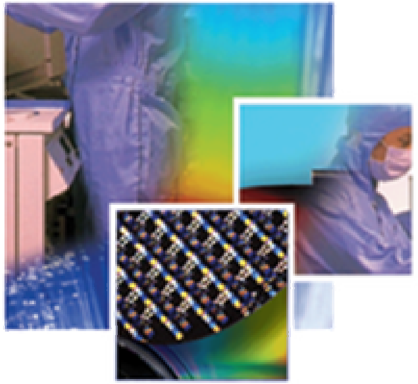

Spectroscopic Ellipsometry for Thin Film Characterization

Theory & Fundamentals

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Thin Film Division
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Tel : 01 64 54 13 00 - Fax : 01 69 74 88 61

HORIBA JOBIN YVON

PRESENTATION OVERVIEW

- Ellipsometry technique : capabilities and advantages
- Ellipsometry definition
- Light and polarization
- Optical constants
- Reflection with films
- EMA theory
- Analysis of ellipsometric data
- Phase Modulation Ellipsometer: How does it work ?
- Basic ellipsometer operations: choice of spectral range, angle of incidence

HORIBA JOBIN YVON A Global Company

- **Creation of Jobin Yvon in 1819**

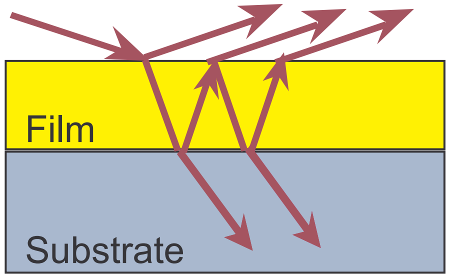
- **Leader company in spectroscopy and analytical instrumentation**
  - Headquarters: France (20 km from Paris)
  - 300 employees - 3 manufacturing plants in France
  - 5 divisions: Molecular & Micro analysis (Raman, fluorescence), elemental analysis, optical components (gratings, spectrometers, monochromators), particle size, emerging business (ellipsometry, process control, forensics)

- **1997: Jobin Yvon merged into HORIBA Group**
  - More than 4400 employees
  - Annual sales: $935,000,000
  - 5 segments: ATS, Semiconductor, P&E, Medical, Scientific

- **2004: Jobin Yvon becomes HORIBA Jobin Yvon**

General Overview of the Thin Film Division

- **Development and manufacture of optical metrology systems for**
  - ➾ Characterization of thin films, surfaces and interfaces
    - Laser and Spectroscopic Ellipsometers from FUV to NIR
    - Combined Ellipsometry and Reflectometry
  - ➾ In-situ Process Control of thin film etching and deposition
    - Laser and Polarized Interferometry
    - Optical Emission Spectroscopy

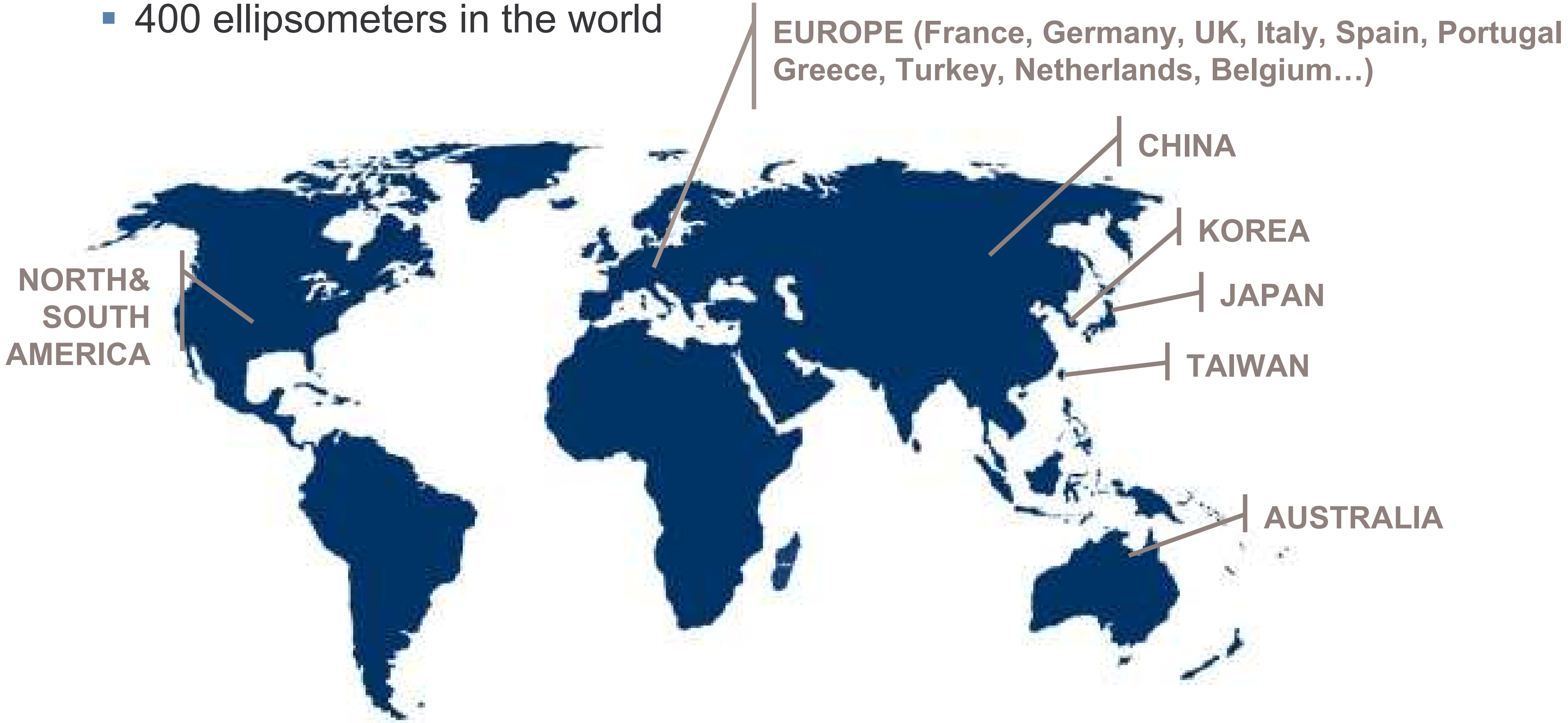


- **Thin Film Division**
  - 55 persons (sales, manufacturing, R&D)
  - Headquarters: France (20 km from Paris)
  - 4 application laboratories worldwide (USA, France, Germany, Japan)

Welcome to

User Profile of HORIBA Jobin Yvon Ellipsometer

- Universities – R&D: 65 %
- Industry: 35 %
- 400 ellipsometers in the world



ELLIPSOMETRY CAPABILITIES

Characterization of thin films, surface and interface

▪ Thickness

- Accurate thin film measurement from a few angstroms to several tens of microns
- Characterization of single layer and complex multilayer stacks
- Characterization of surface and interface

▪ Optical properties

- Refractive index (n) and extinction coefficient (k) from the far-UV to near-IR for complex materials, graded and anisotropic layers

▪ Material properties

- Alloy composition
- Microstructure and crystallinity
- Optical bandgap (Eg)
- Film uniformity by area and depth

Advantages of the Spectroscopic Ellipsometry Technique

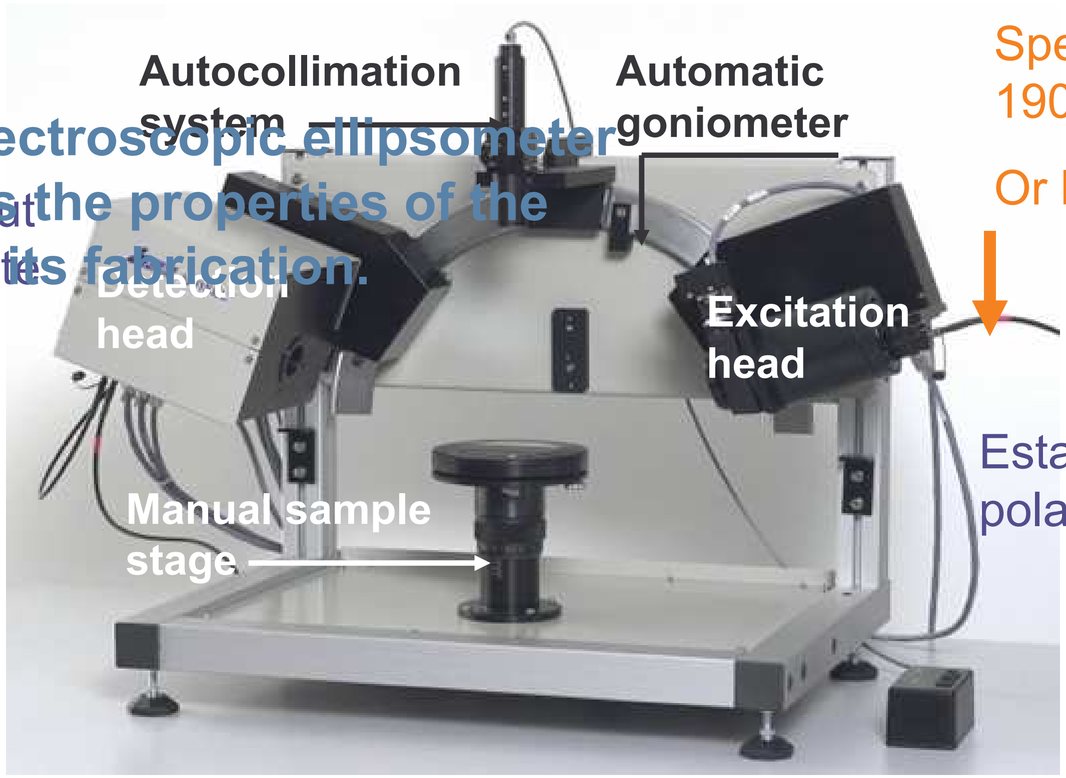
- Non-destructive & contacless technique
- Highly accurate & reproducible
- Can be used in any transparent and semi-transparent medium
- Very sensitive, especially to ultra-thin films (< 10 nm)
- Spectroscopic measurement: wide spectral range from FUV to NIR
- Simultaneous multiple parameter determination
- Mapping – 2D and 3D cartography
- Pattern measurements

Ellipsometer Optical Set up

Light — **Polarizer** — **Sample** — **Analyzer** — **Detector**

- ⇨ **Ex-situ spectroscopic ellipsometer characterizes the properties of the sample after its fabrication.**

Measures output polarization state



Scanning monochromator or CCD

Spectroscopic ~ 190 – 2000 nm

Or laser 633 nm

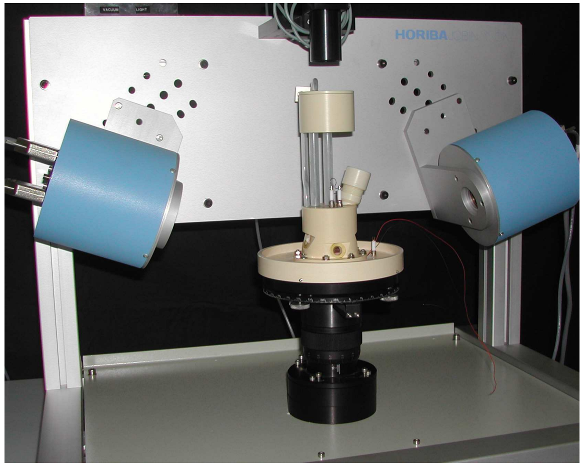
Establishes a linear polarization

The light interacts with the sample and reflects from it. This interaction causes a polarization change of the light.

In Situ Ellipsometry

Real-time monitoring of thin film deposition with submonolayer resolution

- May be mounted on any process chamber with entrance & exit window
- Real-time calculation of thickness & refractive index of deposited/etched layers



- Accessories: liquid cell, electrochemical cell, thermostated sample stage
- Kinetic measurement of surface modifications during the process

⇨ In-situ ellipsometry provides the advantage to probe the fabricated structures, to investigate the surface modifications during the process.

Ellipsometry Definition

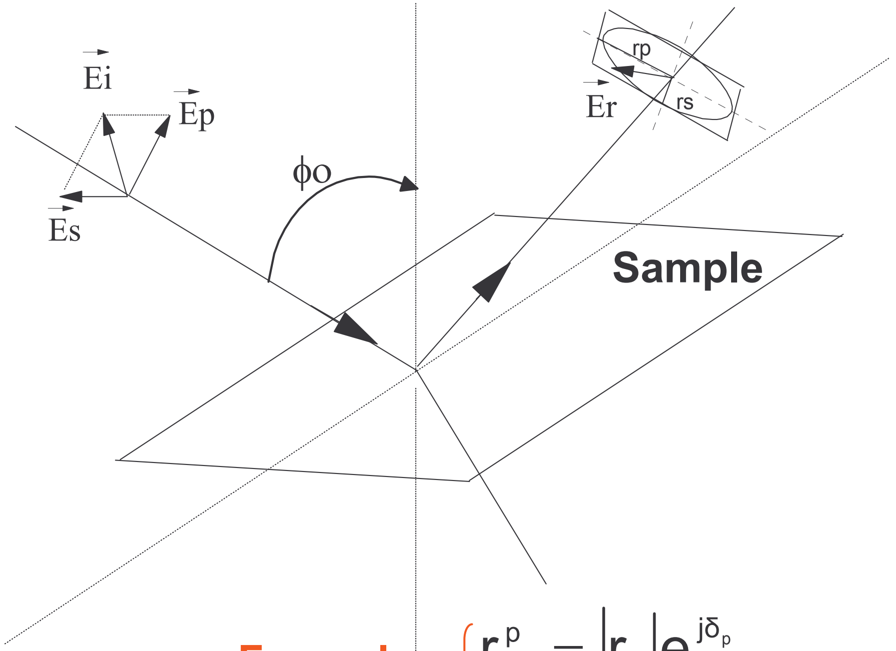
- **Ellipsometry is an optical technique that measures the change in the polarization state of light reflected from the surface of a sample.**

$$\frac{r_p}{r_s} = \rho = \tan\psi \exp(i\Delta)$$

> Ψ and Δ : Ellipsometric angles
Measured data

> $\tan\psi = \frac{|r_p|}{|r_s|}$: Amplitude ratio

> $\Delta = \delta_p - \delta_s$: Phase shift introduced by reflection from sample



Fresnel reflection coefficients

$$\begin{cases} r_{01}^{p} = |r_p| e^{j\delta_p} \\ r_{01}^{s} = |r_s| e^{j\delta_s} \end{cases}$$

Ellipsometry Measurements

Advantages

- **Measure ratio of two parameters**
  - Repeatable & accurate
  - No reference necessary
  - Reduced problems of source fluctuation

↳ Ellipsometry vs Reflectivity

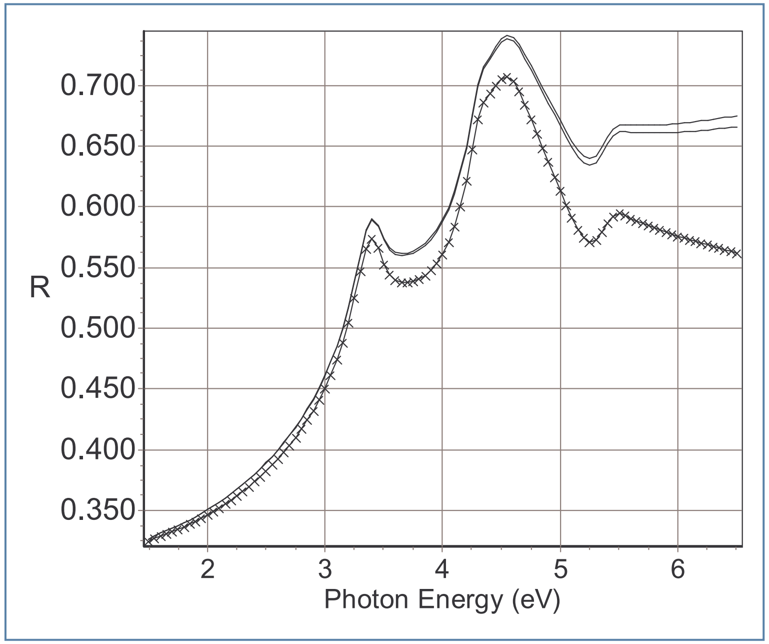
- **Measure a phase Δ**
  - Very sensitive to film thickness (<10 nm)

- **Spectroscopic Ellipsometry**
  - Allows multiple film parameter characterization
  - Eliminates period problem for thick films
  - Measures data at wavelength of interest

↳Spectroscopic vs Laser Ellipsometry

Ellipsometry vs Reflectivity

➩ **Phase (Δ parameter) information measured by ellipsometer gives much higher sensitivity to ultra-thin films**

