As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, Semiconductor Device and Materials Characterization. Every serious microelectronics student should have a copy of this book!
Optical Characterization

Optical Microscopy
Ellipsometry
Transmission
Reflection
Photoluminescence
Optical Excitation

**Emission**
- Photoluminescence
- Raman Spectroscopy
- UV Photoelectron Spectroscopy

**Reflection**
- Optical Microscopy
- Ellipsometry
- Reflection Spectroscopy

**Absorption**
- Photoconductance
- Photoelectron Spectroscopy

**Transmission**
- Absorption Coefficient
- Infrared Spectroscopy
Optical Characterization

- **Photometric Measurements**
  - *Amplitude* of reflected or transmitted light
  - ⇒ Optical constants, absorption coefficients
**Optical Characterization**

- **Interference Measurements**
  - *Phase* of reflected or transmitted light
  - ⇒ Film thickness, surface structure
  - Two emerging light beams are phase shifted
  - ⇒ *Constructive* and *destructive* interference

\[
n_1 \sin \phi' = n_0 \sin \phi
\]

\[
d = \frac{\lambda}{2 \sqrt{n_1^2 - n_0^2 \sin^2 \phi}}
\]
Interference

**Destructive Interference**

- Amplitude
  - A
  - B
  - C

**Constructive Interference**

- Amplitude
  - A
  - B
  - C

Eye

Oxide thickness variations
Interference

- *Blue Morpho* butterfly gets its bright blue color from interference effects
- Interference due to microscopic ridges on the wings
Optical Characterization

- **Polarization Measurements**
  - Ellipticity of reflected light
  - ⇒ Optical constants, film thickness, surface structure
  - Polarizer polarizes the light into particular orientation
  - H-sheet; most popular linear polarizer
    - Polyvinyl alcohol (plastic sheet) is heated and stretched
    - Sheet is dipped into iodine solution
    - Iodine impregnates the plastic, attaching to long-chain molecules, forms “wire” grid

\[ \text{Polarizer} \]

- Horizontal polarization, transmitted
- Vertical polarization, not transmitted
Polarized Light

Electric Field

Magnetic Field

Circular Polarization

Elliptical Polarization

Light Waves Vibrating Perpendicular to the Highway

Light Waves Vibrating Parallel to the Highway

This shows the effectiveness of polarizing filters.
Polarizing Filter Effect

- Colored light from thin-film iridescence in butterflies is often polarized
- Left wings: unmodified
- Right wings: generated by taking two photographs through a polarizing filter rotated by 90° between exposures, and then producing the difference of the two images
- One shows a pattern of polarized and depolarized regions, the other does not
- Wing color important in male attraction to females

Diamonds

What’s so special about diamonds?

Star of South Africa Diamond
83.5 Carats

Taylor Diamond
69 Carats
A diamond is polished into a particular shape for maximum light refraction/reflection/transmission.
Optical Microscopy

- Light cannot be focused to an infinitesimally small spot due to the wave nature of light.
Optical Microscopy

- There is no lower limit to the size of an isolated object that can be detected.
- The minimum separation, $s$, of two point objects occurs when the first maximum of the diffraction pattern of one object falls on the first minimum of the second object.

$$s = \frac{0.61\lambda}{n \sin \theta} = \frac{0.61\lambda}{NA}$$

- $\lambda$ = free space wavelength,
  $n$ = refractive index of immersion medium,
  $\theta$ = half the angle subtended by the lens at the object,
  $NA$ = numerical aperture

Best resolution about 0.25 $\mu$m
for $\lambda \approx 0.4$ $\mu$m, $NA \approx 1$
Different approaches to optical microscopy bring out different features

- Bright Field
- Dark Field
- Interference Contrast
Near Field Optical Microscopy

- Conventional microscopy
  - Images the *far field*, where Raleigh limit prevails
- Near field microscopy
  - Images the *near field*, where solution determined by aperture, not wavelength
  - Detector must be very close to sample
Near Field Optical Microscopy

