Georgia Tech

# ECE 4813

# Semiconductor Device and Material Characterization

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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!***

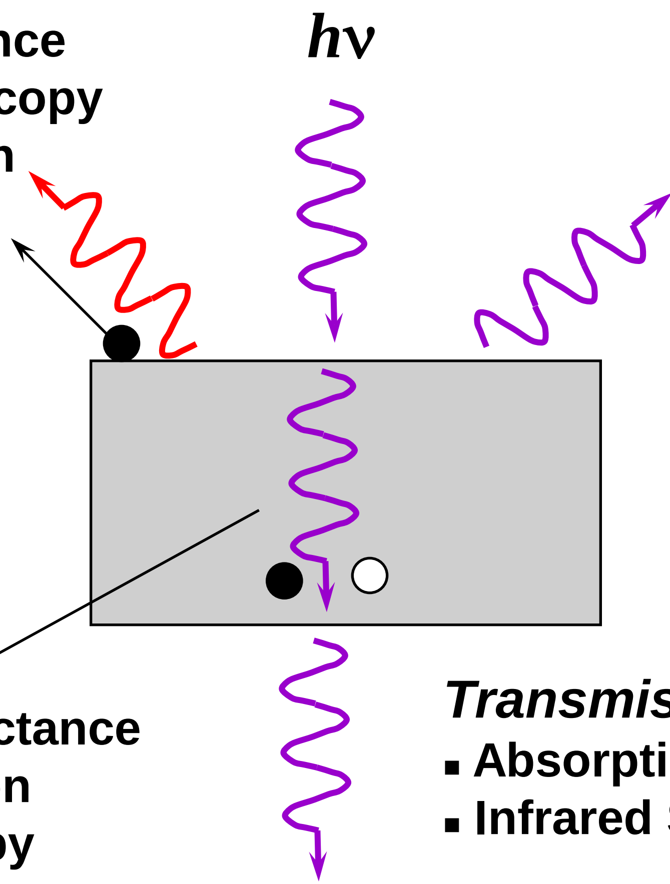
# Optical Characterization

Optical Microscopy
Ellipsometry
Transmission
Reflection
Photoluminescence

# Optical Excitation

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

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



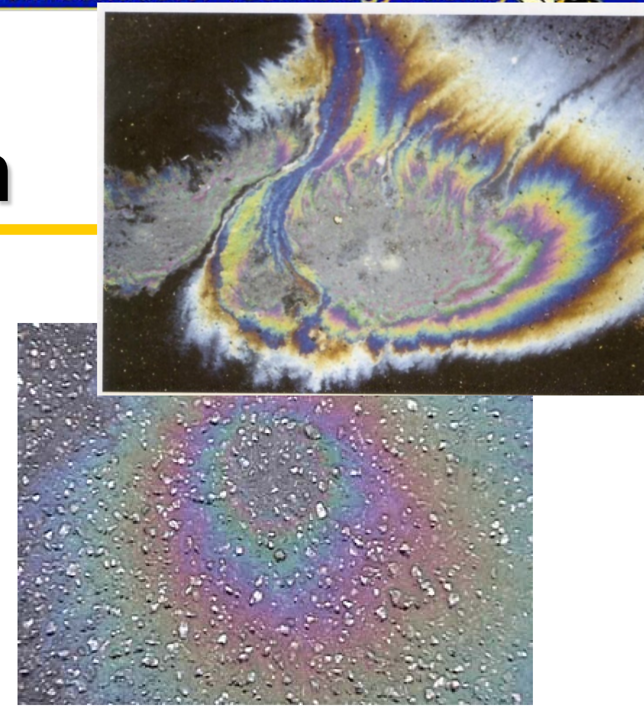

***Absorption***
- Photoconductance
- Photoelectron Spectroscopy

***Transmission***
- Absorption Coefficient
- Infrared Spectroscopy

# Optical Characterization

- ***Photometric* Measurements**
  - ***Amplitude* of reflected or transmitted light**
  - **$\Rightarrow$ Optical constants, absorption coefficients**

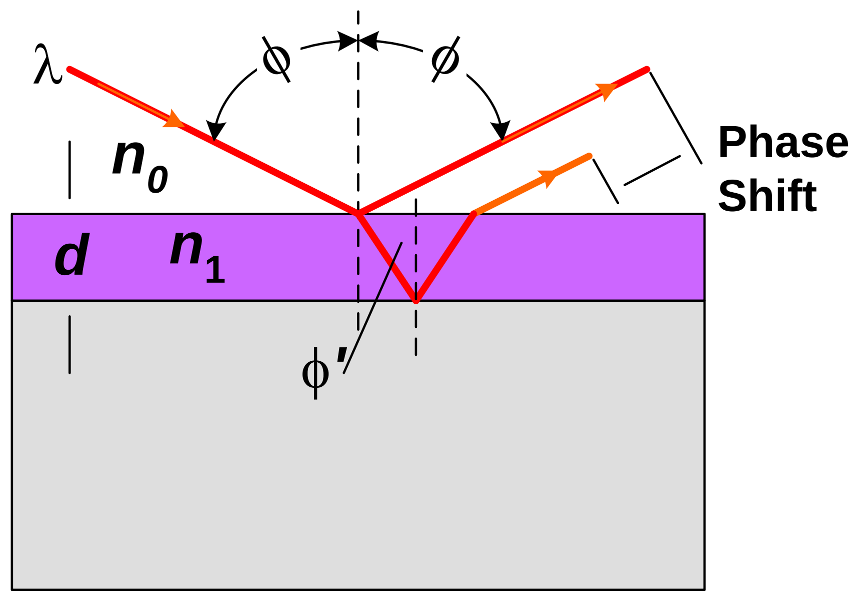
# Optical Characterization



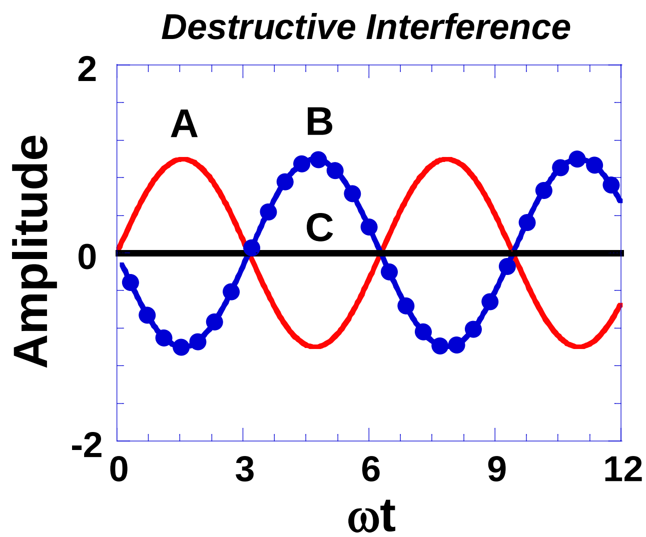
- *Interference* Measurements
  - *Phase* of reflected or transmitted light
  - ⇒ Film thickness, surface structure
  - Two emerging light beams are phase shifted
  - ⇒ *Constructive* and *destructive* interference

