DGM Seminar “Nano-scale Materials: Characterization-Techniques and Applications”

Thin film analysis: Optical analysis and metrology, X-ray reflectometry

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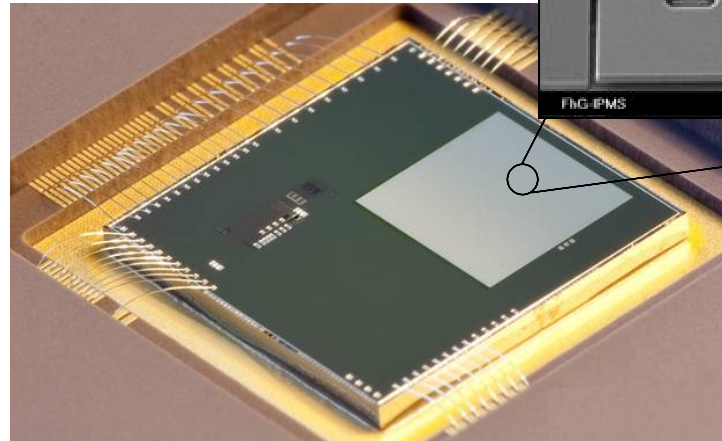

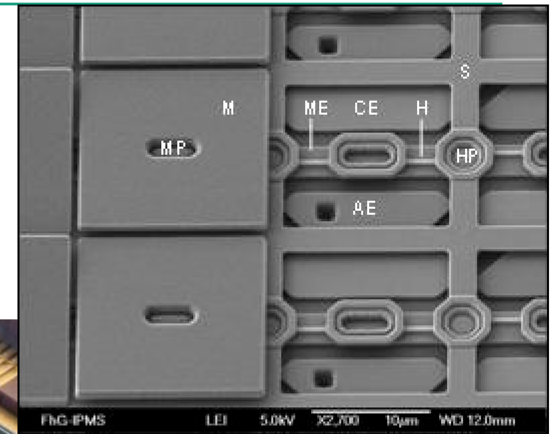

Micromirror array

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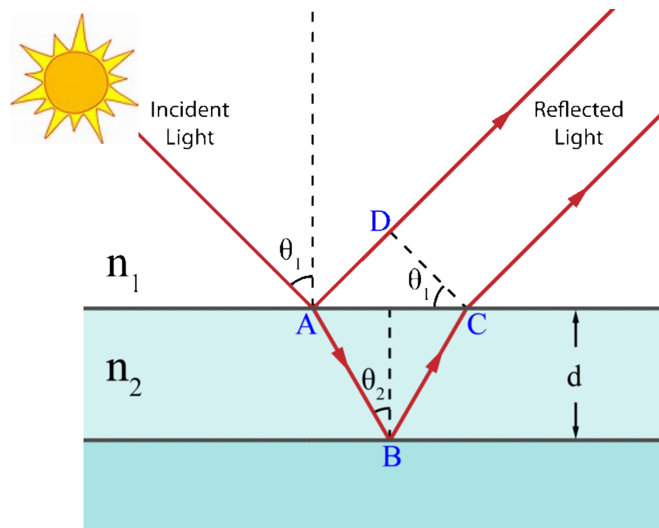
Introduction: Light acting as a non-destructive probe

Light waves reflected from interfaces of a thin film interfere.

The reflected intensity depends on wavelength and angle of incidence.

The resulting interference colors carry information on film thickness.



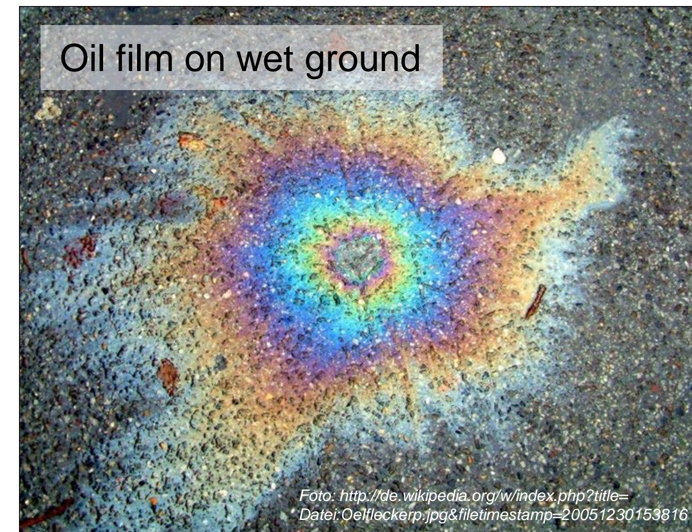


Foto: http://de.wikipedia.org/w/index.php?title=Datei:Oelfleckerp.jpg&filetimestamp=20051230153816

Aim of this talk

To introduce three test methods using light as a non-destructive probe:

Technique	Measured Quantity
Ellipsometry	**Change in polarization** of ligth reflected / transmitted by a planar sample
X-ray reflectometry	**Reflectivity** (vs. angle of incidence or energy) of smooth planar samples for x-rays
Interferometry	**Change in phase** of light reflected at a non-planar surface

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Outline

- Ellipsometry
- X-Ray reflectometry
- White light interferometry
- Application to diffractive MEMS

ELLIPSOMETRY

- Basics
- Measurement principle
- Dispersion models
- Instrumentation
- Applications

Light: Electromagnetic plane wave

Maxwell Eqns. → Wave equations in uniform isotropic source-free medium:

$$\left(\nabla^2 - \mu\varepsilon\frac{\partial^2}{\partial t^2} - \mu\sigma\frac{\partial}{\partial t}\right)\varphi = -\rho/\varepsilon \quad (=0)$$

$$\left(\nabla^2 - \mu\varepsilon\frac{\partial^2}{\partial t^2} - \mu\sigma\frac{\partial}{\partial t}\right)\vec{A} = -\mu\vec{J} \quad (=0)$$

Permeability Permittivity Conductivity Scalar potential Charge density Vector potential Current density

Assumption of harmonic time dependence leads to a special solution:

coupled electro-magnetic transverse plane waves.

Example: Planar wave with field oscillating aling x propagating along z.

$$E_x(z,t) = A_x \cos\left(-\frac{2\pi}{\lambda}(z - vt) + \delta_x\right)$$

Amplitude Wavelength Phase velocity in medium Arbitrary phase

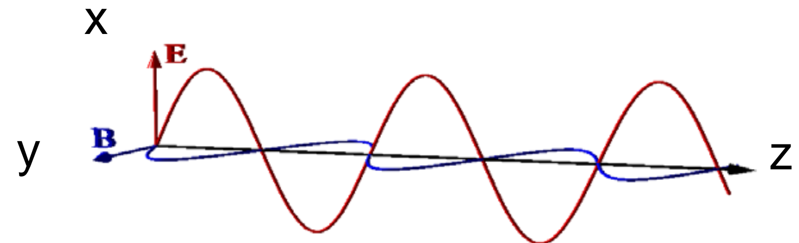
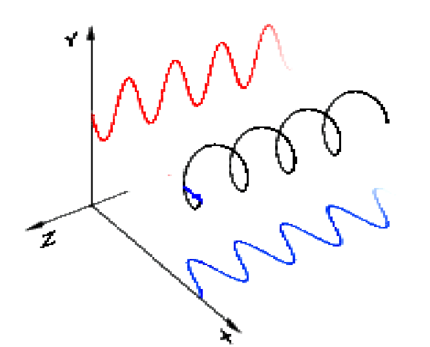


Image: http://www.kristoflodewijks.be/wp-content/uploads/2013/02/EMwave.gif

Polarization of light

monochromatic plane wave traveling in + z direction

$$\vec{E}(\vec{r},t)=\begin{pmatrix}E_x\\E_y\\0\end{pmatrix}=\begin{pmatrix}A_x\cos(\varpi\cdot t-\vec{k}\cdot\vec{r}+\delta_x)\\A_y\cos(\varpi\cdot t-\vec{k}\cdot\vec{r}+\delta_y)\\0\end{pmatrix}$$



States of polarization:

Special case: Linear Polarization
x,y partial waves have phase lag $\delta=\delta_y - \delta_x$ of $\delta = \pm a\cdot\pi$, a={0,1,2,..}

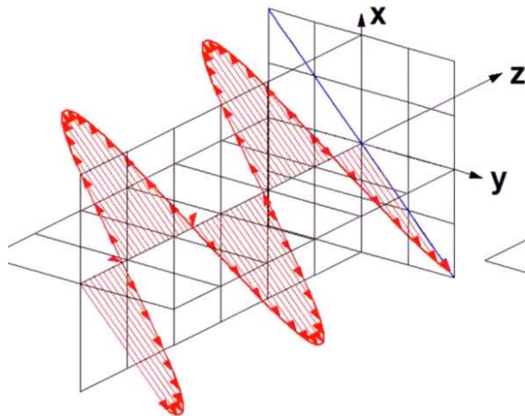
$$E_x=\pm\frac{A_x}{A_y}E_y$$

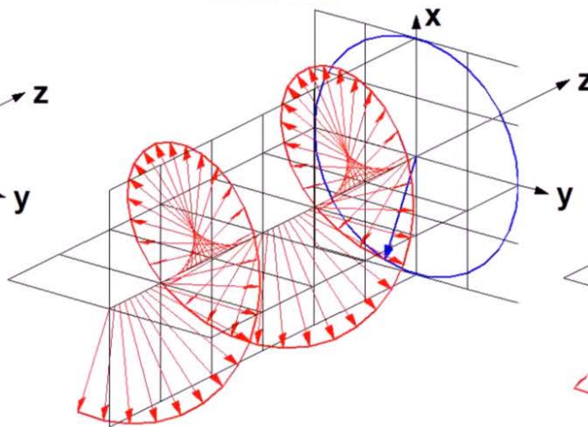
Special case: Circular Polarization
Phase lag $\delta = \pi/2 \pm a\cdot\pi$, a={0,1,2,..}
Amplitudes: $A_x=A=\pm A_y$, $A>0$

$$E_x^{\ 2}+E_y^{\ 2}=A^2$$

General case: Elliptical Polarization
x,y partial waves have arbitrary phase lag δ and arbitrary amplitudes A_x , A_y.

$$\frac{E_x^{\ 2}}{A_x^{\ 2}}+\frac{E_y^{\ 2}}{A_y^{\ 2}}-2\frac{E_xE_y}{A_xA_y}\cos(\delta)+\cos^2(\delta)=1$$





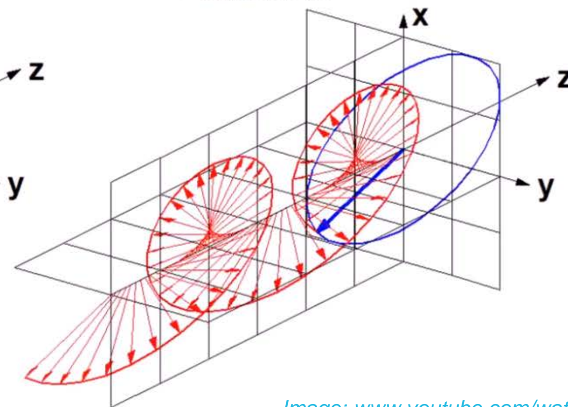


Image: www.youtube.com/watch?v=Q0qrU4nprB0

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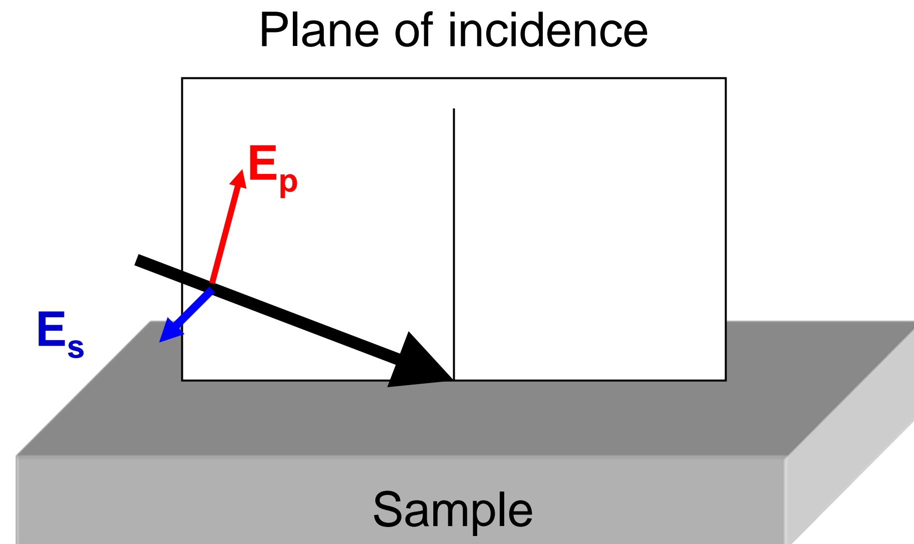
Polarization of light – „s“ and „p“ polarization

- When considering a plane wave incident on an interface, it is favourable to decompose it into two orthogonal waves polarized linearly

  perpendicular (s) and parallel (p)

  to the plane of incidence respectively.

$$\vec{E}(\vec{r},t)=\begin{bmatrix} E_p \\ E_s \end{bmatrix}=\begin{bmatrix} A_p\cos(\varpi\cdot t-\vec{k}\cdot\vec{r}+\delta_p) \\ A_s\cos(\varpi\cdot t-\vec{k}\cdot\vec{r}+\delta_s) \end{bmatrix}$$



Reflection / transmission by a single interface

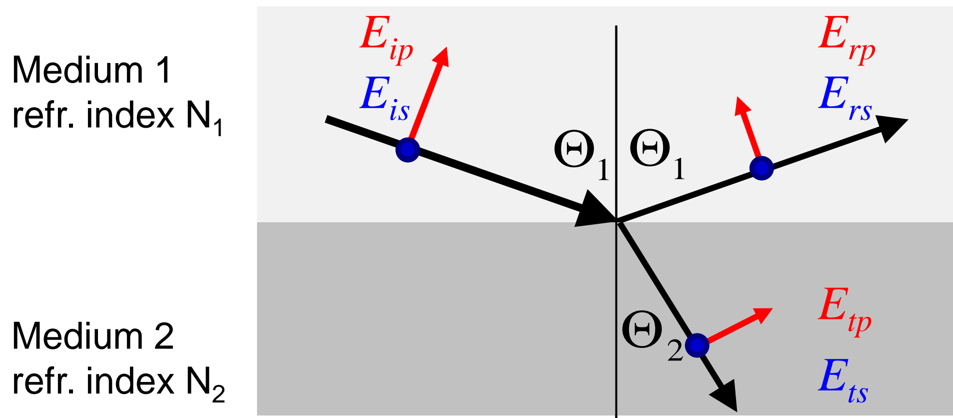
Considering Maxwell's equations and boundary conditions at interfaces (continuity of E||, B⊥, D⊥, H||) an equation for reflection and transmission coefficients for p and s waves can be derived.

Fresnel equations for reflection / transmission at a single interface

$$t_{12p} = \frac{E_{tp}}{E_{ip}} = \frac{2N_1 \cos\Theta_1}{N_2 \cos\Theta_1 + N_1 \cos\Theta_2} \qquad r_{12p} = \frac{E_{rp}}{E_{ip}} = \frac{N_2 \cos\Theta_1 - N_1 \cos\Theta_2}{N_2 \cos\Theta_1 + N_1 \cos\Theta_2}$$

$$t_{12s} = \frac{E_{ts}}{E_{is}} = \frac{2N_1 \cos\Theta_1}{N_1 \cos\Theta_1 + N_2 \cos\Theta_2} \qquad r_{12s} = \frac{E_{rs}}{E_{is}} = \frac{N_1 \cos\Theta_1 - N_2 \cos\Theta_2}{N_1 \cos\Theta_1 + N_2 \cos\Theta_2}$$

t_{12p}, t_{12s}, r_{12p}, r_{12s} are the Fresnel amplitude transmission and reflection coefficients for p and s waves for a single interface respectively.



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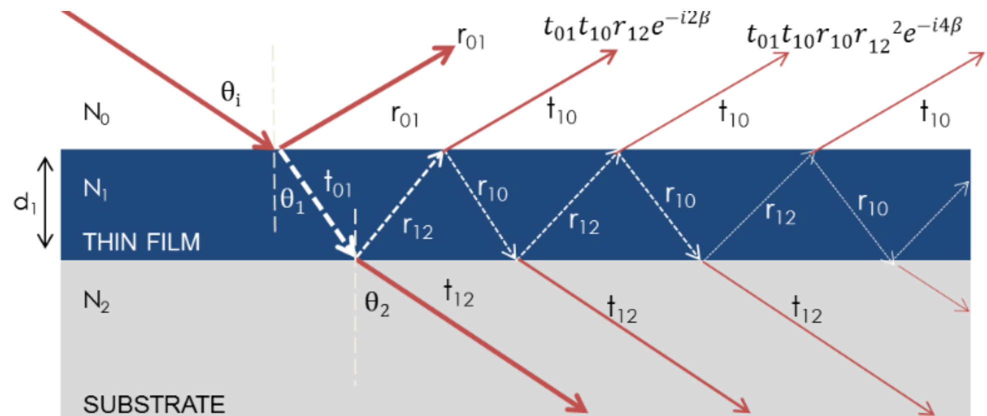
Reflection of single film on substrate

- For multiple interfaces, multiple reflections must be considered.
- The **overall complex amplitude reflection coefficients** are called **Rs and Rp.**
- The case single film on surface has an analytical solution*:

$$R_p = \frac{E_{rp}}{E_{ip}} = \frac{r_{01p} + r_{12p}\exp(-i2\beta)}{1 + r_{01p}r_{12p}\exp(-i2\beta)}$$

$$R_s = \frac{E_{rs}}{E_{is}} = \frac{r_{01s} + r_{12s}\exp(-i2\beta)}{1 + r_{01s}r_{12s}\exp(-i2\beta)}$$

$$\beta = 2\pi\left(\frac{d_1}{\lambda}\right)N_1\cos(\theta_i)$$



- Higher multilayer systems are solved numerically using recursive algorithms.

Image: https://www.jawoollam.com/resources/ellipsometry-tutorial/interaction-of-light-and-materials
Derivation: W.N. Hansen J. Opt. Soc. Of America, Vol 58, Nr. 3, pp. 380-390 (1968)

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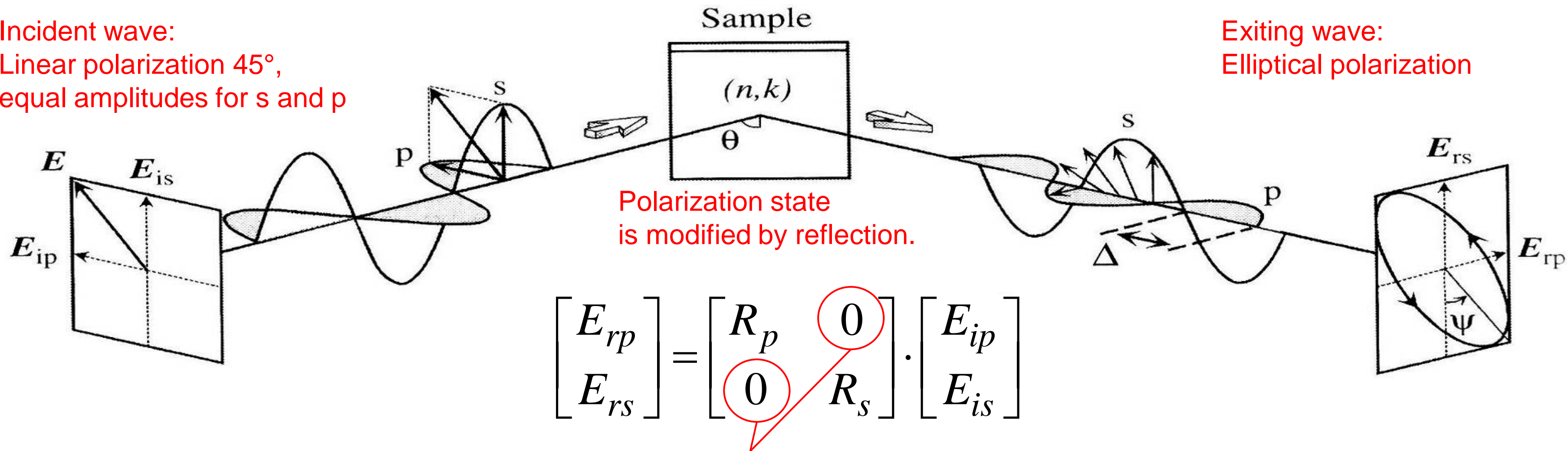
Measurement principle of ellipsometry

Image Source:
Hiroyuki Fujiwara:
"*Spectroscopic ellipsometry : principles and applications.*"
Whiley 2007
DOI: 10.1002/9780470060193



$$\begin{bmatrix} E_{rp} \\ E_{rs} \end{bmatrix} = \begin{bmatrix} R_p & 0 \\ 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} E_{ip} \\ E_{is} \end{bmatrix}$$

Here isotropic materials (cubic symmetry, amorphous) are assumed. s and p waves do not mix upon reflection.
In case of optical anisotropy off-diagonal elements are non-zero, i.e. E_{ip} influences E_{rs}. → Covered by "generalized ellipsometry", not presented here.