- The light is confined to a small aperture
  - Drawn or etched glass fiber

Physics.nist.gov/Divisions/Div844/facilities/nsom/nsom.html
Ellipsometry

**Definition**
- Measurement of the state of polarization of a polarized light wave

**General Scheme**
- A polarized light wave probe interacts with an "optical system", this interaction changes the state of polarization, measurement of the initial and final states is performed this yields information about the optical constants of the "system"
Null Ellipsometer

- Angles P, C, and A lead to ellipsometer quantities $\rho$, $\Psi$ and $\Delta$

$$\rho = \tan \Psi e^{j\Delta}$$

The ellipsometry equation!
Ellipsometry

- Nondestructive technique
- Film thickness measurement; can measure film thicknesses down to 1 nm
- refractive index determination; can measure refractive index of thin films of unknown thickness
- Azimuth angles can be measured with great accuracy
- Measures a ratio of two values
  - Highly accurate and reproducible (even in low light levels)
  - No reference sample necessary
  - Not as susceptible to scatter, lamp or purge fluctuations
- Surface uniformity assessment
- Composition determinations
- Can be used for in situ analysis
Ellipsometer

- Null ellipsometry
  - Polarizer-Compensator-Sample-Analyzer
  - Polarizer and Compensator Angles adjusted for linear polarization upon reflection
  - Analyzer is adjusted to extinguish reflected light

- Rotating Analyzer Ellipsometry
  - Analyzer rotates
    \[ I(\theta) = I_0 [1 + a_2 \cos 2\theta + b_2 \sin 2\theta] \]
    \[ \Psi = \frac{1}{2} \cos^{-1}(-a_2); \quad \Delta = \cos^{-1}\left(\frac{b_2}{\sqrt{1 - a_2^2}}\right) \]

- Spectroscopic Ellipsometry
  - Uses several wavelengths
  - Can also use several angles
Ellipsometry

- Measure change of polarization state of light reflected from a surface

\[ R_p = \frac{E_p(\text{reflected})}{E_p(\text{incident})}; \quad R_s = \frac{E_s(\text{reflected})}{E_s(\text{incident})} \]

\[ \rho = \frac{R_p}{R_s} = \tan \Psi e^{i \Delta} \]

- For an air-solid with an absorbing substrate

\[ n_1^2 - k_1^2 = n_0^2 \sin^2 \phi \left[ 1 + \frac{\tan^2 \phi \left[ \cos^2 2\Psi - \sin^2 2\Psi \sin^2 \Delta \right]}{\left[ 1 + \sin 2\Psi \cos \Delta \right]^2} \right] \]

\[ 2n_1 k_1 = \frac{n_0^2 \sin^2 \phi \tan^2 \phi \sin 4\Psi \sin \Delta}{\left[ 1 + \sin 2\Psi \cos \Delta \right]^2} \]
Transmission / Absorption

Definition

- Absorption - the loss of a photon from an incident flux by the process of exciting an electron from a lower- to a higher-energy state

General Scheme

- Light is incident on a thin sample part of the light is reflected and the remainder is absorbed or transmitted; a measurement is made of the transmitted intensity
- The experiment can be carried out as a function of temperature, externally applied fields, sample thickness, etc.

\[ I_i \quad d \quad I_t \]
Transmission

- Optical transmission measurements
  - Sample thickness
  - Absorption coefficient
  - Impurities in semiconductors (oxygen and carbon in Si)

\[
T = \frac{I_t}{I_i} = \frac{(1 - R_1)(1 - R_2)e^{-\alpha d}}{1 + R_1R_2e^{-2\alpha d} - 2\sqrt{R_1R_2}e^{-\alpha d}\cos\phi}
\]

