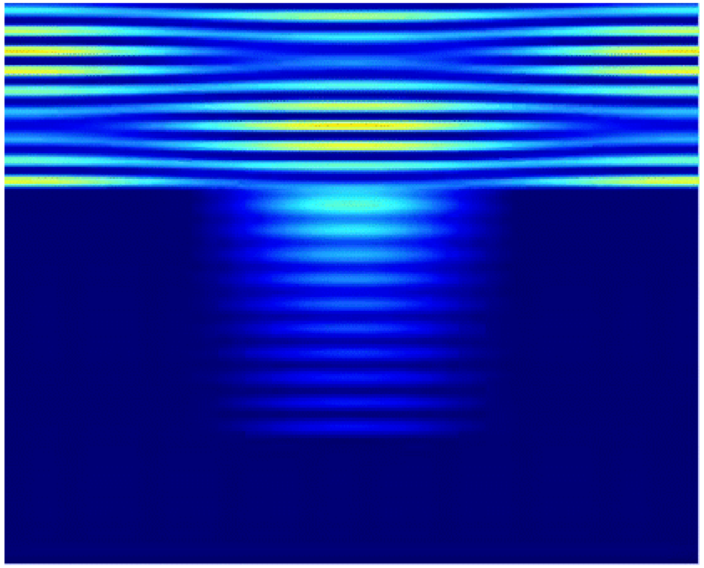
Simulations of Scatterometry down to 22 nm Structure Sizes and beyond

W. Osten, V. Ferreras Paz, K. Frenner, T. Schuster, H. Bloess*

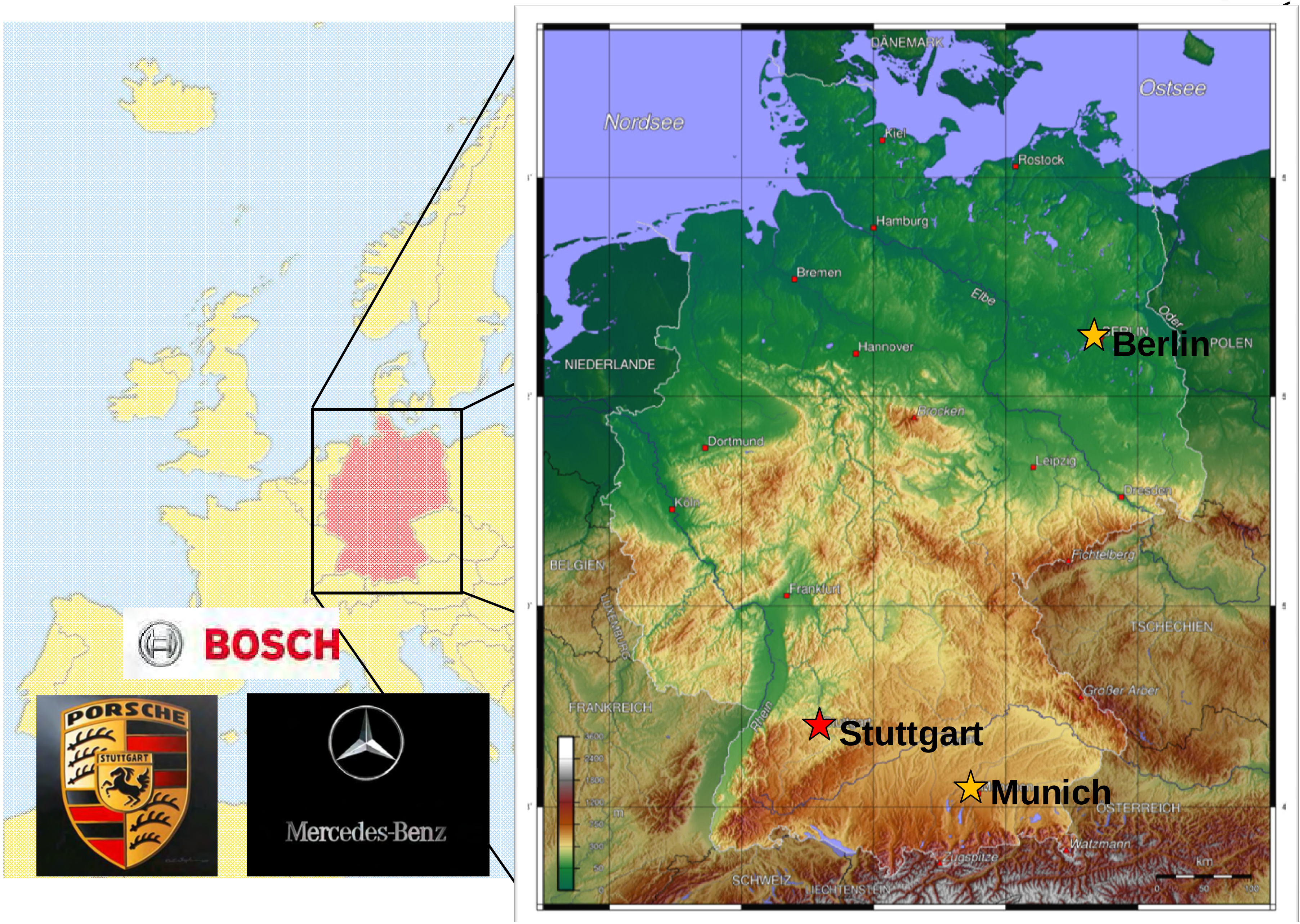


- Introduction: NE Research at ITO
- Motivation & Scatterometry SM
- Influence of LER on SM
- Parameter Sensitivity of SM

* Qimonda

NE Research at ITO at Stuttgart University

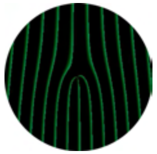
Stuttgart


BOSCH
PORSCHE
STUTTGART
Mercedes-Benz
DÄNEMARK
Ostsee
Nordsee
Kiel
Rostock
Hamburg
Bremen
Elbe
Oder
Berlin
POLEN
NIEDERLANDE
Hannover
Brocken
Dortmund
Leipzig
Köln
Dresden
BELGIEN
Fichtelberg
Frankfurt
LUXEMBURG
TSCHECHIEN
Großer Arber
FRANKREICH
Rhein
Stuttgart
Munich
ÖSTERREICH
Watzmann
Zugspitze
SCHWEIZ
LIECHTENSTEIN
m
km

