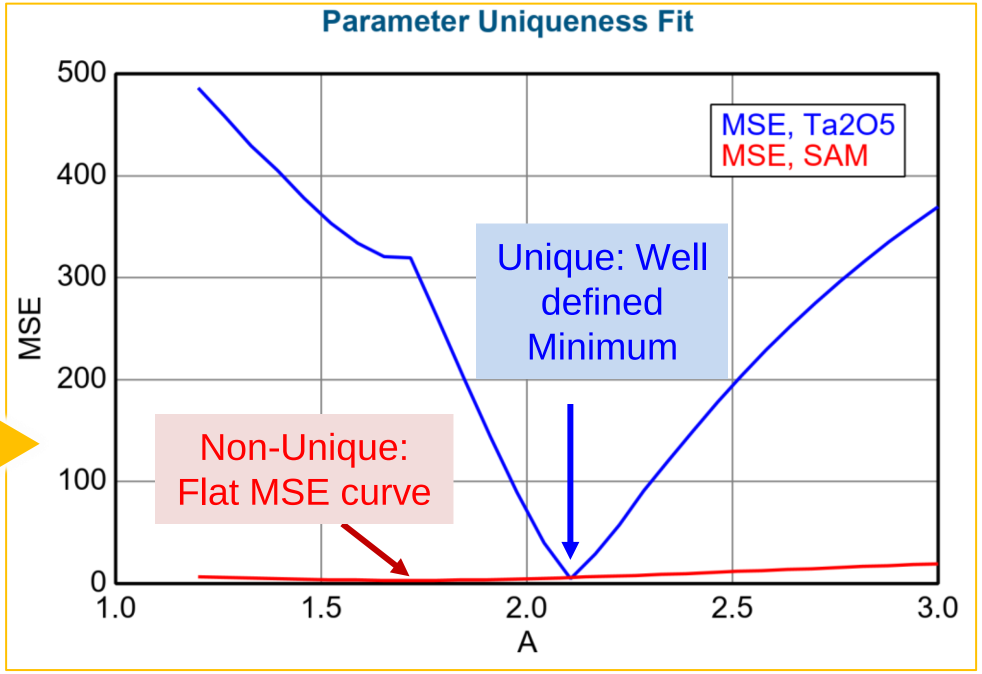
- Does the optical model have good sensitivity to the index of refraction of ultra-thin film?
- How important is the surface layer on substrate?

Parameter Uniqueness Test





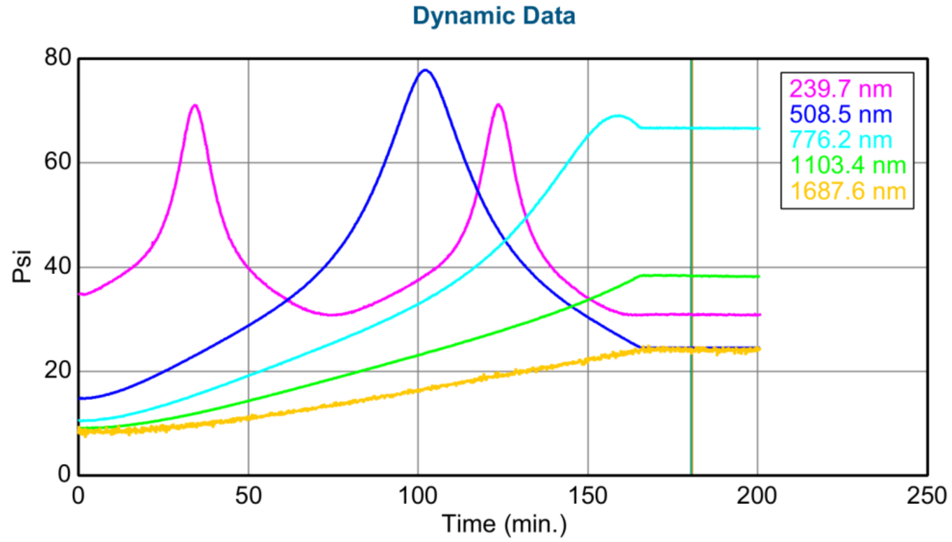
No sensitivity to index of refraction for ultra thin films!



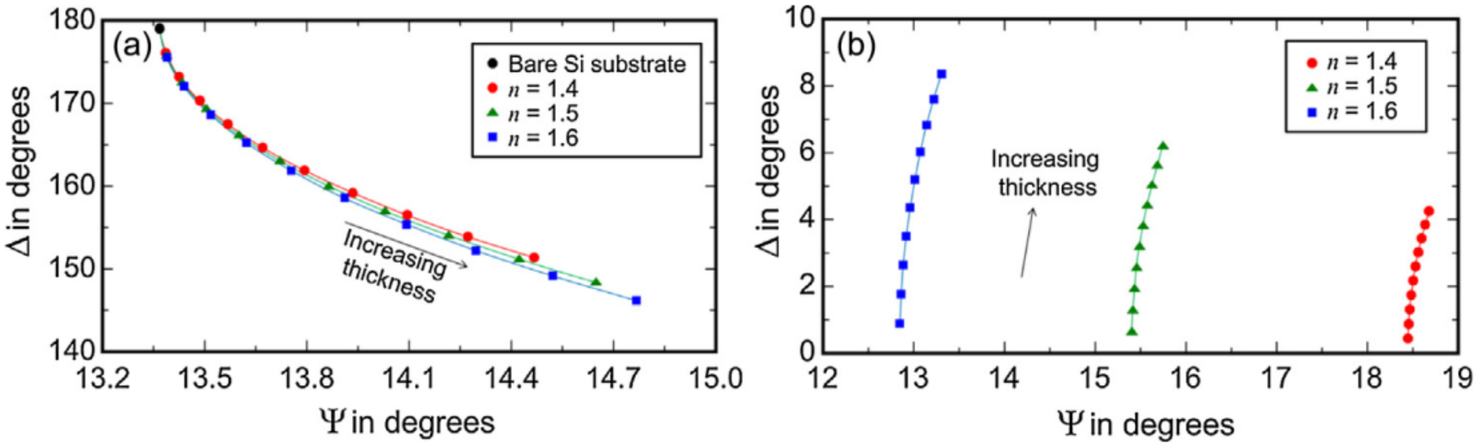
A very useful tool in testing parameter sensitivity, such as in multiple layers, ultra-thin films, and absorbing materials

Tips on Ultra-thin Film – Refractive Index

- Determine from thicker films, such as in ALD
- Use empirical values, often for organics or metal oxide
- Determine from free-standing film



J.N. Hilfiker et al. / Applied Surface Science 421 (2017) 508–512



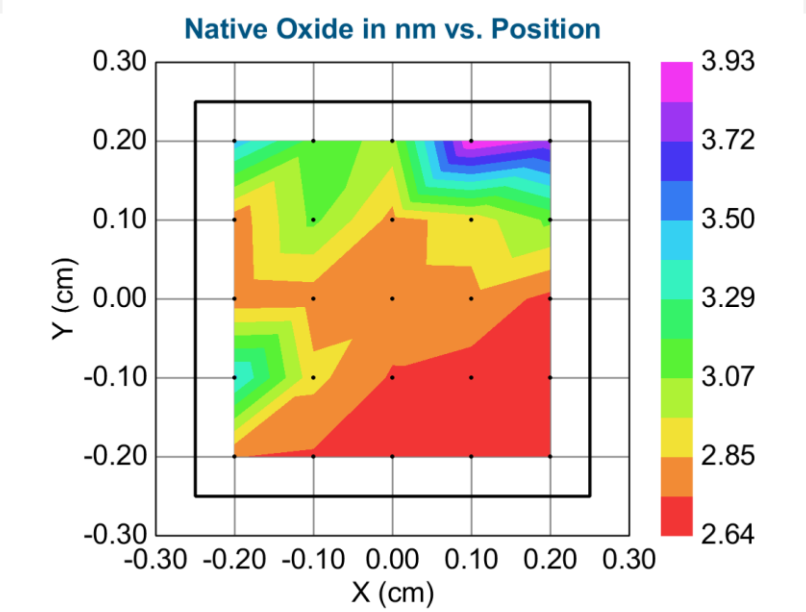
Layer # 2 = Cauchy Thickness # 2 = **5.86 nm** (fit)
A = 1.643 B = 0.00459 C = 0.00015076
+ Urbach Absorption Parameters

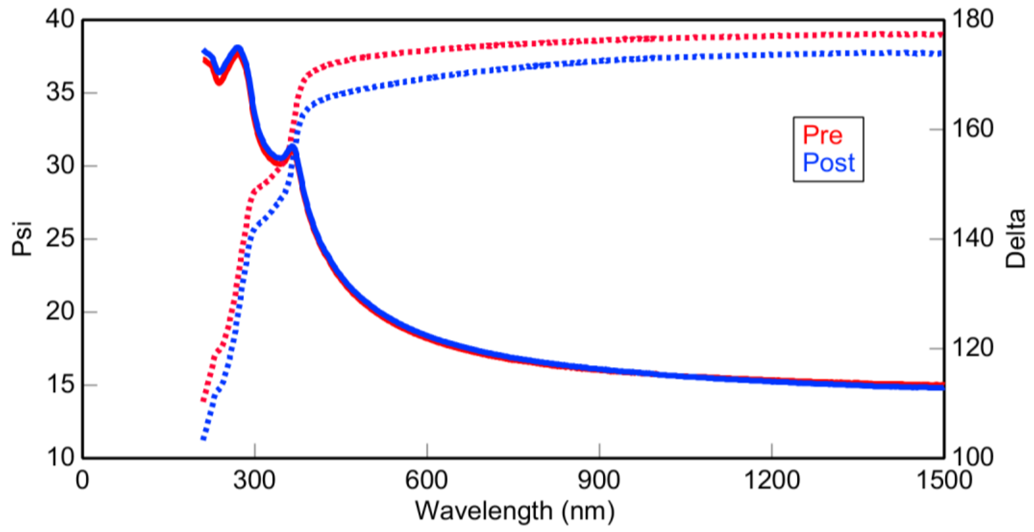
Layer # 1 = NTVE_JAW Thickness # 1 = 3.13 nm

Substrate = Si_Temp_JAW(-25_500C)

Tips on Ultra-thin Film – Surface Layer

- Important to characterize initial oxide or roughness thickness as they are crucial to the thickness accuracy of the ultra-thin films
  - Measure before and after at the same location on the same sample
  - In-situ monitoring if possible





- Layer # 2 = Cauchy Thickness # 2 = **2.68 nm** (fit)
  A = 1.500 B = 0.01000 C = 0.0000
  + **Urbach Absorption Parameters**
Layer # 1 = NTVE_JAW Thickness # 1 = 2.82 nm
Substrate = SI_JAW

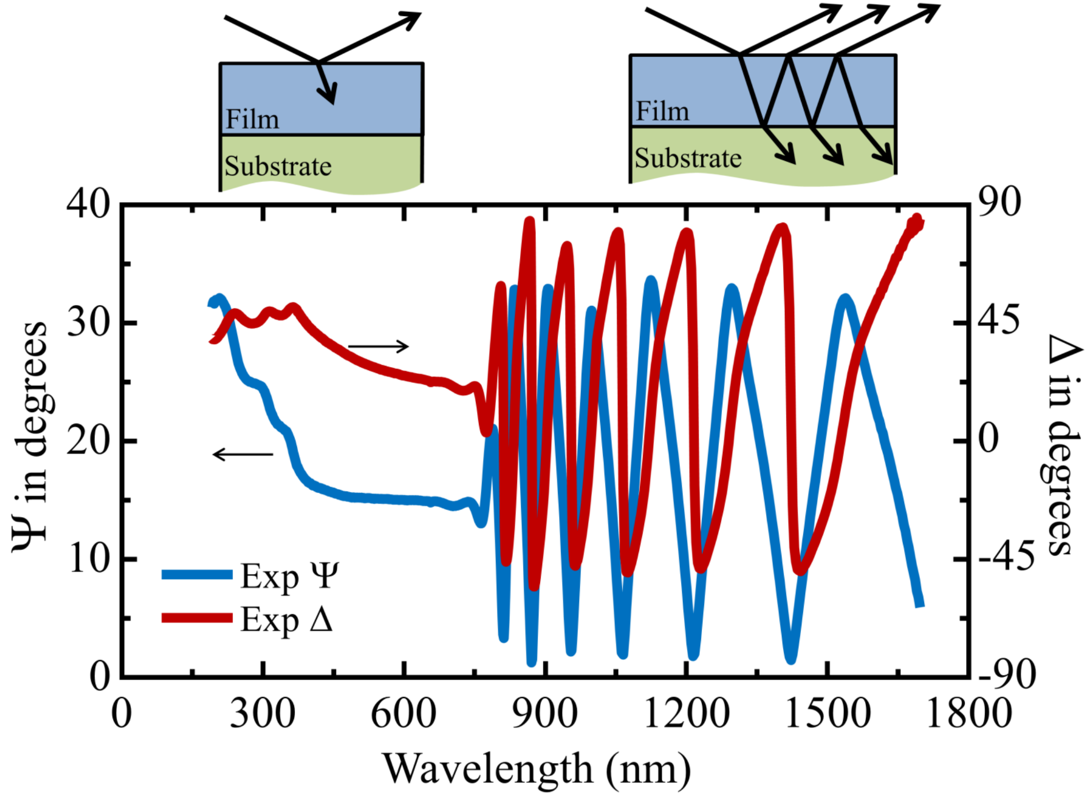
Correct

- Layer # 1 = Cauchy Thickness # 1 = **5.67 nm** (fit)
  A = **1.632** (fit) B = **0.00010530** (fit) C = 0.0000
  + **Urbach Absorption Parameters**
Substrate = SI_JAW

Wrong

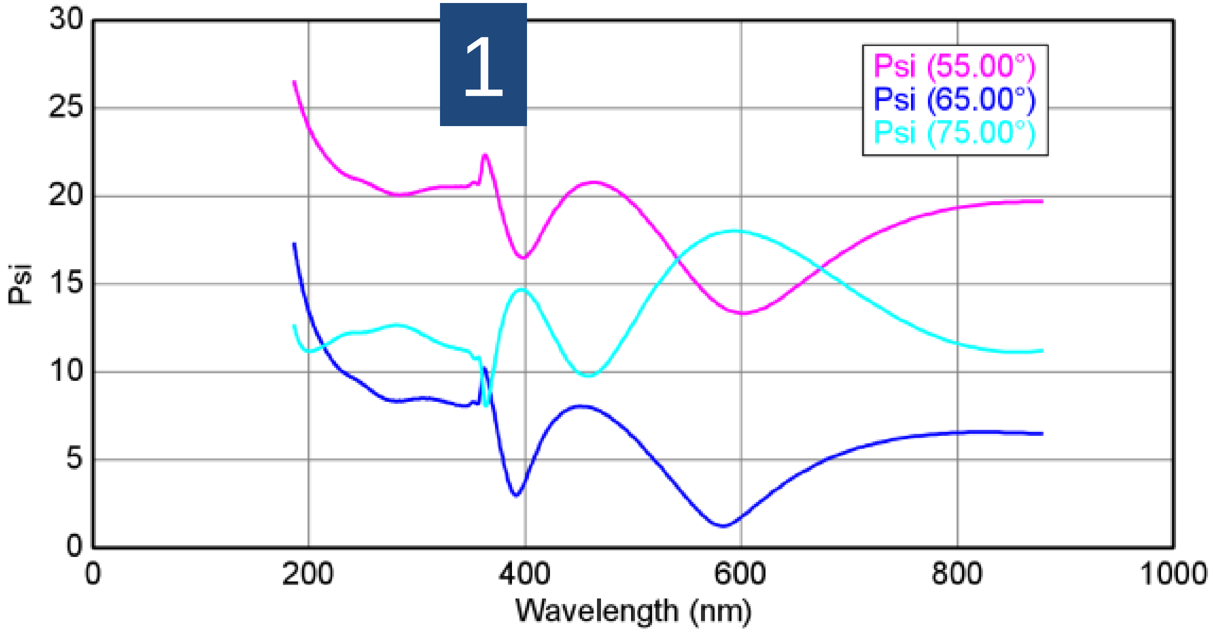
Importance of Transparent Range

1. Needed to determine film thickness.
2. Simplified analysis by considering ONLY the transparent wavelength range – still get thickness and refractive index.

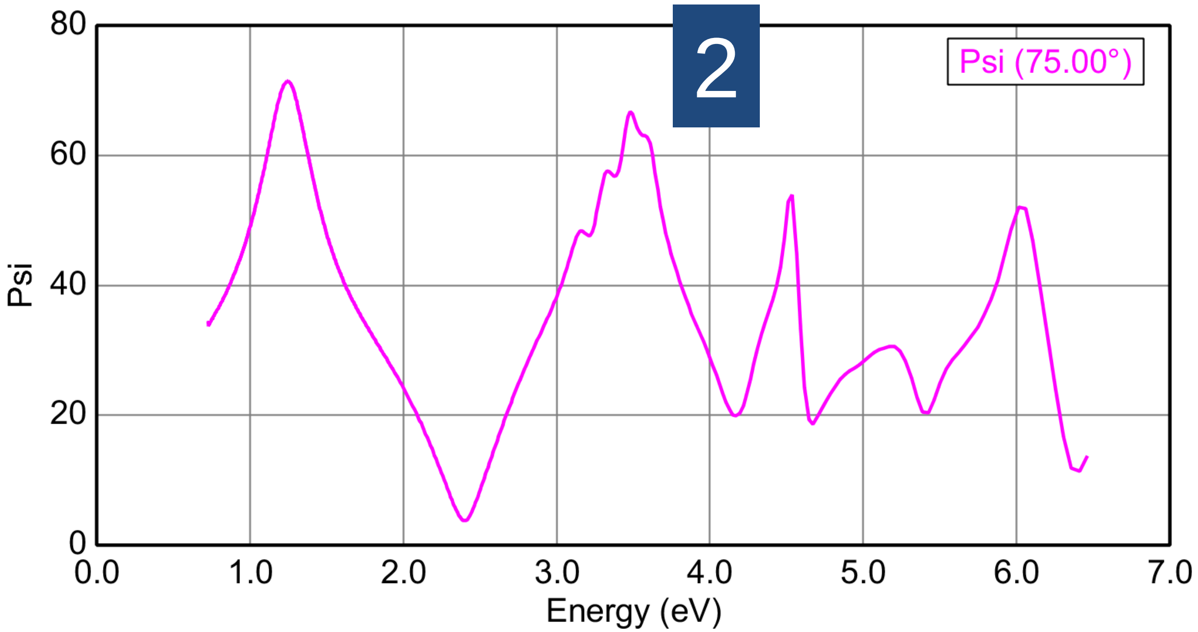


Identifying the Absorbing Region

1. Absorbing region affects "amplitude" of thickness oscillations.
2. Absorptions have different frequency than thickness oscillations.

