Optical Film Thickness Measurements
Oxide, Nitride and Poly

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OUTLINE

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NanoSpec Reflectance Spectrometer
Theory of Operation
E&M Field Equations for Reflection
Excel Calculation of Reflection
Where to Measure
Spectromap
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Ellipsometer
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Homework
INTRODUCTION

Most measurement instruments will give the user a measured value. There are many reasons why the measured value may not be correct including not using the measurement tool correctly, problems with the tool itself or not knowing what you are measuring.

To have a better chance of measuring correctly the user should:
- Know the approximate value before measuring it
- Know where, on the wafer, to make the measurement
- Know what films (and their thickness) that are under the film to be measured
- Understand the limits of the measurement tool
- Understand the theory behind the measurement
- Operate the tool correctly, focus, calibration, filters, etc.

This document was created to help reduce measurement errors for oxide, silicon nitride and poly using the NanoSpec, Spectromap and other optical measurement tools used at RIT.
Use the correct recipe

- Oxide on Silicon: 400-30,000 Å
- Nitride: 400-30,000 Å
- Neg Resist: 500-40,000 Å
- Poly on Ox: 400-10,000 Å
- Neg Resist on Ox: 300-3500 Å
- Nitride on Oxide: 300-3500 Å
- Thin Oxide: 100-500 Å
- Thin Nitride: 100-500 Å
- Polyimide: 500-10,000 Å
- Positive Resist: 500-40,000 Å
- Pos Resist on Ox: 500-15,000-4,000-30,000 Å

Note: Place the filter in for all measurements except for nitride on oxide.

Note: For Poly on Oxide, Resist on Oxide, and Nitride on Oxide you will be asked to enter the thickness of the oxide layer under the film to be measured. (in the range specified above)
INCIDENT WHITE LIGHT, THE INTENSITY OF THE REFLECTED LIGHT IS MEASURED VS WAVELENGTH

NANOSPEC - REFLECTANCE SPECTROMETER

MONOCHROMATOR & DETECTOR

WHITE LIGHT SOURCE

OPTICS

WAFER

3000 Å OXIDE

7000 Å OXIDE
## Optical Film Thickness Measurements

### Oxide Thickness Color Chart

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 Å</td>
<td>Tan</td>
</tr>
<tr>
<td>700</td>
<td>Brown</td>
</tr>
<tr>
<td>1000</td>
<td>Dark Violet - Red Violet</td>
</tr>
<tr>
<td>1200</td>
<td>Royal Blue</td>
</tr>
<tr>
<td>1500</td>
<td>Light Blue - Metallic Blue</td>
</tr>
<tr>
<td>1700</td>
<td>Metallic - very light Yellow Green</td>
</tr>
<tr>
<td>2000</td>
<td>Light Gold or Yellow - Slightly Metallic</td>
</tr>
<tr>
<td>2200</td>
<td>Gold with slight Yellow Orange</td>
</tr>
<tr>
<td>2500</td>
<td>Orange - Melon</td>
</tr>
<tr>
<td>2700</td>
<td>Red Violet</td>
</tr>
<tr>
<td>3000</td>
<td>Blue - Violet Blue</td>
</tr>
<tr>
<td>3100</td>
<td>Blue</td>
</tr>
<tr>
<td>3200</td>
<td>Blue - Blue Green</td>
</tr>
<tr>
<td>3400</td>
<td>Light Green</td>
</tr>
<tr>
<td>3500</td>
<td>Green - Yellow Green</td>
</tr>
<tr>
<td>3600</td>
<td>Yellow Green</td>
</tr>
<tr>
<td>3700</td>
<td>Yellow</td>
</tr>
<tr>
<td>3900</td>
<td>Light Orange</td>
</tr>
<tr>
<td>4100</td>
<td>Carnation Pink</td>
</tr>
<tr>
<td>4200</td>
<td>Violet Red</td>
</tr>
<tr>
<td>4400</td>
<td>Red Violet</td>
</tr>
<tr>
<td>4600</td>
<td>Violet</td>
</tr>
<tr>
<td>4700</td>
<td>Blue Violet</td>
</tr>
<tr>
<td>4900</td>
<td>Blue</td>
</tr>
<tr>
<td>5000</td>
<td>Blue Green</td>
</tr>
<tr>
<td>5200</td>
<td>Green</td>
</tr>
<tr>
<td>5400</td>
<td>Yellow Green</td>
</tr>
<tr>
<td>5600</td>
<td>GreenYellow</td>
</tr>
<tr>
<td>5700</td>
<td>Yellow - &quot;Yellowish&quot; (at times appears to be Lt gray or metallic)</td>
</tr>
<tr>
<td>5800</td>
<td>Light Orange or Yellow - Pink</td>
</tr>
<tr>
<td>6000</td>
<td>Carnation Pink</td>
</tr>
<tr>
<td>6300</td>
<td>Violet Red</td>
</tr>
<tr>
<td>6800</td>
<td>&quot;Bluish&quot; (appears violet red, Blue Green, looks like Yellowish)</td>
</tr>
<tr>
<td>7200</td>
<td>Blue Green - Green</td>
</tr>
<tr>
<td>7700</td>
<td>&quot;Yellowish&quot;</td>
</tr>
<tr>
<td>8000</td>
<td>Orange</td>
</tr>
<tr>
<td>8200</td>
<td>Salmon</td>
</tr>
<tr>
<td>8500</td>
<td>Dull, Light Red Violet</td>
</tr>
<tr>
<td>8600</td>
<td>Violet</td>
</tr>
<tr>
<td>8700</td>
<td>Blue Violet</td>
</tr>
<tr>
<td>8900</td>
<td>Blue</td>
</tr>
<tr>
<td>9200</td>
<td>Blue Green</td>
</tr>
<tr>
<td>9500</td>
<td>Dull Yellow Green</td>
</tr>
<tr>
<td>9700</td>
<td>Yellow - &quot;Yellowish&quot;</td>
</tr>
<tr>
<td>9900</td>
<td>Orange</td>
</tr>
<tr>
<td>10000</td>
<td>Carnation Pink</td>
</tr>
</tbody>
</table>