University Suttgart

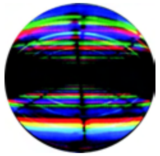
ITO Research Fields

3D-Surface Metrology

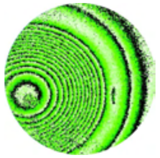


Active Optical Systems & Computational Imaging

High Resolution Metrology & Simulation



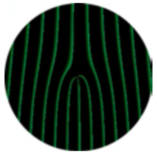
Interferometry & Diffractive Optics



Coherent Metrology

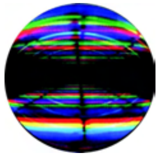
ITO Research Fields

3D-Surface Metrology

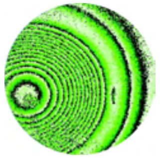


Active Optical Systems & Computational Imaging

High Resolution Metrology & Simulation

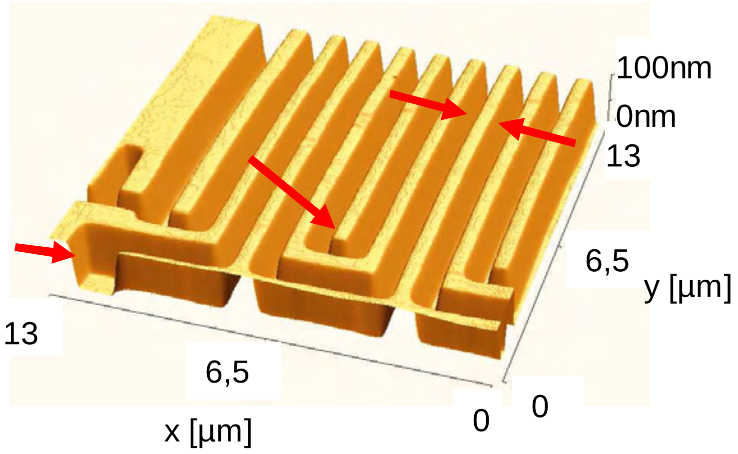


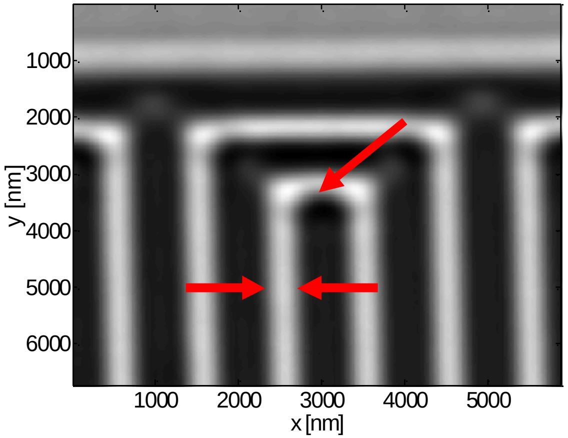
Interferometry & Diffractive Optics



Coherent Metrology

CD-Metrology: Evaluation of the Structure Quality

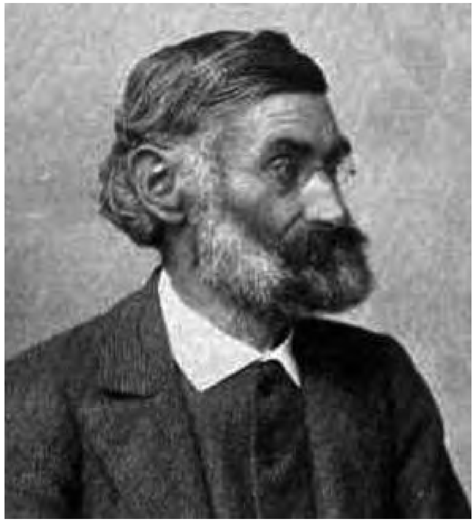


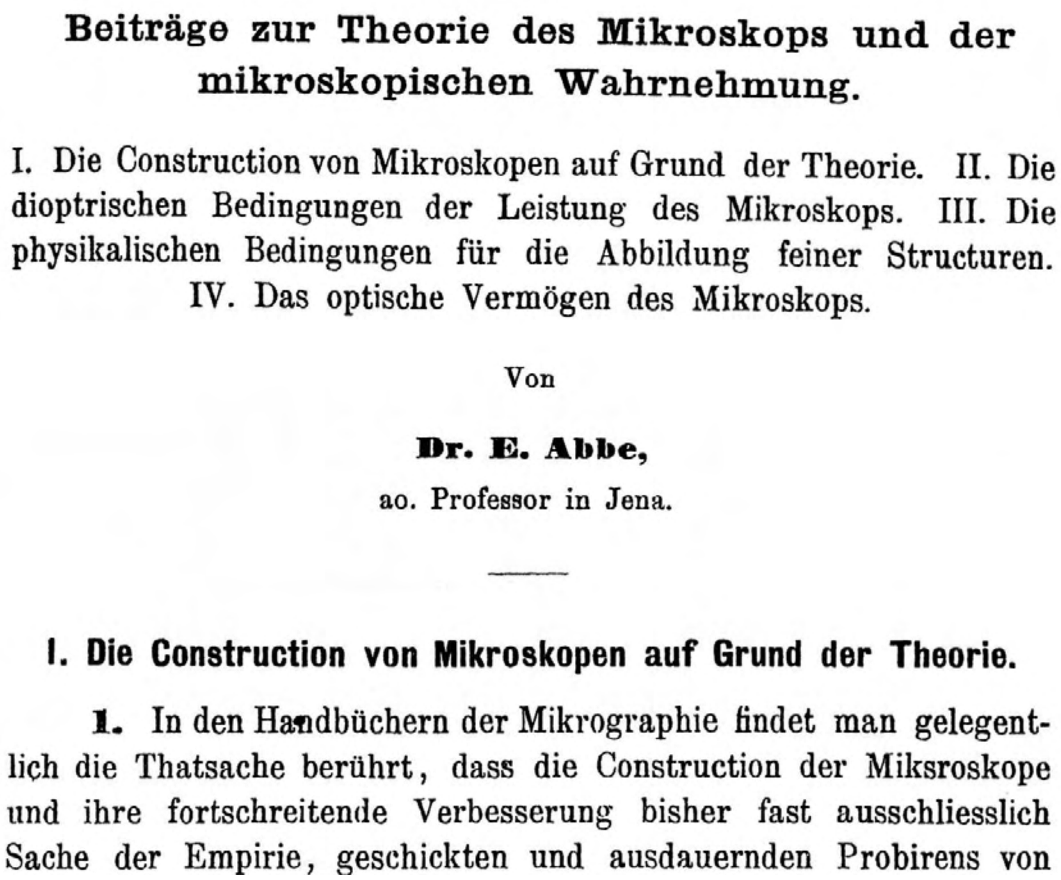


Typical Tasks:

- Dimensional Quantities: Depth, Width, ...
- Structure Shape: Profiles, Curvature, Angle, Roughness,...
- Defects
- Phase

Ernst Abbe (1840-1905): Theory of Image Formation (1873)





Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung.

I. Die Construction von Mikroskopen auf Grund der Theorie. II. Die dioptrischen Bedingungen der Leistung des Mikroskops. III. Die physikalischen Bedingungen für die Abbildung feiner Structuren. IV. Das optische Vermögen des Mikroskops.

Von

Dr. E. Abbe,

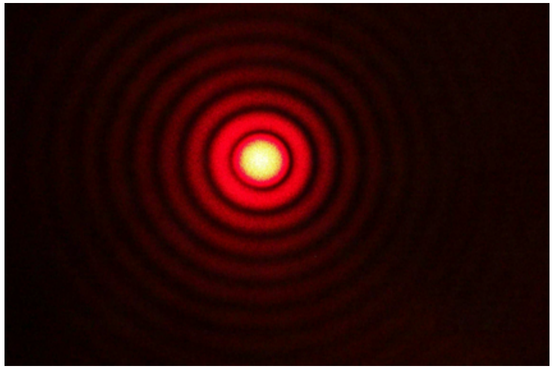
ao. Professor in Jena.

I. Die Construction von Mikroskopen auf Grund der Theorie.

1. In den Handbüchern der Mikrographie findet man gelegentlich die Thatsache berührt, dass die Construction der Miksroskope und ihre fortschreitende Verbesserung bisher fast ausschliesslich Sache der Empirie, geschickten und ausdauernden Probirens von

Archiv für Mikroskopische Anatomie 9(1873), pp. 413-468

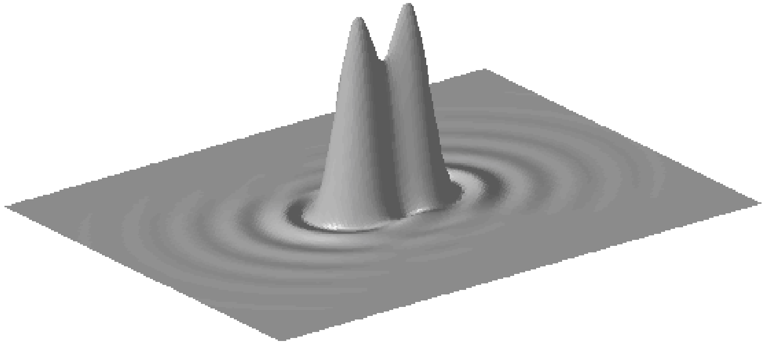
Resolution Limt



$$\Delta x = 0{,}61 \cdot \frac{\lambda}{n \cdot \sin\alpha}$$

Point Image (Airy Spot)

2 Adjacent Point Images



Philosophy

Unresolved Structures: Measurement ⇨ Reconstruction

Approach:

Utilization of „All“ Information Channels of Light

Polarization ⇐ + **Intensity** + ⇒ **Phase**

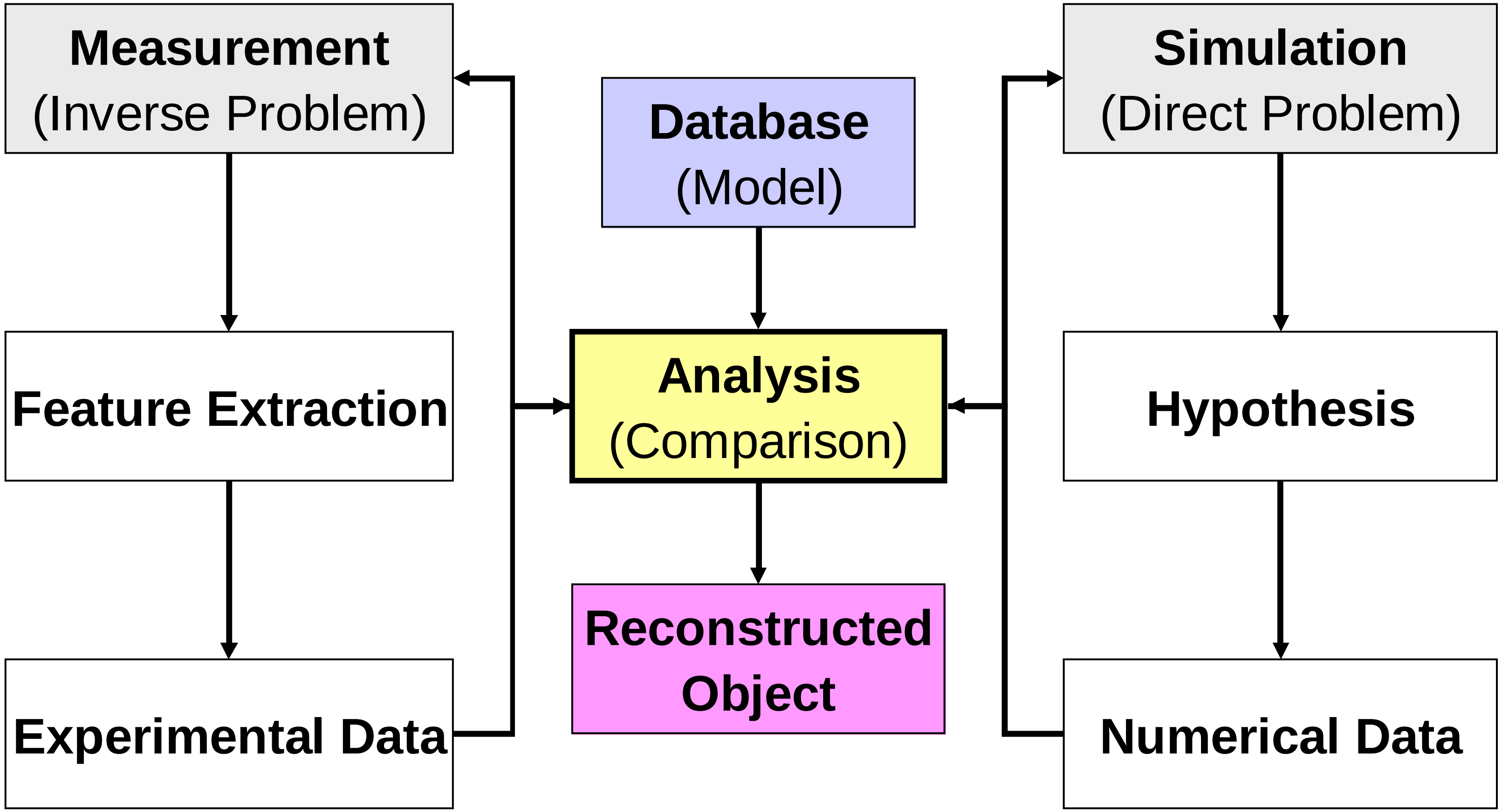
Electromagnetic Interaction

Light ⇔ Object

Unification of

Modelling, Simulation & Metrology

Measurement Strategy



Measurement
(Inverse Problem)

Feature Extraction

Experimental Data

Database
(Model)

