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Document: Woollam SOP	**Revision:** E	**Release Date:** 01/19/2026

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1. Equipment Purpose

1.1. The Woollam tool uses ellipsometry to characterize thin films. Ellipsometry detects the phase change in polarized light as it reflects from, or is transmitted through samples. The Woollam Ellipsometer does not directly measure thickness and optical constants. Rather, it uses collected data to solve models which estimate the thickness and optical parameters of interest.

1.2. Ellipsometry Data Analysis Overview: After a sample is measured, a model is constructed to describe the sample. The model is used to calculate the predicted response from Fresnel's equations which describe each material with thickness and optical constants, or an estimate thereof. The calculated values are compared to experimental data. Any unknown material properties can then be varied to improve the match between experiment and calculation. The number of unknown properties should not exceed the amount of information contained in the experimental data. For example, a single-wavelength ellipsometer produces two data points (Ψ psi and Δ delta) which allows a maximum of two material properties to be determined. Finding the best match between the model and the experiment is typically achieved through regression. An estimator, like the Mean Squared Error (MSE), is used to quantify the difference between curves. The unknown parameters are allowed to vary until the minimum MSE is reached.

2. Equipment Specifications

2.1. Location: West side of the Allen cleanroom, near Fiji 1 and 2
2.2. Maximum sample diameter: 8 in
2.3. Spot size: 2mm normal, 1.1-11.5mm depending on angle of incidence
2.4. Minimum sample size: Must be larger than spot size for reliable result
2.5. Max sample height: 20mm
2.6. Wavelengths of light: 210-1680 nm
2.7. Lamp type: Xe arc lamp
2.8. Calibration frequency: During lamp replacement. See staff for last calibration date

3. Cleanliness Standard

3.1. The Woollam is compatible with all three levels of cleanliness. Clean, Semi-Clean, and gold contaminated

4. Processing Capabilities

4.1. Measures reflected or transmitted polarized light.

4.2. Fits models of optical constants against measured data to determine the thickness and optical constants of a film.

4.3. Complex models of optical data are available. Contact staff for a copy of the manual.

4.4. The Woollam DOES NOT directly measure thickness or optical constants!

5. Becoming a User

5.1. Read and understand all material on nano@stanford website concerning the Woollam M2000 Spectroscopic Ellipsometer.

5.2. Shadow a lab user using the Woollam. If you do not know a current Woollam user, check the Nemo reservation schedule and see if a current user is willing to let you shadow.

5.3. Take the quiz linked on the Tool Control page of the Woollam on Nemo.

5.4. Sign up for the training on Nemo. Qualification consists of attending the training and demonstrating appropriate knowledge to the staff member.

6. Safety

6.1. Do not place hands near pinch points.

6.2. Do not expose eyes to the beam of light.

7. Required equipment

7.1. Cleanroom garments, as are compatible with Allen Building Cleanroom.

8. Operating Procedure

8.1. Starting Procedure

8.1.1. "Enable" the Woollam on Nemo.

8.1.2. Check that the lamp is on. If it is off, press the "Lamp Ignition" button. **Figure 1.**

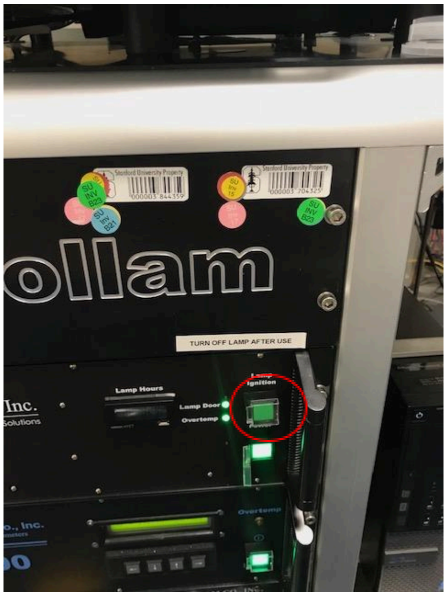


__Figure 1: Lamp Ignition Button circled in red__

8.1.3. Load wafer on sample chuck.

8.1.4. Turn on the vacuum switch. **Figure 2.**

8.1.4.1. Even if your sample is not large enough to cover the vacuum ports, it is still good practice to turn on the vacuum switch.

Figure 2: Location of vacuum switch, lower left corner. Sample stage upper right.