For \(R_1 = R_2\):

\[
T = \frac{(1 - R)^2e^{-\alpha d}}{1 + R^2e^{-2\alpha d} - 2Re^{-\alpha d}\cos\phi}
\]

\[
R = \frac{(n_0 - n_1)^2 + k_1^2}{(n_0 + n_1)^2 + k_1^2} \quad \phi = \frac{4\pi n_1 d}{\lambda}
\]
Transmission

\[ T = \frac{(1 - R)^2 e^{-\alpha d}}{1 + R^2 e^{-2\alpha d} - 2R e^{-\alpha d} \cos \phi} \]

\[ T = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{(1 - R)^2 e^{-\alpha d}}{1 + R^2 e^{-2\alpha d} - 2Re^{-\alpha d} \cos \phi} d\phi \]

- If detector has insufficient resolution

\[ T = \frac{(1 - R)^2 e^{-\alpha d}}{1 - R^2 e^{-2\alpha d}} \]

- If \( \alpha = 0 \)

\[ T = \frac{(1 - R)^2}{1 + R^2 - 2R \cos \phi} \]

\[ T = \frac{(1 - R)^2}{1 - R^2} = \frac{1 - R}{1 + R} \]
Transmission

- Gives absorption coefficient, impurity density (e.g., oxygen, carbon in Si), thickness

\[ \alpha = \frac{1}{d} \ln \left( \frac{(1 - R)^2 + \sqrt{(1 - R)^4 + 4T^2R^2}}{2T} \right) \]
\[ d = \frac{1}{2n_{\Delta}(1/\lambda)} \]
Oscillations are determined by 

\[ \cos \frac{4\pi nd}{\lambda}; \]

Has maxima at 

\[ d = \frac{m\lambda_0}{2n}; \quad d = \frac{(m + 1)\lambda_i}{2n} \quad \text{........} \quad d = \frac{(m + i)\lambda_i}{2n} \]

\[ \Rightarrow m = \frac{i\lambda_i}{\lambda_o - \lambda_i} \]

\[ d = \frac{1\lambda_o\lambda_i}{2n(\lambda_o - \lambda_i)} = \frac{i}{2n(1/\lambda_i - 1/\lambda_o)} \]

For \( i = 1 \): 

\[ d = \frac{1}{2n(1/\lambda_1 - 1/\lambda_0)} = \frac{1}{2n\Delta(1/\lambda)} \]
Two types of instruments are used

**Monochromator**

\[ m\lambda = 2d \sin(\theta)\cos(\phi) \]

\[ m = 1, 2, 3 \ldots \]

\[ d = \text{line spacing of grating} \]
Interferometer

- Let source be $\cos 2\pi fx$
  - $f$: frequency of light
  - $x$: movable mirror location
- $L_1 = L_2$
  - Constructive interference
  - Maximum detector output
- $L_1 = L_2 + \lambda/4$
  - Destructive interference
  - Zero detector output
Fourier Transform Infrared Spectroscopy

- Fourier transform infrared spectroscopy (FTIR)

\[ I(x) = B(f)[1 + \cos 2\pi xf] \quad I(x) = \int_0^f B(f)[1 + \cos 2\pi xf] df \]

\[ I(x) = \int_0^{f_1} A\cos 2\pi xf\, df = Af_1 \frac{\sin 2\pi f_1}{2\pi f_1} \]

\[ B(f) = \int_{-\omega}^{\omega} I(x)\cos 2\pi xf\, dx \]
Interferogram - Spectrum

**Interferogram**

![Interferogram](www.chem.orst.edu/ch361-464/ch362/irinstrs.htm)

**Spectrum**

![Spectrum](www.chem.orst.edu/ch361-464/ch362/irinstrs.htm)
FTIR Applications

- Determine oxygen and carbon density by transmission dip.
Reflection measurements