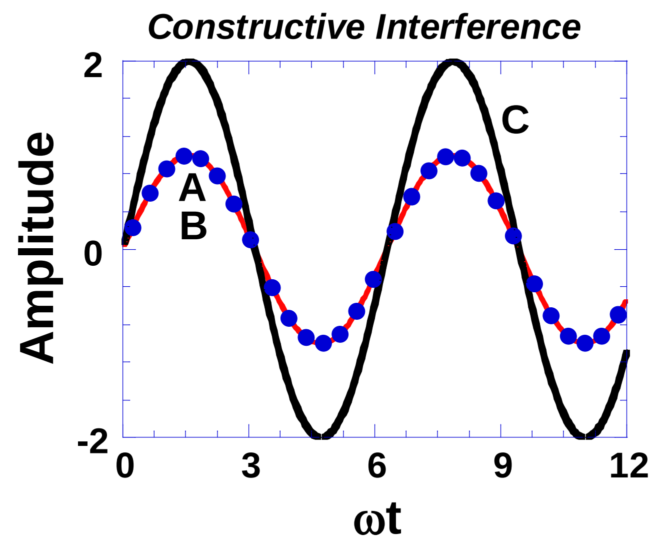
$$n_1 \sin\phi' = n_0 \sin\phi$$

$$d = \frac{\lambda}{2\sqrt{n_1^2 - n_0^2 \sin^2\phi}}$$

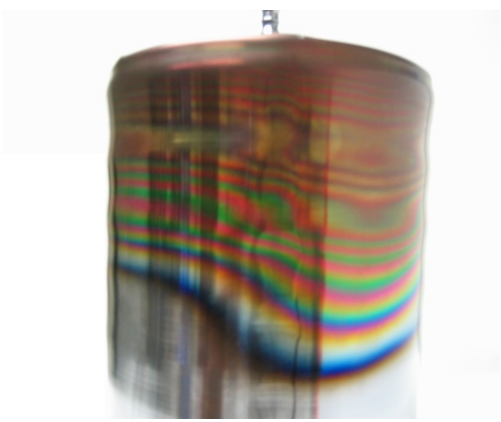


# Interference



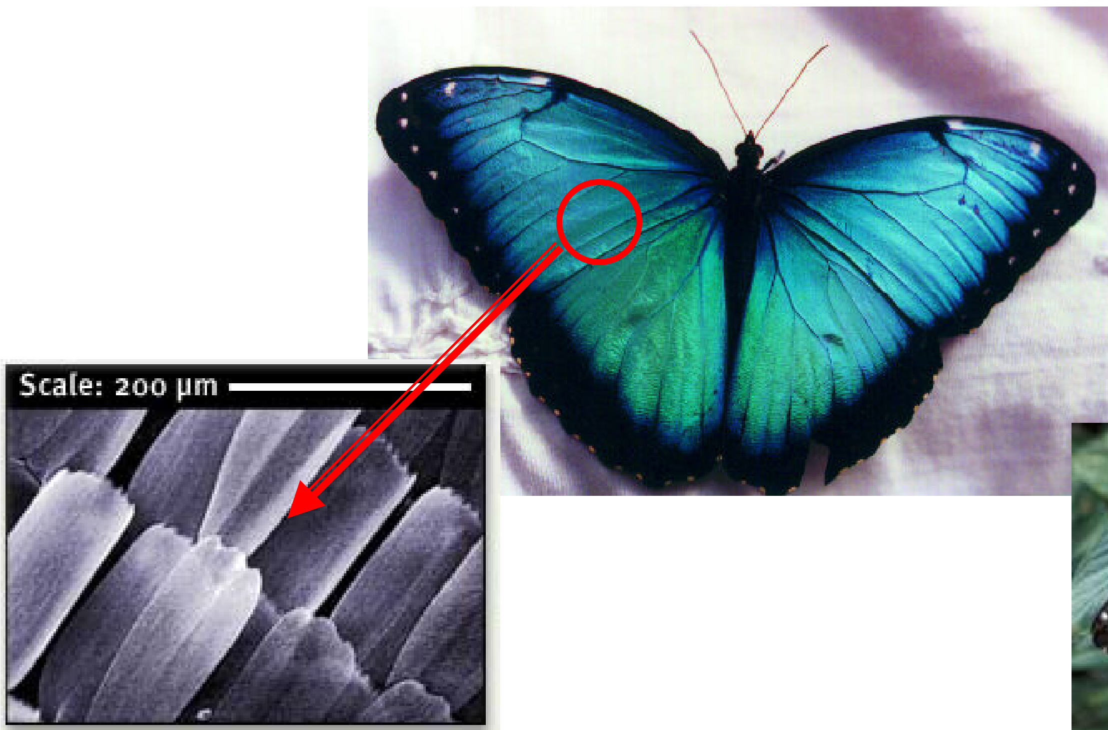

Eye



**Oxide thickness variations**

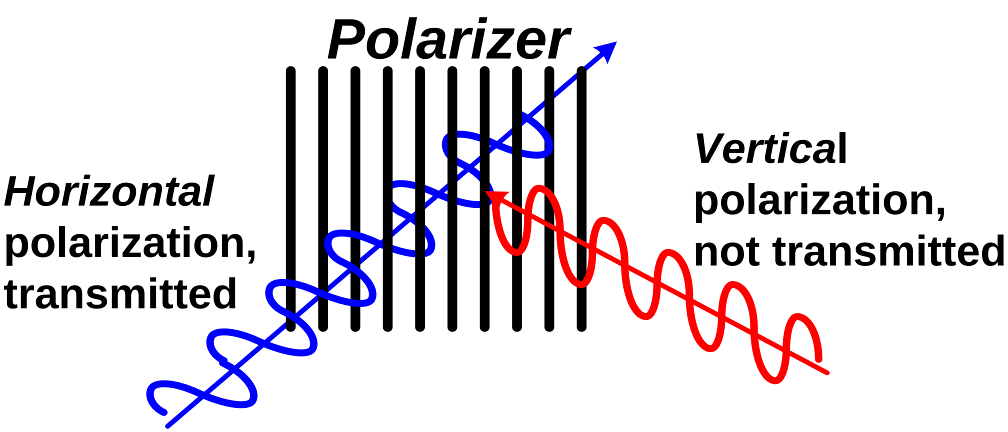
# Interference

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

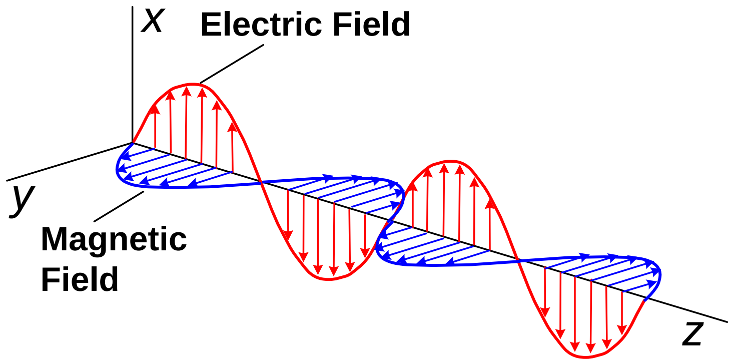


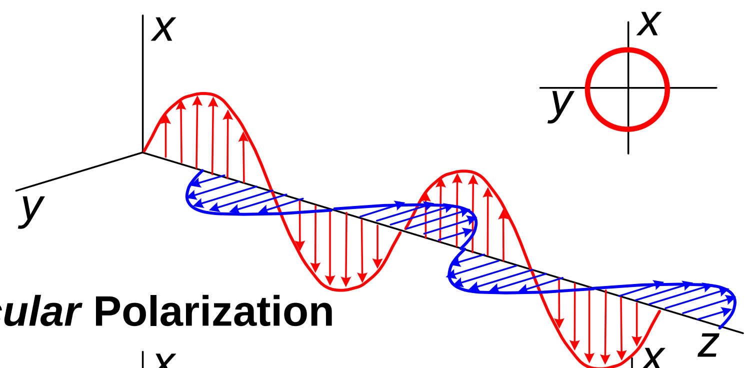

# Optical Characterization

- ***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, attaches to long-chain molecules, forms "wire" grid**

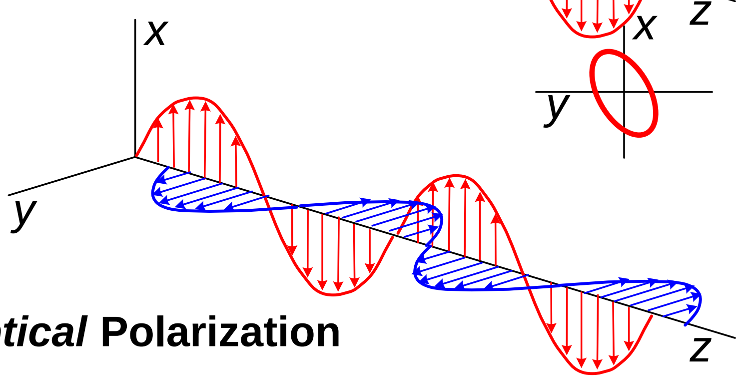


# Polarized Light

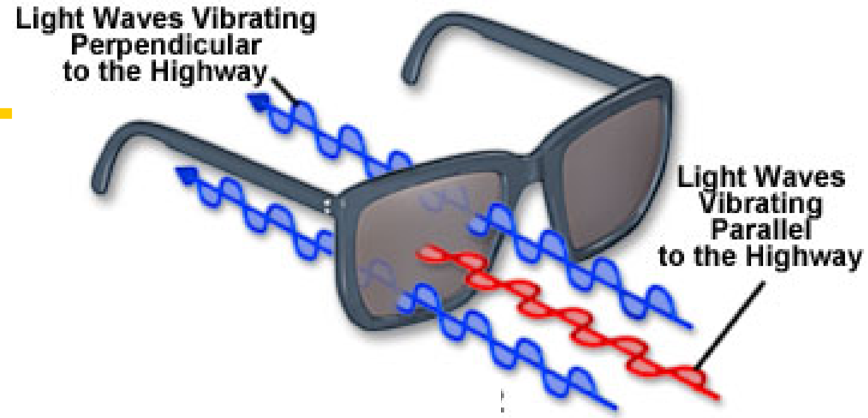


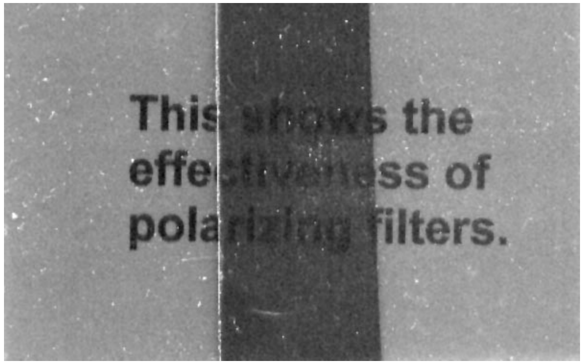



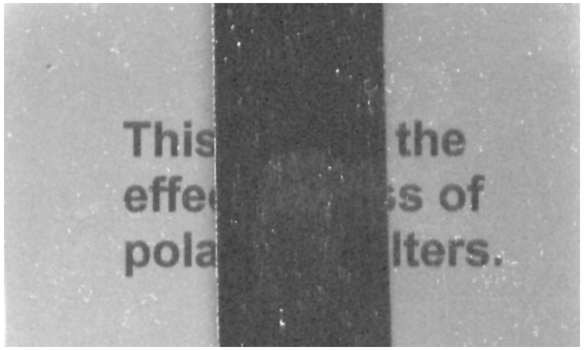

*Circular* Polarization




*Elliptical* Polarization



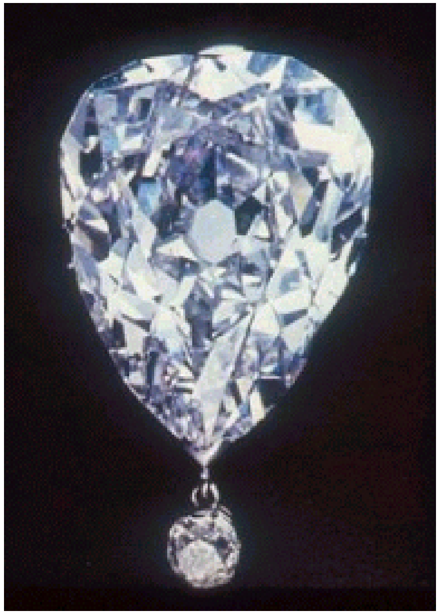
# Polarizing Filter Effect

- 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

A. Sweeney et al. *Nature* **423**, 31 (2003)

# Diamonds

- What's so special about diamonds?

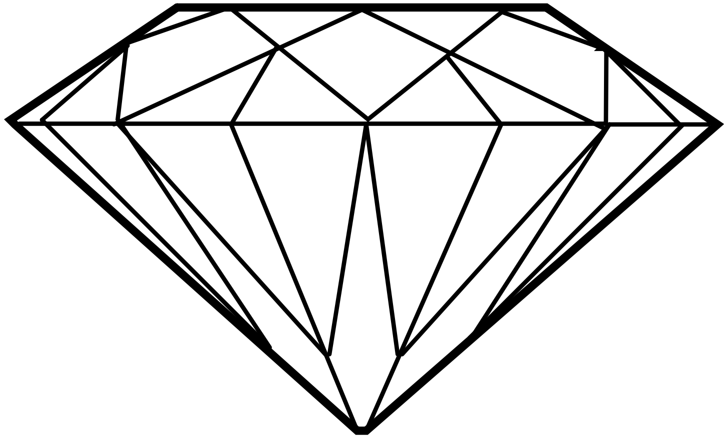


Star of South Africa Diamond
83.5 Carats

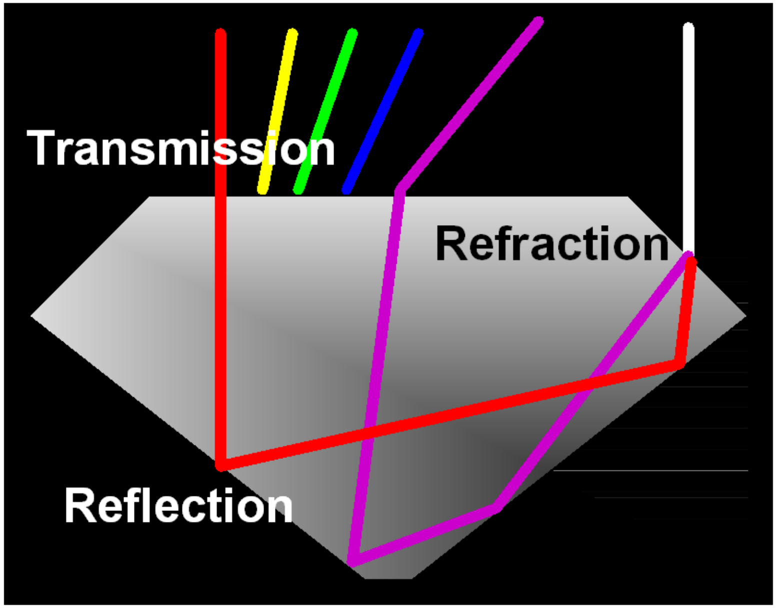
Taylor Diamond
69 Carats

# Transmission, Reflection, Refraction

- **A diamond is polished into a particular shape for maximum light refraction/reflection/transmission**