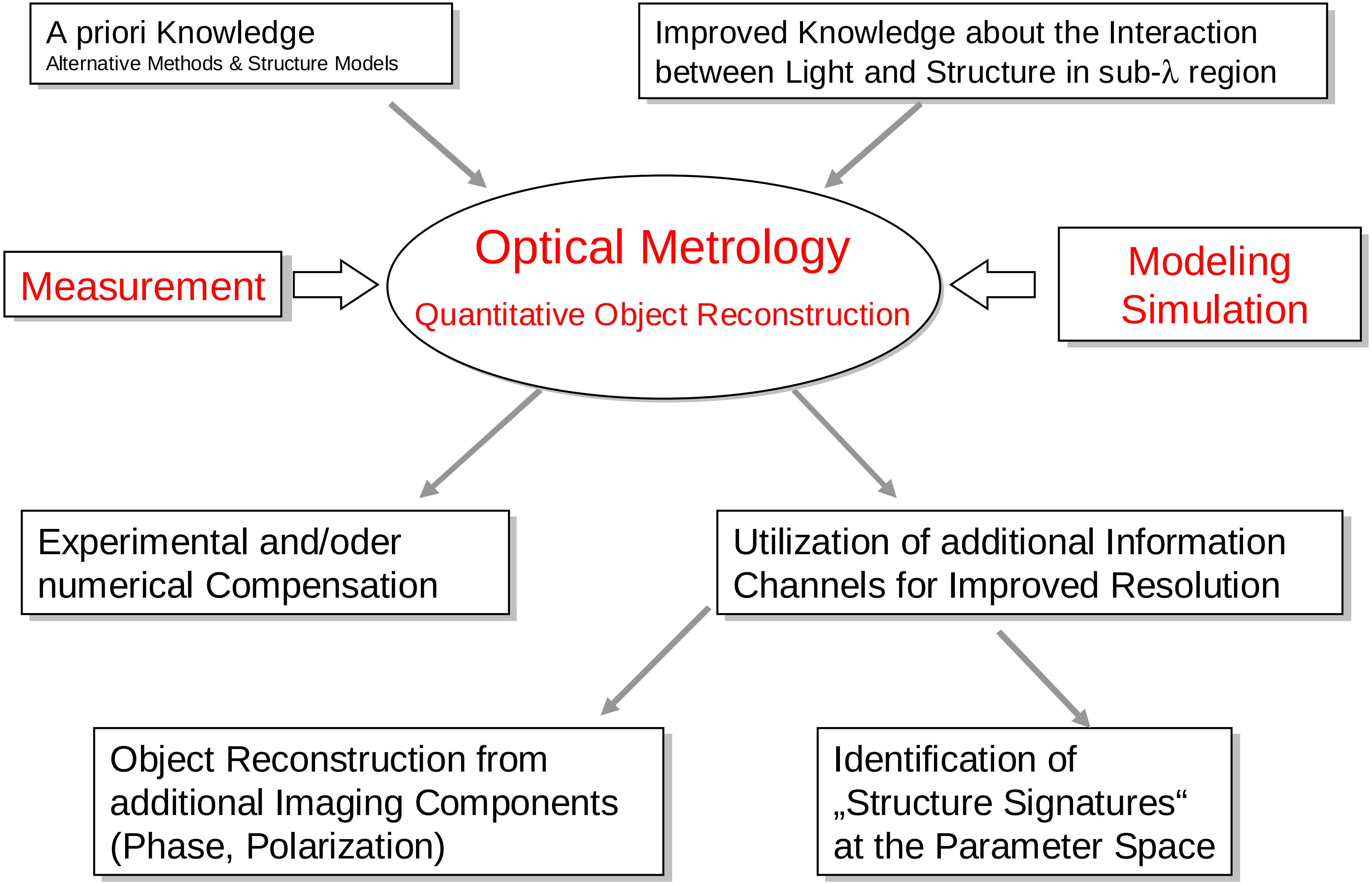
Analysis
(Comparison)

Reconstructed Object

Simulation
(Direct Problem)

Hypothesis

Numerical Data



A priori Knowledge
Alternative Methods & Structure Models

Improved Knowledge about the Interaction between Light and Structure in sub-λ region

Measurement

Optical Metrology
Quantitative Object Reconstruction

Modeling
Simulation

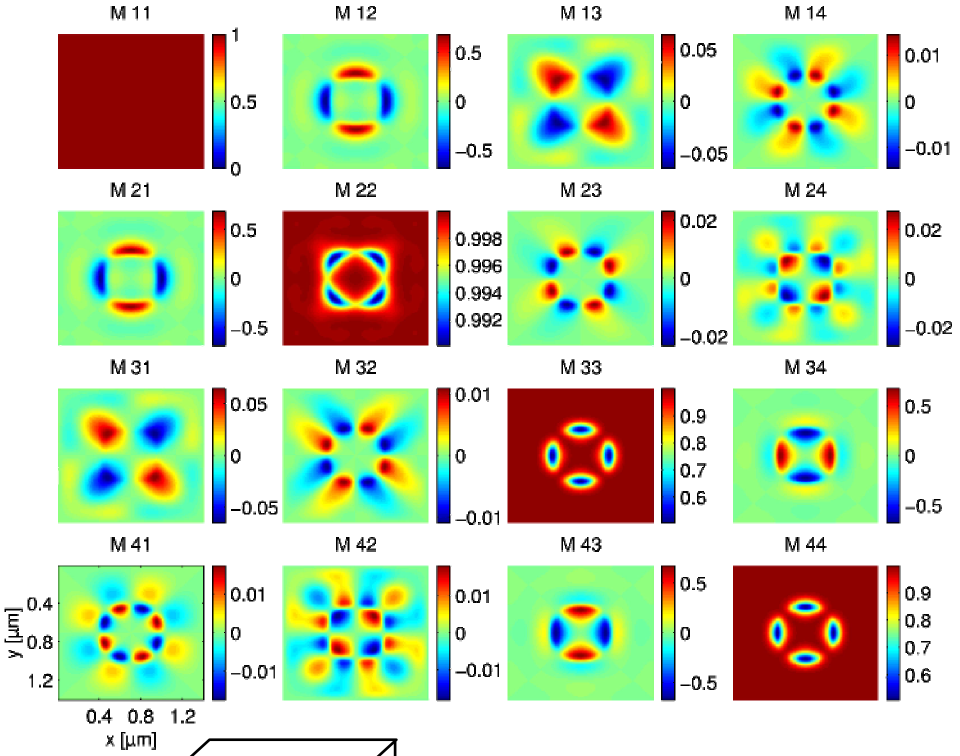
Experimental and/oder numerical Compensation

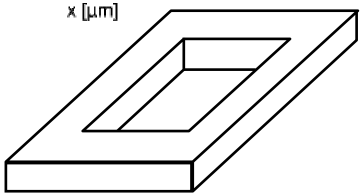
Utilization of additional Information Channels for Improved Resolution

Object Reconstruction from additional Imaging Components (Phase, Polarization)

Identification of „Structure Signatures“ at the Parameter Space

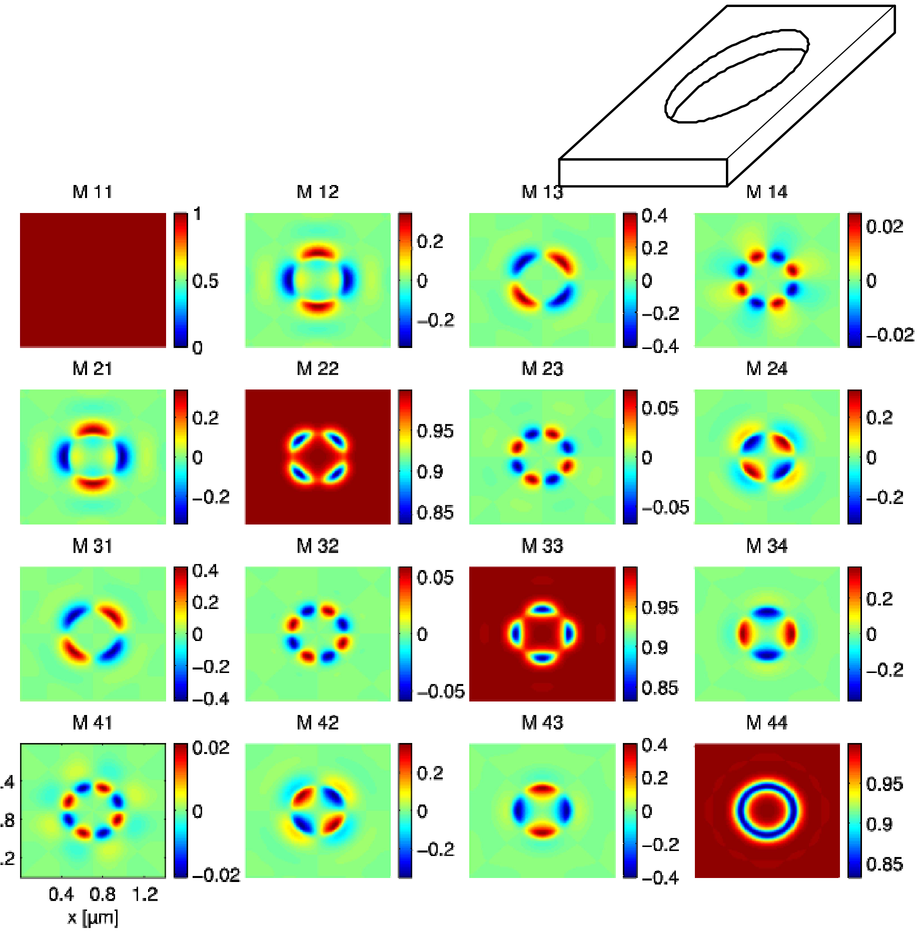
Simulation: Mueller Matrix of Si-Structures



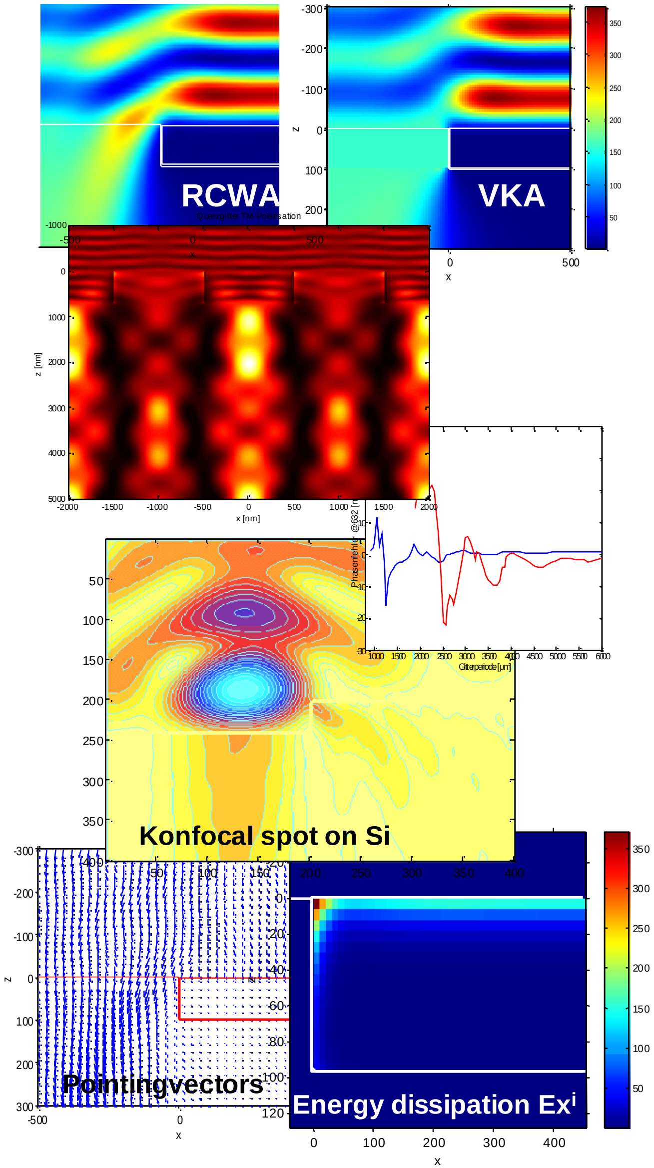


Silicon, 800x800x100 [nm]