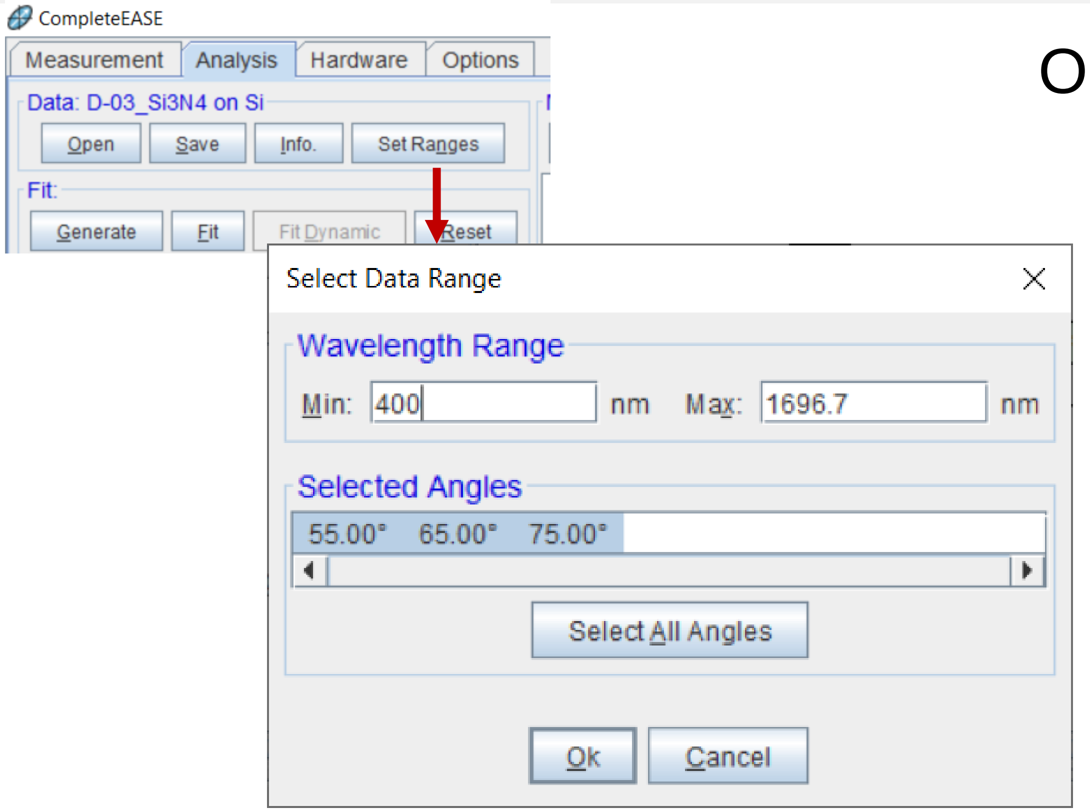


Variable Angle Spectroscopic Ellipsometric (VASE) Data

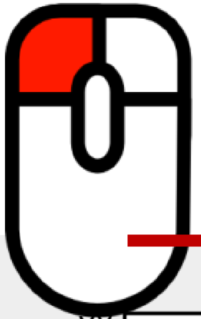


CTRL-ALT-W
switches between
Wavelength and Energy

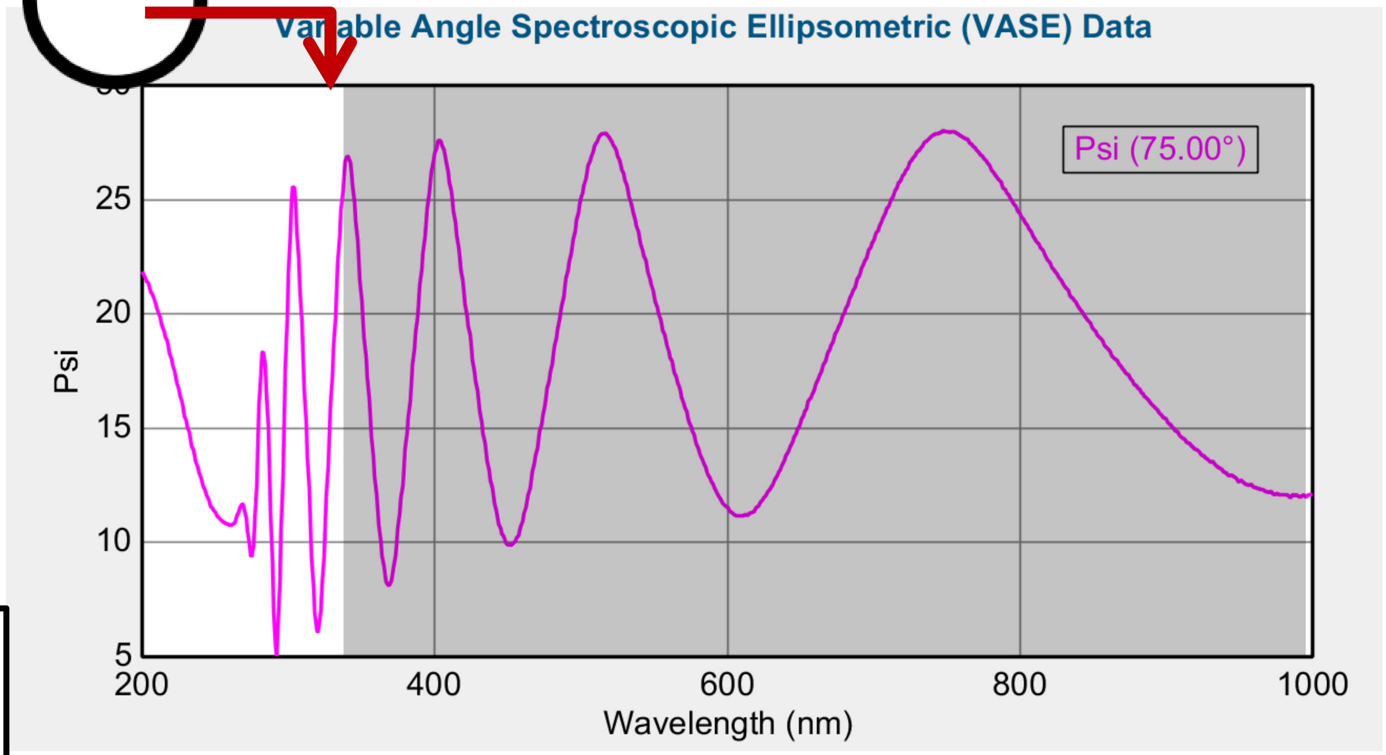
How to Range-Select Wavelengths



OR



Drag Mouse across Graph



Double-click on Graph to Select All Wavelengths

2-06 YbF_3 on Ge

- Find index and thickness for YbF3 in transparent region
  - Where is the film transparent?
  - Can you use built-in model?

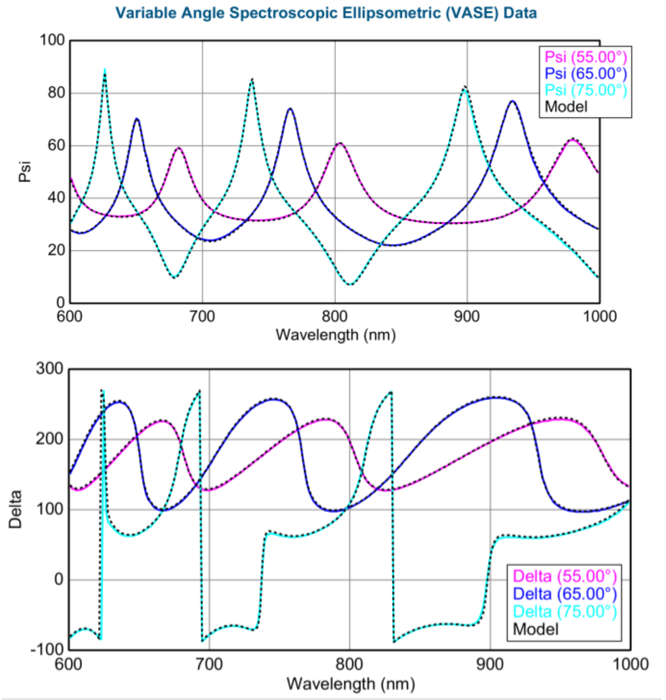
What happens if you use the wrong substrate in the model?

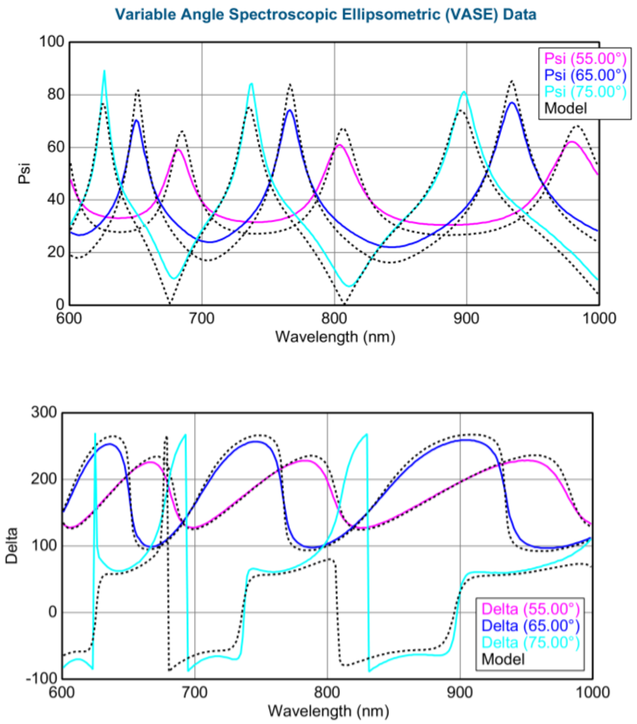
- Compare MSE for best fit with Si_jaw.mat and Ge.mat as the substrate material

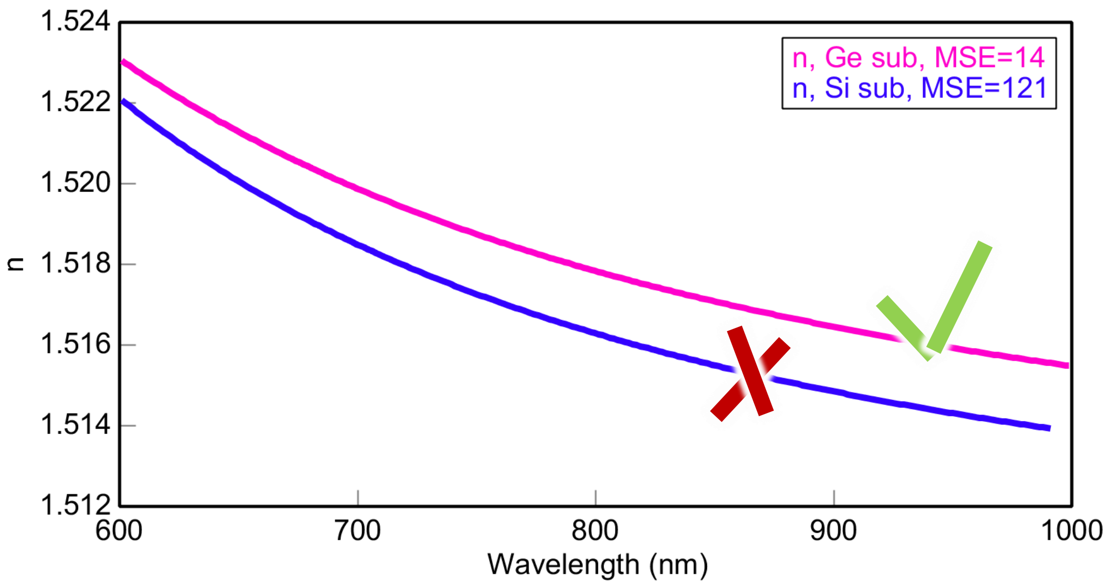
2-06 YbF_3 on Ge: Results

Ge sub, MSE=14

Si sub, MSE=121







Restricting Data Range in Model

Layer Commands: **Add** **Delete** **Save**

Include Surface Roughness = ON Roughness = **14.30 nm** (fit)

+ Layer # 1 = Cauchy Film Thickness # 1 = **1730.80 nm** (fit)

Substrate = Ge

+ **MODEL Options**

- **FIT Options**

Perform Thickness Pre-Fit = OFF

Use Global Fit = OFF

Fit Weight = N,C,S

Limit Wvl. for Fit = ON Range = 600.0 nm - 1000.0 nm

Limit Angles for Fit = OFF

Max. Acceptable MSE = 100.000

+ Include Derived Parameters = ON

+ **OTHER Options**

Configure Options

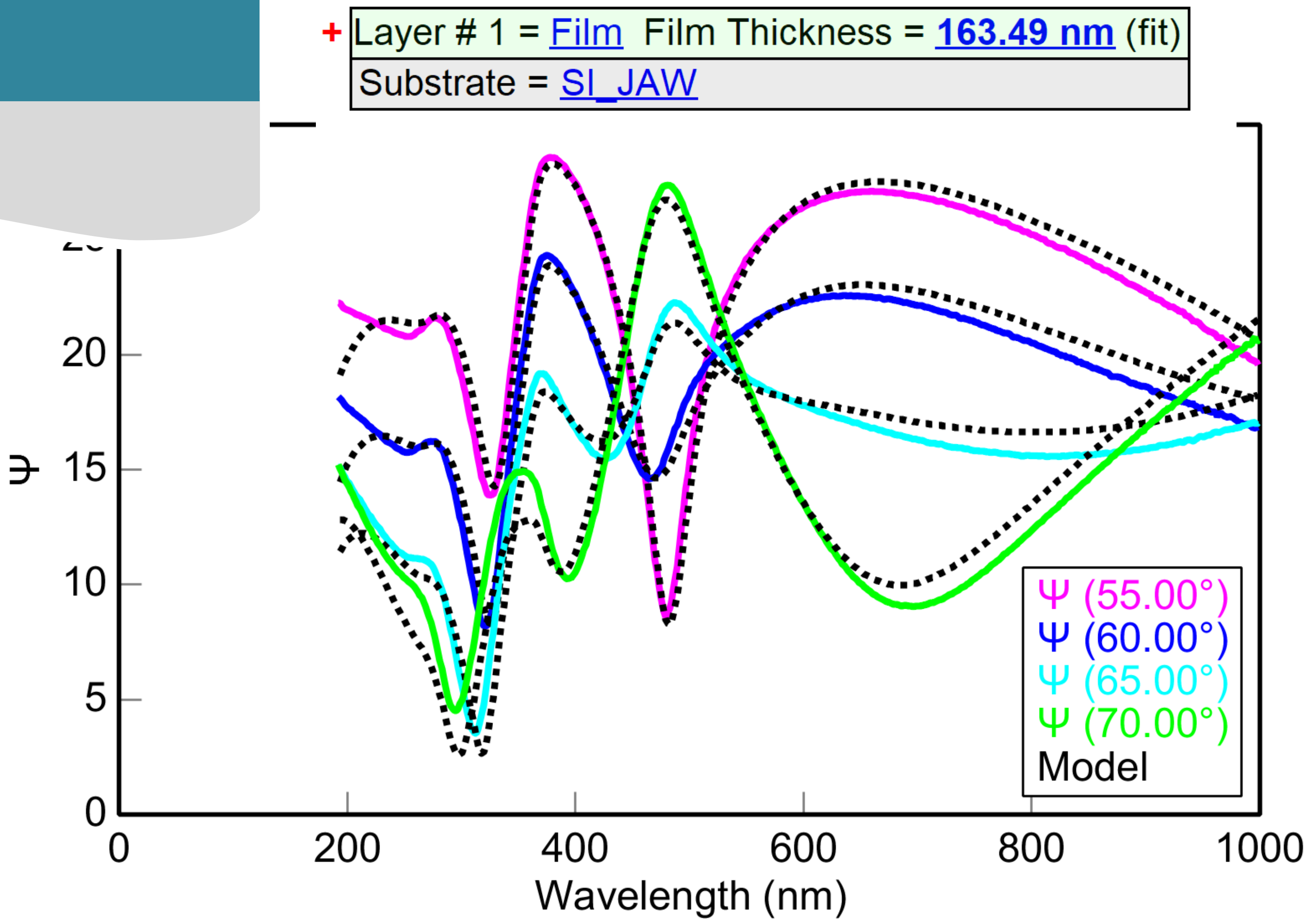
Turn Off All Fit Parameters

Useful when automating a model for repeat use.

Recap: Transparent Thin Films

- We use **Cauchy** layer to determine the index of refraction $n(\lambda)$.
- Cauchy is **only** valid in transparent region
- Successful fitting requires good initial estimate for thickness and index.
- Use **built-in model** to automate.
  - Identify the transparent region before using the built-in model
- For **ultrathin** films (< 10-30 nm), determine thickness only!
- Save **model** for later use.

What's next when ideal model is not adequate?



2B: Typical Thin Film Complexities

Fit Thickness & Cauchy Parameters

⇩

<u>Add to improve MSE</u>:
Roughness?
Index Grading?
Anisotropy?
Non-idealities?
Absorption?

Roughness often improves fit for higher index and absorbing films. Tends to "tip" Delta curves.

Grading is common with many metal-dielectrics.

Anisotropy is common with polymers.