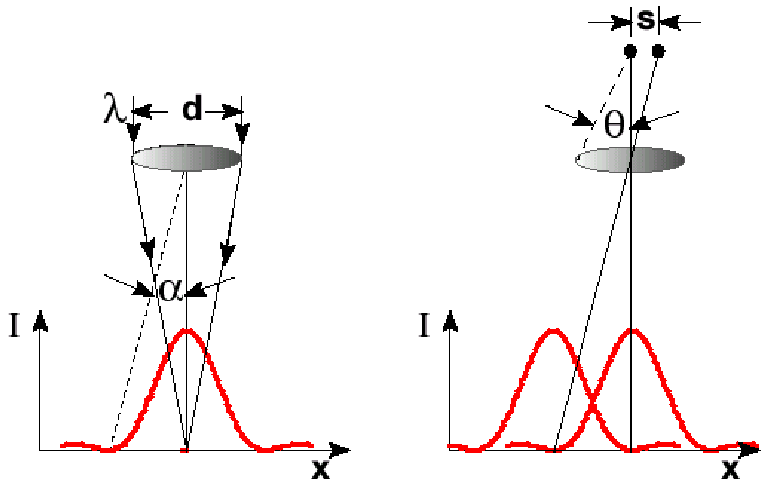


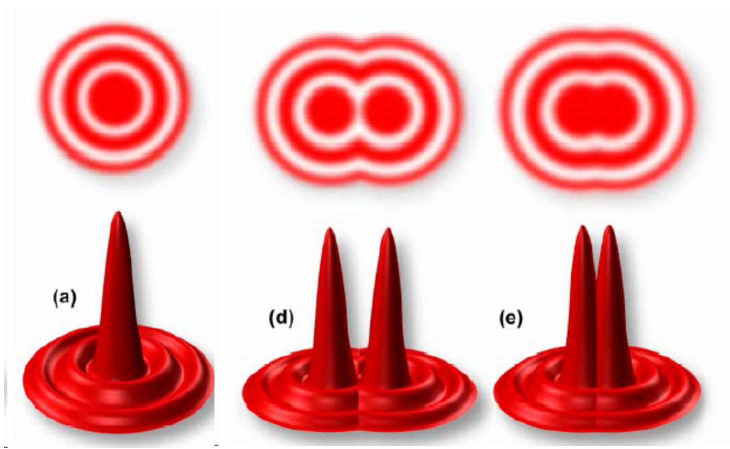
58 Facets



# Optical Microscopy

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

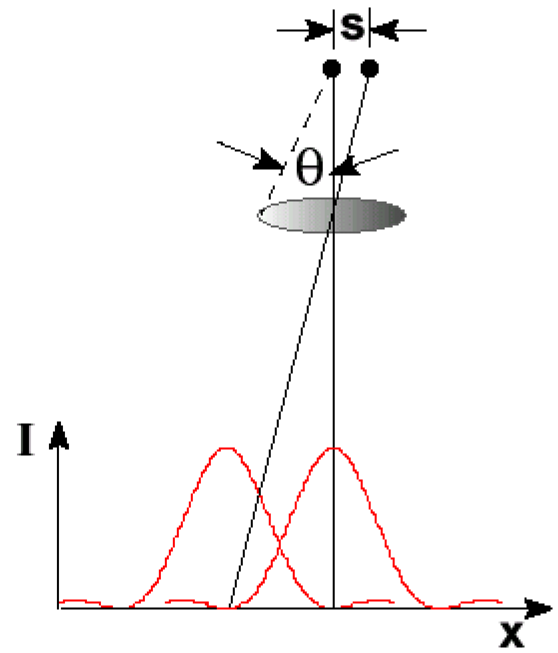



# Optical Microscopy

- 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

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

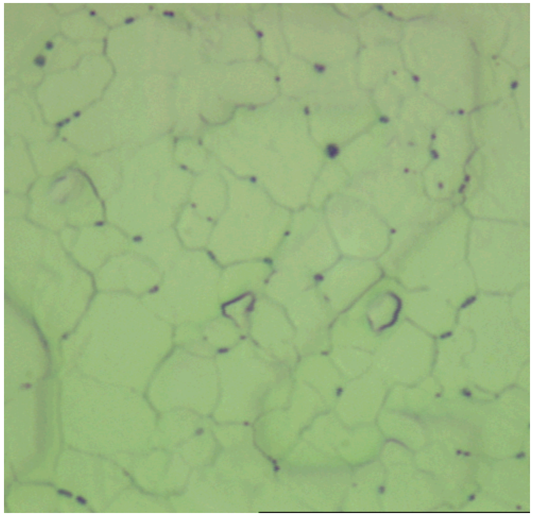



- $\lambda$ = free space wavelength,
  *n* = refractive index of immersion medium, θ = half the angle subtended by the lens at the object,
  *NA* = numerical aperture

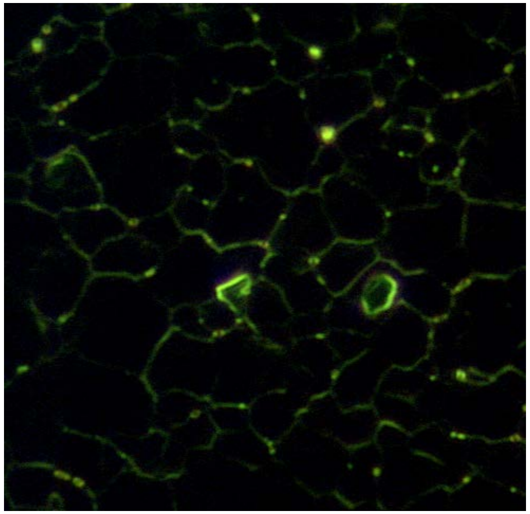
***Best resolution about 0.25 µm for $\lambda \approx 0.4$ µm, NA ≈ 1***

# Optical Microscopy

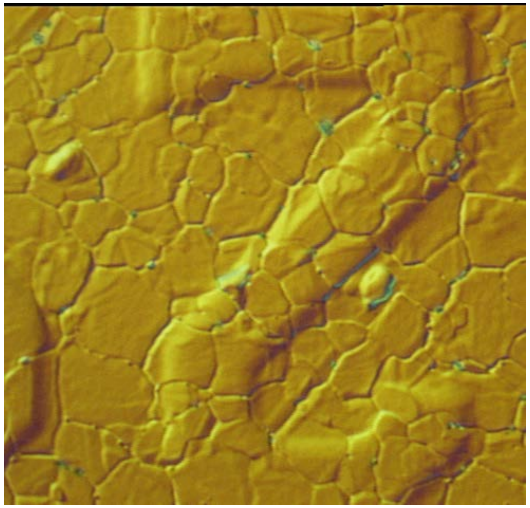
- Different approaches to optical microscopy bring out different features



Bright Field



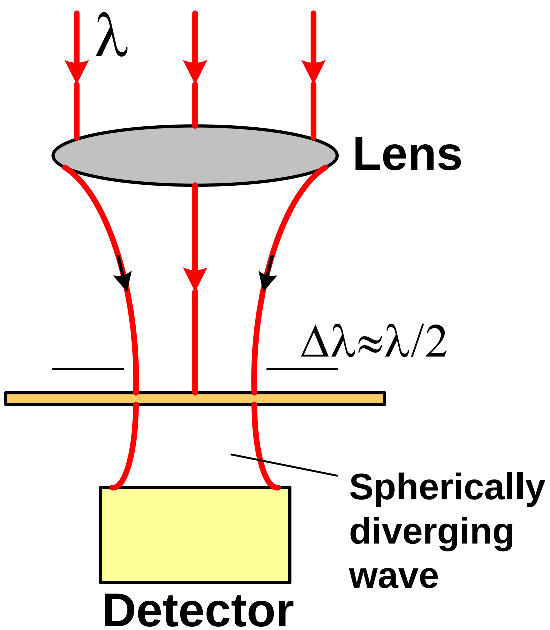
Dark Field

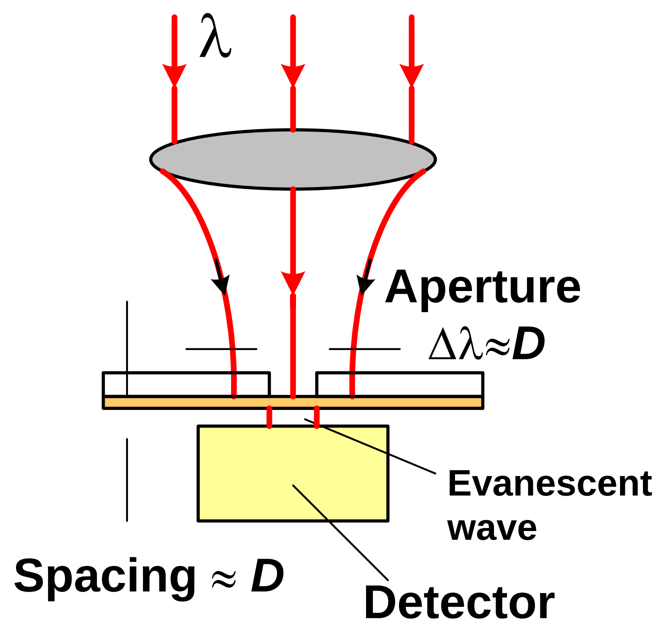


Interference Contrast

# Near Field Optical Microscopy

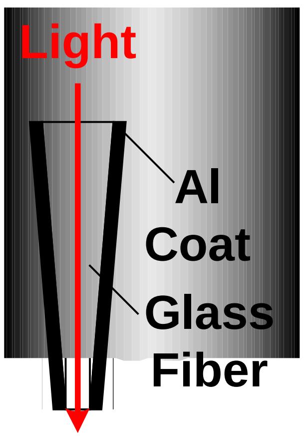
- Conventional microscopy
  - Images the *far field*, where Raleigh limit prevails
- Near field microscopy
  - Images the *near field*, where solution determined by aperture, not wavelength
  - Detector must be very close to sample