Silicon, diameter 800nm, depth 100nm



ITO Simulation System: MicroSim



Rigorous Computing of the Light-Object-Interaction

- RCWA, VKA, FDTD, FEM
- Rigorous Scattering Theory
- Diffractometry, Scatterometry, Digital Holography

Visualization of Near- and Farfield in 2D and 3D

- Amplitude, Phase
- Vector Components
- Energy Dissipation, Pointing-Vectors

Simulation of Microscopic Imaging Process

- Brightfield-Microscopy, Darkfield-Microscopy
- Interference Microscopy, Polarization Microscopy
- Quantitative Phase Contrast, DIC

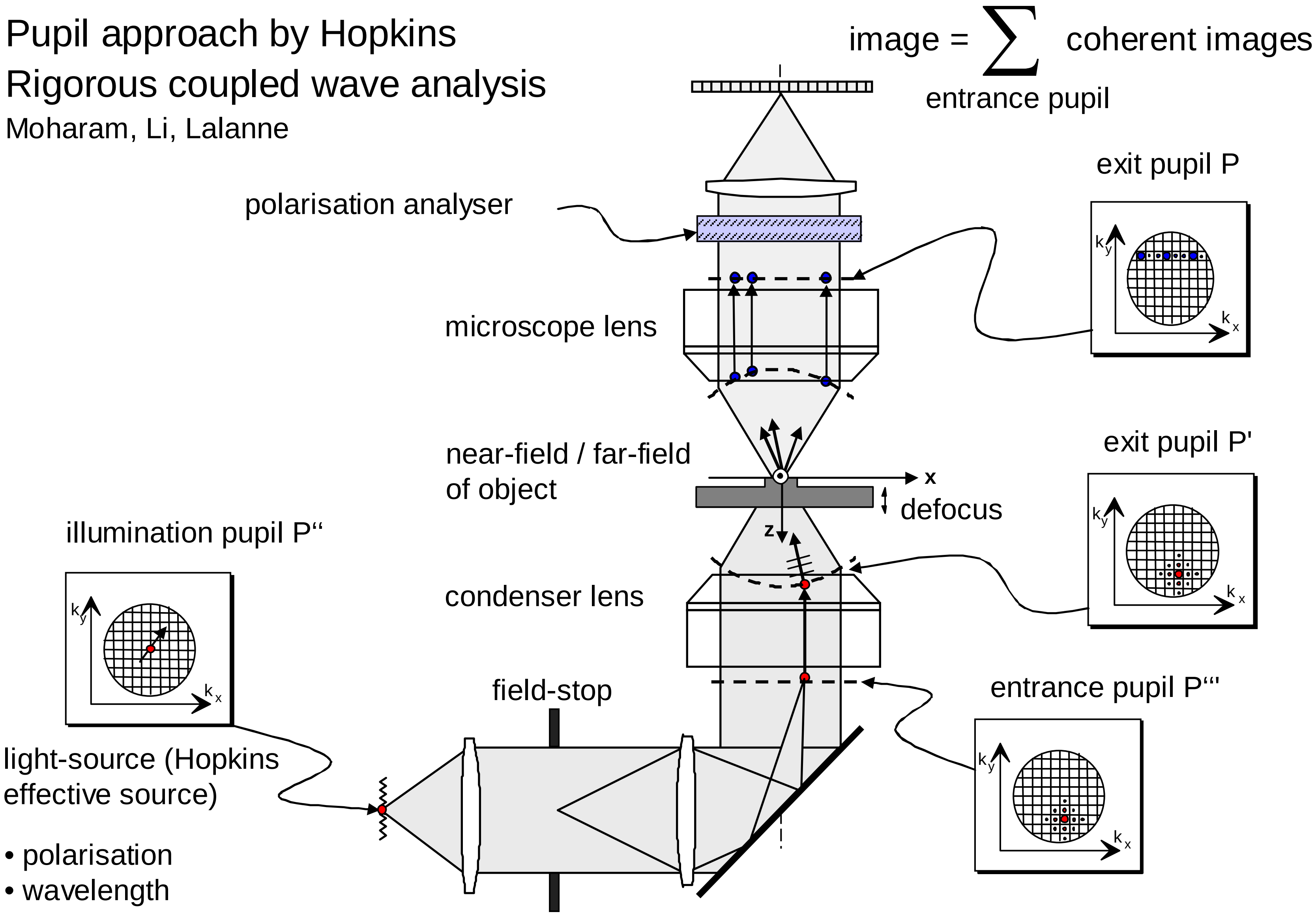
How does MicroSim work?

Pupil approach by Hopkins

Rigorous coupled wave analysis

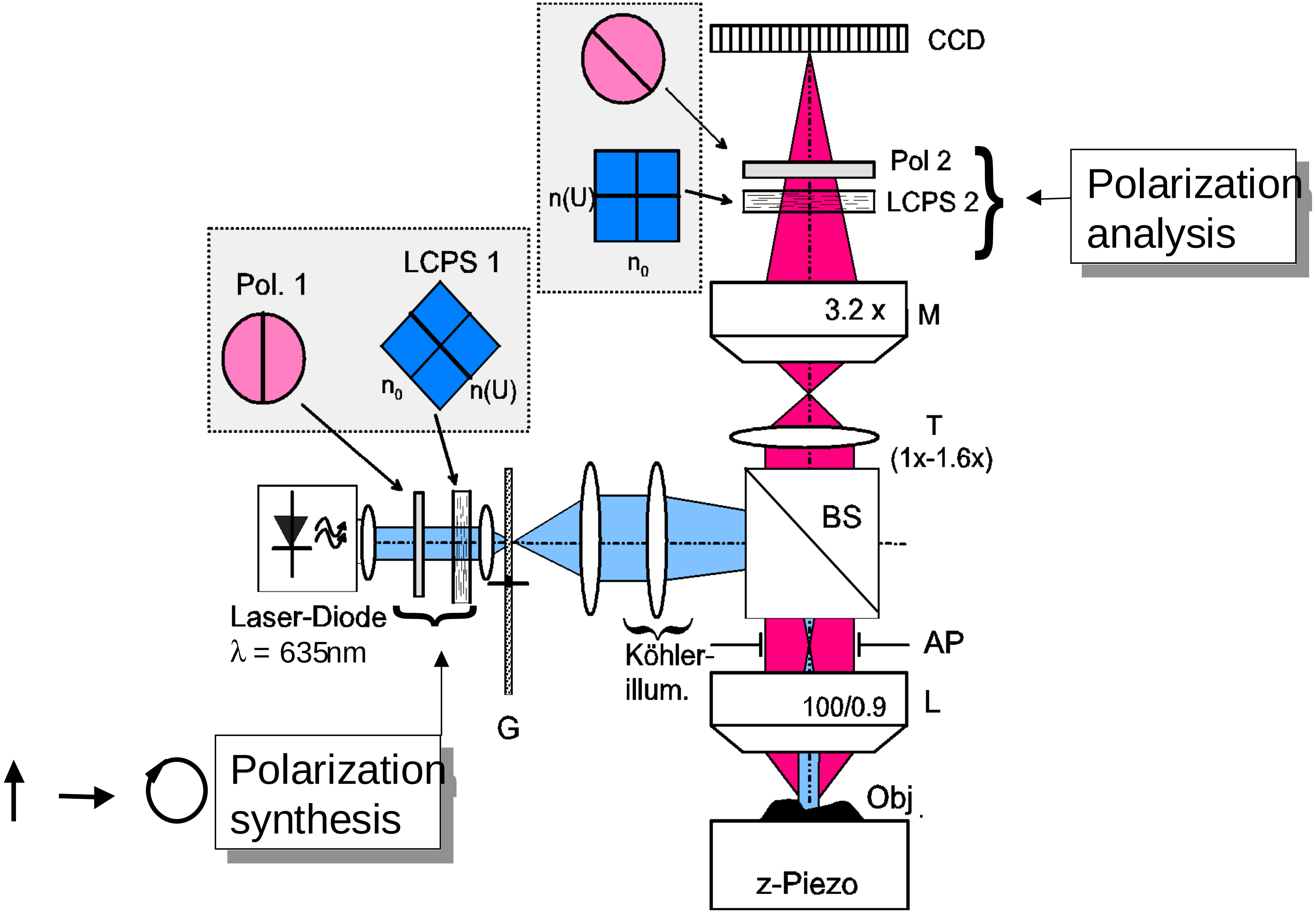
Moharam, Li, Lalanne

$$\text{image} = \sum_{\text{entrance pupil}} \text{coherent images}$$



- polarisation
- wavelength
- degree of coherence

Setup for PSPI for Microstructure Inspection

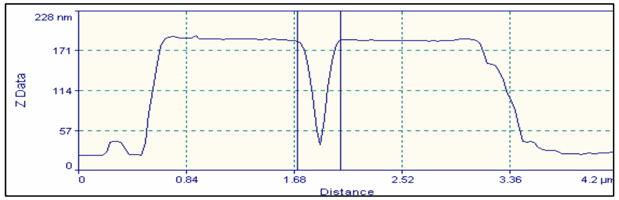


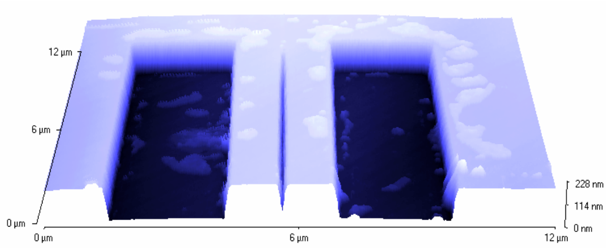
Polarization analysis

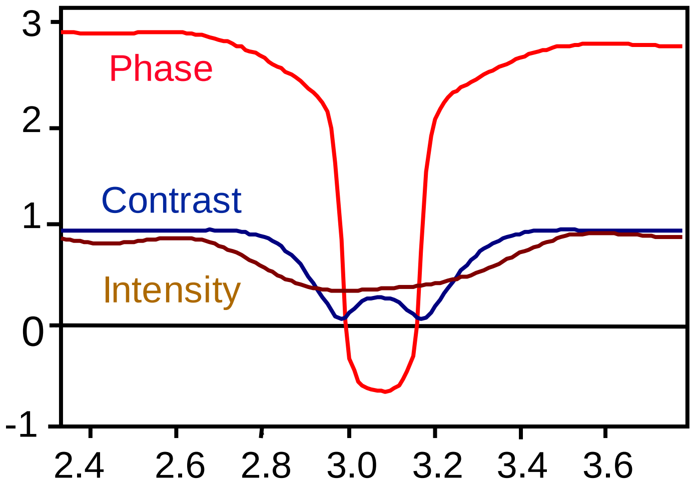
Polarization synthesis

PSPI for sub-λ microstructure inspection

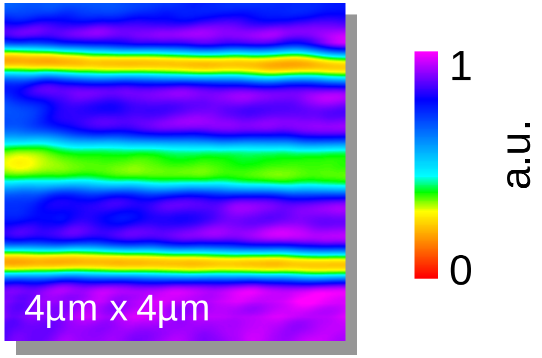
Sub-λ Groove: 330 nm (λ=635nm)