Non-uniformity affect the data more as film gets thicker (bandwidth has similar effect)

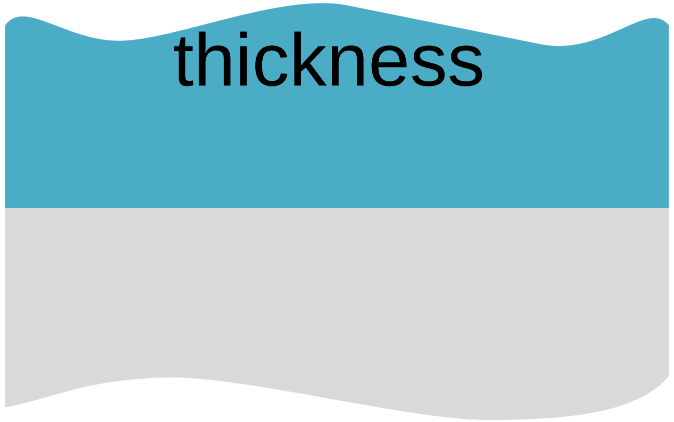
Absorption reduces oscillation amplitudes

Non-Ideal Thin Films in CompleteEASE

Rough surface

Roughness = 1.37 nm (fit)
+ Layer # 1 = Cauchy Film Thickness # 1 = 152.57 nm (fit
Substrate = SI_JAW

Non-uniform thickness



Layer Commands: Add Delete Save
Include Surface Roughness = OFF
+ Layer # 1 = Cauchy Film Thickness # 1 = 152.57 nm (fit
Substrate = SI_JAW

- MODEL Options
  - Angle Offset = 0.00
  - Include Substrate Backside Correction = OFF
  - Model Calculation = Include Thickness Non-uniformity
    - % Thickness Non-uniformity = 10.00
    - # of Pts = 9
+ FIT Options
+ OTHER Options

Configure Options
Turn Off All Fit Parameters

Index Grading

Include Surface Roughness = OFF
+ Layer # 1 = Cauchy Film Thickness # 1 = 152.57 nm (fit)
Substrate =

+ MODEL Opt
+ FIT Options
+ OTHER Opt

Configure
Turn Off All

Graph Layer Optical Constants
Graph Layer Absorption Coefficient
Rename Layer and Fit Parameters
Save Layer Optical Constants
Parameterize Layer
View Layer Comment
Convert To EMA
Convert To Transparent B-Spline
Convert To Anisotropic
Grade Layer
Start Superlattice

- Graded Layer Thickness # 1 = 152.57 nm (fit
  - Grade Type = Simple # of Slices = 5
  - % Inhomogeneity = 0.00 (fit)
  - + Material = Cauchy Film

Substrate = SI_JAW

Roughness and Non-uniformity differ on lateral length-scales

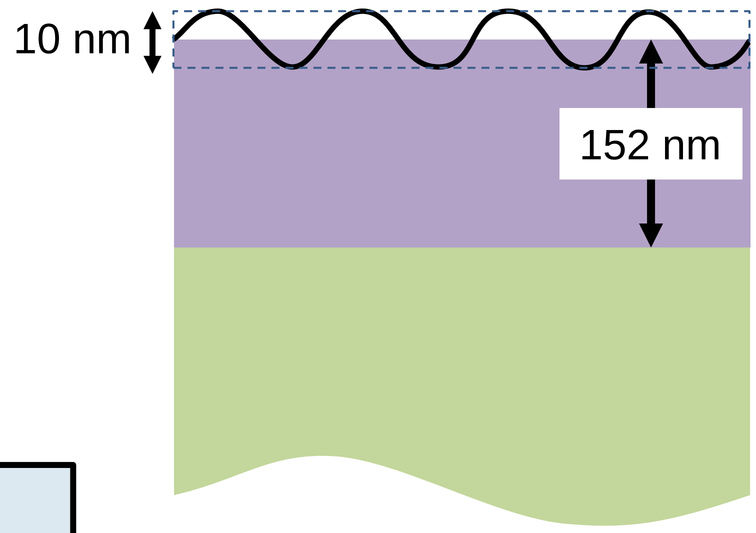
Surface Roughness

- Describes ultra-thin layers (< 10nm) on a surface.
  - Roughness, oxidation, adsorbed organic contaminates…
- Modeled by mixing index of top layer with void (50% - 50%)

Roughness = **10.00 nm** (fit)

\+ Layer # 1 = Cauchy Film Thickness # 1 = **152.34 nm** (fit

Substrate = SI_JAW

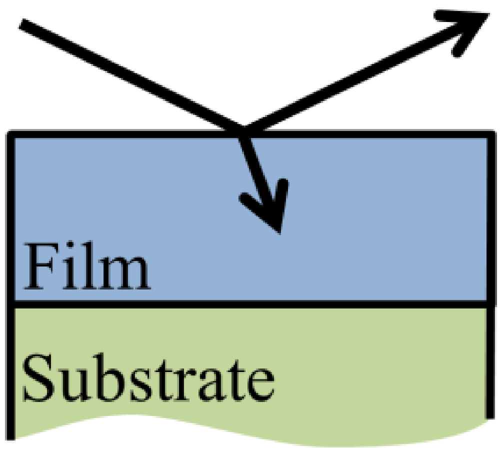


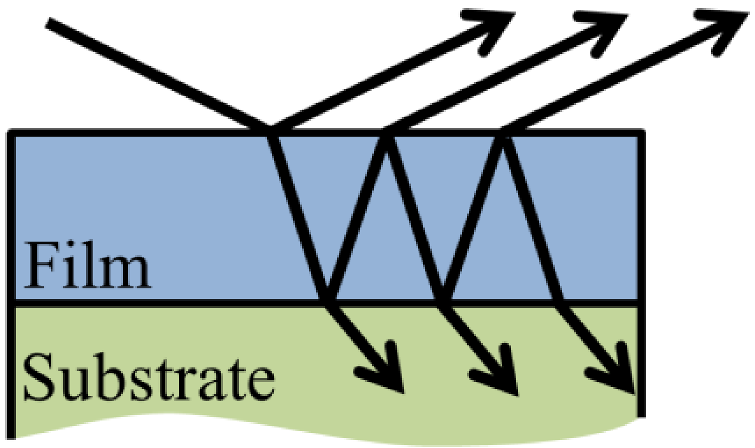
Total thickness = Film thickness + ½ roughness

Roughness **is a “stealing” layer –**
it takes ½ its thickness from layer below.
This avoids moving peaks/valleys.

Surface Roughness

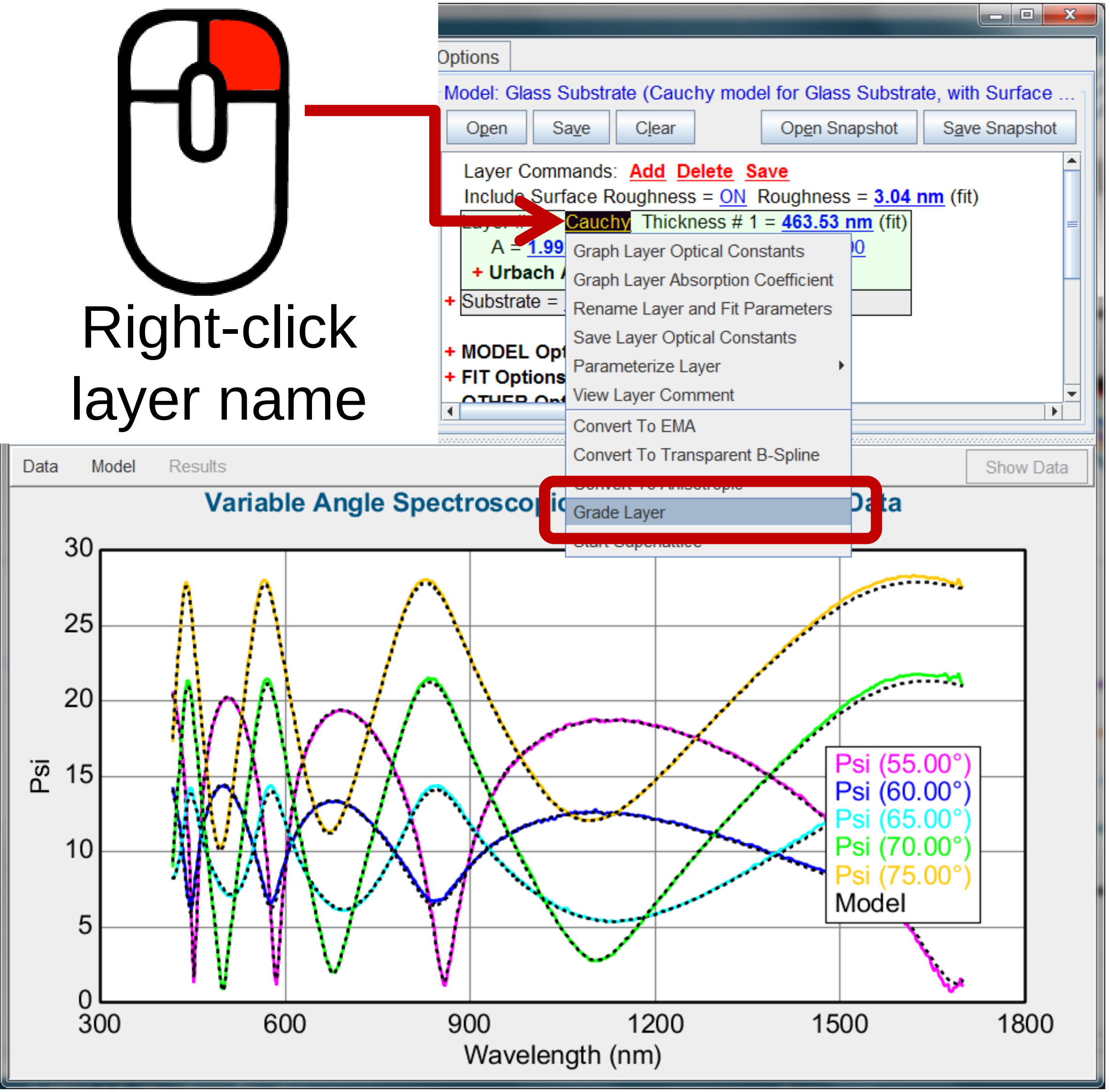
- Best sensitivity to surface roughness when:
  - Top layer has large index
    - More contrast for surface that is mixed with void (n=1)
  - Top layer is absorbing
    - No light penetrates the film, so all detected light is from surface!



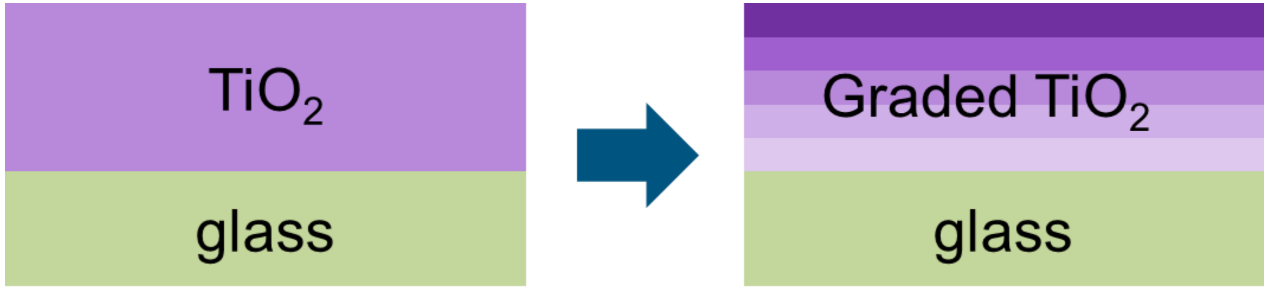


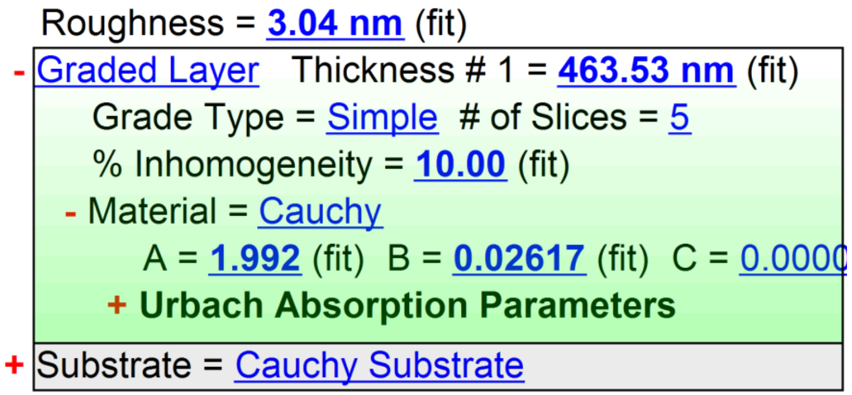
Index Grading

Right-click layer name



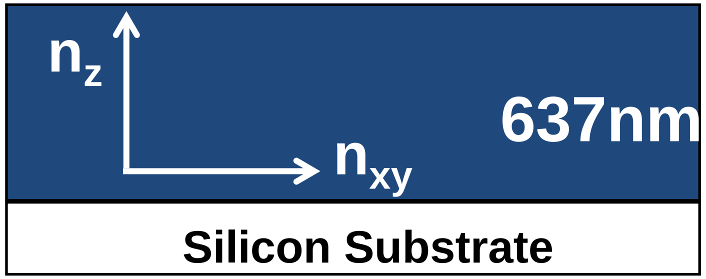
Divides film into ‘slices’ with varying index.

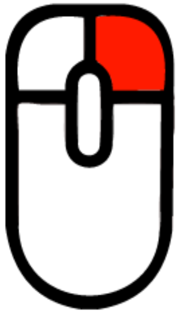




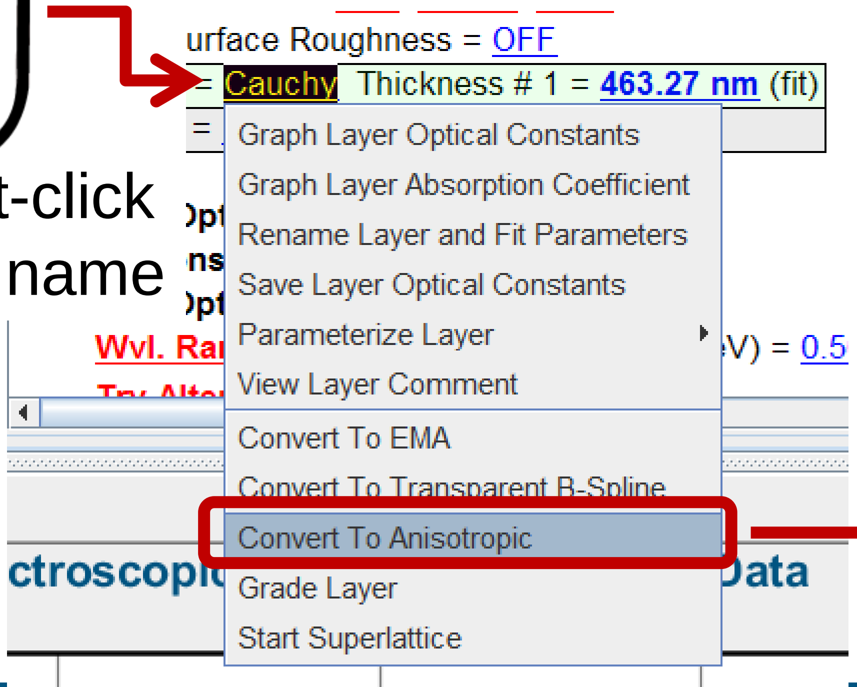
Anisotropy

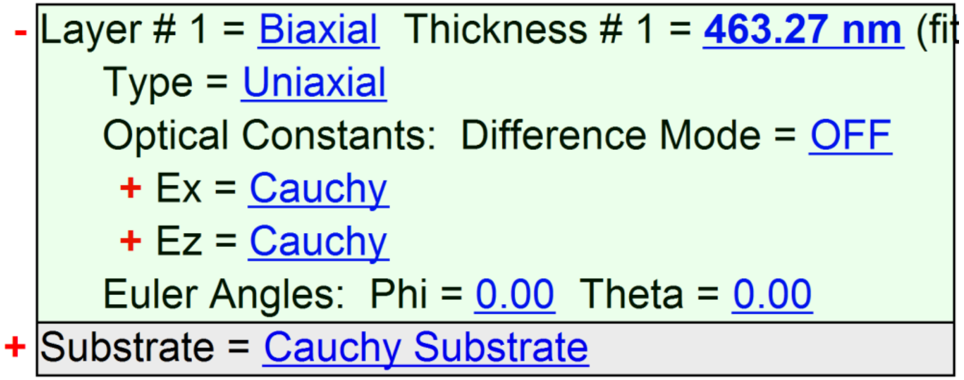
- Index varies with direction.

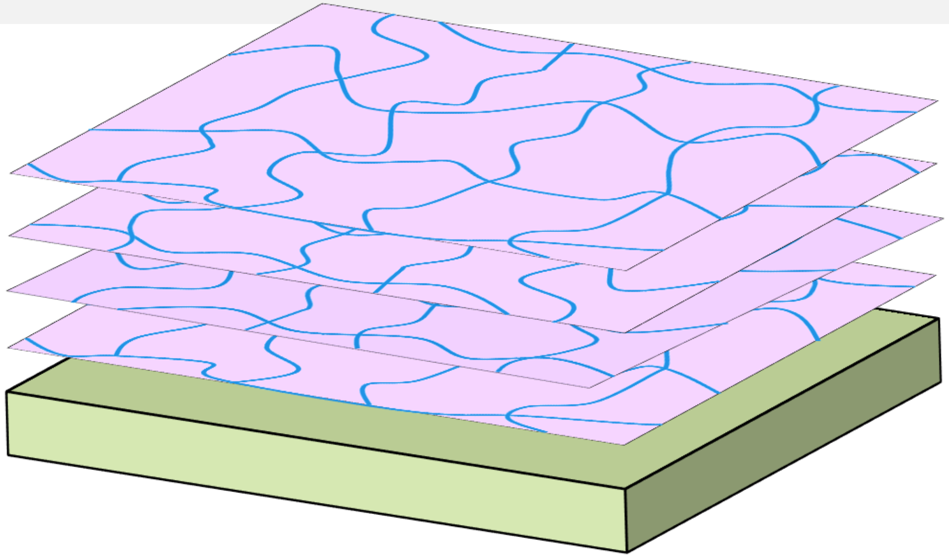




Right-click layer name







Shortcut: Try Alternate Models

Layer Commands: **Add** **Delete** **Save**
Include Surface Roughness = OFF
- Layer # 1 = Cauchy Film Thickness # 1 = **129.79 nm** (fit)
  A = **1.879** (fit) B = **0.01903** (fit) C = **-0.00129** (fit)
  + **Urbach Absorption Parameters**
Substrate = SI_JAW

+ **MODEL Options**
+ **FIT Options**
- **OTHER Options**

  Try Alternate Models MSE Improvement Threshold = 25 %
  Fit Parameter Error Estimation
  Add Opt. Const. to Report = OFF

Configure Options
Turn Off All Fit Parameters

Analysis Results

Copy Table to Clipboard

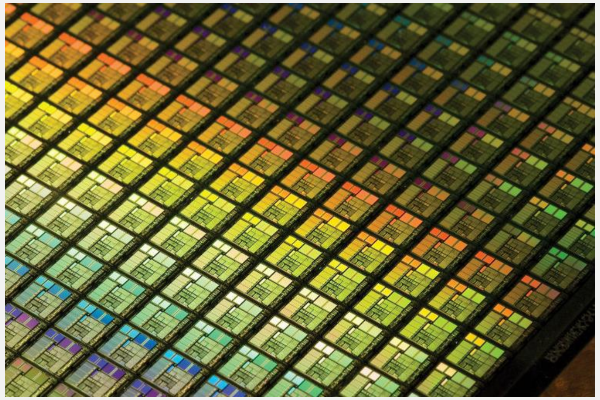
Parameter	Ideal	Roughness	Grading	Roughness & Grading	Anisotropy
MSE	25.415	25.259	17.201	14.079	24.940
Roughness	N/A	-1.72 ± 0.426 nm	N/A	6.35 ± 0.260 nm	N/A
A	1.887 ± 0.00088467	1.882 ± 0.001564	1.865 ± 0.00081890	1.874 ± 0.00091512	1.882 ± 0.001022
B	0.01278 ± 0.00058122	0.01724 ± 0.001271	0.02775 ± 0.00054623	0.01970 ± 0.00066902	0.01436 ± 0.00059163
C	-0.00037363 ± 5.6772E-05	-0.00078979 ± 0.00011954	-0.00100 ± 4.3315E-05	3.6114E-05 ± 6.9339E-05	-0.00054004 ± 5.8270E-05
% Inhomogeneity	N/A	N/A	24.08 ± 0.498	34.59 ± 0.620	N/A
Thickness # 1	129.62 ± 0.058 nm	129.39 ± 0.081 nm	125.43 ± 0.088 nm	124.51 ± 0.081 nm	130.10 ± 0.078 nm
n of Cauchy Film @ 632.8 nm	1.91677	1.92015	1.92855	1.92387	N/A

<< **Apply Chosen Model** >>

Show Graphs

2-07 SiO_xN_y on Si

- **Use Automated Model to find Cauchy for SiO_xN_y**



Estimate Index & Thickness

⇩

Fit Thickness & Cauchy Parameters

⇩

Add roughness, does it improve MSE?