8.1.5. Log On to the computer, the password is posted on the keyboard.

8.1.6. Open the CompleteEASE software. **Figure 3.**

  8.1.6.1. Do not open WVase or WVase Manager, they are completely different programs.

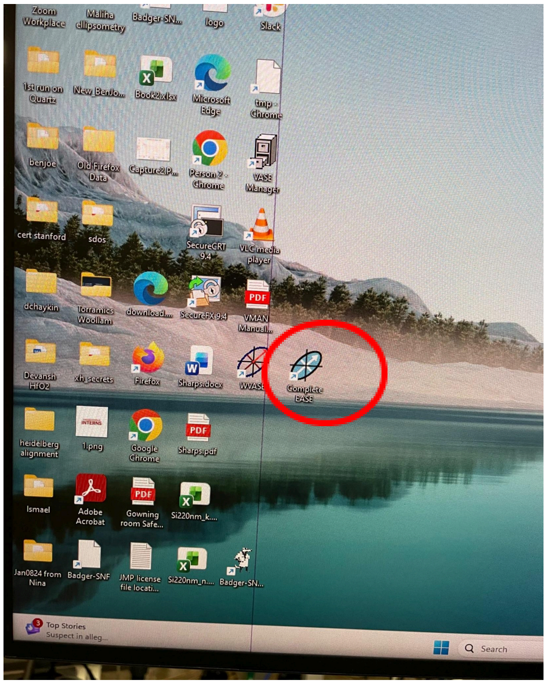


Figure 3: CompleteEase application on Desktop

8.2 Acquire Data: Measurement Tab

8.1.7. Once the software opens, you will see four tabs at the top left of the screen. Click on the “Measure” tab. **Figure 4.**

  8.1.7.1. Do not calibrate the system, calibrations are done by staff. Do not change any settings under the Hardware or Option tabs. Talk to Staff if you need to take advanced measurements.

8.1.8. Select a Recipe from the drop down menu. **Figure 4.**

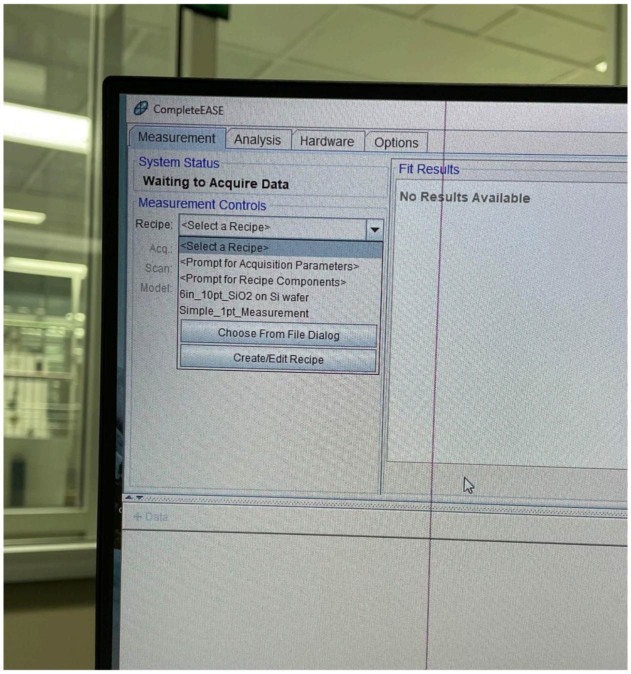
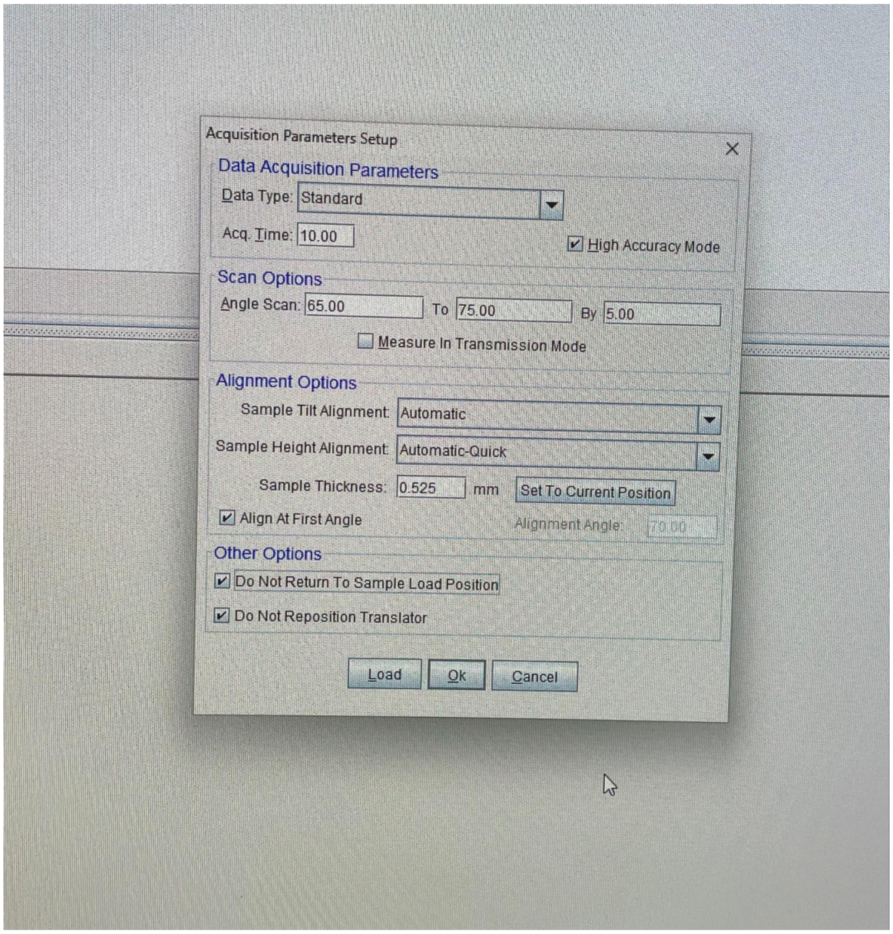