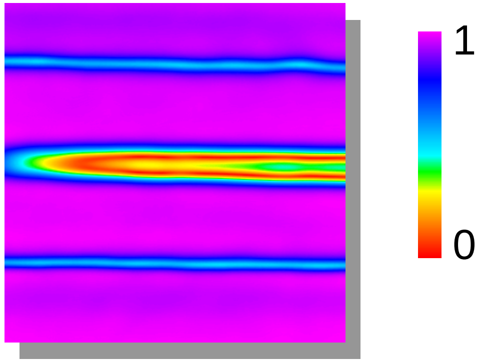




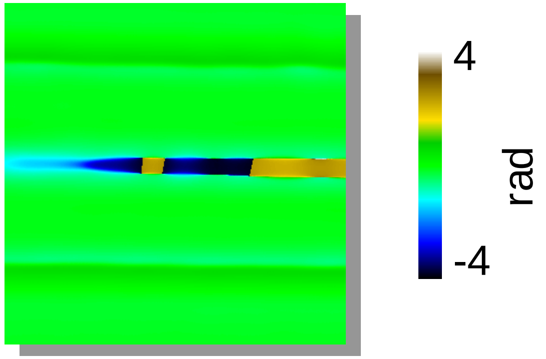
Intensity



Contrast



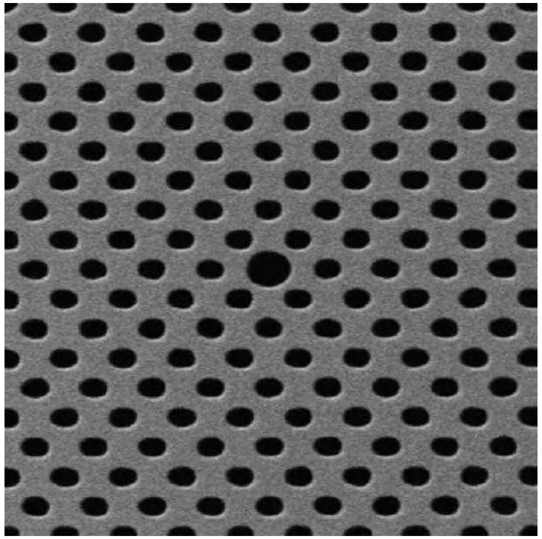
Phase



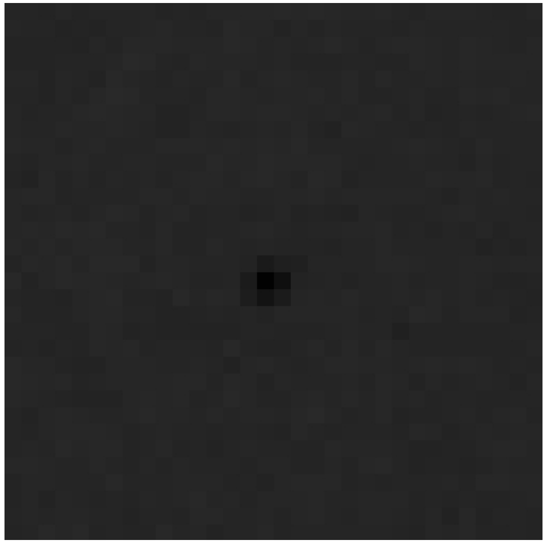
ICFCNM 2009

Defectoscopy: SEM Images

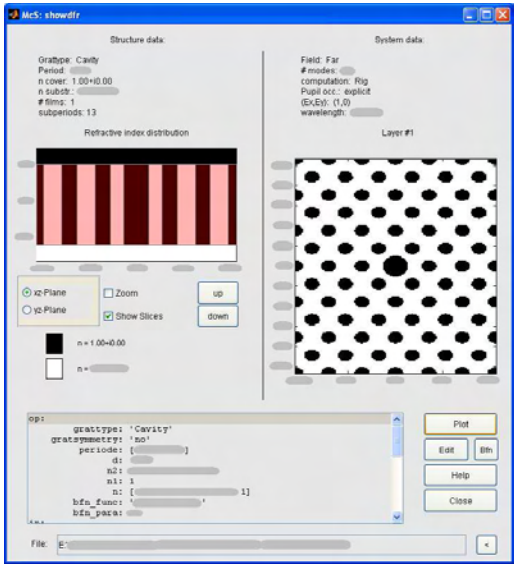
Cavity



Imaging with Microscope



Simul. with MicroSim



Structure data:

Grattype: Cavity
Period: [redacted]
n cover: 1.00+i0.00
n substr.: [redacted]
films: 1
subperiods: 13

System data:

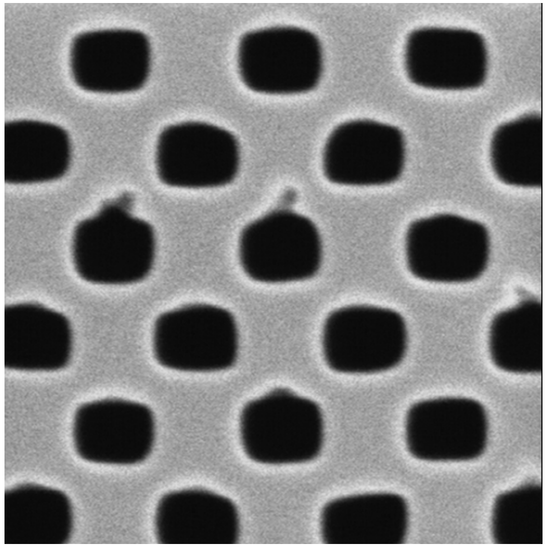
Field: Far
modes: [redacted]
computation: Rig
Pupil occ.: explicit
(Ex,Ey): (1,0)
wavelength: [redacted]

■ n = 1.00+i0.00
☐ n = [redacted]

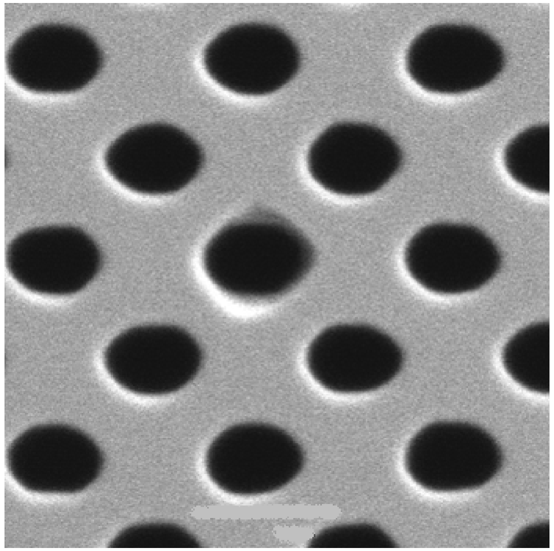
```
op:
       grattype: 'Cavity'
   gratsymmetry: 'no'
        periode: [[redacted]]
              d: [redacted]
             n2: [redacted]
             n1: 1
              n: [[redacted] 1]
       bfn_func: '[redacted]'
       bfn_para: [redacted]
```

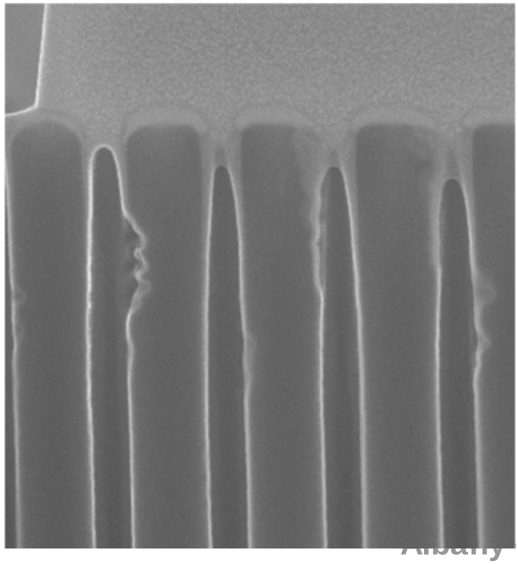
File: E:[redacted]