Si with Transparent Film.mod

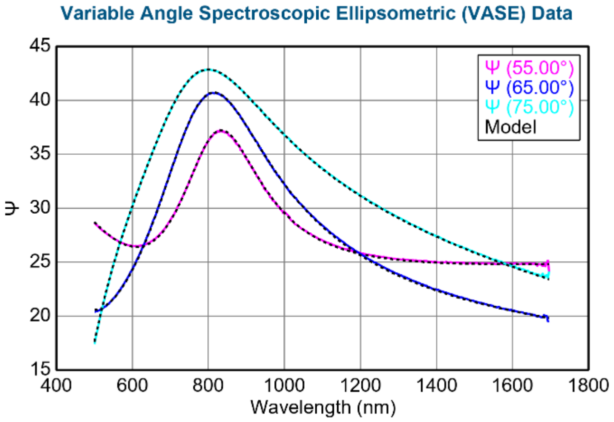
<u>YOU</u> will have to choose the transparent wavelength range for all examples

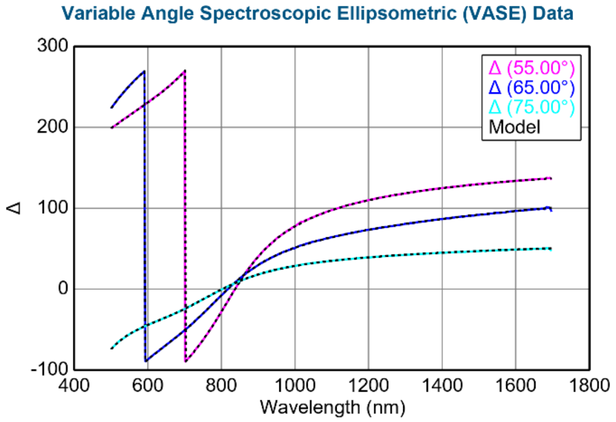
2-07 SiOxNy on Si: Results

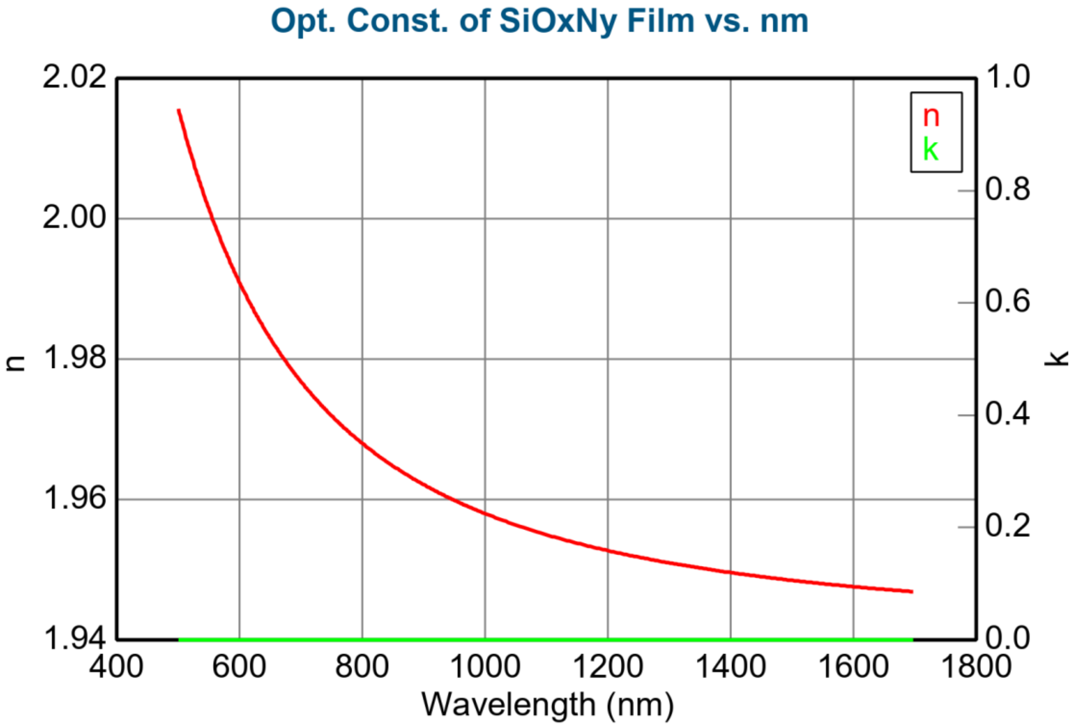
SiOxNy on Si

Fit Results	Optical Model
MSE = 2.391 Roughness = 6.67 ± 0.046 nm Thickness # 1 = 118.11 ± 0.008 nm A = 1.941 ± 0.00027878 B = 0.01623 ± 0.00026828 C = 0.00060462 ± 6.1831E-05 n of Cauchy Film @ 632.8 nm = 1.98546	Roughness = **6.67 nm** (fit) + Layer # 1 = Cauchy Film Thickness # 1 = **118.11 nm** (fit) Substrate = SI_JAW

Experimental and Model Generated Data Fits

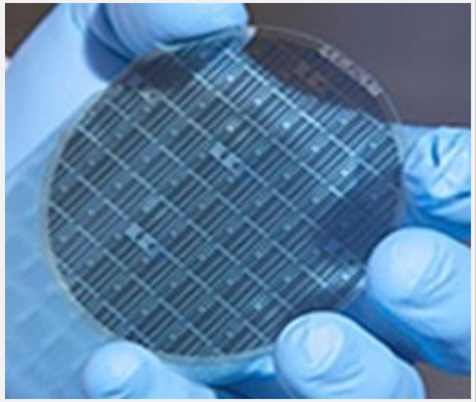






SiC on Si

- **Find best model for SiC on Si**



Fit Thickness & Cauchy Parameters

⇩

<u>Add to improve MSE</u>:
Roughness?
Index Grading?
Anisotropy?
Thickness Non-uniformity?

2-08 SiC on Si: Results

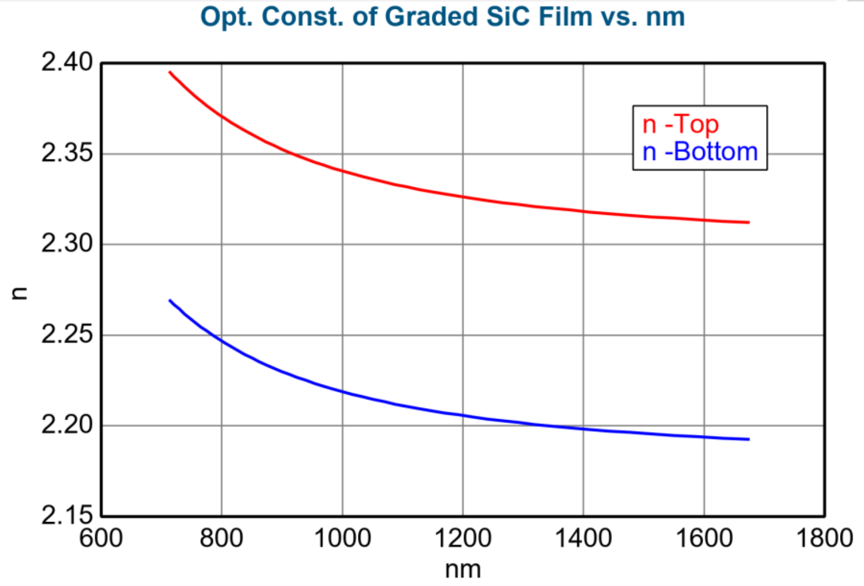
SiC on Si

Fit Results

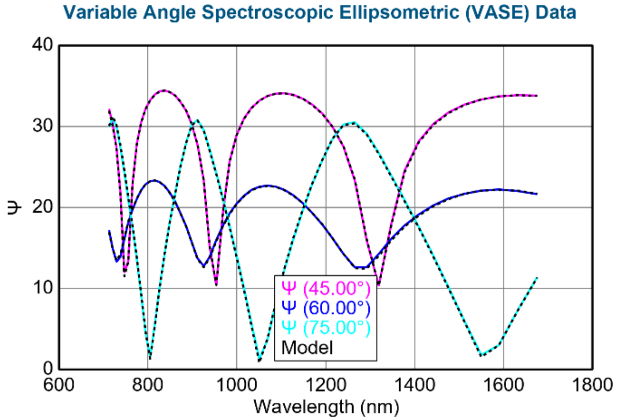
MSE = 3.471
Roughness = 1.29 ± 0.093 nm
A = 2.241 ± 0.00080736
B = 0.03236 ± 0.001048
C = 0.00747 ± 0.00041129
% Inhomogeneity = 13.20 ± 0.176
Thickness # 1 = 766.45 ± 0.222 nm
n of Cauchy Film @ 632.8 nm = 2.36805

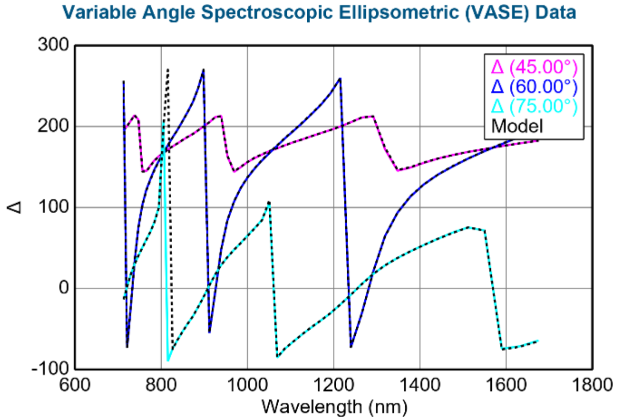
Optical Model

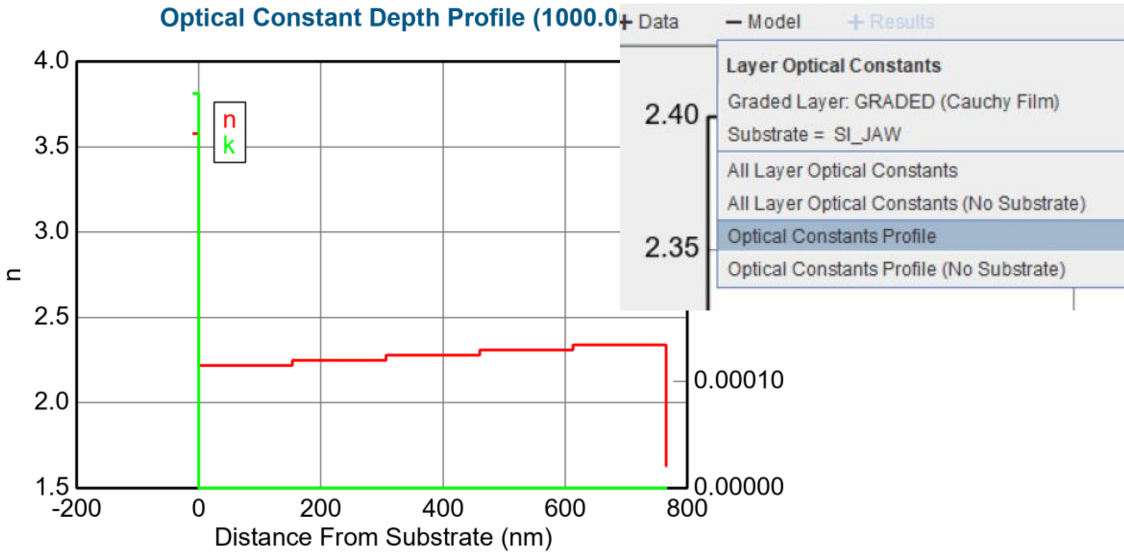
Roughness = 1.29 nm (fit)
- Graded Layer Thickness # 1 = 766.45 nm (fit)
  Grade Type = Simple # of Slices = 5
  % Inhomogeneity = 13.20 (fit)
  + Material = Cauchy Film
Substrate = SI_JAW



Experimental and Model Generated Data Fits







2-09 Polymer on Si

- **Find a model that matches this data.**

Fit Thickness & Cauchy Parameters

⇩

<u>Add to improve MSE</u>:
Roughness?
Index Grading?
Anisotropy?
Thickness Non-uniformity?

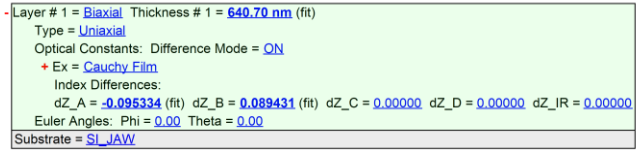
2-09 Polymer on Si: Results

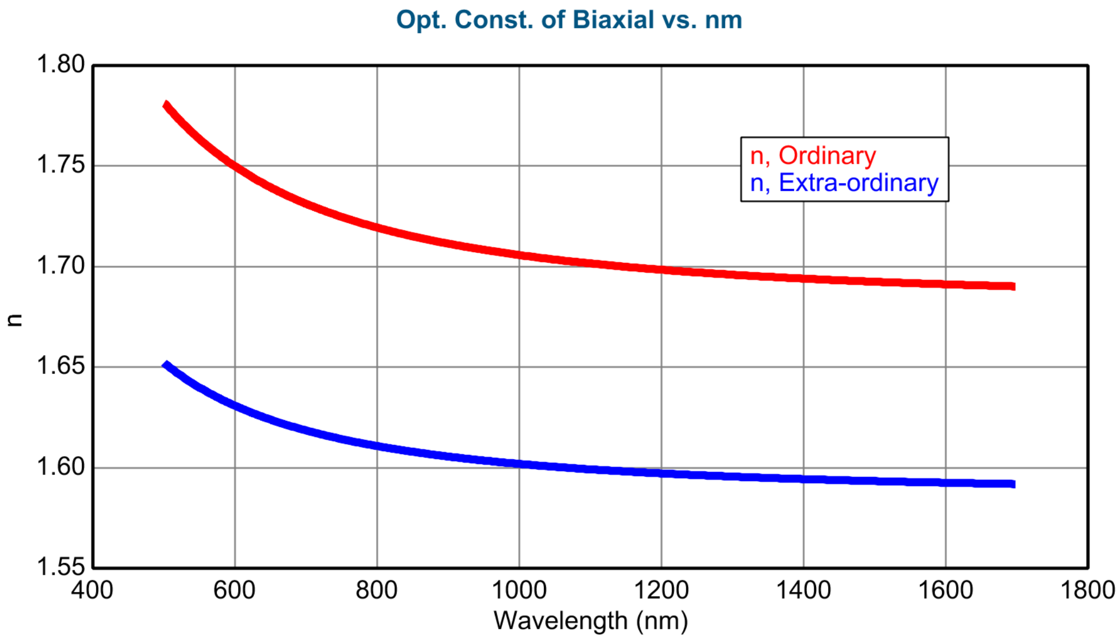
Polymer on Si

Fit Results

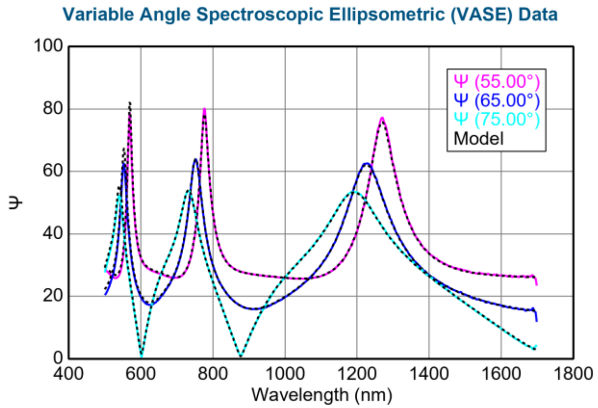
MSE = 17.186
Thickness # 1 = 640.70 ± 0.211 nm
A = 1.682 ± 0.00045756
B = 0.02330 ± 0.00027551
C = 0.00039654 ± 6.4547E-05
dZ_A = -0.095334 ± 0.00071389
dZ_B = 0.089431 ± 0.0039384
n_o of Biaxial @ 632.8 nm = 1.74271
n_e of Biaxial @ 632.8 nm = 1.62608

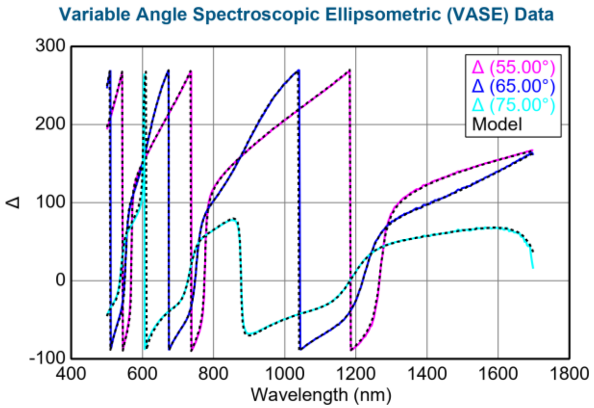
Optical Model


- Layer # 1 = Biaxial Thickness # 1 = 640.70 nm (fit)
    Type = Uniaxial
    Optical Constants: Difference Mode = ON
    + Ex = Cauchy Film
      Index Differences:
      dZ_A = -0.095334 (fit) dZ_B = 0.089431 (fit) dZ_C = 0.00000 dZ_D = 0.00000 dZ_IR = 0.00000
    Euler Angles: Phi = 0.00 Theta = 0.00
Substrate = SI_JAW