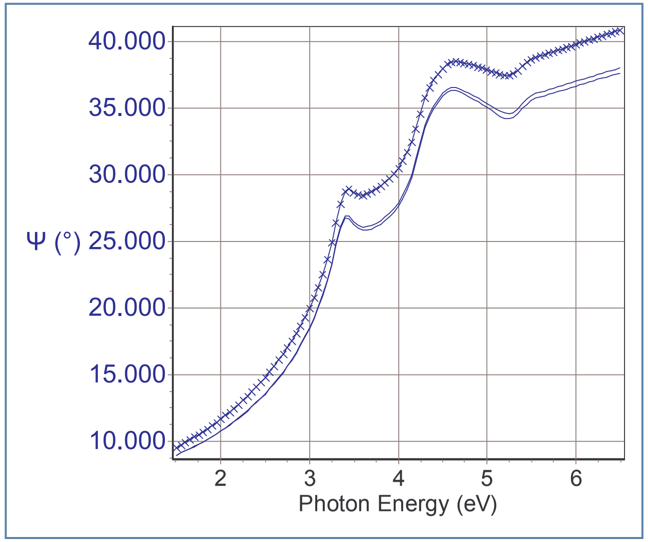


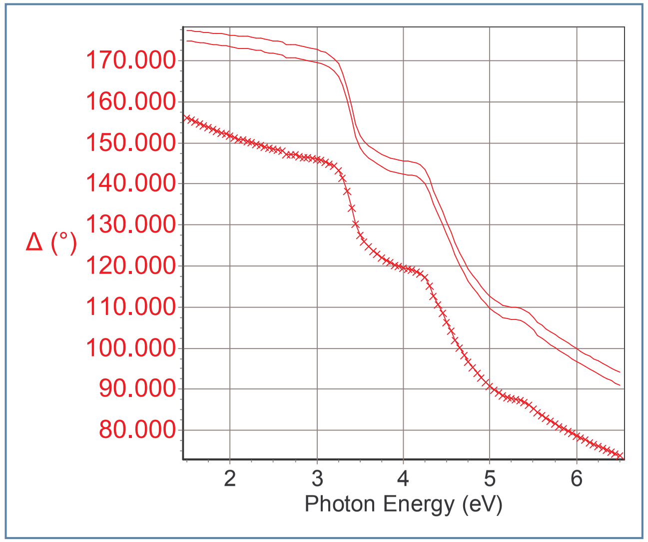
1 nm ———

2 nm - - - - - - -

10 nm —x—

Oxide on c-Si

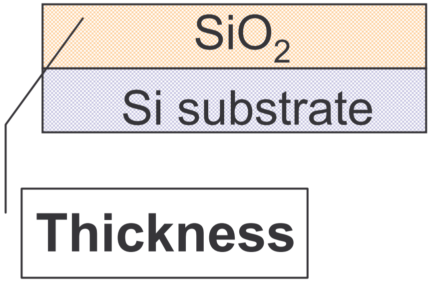


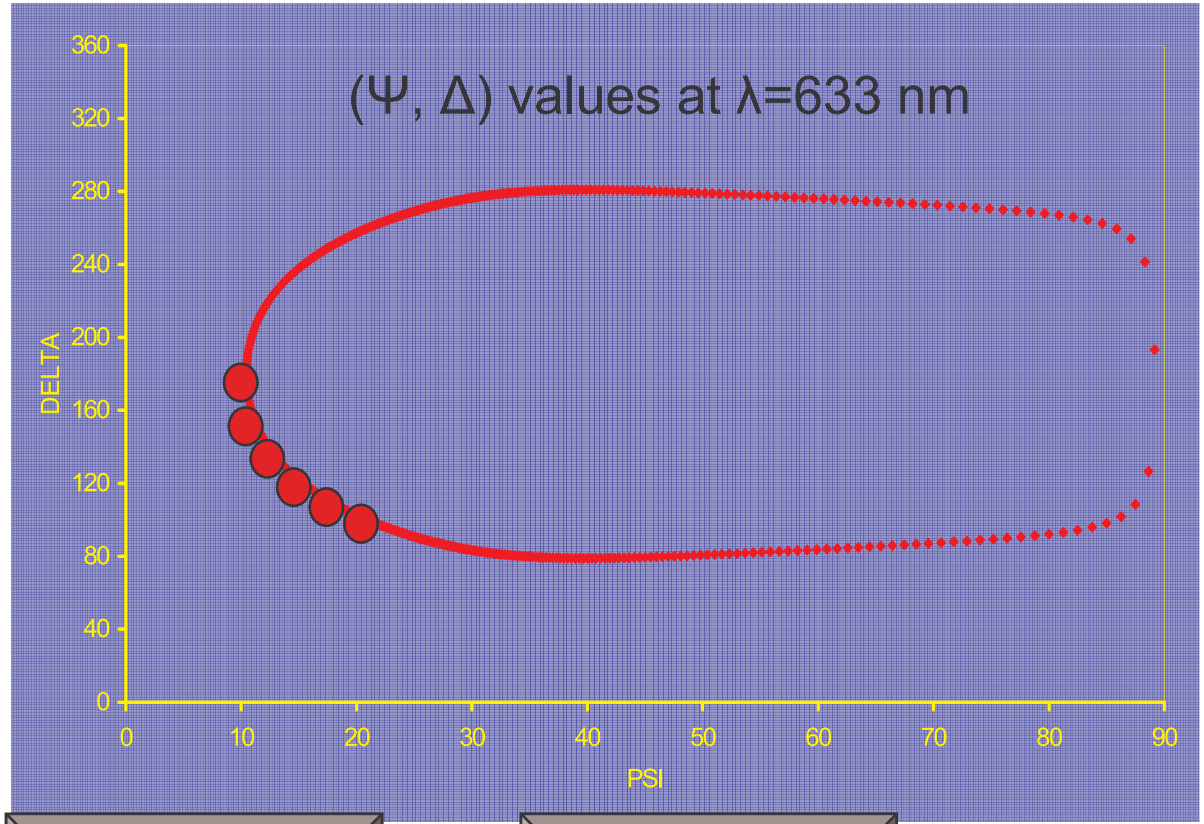


Spectroscopic Ellipsometry vs Laser Ellipsometry

⇨ **Data cycle as film thickness increases**

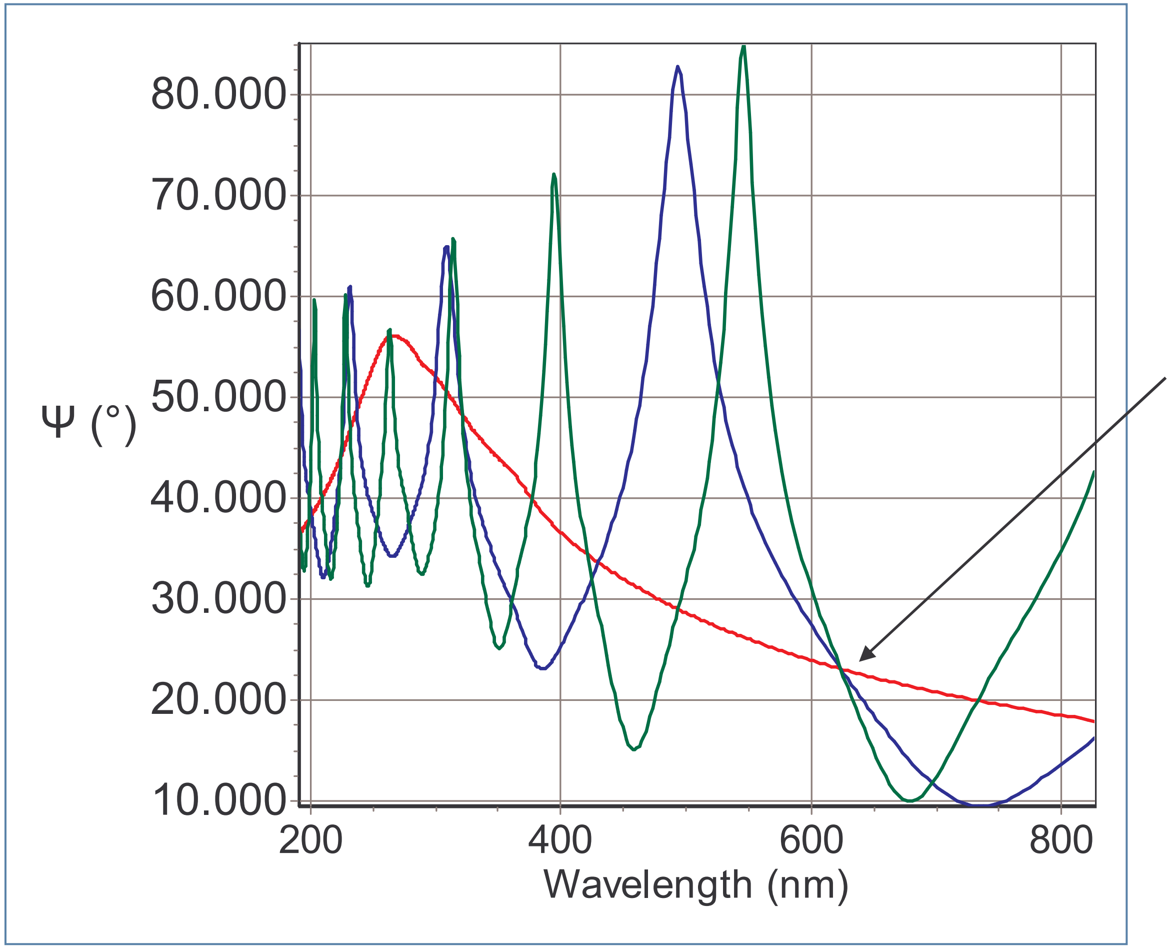
$$D_{\phi} = \frac{\lambda}{2\sqrt{\tilde{n}_1^2 - \tilde{n}_0^2 \sin^2 \phi}}$$





500 Å or **3300 Å** or **6100 Å** or…..

Spectroscopic Ellipsometry vs Laser Ellipsometry



- **Vary wavelength**
  - Probe different (n,k)
  - Thickness constant

Data match at 633 nm

Interaction of Light with Matter

- **Description of light as an electromagnetic plane wave**
  - Derives from Maxwell's equations
  - Consists of an electric and magnetic field vector oscillating perpendicularly to the direction of propagation

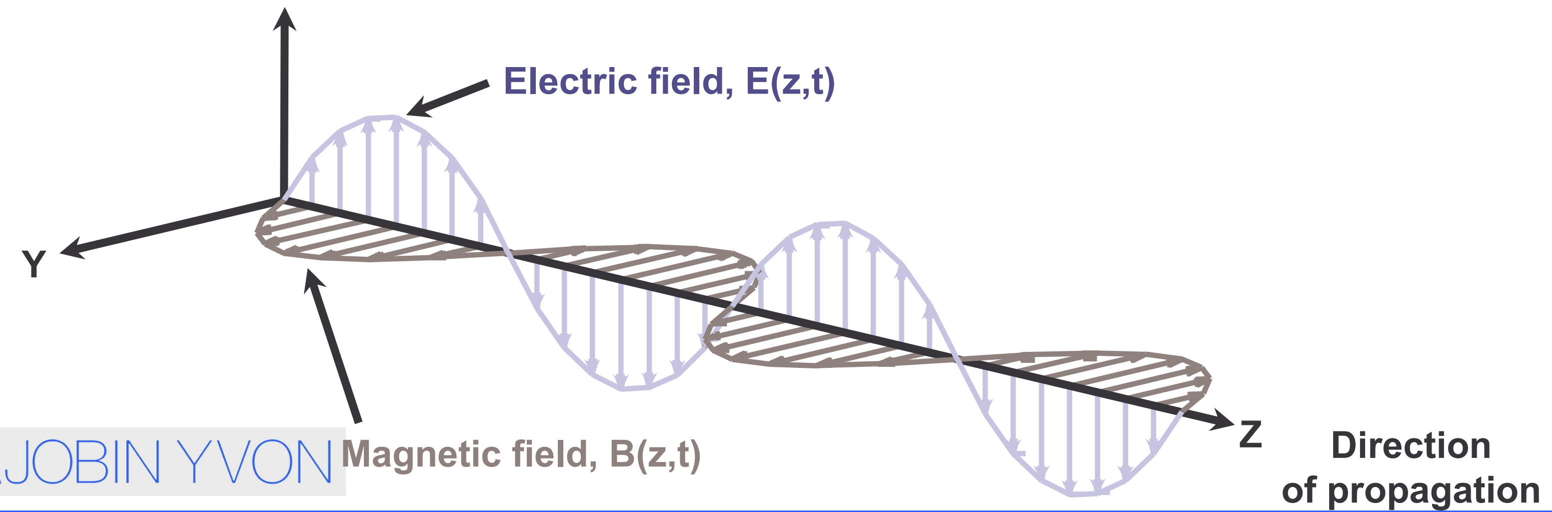
$$E = Re\left[E_0 \exp i(wt - k.r + \phi)\right]$$

amplitude

phase

frequency $2\pi f = \frac{2\pi\lambda}{c}$

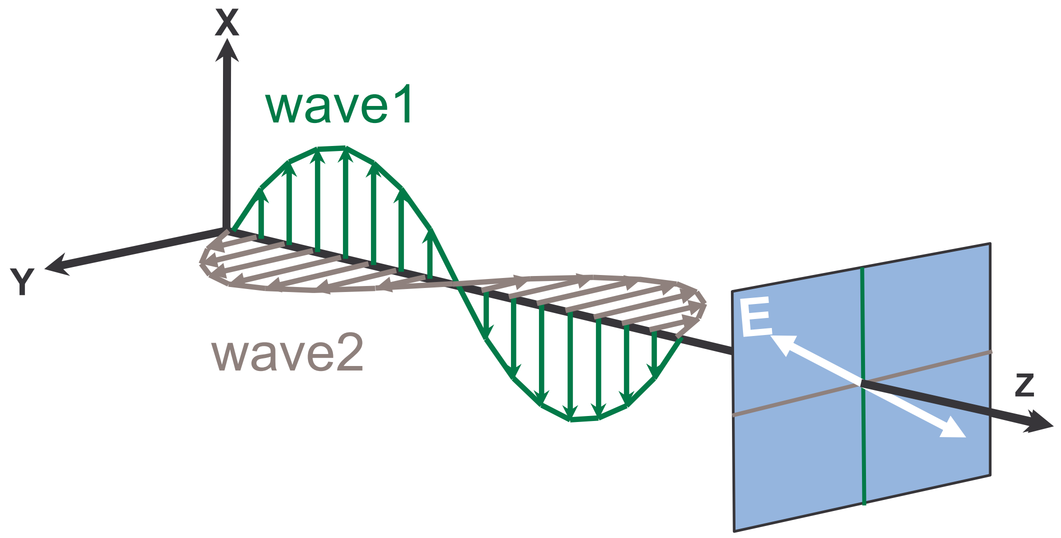
propagation vector $\frac{2\pi}{\lambda}z$



Light Polarization

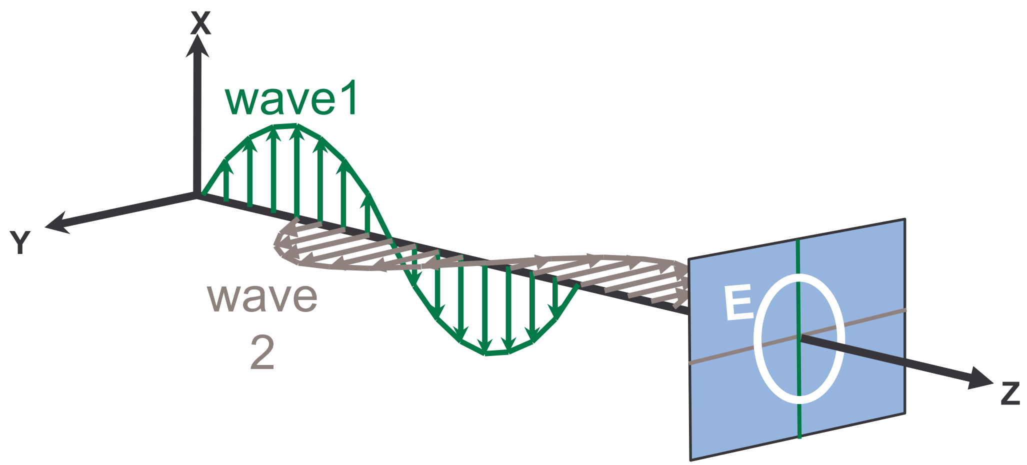
- **Polarization State**
  - Defined by 2 parameters: phase & amplitude of the electric field
  - Describes the direction of the electric field

- **3 Polarization States**
  - Linear polarization
    - > Orthogonal E_x & E_y propagating in same direction
    - > Waves are in phase with each others



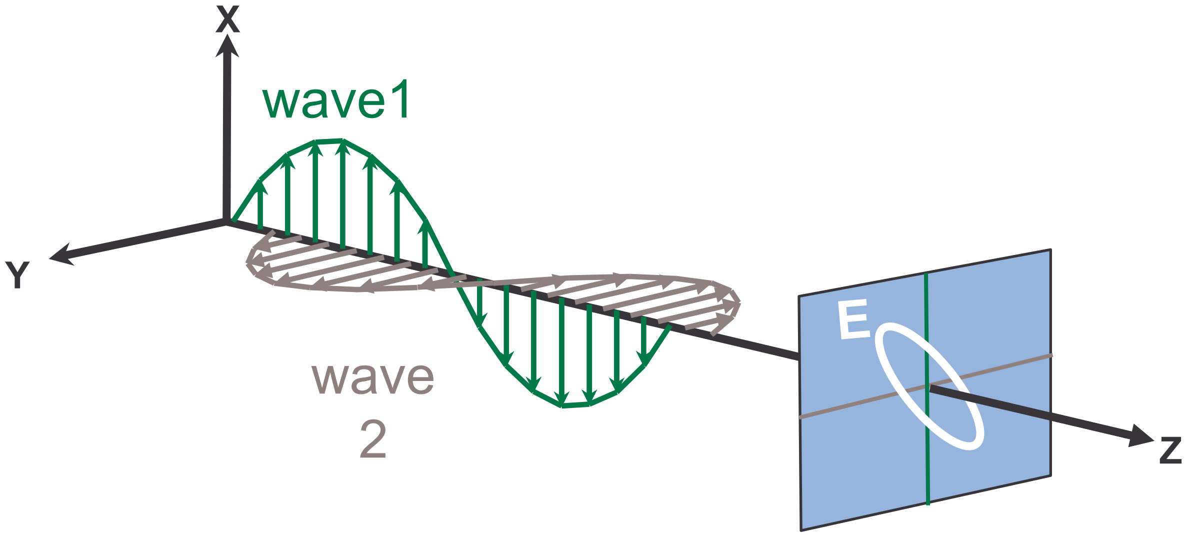
Light Polarization

- **3 Polarization States**
  - Circular polarization
    - > Orthogonal E_x & E_y are 90° out of phase
    - > Equal amplitude



Light Polarization

- **3 Polarization States**
  - Elliptical polarization
    - > Orthogonal E_x and E_y have different phase and amplitude