Nitride Thickness = (Oxide Thickness)(Oxide Index/Nitride Index)

Eg. Yellow Nitride Thickness = (2000)(1.46/2.00) = 1460
EMISSION SPECTROSCOPY

Light Emission
(Many $\lambda$)

Prism or Diffraction Grating

Light
(Single $\lambda$)

Detector

White Light Emission

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NANOSPEC THEORY OF OPERATION

The NanoSpec illuminates the sample with white light and measures the reflected light versus wavelength. Thick films have many closely spaced peaks and valleys. Thinner films have fewer peaks and valleys. The difference in the wavelength at which the first peak and the first valley occurs is used to give the film thickness. A second algorithm uses the difference in the wavelength at which the first valley or the first peak occurs. For very thin films ~ < 500 Å there are no peaks or valleys so the reflectance at a fixed wavelength (470 nm) is used to give the film thickness.
CALCULATION OF IRRADIANCE IN A SYSTEM WHERE THERE ARE MULTIPLE REFLECTING LAYERS

Light is an electromagnetic wave. The electric field is calculated from the irradiance value at the surface of the photoresist. Using the reflection and transmission coefficients for the boundary of two dielectrics a system of equations is built for a multi-layer substrate. The dielectric materials are described by their complex index of refraction.

The relationship between Irradiance and electric or magnetic field is:

\[ \text{Irradiance} = \frac{\text{average Power}}{\text{unit area}} \]

\[ I = \frac{c \varepsilon_0 E^2}{2} \quad \text{or} \quad I = \frac{c}{2 \mu_0} B^2 \]

where \( c \) is speed of light \( 3\times10^8 \text{m/s} \)
\( \varepsilon_0 \) is permittivity, \( \mu_0 \) is permeability
As light traverses a dielectric material there is a phase shift, \( \delta n \)

\[
E^\text{n+}(0) = E^\text{n+}(dn) e^{j \delta n}
\]

where \( \delta n = 2 \pi N_n^\text{^} \text{dn} / \lambda \)

\[
\begin{align*}
E^\text{n+}(dn) &= E^\text{n+}(0) e^{j \delta n} \\
E^\text{n-}(0) &= E^\text{n-}(dn) e^{-j \delta n}
\end{align*}
\]

\[
\begin{align*}
E^\text{m+} &= \text{tn} E^\text{n+} + \text{rn} E^\text{m-} \\
E^\text{n-} &= \text{rn} E^\text{n+} + \text{tn} E^\text{m-}
\end{align*}
\]

\[
\text{rn} = (N_n - N_m) / (N_n + N_m) \\
\text{tn} = (2N_n) / (N_n + N_m)
\]
REFLECTION CALCULATIONS