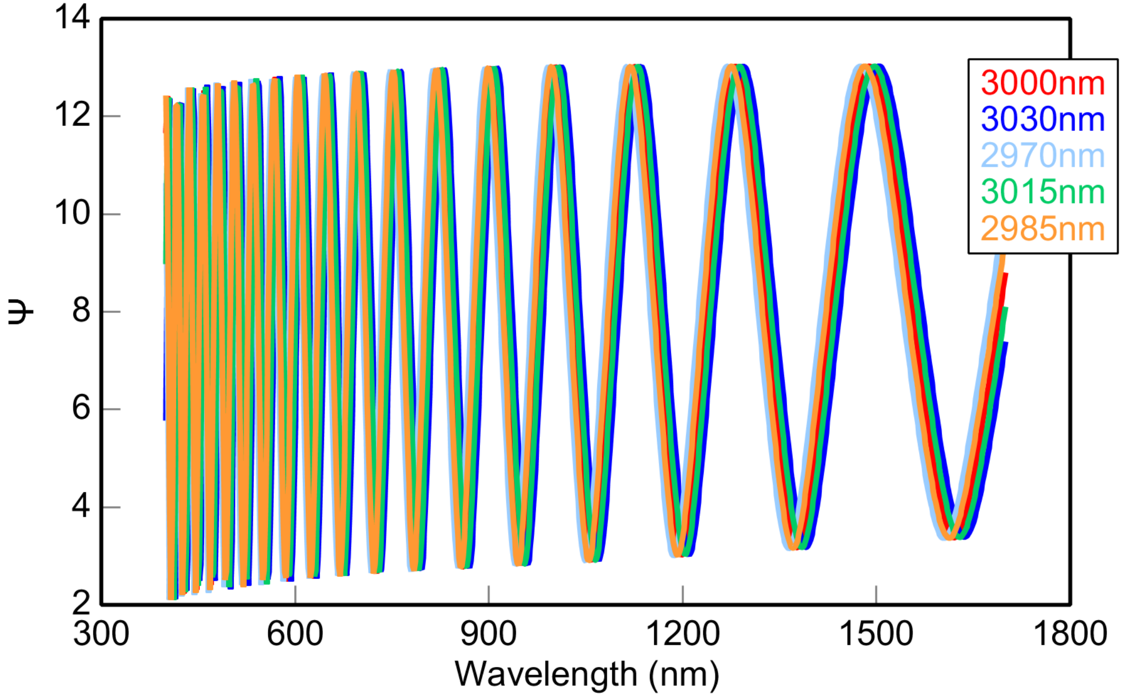


Experimental and Model Generated Data Fits

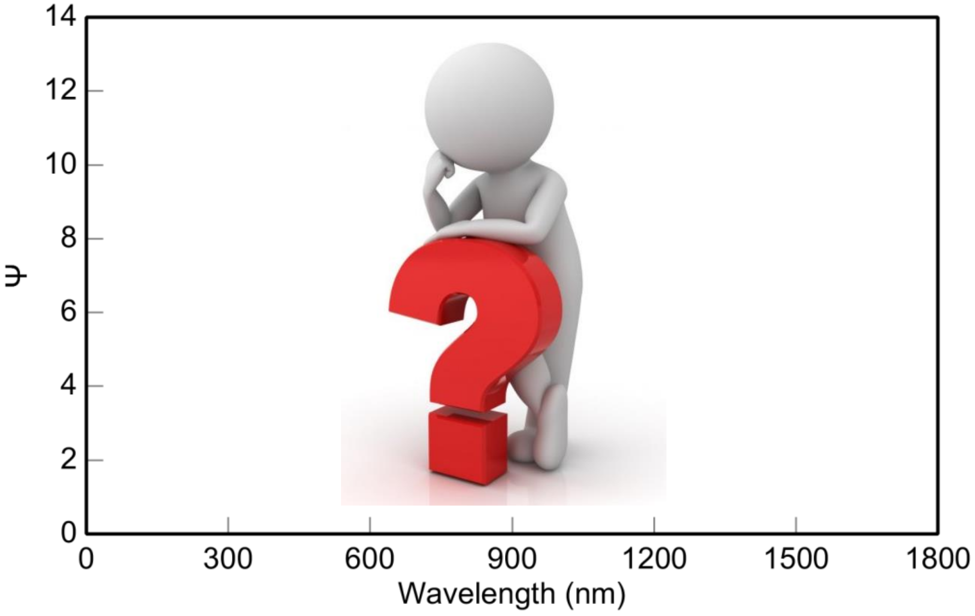




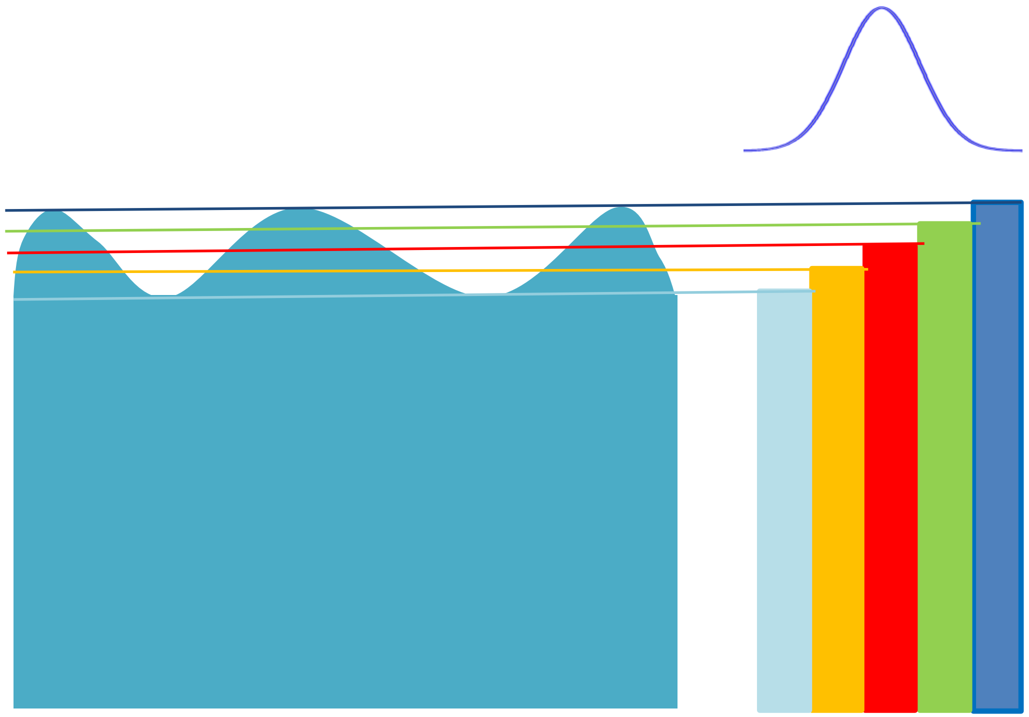
Thickness effect on SE Data

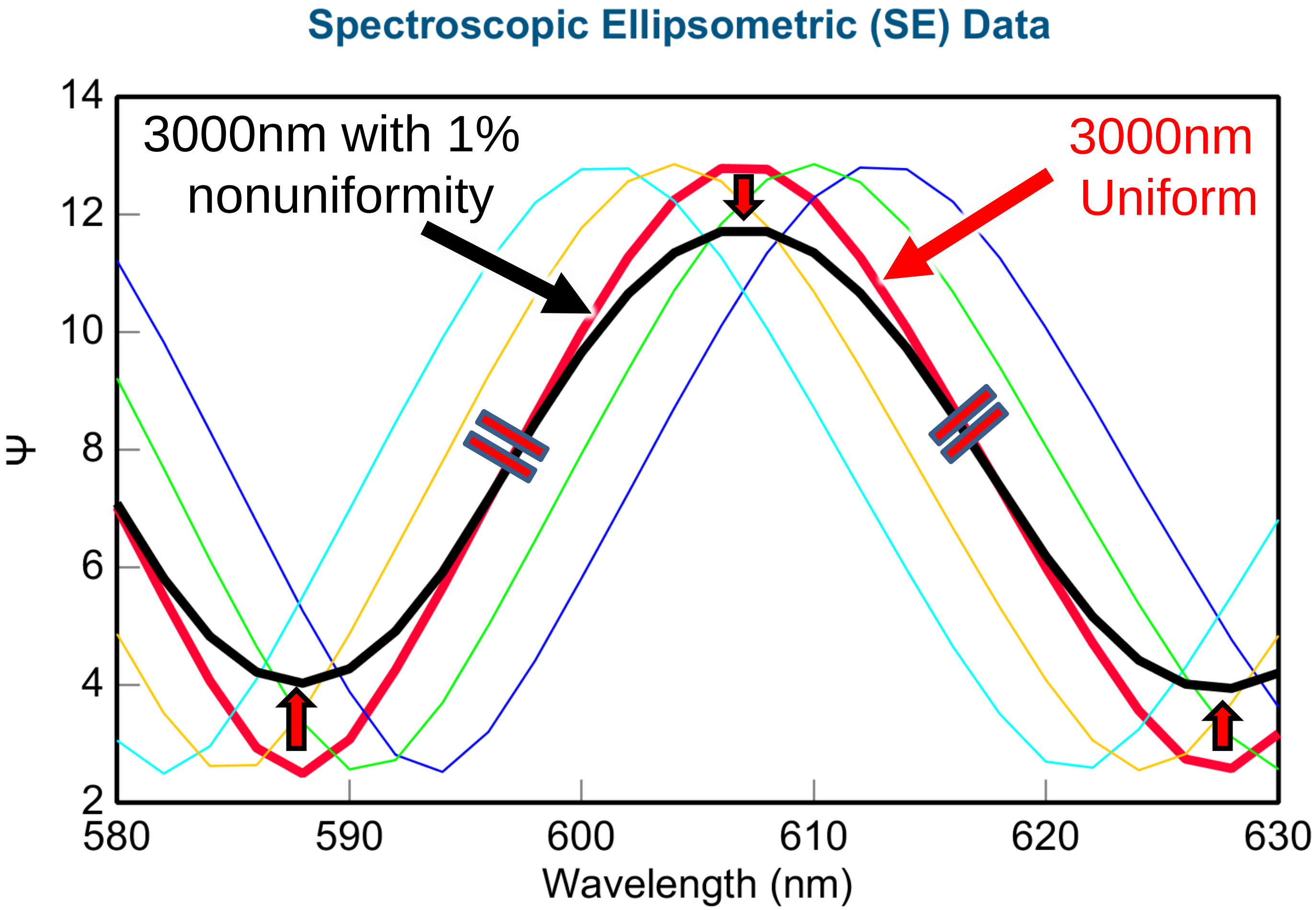


Spectroscopic Ellipsometric (SE) Data

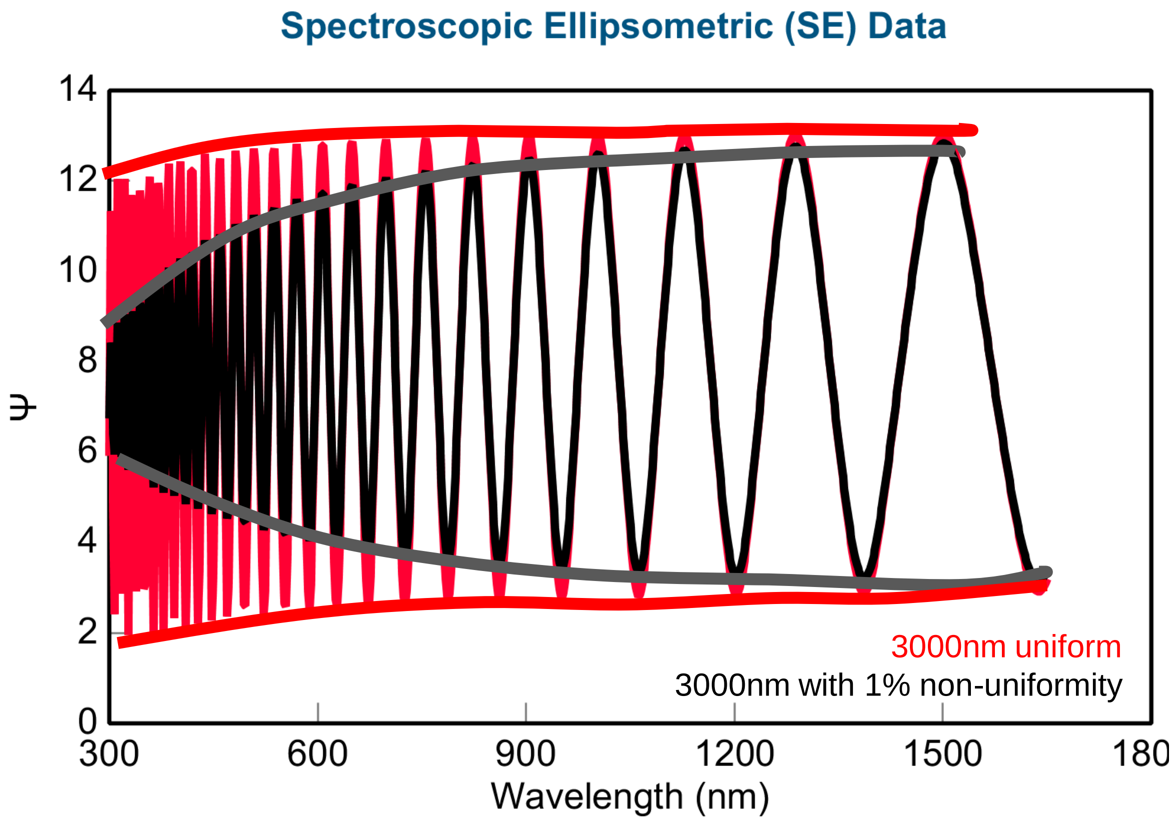


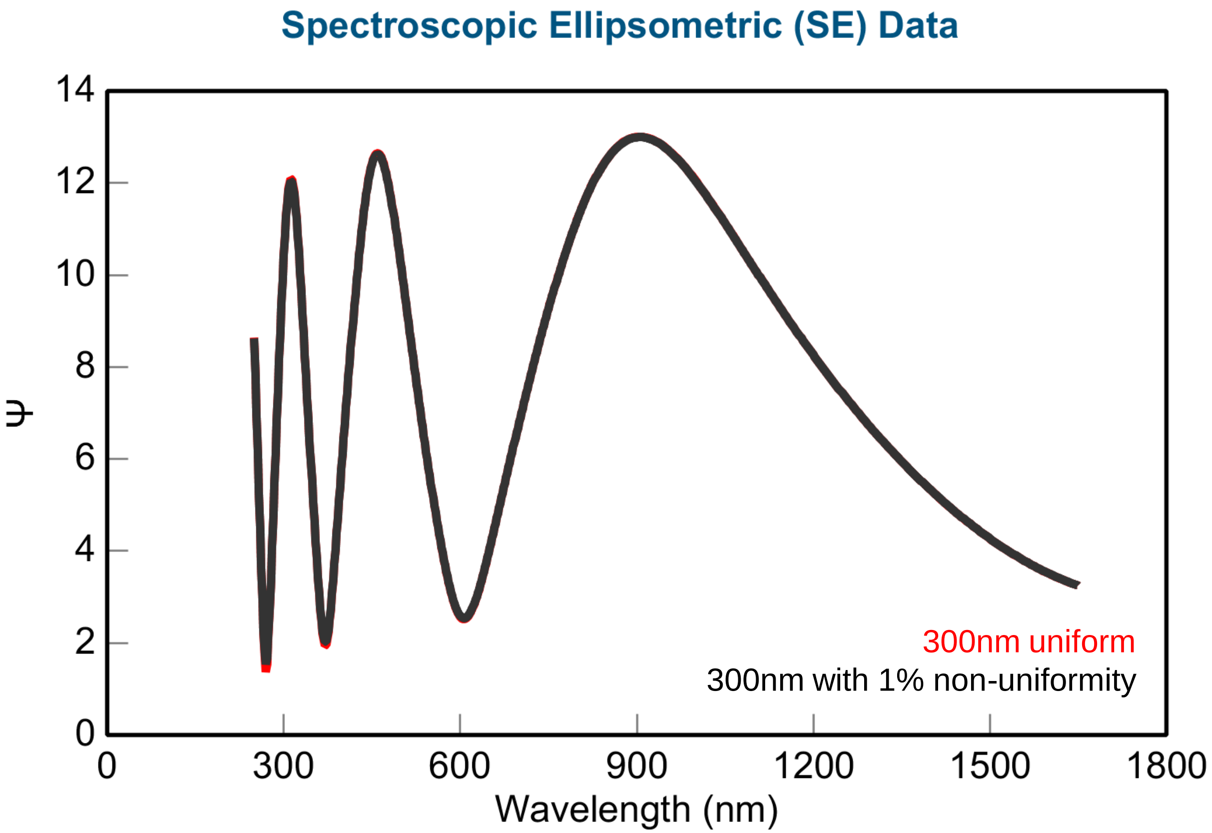
Non-Uniformity Effect on Raw Data





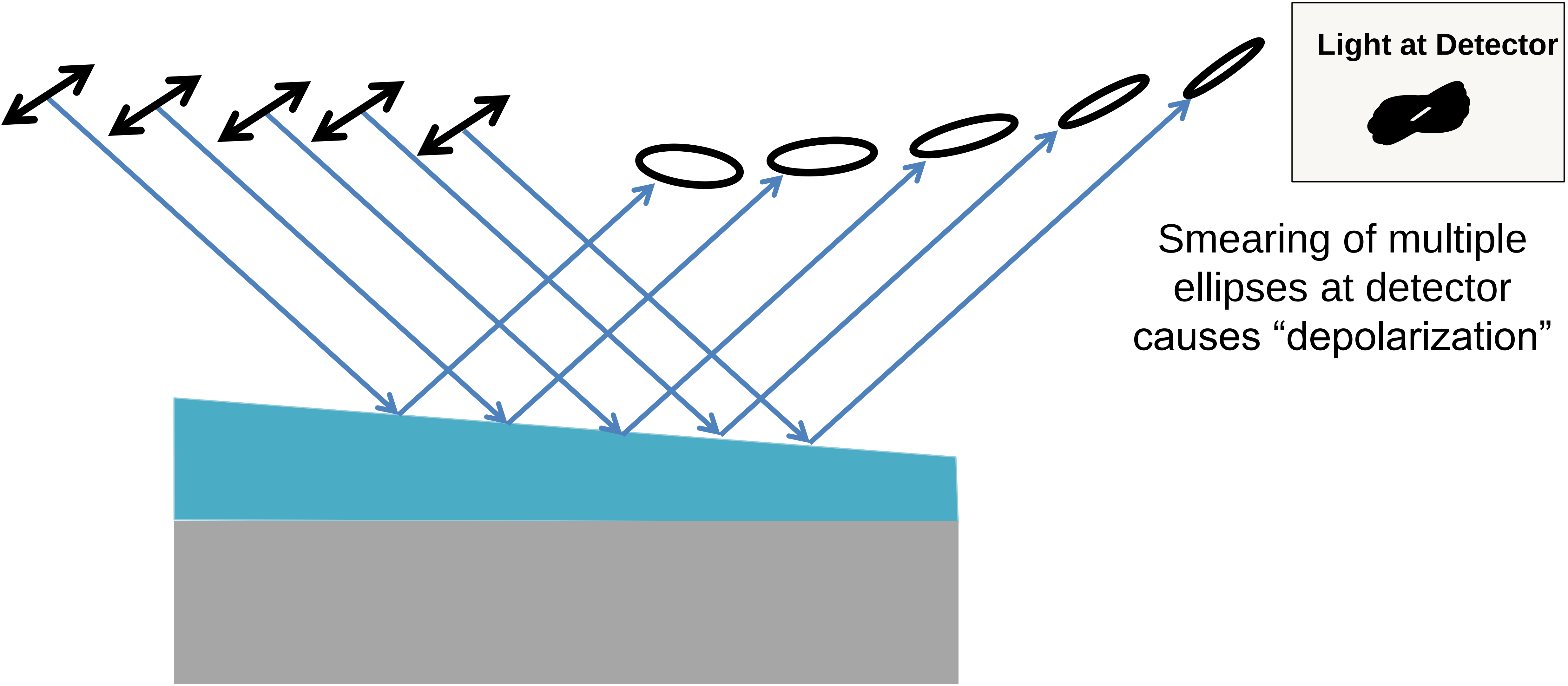
Non-Uniformity Effect





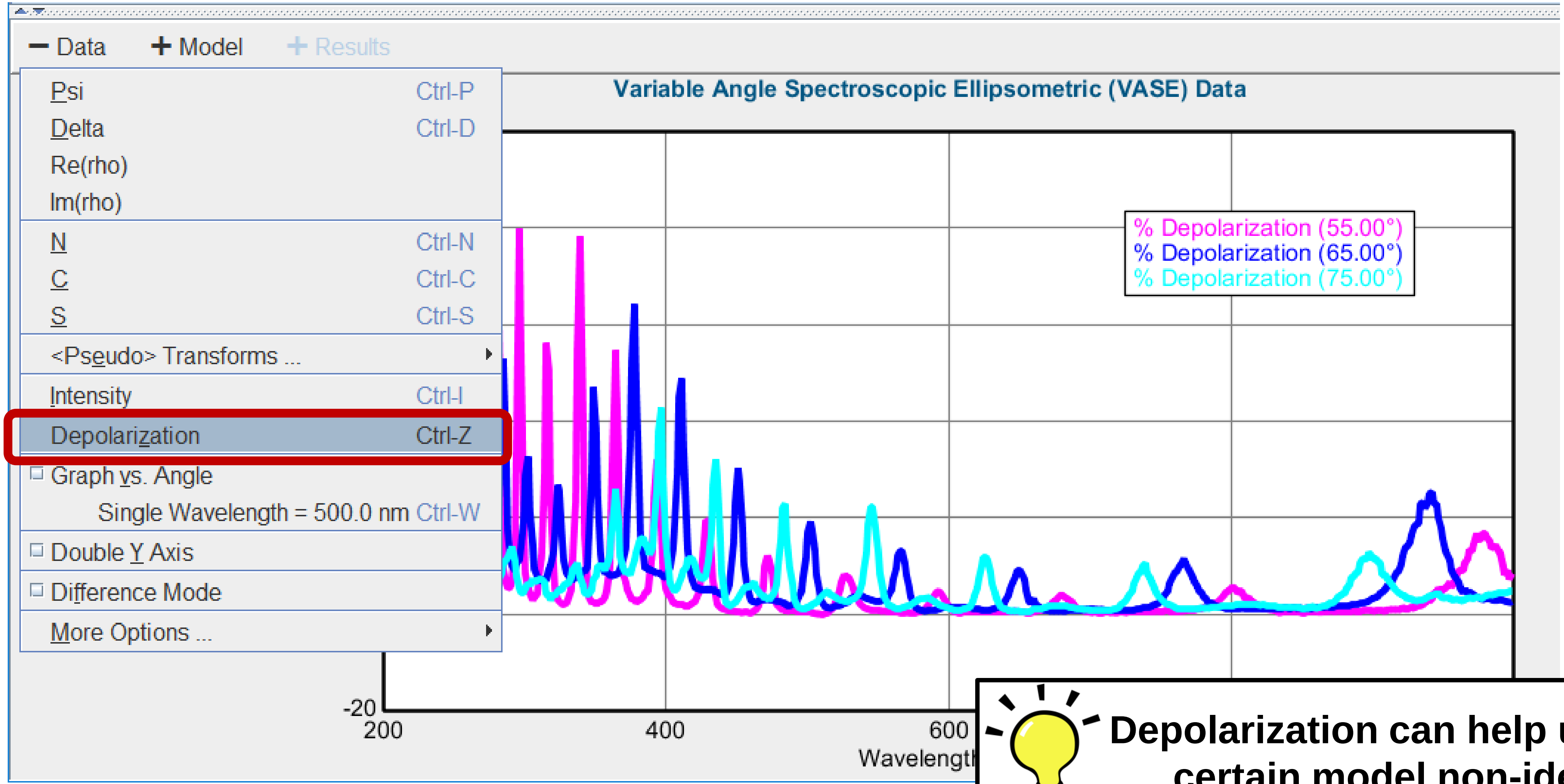
- Nonuniformity produces differences at peaks and valleys comparing to uniform films
- The differences are more pronounced towards short wavelength
- Better sensitivity to nonuniformity in thicker films.

Thickness Non-Uniformity on Polarization States



Smearing of multiple ellipses at detector causes “depolarization”

Depolarization



Depolarization can help us identify certain model non-idealities

Causes of Depolarization

Instrument related:

- Bandwidth
- Angular spread

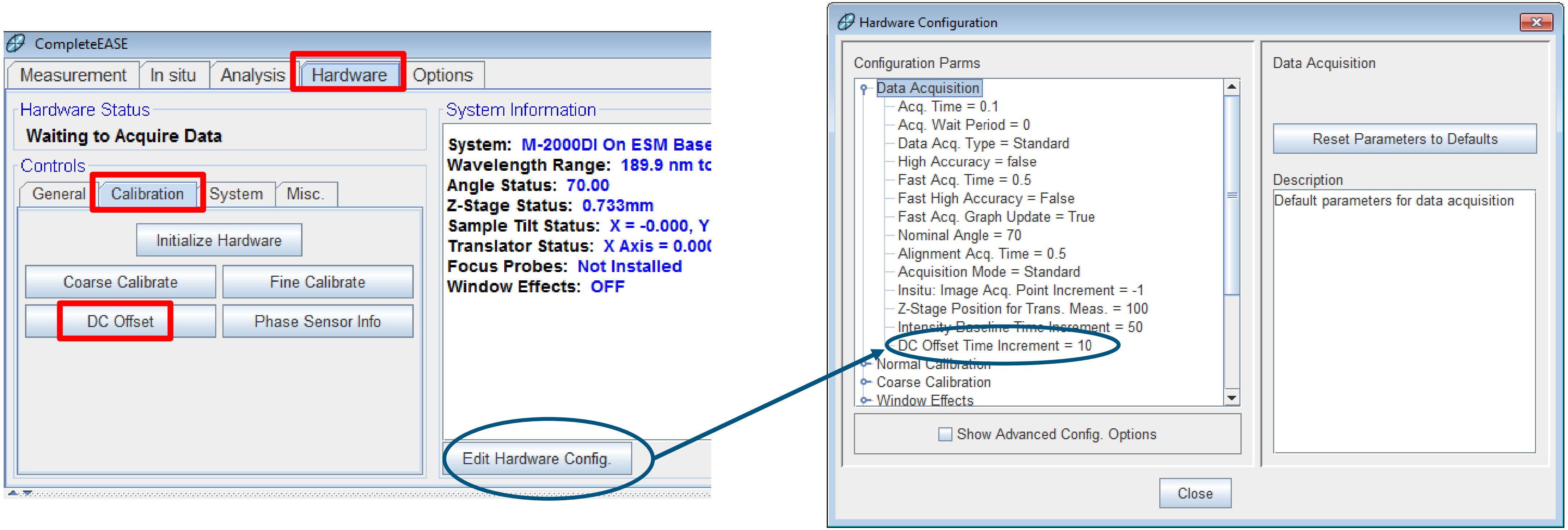
Sample related:

- Backside reflections
- Thickness non-uniformity

- These sample related features do NOT cause depolarization
  - Roughness
  - Grading
  - Anisotropy
  - Absorption

Acquiring Good Depolarization Data

- DC Offset calibration necessary to obtain good Depolarization data
- Can set time increment in “Edit Hardware Config.” menu