Electromagnetic Spectrum

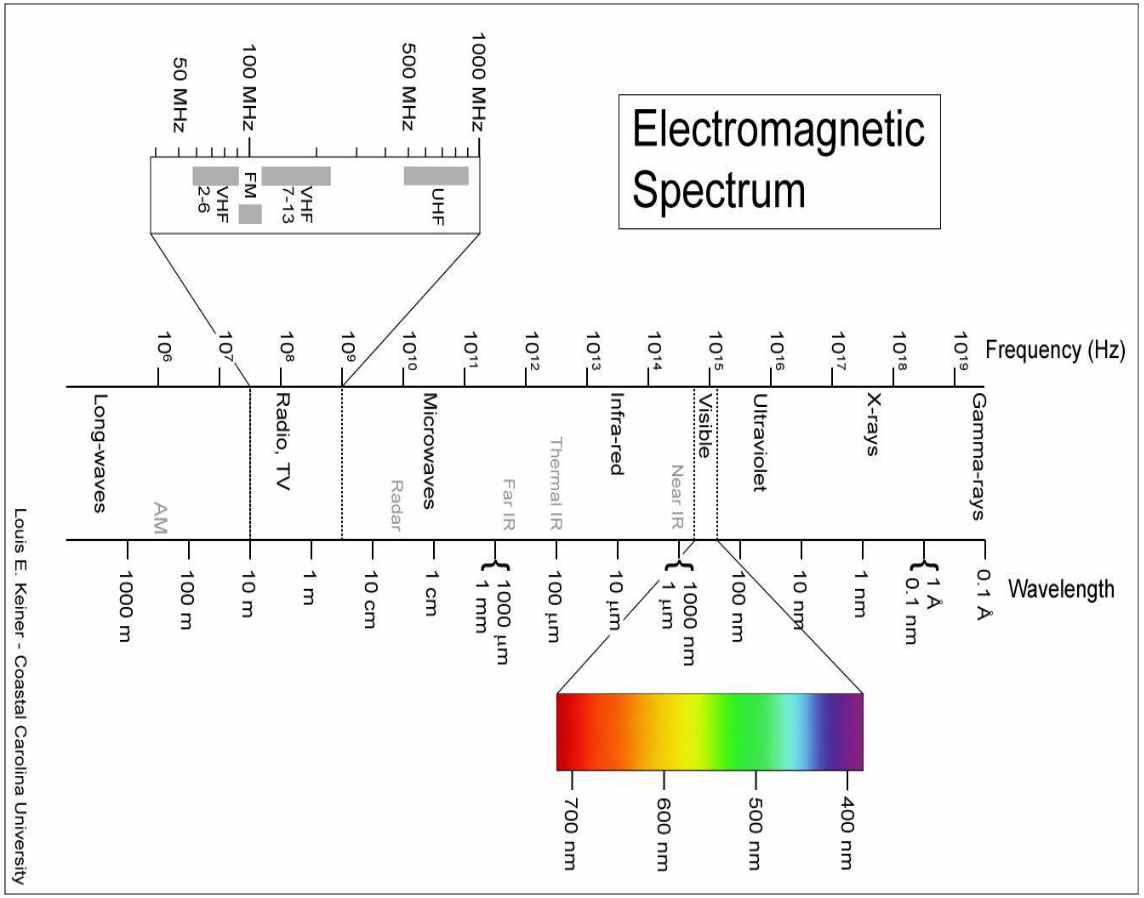
- **Wavelengths units**
  - Wavelength (λ)
  - Photon energy (eV)
  - Wavenumber (K)

- **Relationships**

$$E(eV) = h\upsilon = \frac{1240}{\lambda(nm)}$$

E(nm) = E(microns) x 1000

$$\lambda(\mu m) = \frac{10000}{K(cm^{-1})}$$



Louis E. Keiner - Coastal Carolina University

What are optical constants ?

- 2 parameters used to describe the interaction of light with matter

- Complex Index of refraction : $\tilde{N} = n - ik$

- Complex dielectric constant : $\tilde{\varepsilon} = \varepsilon_1 - i\varepsilon_2$

$$\left.\begin{matrix} \tilde{N} = n - ik \\ \tilde{\varepsilon} = \varepsilon_1 - i\varepsilon_2 \end{matrix}\right\} \tilde{\varepsilon} = \tilde{N}^2$$

And
$n^2 - k^2 = \varepsilon_1$
$2nk = \varepsilon_2$

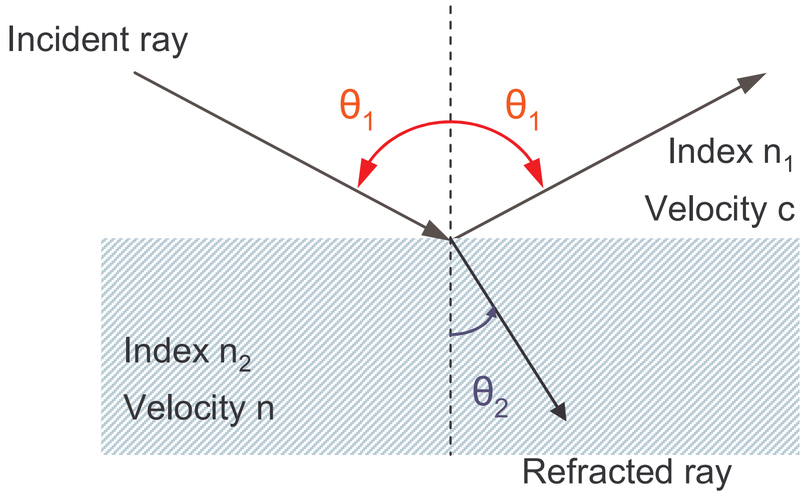
- Ratio of the velocity of light in vacuum (c) to its velocitity (v) in the medium

  - Refractive index (or index of refraction) : $n = c/v$

- Amount of absorption loss when light propagates through the material

  - Extinction coefficient : k

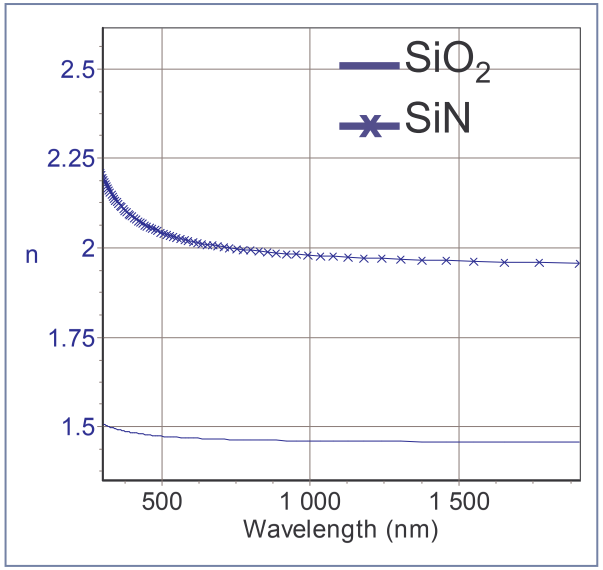
- Absorption coefficient $\alpha = \dfrac{4\pi k}{\lambda}$



Optical Constants

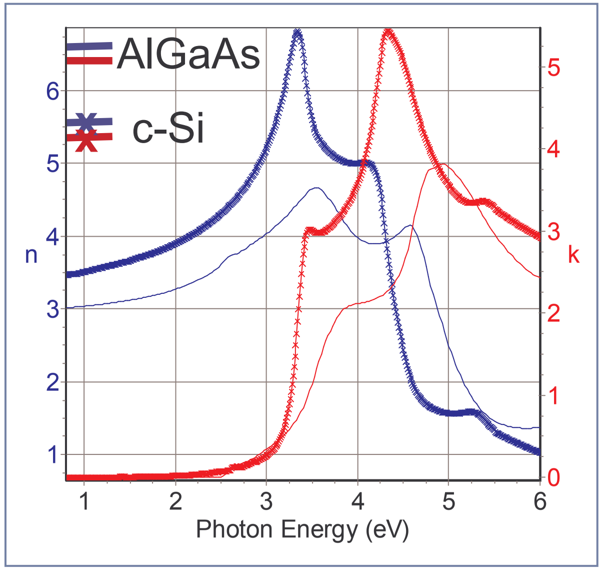
- Depend on properties of the material
- Depend on wavelength range measured

Dielectric or insulator



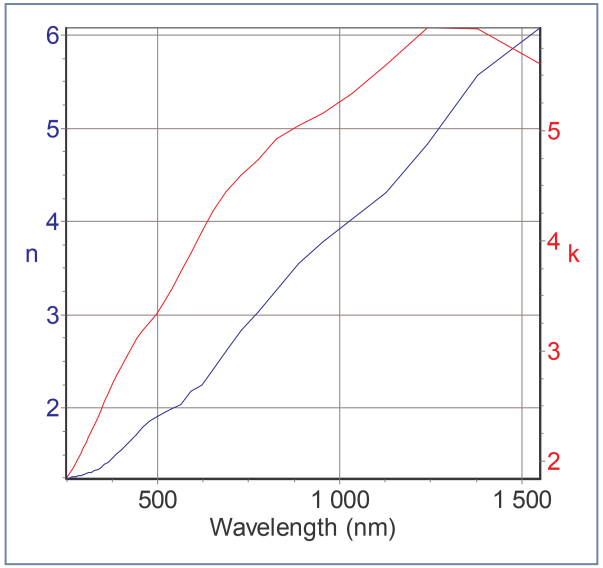
Transparent in the NIR-VIS

Semiconductor



Opaque in the VIS

Metal



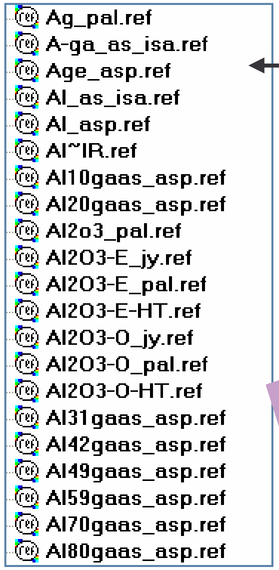
Highly absorbing in the NIR

Optical Constants

- Representing the (n,k) of the material in the ellipsometric model

  ➪ **Tabulated references**

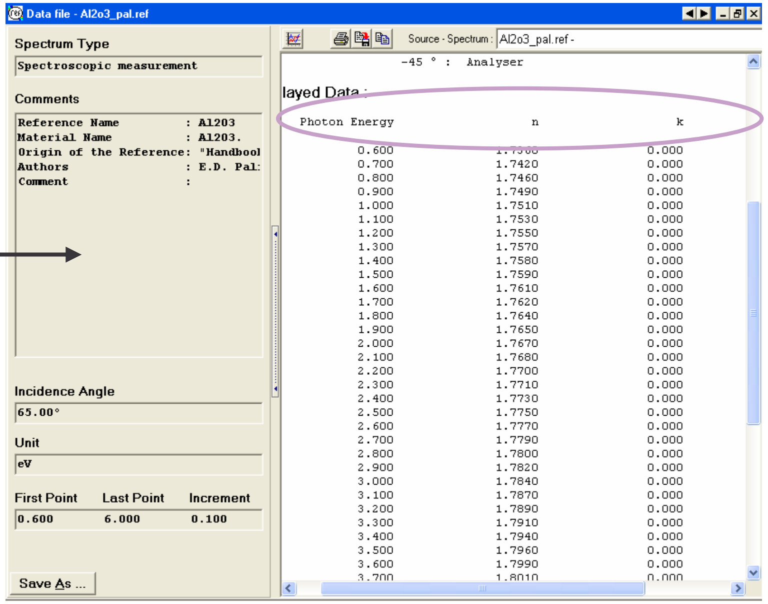
  – No variation, fixed (n,k) values, often used as a starting values



```
Ag_pal.ref
A-ga_as_isa.ref
Age_asp.ref
Al_as_isa.ref
Al_asp.ref
Al~IR.ref
Al10gaas_asp.ref
Al20gaas_asp.ref
Al2o3_pal.ref
Al2O3-E_jy.ref
Al2O3-E_pal.ref
Al2O3-E-HT.ref
Al2O3-O_jy.ref
Al2O3-O_pal.ref
Al2O3-O-HT.ref
Al31gaas_asp.ref
Al42gaas_asp.ref
Al49gaas_asp.ref
Al59gaas_asp.ref
Al70gaas_asp.ref
Al80gaas_asp.ref
```

Library of >100 materials

List of (n,k) values with wavelengths



Spectrum Type: Spectroscopic measurement

Comments

```
Reference Name         : Al203
Material Name          : Al203.
Origin of the Reference: "Handbool
Authors                : E.D. Pal:
Comment                :
```

Incidence Angle: 65.00°

Unit: eV

First Point	Last Point	Increment
0.600	6.000	0.100

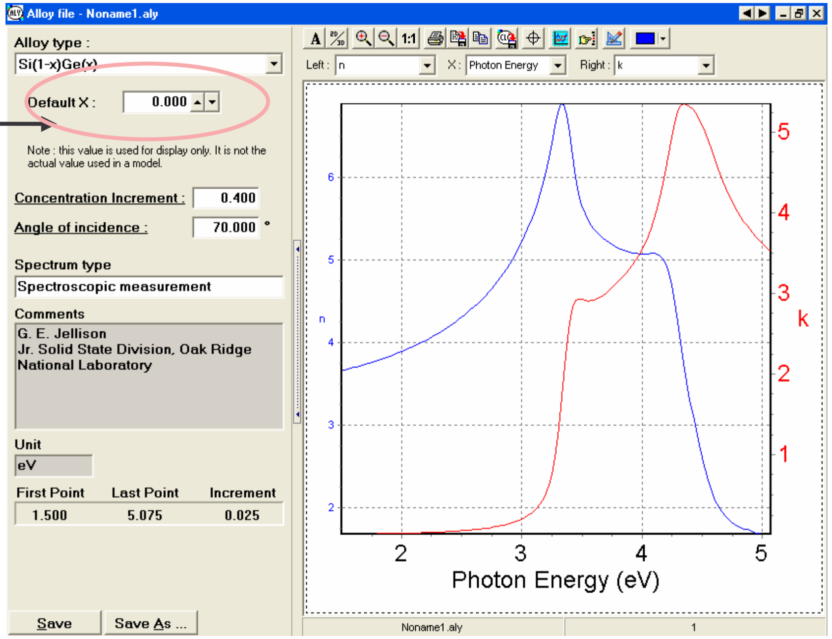
```
          -45 ° :  Analyser

layed Data :
 Photon Energy          n            k
        0.600       [illegible]      0.000
        0.700       1.7420       0.000
        0.800       1.7460       0.000
        0.900       1.7490       0.000
        1.000       1.7510       0.000
        1.100       1.7530       0.000
        1.200       1.7550       0.000
        1.300       1.7570       0.000
        1.400       1.7580       0.000
        1.500       1.7590       0.000
        1.600       1.7610       0.000
        1.700       1.7620       0.000
        1.800       1.7640       0.000
        1.900       1.7650       0.000
        2.000       1.7670       0.000
        2.100       1.7680       0.000
        2.200       1.7700       0.000
        2.300       1.7710       0.000
        2.400       1.7730       0.000
        2.500       1.7750       0.000
        2.600       1.7770       0.000
        2.700       1.7790       0.000
        2.800       1.7800       0.000
        2.900       1.7820       0.000
        3.000       1.7840       0.000
        3.100       1.7870       0.000
        3.200       1.7890       0.000
        3.300       1.7910       0.000
        3.400       1.7940       0.000
        3.500       1.7960       0.000
        3.600       1.7990       0.000
        3.700       1.8010       0.000
```

Optical Constants

- Representing the (n,k) of the material in the ellipsometric model
  - ➩ **Compound alloy semiconductor references**
    - – Known variation

Adjust the composition and generate the (n,k)



Alloy file - Noname1.aly

Alloy type : Si(1-x)Ge(x)

Default X : 0.000

Note : this value is used for display only. It is not the actual value used in a model.