- **Ellipsometry measures the change in polarization** in terms of Δ, the change in phase lag between s and p waves, and tan Ψ, the ratio of amplitude diminutions.

$$\Delta = \left(\delta_{rp} - \delta_{rs}\right) - \left(\delta_{ip} - \delta_{is}\right) \qquad \tan\Psi = \frac{|E_{rp}|/|E_{ip}|}{|E_{rs}|/|E_{is}|}$$

$$R_p = |E_{rp}|/|E_{ip}| \cdot e^{i(\delta_{rp} - \delta_{ip})}$$

$$R_s = |E_{rs}|/|E_{is}| \cdot e^{i(\delta_{rs} - \delta_{is})}$$

- **"Basic equation of ellipsometry"**
  (Here ρ is called "relative polarization ratio").

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

Elements of model analysis

- Flowchart of ellipsometry data analysis
- Parametric dispersion models: Description of optical constants vs. wavelength with few parameters

Flow of ellipsometry data analysis

Measure experimental data

↓

Setup sample model and generate data

↓

Fit generated to experimental data
Simulate data. Minimize deviation between experimental and simulated data by model parameter adjustment.

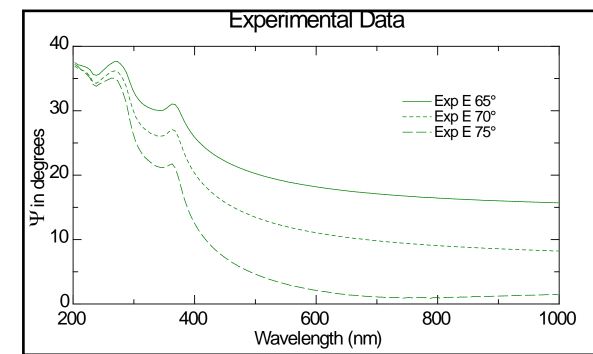
Good fit obtained | No good fit: Change model! (→ back to setup sample model)

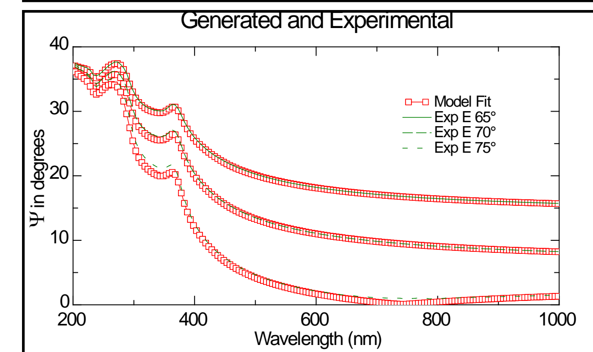
Extract model parameters
Optical constants, thickness, roughness …

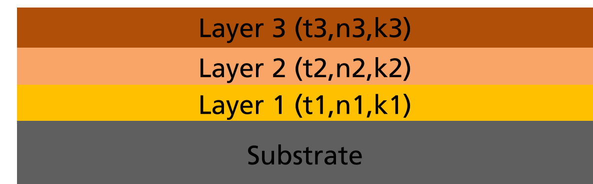
↓

Judge results, check for plausibility
Consider possible parameter correlations, confidence limits…

All ok: **DONE** | Not plausible: improve model (→ back to setup sample model)







User knowledge required:

- Basic sample structure: layers, interfacial layers, roughness
- Dispersion models ni(λ), ki(λ)
- Initial parameter values

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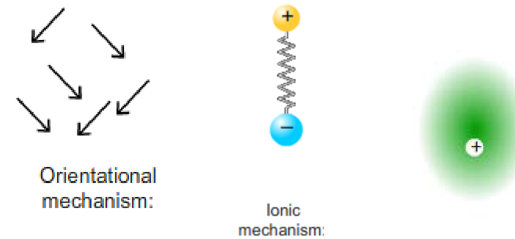
The dispersion of permittivity and optical constants

The wavelength dependence or dispersion of optical constants is governed by

- Electronic mechanism
- Ionic mechanism
- Orientational mechanism

In the visible and UV spectral range resonances of electronic polarization occur.

Depending on material and spectral range different **dispersion models** models are used. Advantage: description of the dispersion of optical constants with few model parameters.



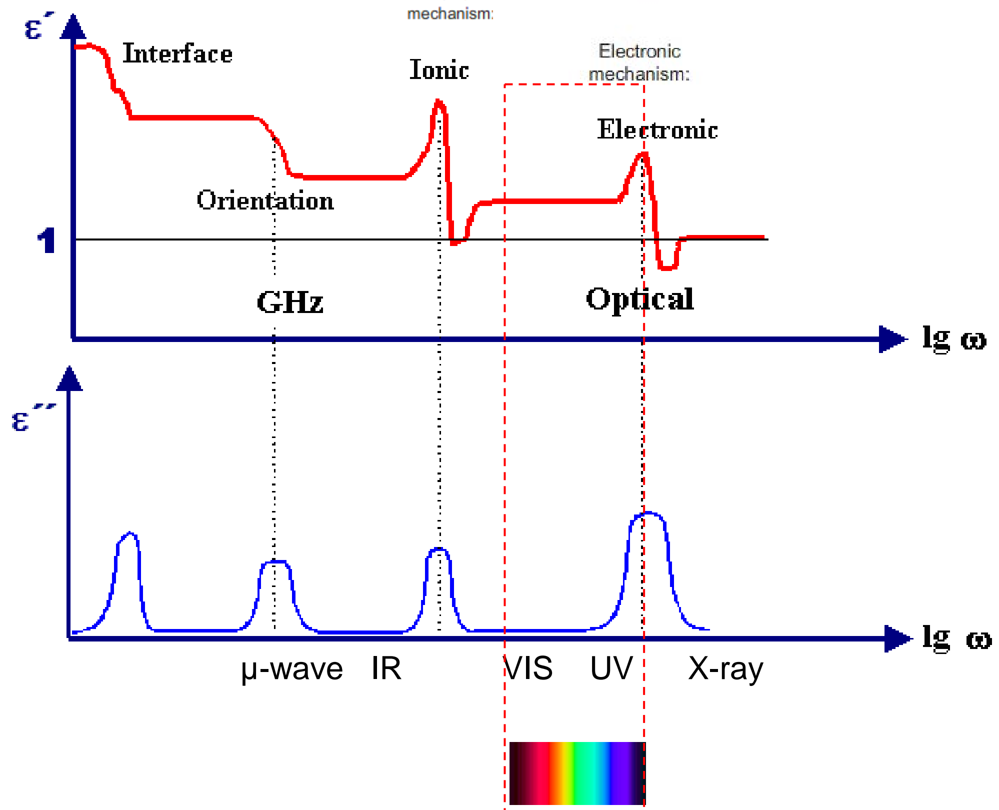


Image sources:
https://www.doitpoms.ac.uk/tlplib/dielectrics/variation.php
http://www.tf.uni-kiel.de/matwis/amat/elmat_en/kap_3/backbone/r3_3_5.html

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Parametric models: Sellmeier model – normal dispersion

- Empirical model published in 1871 by Wolfgang von Sellmeier (1)
- „Sellmeier transparent“ dispersion for non-absorbing materials (2)

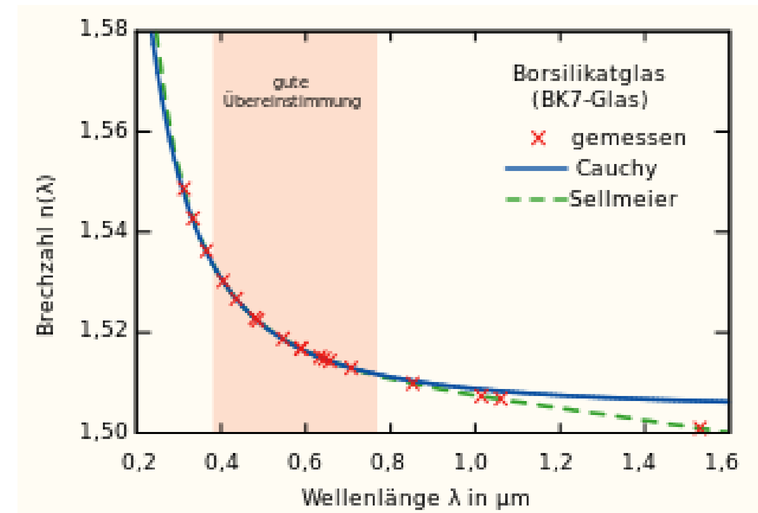
$$n^2(\lambda) = A + B \times \frac{\lambda^2}{\lambda^2 - \lambda_0^2}$$

$$k(\lambda) = 0$$

- „Sellmeier absorbing“ dispersion for weekly absorbing materials (2)

$$n^2(\lambda) = \frac{1 + A}{1 + \frac{10^4 \cdot B}{\lambda^2}}$$

$$k(\lambda) = \frac{C}{10^{-2} \cdot n \cdot D \cdot \lambda + \frac{10^2 \cdot E}{\lambda} + \frac{1}{\lambda^3}}$$



Comparison of Cauchy and Sellmeier fits to refactive index of BK7 glass (3)

References:

(1) Wolfgang von Sellmeier: *Zur Erklärung der abnormen Farbenfolge in Spectrum einiger Substanzen*. In: *Annalen der Physik und Chemie*. 143, 1871, S. 272–282, doi:10.1002/andp.18712190612

(2) http://www.horiba.com/fileadmin/uploads/Scientific/Downloads/OpticalSchool_CN/TN/ellipsometer/Cauchy_and_related_empirical_dispersion_Formulae_for_Transparent_Materials.pdf

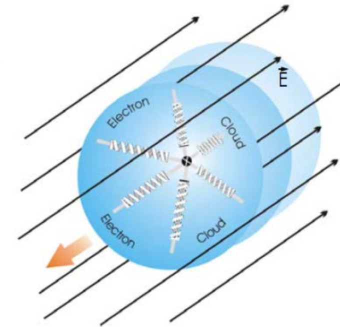
(3) https://de.wikipedia.org/wiki/Sellmeier-Gleichung

Parametric models: Lorentz model - interband transitions

- Model named after Hendrik Antoon Lorentz (1853-1928), published 1878
- Model describes interaction of harmonic light field with bound electronic charges.
- Applicable to transparent and weakly absorbing materials (insulators and semiconductors).

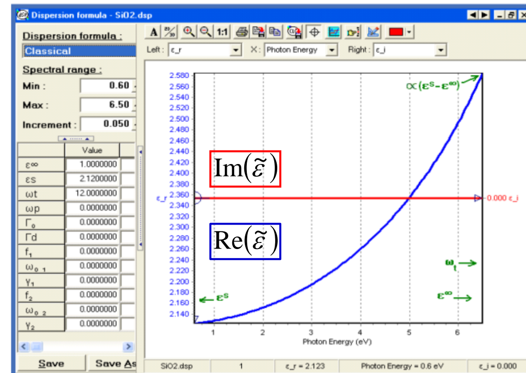
$$m \cdot \frac{d^2\vec{r}}{dt^2} + m \cdot \Gamma_0 \cdot \frac{d\vec{r}}{dt} + m \cdot \omega_t^2 \cdot \vec{r} = -e \cdot \vec{E}_{loc}$$

$$\vec{r}(\omega) = \frac{1}{m} \cdot \frac{-e \cdot \vec{E}_{loc}}{\left(\omega_t^2 - \omega^2\right) + i \cdot \Gamma_0 \cdot \omega}$$

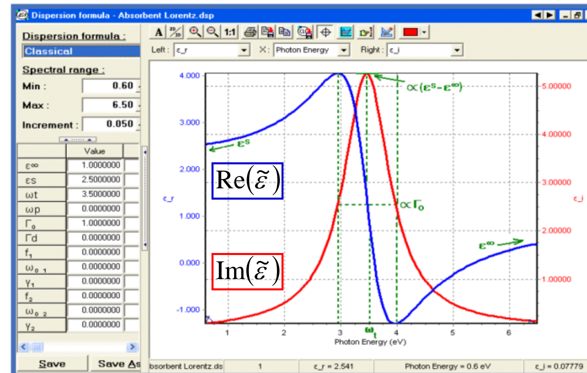


$$\tilde{\varepsilon}(\omega) = \varepsilon_\infty + \sum_{j=1}^{N} \frac{f_j \cdot \omega_{0j}^2}{\omega_{0j}^2 - \omega^2 + i \cdot \gamma_j \cdot \omega}$$

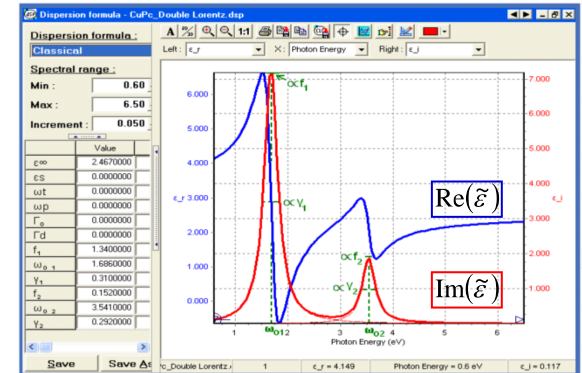
Representation of single-oscillator „Transparent Lorentz function" N=1, γ1=0.



Representation of single-oscillator „Absorbing Lorentz function"



Representation of multiple-oscillator „Absorbing Lorentz function"



Source of images: (*) http://www.horiba.com/fileadmin/uploads/Scientific/Downloads/OpticalSchool_CN/TN/ellipsometer/Lorentz_Dispersion_Model.pdf

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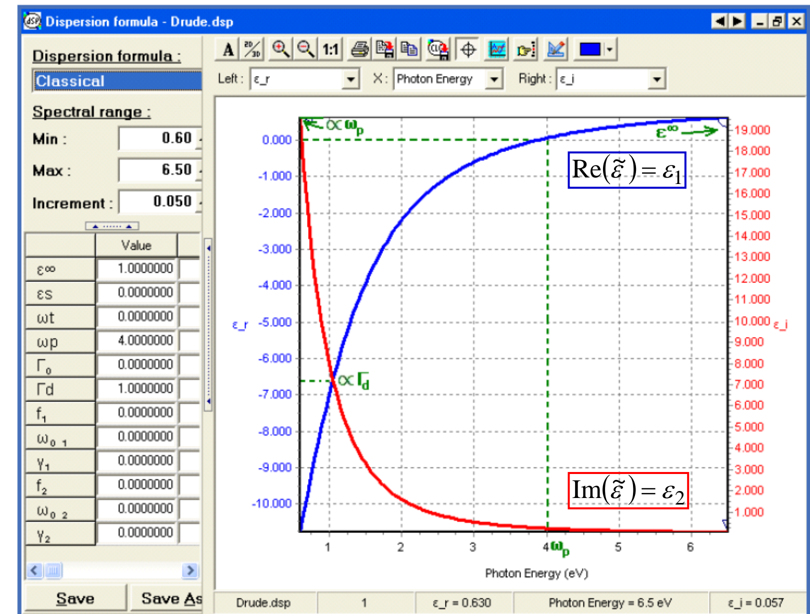
Parametric models: Drude model – free carrier absorption

- The model named after Karl Ludwig Paul Drude (1863-1906) was published 1900*.
- It describes interaction of the light with free electrons. It can be regarded as limiting case of Lorentz model (restoring force and resonance frequency of electrons are null).
- Applicable to metals, conductive oxides and heavily doped semiconductors.
  - Does not take into account the notion of energy band gap Eg in semiconductors and quantum effects

$$\tilde{\varepsilon}(\omega)=1-\frac{Ne^2}{m\varepsilon_0}\cdot\frac{1}{(\omega^2-i\Gamma_d\,\omega)}=1-\frac{\omega_p^2}{-\omega^2+i\cdot\Gamma_d\cdot\omega}$$

$$\varepsilon_1(\omega)=1(\varepsilon(\infty))-\frac{\omega_p^2}{\omega^2+\Gamma^2}\qquad\varepsilon_2(\omega)=\frac{\omega_p^2\cdot\Gamma}{\omega\cdot(\omega^2+\Gamma^2)}$$



- Parameters:
  - Electron density, mass, charge N, m
  - Collision frequency Γ [eV]
  - Plasma frequency $\omega_p=\sqrt{\frac{N\cdot e^2}{m\cdot\varepsilon_0}}$

References
* M. Dressel, M. Scheffler (2006). "Verifying the Drude response". Ann. Phys. **15** (7–8): 535–544. Bibcode:2006AnP...518..535D. doi:10.1002/andp.200510198.
Image: http://www.horiba.com/fileadmin/uploads/Scientific/Downloads/OpticalSchool_CN/TN/ ellipsometer/Drude_Dispersion_Model.pdf

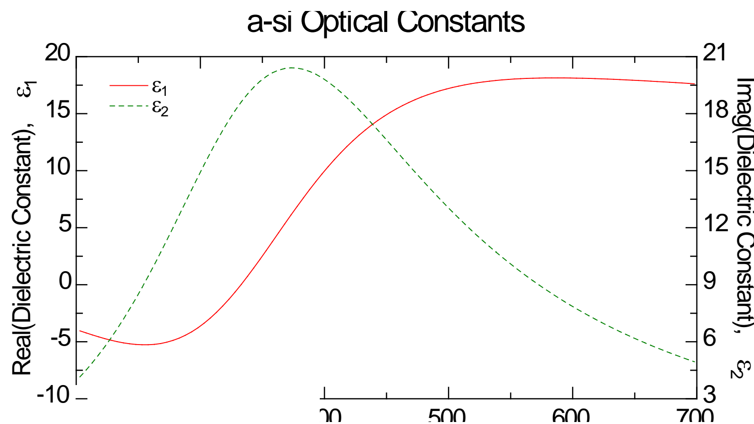
„Tauc-Lorentz Model“: Amorphous materials in interband region