  - Negative increments turn off DC offset calibration
  - Set to “0” to perform DC offset calibration before every measurement



Modeling non-idealities that cause depolarization

Layer Commands: **Add** **Delete** **Save**

Include Surface Roughness = OFF

+ Layer # 1 = Cauchy Film Thickness # 1 = **9708.94 nm** (fit)

Substrate = SI_JAW

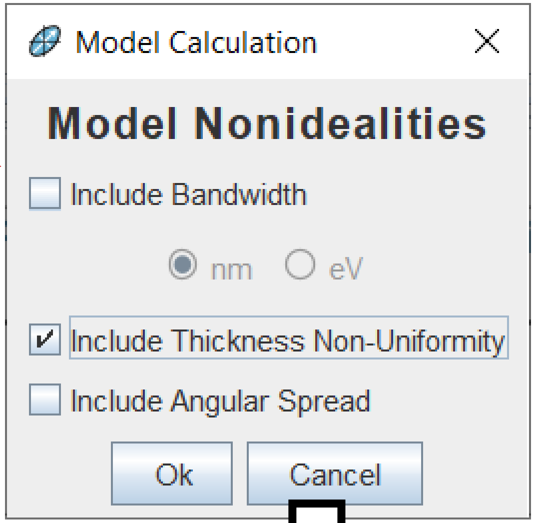
- MODEL Options

Angle Offset = 0.00

Include Substrate Backside Correction = OFF

Model Calculation = Ideal

1) select



2) select desired Model calculation type

+ Layer # 1 = Cauchy Film Thickness # 1 = **9687.26 nm** (fit)

Substrate = SI_JAW

- MODEL Options

Angle Offset = 0.00

Include Substrate Backside Correction = OFF

Model Calculation = Include Thickness Non-uniformity

% Thickness Non-uniformity = **0.96** (fit)

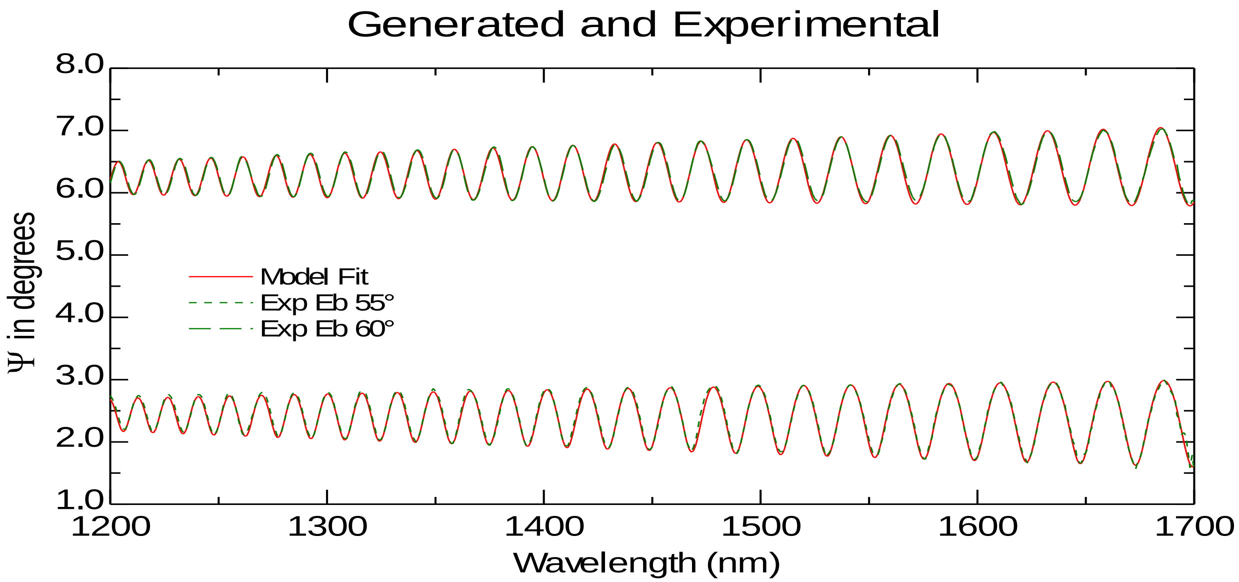
# of Pts = 9

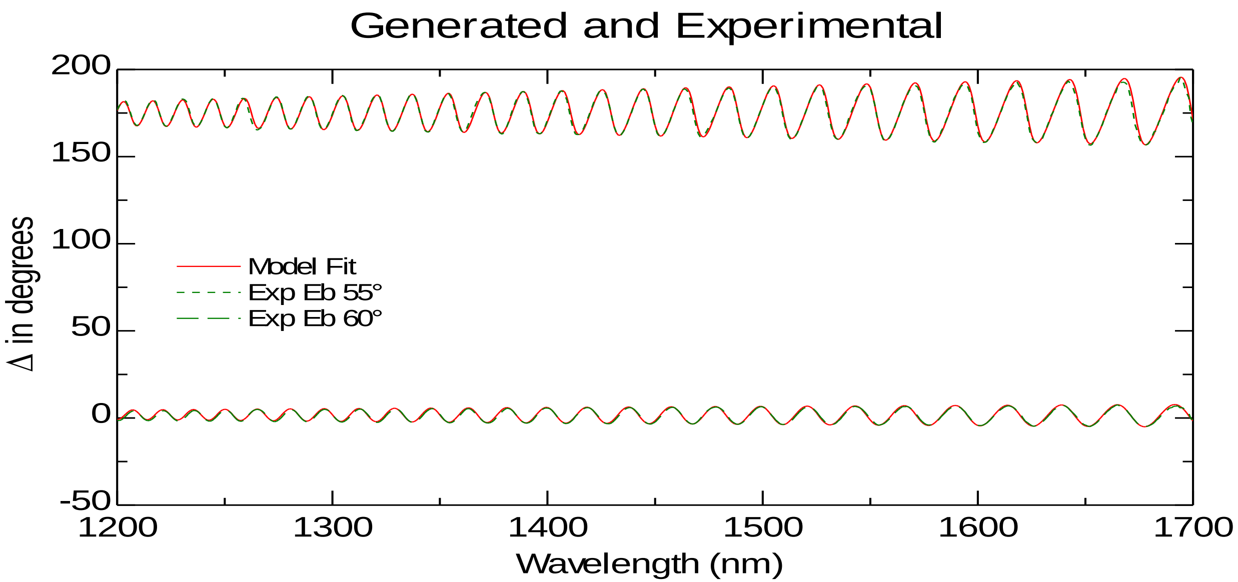
3) Fit

Thick Films

- Become trickier:
  - Need (i) fine wavelength resolution, (ii) uniform film, and (iii) longer wavelengths to resolve oscillations.

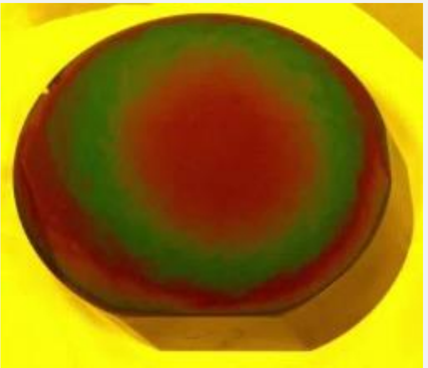
Roughness	5 nm
Epoxy Film	**42.16 µm**
Glass	2.28 mm





2-10 Ultra thick Photoresist on Si

- **Find a model that matches this data.**



Fit Thickness & Cauchy Parameters

⇩

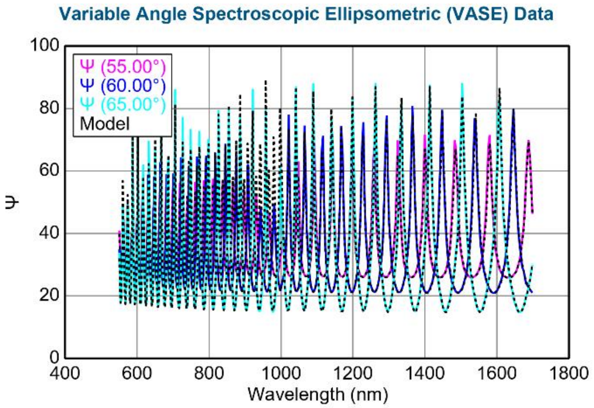
<u>Add to improve MSE</u>:
Roughness?
Index Grading?
Anisotropy?
Thickness Non-uniformity?