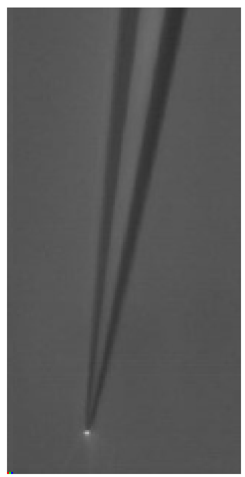


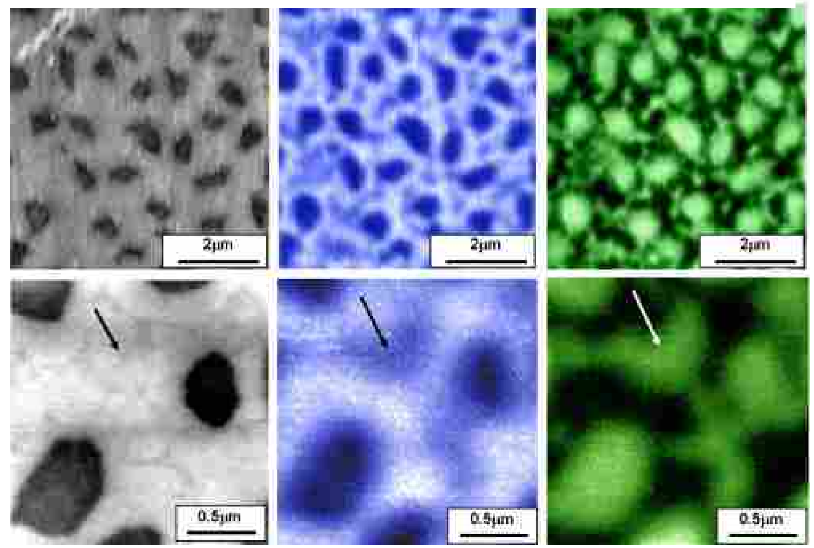
# Near Field Optical Microscopy

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



Topography Transmission Fluorescence




*Polymer Sample*

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

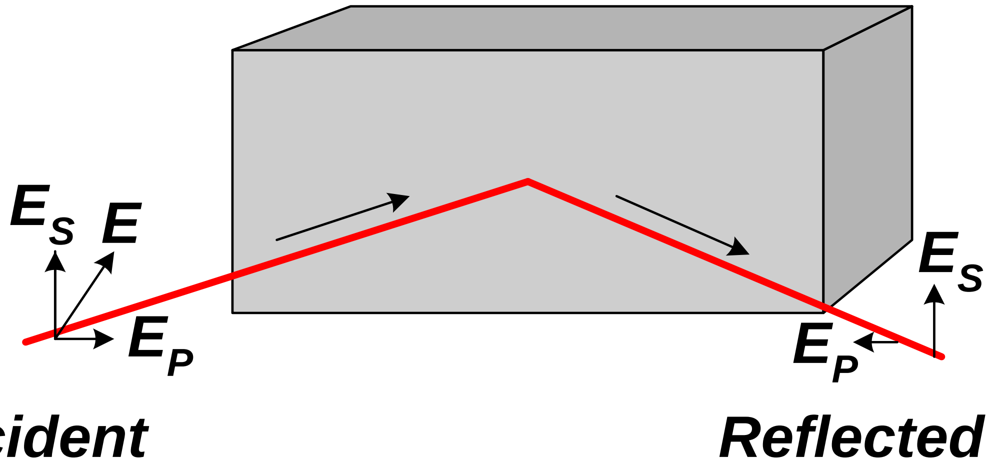
# Ellipsometry

## *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"

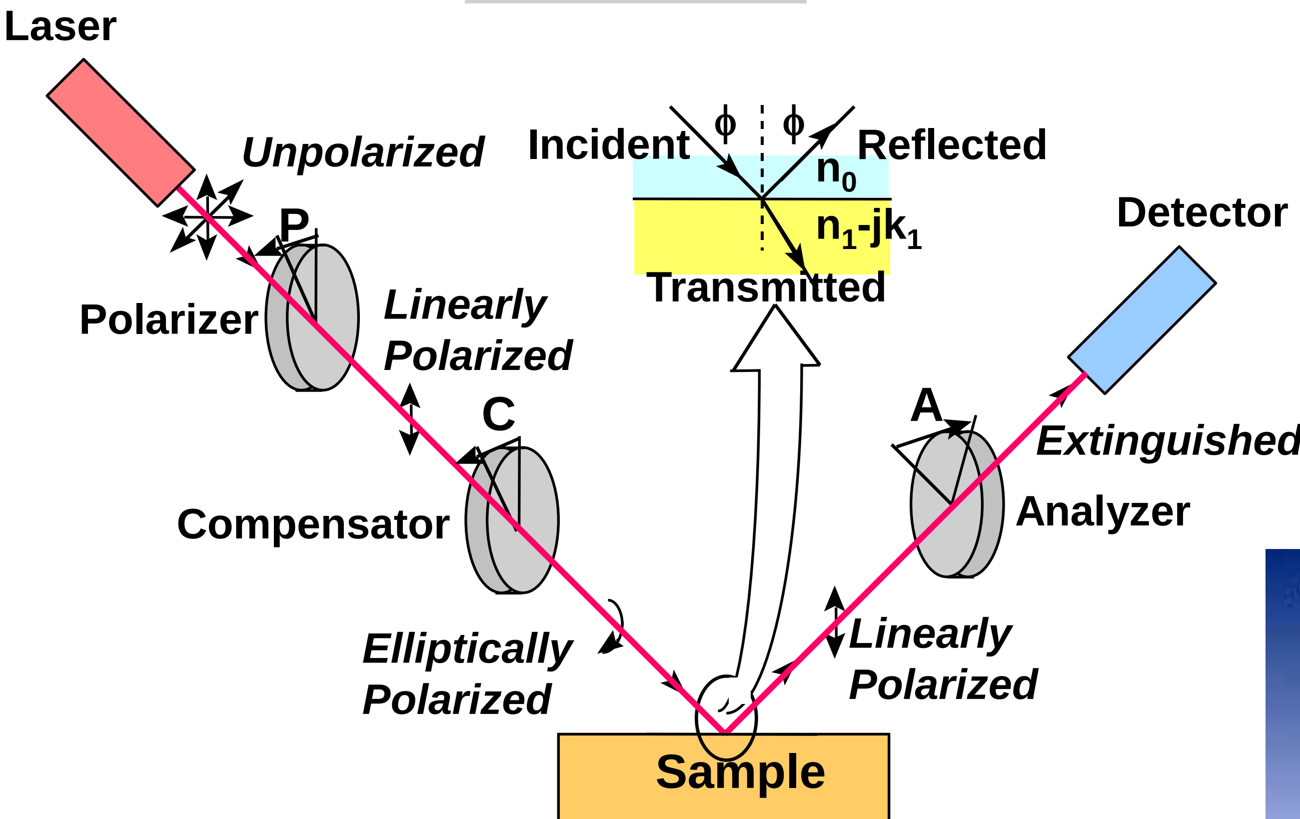


# Null Ellipsometer

- **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

$$I(\theta) = I_0\left[1 + a_2 \cos 2\theta + b_2 \sin 2\theta\right]$$

$$\Psi = \frac{1}{2}\cos^{-1}(-a_2); \quad \Delta = \cos^{-1}\left(\frac{b_2}{\sqrt{1-a_2^2}}\right)$$

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

# Ellipsometry

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

$$R_p = \frac{E_p(reflected)}{E_p(incident)}; \quad R_s = \frac{E_s(reflected)}{E_s(incident)}$$

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

- For an air-solid with an absorbing substrate

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

$$2n_1k_1 = \frac{n_0^2 \sin^2\phi \tan^2\phi \sin 4\Psi \sin\Delta}{\left[1+\sin 2\Psi \cos\Delta\right]^2}$$

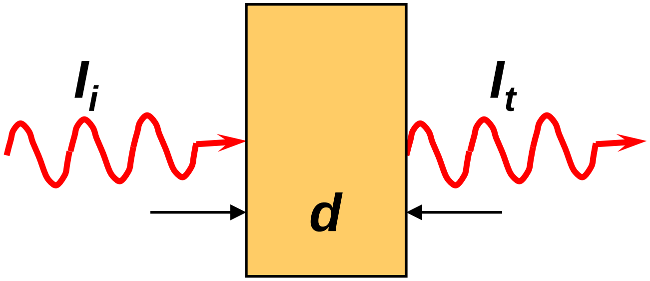
# Transmission / Absorption

## 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**

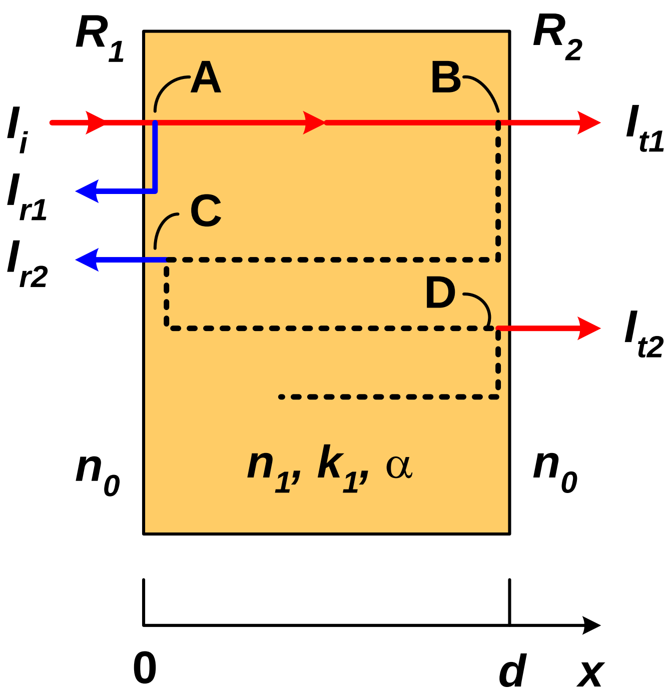
## General Scheme

- **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.**



# 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 $R_1 = R_2$:

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

$$R = \frac{(n_0-n_1)^2+k_1^2}{(n_0+n_1)^2+k_1^2} \qquad \phi = \frac{4\pi n_1 d}{\lambda}$$

# Transmission

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

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

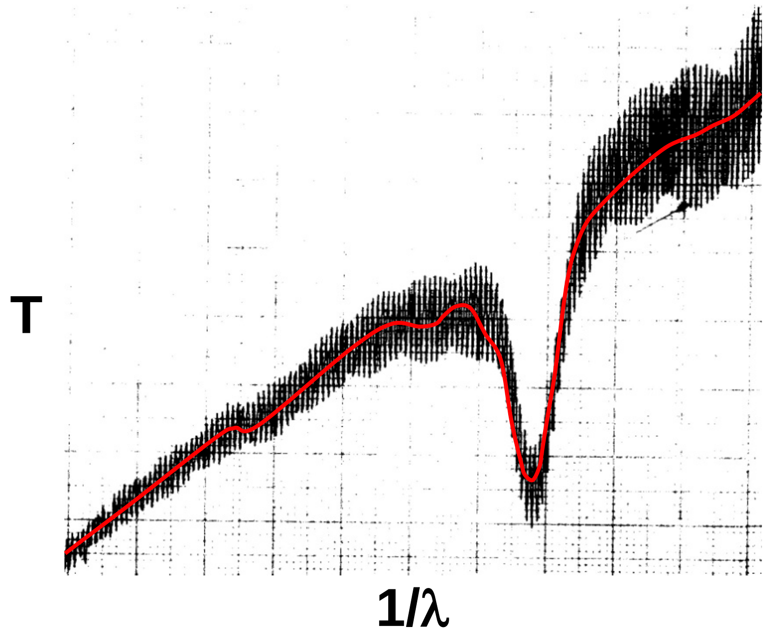
- **If detector has insufficient resolution**

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

- **If $\alpha = 0$**

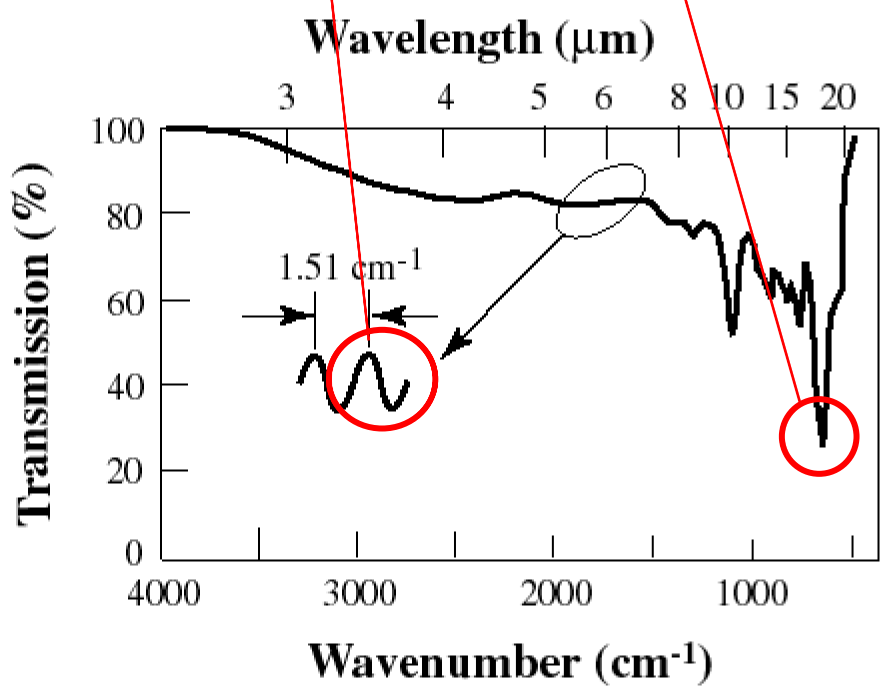
$$T = \frac{(1-R)^2}{1 + R^2 - 2R\cos\phi}$$

$$T = \frac{(1-R)^2}{1-R^2} = \frac{1-R}{1+R}$$



# Transmission

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




$$\alpha = \frac{1}{d}\ln\left(\frac{(1-R)^2+\sqrt{(1-R)^4+4T^2R^2}}{2T}\right);\ d = \frac{1}{2n_1\Delta(1/\lambda)}$$