Concentration Increment : 0.400

Angle of incidence : 70.000 °

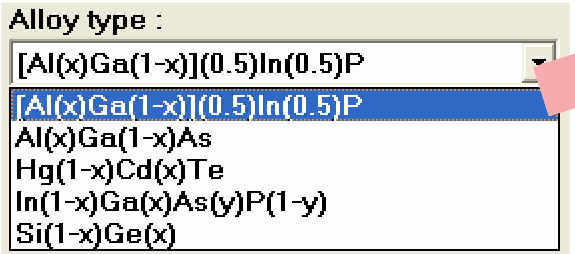
Spectrum type: Spectroscopic measurement

Comments:
G. E. Jellison
Jr. Solid State Division, Oak Ridge
National Laboratory

Unit: eV

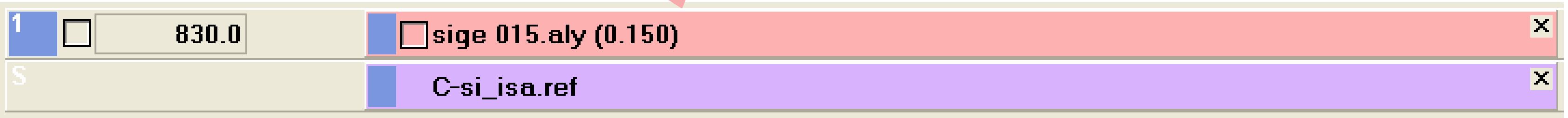
First Point	Last Point	Increment
1.500	5.075	0.025

Library of 5 semiconductor alloys



Alloy type : [Al(x)Ga(1-x)](0.5)In(0.5)P

- [Al(x)Ga(1-x)](0.5)In(0.5)P
- Al(x)Ga(1-x)As
- Hg(1-x)Cd(x)Te
- In(1-x)Ga(x)As(y)P(1-y)
- Si(1-x)Ge(x)



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Optical Constants

- Representing the (n,k) of the material in the ellipsometric model

  ⇨ **Dispersion relationships**

  – Build « by yourself » the (n,k) of your material

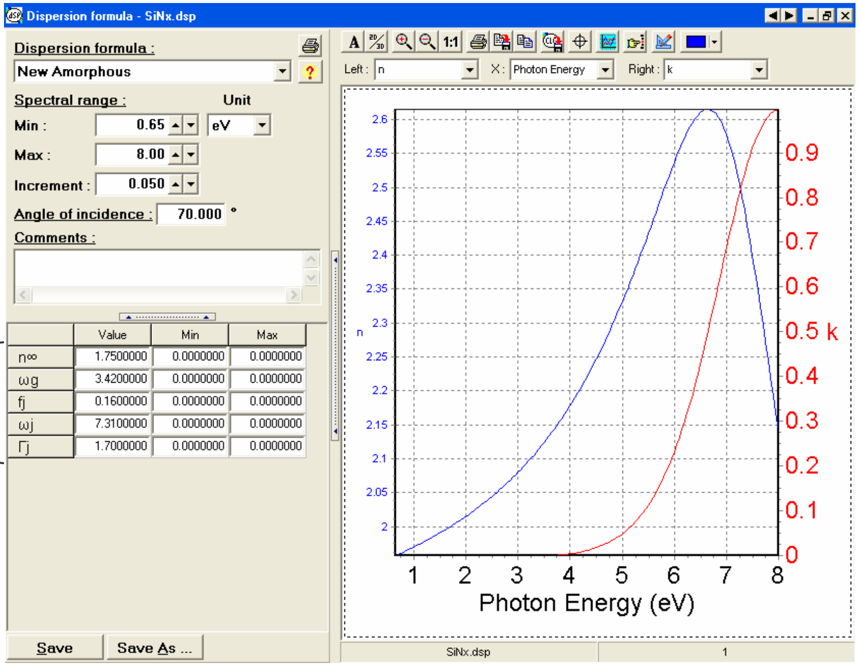
Dispersion formula :

Adachi-3 Forouhi

- Adachi-3 Forouhi
- Adachi-Forouhi
- Adachi-New Forouhi
- Afromovitz
- Amorphous
- Cauchy Absorbent
- Cauchy Transparent
- Classical
- Conrady
- Double Amorphous
- Double New Amorphous
- Excitonic
- Fixed Index
- Haltman
- Kato-Adachi
- Kato-Adachi IR
- New Amorphous
- Quatre Amorphous
- Quatre Oscillators
- Schott (Briot)
- Sellmeier Absorbent
- Sellmeier Transparent
- Tanguy
- Tanguy Extended
- Tauc Lorentz
- Tauc Lorentz2
- Tauc Lorentz3
- Triple Amorphous
- Triple New Amorphous

Library of > 30 dispersion formula

Setting values of parameters describing the dispersion formula



Dispersion formula - SiNx.dsp

Dispersion formula : New Amorphous

Spectral range :

Min : 0.65 eV

Max : 8.00

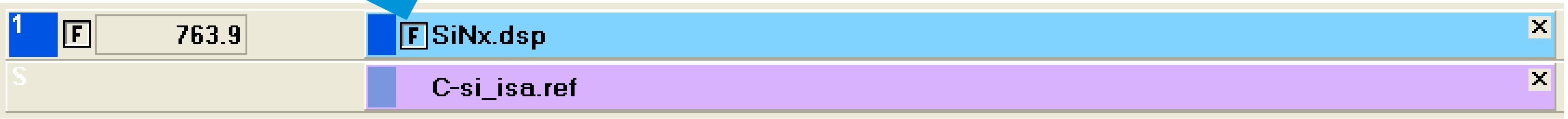
Increment : 0.050

Angle of incidence : 70.000 °

Comments :

	Value	Min	Max
n∞	1.7500000	0.0000000	0.0000000
ωg	3.4200000	0.0000000	0.0000000
fj	0.1600000	0.0000000	0.0000000
ωj	7.3100000	0.0000000	0.0000000
Γj	1.7000000	0.0000000	0.0000000

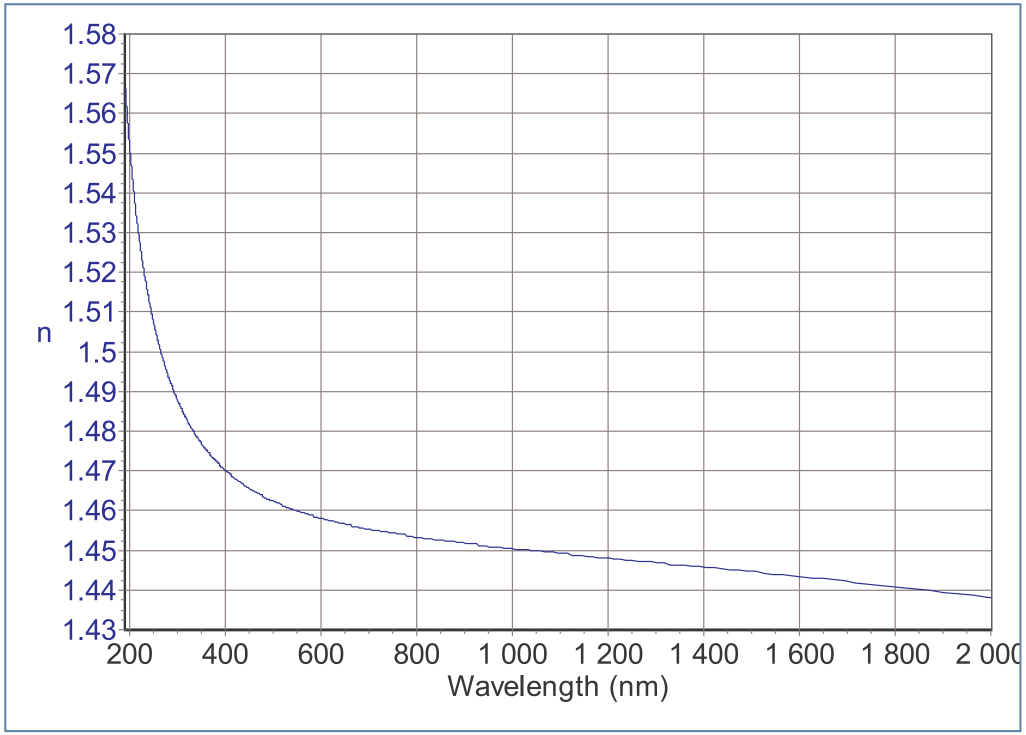
Left : n X : Photon Energy Right : k



Material Dispersion in Optics

- Materials dispersion comes from a wavelength dependant response of a material to waves.

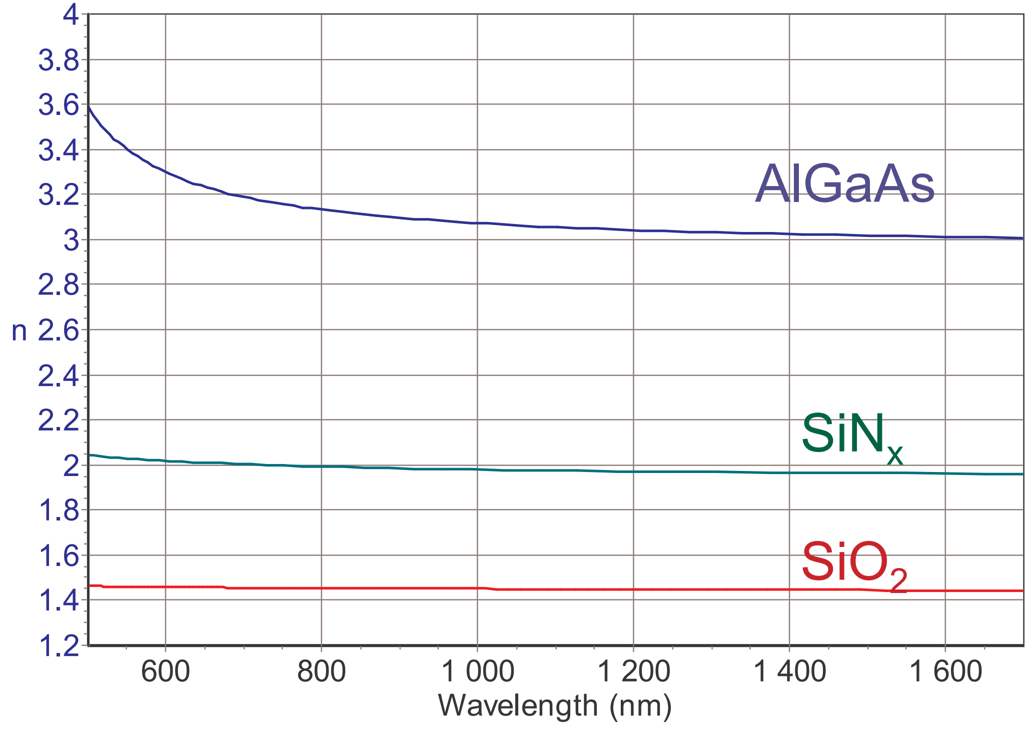
  ⇨ Optical constants vary with wavelength, it is called a dispersion.



Normal Dispersion: Transparent Material

- Refractive index decreases with increasing wavelength λ
- No absorption (k=0): transparent material
- Higher index for stronger UV absorption

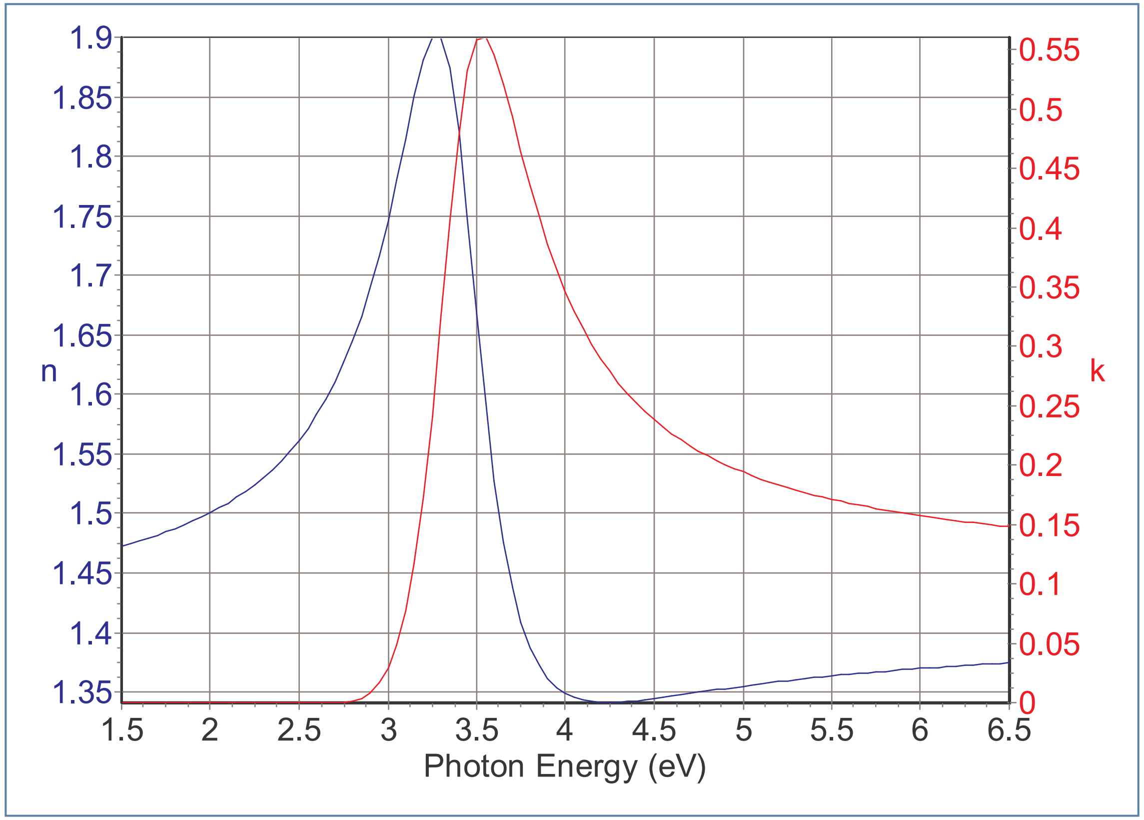
➾ Normal dispersion



Anomalous Dispersion: Absorbing Material

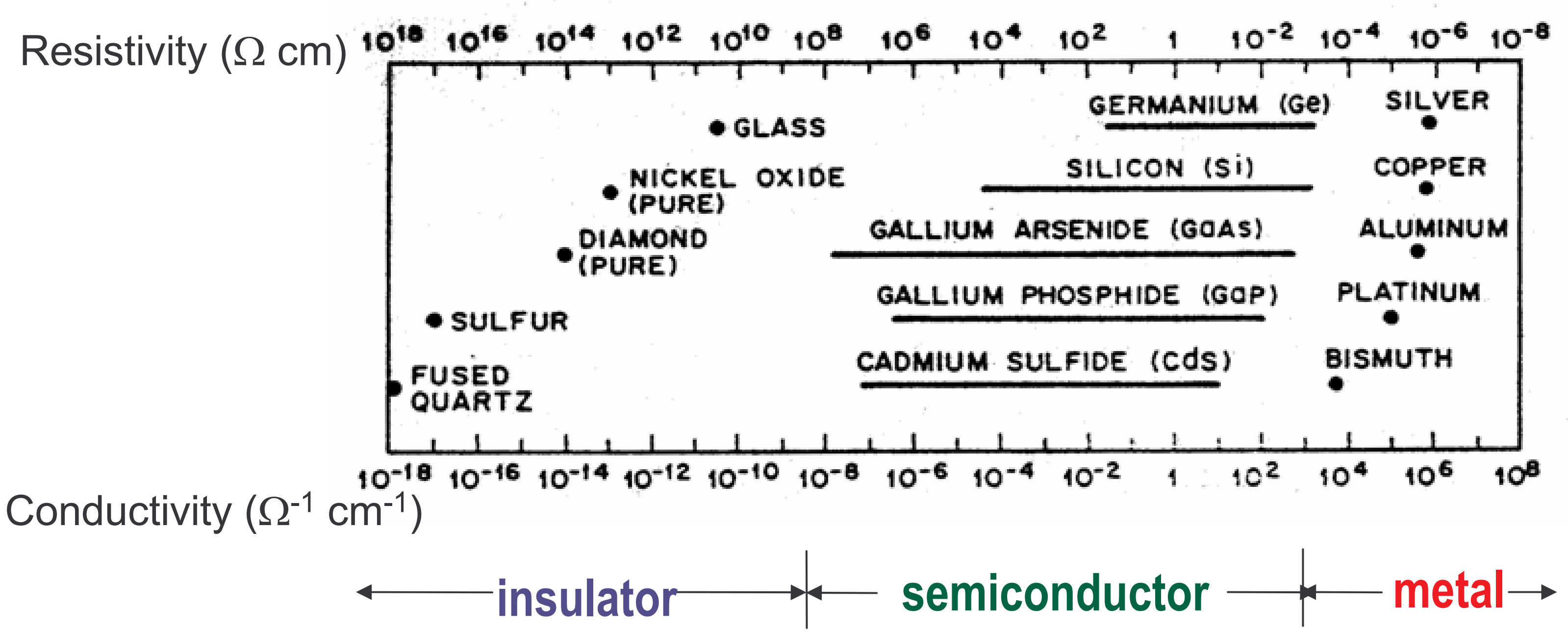
- Refractive index increases with increasing wavelength λ
- Absorption (k≠0): absorbing material
- Higher index for stronger UV absorption

⇨ Anomalous dispersion



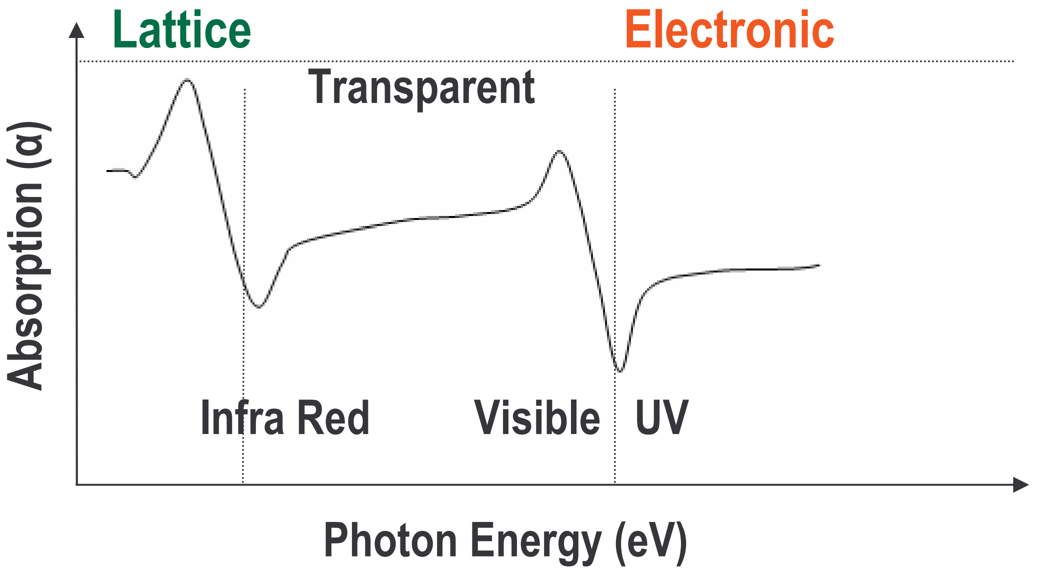
Classes of Materials

- Classified versus electrical conductivity
  - Metal: no gap Eg = 0
  - Insulator (dielectric): large gap Eg > 4 Ev
  - Semiconductor: 0 < Eg < 4eV



Material Absorption Theory

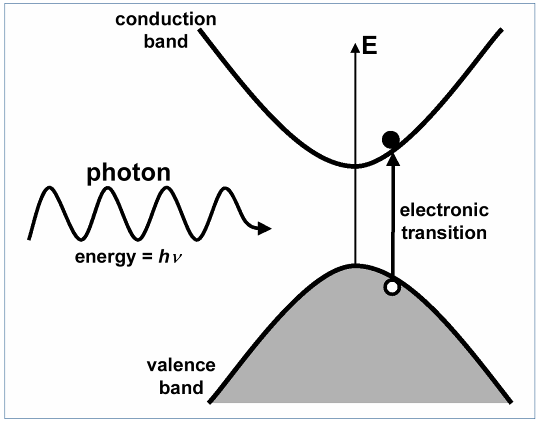
- **3 fundamental processes involving interaction between material and EM wave**
  - Electronic absorption
  - Lattice or phonon absorption
  - Free carrier absorption