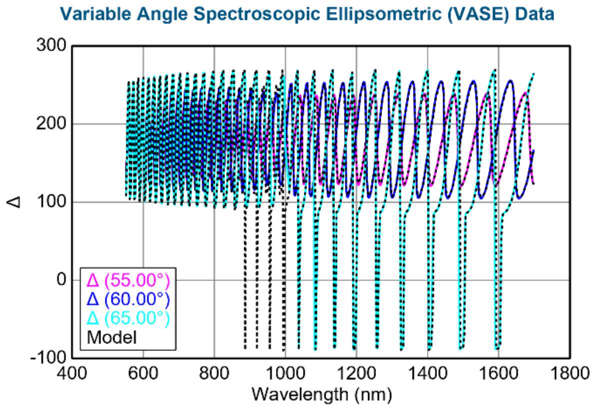
2-10 Ultra Thick PR on Si: Results

Ultra thick PR on Si

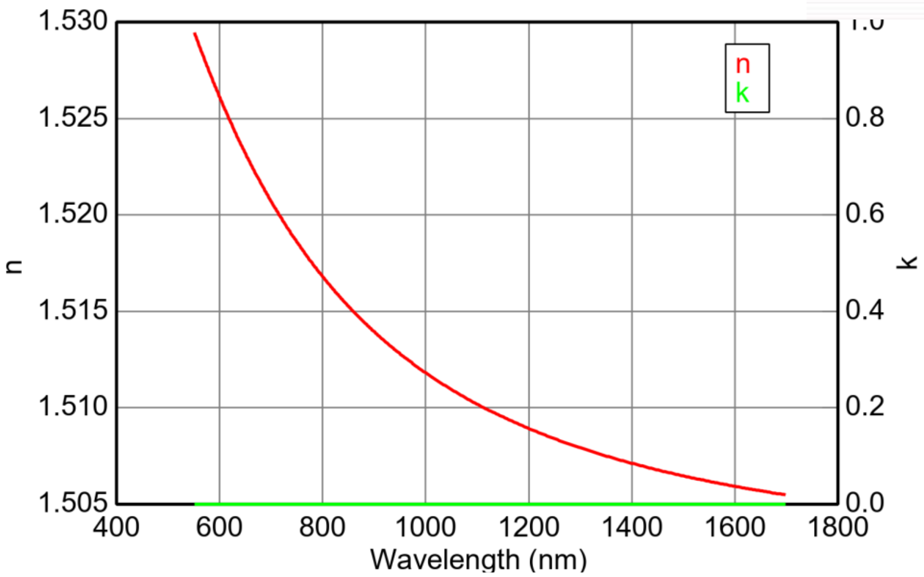
Fit Results	Optical Model
MSE = 58.084 Thickness # 1 = 9687.09 ± 3.421 nm A = 1.502 ± 0.00035882 B = 0.01059 ± 7.8812E-05 C = -0.00067494 ± 2.1864E-05 % Thickness Non-uniformity = 0.96 ± 0.00767 n of Cauchy Film @ 632.8 nm = 1.52414	- Layer # 1 = Cauchy Film Thickness # 1 = 9687.09 nm (fit) A = 1.502 (fit) B = 0.01059 (fit) C = -0.00067494 (fit) + Urbach Absorption Parameters Substrate = SI_JAW

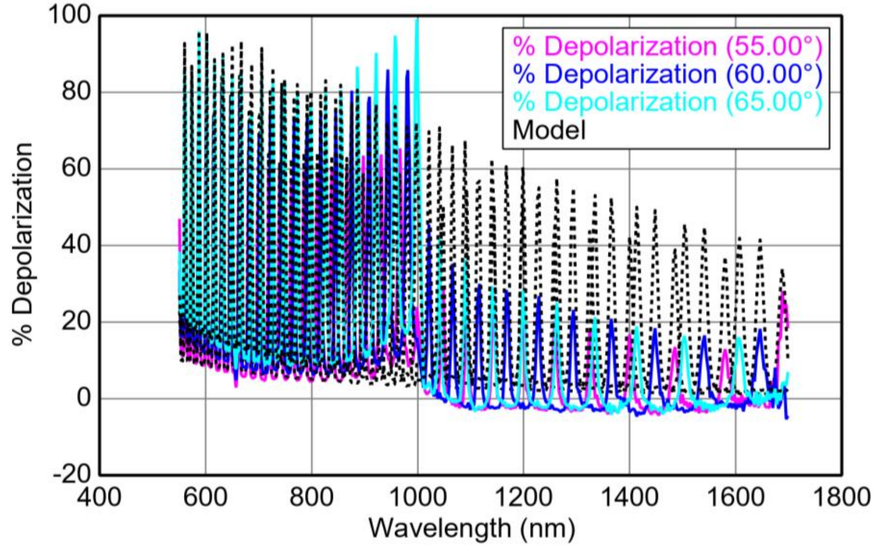
Experimental and Model Generated Data Fits





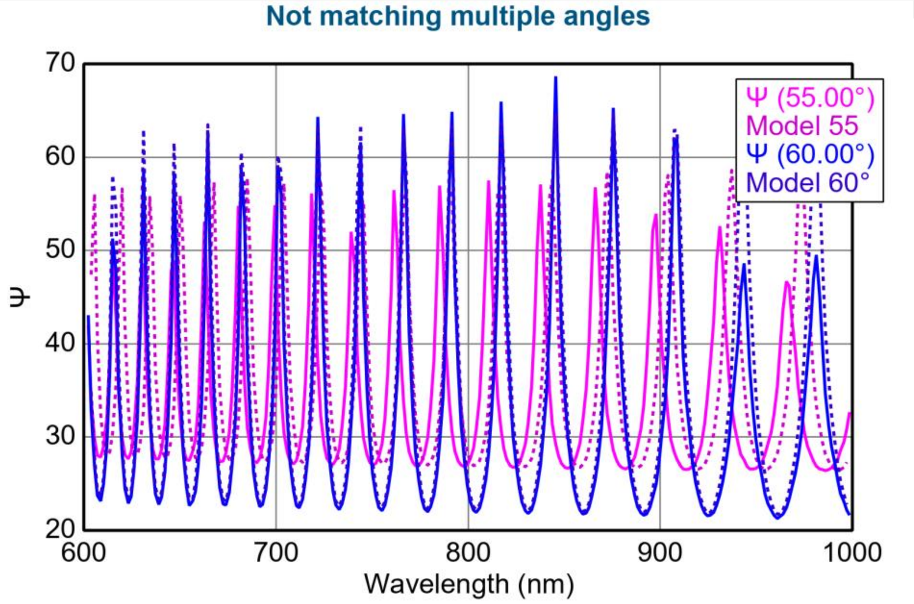
Opt. Const. of PR Film vs. nm

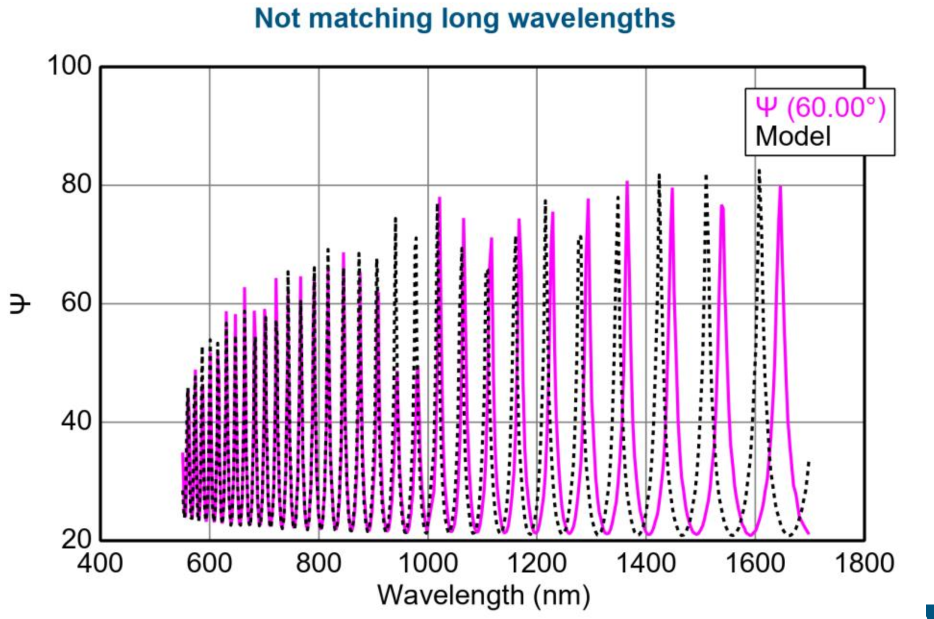


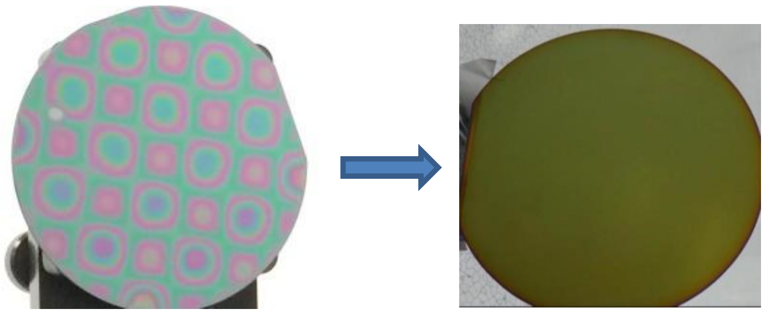


Tips on Thick Films

- Make the film as uniform as possible
- Measure at Multiple angles of incidence
- Measure into longer wavelength range
- Reduce the measurement area
- Modify process conditions to reduce film thi

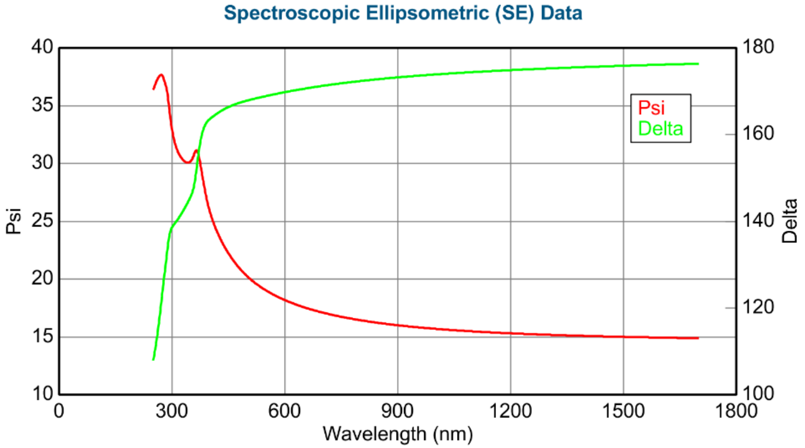






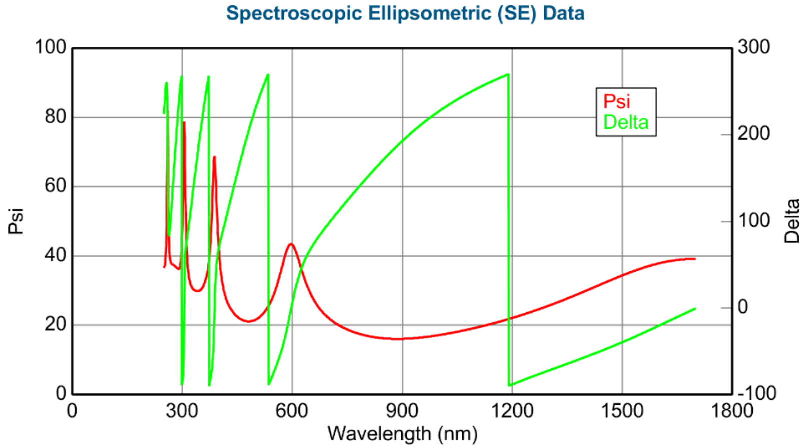
Thickness Ranges

Ultra-thin films



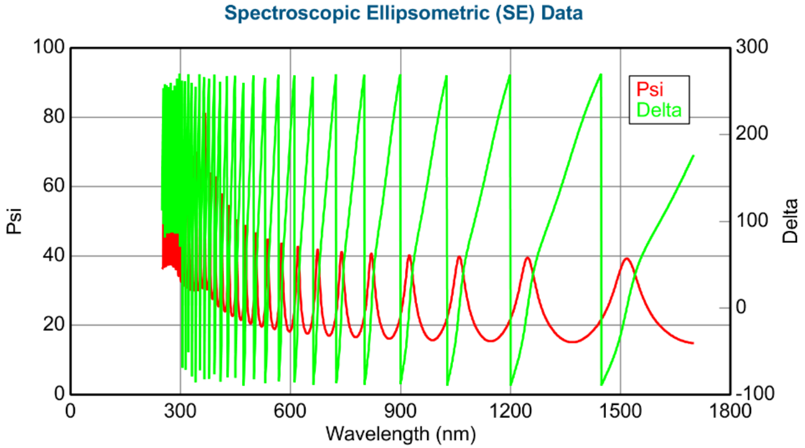
- 10 to 30nm or less
- No interference peaks
- Sensitive to thickness
- Not sensitive to refractive index (use fixed RI)

Thin films



- Tens of nms up to a couple of microns
- A few interference peaks and valleys
- Sensitive to both thickness and index

Thick films

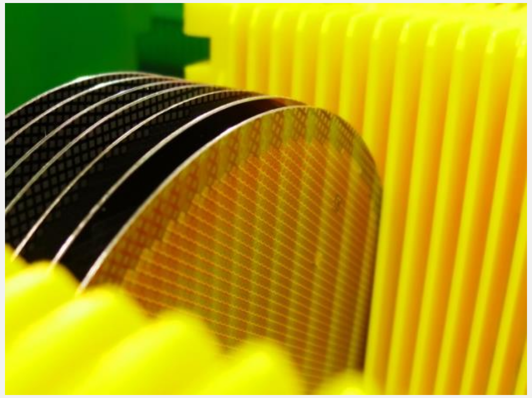


- Hundreds of nms to a few microns
- Many interference peaks and valleys
- Sensitive to thickness non-uniformity
- Long wavelength range and multiple AOIs are recommended

Practice Set

2-11 TiOx on Si

- **Find a model that best matches data.**



Fit Thickness & Cauchy Parameters

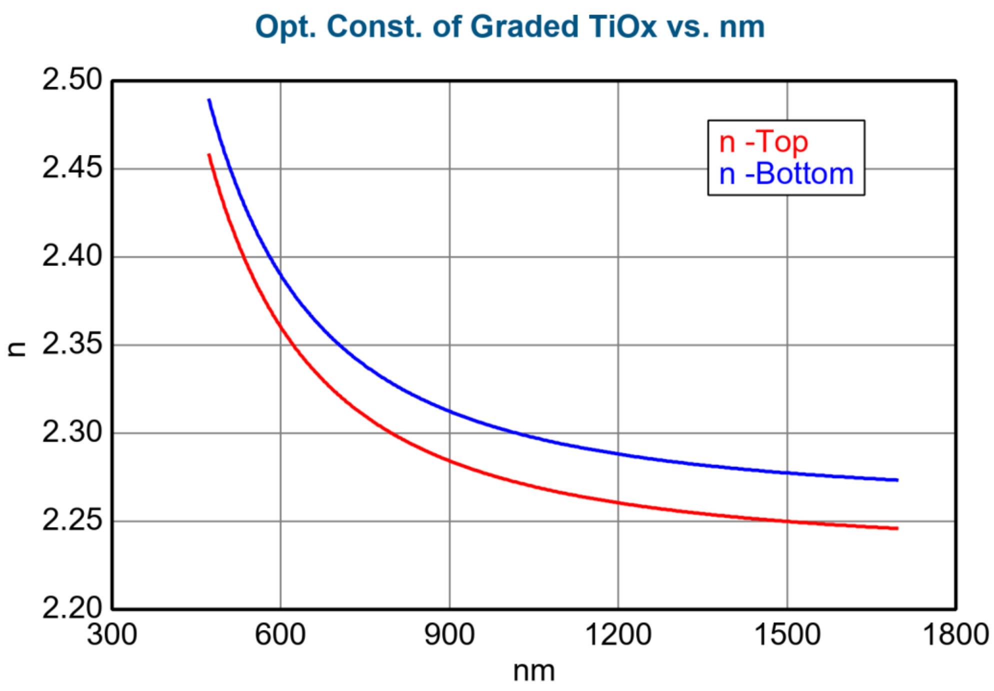
⇩

<u>Add to improve MSE</u>:
Roughness?
Index Grading?
Anisotropy?

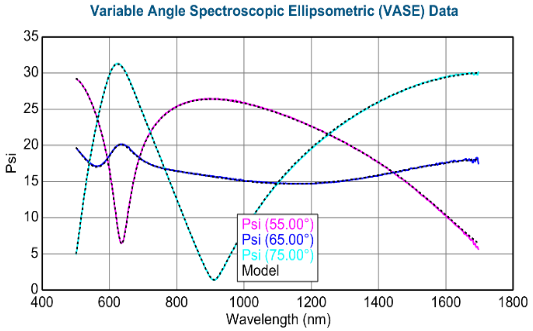
2-11 TiOx on Si: Results

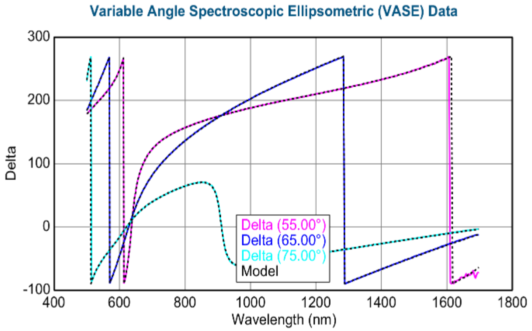
TiOx on Si

Fit Results	Optical Model
MSE = 2.720 Roughness = 3.66 ± 0.021 nm Thickness # 1 = 216.70 ± 0.020 nm A = 2.245 ± 0.00021244 B = 0.04193 ± 0.00028478 C = 0.00190 ± 6.8897E-05 % Inhomogeneity = -2.81 ± 0.0380 n of Cauchy Film @ 632.8 nm = 2.36106	Roughness = 3.66 nm (fit) - Layer # 1 = Graded Layer Thickness # 1 = 216.70 nm (fit) Grade Type = Simple # of Slices = 5 % Inhomogeneity = -2.81 (fit) + Material = Cauchy Film Substrate = SI_JAW

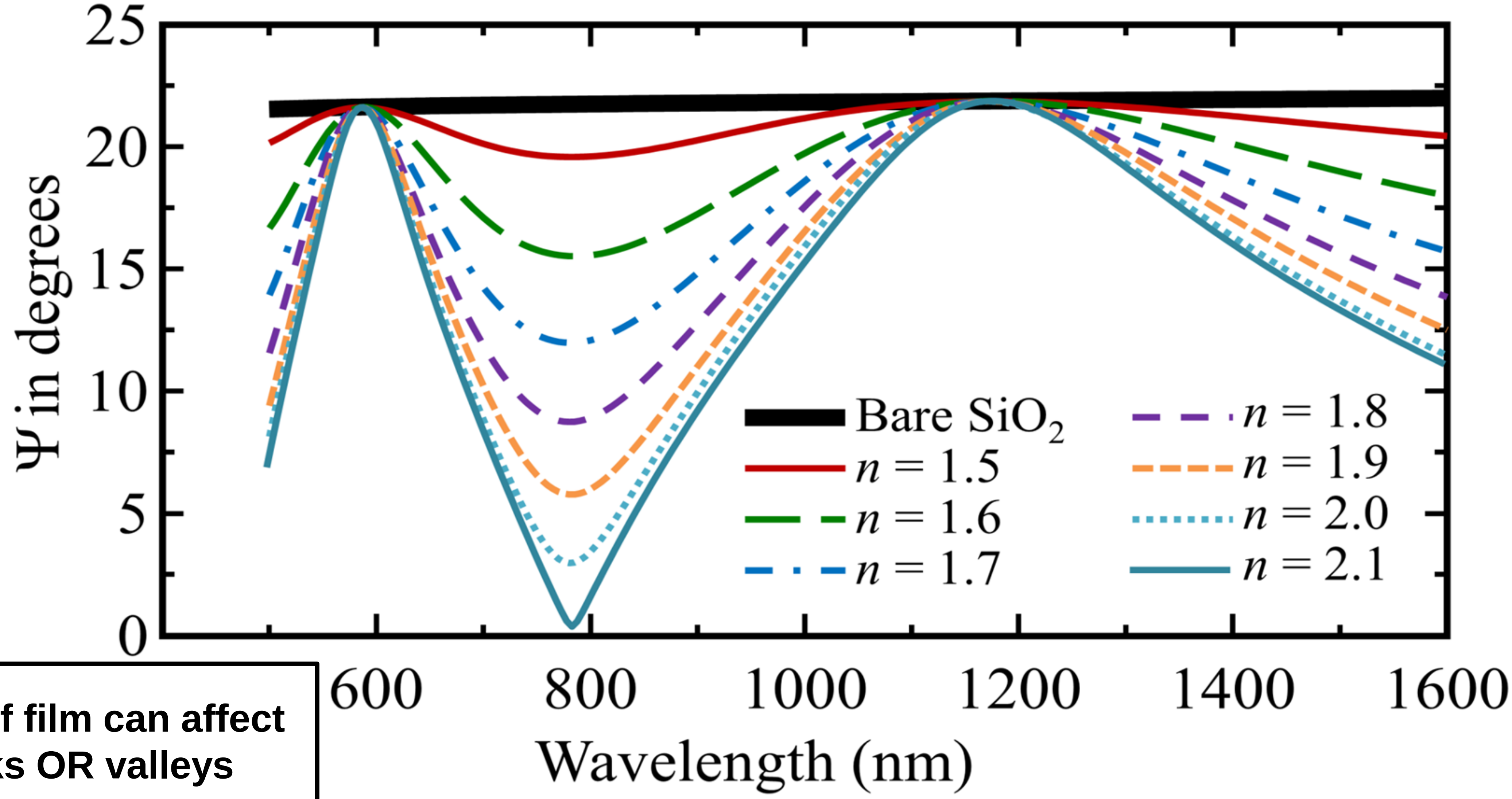


Experimental and Model Generated Data Fits





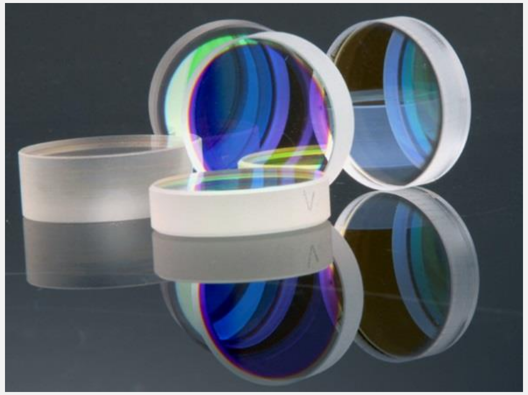
Data Features - Thin Films on Glass



Index of film can affect peaks OR valleys

2-12 Oxide on Fused Silica

- **Determine index and thickness of oxide.**
  - Fused silica is "2-12_Fused Silica_Genosc.mat"



Estimate Index & Thickness

⇩

Fit Thickness & Cauchy Parameters

⇩

What else to improve MSE?