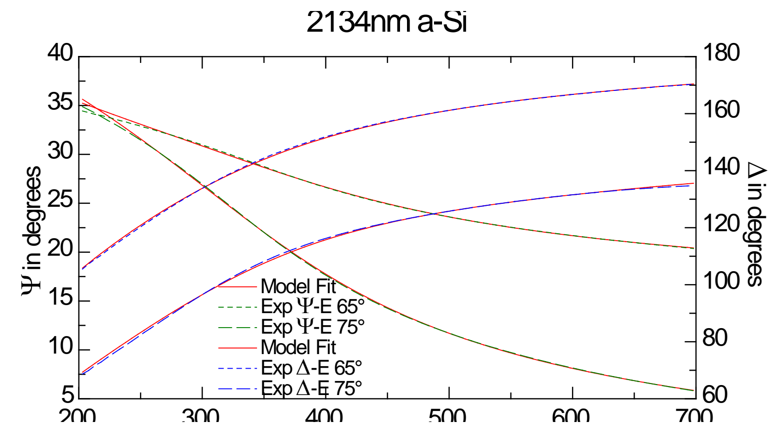
- Published by Jellison and Modine (1996): applicable to SiO2, Si3N4, a-Si, …
- Kramers-Kronig consistent. Neglects intraband absorption.
- Yields meaningful parameters (e.g. opt. band gap E_g).

$$\epsilon_{1\mathrm{TL}}(E)=\epsilon_{1\mathrm{TL}}(\infty)+\frac{1}{2}\frac{A}{\pi}\frac{C}{\zeta^4}\frac{a_{\ln}}{\alpha E_0}\ln\left[\frac{(E_0^2+E_g^2+\alpha E_g)}{(E_0^2+E_g^2-\alpha E_g)}\right]-\frac{A}{\pi\cdot\zeta^4}\frac{a_{\mathrm{atan}}}{E_0}\left[\pi-\mathrm{atan}\left(\frac{2E_g+\alpha}{C}\right)+\mathrm{atan}\left(\frac{-2E_g+\alpha}{C}\right)\right]+2\frac{AE_0C}{\pi\zeta^4}\left\{E_g(E^2-\gamma^2)\left[\pi+2\,\mathrm{atan}\left(\frac{\gamma^2-E_g^2}{\alpha C}\right)\right]\right\}-2\frac{AE_0C}{\pi\zeta^4}\frac{E^2+E_g^2}{E}\ln\left(\frac{|E-E_g|}{E+E_g}\right)+2\frac{AE_0C}{\pi\zeta^4}E_g\ln\left[\frac{|E-E_g|(E+E_g)}{\sqrt{(E_0^2-E_g^2)^2+E_g^2C^2}}\right],$$

$$\epsilon_{2\mathrm{TL}}(E)=\begin{cases}\left[\dfrac{AE_0C(E-E_g)^2}{(E^2-E_0^2)^2+C^2E^2}\cdot\dfrac{1}{E}\right], & E>E_g,\\ =0 & E\leq E_g.\end{cases}$$

Jellison et al., Parameterization of the optical functions of amorphous materials in the interband Region, Appl. Phys. Lett. **69**, 371 (1996); http://dx.doi.org/10.1063/1.118064





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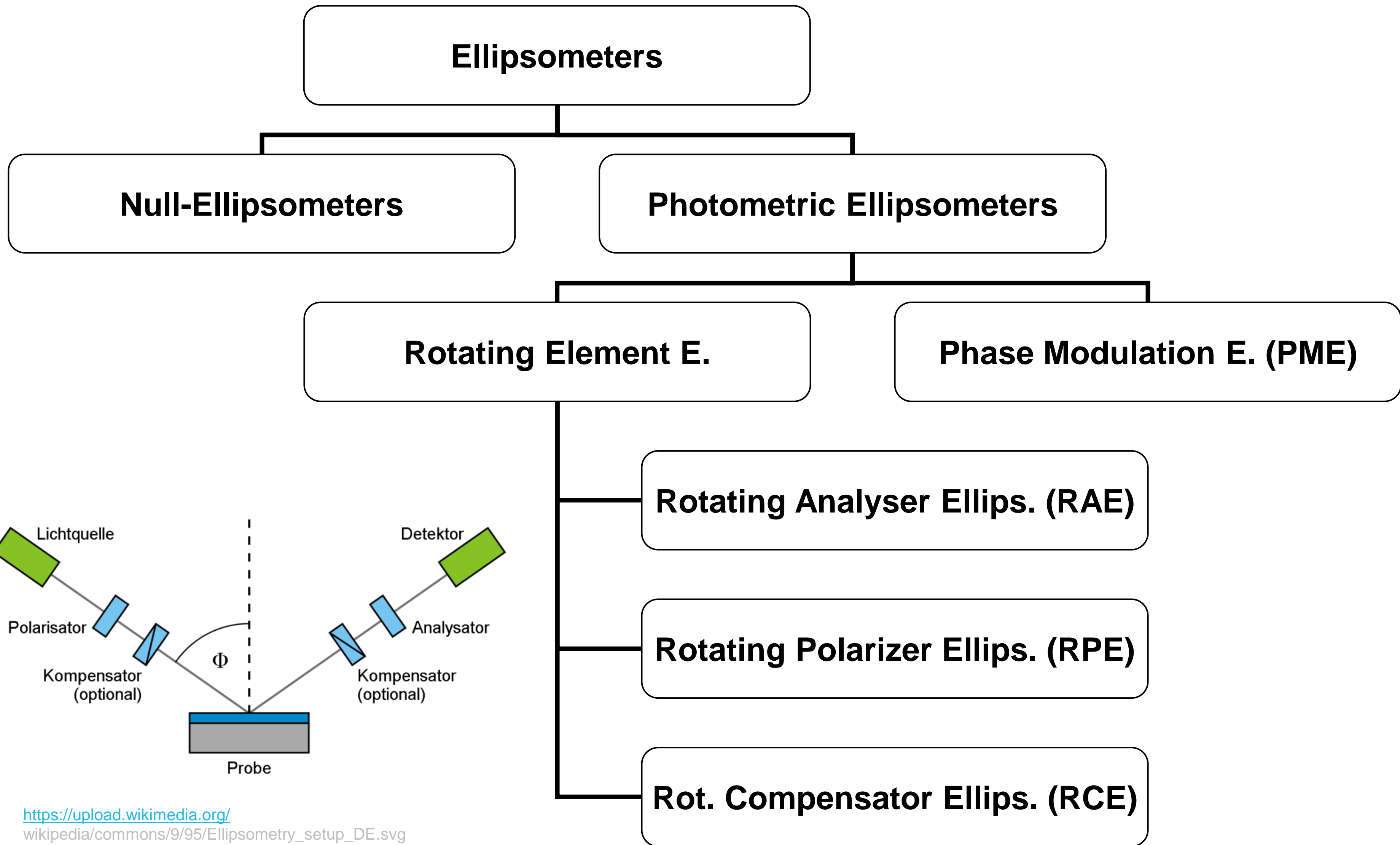
Ellipsometry Instrumentation

Classification of ellipsometers by operation principle



https://upload.wikimedia.org/
wikipedia/commons/9/95/Ellipsometry_setup_DE.svg

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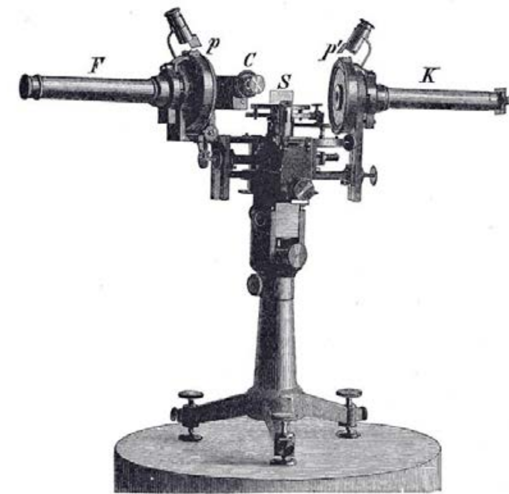
Null Ellipsometer

- Change in polarisation caused by sample is compensated by adjusting polarizer and compensator so that the intensity at the detector detected is „nulled“.
- Now, sample parameters ψ and Δ can be calculated from the known positions of polarizer, analyzer, and compensator.
- In principle no electronics is needed. Eye can be used as detector. Accurate, but slow technique.

- Until the 1970‘s the dominant concept. With advent of computers the faster photometric ellipsometers became more popular.
- Today the concept of Null ellipsometry is still used, e.g. in imaging ellipsometry for visualisation of very thin films.



Historical ellipsometer
Reference: Paul Drude, Lehrbuch der Optik, Leipzig, 1906

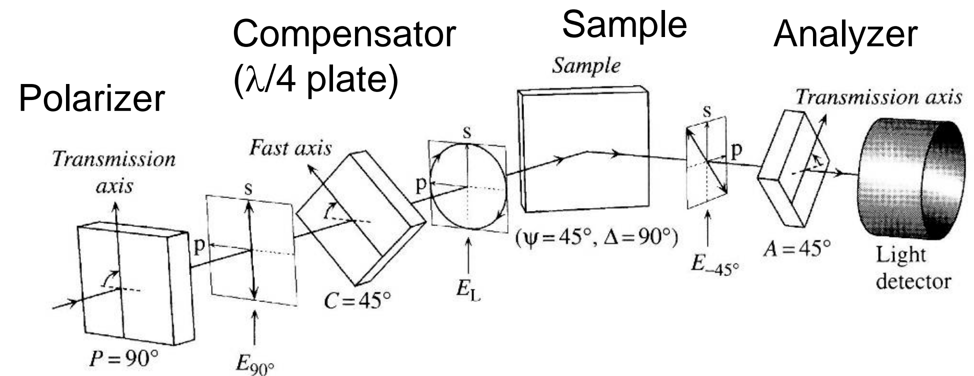


Figure 4.15 Schematic diagram of measurement in null ellipsometry. In this figure, the (ψ, Δ) values of a sample are assumed to be ψ = 45° and Δ = 90°. In this measurement, the detected light intensity is zero.

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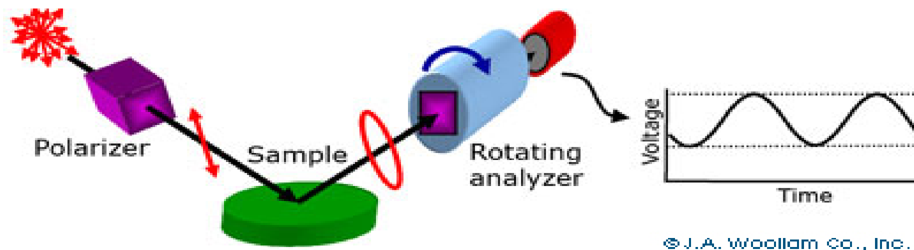
Photometric ellipsometers

Source: Hiroyuki Fujiwara, Spectroscopic Ellipsometry - Principles and Applications, Whiley (2007)

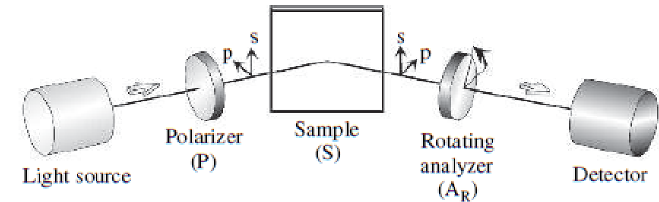
Concept:

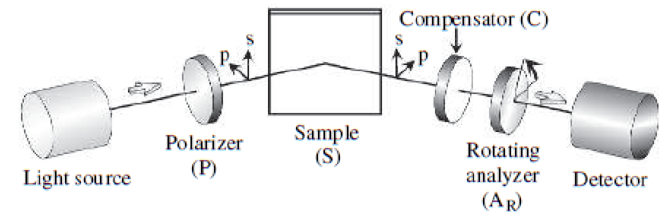
Either a rotating element (polarizer, analyzer, compensator) or an electro-optic phase modulator continuously modulate the beam. A computer calculates from the resulting harmonic intensity signal the ellipsometric data Δ and tan(Ψ).

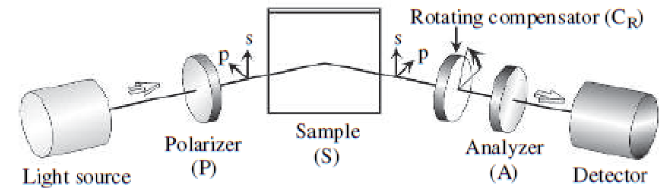
In contrast to the very fast phase modulating ellipsometers, rotating element ellipsometers may measure fast in a wide spectral range.

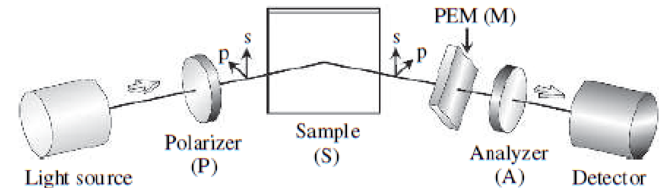


Different photometric ellipsometery variants

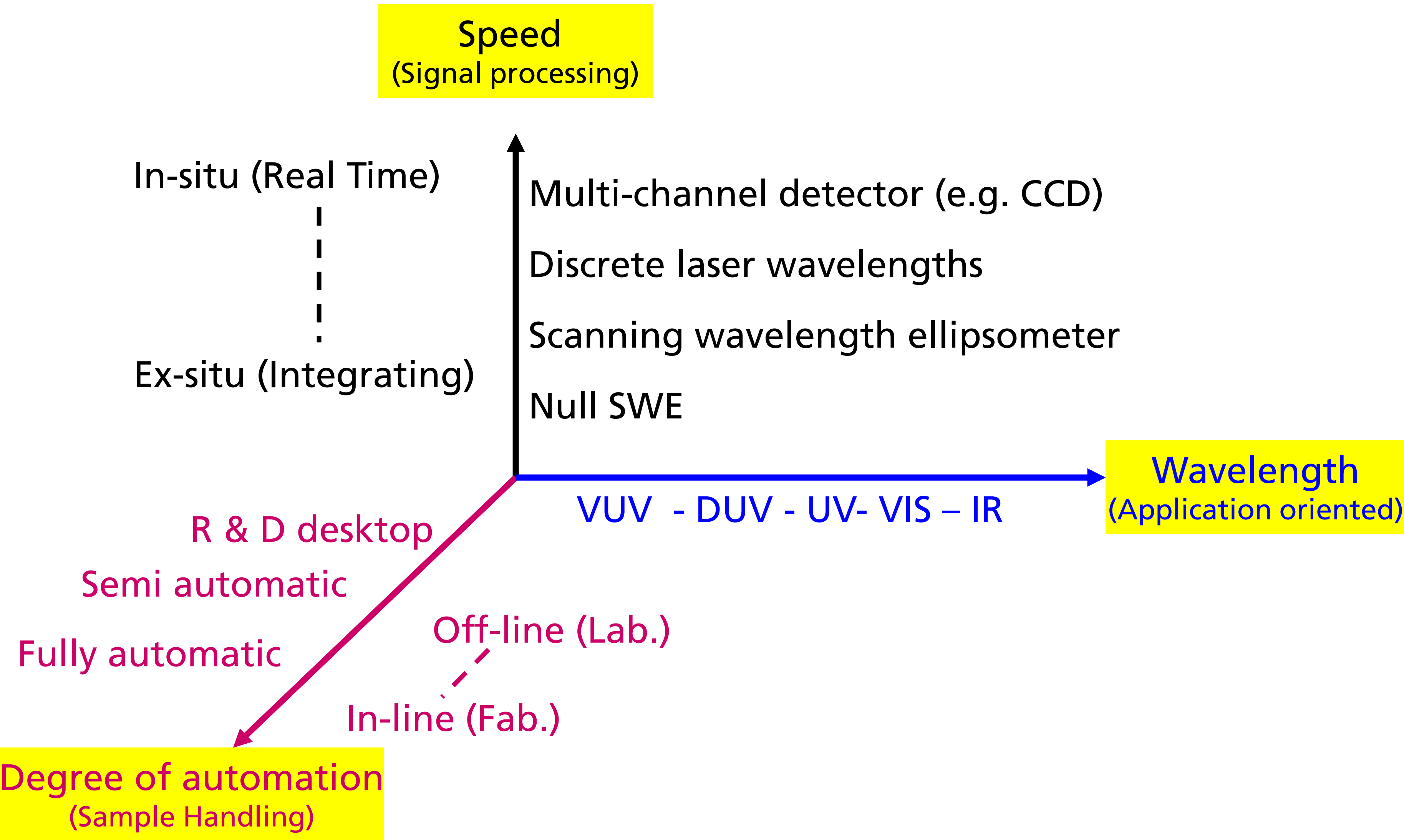








Ellipsometry systems: Classification by speed, wavelength range and automatization



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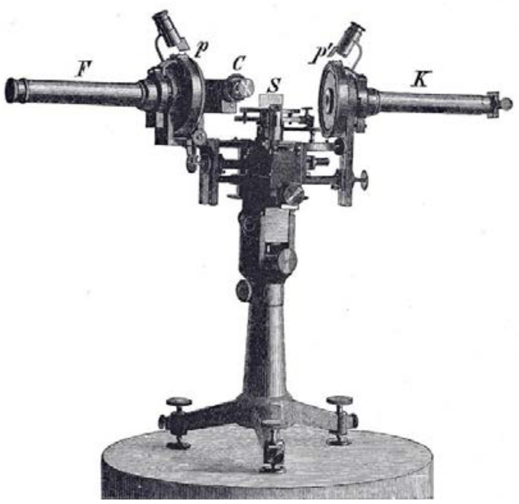
Ellipsometry systems:
Classification by Speed, Wavelength and Automatization

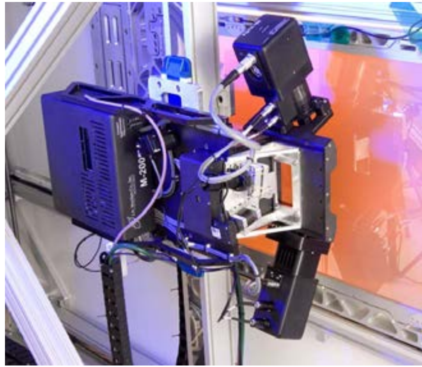


Historical ellipsometer
Reference: Paul Drude, Lehrbuch der Optik, Leipzig, 1906

Alpha-SE (Woollam):
Multi-wavelength 380-900nm, angles: 65°, 70°, 75° or 90°
https://www.jawoollam.com/products

VASE (Woollam):
Scanning wavelength 190-1700nm, variable angle SE
https://www.jawoollam.com/products

IR-VASE MARK II (Woollam) :
Variable angle, scanning wavelength SE. Range 1.7-33µm
https://www.jawoollam.com/download/pdfs/ir-vase-brochure.pdf



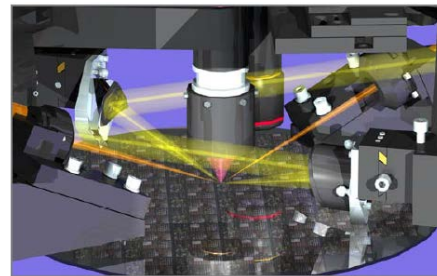
M2000 (Woollam) : real-time SE with high speed CCD detector
https://www.jawoollam.com/products/m-2000-ellipsometer

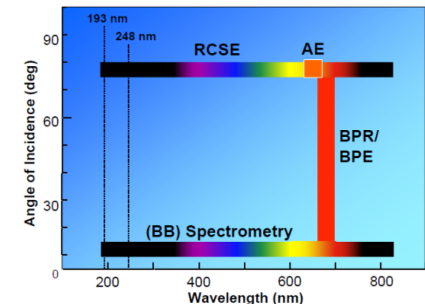
UVISEL 2 VUV (Horiba): 147-2100nm VUV-NIR SE
http://www.horiba.com/scientific/products/ellipsometers/ spectroscopic-ellipsometers/uvisel-vuv/uvisel-2-vuv-23265/