Figure 4: Measurement Tab and Selecting a Recipe

8.1.9. For most cases, select “Prompt for Acquisition Parameters”. This opens a window where you can specify your parameters. **Figure 5.**



Data Type: Standard
Acq. Time: 10.00
☑ High Accuracy Mode
Angle Scan: 65.00 To 75.00 By 5.00
☐ Measure In Transmission Mode
Sample Tilt Alignment: Automatic
Sample Height Alignment: Automatic-Quick
Sample Thickness: 0.525 mm
☑ Align At First Angle
Alignment Angle: 70.00
☑ Do Not Return To Sample Load Position
☑ Do Not Reposition Translator

Figure 5: Acquisition Parameters Setup

8.1.10. In the scan window, you may want to change some of the parameters:

8.1.10.1. Data Type: Standard is good for most uses.

8.1.10.2. Acq. Time: The default setting for the acquisition time is 10. A higher value will decrease the amount of noise in the data collection but will also take longer. (Typical value is 40 revs/measurement).

8.1.10.3. Scan Options: Choose a range of angles near the Brewster Angle for your substrate (Typical selection for Si is 65-75 degrees), and choose the step size by which you want to take the measurements. More angles will give you more data and improve confidence in the results, but will also take more time. (Typical selection for a single thin film on silicon is 3 angles, so the angle step size would be 5 to measure at 65, 70, and 75 degrees).

8.1.10.3.1. Transition Mode is a different kind measurement for which your sample would be placed perpendicular to the stage. Ask a staff member to show you the attachment and settings for that, otherwise leave that box unchecked.

8.1.10.4. Alignment Options: Leave all settings as is, except for the sample thickness. You can set the sample thickness to your best guess. Note that this is in mm and refers to your entire sample thickness