- Film thickness
- Reflectivity

\[
R = \frac{r_1^2 e^{\alpha d_1} + r_2^2 e^{-\alpha d_1} + 2 r_1 r_2 \cos \phi_1}{e^{\alpha d_1} + r_1^2 r_2^2 e^{-\alpha d_1} + 2 r_1 r_2 \cos \phi_1}
\]

\[
r_1 = \frac{n_0 - n_1}{n_0 + n_1}, \quad r_2 = \frac{n_1 - n_2}{n_1 + n_2}
\]

\[
\phi_1 = \frac{4 \pi n_1 d_1 \cos \phi'}{\lambda}
\]

\[
\phi' = \sin^{-1} \left[ \frac{n_0 \sin \phi}{n_1} \right]
\]
Reflection Examples

Rearview Mirror

Hot air near desert has a lower index of refraction than the cooler air above.

http://sol.sci.uop.edu/~jfalward/refraction/refraction.html
Total Internal Reflection

- Snell’s law: $n_0 \sin \theta_0 = n_1 \sin \theta_1$
- For $\theta_1 = \theta_c = \sin^{-1}(n_0/n_1)$ (critical angle) $\Rightarrow \theta_0 = 90^\circ$
  - Total internal reflection
Reflection

- $R$ versus $\lambda$ yields plots with *unequal* wavelength spacings
- $R$ versus $1/\lambda$ (wavenumber) gives *equal* spacings

\[
\lambda(\text{max}) = \frac{2n_1d_1\cos \phi'}{m}
\]

\[
m = 1, 2, 3, \ldots
\]

\[
d_1 = \frac{i\lambda_0\lambda_i}{2n_1(\lambda_i - \lambda_0)\cos \phi'}
\]

\[
i = \frac{i}{2n_1(1/\lambda_0 - 1/\lambda_i)\cos \phi'}
\]

$i$: number of complete cycles from $\lambda_0$ to $\lambda_i$
Reflection FTIR Applications

- FTIR is used in many solid state and chemical applications

www.mee-inc.com/ftir.html#analytical
Scatterometry uses scattered or diffracted light.

From diffracted signature can determine:

- Line height
- Line width
- Corner rounding
- Sidewall slope/angle

Special test structure

Luminescence

Luminescence is the emission of light due to:

- Incandescence: energy supplied by heat
- Photoluminescence: energy supplied by light
- Fluorescence: energy supplied by ultraviolet light
- Chemiluminescence: energy supplied by chemical reactions
- Bioluminescence: energy supplied by chemical reactions in living beings
- Electroluminescence: energy supplied by electric current/voltage
- Cathodoluminescence: energy supplied by electron beams.
- Radioluminescence: energy supplied by nuclear radiation
- Phosphorescence: delayed luminescence or "afterglow"
- Triboluminescence: energy supplied by mechanical action
- Thermoluminescence: energy supplied by heat
Photoluminescence

- Incident laser creates electron-hole pairs (ehp)
- When the ehp recombine, they emit light

\[ h\nu = E_D - E_A \]

Sample → Detector

\[ h\nu = E_G - E_V \]

Exciton
How Does PL Work And How Can It Be Used?

- Carrier generation depth
  - Wavelength $\Rightarrow$ depth information
- Recombination
  - Shockley-Read-Hall (impurities) $\Rightarrow$ impurity information
  - Auger (high carrier densities) $\Rightarrow$ doping density information
  - Surface (surface states, impurities) $\Rightarrow$ surface information
  - Radiative (light emission) $\Rightarrow$ detection mechanism

This is what we want!
Depth Dependent PL Signals
Iron In Si by PL And PCD

Mean: 465 mV
Dev.: 7.74 mV

Mean: 175 µs
Dev.: 120 µs

Mean: 2.4x10^{11} cm^{-3}
Dev.: 2.9x10^{11} cm^{-3}
Review Questions

- What determines the resolution limit in conventional optical microscopy?
- What is near field optical microscopy?
- What are the basic elements of ellipsometry?
- How does FTIR work?
- Where are transmission measurements used?
- Where are reflection measurements used?
- What is luminescence?
- How can photoluminescence be used in Si characterization?