Si with Transparent Film.mod

Change substrate

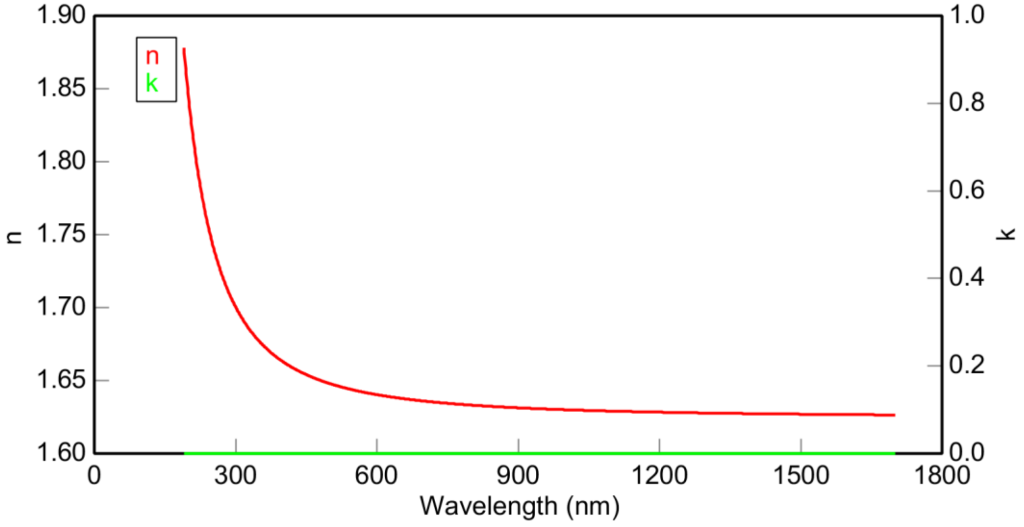
What happens when wrong material file, such as <u>7059 Glass.mat</u> is used as substrate?

2-12_Oxide on Fused Silica: Results

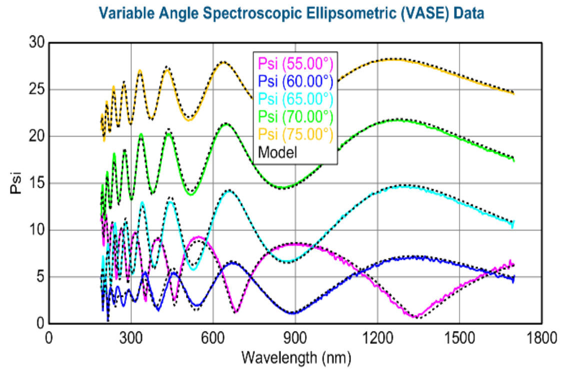
Sample: 2-12_Oxide on Fused Silica

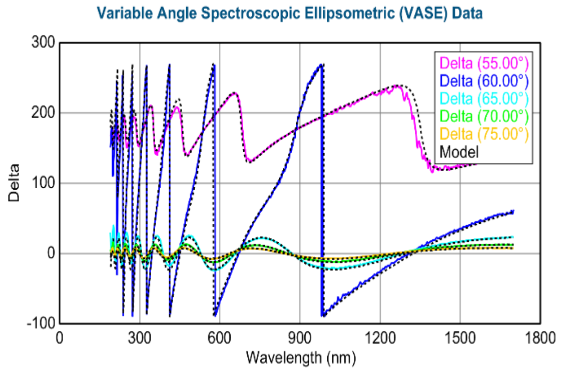
Fit Results	Optical Model
MSE = 10.792 Thickness # 1 = 480.14 ± 0.132 nm A = 1.625 ± 0.00030898 B = 0.00527 ± 7.3463E-05 C = 0.00013987 ± 3.2436E-06 % Thickness Non-uniformity = 7.28 ± 0.0630 n of Cauchy Film @ 632.8 nm = 1.63863	+ Layer # 1 = Cauchy Film Thickness # 1 = **480.14 nm** (fit) + Substrate = 2-12_Fused Silica_Genosc

Optical Constants of Oxide



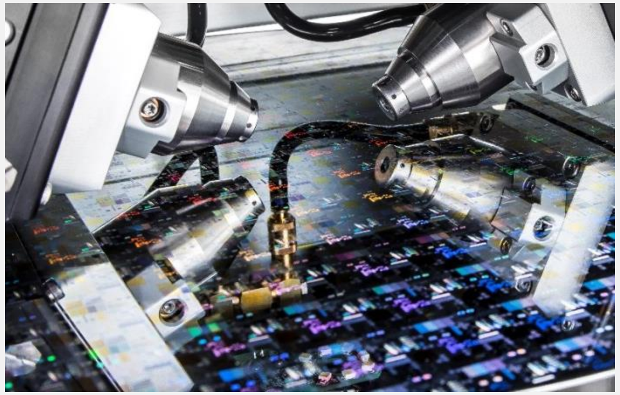
Experimental and Model Generated Data Fits





SiN_x on Si

- **Find a model that matches this data.**



Fit Thickness & Cauchy Parameters

⇩

<u>Add to improve MSE</u>:
Roughness?
Index Grading?
Anisotropy?
Thickness Non-uniformity?

2-13 SiN_x on Si: Results

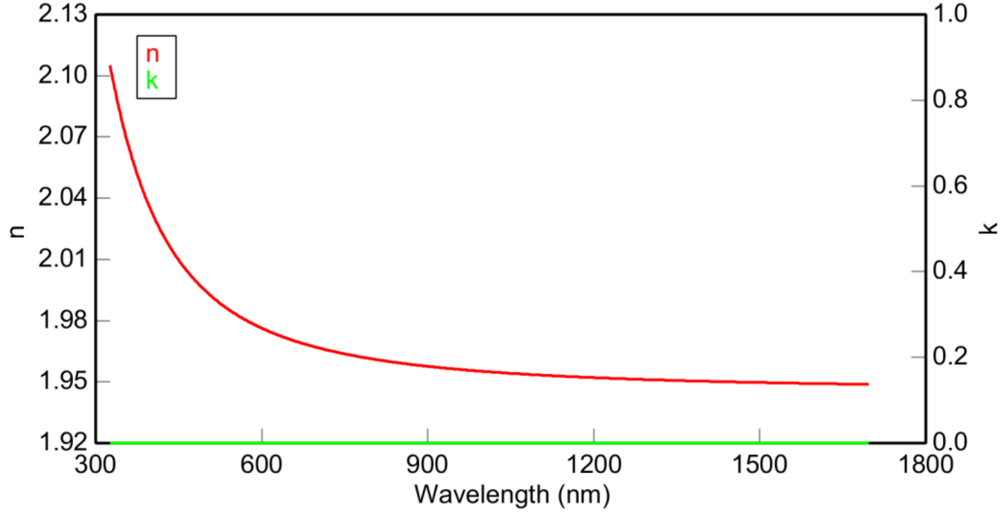
Sample: 2-13_SiNx on Si

Fit Results
MSE = 8.964
Thickness # 1 = 104.61 ± 0.018 nm
A = 1.946 ± 0.00053876
B = 0.00853 ± 0.00033049
C = 0.00089549 ± 3.6230E-05
# Back Reflections = 0.558 ± 0.003123
n of Cauchy Film @ 632.8 nm = 1.97260

Optical Model

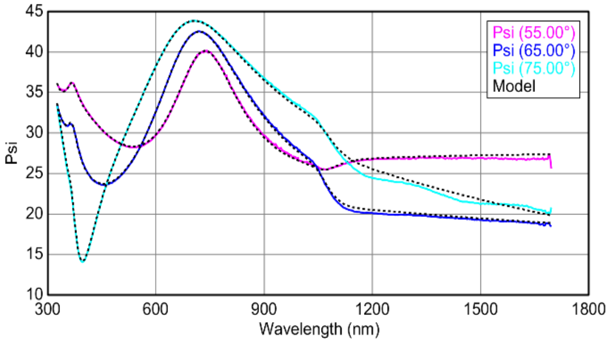
+ Layer # 1 = Cauchy Film	Thickness # 1 = 104.61 nm (fit)
Substrate = SI_JAW	Substrate Thickness = 0.7500 mm

Optical Constants of SiNx

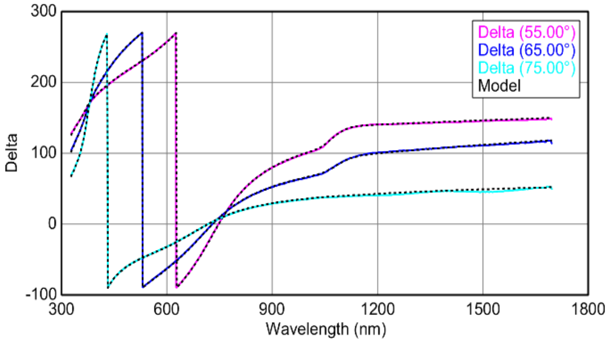


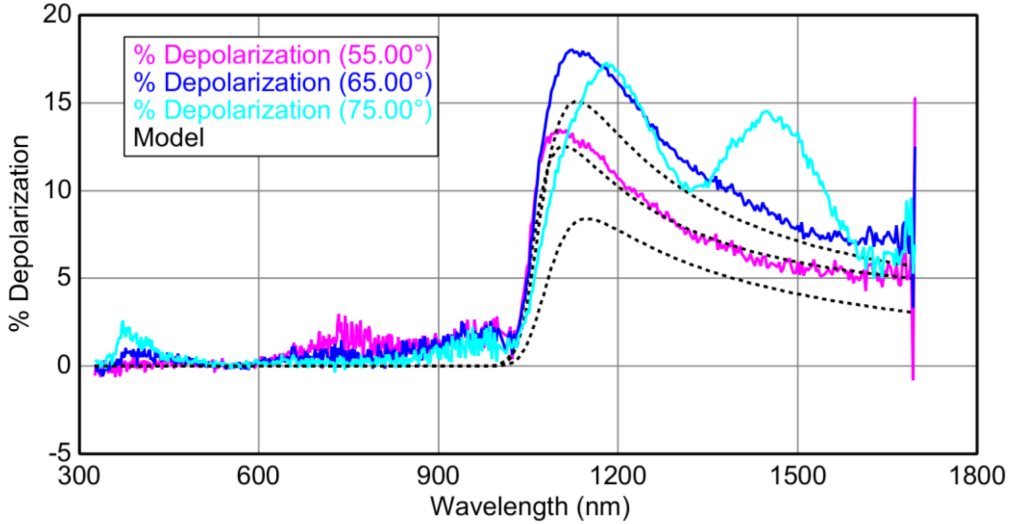
Experimental and Model Generated Data Fits

Variable Angle Spectroscopic Ellipsometric (VASE) Data



Variable Angle Spectroscopic Ellipsometric (VASE) Data





Summary Transparent films

Transparent Films

Fit Thickness & Cauchy

Use *Si with Transparent Film.mod*

Switch substrate mat file if necessary (i.e., germanium, glass, GaAs etc.)

Roughness, Grading, Anisotropy?

Try Alternate Models

MSE still large? Check for Depolarization

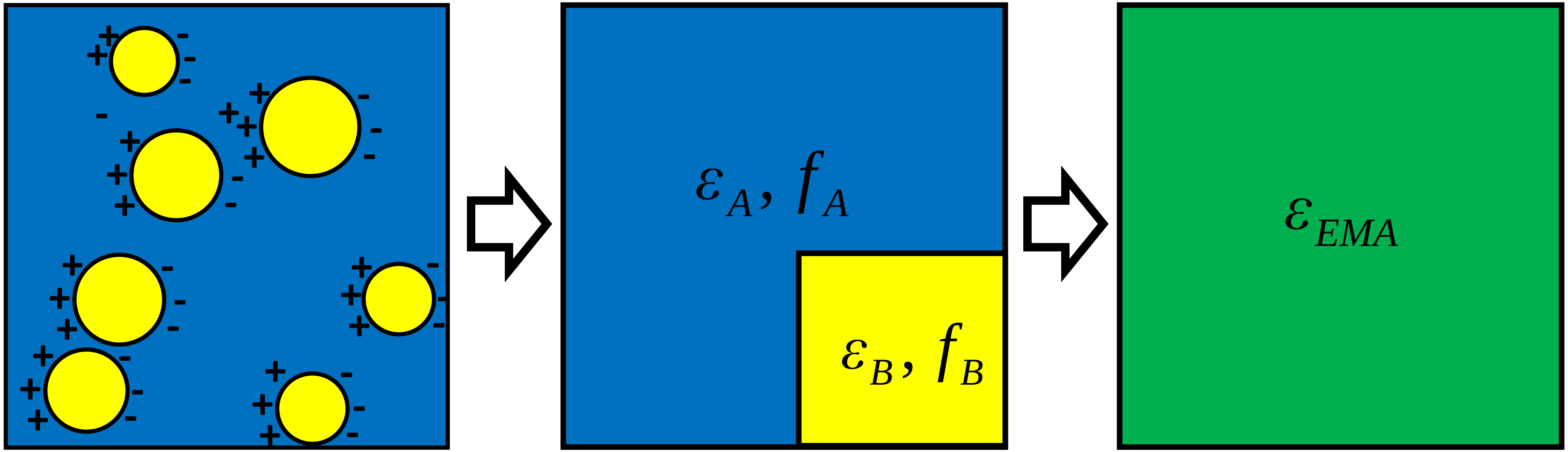
Depolarization: Consider Thickness Non-uniformity and backside reflection for transparent substrate

Range-select data to avoid absorptions (problem areas)

EXTRA SLIDES

Effective Medium Approximation (EMA)

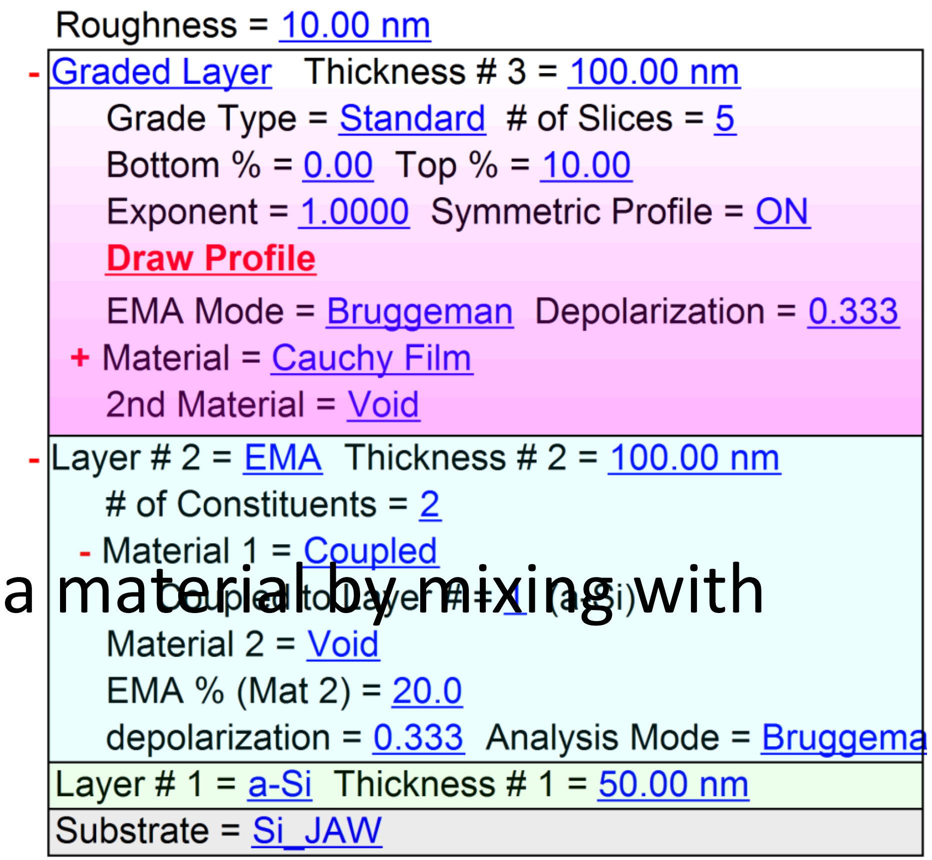
- Composites of more than 1 material are often described by EMA
- EMA considers volume fractions and possible charge screening:



$$f_a \frac{\varepsilon_a - \varepsilon_{EMA}}{\varepsilon_a + 2\varepsilon_{EMA}} + (1 - f_a) \frac{\varepsilon_b - \varepsilon_{EMA}}{\varepsilon_b + 2\varepsilon_{EMA}} = 0$$

Using EMA in CompleteEASE

- Roughness:
  50%-50% void and layer below
- EMA.mat: Use to mix multiple 2-3 mats
  - Coupled.mat helps “tie” to other layers
- Graded Layer: Can increase/decrease index of a material by mixing with void.



TRY ALTERNATE MODELS