# Thickness

- **Oscillations are determined by**

$$\cos 4\pi nd / \lambda;$$

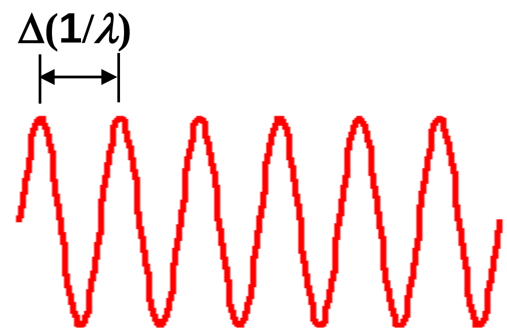
- **Has maxima at**

$$d = \frac{m\lambda_0}{2n};\ d = \frac{(m+1)\lambda_1}{2n} \ldots\ldots\ldots d = \frac{(m+i)\lambda_i}{2n}$$

$$\Rightarrow m = \frac{i\lambda_i}{\lambda_o - \lambda_i}$$

$$d = \frac{1\lambda_0\lambda_i}{2n(\lambda_0 - \lambda_i)} = \frac{i}{2n(1/\lambda_i - 1/\lambda_0)}$$

$$For\ \ i = 1: d = \frac{1}{2n(1/\lambda_1 - 1/\lambda_0)} = \frac{1}{2n\Delta(1/\lambda)}$$

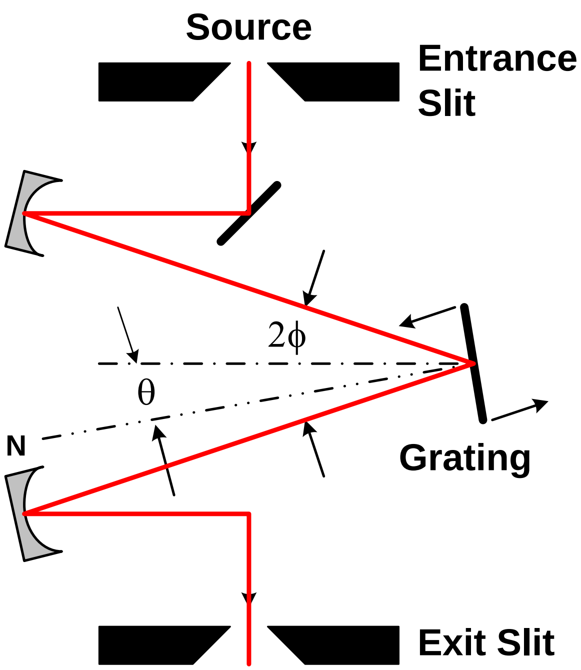



$1/\lambda$: Wave number

# Instrumentation

- Two types of instruments are used

*Monochromator*

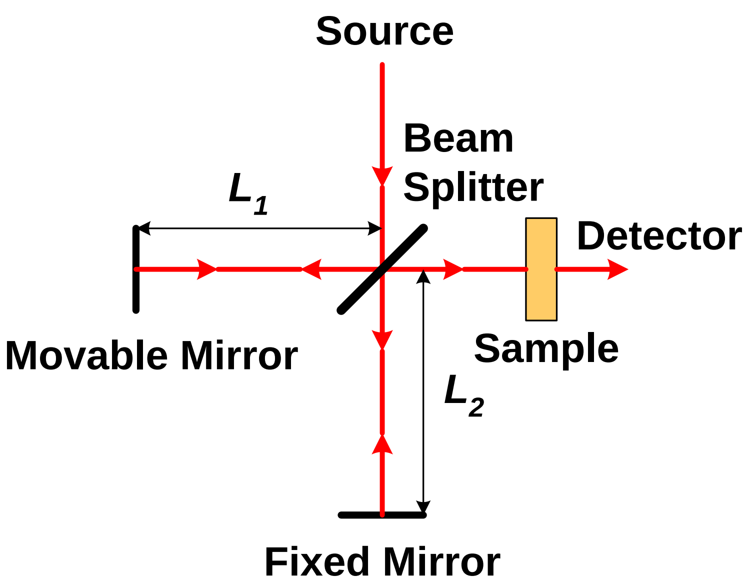



$m\lambda = 2d \sin(\theta)\cos(\phi)$

$m = 1, 2, 3$ ..;

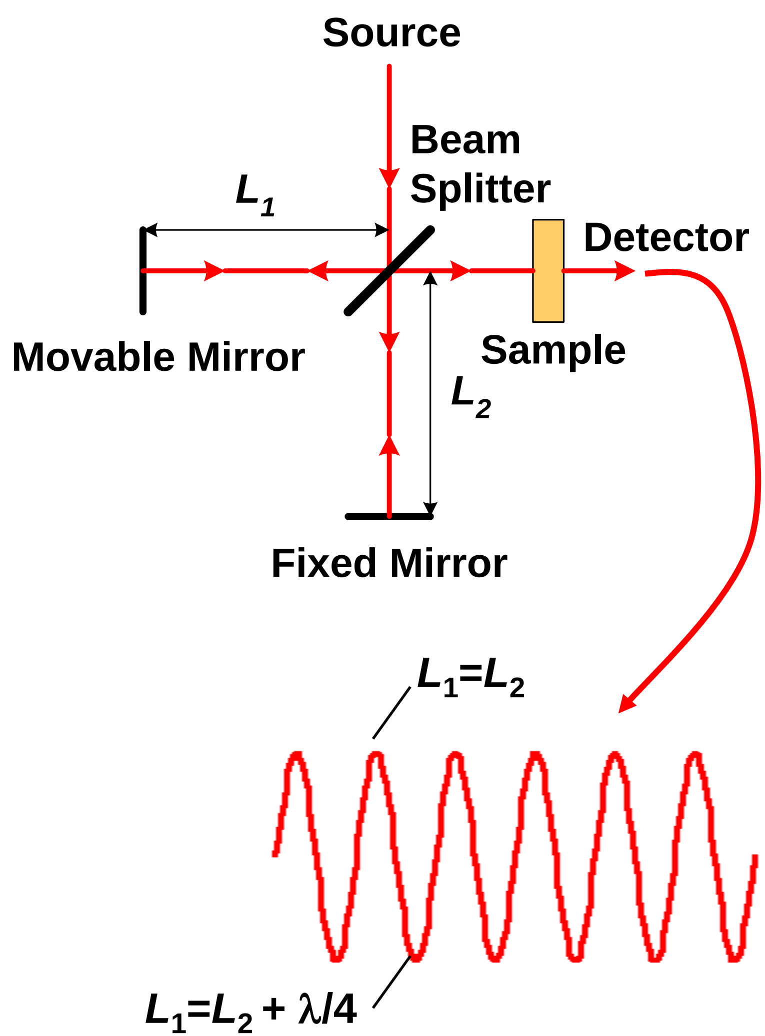
$d$ = line spacing of grating

*Interferometer*



# Interferometer

- Let source be cos2$\pi fx$
  - $f$: 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



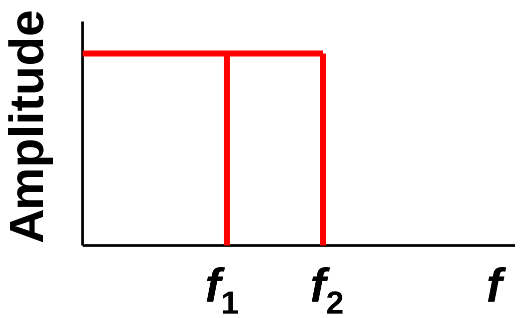
# Fourier Transform Infrared Spectroscopy

- Fourier transform infrared spectroscopy (FTIR)

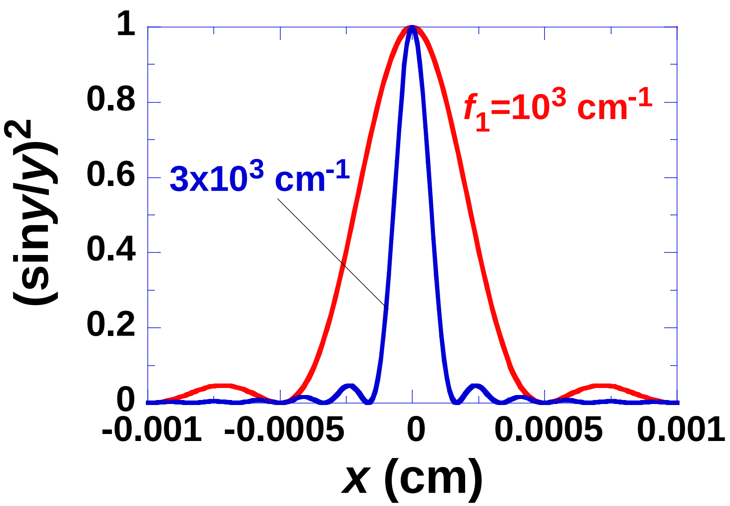
$$I(x) = B(f)[1 + \cos 2\pi x f] \qquad I(x) = \int_0^f B(f)[1 + \cos 2\pi x f]\,df$$