The two equations on the previous page are rearranged so input quantities are on the left and output quantities are on the right. The equations are converted to matrix format for simplicity. This allows for concise representation of a system of any number of layers.

\[
\begin{align*}
E_{n+}^\wedge & \rightarrow [d_1, d_2, d_3, d_4, \ldots, L] \\
E_{n-}^\wedge & \rightarrow [1, 2, 3, 4, \ldots, L]
\end{align*}
\]

\[
\begin{bmatrix}
E_1^+ \\
E_1^-
\end{bmatrix} =
\begin{bmatrix}
R & R & T_2 & 0 & R & R & T_3 & 0 & TL & 0 & R & R & EL^+ \\
R & R & 0 & T_2 & R & R & 0 & T_3 & 0 & TL & R & R & EL^-
\end{bmatrix}
\]
FLOW CHART FOR CALCULATIONS

1. Initialize the Electric Field in the Bottom Layer

2. Update Optical parameters in all layers at this wavelength

3. Calculate Tcoef, Rcoef, Real and Img. parts of E+ and E- after translation across a boundary

4. Last Layer? (one)
   - yes
   - no
      - Calculate Real and Img parts of E+ and E- after translation across a layer of thickness d, in steps of desired increment

5. Calculate Irradiance Values, Reflectance, etc.

6. Is this the last wavelength?
   - no
   - yes
      - End
# INDEX FOR OXIDE, NITRIDE AND POLY AT DIFFERENT $\lambda$

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>Oxide</th>
<th>Nitride</th>
<th>Poly</th>
<th>Silicon (Cry)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>1.47</td>
<td>1.98</td>
<td>5.51</td>
<td>5.24</td>
</tr>
<tr>
<td>425</td>
<td>1.47</td>
<td>1.98</td>
<td>5.09</td>
<td>4.75</td>
</tr>
<tr>
<td>450</td>
<td>1.47</td>
<td>1.98</td>
<td>4.76</td>
<td>4.42</td>
</tr>
<tr>
<td>475</td>
<td>1.47</td>
<td>1.98</td>
<td>4.50</td>
<td>4.30</td>
</tr>
<tr>
<td>500</td>
<td>1.47</td>
<td>1.98</td>
<td>4.31</td>
<td>4.18</td>
</tr>
<tr>
<td>525</td>
<td>1.47</td>
<td>1.98</td>
<td>4.17</td>
<td>4.08</td>
</tr>
<tr>
<td>550</td>
<td>1.47</td>
<td>1.98</td>
<td>4.06</td>
<td>4.00</td>
</tr>
<tr>
<td>575</td>
<td>1.47</td>
<td>1.98</td>
<td>3.98</td>
<td>3.95</td>
</tr>
<tr>
<td>600</td>
<td>1.47</td>
<td>1.98</td>
<td>3.92</td>
<td>3.88</td>
</tr>
<tr>
<td>625</td>
<td>1.47</td>
<td>1.98</td>
<td>3.86</td>
<td>3.82</td>
</tr>
<tr>
<td>650</td>
<td>1.47</td>
<td>1.98</td>
<td>3.81</td>
<td>3.77</td>
</tr>
<tr>
<td>675</td>
<td>1.47</td>
<td>1.98</td>
<td>3.76</td>
<td>3.72</td>
</tr>
<tr>
<td>700</td>
<td>1.47</td>
<td>1.98</td>
<td>3.72</td>
<td>3.70</td>
</tr>
<tr>
<td>725</td>
<td>1.47</td>
<td>1.98</td>
<td>3.62</td>
<td>3.68</td>
</tr>
<tr>
<td>750</td>
<td>1.47</td>
<td>1.98</td>
<td>3.65</td>
<td>3.66</td>
</tr>
<tr>
<td>775</td>
<td>1.47</td>
<td>1.98</td>
<td>3.67</td>
<td>3.64</td>
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<tr>
<td>800</td>
<td>1.47</td>
<td>1.98</td>
<td>3.60</td>
<td>3.62</td>
</tr>
<tr>
<td>825</td>
<td>1.47</td>
<td>1.98</td>
<td>3.63</td>
<td>3.60</td>
</tr>
<tr>
<td>850</td>
<td>1.47</td>
<td>1.98</td>
<td>3.55</td>
<td>3.60</td>
</tr>
</tbody>
</table>
REFLECTANCE CALCULATION USING EXCEL

To use this spreadsheet change the values in the white boxes. The rest of the sheet is protected and should not be changed unless you are sure of the consequences. The calculated results are shown in purple boxes.