In-line ellipsometer system for wafer fabs: Thermawave Opti-Probe 5240

(Status of 2005)

- Beam Profile **Reflectometer** (BPR)
  - Solid-state laser
  - Angular-dependent film reflectivity data
- Beam Profile **Ellipsometer** (BPE)
  - BPR source and optics
  - Basic polarization data w/ smallest box size
- Absolute **Ellipsometer** (AE)
  - He/Ne laser
  - High precision ellipsometer for the very thinnest films
- Broad-Band **Spectrometer** (BB)
  - Continuous spectral source (190-840nm)
  - Provides spectroscopic characterization of materials
- DUV Rotating Compensator **Spectroscopic Ellipsometry** (RCSE)
  - Continuous spectral source (190-840nm, same source as BB)
  - Complex spectral and phase data for initial multiple parameter characterization of film stacks





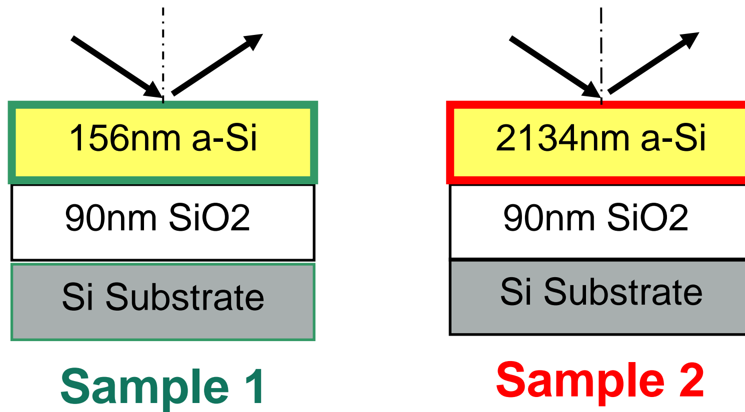
Potential of Spectroscopic Ellipsometry

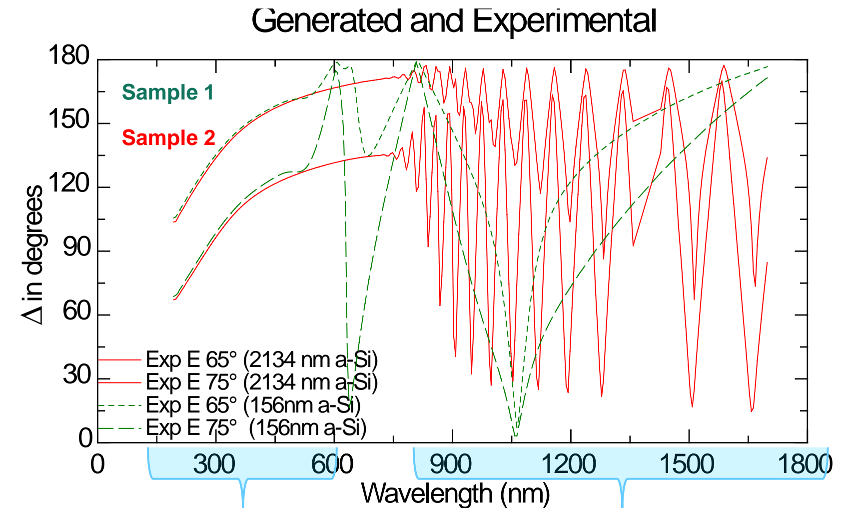
EXAMPLARY APPLICATIONS OF ELLIPSOMETRY

Example:
Spectroscopic Ellipsometry of a-Si -
Thickness measurement in transparent spectral region

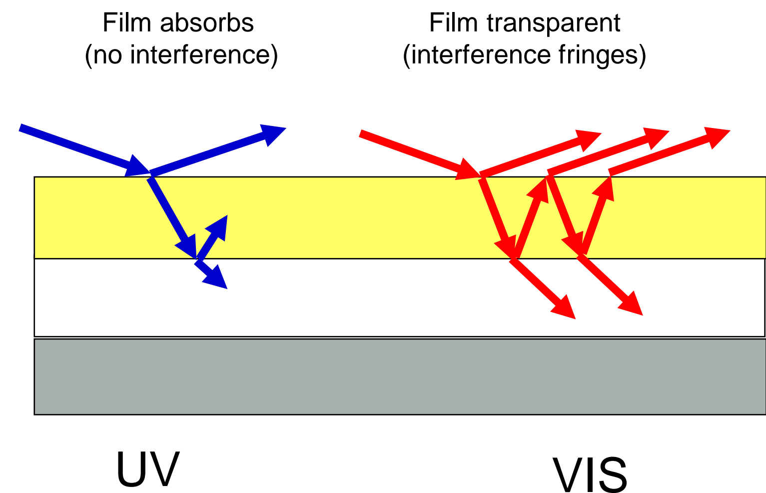
Example: Ellipsometry of UV absorbing films

Thickness measurement of a-Si films





- In DUV-UV where a-Si is strongly absorbing, both datasets coincide:
- Spectra are independent of a-Si thickness, since no reflected light from lower film interface is measured.
- In the transparent region, thickness-dependent interferences are observed.
- Narrow / wide spacing of fringes indicates thinner / thicker film.



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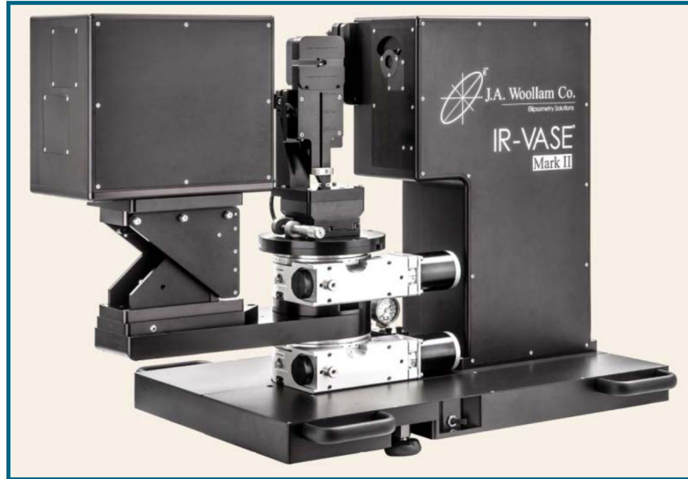
Example:

**Infrared spectroscopic ellipsometry:
Chemical analysis of nm-thick films**

Spectroscopic ellipsometry for specific sample properties

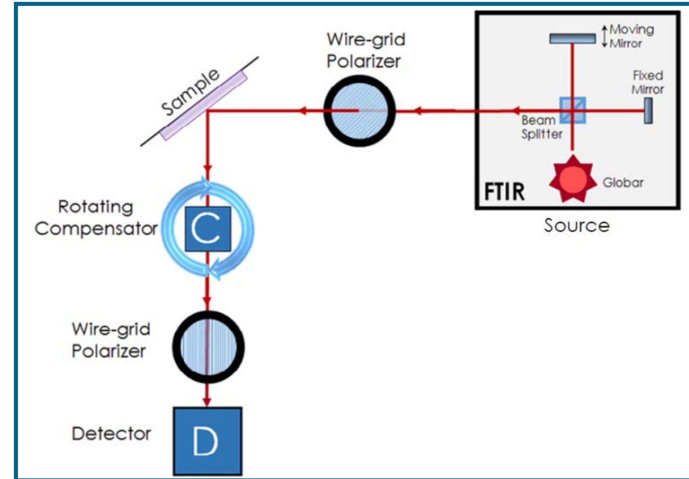
Thickness and chemical nature of nm-thick films by VASE in IR spectral range



Woollam IR-VASE „Mark II“

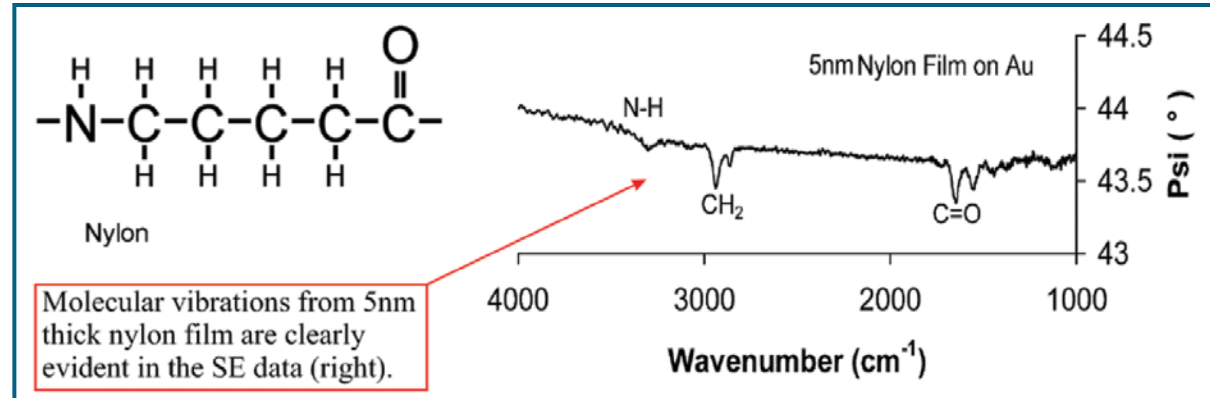
Spectral Range:
1.7-30µm /
333-5900cm^{-1}

Angular range:
32..90°



Benefits of IR-VASE

- n,k in measured spectral range w/o need to extrapolate beyond measured range (as for Kramers-Kronig analysis)
- High sensitivity to thickness and chemical composition
- No reference sample / baseline measurement required.



Summary on Ellipsometry

- Probed is the change in polarization induced by reflection (transmission) of light by a smooth sample.

- By means of model-analysis sample parameters can be deduced.
  - Precise thickness (down to few nm), and roughness of thin films and multilayers
  - Spectroscopic ellipsometry: dielectric constants from VUV to IR

- Advantages of the method are
  - Non-destructive
  - Real-time measurements possible

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http://www.itp.uni-hannover.de/~zawischa/ITP/zweistrahl.html

http://www.titaniumart.com/titanium-info.html

X-ray reflectometry

- Measurement principle
- Examples

X-ray reflectometry: What is it all about

- X-ray reflectometry is a measurement of reflectance vs. angle near grazing incidence at a fixed wavelength in the hard x-ray range.

- The technique allows to investigate
  - thickness of single or multilayers incl. metals
  - interface and surface roughness

- Limitations
  - Requires samples of low roughness
  - Max. measurable thickness limited by angular resolution of primary beam and goniometer. (Typically <150nm.)
  - Size of measurement spot is > some mm2

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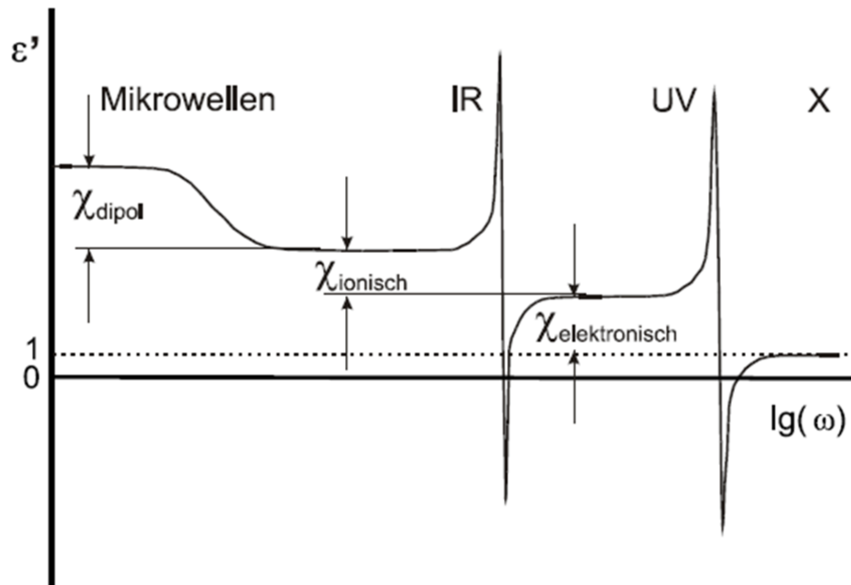
X-ray reflectometry: What is it all about

- For x-rays all materials are quasi transparent. Their optical indices can be expressed as

  $N = 1 - \delta + i\beta$, where δ, β are small (~ 10e-5 ..10e-6)

- Since air is optically more dense than any film, total external reflection is observed at small angle of incidence.



W. Kriegseis, Röntgen-Reflektometrie zur Dünnschichtanalyse, 2002
http://www.uni-giessen.de/cms/fbz/fb07/fachgebiete/physik/lehre/fprak/anleitungen/reflekto2

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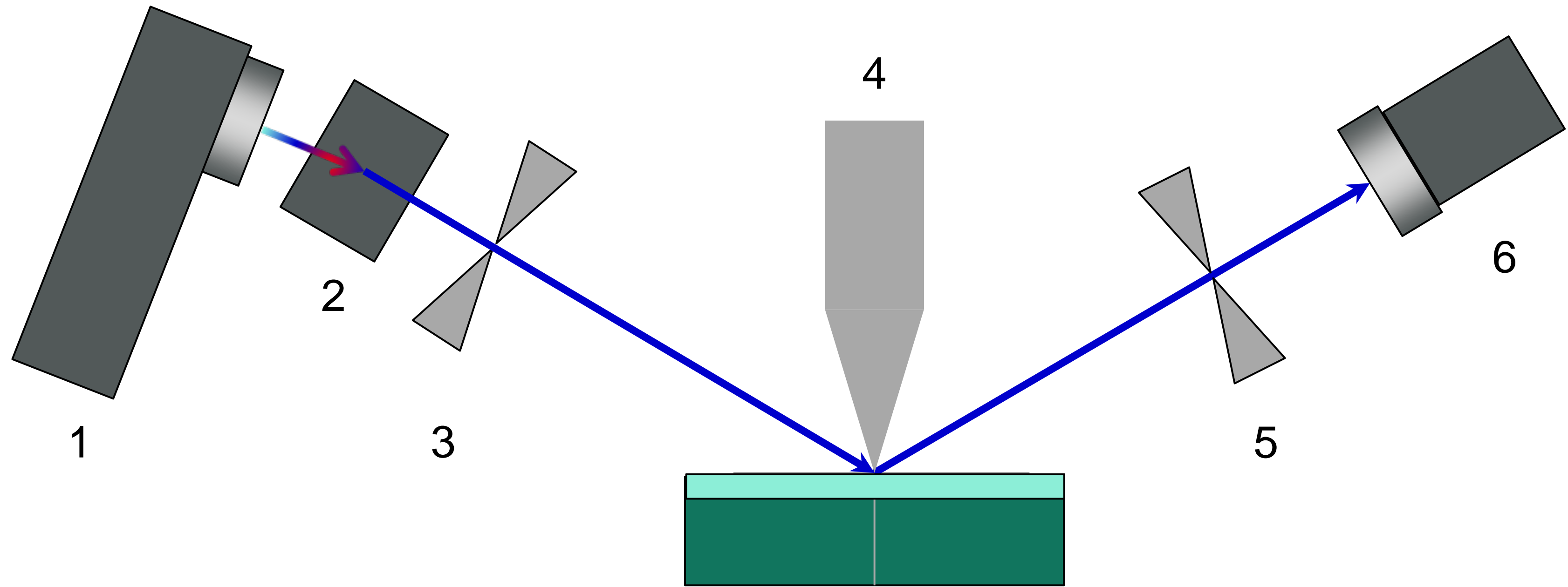
X-ray reflectometry: Measurement setup



#	Component	Function
1	X-ray tube	Emitts divergent polychromatic radiation (char.+braking radiation)
2	Göbel mirror	Multilayer mirror on parab. substrate, spectral filter, collimates beam
3	Slit 1	Beam limiter
4	Knife edge absorber	Limites the analyzed area on sample. Almost touches surface.
5	Slit 2	Beam limiter
6	Detector	Intensity measurement. ~5-6 decades dynamic range.

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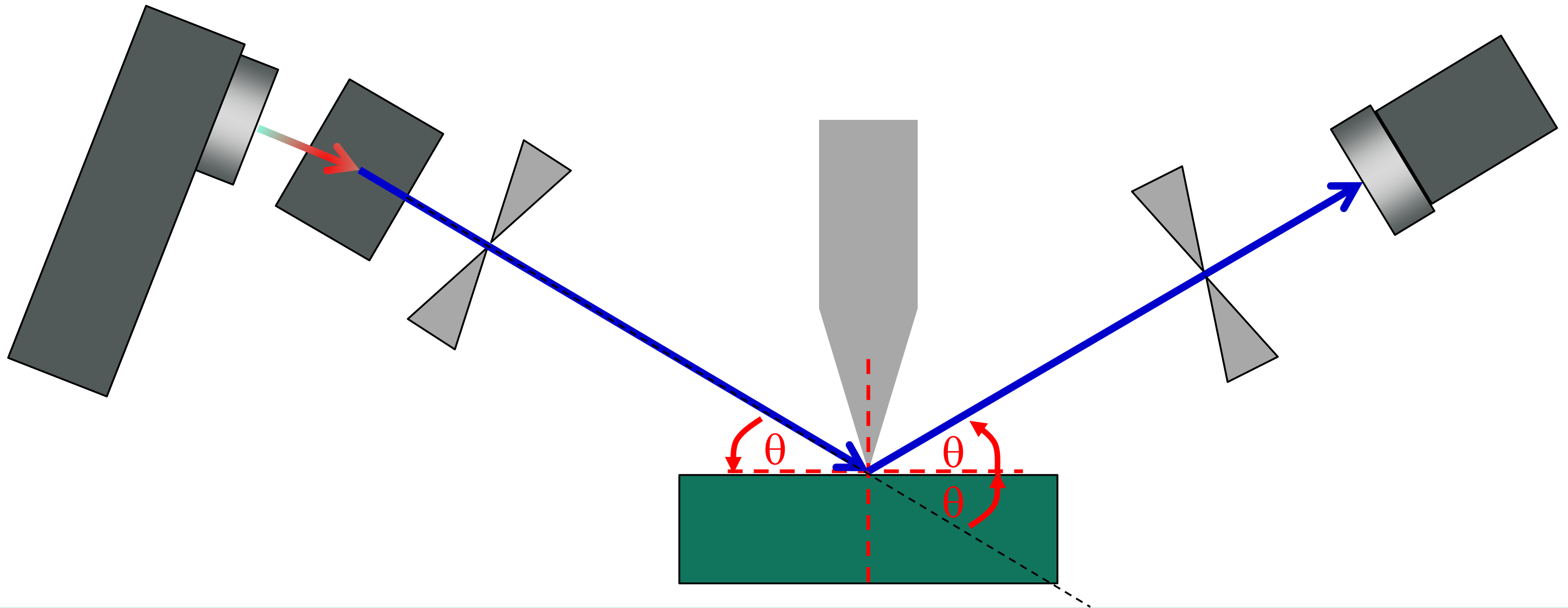
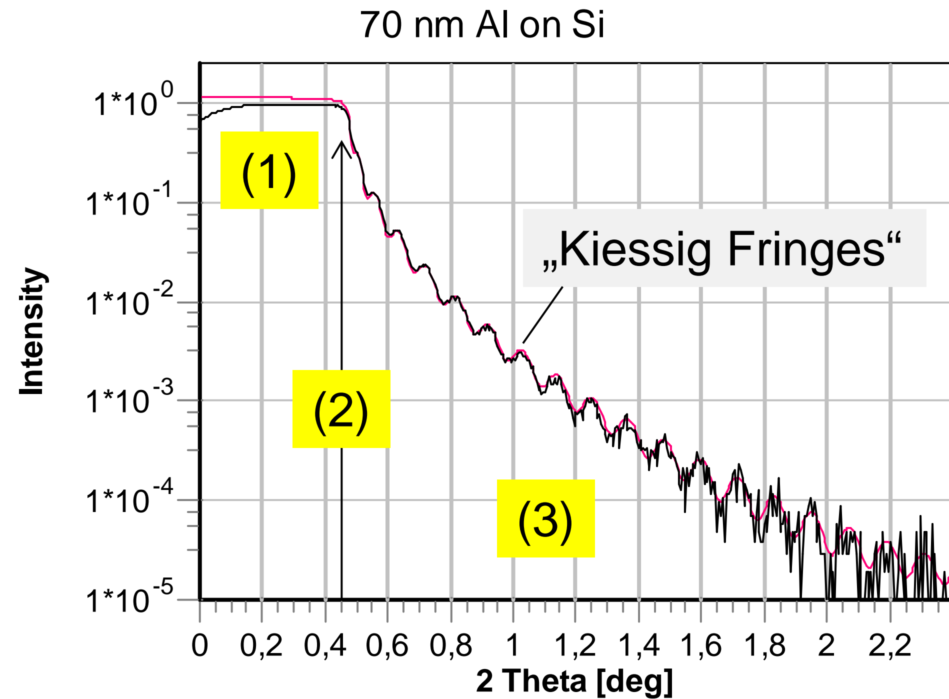
X-ray reflectometry: Measurement principle