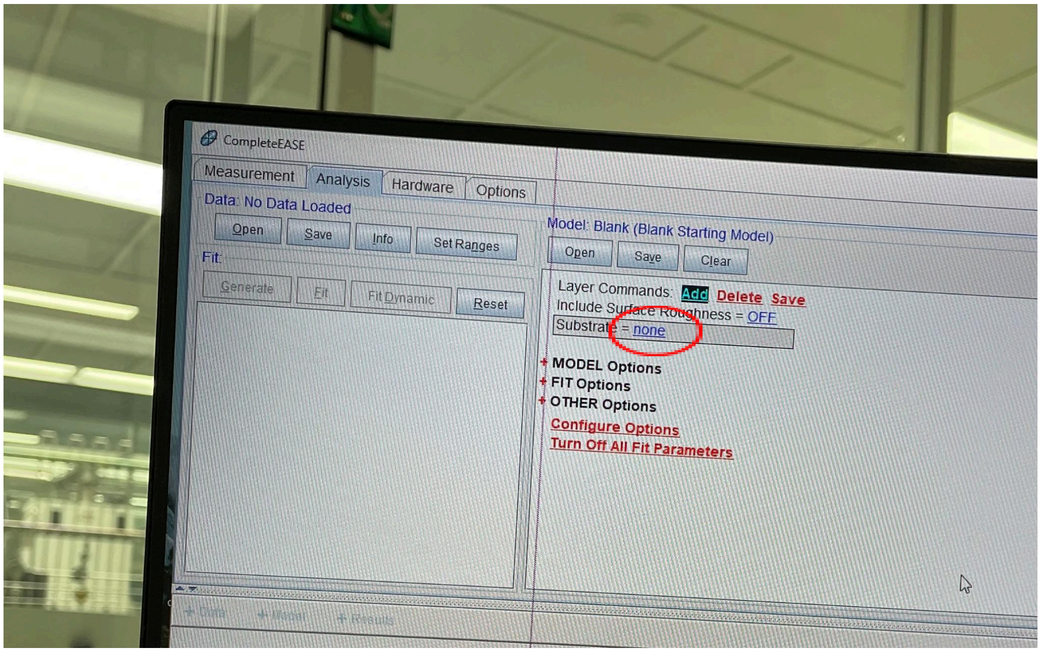
8.1.10.5. Other Options: Both of these boxes should be left checked.

8.1.11. After reviewing the parameters, click “Ok” to start the scan

8.2. Create a Model: Analysis Tab

8.2.1. Click on the Analysis Tab. Note, the word “model” here refers to the layers of your sample. You need to tell the tool your best guess at the layers and thicknesses and then it will use mathematical models to estimate the thickness and optical parameters of interest.

8.2.2. Click the word “none” in the Substrate box to select your substrate material. **Figure 6.**



Data: No Data Loaded

Model: Blank (Blank Starting Model)

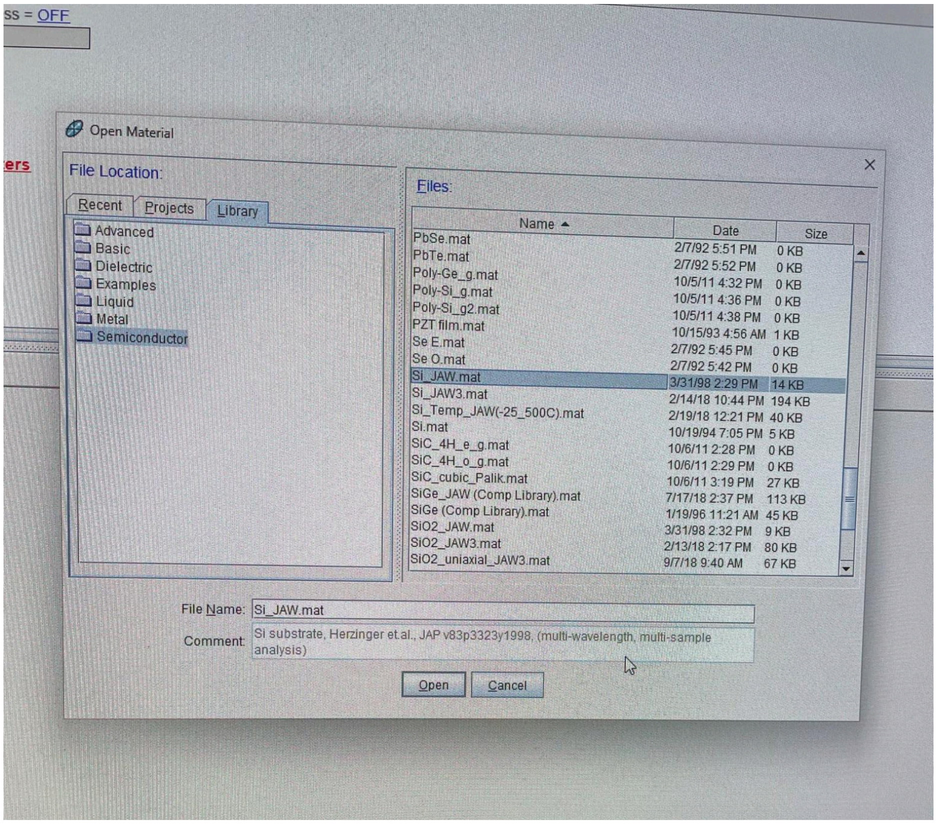
Include Surface Roughness = OFF

Substrate = none

Figure 6: Creating a Model on the Analysis Tab

8.2.3. After clicking “none’, an “Open Material” window will appear. Click on the “Library” tab. You will see a list of folders that organize types of substrates. The “Semiconductor” folder has many common materials, including Si. There may be several options for a layer, such as for Si we can see there are four. It doesn’t really matter which of these you chose, but when you click on any one you can read about its data origin in the comment box at the bottom of the window. **Figure 7.**

8.2.4. It can be helpful to iterate through several different models to achieve the lowest MSE. It is often a good idea to start with the most recent model.