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

$$B(f) = \int_{-\omega}^{\omega} I(x)\cos 2\pi x f\,dx$$

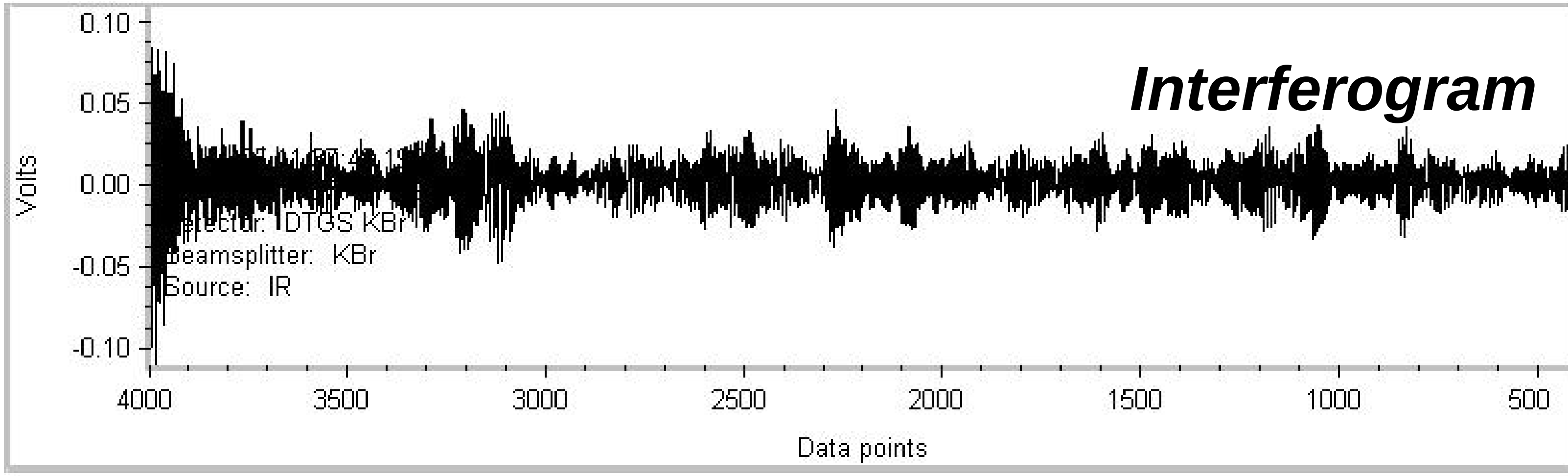


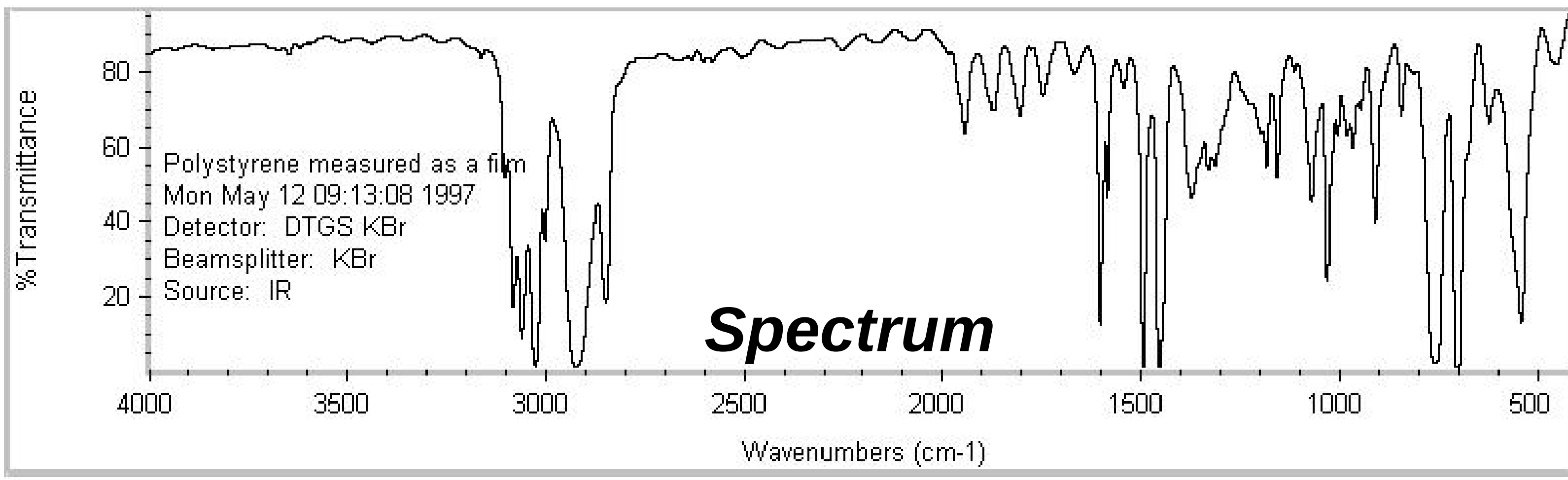

*Spectrum*




*Interferogram*

# Interferogram - Spectrum

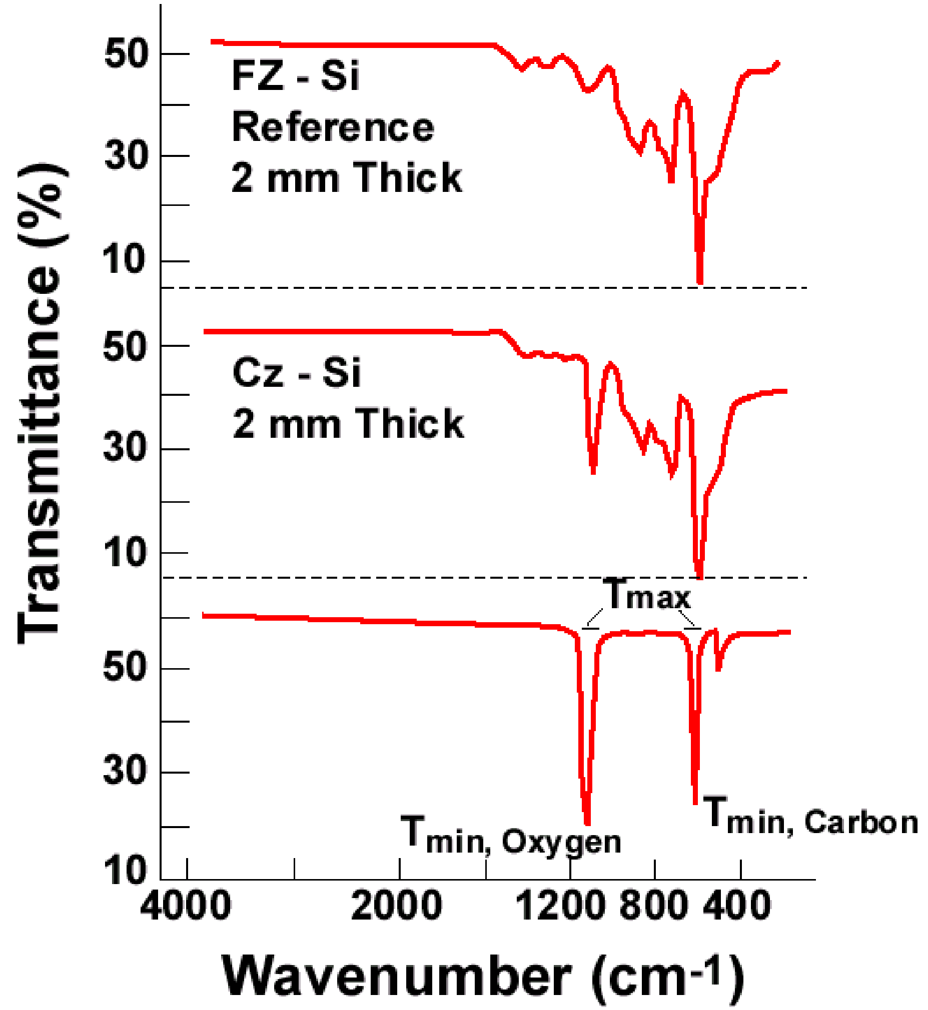



www.chem.orst.edu/ch361-464/ch362/irinstrs.htm

# FTIR Applications

- Determine oxygen and carbon density by transmission dip



# Reflection

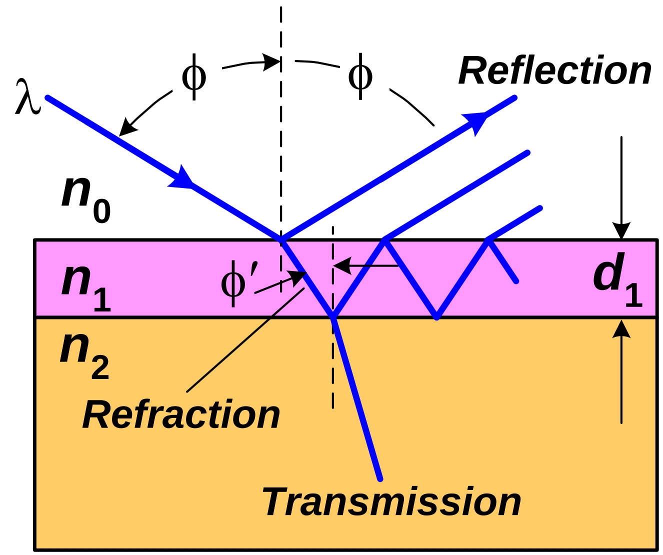
- Reflection measurements
  - Film thickness
  - Reflectivity

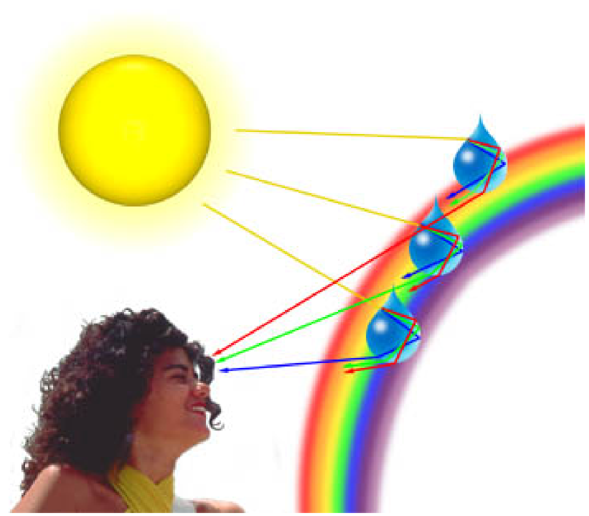
$$R = \frac{r_1^2 e^{\alpha d_1} + r_2^2 e^{-\alpha d_1} + 2 r_1 r_2 \cos\phi_1}{e^{\alpha d_1} + r_1^2 r_2^2 e^{-\alpha d_1} + 2 r_1 r_2 \cos\phi_1}$$

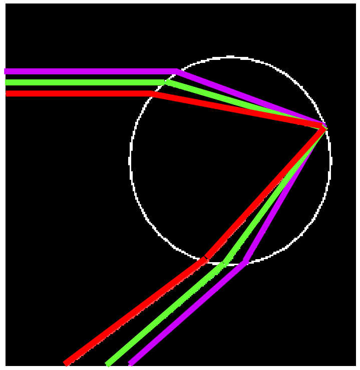
$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}; r_2 = \frac{n_1 - n_2}{n_1 + n_2}$$

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

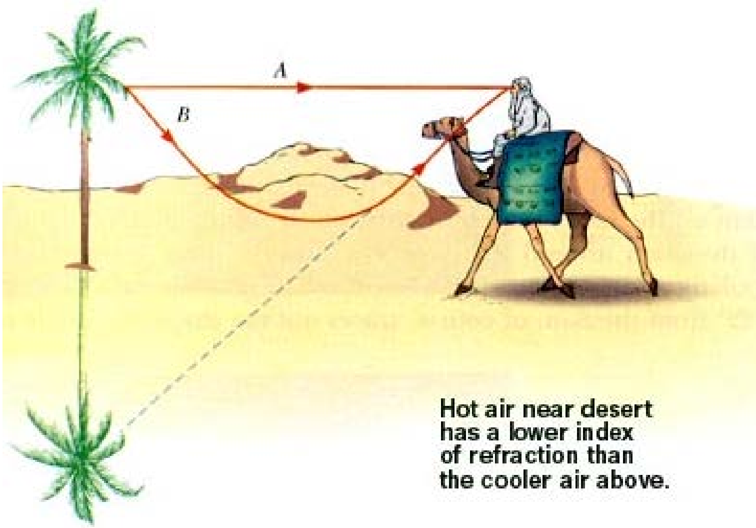
$$\phi' = \sin^{-1}\left[\frac{n_0 \sin\phi}{n_1}\right]$$