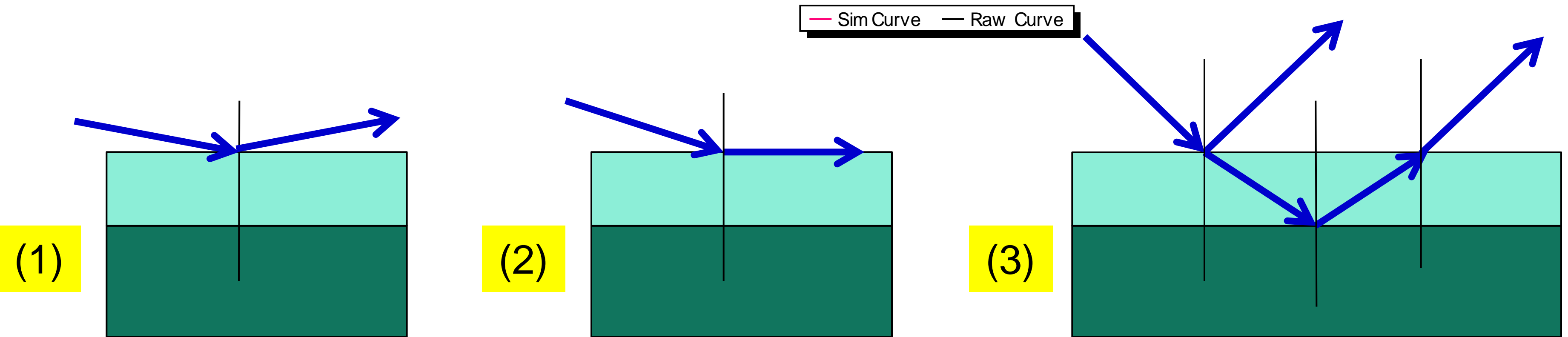
- In a setup with fixed x-ray tube, sample and detector are rotated about a common axis of rotation by angle θ and 2θ respectively.
- Typical values: θ range 0..3 deg, step width $d\theta$ ~ 0.001 to 0.05 deg, depending on film thickness to be measured.



X-ray reflectometry: Understanding data features

1. At small angle of incidence Θ, total external reflection occurrs.
2. At a „critical angle“ Θ_c, evanescent waves exist at the sample surface, but still no beams propagate into the film. Θcrit correlates with mass density of (the top layer of) the sample. Examples: $\Theta_{c,\mathbf{Be}}$=0,186°, $\Theta_{c,\mathbf{Pt}}$=0,583°
3. At higher Θ, diffracted x-rays enter the film, are reflected at interfaces, and leave the sample parallel to the beam reflected at the top surface. Interference causes oscillations in intensity as Θ is varied. From the period of oscillations the film thickness is derived.





X-ray reflectometry: Sensitivity to sample parameters

Single Metal Film + Substrate

Pt film on Si (Simulations)

Legend:

		Sample1	Sample2	Sample3	Sample4	Sample5
Platinum						
Thickness	nm	10	50	50	50	no Pt film
Roughness	nm	0	0	0	1.5	
Density	21.44 g/cm3					
Silicon						
Thickness	infinite					
Roughness	nm	0	0	1.5	0	0
Density	2.23 g/cm3					

- XRR Method is sensitive to
  - Film Thickness
  - Film Roughness
  - Film density
  - Interface Roughness

Intensity
1.E+0
1.E-1
1.E-2
1.E-3
1.E-4
1.E-5
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
2 Theta [deg]
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5

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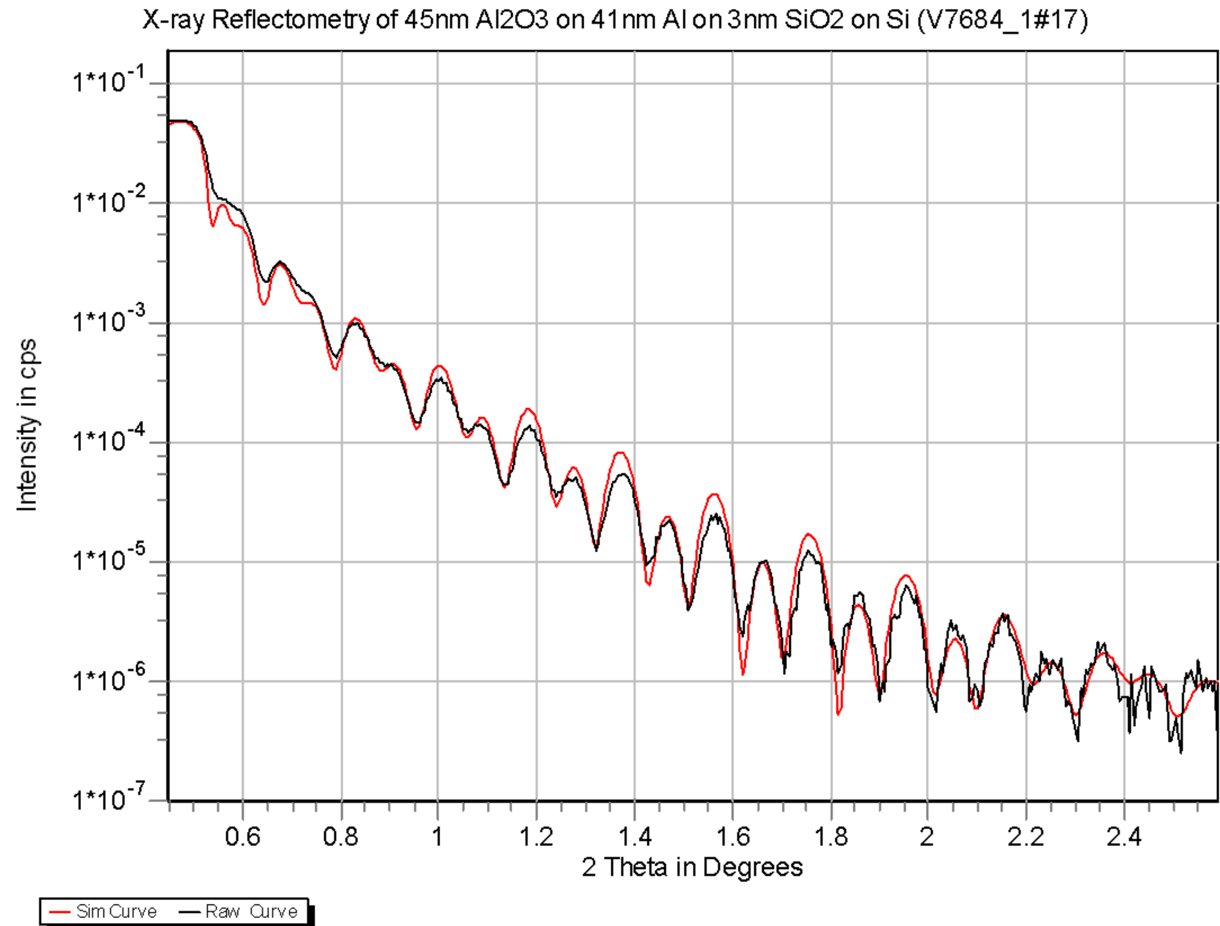
X-ray reflectometry: Application – Reflectors for MEMS

Bilayer + Substrate
Al_2O_3+Al on Si



Summary on X-ray reflectometry

- Probed is x-ray reflectance as function of angle or energy.
- Samples are smooth, unstructured.

- By means of model-analysis sample parameters can be deduced.
  - Very precise thickness (down to sub-nm films), and roughness of thin films and multilayers.
  - Due to low absorption of x-rays, even metal films can be measured.
  - Film density can be estimated.

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Outline

- Ellipsometry
- X-Ray reflectometry
- White light interferometry
  - Application to diffractive MEMS

WHITE LIGHT INTERFEROMETRY (WLI)

- Principle & Instrumentation
- Application to diffractive MEMS

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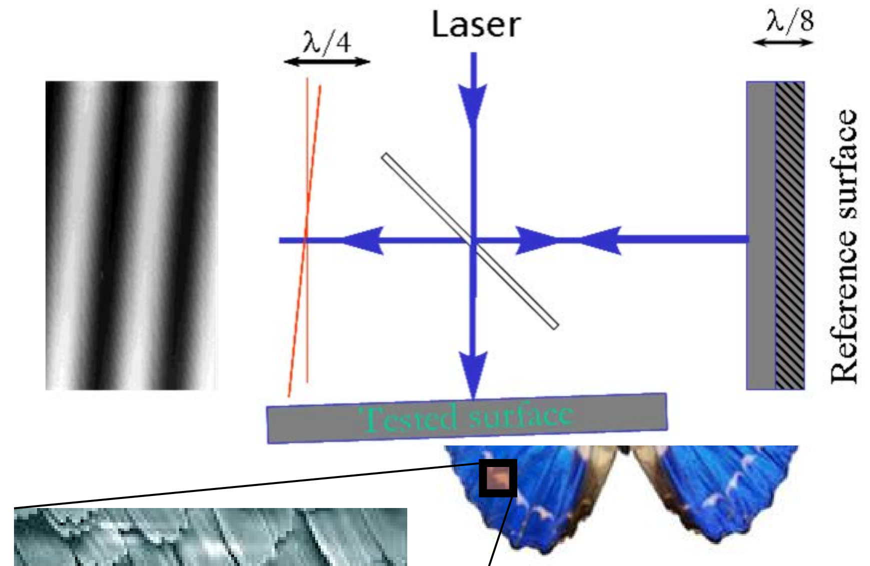
Introduction

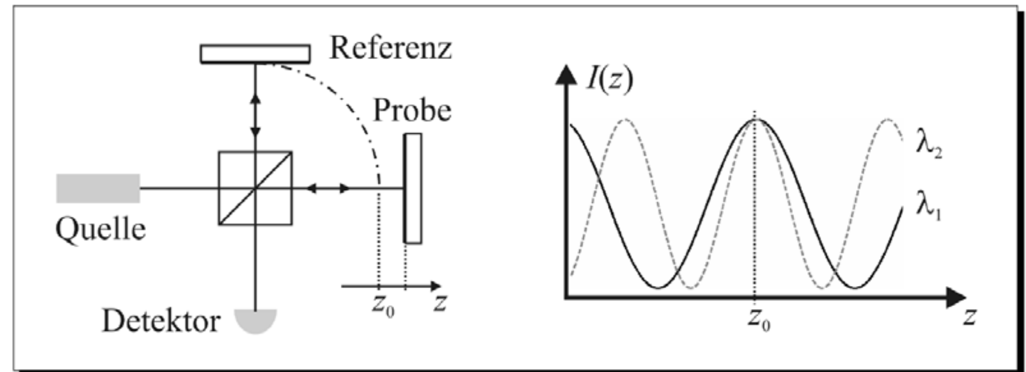
- Interference of light can be used for the precise measurement of surface profiles

"phase shift interferometry"

  - Key: monochromatic light

- Does it make sense to use broad spectra to extract signals of nanostructures unlike classical phase-shift interferometry ?





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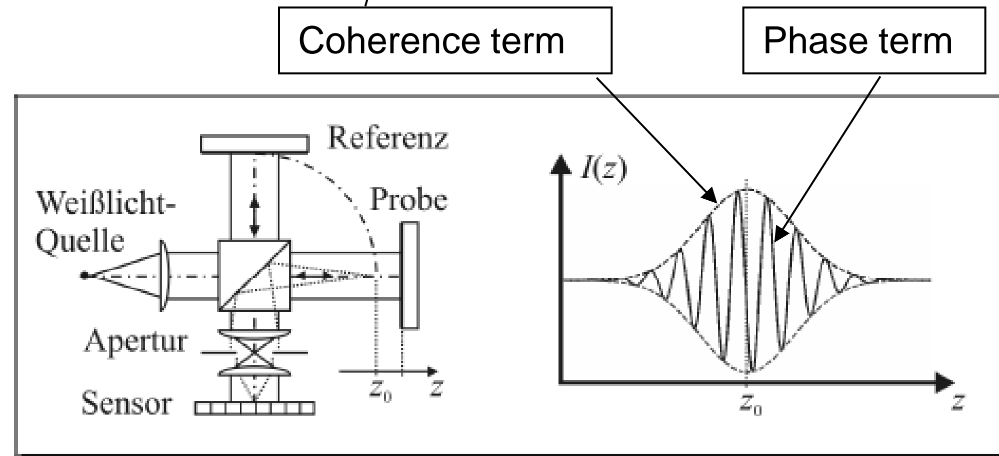
Principle

- Superposition of two polychromatic waves
- Interference signal
  - Standard phase term
  - Spectral coherence function as envelope (key parameter – coherence length l_c)
- Gain
  - Direct determination of the object position - "envelope maximum"

(Resolve ambiguity of phase shift interferometry)

$$E_{Sensor} = E_{reference} + E_{object}$$

$$I_{sig}(z) = I_1 + I_2 \cdot \gamma_{12}(z - z_0)\cos\left[k_0(z - z_0) + \alpha_{12}\right]$$



Sources:
M. Hering, Dissertation (2007) Heidelberg

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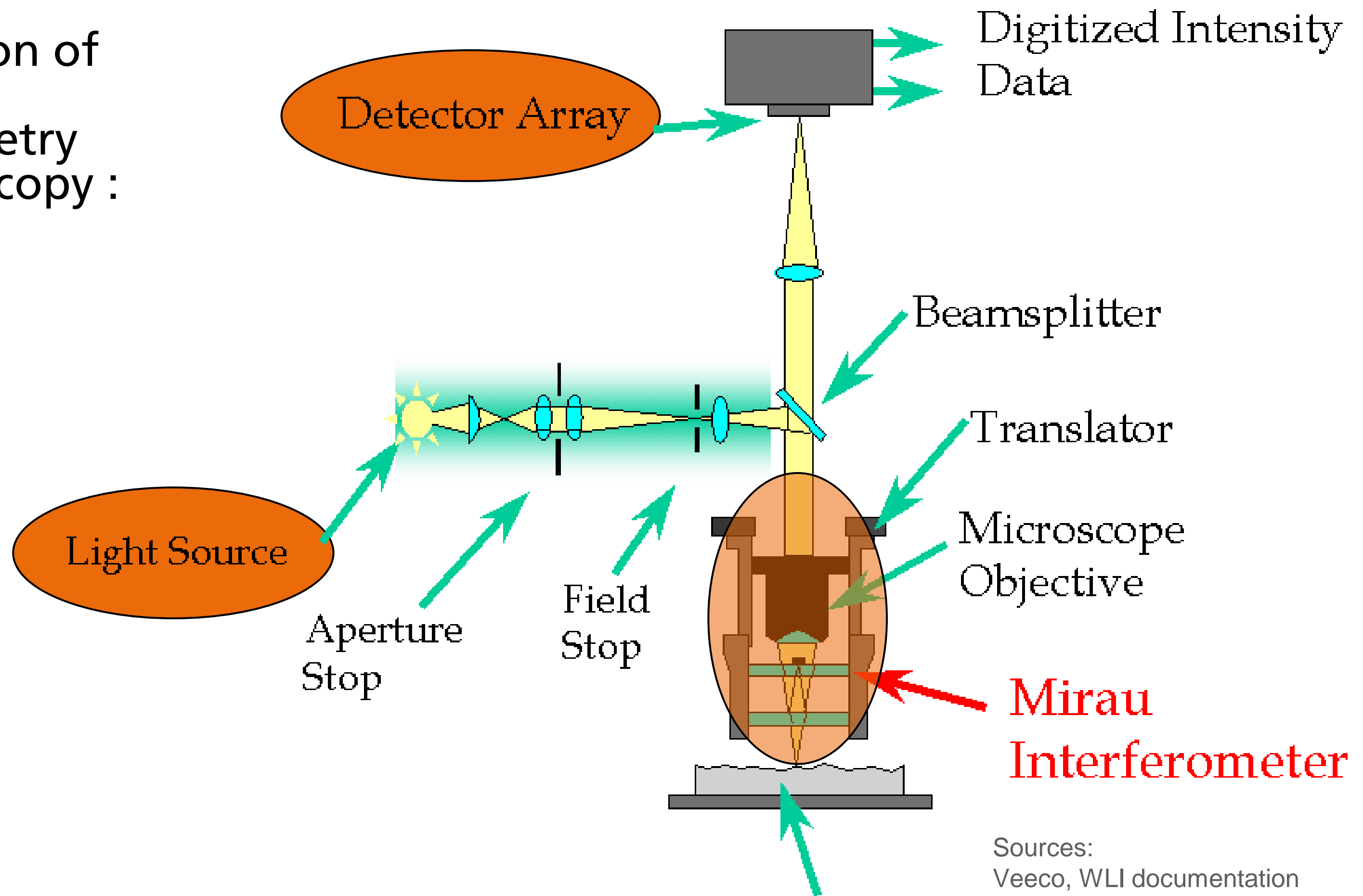
INSTRUMENTATION

Optical analysis of *micro- and nanostructures*

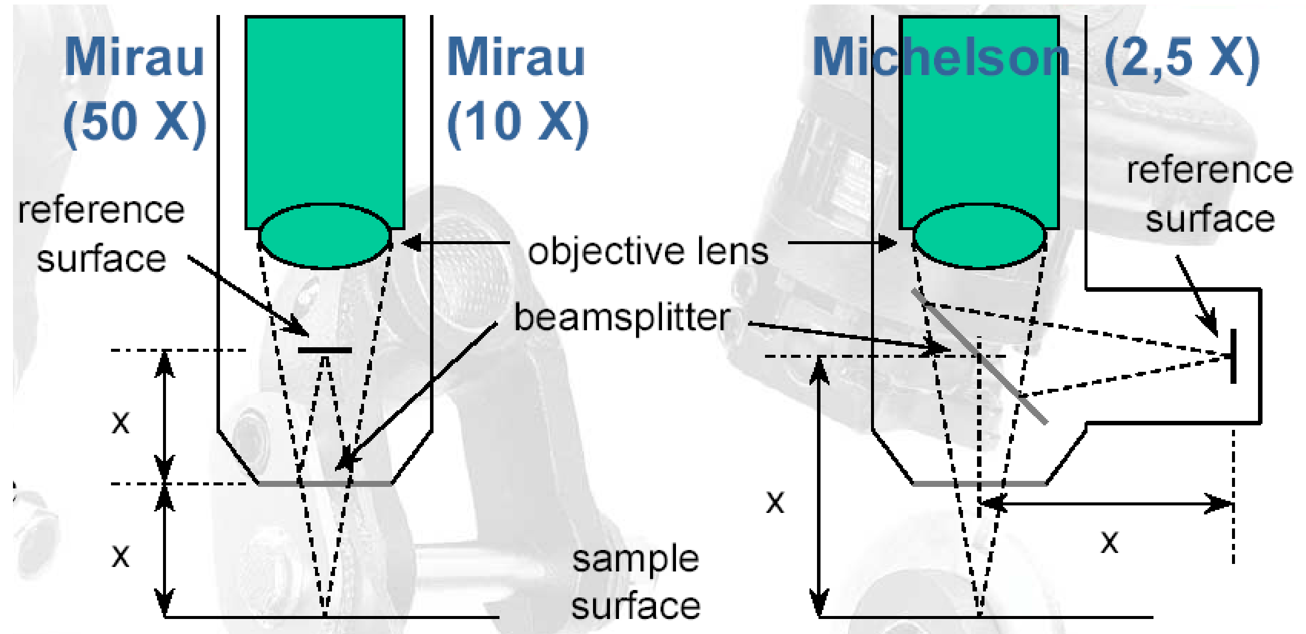
- Combination of white light interferometry and microscopy :