Name ▲	Date	Size
PbSe.mat	2/7/92 5:51 PM	0 KB
PbTe.mat	2/7/92 5:52 PM	0 KB
Poly-Ge_g.mat	10/5/11 4:32 PM	0 KB
Poly-Si_g.mat	10/5/11 4:36 PM	0 KB
Poly-Si_g2.mat	10/5/11 4:38 PM	0 KB
PZT film.mat	10/15/93 4:56 AM	1 KB
Se E.mat	2/7/92 5:45 PM	0 KB
Se O.mat	2/7/92 5:42 PM	0 KB
Si_JAW.mat	3/31/98 2:29 PM	14 KB
Si_JAW3.mat	2/14/18 10:44 PM	194 KB
Si_Temp_JAW(-25_500C).mat	2/19/18 12:21 PM	40 KB
Si.mat	10/19/94 7:05 PM	5 KB
SiC_4H_e_g.mat	10/6/11 2:28 PM	0 KB
SiC_4H_o_g.mat	10/6/11 2:29 PM	0 KB
SiC_cubic_Palik.mat	10/6/11 3:19 PM	27 KB
SiGe_JAW (Comp Library).mat	7/17/18 2:37 PM	113 KB
SiGe (Comp Library).mat	1/19/96 11:21 AM	45 KB
SiO2_JAW.mat	3/31/98 2:32 PM	9 KB
SiO2_JAW3.mat	2/13/18 2:17 PM	80 KB
SiO2_uniaxial_JAW3.mat	9/7/18 9:40 AM	67 KB

File Name: Si_JAW.mat

Comment: Si substrate, Herzinger et.al., JAP v83p3323y1998, (multi-wavelength, multi-sample analysis)

Figure 7: Browse the Library to Find Your Substrate Material

8.2.5. Click “Open” to use this layer and dismiss the popup window.

8.2.6. Adding Layers. You can add layers to the model in the same order as they are on your sample, from bottom to top. Click Add Layer

    8.2.6.1. There will be a diagram of the existing layers, and a blue line you can move around. The blue line indicates where the layer will be added. **See Figure 8.**