Etching under Top Layer



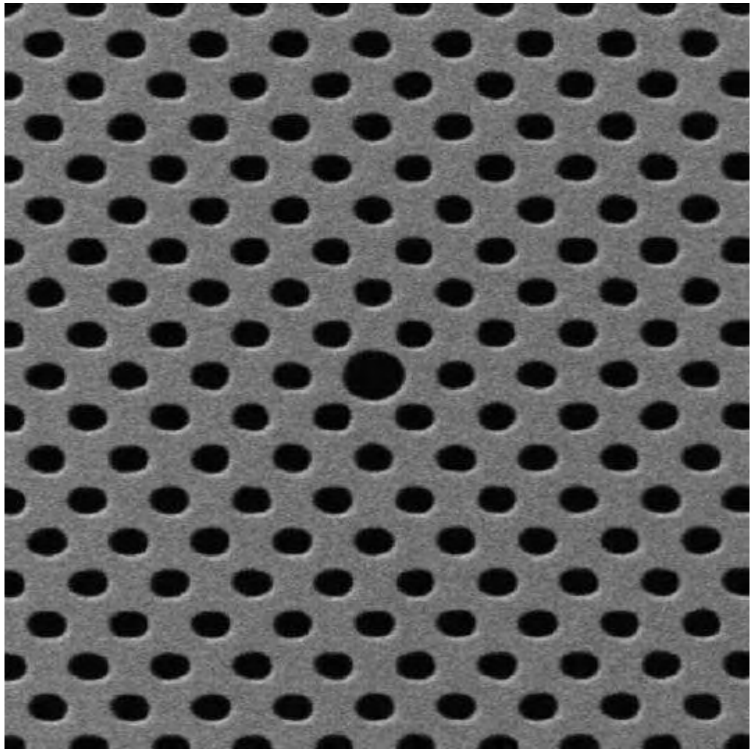
Imperfect Etching



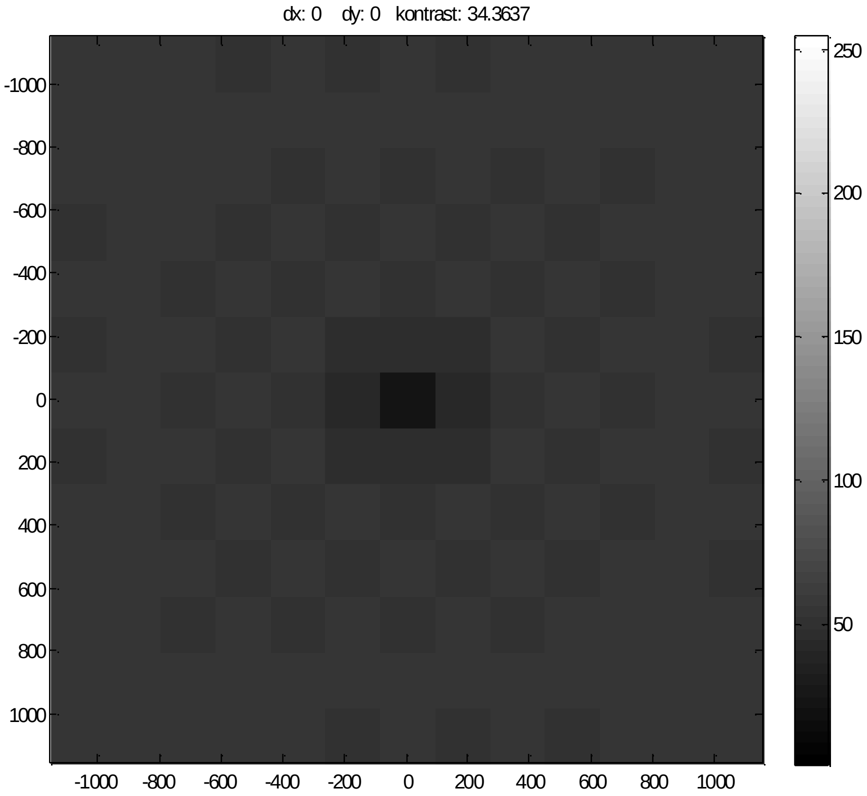


Example: Cavity

SEM-Image of Defect



Simulation Result



Interesting Points: - Influence of Mode Number

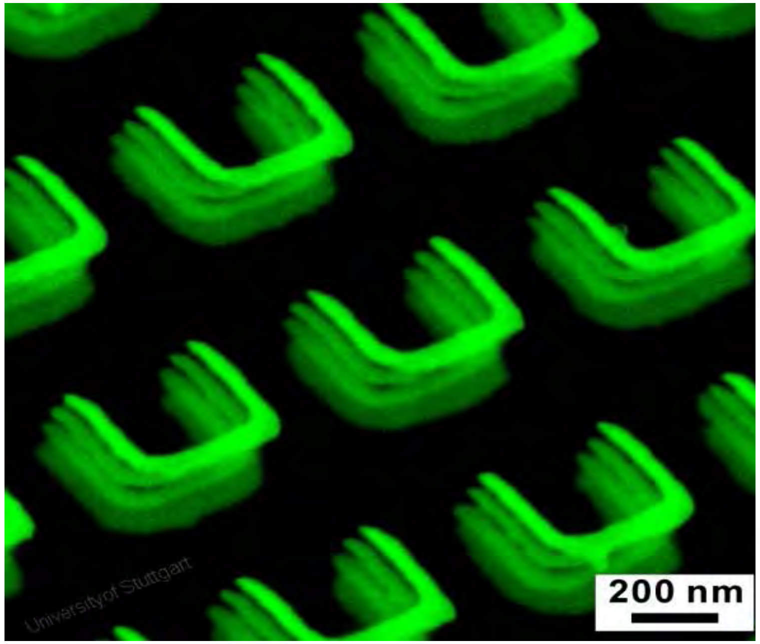
- Pupil Discretization

Bringing Microscopy back: Superresolution??

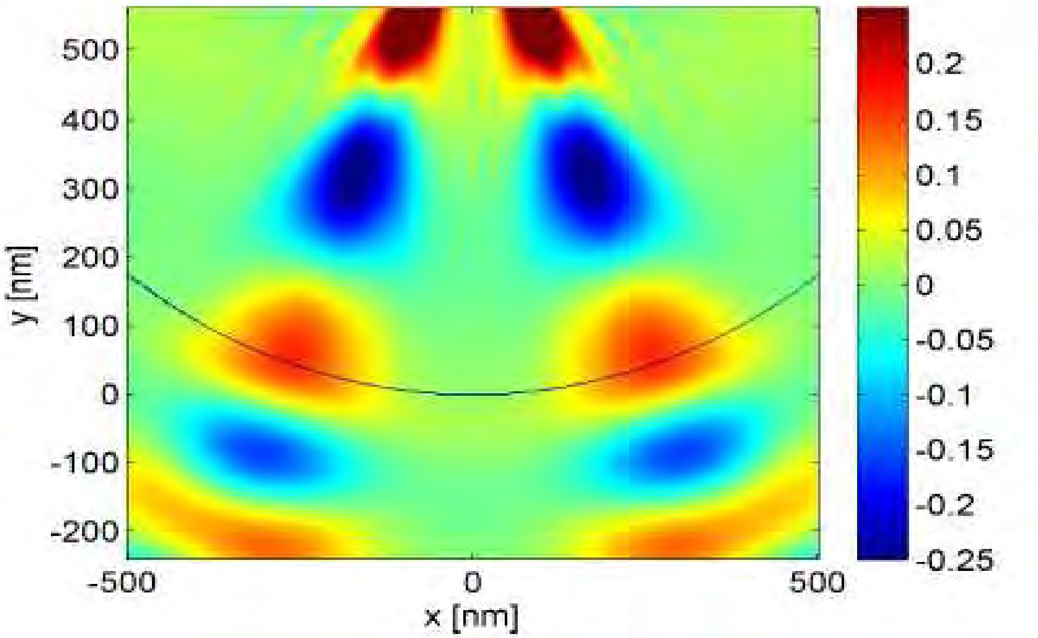
Meta-Material + Special Superlattice

Hyperlense-Imaging

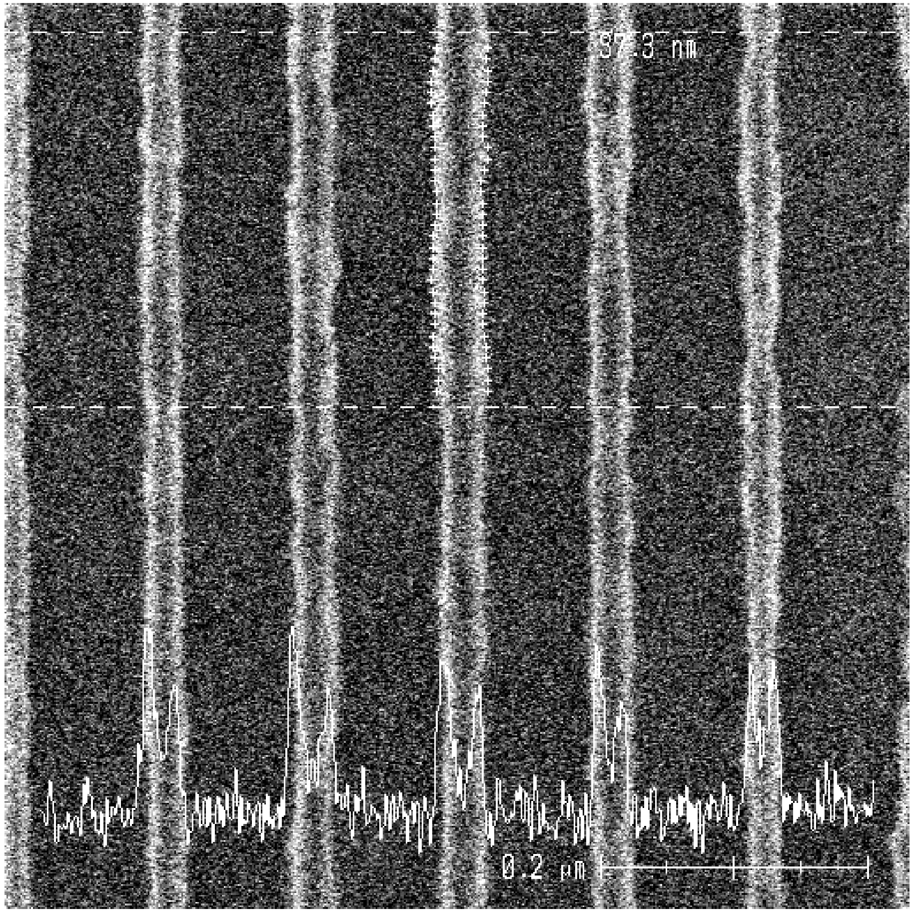
Negative Index (Meta-)Materials



Far Field Propagation



Motivation



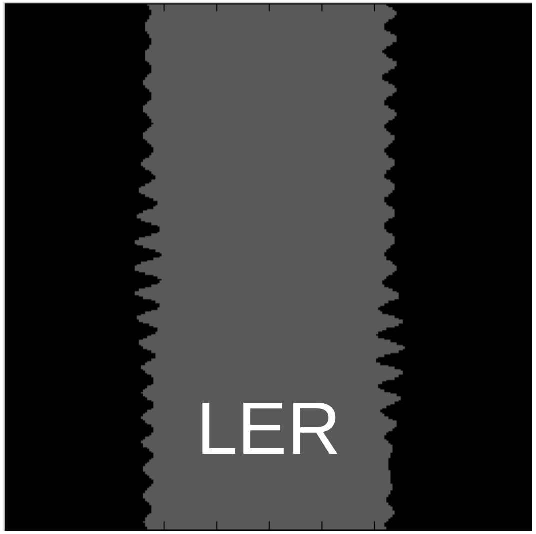
Motivations:

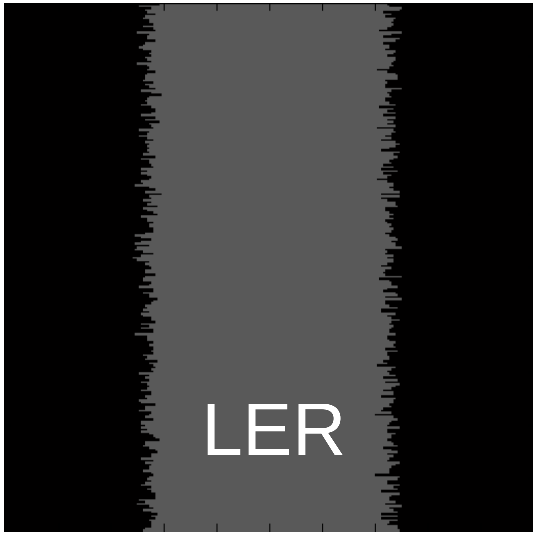
– Scatterometry: powerful tool for CD metrology

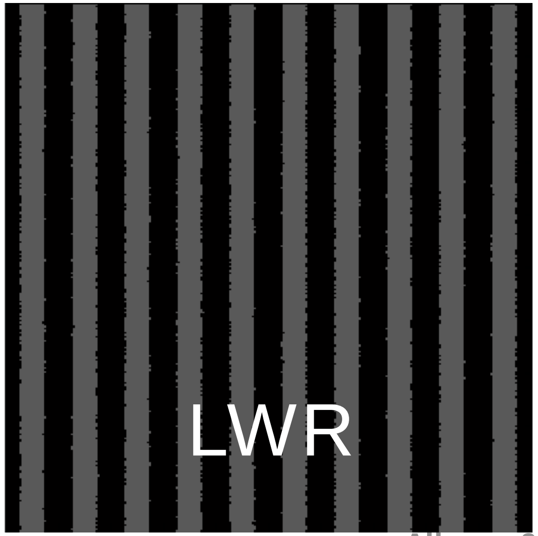
– structure sizes: ↓

– CD fluctuations & LER: (↑)

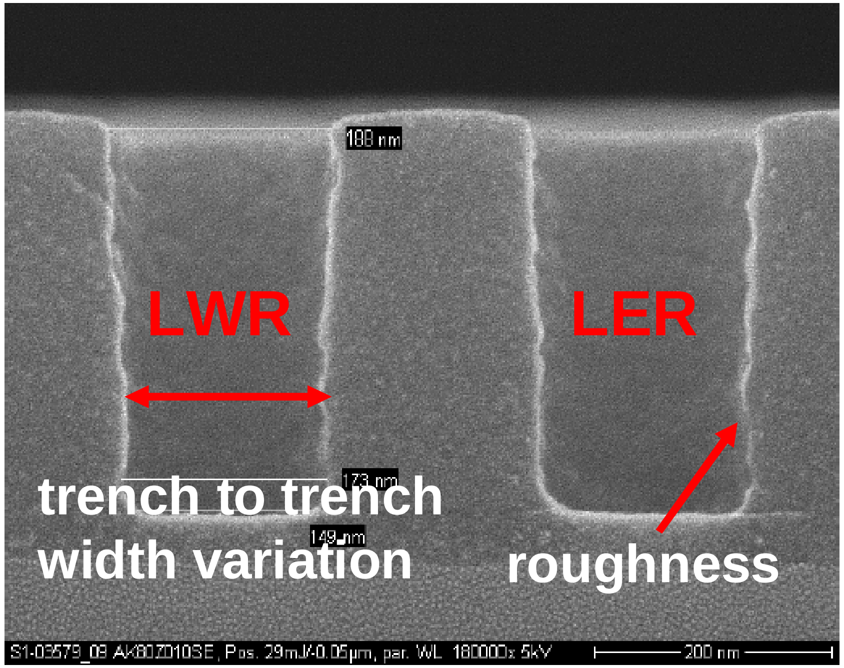
- realistc modeling/consideration of LER for reconstr.


quasi-mono noise

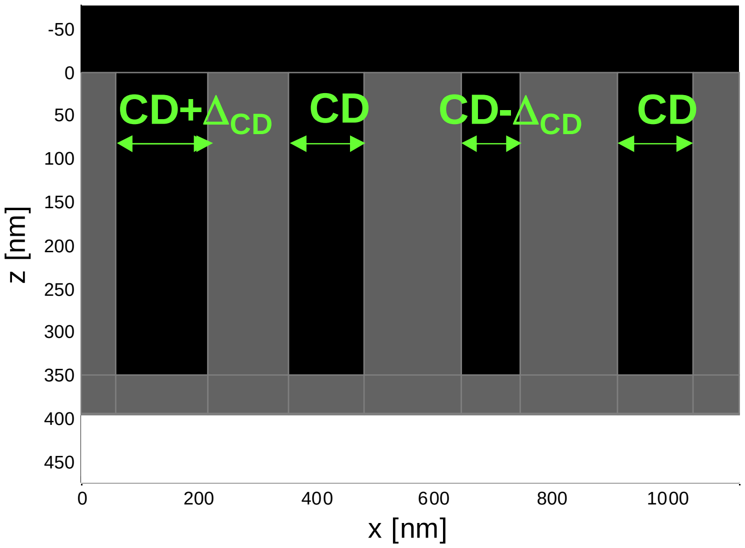

colored or white noise


superlattices

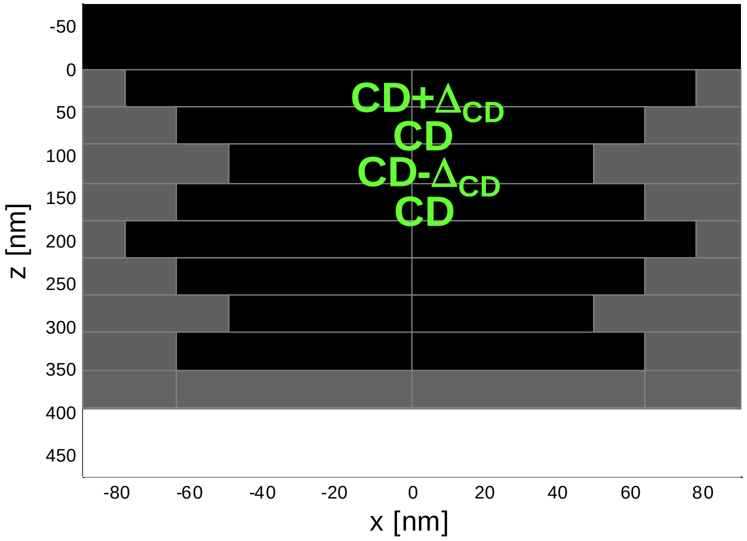
Example: Investigation of Fluctuations



Trench to trench variation of trench width



Sidewall roughness

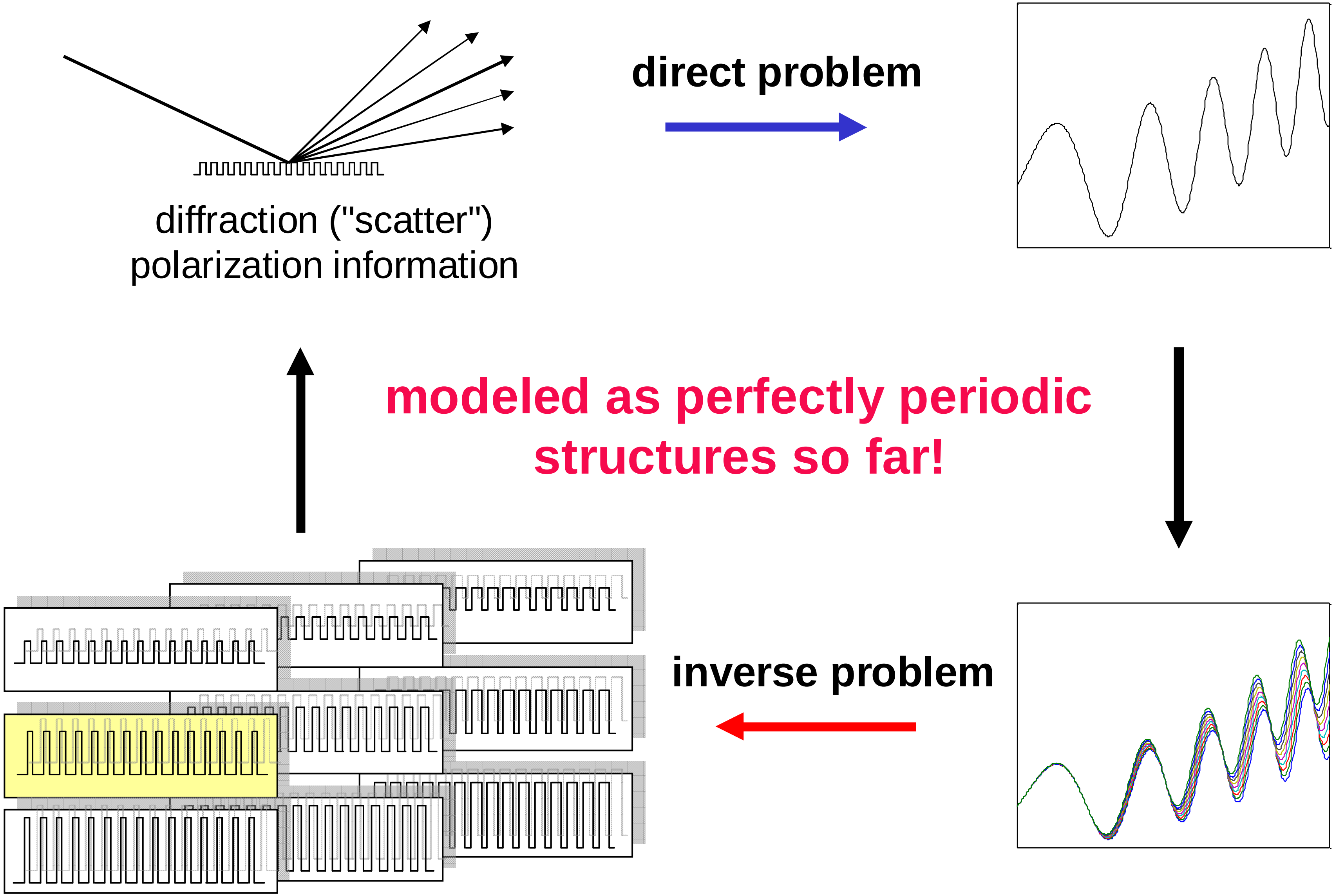


Is it possible to ...

- measure mean values despite the presence of fluctuations?
- measure mean values and fluctuations independently of each other?

Scatterometry

Scatterometry: Principle



diffraction ("scatter")
polarization information

direct problem

modeled as perfectly periodic structures so far!