Sources:
Veeco, WLI documentation

Optical analysis of *micro- and nanostructures*

- Optical magnification determines interferometry-principle
- Resolution
  - < 1nm vertical Interferometry
  - <1 µm lateral "Microscopy"
- Through-glass measurement possible



Sources:
Veeco, WLI documentation

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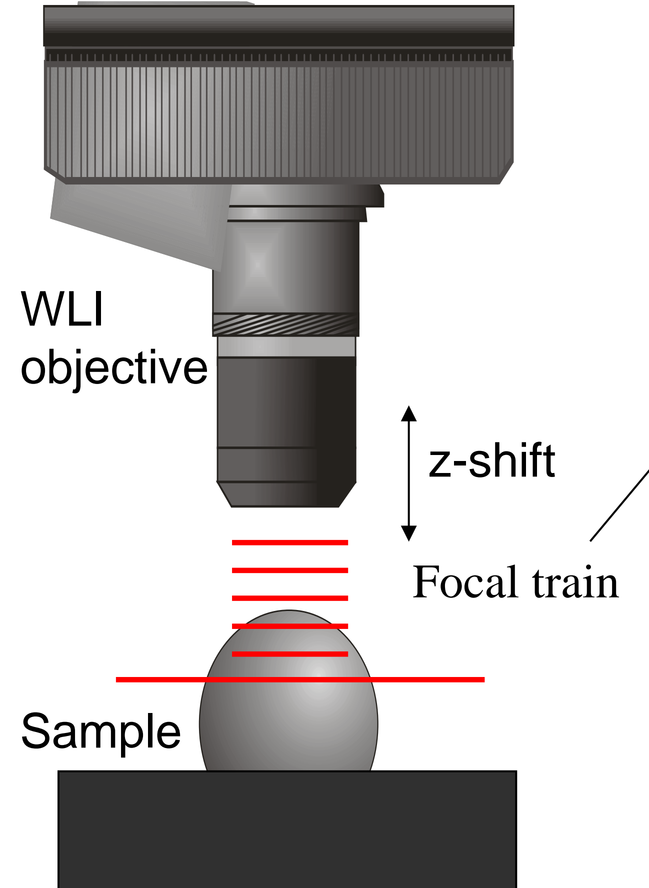
Optical analysis of *micro- and nanostructures*

Illustrated measurement scan:

- Movement of sample, objective or reference plane
- Record intensity at each camera-pixel
- Analyze the pixel-intensity while moving through focus "interferogram"

→ How to extract the surface topography *at each pixel?*



Sources:
Veeco, WLI documentation

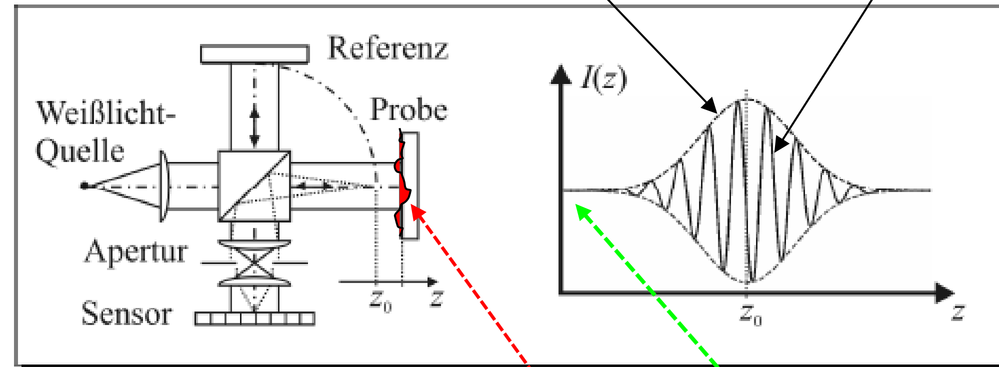
The WLI signal

$$I_{sig}(z) = I_1 + I_2 \cdot \gamma_{12}(z - z_0)\cos[k_0(z - z_0) + \alpha_{12}]$$

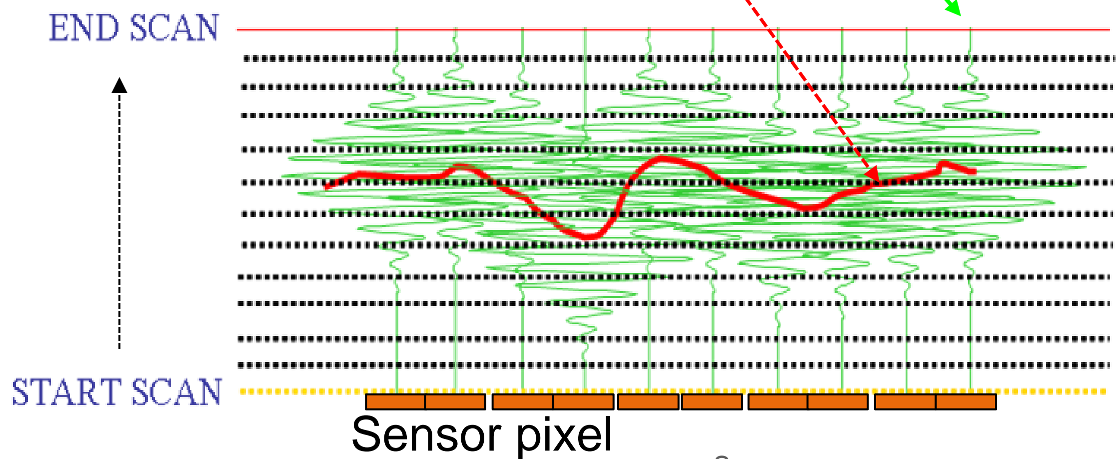
Coherence term

Phase term

- Best focus corresponds to zero optical path difference
  - → straight forward height determination by z-scan
- SW extraction of envelope maxima
  - Hilbert transform
  - Wavelet transform
  - other techniques



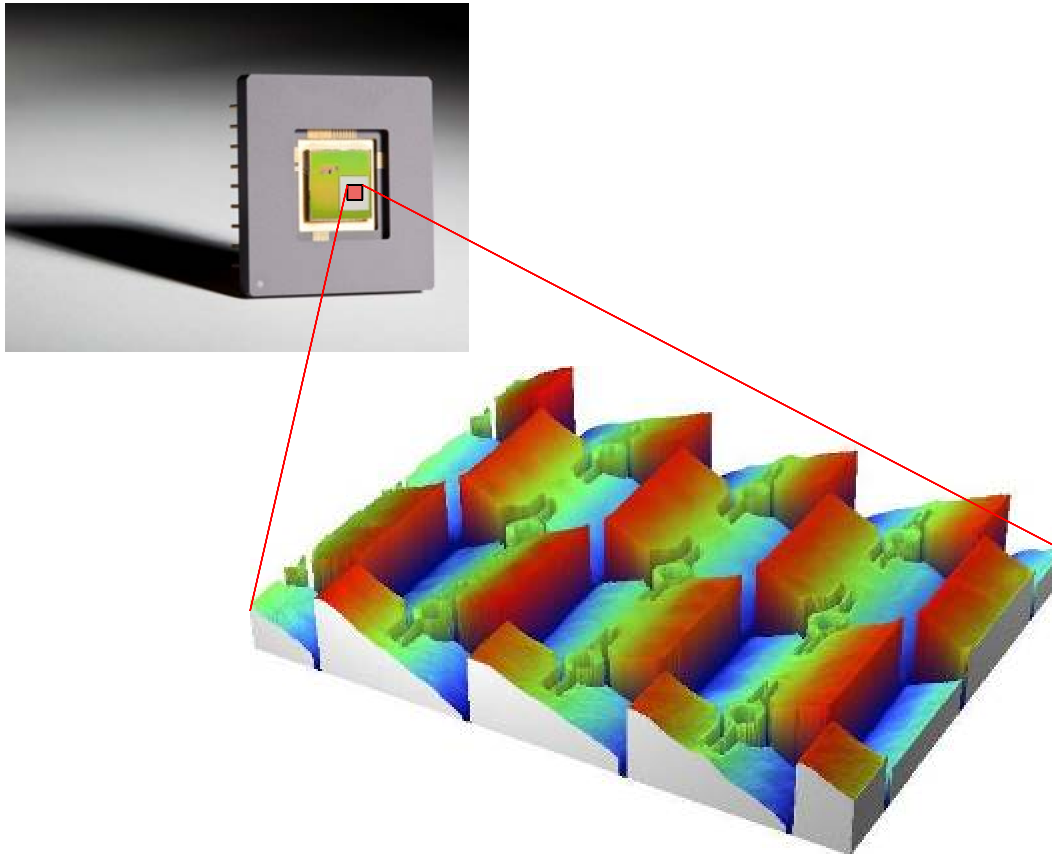
What is the "surface"?



Sources:
Zygo, WLI documentation

Optical analysis of *micro- and nanostructures*

- Measurement section of a MEMS array – torsion micromirrors
  (Field of view 70 µm x 50 µm, 0.2 nm vertical resolution)



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Summary - White Light Interferometry (WLI)

- WLI is an optical method measuring the phase-change of light

- Topography properties can be directly determined - without user interaction.

- Advantages
  - < 1nm (z-resolution) with dynamic range >100µm
  - Non-destructive
  - Direct and parallel data acquisition without model assumption
  - Inspection of optical constants & thickness of structured thin films optionally

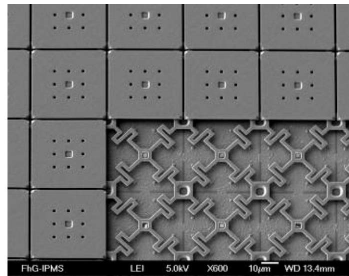
- Typical application ?

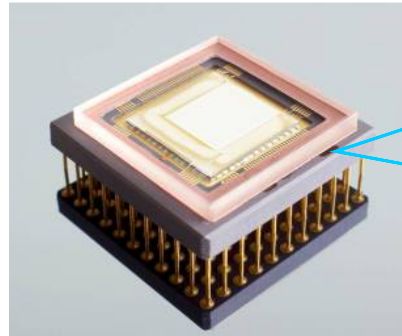
APPLICATION EXAMPLE:

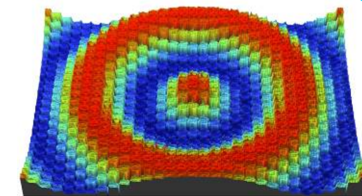
WLI characterization and MEMS micromachining

Overview: Micromirror Arrays – diffractive MEMS modulators

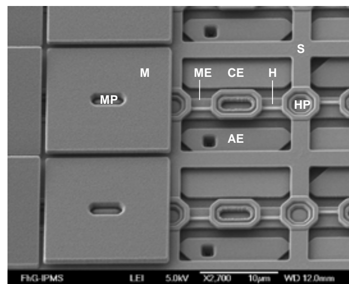
- Piston mirror array
  - 48k

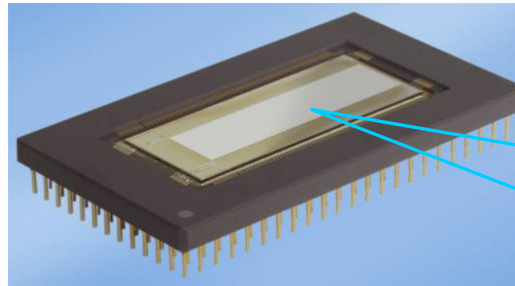


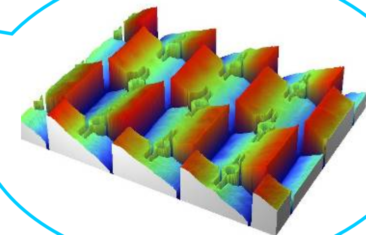




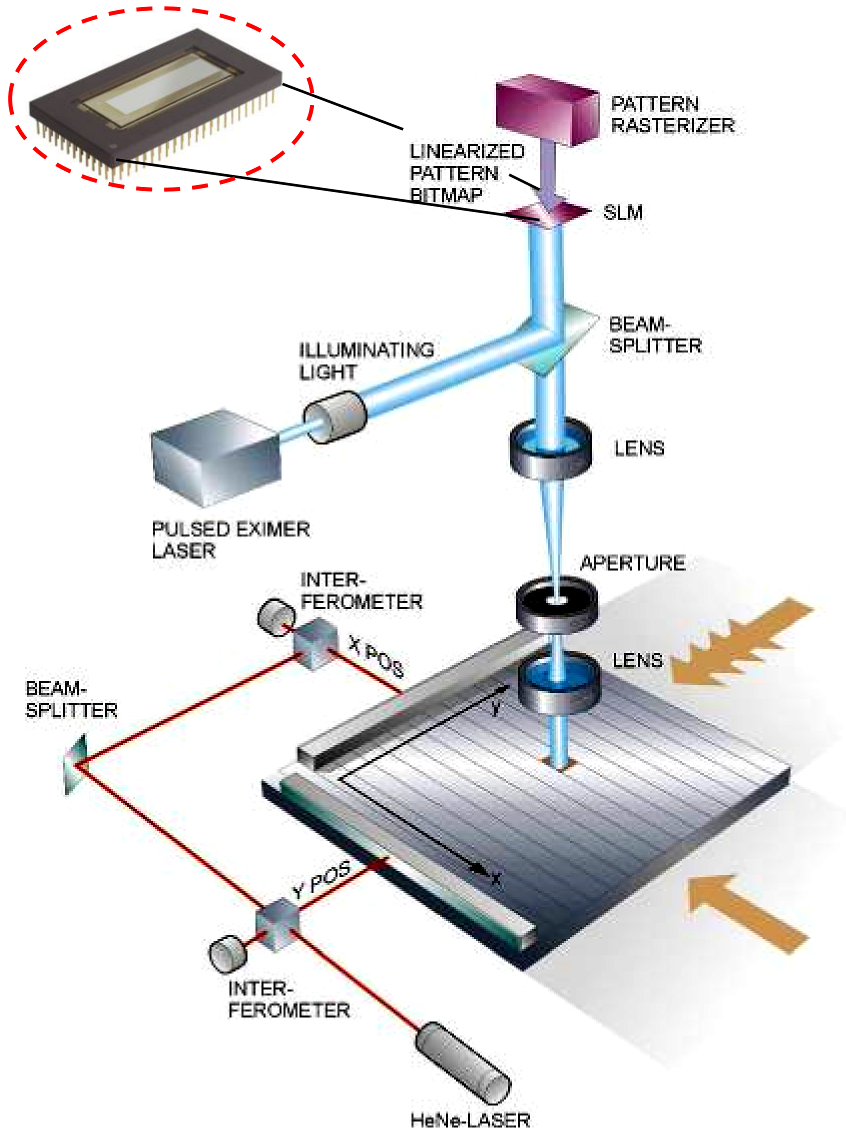
- Single axis tilting mirror array
  - 1 M





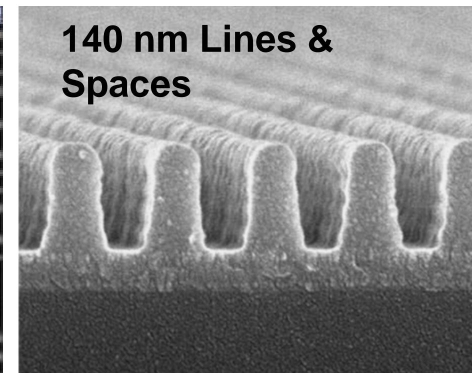


Laser Mask Writing: Operational Principle & Results



Micronic Sigma7500
SLM-based semiconductor mask writer

Pattern in resist



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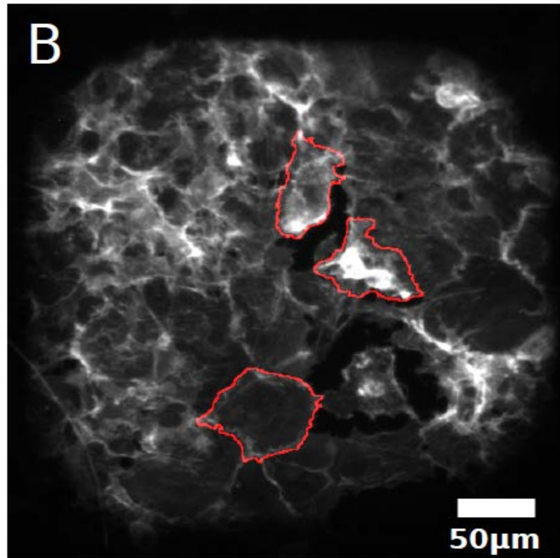
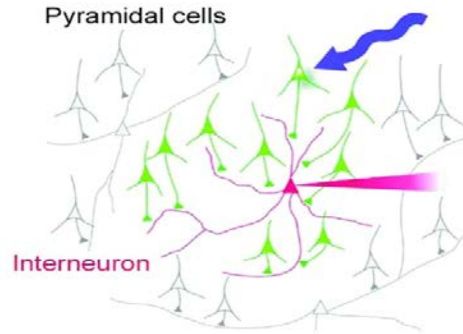
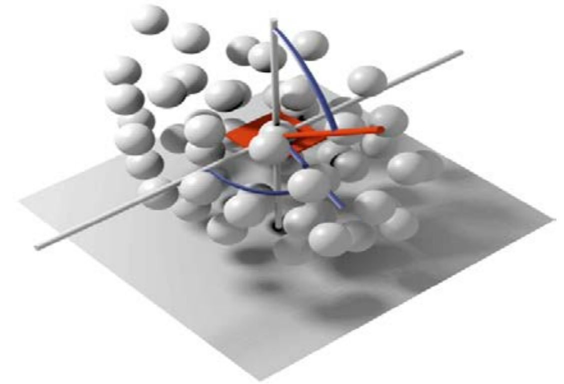
Optogenetics: Operational Principle & Results

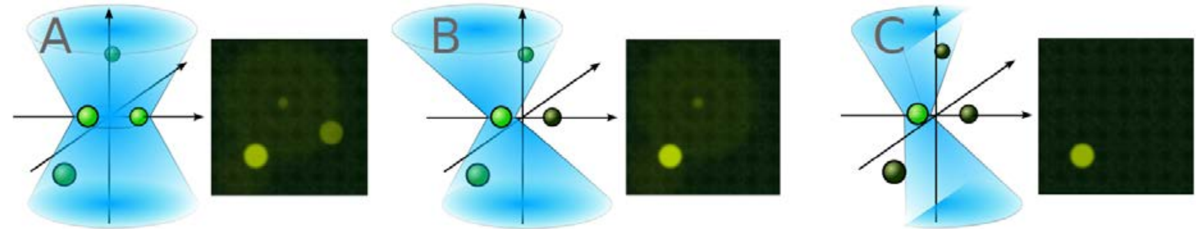
Controlled neuron excitation and gene activity