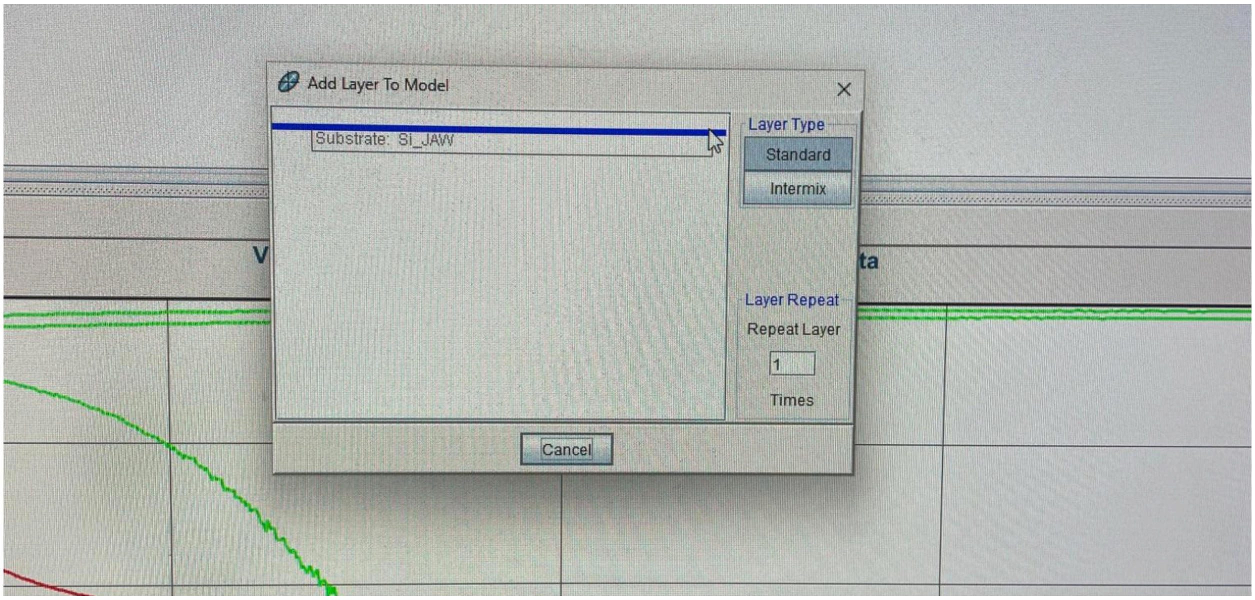


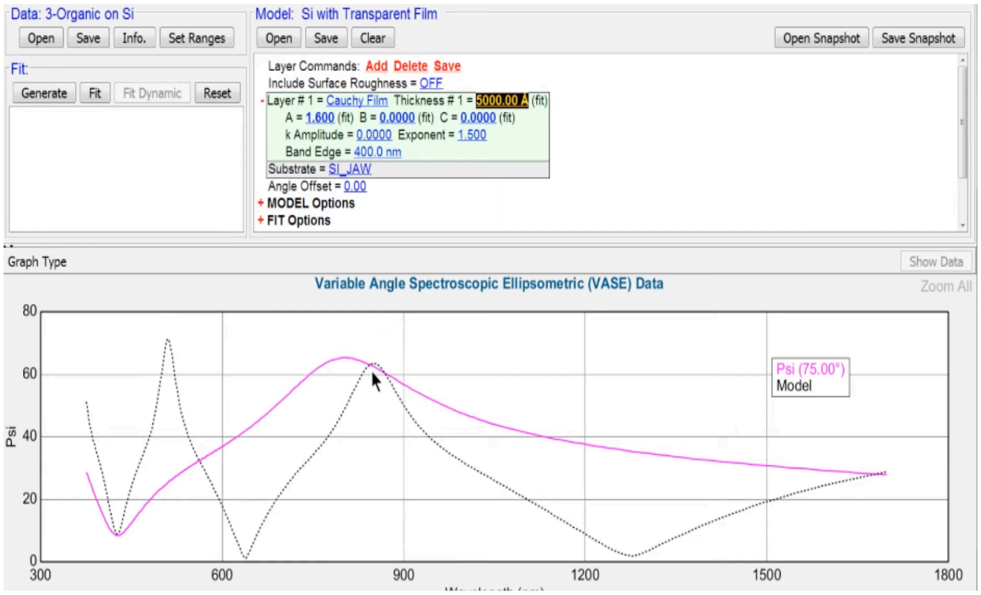
Figure 8: The blue line indicates where the new layer will be

8.2.7. Once you have included the desired layers in your model, look to the left for the “Fit” box and click on “Generate”.

8.2.8. After the program Generates, click “Fit”.

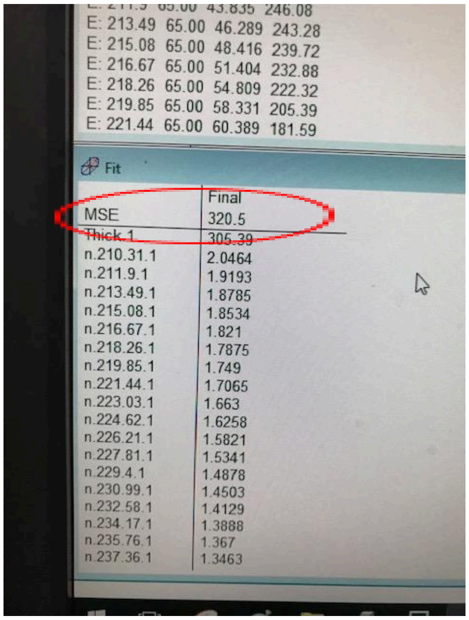
8.2.9. You are looking for the dashed model line to match the colored lines as closely as possible. The MSE (Mean Square Error of this non-linear regression model) is an indicator of good fit. This is where the process becomes iterative.