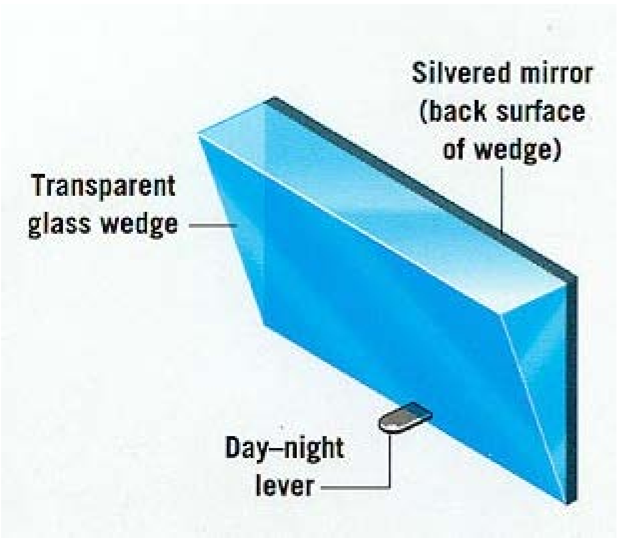



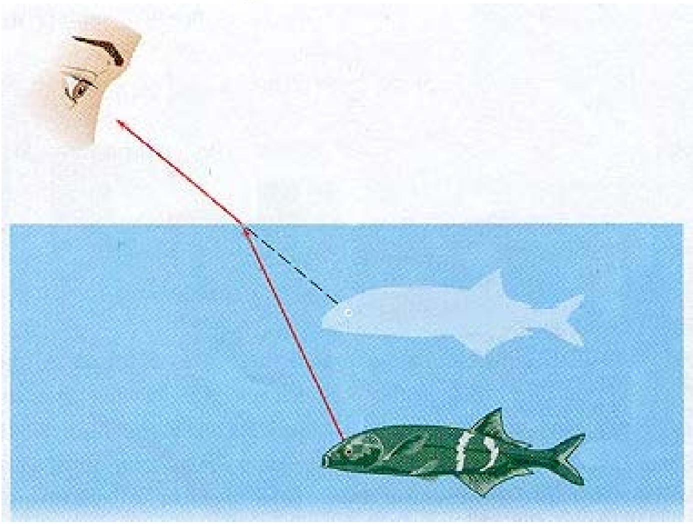


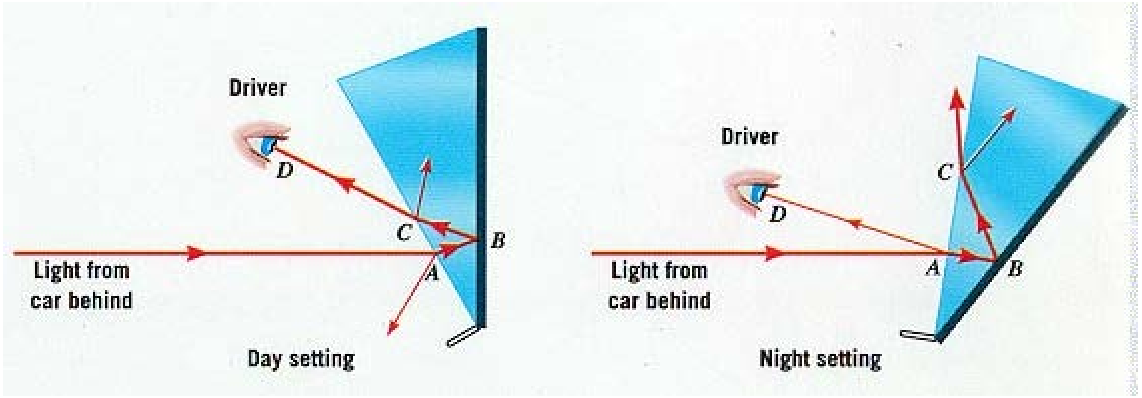
# Reflection Examples




## Rearview Mirror



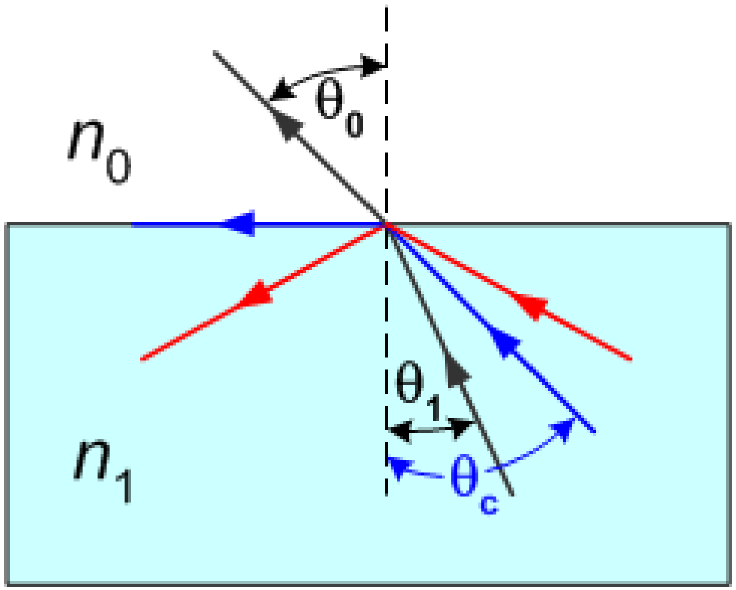






http://sol.sci.uop.edu/~jfalward/refraction/refraction.html

# 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) $\Rightarrow \theta_0 = 90°$
  - Total internal reflection




# Reflection

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

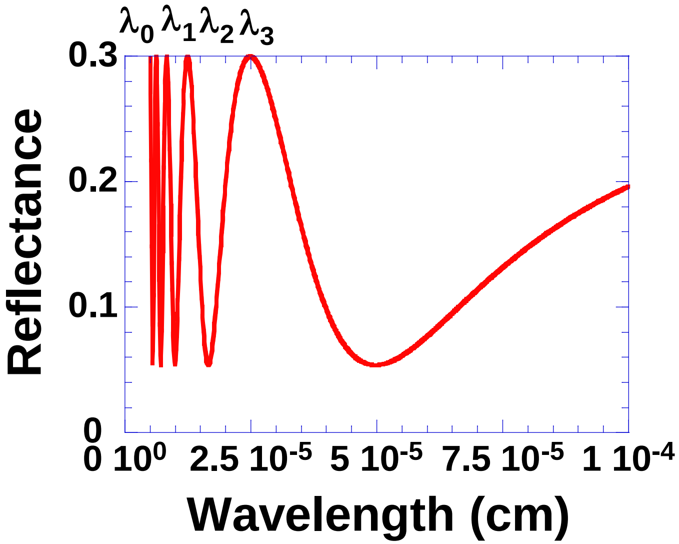
$$\lambda(\max) = \frac{2n_1 d_1 \cos\phi'}{m}$$

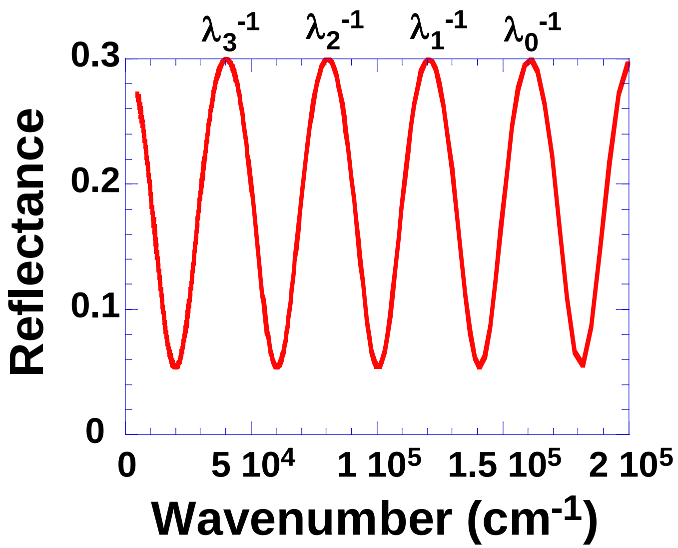
m = 1, 2, 3…

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

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

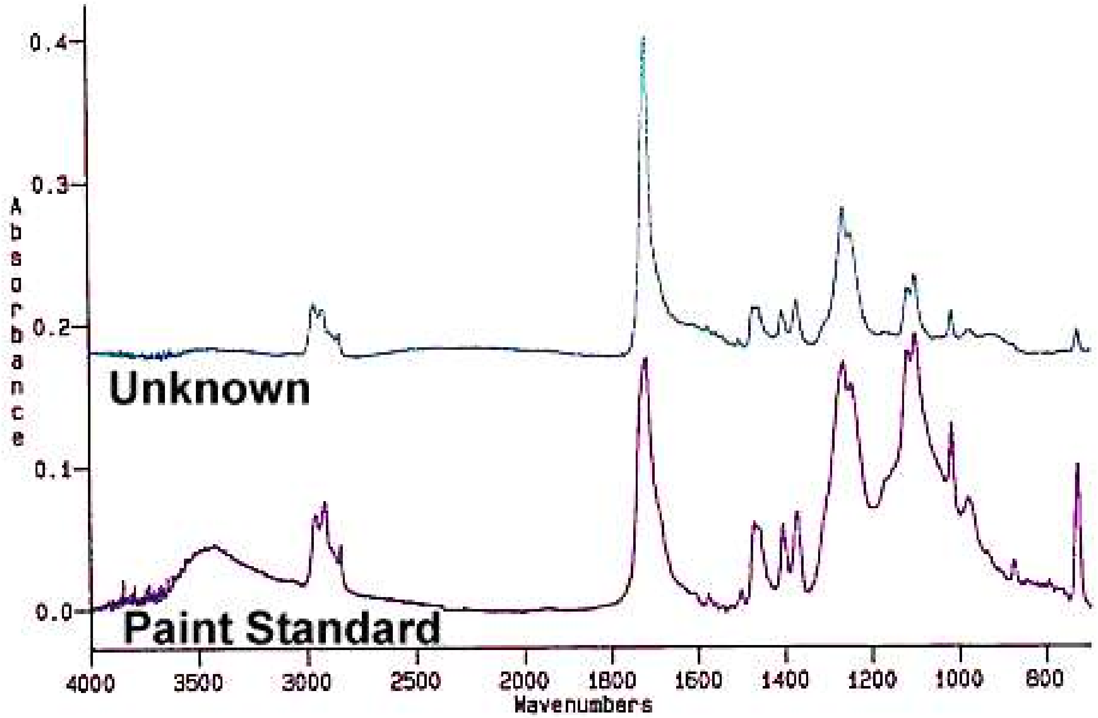
*i*: number of complete cycles from $\lambda_0$ to $\lambda_i$



# Reflection FTIR Applications

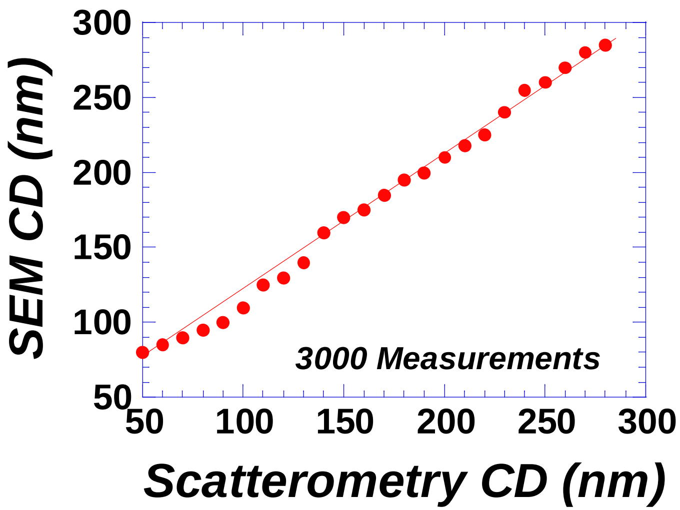
- FTIR is used in may solid state and chemical applications