Macunso et al., Experimental Physiology, 2010





Application of double-MMA for structured microscope illumination

Feedback System
Take image of sample. Use of gratings allows sectioning.
Image processing
Illumination control
Widefield detection
Image reconstruction

FhG-IPMS LEI 5.0kV X2,700 10µm WD 12.0mm

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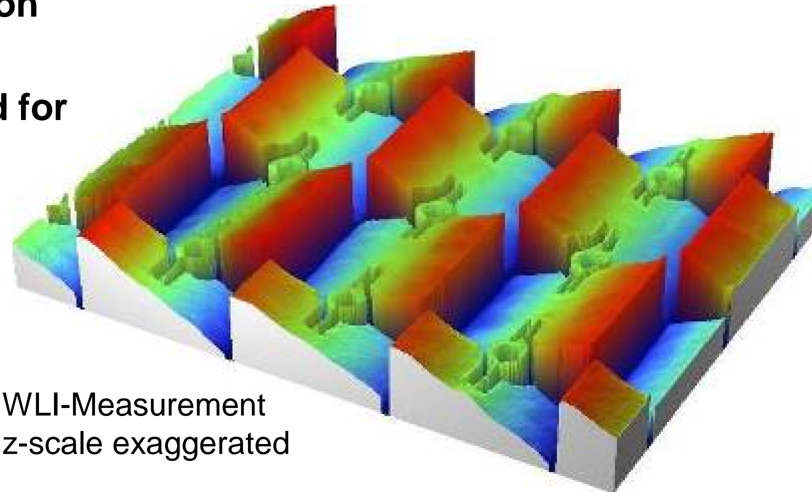
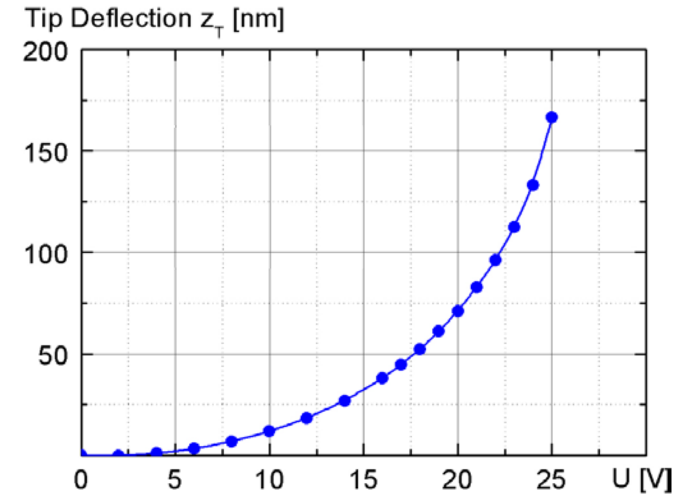
<u>Example 1</u>: Spot-characterization of diffractive micro-mirror arrays

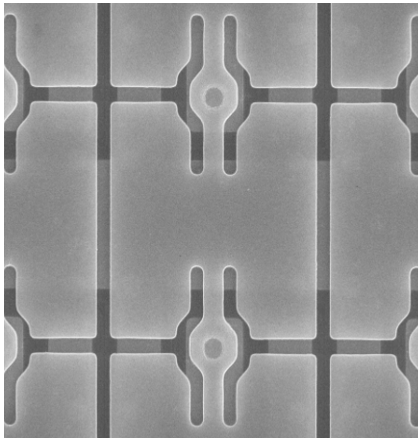
Characteristics of 16 µm Tilt-Mirrors

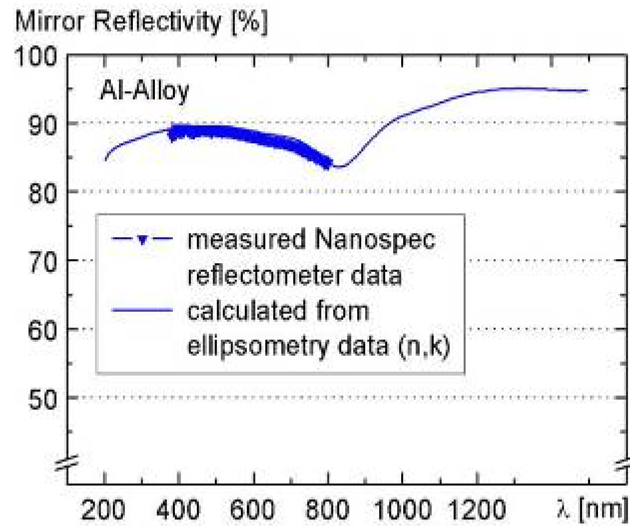
- **Tip deflection > 150 nm**
- **λ/4 required for max. image contrast**

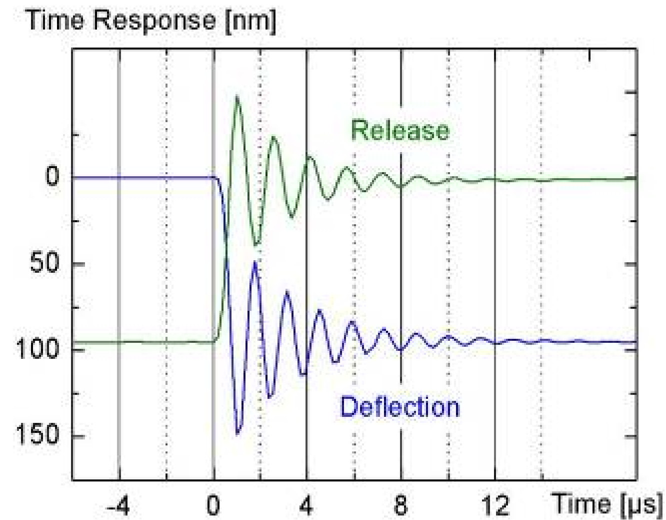


WLI-Measurement
z-scale exaggerated



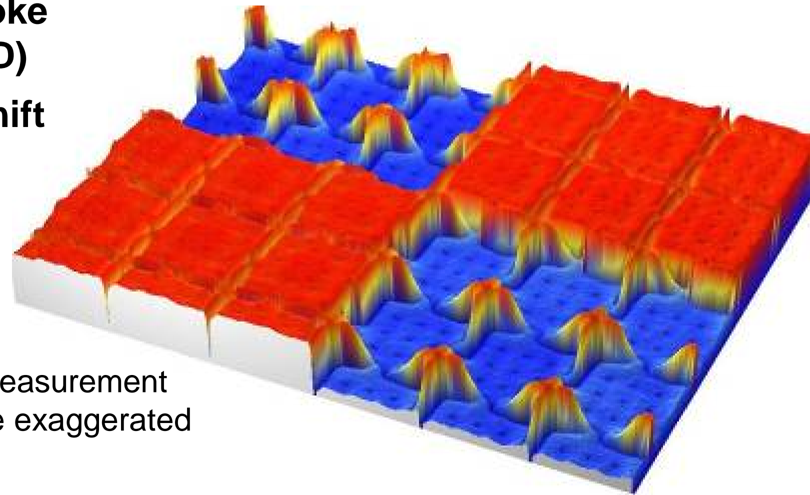


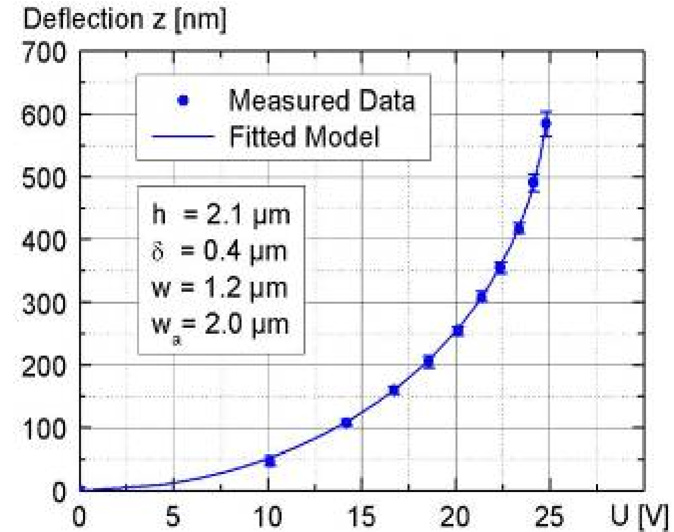




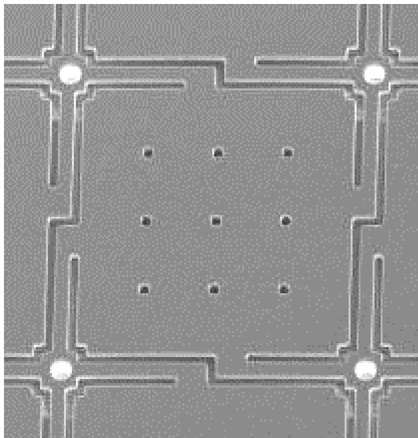
Characteristics of 40 µm Piston-Mirrors (1-Level Design)

- **500 nm stroke (1.0 µm OPD)**
- **2π phase shift in the VIS**

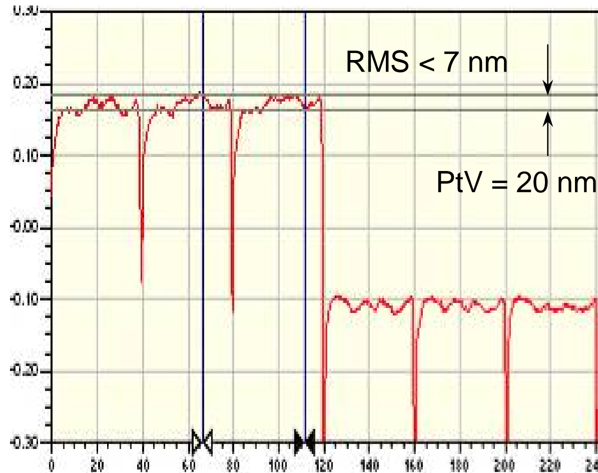




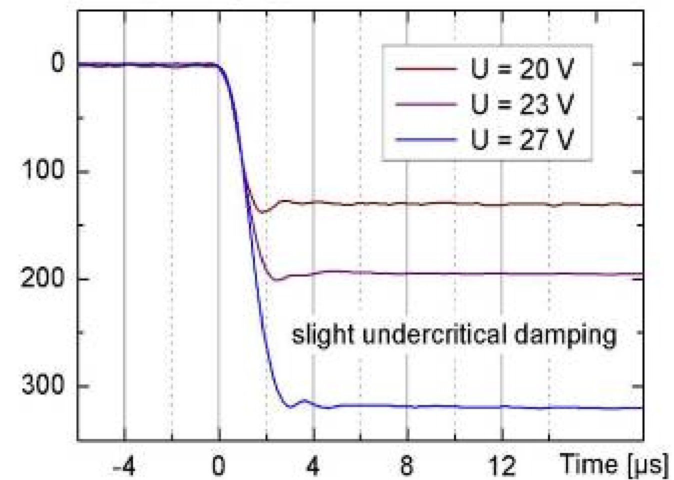
Mirror SEM



Mirror Planarity



Time Response [nm]



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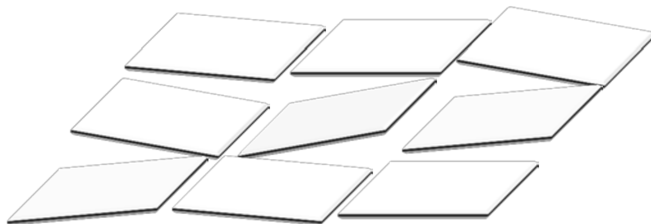
Example 2: Calibration of diffractive micro-mirror arrays

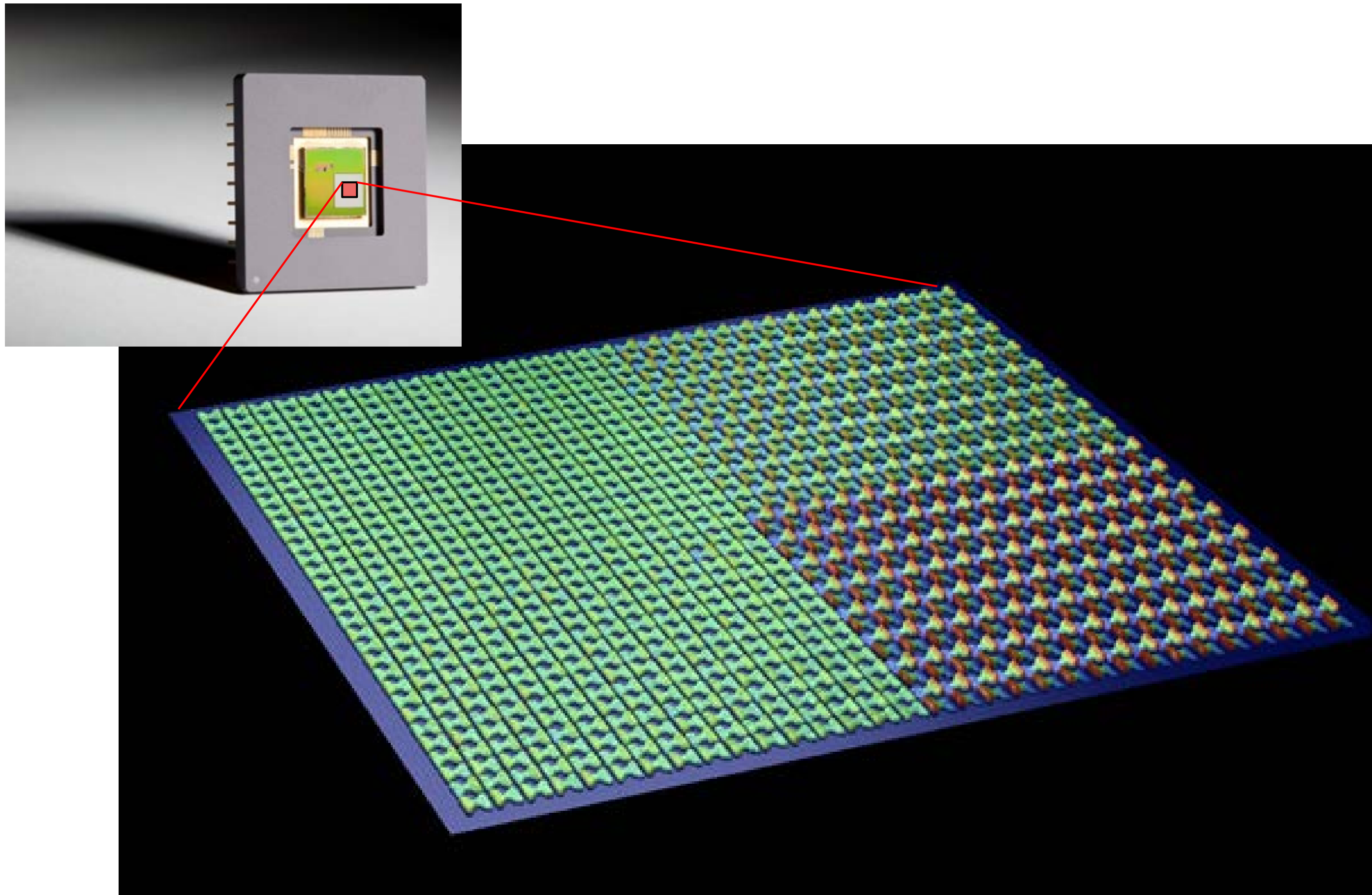
- MMA profile:



- Desired state:

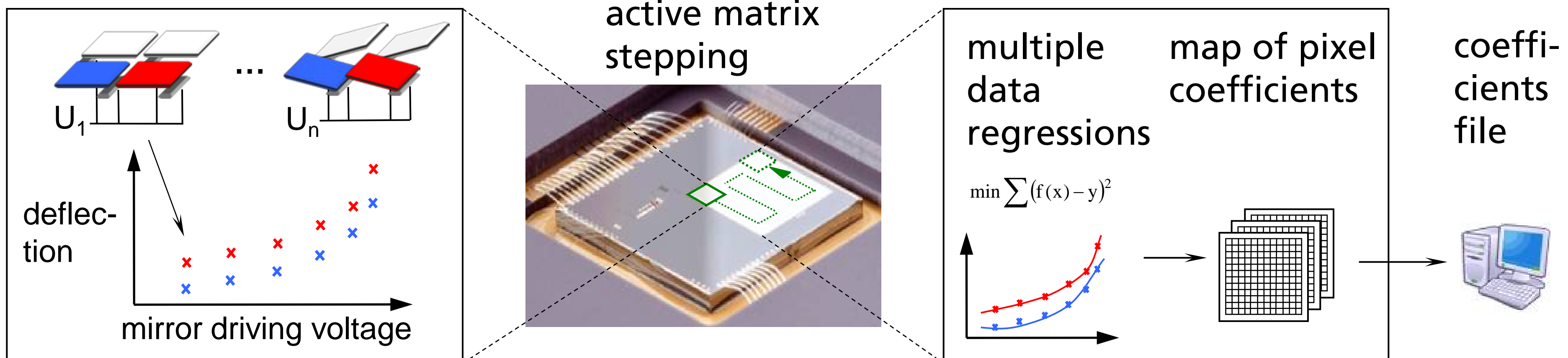
Optical analysis of *micro- and nanostructures*

- How to measure a complete array of 64526 micromirrors with sub-nanometer z-resolution?