### INPUT:
- Wavelength: 0.8326 microns
- Real part of the index of refraction: 1
- Imaginary part of the index of refraction: 0
- Layer 1 n = 1.00
- Layer 1 t = 1.650
- Layer 2 n = 1.40
- Layer 2 t = 3.0
- Layer 3 n = 3.0

### OUTPUT:
- Reflectance: 24%

### Calculations

**Reflectance Calculation**

For a multi-layer system, the reflectance can be calculated using the following steps:

1. **Input Parameters**:
   - Wavelength: 0.8326 microns
   - Index of refractions for each layer
   - Thicknesses for each layer

2. **Matrix Calculation**:
   - Use matrices to calculate the reflectance for each interface.
   - The matrix method involves the use of the Fresnel equations and complex matrix operations.

3. **Output**:
   - Reflectance calculated: 24%

**Sample Data**

- Layer 1: n = 1.00, t = 1.650
- Layer 2: n = 1.40, t = 3.0
- Layer 3: n = 3.0

**Reflectance**

Reflectance (R) can be calculated using the formula:

\[ R = \frac{|E_1|^2}{|E_0|^2} \]

Where:
- \( E_1 \) is the electric field of the reflected wave
- \( E_0 \) is the electric field of the incident wave

**Example Calculation**

For a given thickness of 4000 Å, the reflectance is calculated to be 24%.
CALCULATED REFLECTANCE VS WAVELENGTH

3000Å

2000Å

1000Å
CALCULATED REFLECTANCE VS WAVELENGTH

500Å
R=8%

400Å
R=14%

300Å
R=18%
### CALCULATED REFLECTANCE FOR TWO LAYERS

Excel calculations for two layers on silicon.

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=1.48</td>
<td>n=1.45</td>
<td>0.04</td>
</tr>
<tr>
<td>ε=5.96</td>
<td>ε=6.5</td>
<td></td>
</tr>
<tr>
<td>d=0.046</td>
<td>d=0.024</td>
<td></td>
</tr>
</tbody>
</table>

Calculations:

- E field in layer 3 at 314 interface - reflection matrix times E field in substrate
- E field in layer 3 at 314 interface - reflection matrix times E field in 3 at 314 interface
- E field in layer 2 at 213 interface - reflection matrix times E field in 2 at 213 interface
- E field in layer 2 at 213 interface - reflection matrix times E field in 2 at 213 interface
- E field in layer 1 at 112 interface - reflection matrix times E field in 1 at 112 interface
- E field in layer 1 at 112 interface - reflection matrix times E field in 1 at 112 interface

The calculated reflectance values are shown in the table above. The reflectance is calculated for each layer and is shown in the last column. The thickness and dielectric constants of the layers are also provided.
HOW TO MEASURE A SPECIFIC SPOT ON THE WAFER

To measure film thickness, focus on the feature that will be measured. The black circle in the center of the view is the area that will be measured. If the black circle is too large, go back and select a different objective lens. Measure the reference wafer again with the higher magnification lens.

Know what the thickness should be and what films (and their thickness) that are under the film to be measured.
Optical Film Thickness Measurements

JOHN GALT CMOS TEST CHIP

BIG NMOS

BIG PMOS
Optical Film Thickness Measurements

KNOW WHERE TO MEASURE

Step 21  Step 37  Step 53  Step 63  Step 67

After Well Drive  After Poly Deposition  After Poly Etch  After CC Etch  After Metal 1 Etch