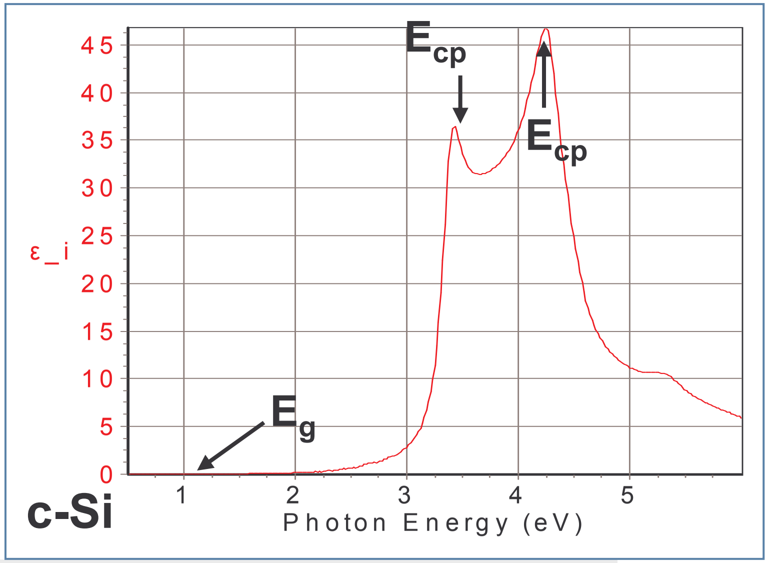
Absorbing Regions

Electronic transitions

- Result of interaction between the incident light and the motions of e^- or holes within the material



- Electrons in valence band
- Gap between valence & conduction band
- If photon has energy larger than gap, electron may excite to higher state



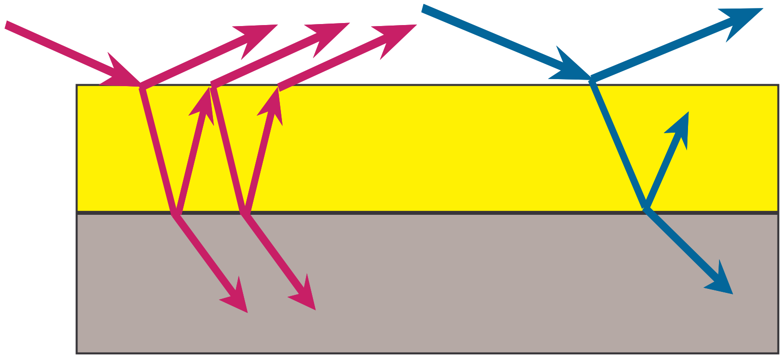
- Absorption associated with each transition
- Band-gap energy (E_g): minimum energy where transitions can occur
- Critical point energies (E_{cp}) = photon energies where there is a high probability of band-to-band transitions

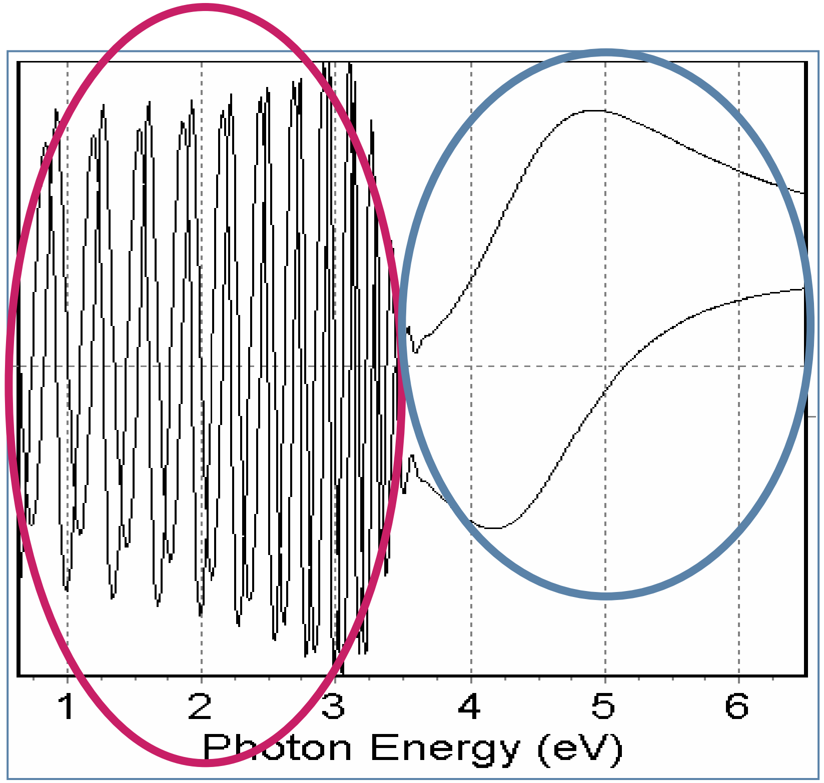
Reflections with Films

- **Transparent film**: see interference fringes (>1000 Å)

  ⇨ Thicker films produces more interference fringes (in the exemple TiO_2 layer thickness: 8000 Å)

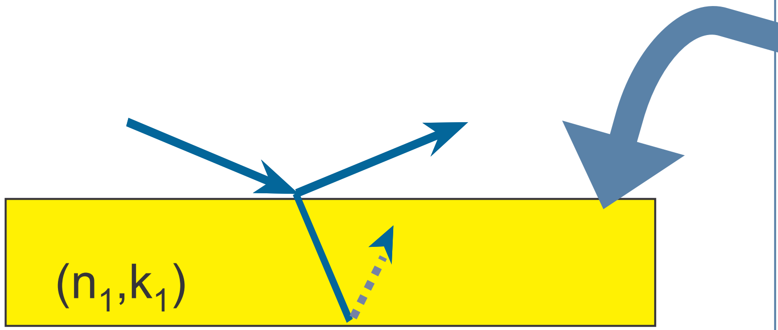
- **Absorbing film:** no interference fringes, behaves as a substrate

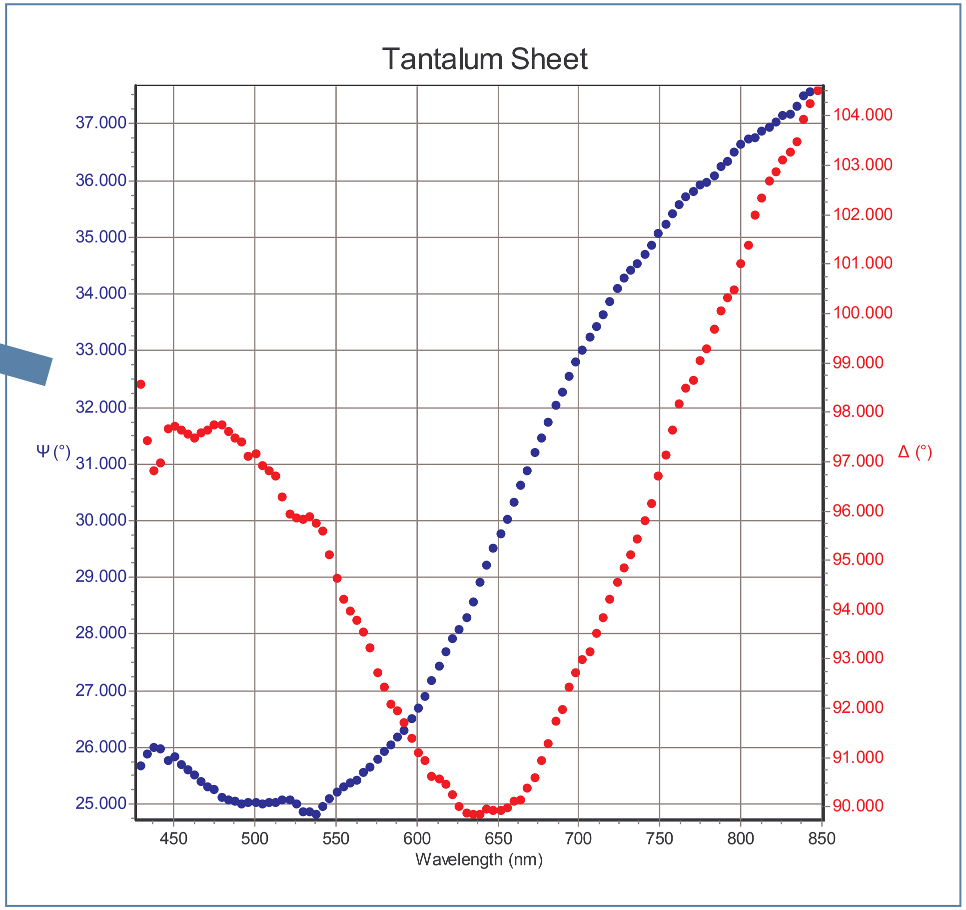




Bulk Sample or Substrate

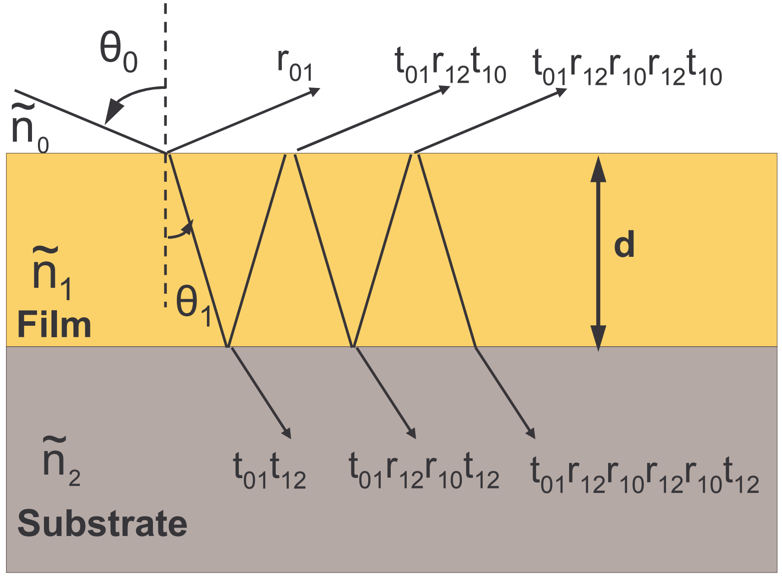
- **Measurement of a bulk sample gives directly the (n,k) of the material**
  - Ratio $\rho \Rightarrow (\Psi,\Delta) = f(\varepsilon_0, \varepsilon_1, \theta_0)$
  - 2 measured parameters : (Ψ,Δ)
  - 2 unknowns : n_1 k_1





Thin Film on Substrate

- **Thin film characterization: thickness and (n,k)**



R = Σ r related to the 1&2 interfaces

$$R = \frac{r_{01} + r_{12}e^{-2j\beta}}{1 + r_{01}r_{12}e^{-2j\beta}}$$

β : Film phase thickness

$$\beta = 2\pi\left(\frac{d}{\lambda}\right)n_1\cos\phi_1$$

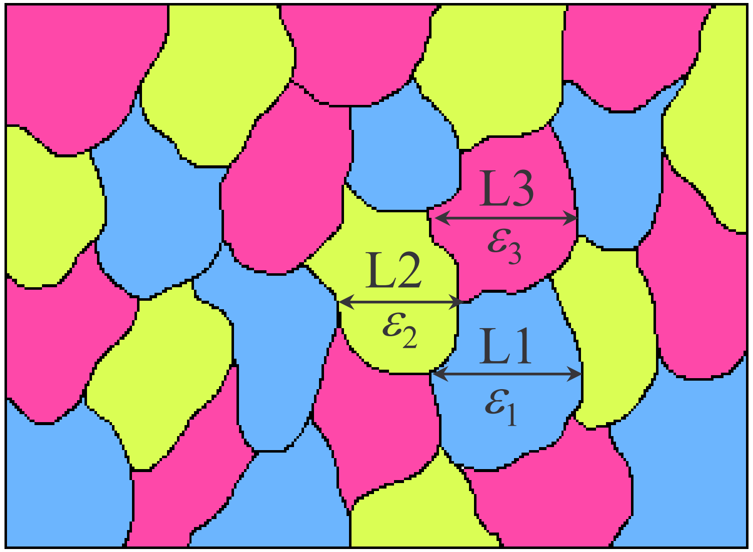
Ratio $\rho \Rightarrow (\Psi,\Delta) = f(\varepsilon_0, \varepsilon_1, \varepsilon_2, \theta_0, d, \lambda_0)$

2 measured parameters : (Ψ,Δ)

3 unknowns : n_1 k_1 and d

Effective Medium Approximation Theory

- All materials are inhomogeneous on atomic scale
- Part of macroscopically homogeneous materials is inhomogeneous on microscopic scale



If each separate region is large
enough to possess their own
dielectric identities, but small
compared to wavelength of light

$$(L_1, L_2, L_3 < \lambda)$$

⇩

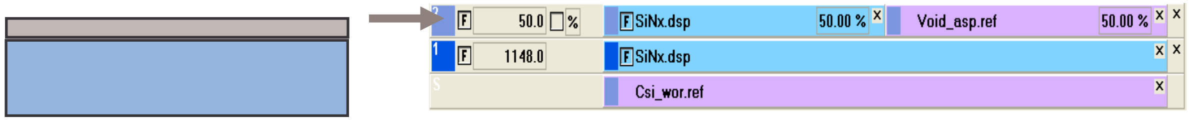
Effective Medium Approximation
can be used

- EMA is used to calculate the dielectric functions of mixed phases based on their microstructure and component volume fractions

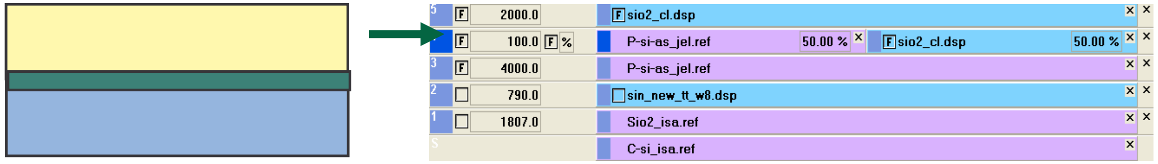
Effective Medium Approximation (EMA)

➪ **Calculate optical constants of mixed materials (handled by the software !)**

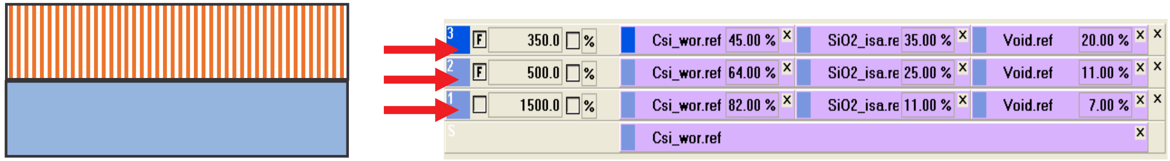
Surface roughness


2 F 50.0 ☐ % | F SiNx.dsp 50.00 % | Void_asp.ref 50.00 %
1 F 1148.0 | F SiNx.dsp
S | Csi_wor.ref

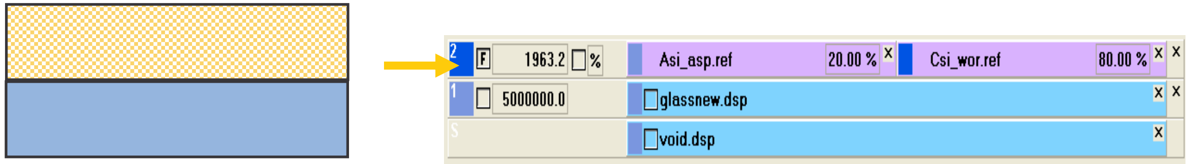
Interface


5 F 2000.0 | F sio2_cl.dsp
4 F 100.0 F % | P-si-as_jel.ref 50.00 % | F sio2_cl.dsp 50.00 %
3 F 4000.0 | P-si-as_jel.ref
2 ☐ 790.0 | ☐ sin_new_tt_w8.dsp
1 ☐ 1807.0 | Sio2_isa.ref
S | C-si_isa.ref

Porosity


3 F 350.0 ☐ % | Csi_wor.ref 45.00 % | SiO2_isa.re 35.00 % | Void.ref 20.00 %
2 F 500.0 ☐ % | Csi_wor.ref 64.00 % | SiO2_isa.re 25.00 % | Void.ref 11.00 %
1 ☐ 1500.0 ☐ % | Csi_wor.ref 82.00 % | SiO2_isa.re 11.00 % | Void.ref 7.00 %
S | Csi_wor.ref

Polycrystalline materials


2 F 1963.2 ☐ % | Asi_asp.ref 20.00 % | Csi_wor.ref 80.00 %
1 ☐ 5000000.0 | ☐ glassnew.dsp
S | ☐ void.dsp

Effective Medium Theory

Maxwell Garnett and Bruggeman models

- **Maxwell Garnett model**
  - The Maxwell-Garnett is derived assuming spherical inclusions (denoted ε_i) with a volume fractions f exist in a host matrix of the second material (denoted ε_h)

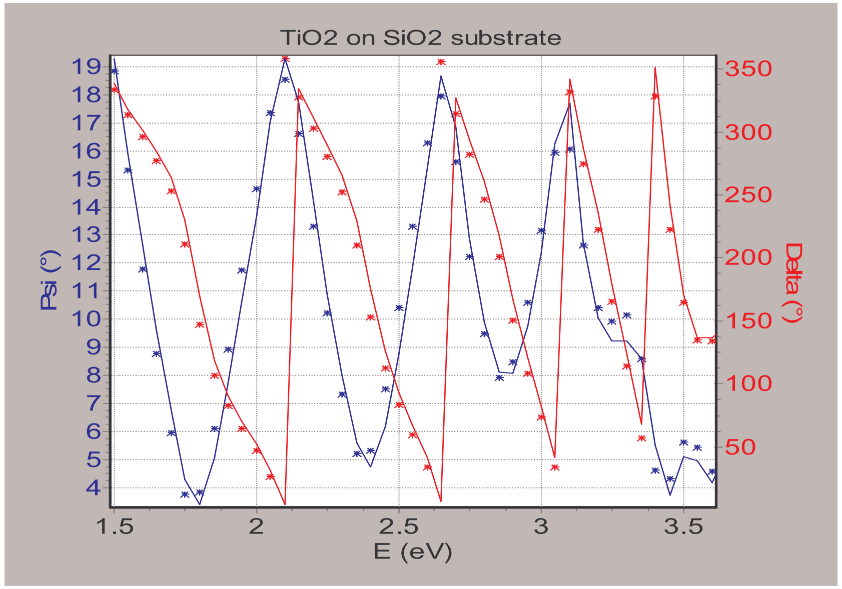
$$\varepsilon = \varepsilon_h \frac{\varepsilon_i(1+2f)+2\varepsilon_h(1-f)}{\varepsilon_i(1-f)+\varepsilon_h(2+f)}$$