Algorithm for single pixel MMA correction

1. Determination of micromirror’s voltage-deflection response curves with a profilometric measurement system based on interferometry
2. Stepping of active MEMS area (>60.000 single mirrors)
3. Multiple data regressions to generate continuous response curves
4. Storage of coefficients



Source: D. Berndt, Proc. SPIE 8191 81910O-1

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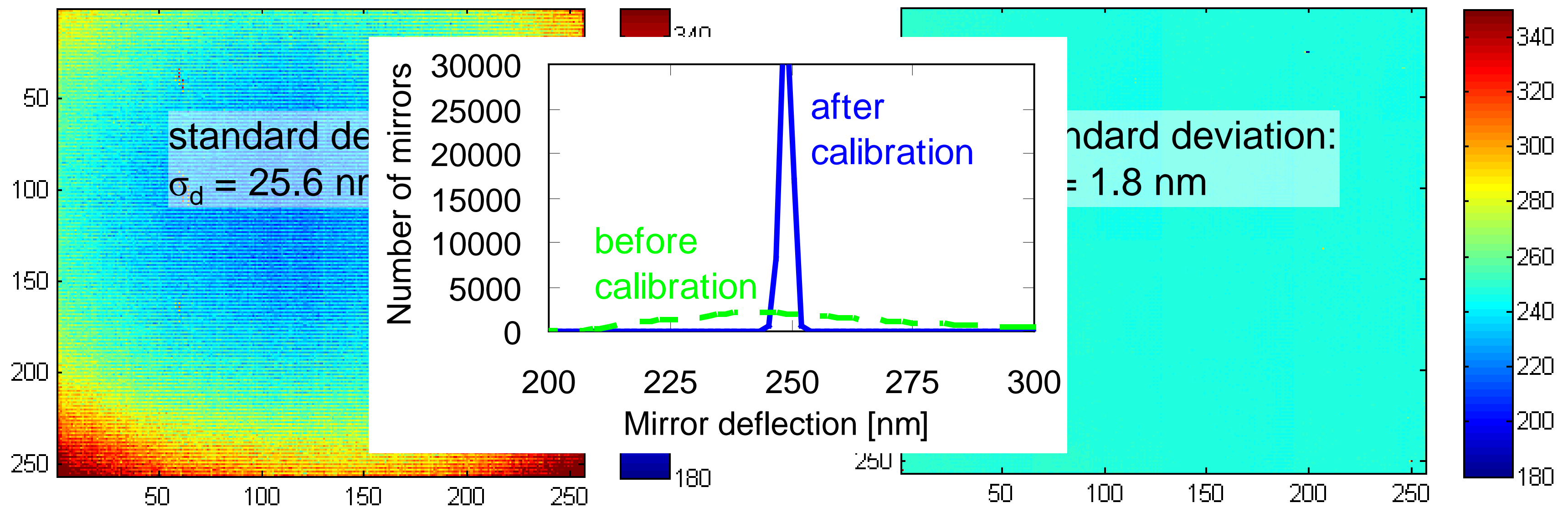
Calibration results – deflection homogeneity

Micromirror mapping - target deflection 250 nm

- MMA deflection without calibration
- Calibrated MMA deflection

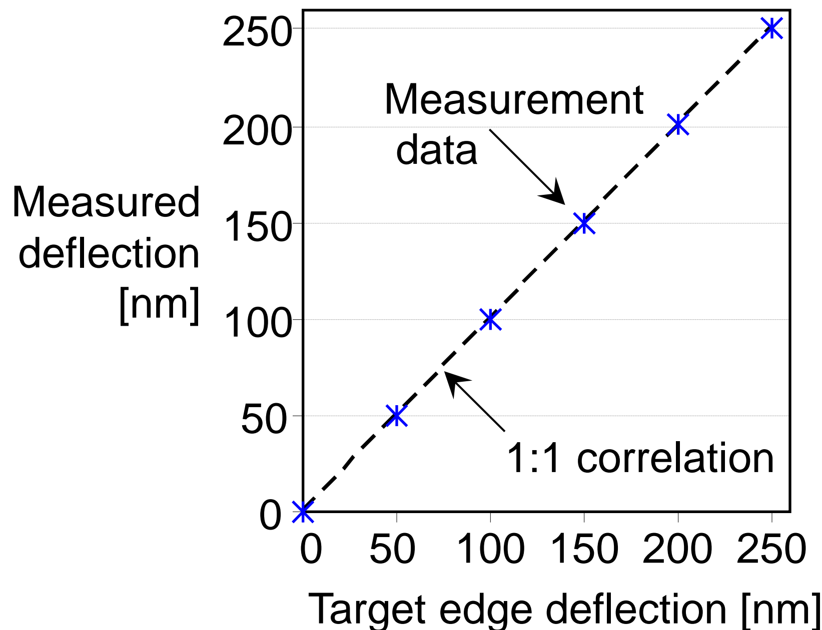


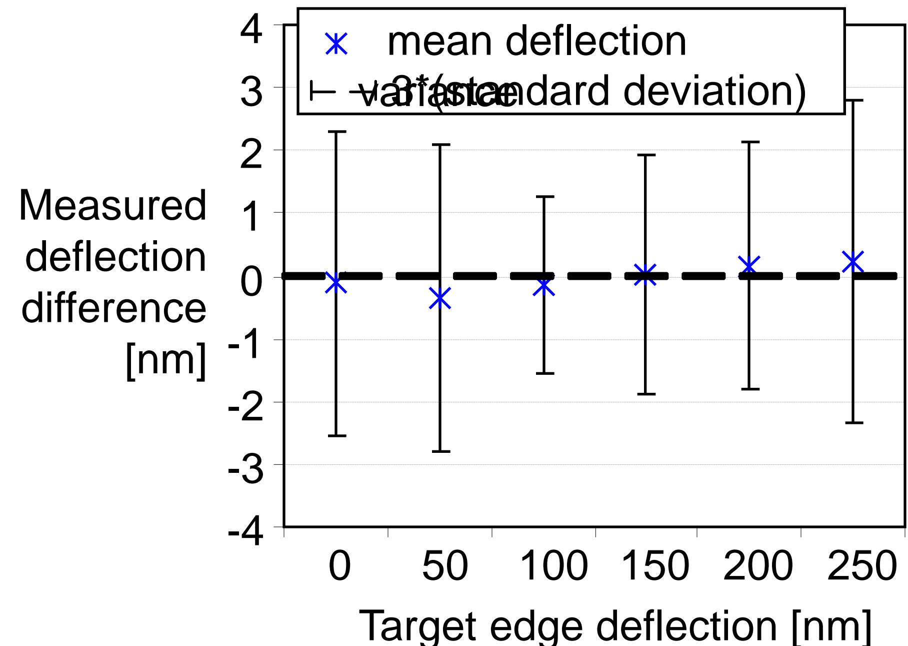
→ Decrease of deflection spread by more than a factor of 10

Source: D. Berndt, Proc. SPIE 8191 81910O-1

Calibration results – deflection accuracy

➞ WLI resolution determines measured deflections:



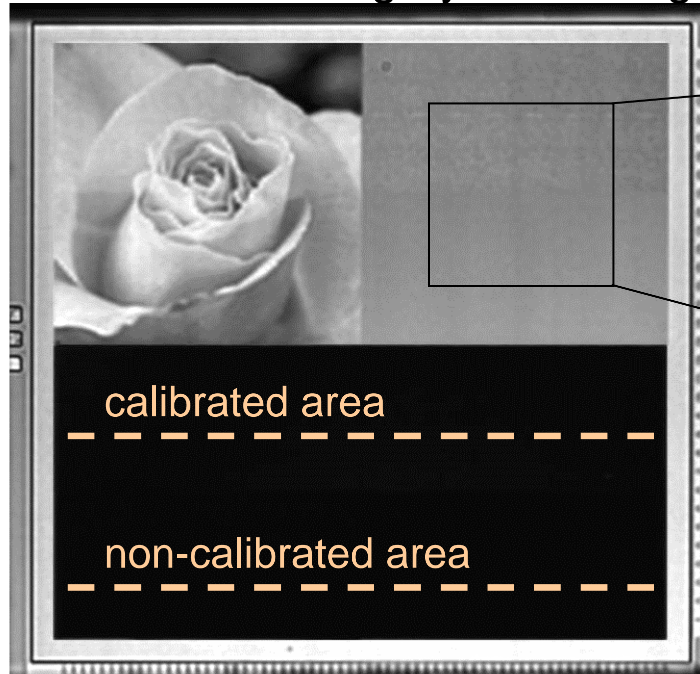


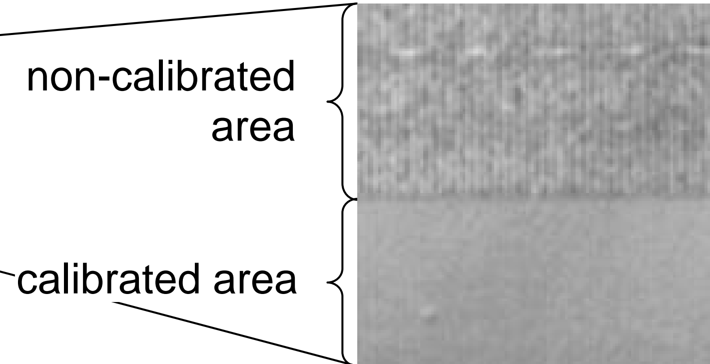
➞ Accuracy of voltage-deflection response better than λ/100

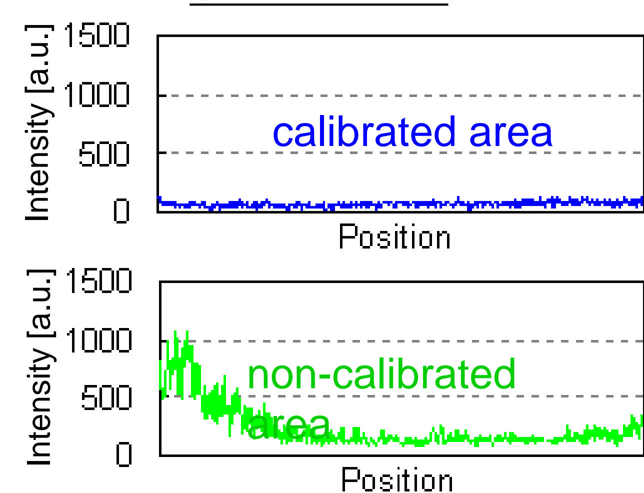
Source: D. Berndt, Proc. SPIE 8191 81910O-1

Calibration results – Optical effects

MMA modulated grayscale image







- Contrast >1000, Homogeneity ~ 1 %
- WLI inspection with robust industrial system (~ hours of measurement) !

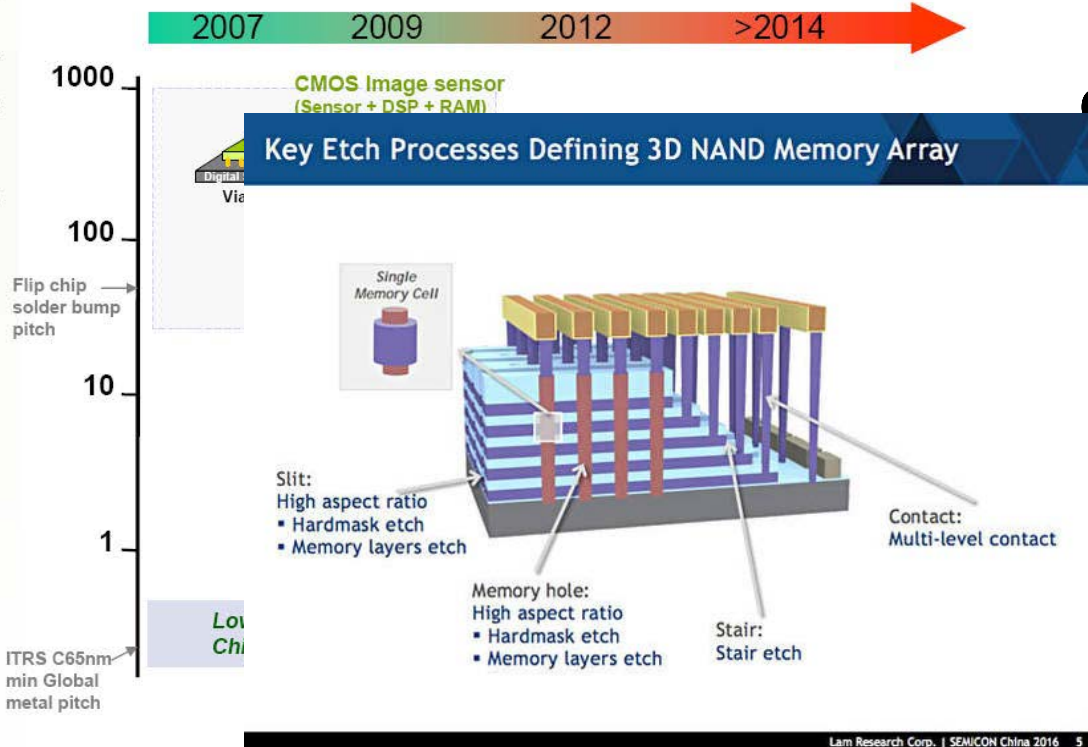
Source: D. Berndt, Proc. SPIE 8191 81910O-1

Example 3: Analysis of wafer structures for SC manufacturing – „Vias and Trenches“

- “Through Silicon Via (TSV)” E. Novak, 2010, Veeco

Analysis of Vias (and Trenches) for SC-M

- Via structures and SC development



Characteristics

Size:

2 µm lateral

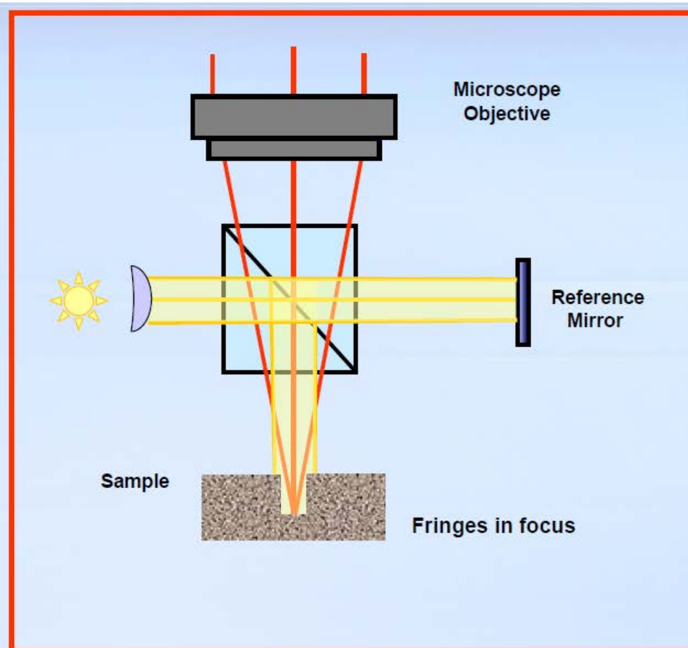
>10 µm vert.

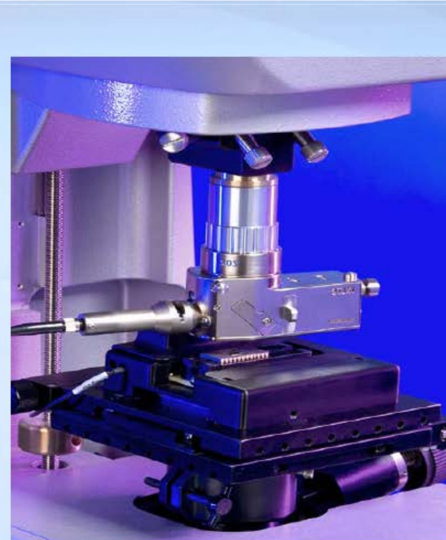
„high aspect-ratio“

~ 1: > 5 …

Analysis of Vias (and Trenches) for SC-M

- Experimental challenge: how to image a profile with "high aspect ratio"?





Advantages of illumination from below of the objective
- Collimated illuminating beam better penetrates the via
- High numerical aperture of objective captures most light

WLI specifics:
- Use of (partial) coherent imaging
- Advanced data processing

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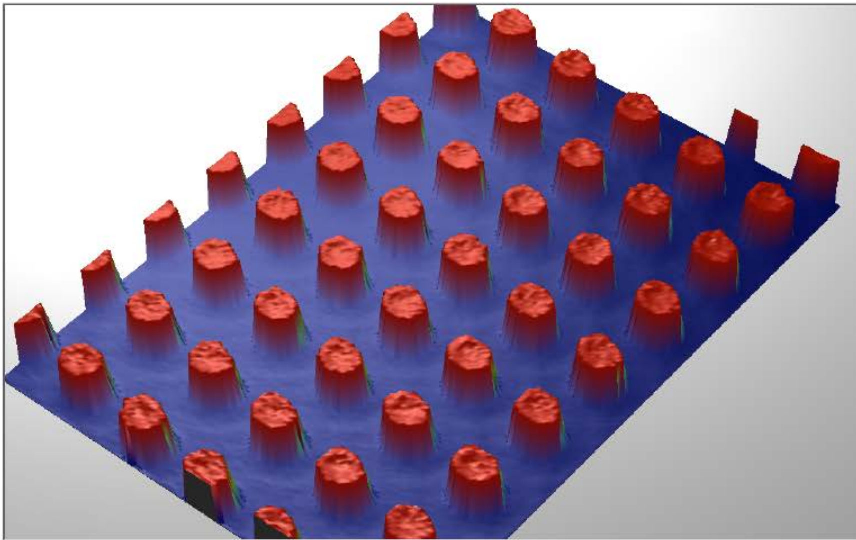
Analysis of Vias (and Trenches) for SC-M

- Results of WLI tests:

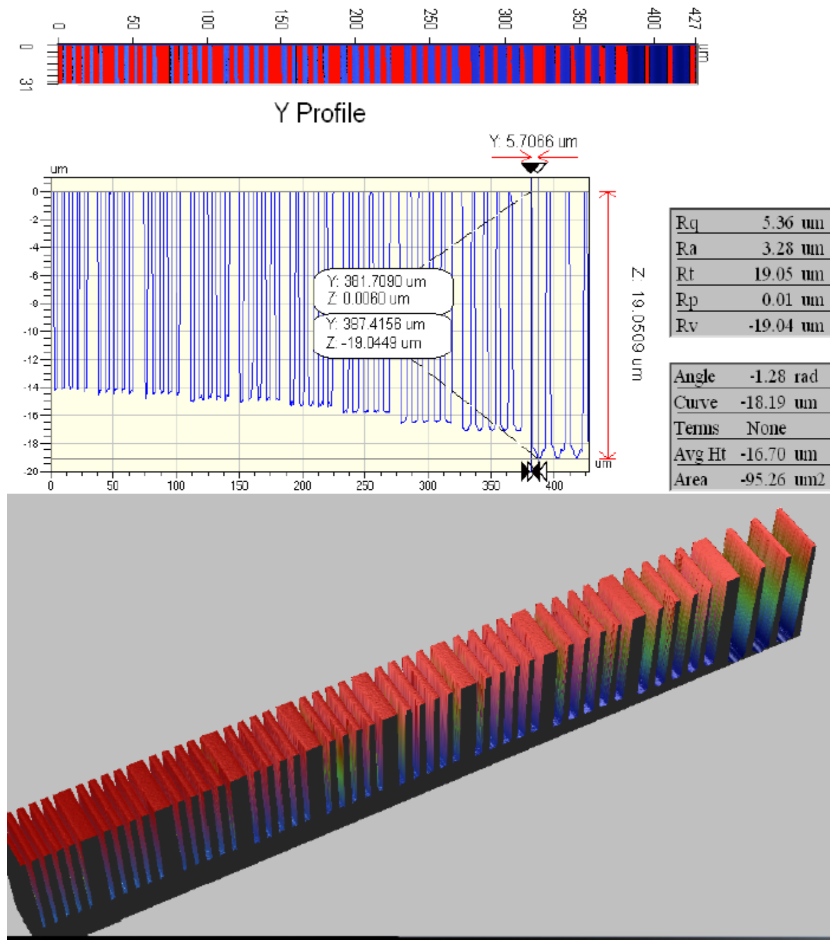


- 10 measurements, no remove/replace
- 3 micron vias:
  - Average Depth: 34.63 µm
  - Average width: 3.4 µm
- Data is shown inverted for clarity

- Via analysis starting at 1,5µm diameter amenable
- Aspect ratio **1 : 10…15**

Analysis of Vias (and Trenches) for SC-M

- Results of WLI tests:



- Integrated image processing automatically identifies and reports individual trench data
- Average Depth: 14.3 microns (across all the lines)
- Width from 1 to 10 microns
- Average 1 Sigma Standard Deviation of depth: 70nm

- Trench analysis starting at 2 µm „line width“
- Aspect ratio **1: 20…40**

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Summary - White Light Interferometry (WLI)

- WLI is an optical method measuring the change in phase of light.
- By means of numerical analysis, topography properties of micro and nanostructures can be indirectly determined - without user interaction.
- Advantages
  - Precise determination of structure properties
    - < 1nm (z-resolution) with >100µm dynamic range
  - MEMS properties like micromirror deflection, cantilever mobility, micromechanical stability become amenable
  - Access to optical constants & thickness of *structured* thin films
  - Non-destructive, fast
- Typical application:
  - Combination with microscopy (< 1 µm lateral resolution)
  - Time resolved analysis (stationary, < 100 ns resolution)

CONCLUSION

Ellipsometry, X-ray Reflectometry, Interferometry

- Photons are a versatile tool for the non-destructive analysis of micro and nanostructures even at sub-nanometer scales
- The combination of high resolution capabilities together with spectral- and time-resolved information steadily extends the industrial application range

Thank you for your attention!