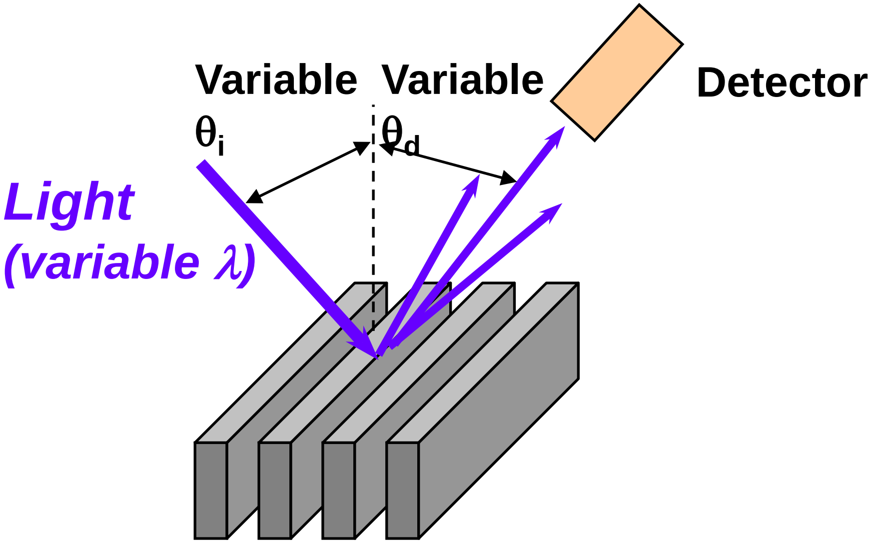



www.mee-inc.com/ftir.html#analytical

# Line Width

- Scatterometry uses scattered or diffracted light
- From diffracted signature can determine
  - Line height
  - Line width
  - Corner rounding
  - Sidewall slope/angle
- Special test structure




C.J. Raymond in *Handbook of Si Semiconductor Metrology* (A.C. Diebold, ed.) Marcel Dekker, 2001.

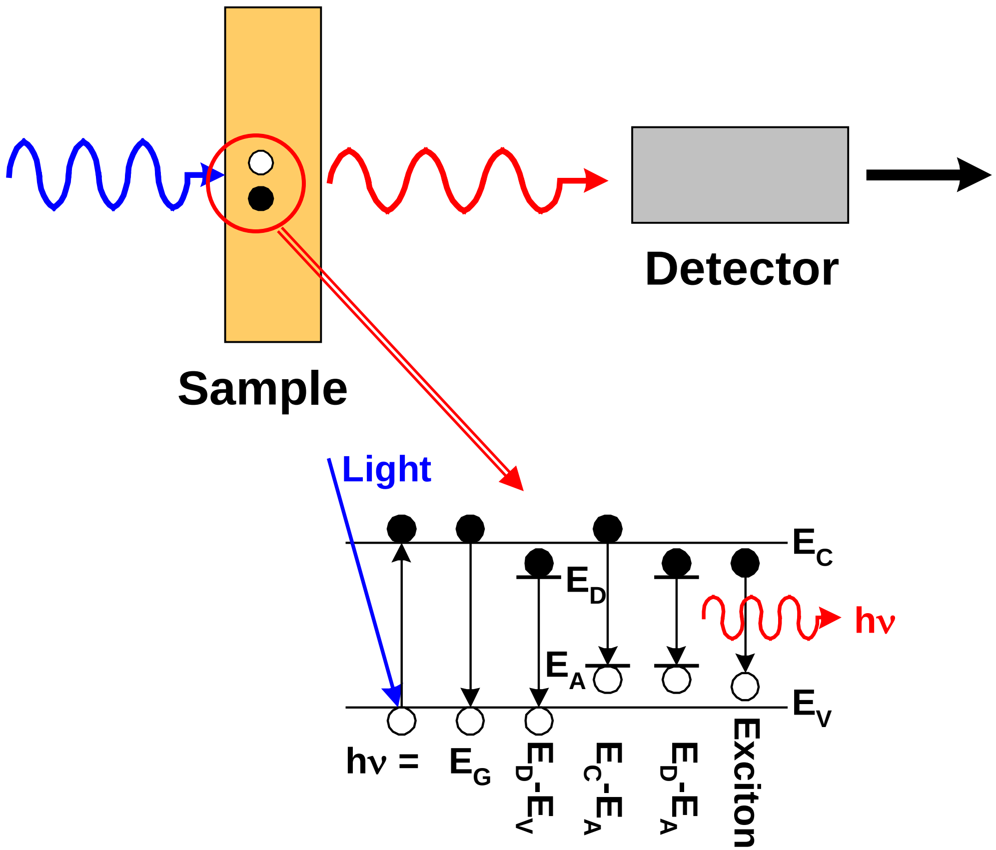
# Luminescence

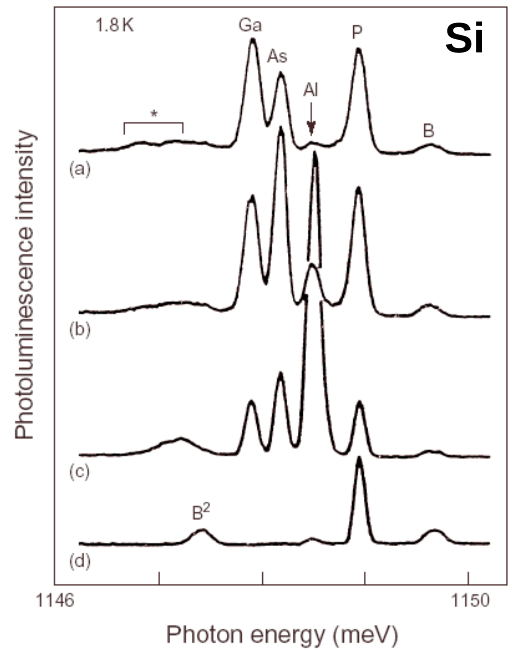
## Luminescence is the emission of light due to:

- 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

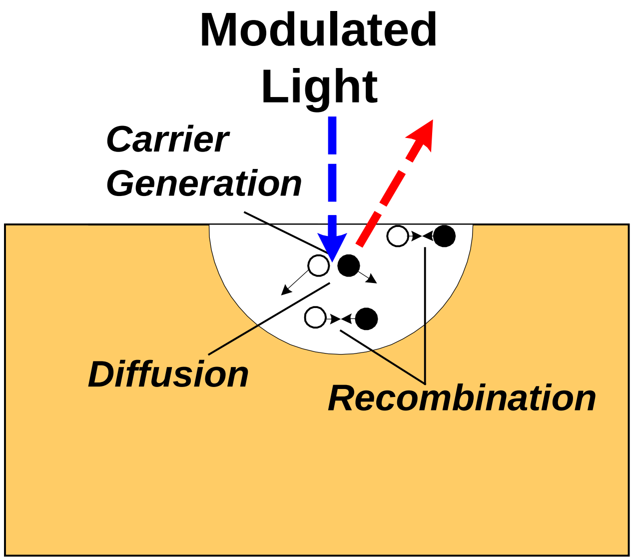


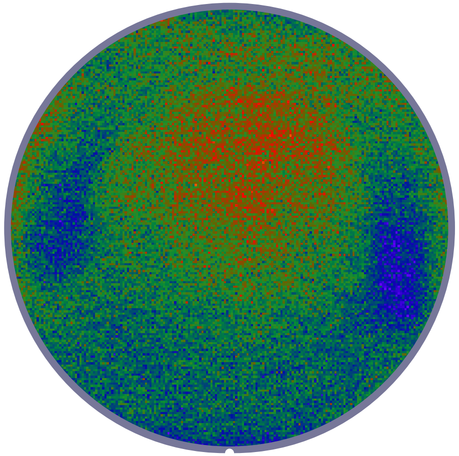
# How Does PL Work And How Can It Be Used?

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

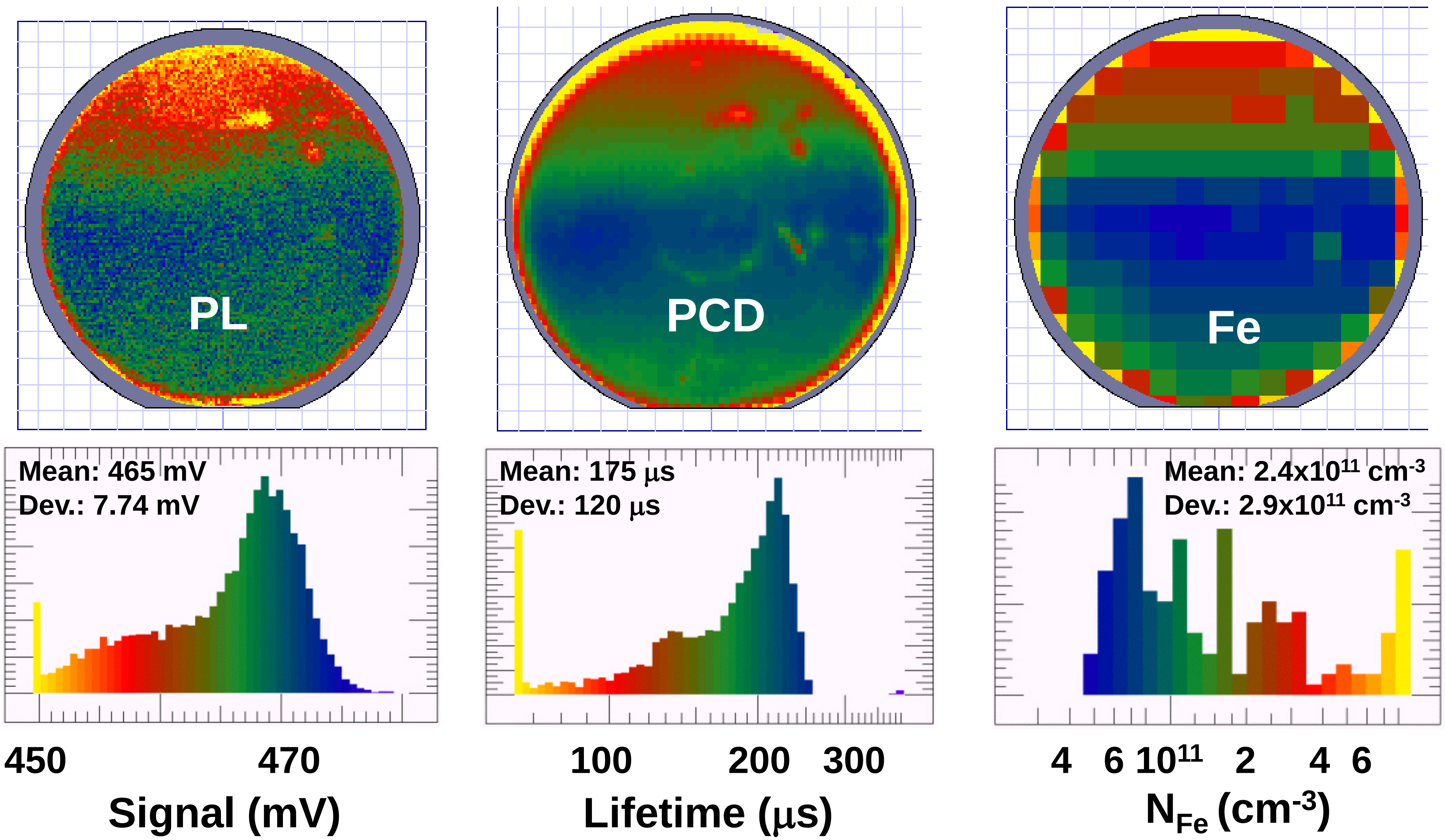
*This is what we want!*



# Depth Dependent PL Signals



# Iron In Si by PL And PCD



# 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?