- **Bruggeman model**
  - Non restrictive of the number of components of the mixture which are treated in an equivalent way by holding account only of their proportion
  - Self-consistent theory: Host material complex dielectric function equalling the final effective complex dielectric function of the multi-constituent material

$$\sum_i f_i \frac{\varepsilon_i - \varepsilon}{\varepsilon_i + 2\varepsilon}$$

ANALYSIS OF ELLIPSOMETRIC DATA

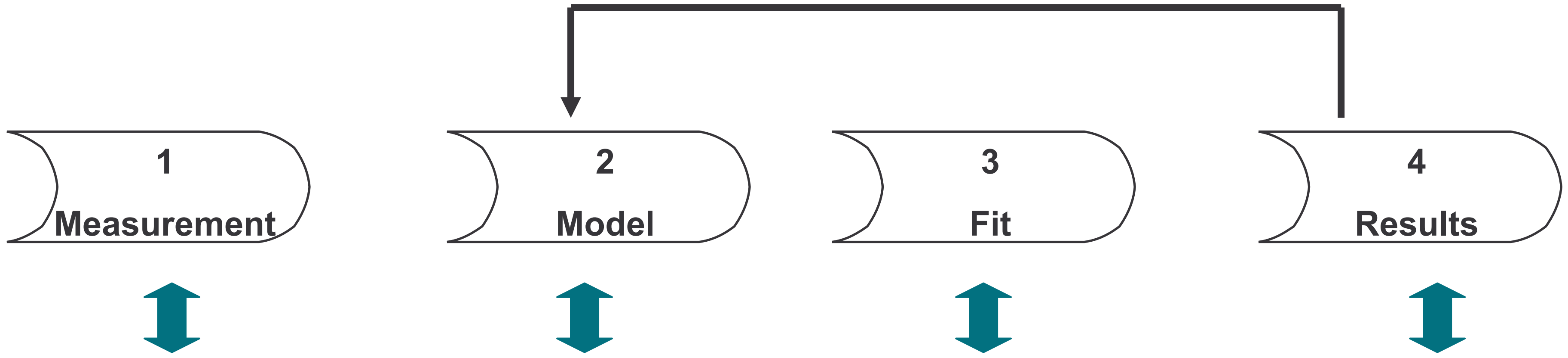
- Ellipsometry does not measure film thicknesses or optical constants, it measures Ψ and Δ



- To extract these informations from a sample, it is necessary to perform a **model dependant analysis** of the ellipsometric angles

- A model is an idealized mathematical representation of the sample

SPECTROSCOPIC ELLIPSOMETRY DATA ANALYSIS FLOWCHART

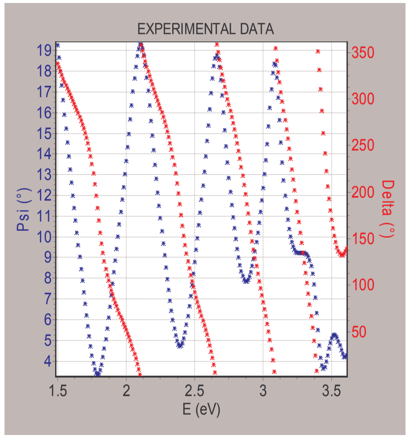


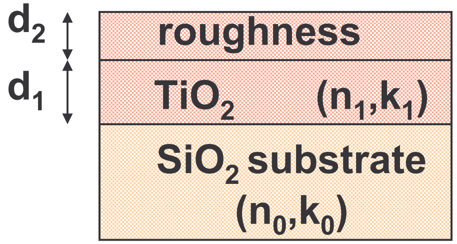
1 **Measurement**

2 **Model**

3 **Fit**

4 **Results**

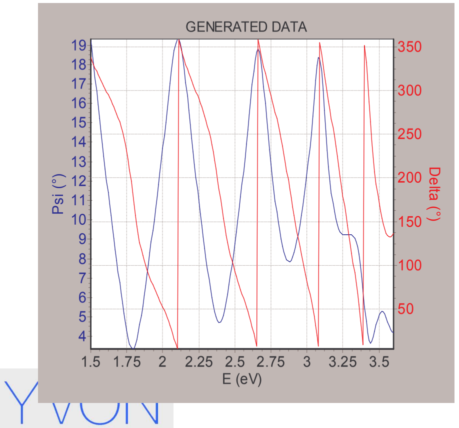


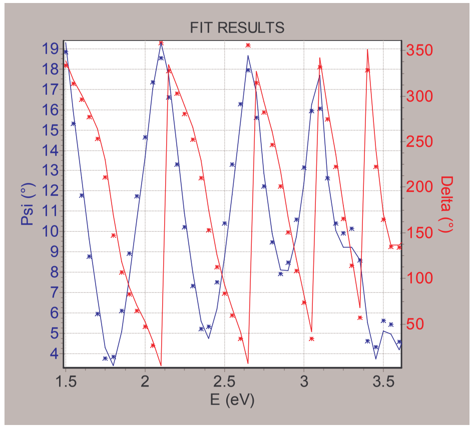


roughness

TiO_2 (n_1,k_1)

SiO_2 substrate (n_0,k_0)

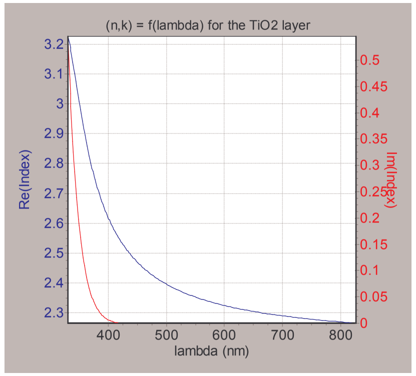




χ^2= 2.1 ⇨ χ^2= 1.6

d_{TiO2} = 4200 Å

d_{rough}= 20 Å



Data Fitting

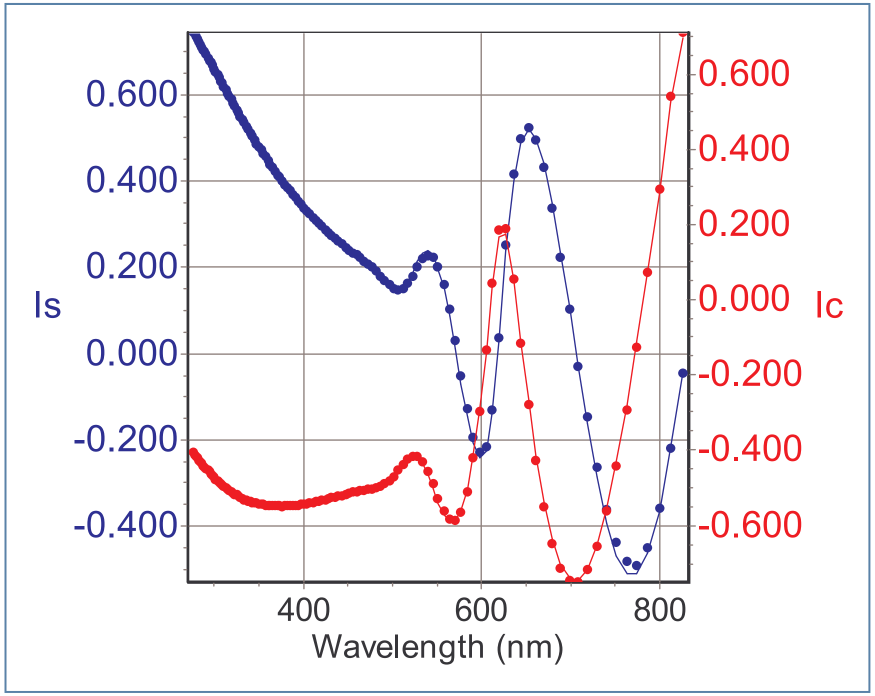
$$\chi^2 = \min \sum_{i=1}^{n} \left[\frac{(\Psi_{th} - \Psi_{exp})_i^2}{\Gamma_{\Psi,i}} + \frac{(\Delta_{th} - \Delta_{exp})_i^2}{\Gamma_{\Delta,i}} \right]$$

- χ^2 parameter quantifies the difference between experimental and model data

- Software adjusts fit parameters to find best match between model and experimental curves

Roughness	23 Å
a-Si	2353 Å
Glass substrate	

Results ***X^2 = 7.8*** → ***X^2 = 0.5***

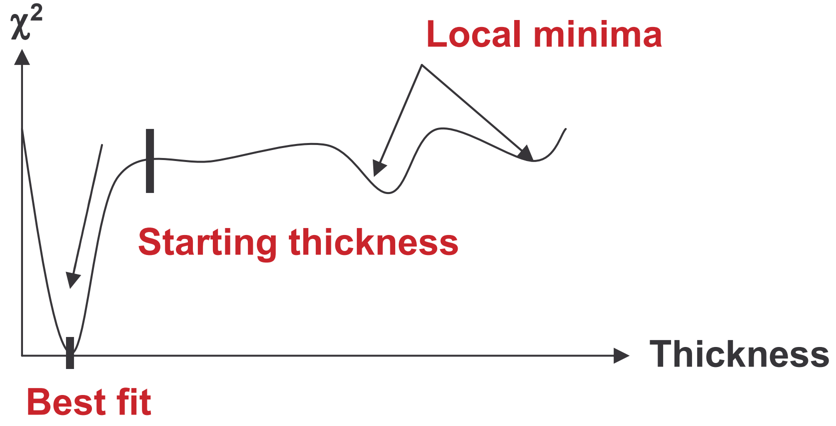


- A smaller χ^2 implies a better fit

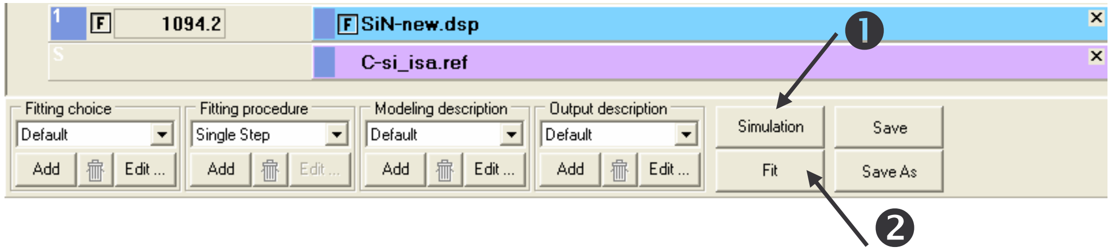
Data Fitting

- **Minimization methods**
  - Levenberg-Marquardt algorithm : commonly used
  - Others: Simplex, …

- **Difficulties**
  - Local minimum
  - Many variables
  - Setting starting parameters: have to be close to the final solution



- **Getting good starting values**
  - ❶ Use the simulation function
    - Generate from model and compare with experimental data
  - ❷ Fit the selected parameters



Evaluate the Quality of Results

- Compare experimental data with generated data

- How low is the χ^2 ? Can it be reduced further by increasing model complexity ?

- Are fit parameters physical ?

- Check the correlation matrix. Values close to 1 mean correlated parameters, and a non-unique solution.

Correlation matrix ⇒ 6 fit parameters

```
 =1=     =2=     =3=     =4=     =5=     =6=
1.000  -0.431  -0.148  -0.012  -0.225   0.115
        1.000   0.475   0.127  -0.746  -0.014
                1.000   0.890  -0.474   0.765
                        1.000  -0.205   0.970
                                1.000  -0.123
                                        1.000
```

General Rules for Ellipsometric Data Analysis

3 essential steps

1 - Experimental measurement

→ Check the good working of the ellipsometer (NIST)

→ Sample preparation

→ Acquisition parameter choices
- Spectral range (NIR-FUV) / sample properties
- Monochromator step / layer thickness
- Angle of incidence (brewster)
- Beam diameter

General Rules for Ellipsometric Data Analysis

3 essential steps

2 - Modeling

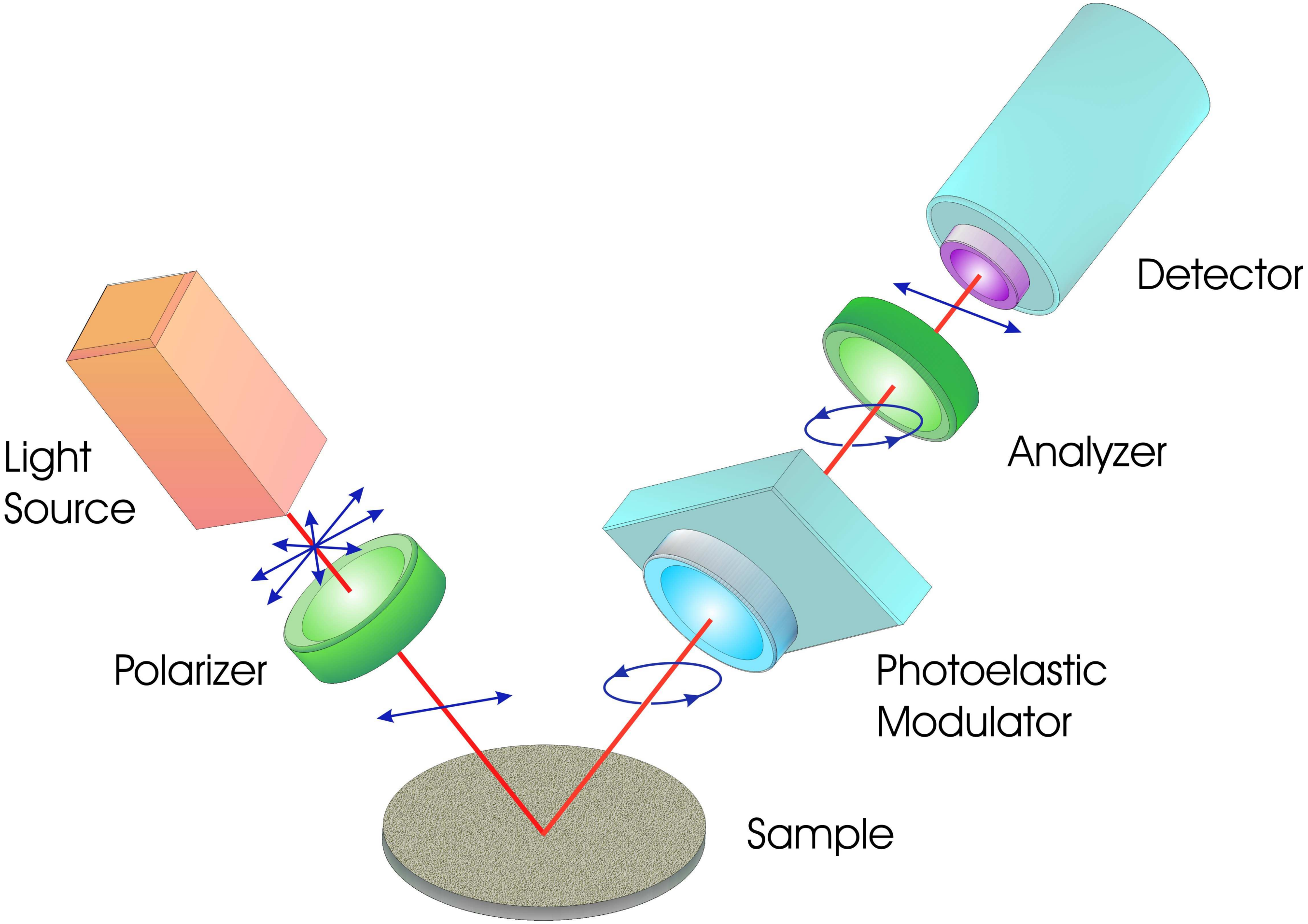
→ Build the most realistic optical model

3 - Reliable model choice

→ Criteria and quality of a good fit
- Physical result (model and parameter values)
- Slight correlation between parameters : uniqueness of the solution
- Final result independent of initial parameters
- Quick convergence

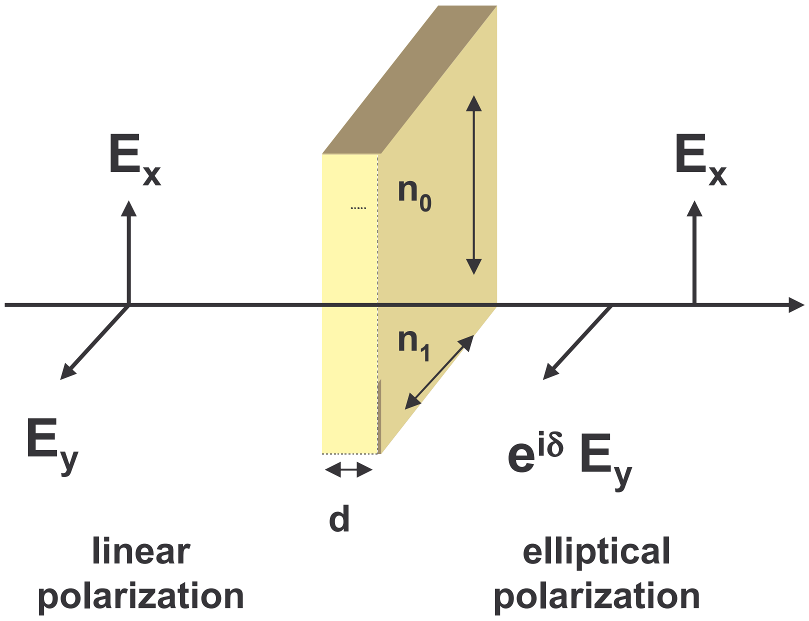
Phase Modulation Spectroscopic Ellipsometer

Optical Set-up



UVISEL

What is a photoelastic modulator and How does it work ?