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SUB-CMOS 150 PROCESS

SUB-CMOS Versions 150

1. CL01
2. OX05-- pad oxide, Tube 4
3. CV02- Si3N4-1500 Å
4. PH03 –1- JG nwell
5. ET29 – Nitride Etch
6. IM01 – n-well
7. ET07 – Resist Strip
8. CL01
9. OX04 – well oxide, Tube 1
10. ET19 – Hot Phos Si3N4
11. IM01 – p-well
12. OX06 – well drive, Tube 1
13. ET06 - Oxide Etch
14. CL01
15. OX05 – pad oxide, Tube 4
16. CV02 – Si3N4 -1500 Å
17. PH03 – 2 – JG Active
18. ET29 – Nitride Etch
19. ET07 – Resist Strip
20. PH03 - -Pwell Stop
21. IM01- stop
22. ET07 Resist Strip
23. CL01
24. OX04 – field, Tube 1
25. ET19 – Hot Phos Si3N4
26. ET06 – Oxide Etch
27. OX04 – Kooi, Tube 1
28. IM01 – Blanket Vt
29. PH03 – 4-PMOS Vt Adjust
30. IM01 - Vt
31. ET07 – Resist Strip
32. ET06 – Oxide Etch
33. CL01
34. OX06 – gate, Tube 4
35. CV01 – Poly 5000A
36. IM01 - dope poly
37. OX08 – Anneal, Tube 3
38. DE01 – 4 pt Probe
39. PH03-5-JG poly
40. ET08 – Poly Etch
41. ET07 – Resist Strip
42. PH03 – 6 - n-LDD
43. IM01
44. ET07 – Resist Strip
45. PH03 – 7 - p-LDD
46. IM01
47. ET07 – Resist Strip
48. CL01
49. CV03 –TEOS, 5000A
50. ET10 - Spacer Etch
51. PH03 – 8 - N+D/S
52. IM01 – N+D/S
53. ET07 – Resist Strip
54. PH03 – 9 P+ D/S
55. IM01 – P+ D/S
56. ET07 – Resist Strip
57. CL01 Special - No HF Dip
58. OX08 – DS Anneal, Tube 2
59. CV03 – TEOS, 4000A
60. PH03 – 10 CC
61. ET26 - CC Etch
62. ET07 – Resist Strip
63. CL01 Special - Two HF Dips
64. ME01 – Metal 1 Dep
65. PH03 -11- metal
66. ET15 – plasma Etch Al
67. ET07 Resist Strip
68. SI01 - Sinter
69. CV03 – TEOS- 4000Å
70. PH03 – VIA
71. ET26 – Via Etch
72. ET07 – Resist Strop
73. ME01 – Metal 2 Dep
74. PH03- M2
75. ET15 – plasma Etch Al
76. ET07 - Resist Strip
77. SEM1
78. TE01
79. TE02
80. TE03
81. TE04

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AFTER POLY ETCH AND STRIP RESIST

Poly Target Thickness 5000Å
Gate Oxide Target 150Å
Field Oxide Target 5000Å

Do lot history to get exact thickness values of underlying layers

~5000 Å Field Oxide

P-well

N-well
Optical Film Thickness Measurements

SPECTROMAP

Mean
Std Deviation
Min
Max
No of Points
TENCORE SPECTROMAP

The Spectromap illuminates the sample with white light and collects the reflected light intensity versus wavelength. The raw data is compared to theoretical simulated intensity versus wavelength. The best fit is determined and the film thickness is determined. This tool can be programed to make measurements at many locations on the wafer and provide statistical information about the measurements such as mean, standard deviation, minimum, and maximum. The programmed locations are not precise enough to measure inside small features on the wafer and no alignment mechanism is available for aligning the wafer with the x and y axis of the stage. Best results are obtained on uniformly coated blank wafers. Multi-layer films can be measured if the underlying film properties (index and thickness) are known.
TENCORE FILM THICKNESS FT350
The FT350 is an optical film thickness measurement tool that is very similar to the Tencore Spectromap. However, it does have accurate programmable stage positioning that provides for precise measurement in preprogrammed locations on a patterned wafer.
ELLIPSOMETER

Rudolph Ellipsometer

Variable Angle Spectroscopic Ellipsometer
The light source is unpolarized, upon traversing the polarizer the light becomes linearly polarized. Turning the polarizer adjusts the azimuth of linearly polarized light with respect to the fast axis of the quarter-wave plate in such a way as to vary the ellipticity of the light incident on the surface. This ellipticity is adjusted until it is just cancelled by the ellipticity introduced by the reflection. The result is again linearly polarized light. The analyzer polarizing prism is rotated until its axis of polarization is perpendicular to the azimuth of the linearly polarized light, creating a null. Thus no light is transmitted to the detector. The common technique is to fix the quarter-wave plate with fast axis at 45° to the plane of incidence, and to alternately move the polarizer and analyzer, continuously reducing the transmitted light until a null is reached. The relevant light parameters $\Delta$ and $\Psi$ are readily calculated from the instrument parameters (P, polarizer angle, Q, quarter-wave plate angle, and A, analyzer angle. Values for film thickness and index of refraction are found. Thickness values that correspond to these parameters repeat with multiples of the light source wavelength so the approximate thickness must be known.
REFERENCES

1. Calculate the reflection…..