8.2.10. See **Figure 9** and **Figure 10** for examples of bad fit.



Layer Commands: Add Delete Save
Include Surface Roughness = OFF
Layer # 1 = Cauchy Film Thickness # 1 = 5000.00 A (fit)
A = 1.600 (fit) B = 0.0000 (fit) C = 0.0000 (fit)
k Amplitude = 0.0000 Exponent = 1.500
Band Edge = 400.0 nm
Substrate = SI_JAW
Angle Offset = 0.00
+ MODEL Options
+ FIT Options

Figure 9: Example of a bad fit. Notice the black fit curve does not match the pink data curve



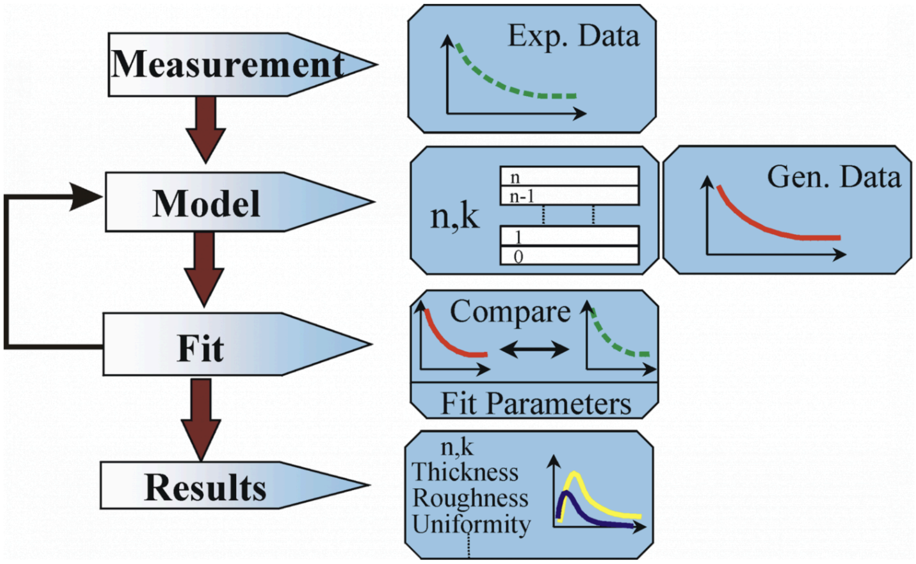
```
E: 213.49 65.00 46.289 243.28
E: 215.08 65.00 48.416 239.72
E: 216.67 65.00 51.404 232.88
E: 218.26 65.00 54.809 222.32
E: 219.85 65.00 58.331 205.39
E: 221.44 65.00 60.389 181.59
```

	Final
MSE	320.5
Thick.1	305.39
n.210.31.1	2.0464
n.211.9.1	1.9193
n.213.49.1	1.8785
n.215.08.1	1.8534
n.216.67.1	1.821
n.218.26.1	1.7875
n.219.85.1	1.749
n.221.44.1	1.7065
n.223.03.1	1.663
n.224.62.1	1.6258
n.226.21.1	1.5821
n.227.81.1	1.5341
n.229.4.1	1.4878
n.230.99.1	1.4503
n.232.58.1	1.4129
n.234.17.1	1.3888
n.235.76.1	1.367
n.237.36.1	1.3463

Figure 10: Example of large MSE

8.3. Modify the model if necessary until you have minimized the MSE value, or are satisfied with the result. A value less than 10 is good, though not always possible depending on the complexity of the model.

8.4. Ellipsometry can take a bit of practice and iteration to get the best information for your sample. The J A Woollam website has additional resources to learn about what is going on behind the scenes, but in general the process is as depicted in **Figure 11.** Once you take measurements using the tool, you can transfer your data via flash drive and take it to the computer in the bull pen area to analyze it further.



Flow chart for ellipsometry data analysis.

<u>Figure 11: Data Analysis Flow from J.A. Woollam</u>

8.5. Turn off the vacuum and remove the wafer.

8.6. Please leave the lamp on for the next user.

8.7. Close the CompleteEASE software and lock the computer screen.

9. Operating Guide

9.1. Enable Woollam in NEMO. The Red LED strip behind the tool will turn off when the tool is enabled.
9.2. The lamp should be on, if not push the Lamp Ignition button to turn it on.
9.3. Load sample onto stage
9.4. Turn on vacuum switch
9.5. Open CompleteEASE
9.6. Wait 30 seconds while hardware initializes
9.7. Select the check box if you would like to save your data
    9.7.1. If you leave it checked, you will be prompted where you want to save the data. Scans should be saved to a flash drive, as the computer is not connected to the internet. It is not recommended to leave your data on the desktop because the computer may be replaced or wiped at any time.
9.8. From the “Recipe” drop down list, select “Prompt for Acquisition Parameters”.
9.9. Click “Measure”
    9.9.1. Adjust the scan angles to match the Brewster angle of your substrate
        9.9.1.1. For Si substrates, the brewster angle is 74 degrees. Common scan angles for Si are 65-75 degrees, by 5 degree increments.
    9.9.2. Leave the alignment set to Automatic Alignment
    9.9.3. Leave bottom two check boxes checked
    9.9.4. Click “ok”, the sample will align and the scan will start
9.10. Analysis tab
    9.10.1. Click “Substrate” box to define your substrate material
    9.10.2. Click “Add Layer”
        9.10.2.1. Use the library tab to find the library of materials
        9.10.2.2. Find your material and click “Ok"
        9.10.2.3. Once the layer is selected and in your model, click the layer to assign it a thickness and/or check the “fit” box.
    9.10.3. Repeat step 9.9.4 to add as many layers as you need
    9.10.4. In the same tab, click “Generate"