- **PEM definition**

→ fused silica bar sandwiched between piezo oscillating at the frequency w=***50 kHz***

- **Stress effect**

→ creation of an optical anisotropy in the silica bar

- **Strain modulation**

→ optical anisotropy modulated

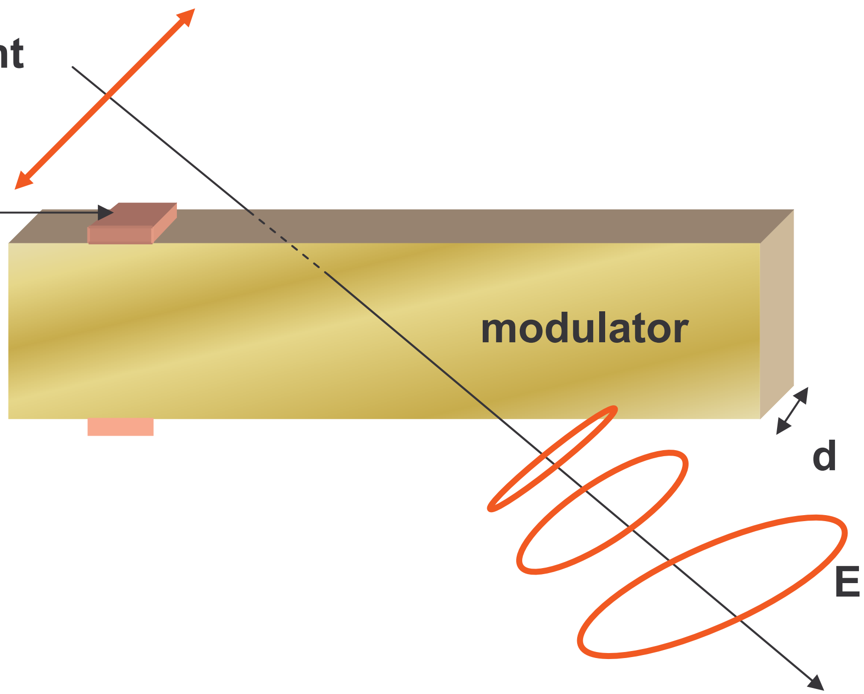
→ polarization modulated

- **Modulated phase shift $\delta(t)$**

$$\delta(t) = A \sin wt$$

with : $A = 2\Pi\ d\ (N1-N0)/\lambda$

What is a photoelastic modulator and How does it work ?



Linearly polarized light

Piezo electric transducer

(50 kHz)

modulator

d

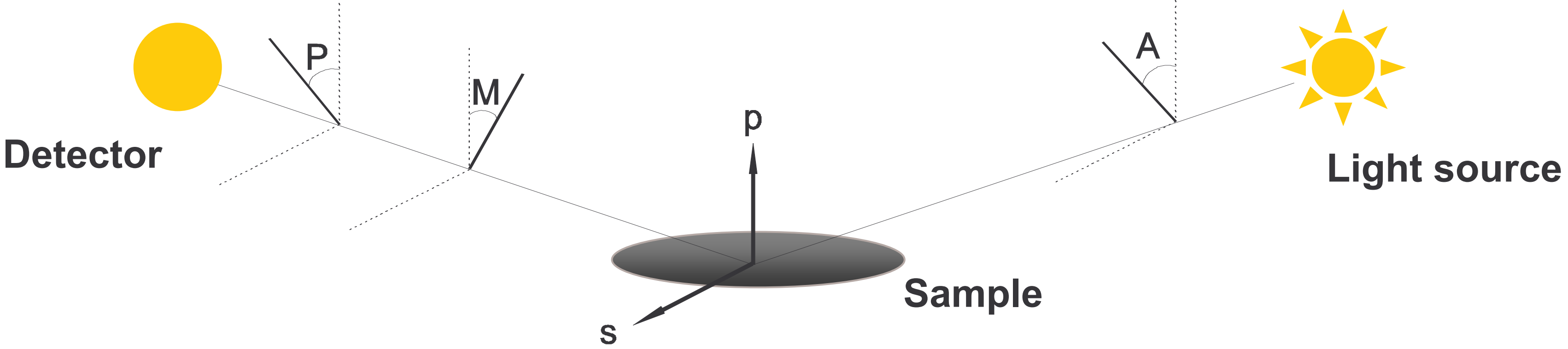
Elliptically modulated
polarized light

Phase Modulation Formalism

Based on Jones Formalism

- Reference basis $(\vec{p}, \vec{s})$
- Each element of the optical chain is associated to a matrix (2x2)
  - Sample $E = \begin{pmatrix} r_p & 0 \\ 0 & r_s \end{pmatrix}$
  - Polarizer $P = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$
  - Modulator $M = \begin{pmatrix} e^{i\delta} & 0 \\ 0 & 1 \end{pmatrix}$
- Coordinate system rotation $R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$

Phase Modulation Formalism



- Jones formalism for transmitted field : $E_t = T(A\ R_A\ S\ R_M\ M\ R_{P\text{-}M}\ P)\ E_i$ (I)
- Leading to detected intensity : $I(t) = E_t E_t^* = I\ [I_0 + I_S \sin\delta(t) + I_C \cos\delta(t)]$
- Development of equation (I) leads to :

$$I_0 = 1 - \cos2\Psi\ \cos2A + \cos2(P\text{-}M)\ \cos2M\ (\cos2A - \cos2\Psi) + \cos2(P\text{-}M)\ \sin2A\ \sin2M\ \sin2\Psi\ \cos\Delta$$

$$I_S = \sin2(P\text{-}M)\ \sin2A\ \sin2\Psi\ \sin\Delta$$

$$I_C = \sin2(P\text{-}M)\ [\sin2M\ (\cos2\Psi - \cos2A) + \sin2A\ \cos2M\ \sin2\Psi\ \cos\Delta]$$

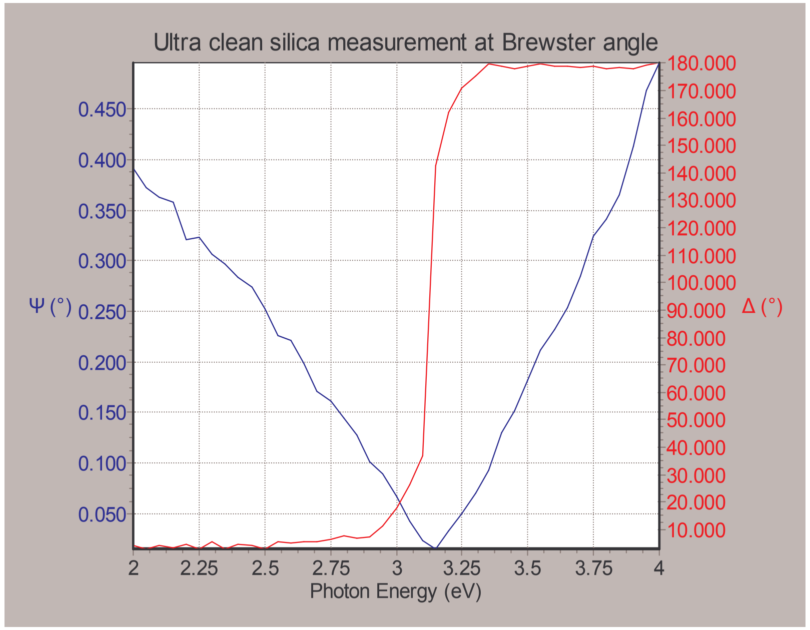
Phase Modulation Formalism

- **2 Common Measurement Configurations**
  - Configuration II: P – M=45 [90]; M = 0 [90]; A = 45 [90]
    - ➔ **$I_s = \sin 2\Psi \sin\Delta$**
      $I_c = \sin 2\Psi \cos\Delta$
    - ➔ **Accurate measurement of Δ over [0-360°]**
  - Configuration III: P – M=45 [90]; M = 45 [90]; A = 45 [90]
    - ➔ **$I_s = \sin 2\Psi \sin\Delta$**
      $I_c' = \cos 2\Psi$
    - ➔ **Accurate measurement of Ψ over [0-90°]**

- **Depolarization Measurement**
  - Given by: $P = (I_s)^2 + (I_c)^2 + (I_c')^2$
  - P=1: the sample is not depolarizing
  - P<1: the sample is depolarizing

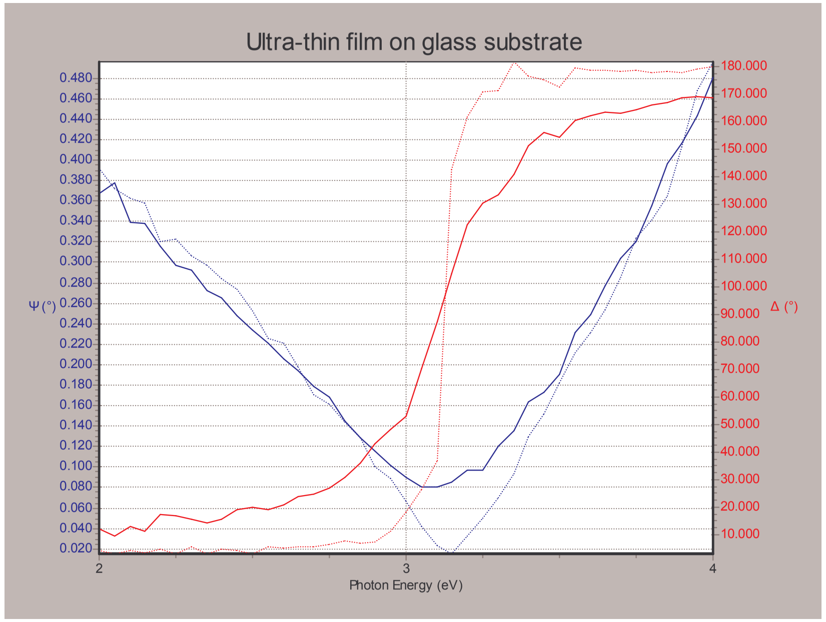
High Accuracy, High Sensitivity Phase Modulation Ellipsometer

➔Accurate measurement of Δ parameter around 0 & 180°



Measurement of silica substrate at the Brewster angle

➔High sensitivity to ultra-thin films

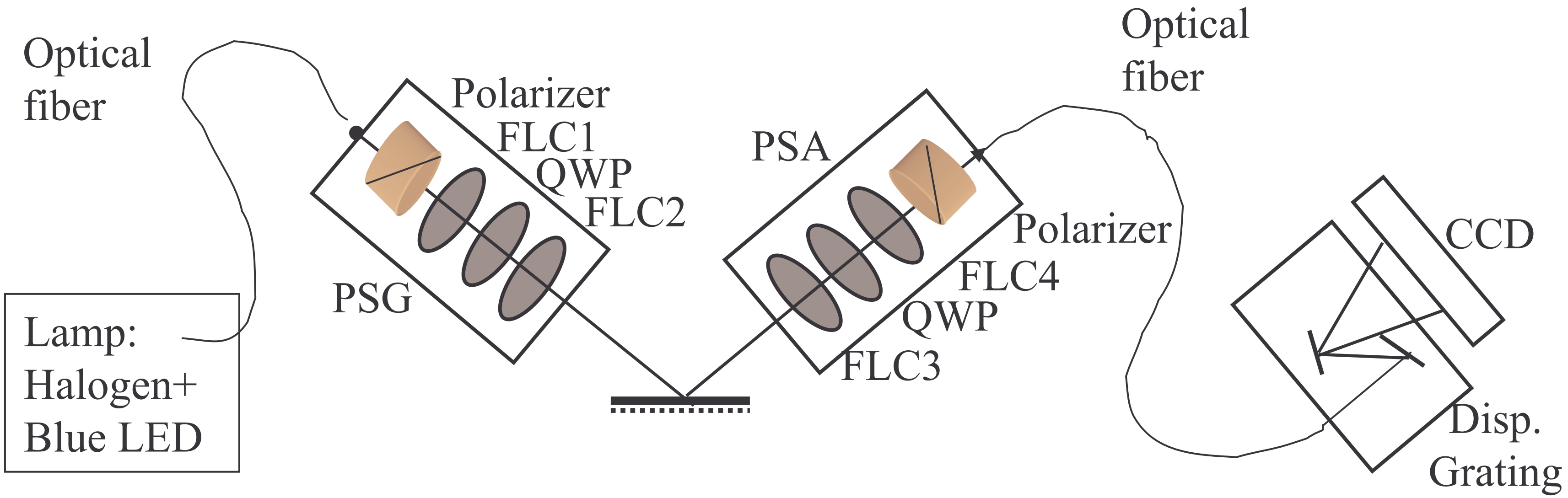


10 Å monolayer deposition on silica substrate

- - - Ultra-thin monolayer
—— Silica substrate

Liquid Crystal Modulation Spectroscopic Ellipsometer

Optical Set-up



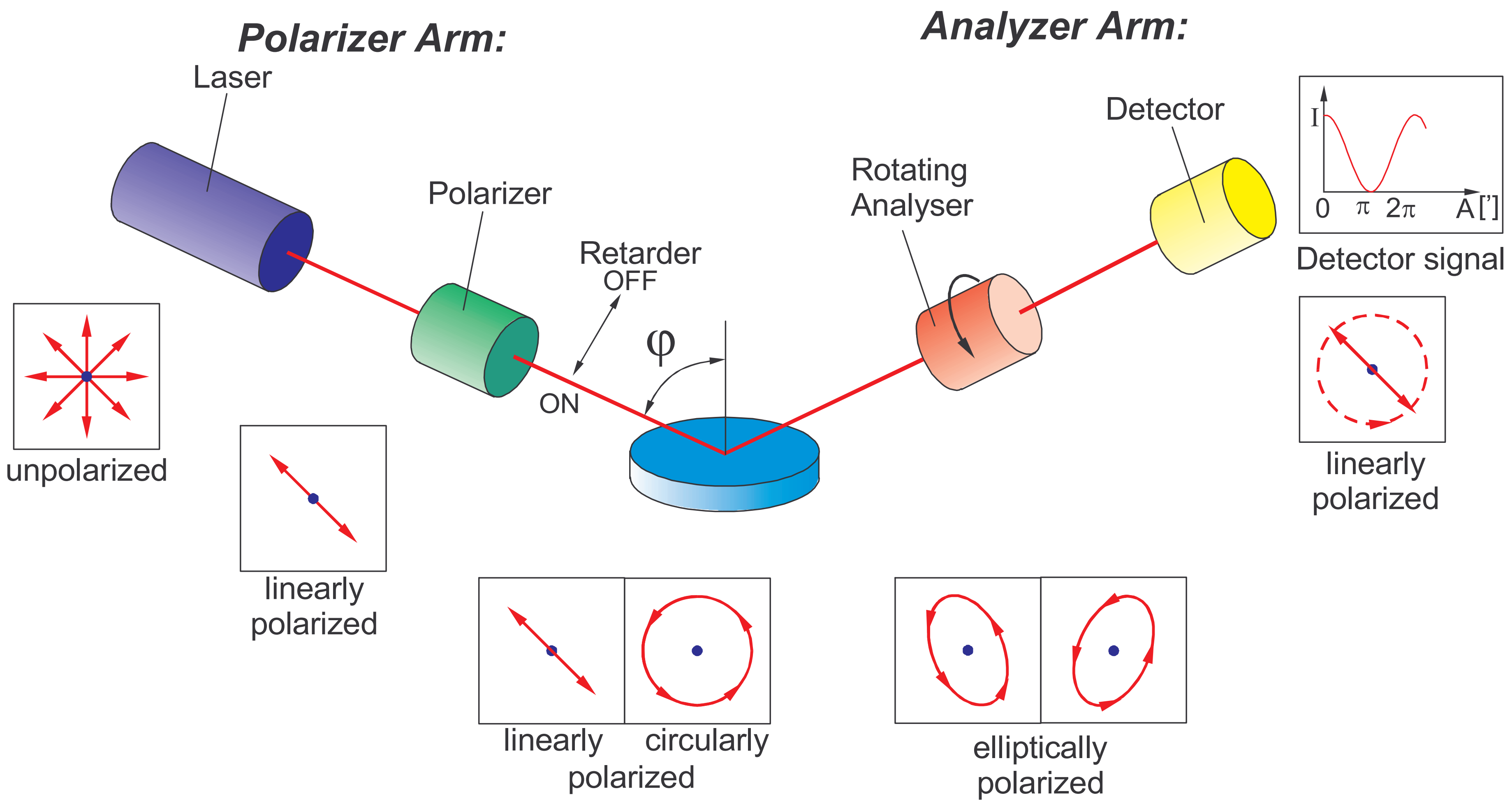
> Input and output heads are symmetrical

- Polarizer
- LC Modulator – states 0° and 45°
- Quarter Waveplate
- LC Modulator – states 0° and 45°

MM-16

Laser Ellipsometer

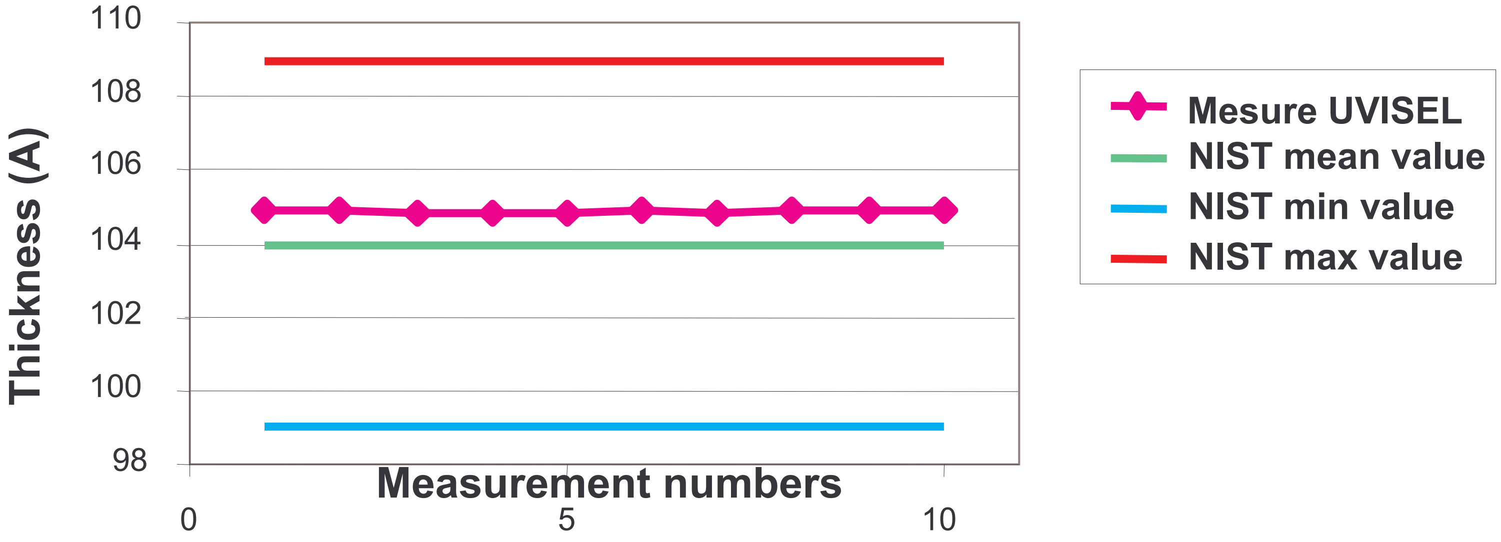
Optical Set-up



PZ2000

Ellipsometer Accuracy

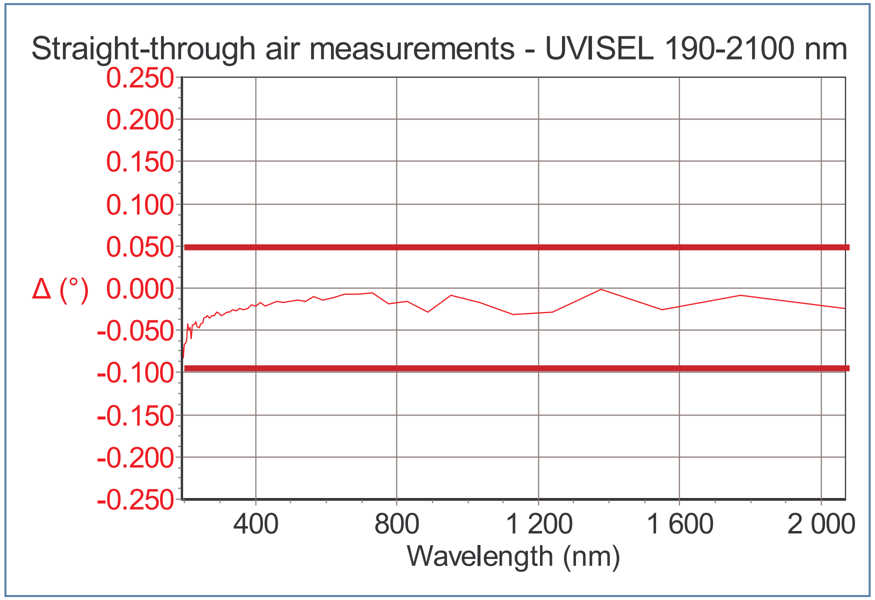
- **Reference standards NIST**
  - Check the good working of the ellipsometer by measuring one time per week your standard sample.

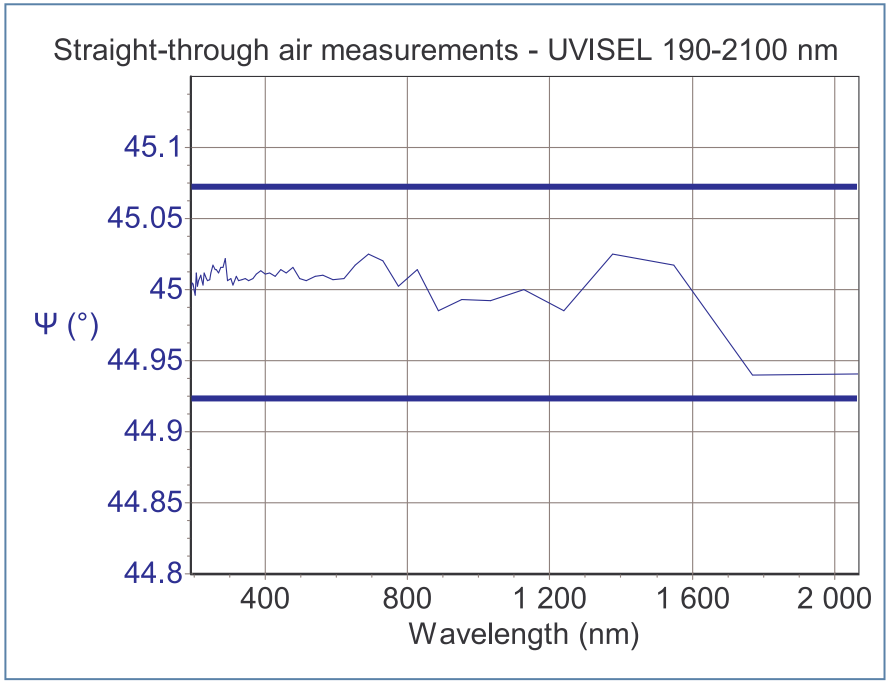


- **Straight-through air measurements**
  - The only material for which the ellipsometric parameters are absolutely known is “Air”
  - An ellipsometric measurement in the straight-through configuration should by definition return $\Psi=45°$ and $\Delta=0°$

Ellipsometer Accuracy

Straight-through air measurements





- **HJY UVISEL Specifications**
  ➔ Δ= 0° ± 0.083°
  – Spectral range: 190 – 2100 nm

- **HJY UVISEL Specifications**
  ➔ Ψ= 45° ± 0.06°
  – Spectral range: 190 – 2100 nm

Setting up Ellipsometric Measurement

Spectral range

- **What are your materials ?**
  - Semiconductor: transparent in NIR, strongly absorbing in VIS-FUV
  - Dielectric: transparent, absorbing in the FUV
  - Metal: strongly absorbing from NIR to FUV, especially in NIR

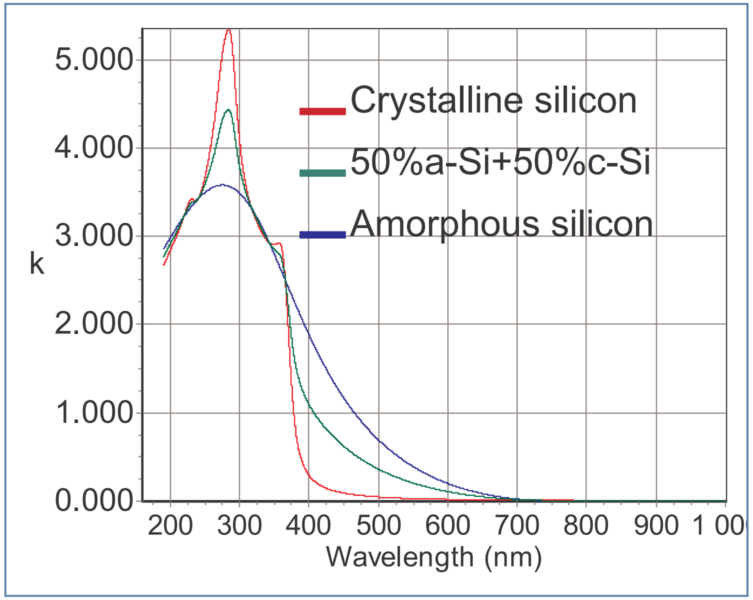
- **Which properties of interest ?**
  - Thickness
  - Optical constants
  - Material properties: composition, crystallinity…

- **Final applications**
  - Telecommunications, data storage applications require NIR wavelengths
  - Lithography requires FUV wavelengths
  - Advanced applications may require a special spectral range to provide accurate results

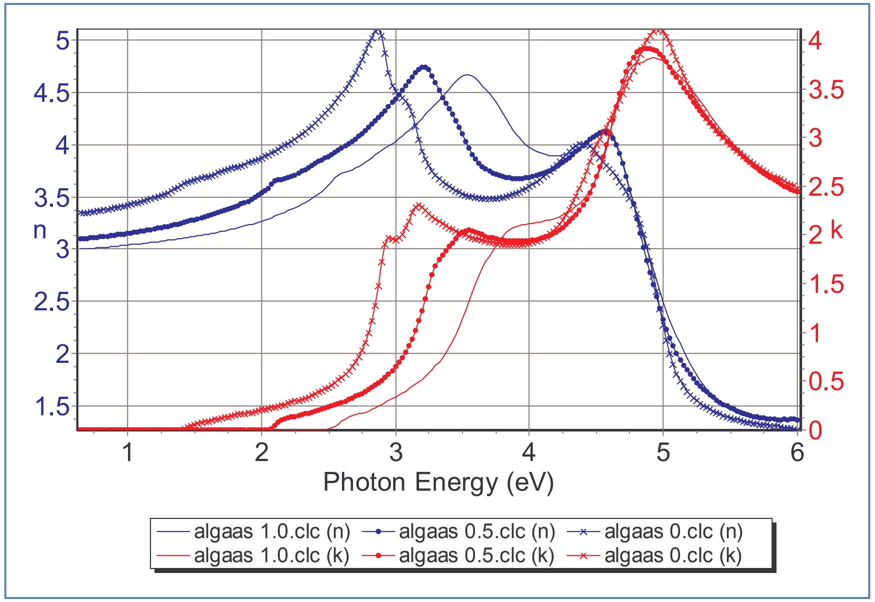
Spectral range

➪ Transparent region: thickness characterization

➪ Absorptive region: crystallinity, composition characterization



- **Electronic transitions critical point broaden in amorphous materials**



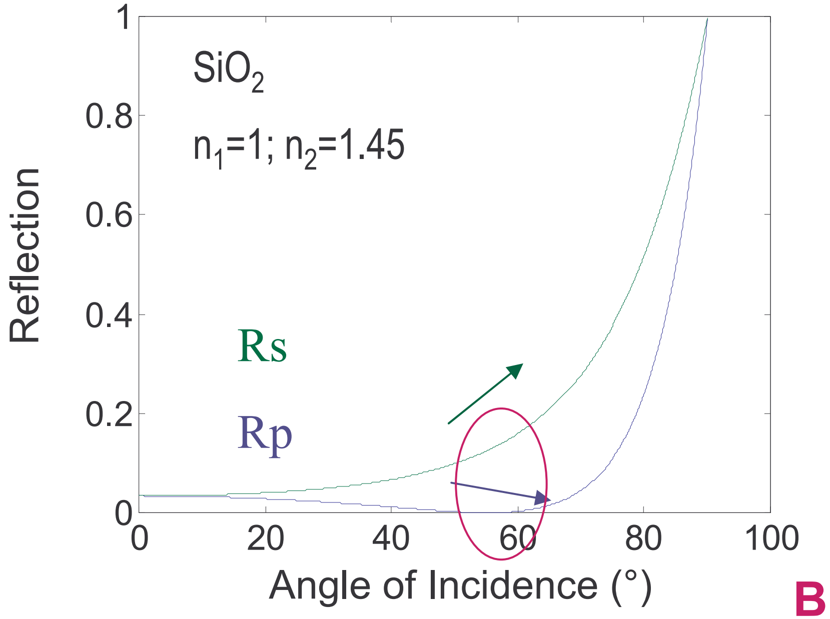
- **Increasing Al increases the bandgap, which shifts the absorption edge to shorter λ**

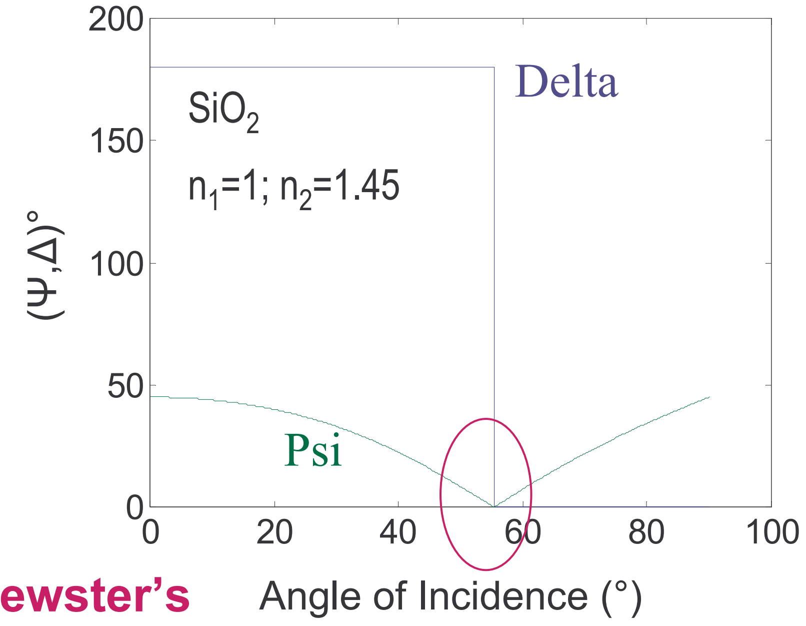
Angles of incidence

- **Ellipsometry measurements are acquired at oblique angle of incidence**

- **Why typically between 50° and 80° ?**
  - To maximize the difference between s and p polarized light

⇨ **Brewster Angle**

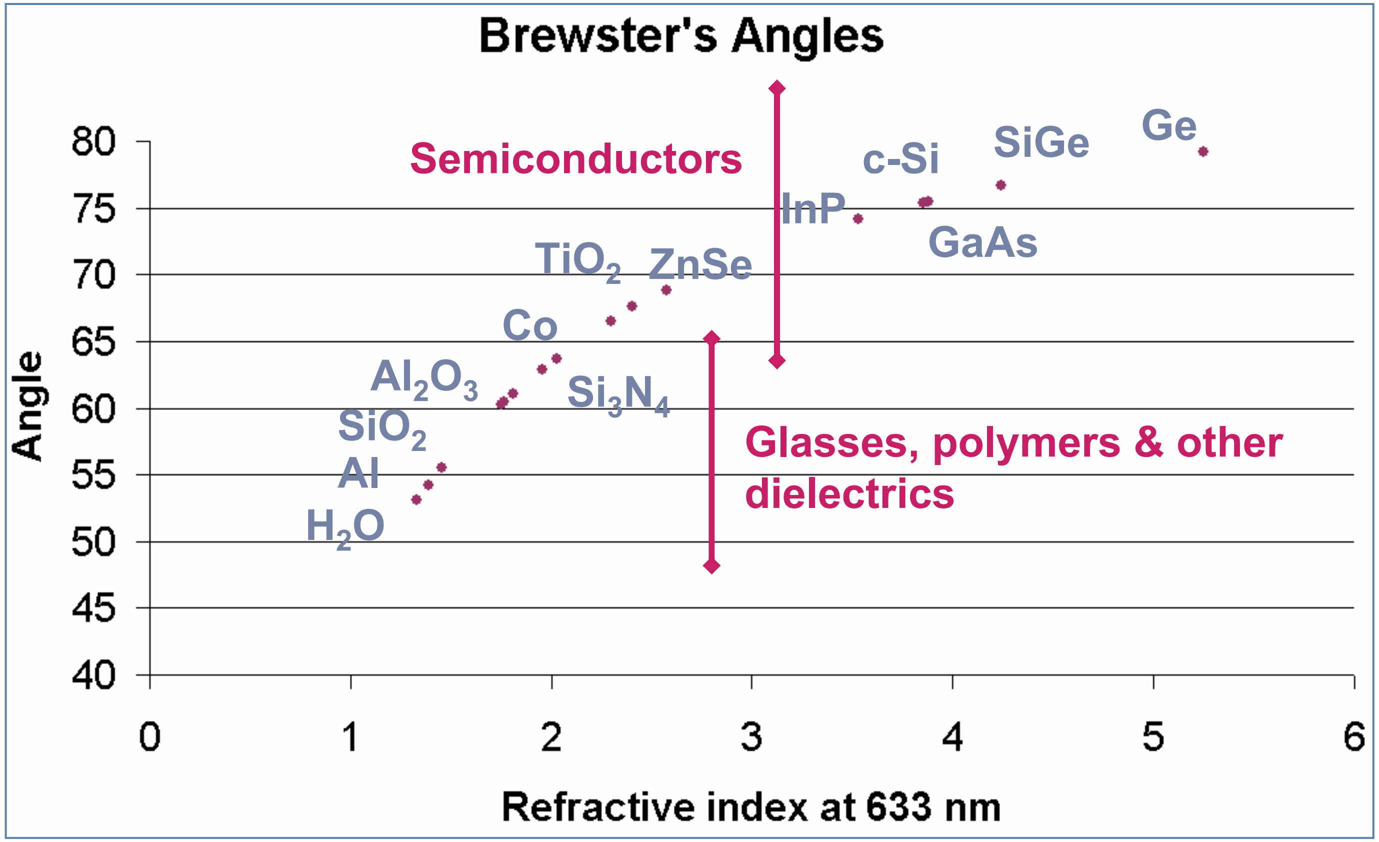




Brewster's angle

Brewster’s Angles

- Brewster angle defined by $\tan \phi_B = \frac{n_2}{n_1}$



Ellipsometry = Versatile Technology

Overview of Applications Fields

- **Semiconductor** S
  - Transistors, memories, nanostructures…
- **Optoelectronic technologies** OT
  - Flat panel display, photovoltaic cells
- **Optical coatings** OC
  - ARC, electrochromic coating, auto-cleaning glass, mirror …
- **Telecommunications** T
  - IR materials, data storage, non linear optical devices
- **Bio-Nano technology** BNT
  - Protein adsorption, SAM, surface chemistry, carbon nanotubes
- **Packaging** P
  - Barrier coating for food plastic film, bottles

CONCLUSION

- Why are Spectroscopic Ellipsometers powerful tools for materials characterization ?
  - Non destructive technique
  - Wide range of materials properties and excellent thickness resolution
  - Interesting correlation with many others techniques
  - Modular design
  - Robust technique for both research and industry