    - 9.10.5. Click “Fit"
    - 9.10.6. This will give you the fit and MSE, repeat 9.10 steps as needed.
- 9.11. Turn off vacuum and remove sample
- 9.12. Leave the lamp on for the next lab member
- 9.13. Disable NEMO

10. Converting Between WVASE and CompleEASE

10.1. Information on converting between WVASE and CompleteEASE can be found in the data analysis manual at this link: CompleteEase Software Manual

10.2. This transfer can be done, but it will take a bit of time and effort as the data files in CompleteEASE and WVASE32 are not directly compatible because they have different file formats. CompleteEASE files are “encrypted” as a copy-protection mechanism because the software no longer requires the “activator key” like WVASE32, which were written in ASCII text.

11. Definitions and Process Terminology

11.1. MSE: Mean Squared Error. This is the difference between the calculated fit and the experimental data. Less than 10 is a good value for MSE.

11.2. Cauchy Film / Cauchy Equation: in thin-film optics, a parameterized dispersion model in ellipsometry used to determine the optical constants n (refractive index) and k (extinction coefficient) of a transparent or weakly absorbing layer. Cauchy’s equation is used to calculate n and often includes an exponential absorption model for k: ($n(\lambda) = A + B/\lambda^2 + C/\lambda^4$)

  11.2.1. Parameter A:The primary refractive index coefficient; represents the baseline refractive index of the material at infinite wavelengths.

  11.2.2. Parameter B: First-order dispersion term; describes how the refractive index changes with wavelength.

  11.2.3. Parameter C: Second-order dispersion term; provides additional wavelength-dependent correction for better fit accuracy.

11.3. ñ: Complex Refractive Index. The relationship of phase velocity, path, and absorption of *how light is affected by the material*. This is composed of two values which describe the optical properties that determine how light interacts with a material. ñ=n+ik

  11.3.1. n: Refractive index (real part). Describes how light slows down and bends when passing through the material.

11.3.2. k: Extinction coefficient (imagined part). Describes how much light is absorbed by the material.

11.4. Ψ Psi: The amplitude ratio change upon *reflection.*

11.5. Δ Delta: The phase difference changes upon reflection.

11.6. Ẽ Complex Dielectric Function: How *the material is affected by light*. This is related to the Complex Refractive Index as follows: $\tilde{E} = \tilde{n}^2$.

11.7. EMA = Effective Medium Approximation. A model that treats compositor mixed materials as a single medium with averaged optical properties (mixture of material and air). Used with surface roughness cases, typically a refractive index lower than the bulk film.

12. Troubleshooting

Symptom	Issue	Resolution
Polarizer Error	● Not Enabled in Nemo	● Enable in Nemo
Cannot Align	● Stage not in home position ● Lamp is not on	● Hardware tab, home stage ● Turn on lamp
Failure to Enable	● NEMO malfunction	● Unplug the Badger box on the side of the Woollam, wait 30 seconds before plugging in. Wait one minute for Badger to establish a connection. Then enable the Woollam again.
High MSE	● Model doesn't match material ● Too wide of scan wavelengths ● Other	● Verify deposited material and model match ● Reduce wavelengths scanned over ● See staff

13. Revision Block

Revision	**Date**	**Description of Change**	**Author**

A	12/1/2022	Initial Release	A.Denton
B	08/15/2023	Added Transmission Scan, Bit Locker, Changing Units, Z Height Error.	A.Denton
C	07/15/2024	Corrected 9.1 from Badger to NEMO	A.Denton
D	04/03/2025	Clarified Section 11	A.Denton
E	01/19/2026	Updated language for Nemo and CompleteEASE, leaving the lamp on, and added a few new photos.	E.Casey