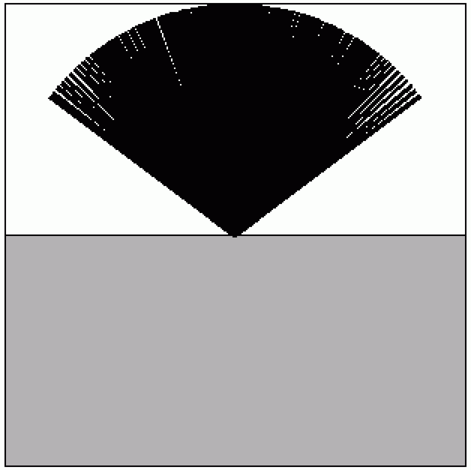
inverse problem

Scatterometry: History

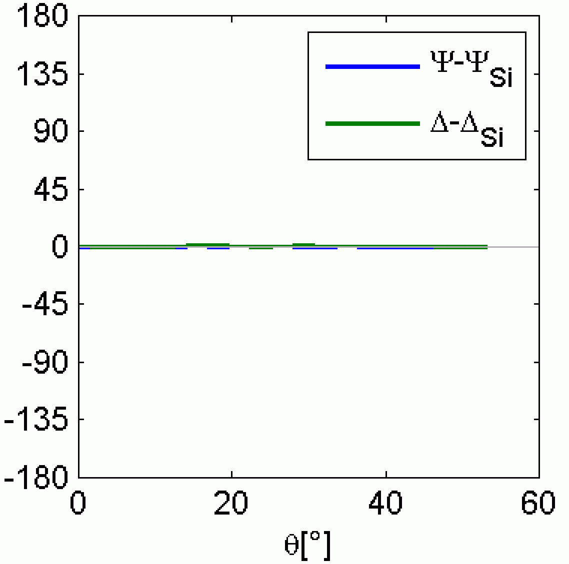
1976	Kasdan und George	Masks, Fourier-Optics, Fraunhofer Theory
1978 / 80	Kleinknecht und Meier	Etched Structures& Masks, 1 Diff.-Order, 1 Angle, Fraunhofer Theory
1984	Moharam et al.	Resist, different Diffractiion Orders, angle & wavelength dependent, RCWA,
1992	McNeil et al.	"Scatterometry“, orthog. incidence & Goniometer, 2θ-Scatterometer
1995	Bischoff et al.	3D Structures, resist, 2θ-Scatterometer
1997	Ziger et al.	Normal-Incidence-Reflektometry
1997	Takeuchi et al.	Ellipsometry
1999	Niu et al.	Spectral-Ellipsometry
2002	Hettwer et al.	Phi-Scatterometry
2004	Boher et al. / Silver et al.	Fourier-Scatterometry / Scatterfield Microscopy

Scatterometry: Relevant Scale, 193nm

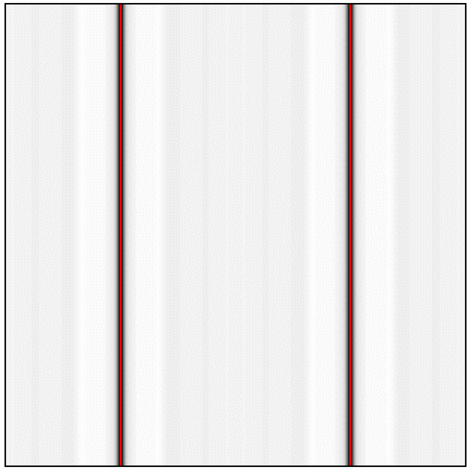
Beugungsordnungen, 10000 nm



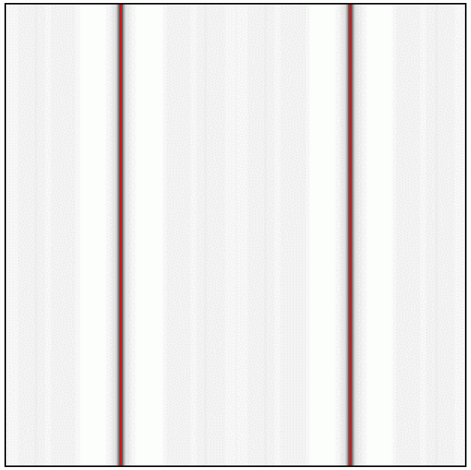
Polarisations-Information, 10000 nm



Mikroskop-Bild x pol, 10000 nm

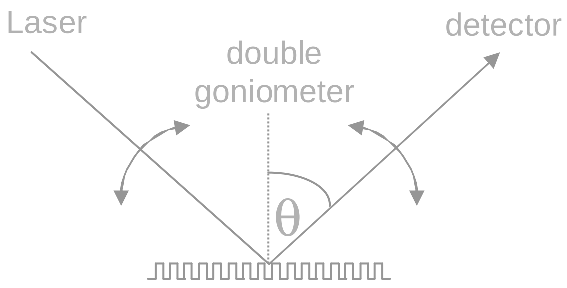


Mikroskop-Bild y pol, 10000 nm

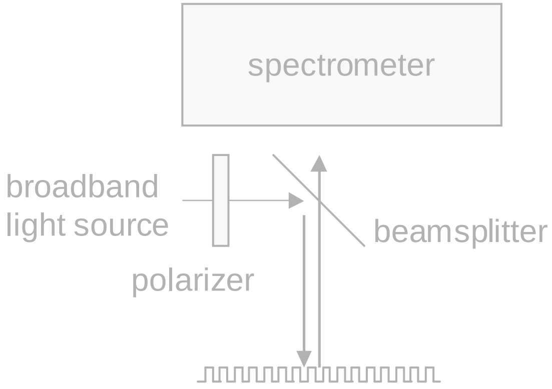


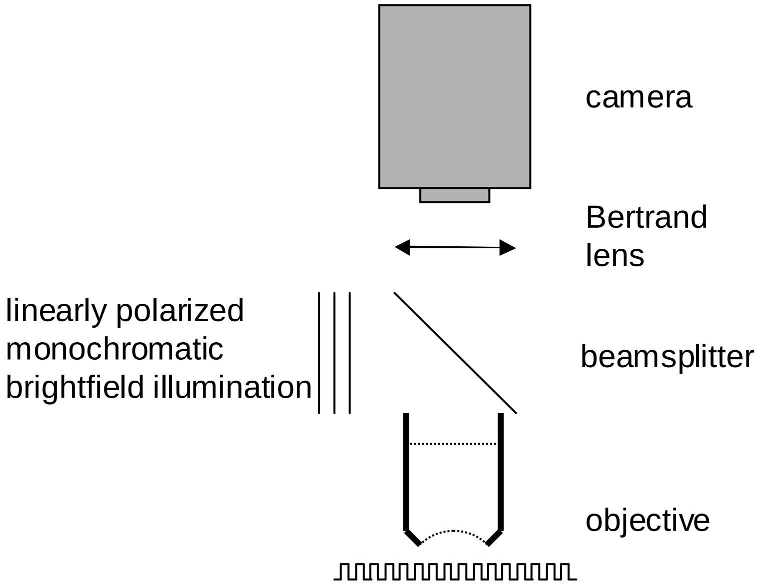
Scatterometry Configurations

2θ-Scatterometry

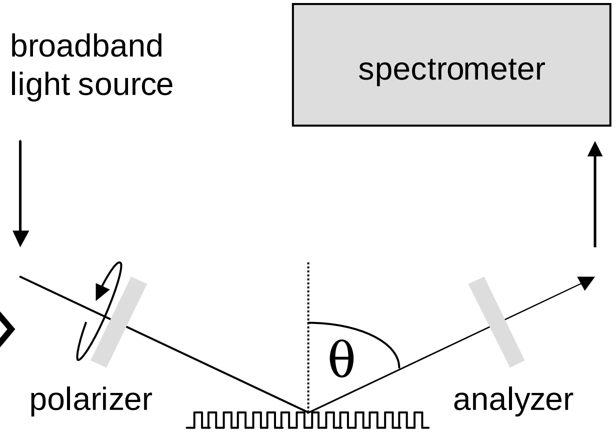


Reflectometry





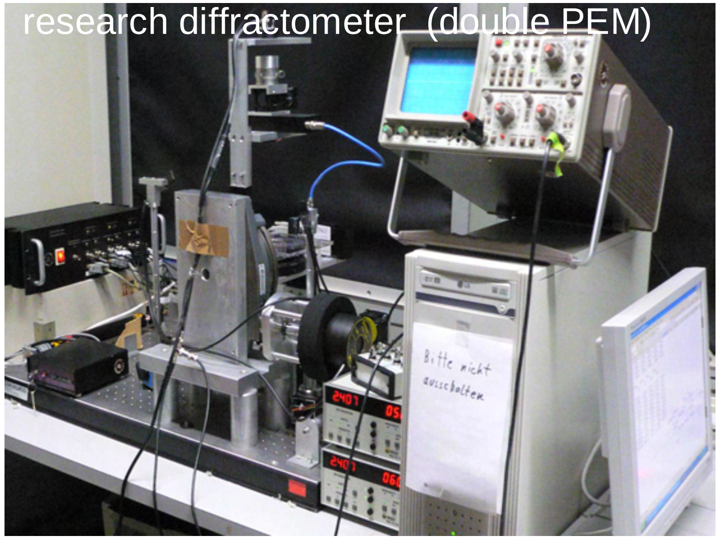
Fourier Scatterometry

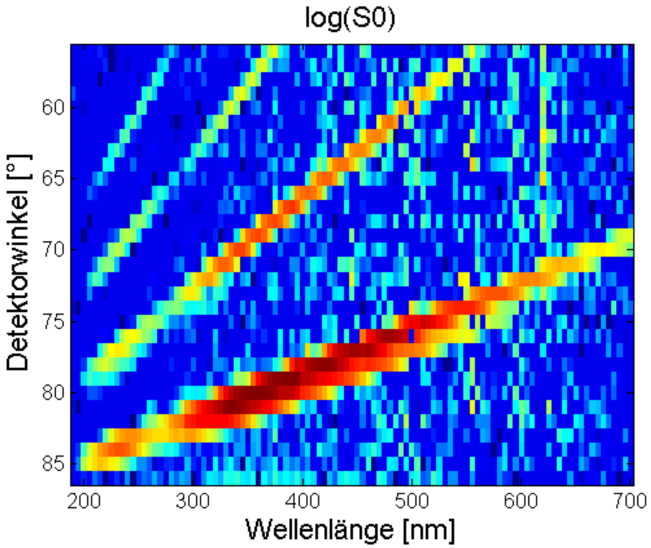


Spectroscopic Ellipsometry

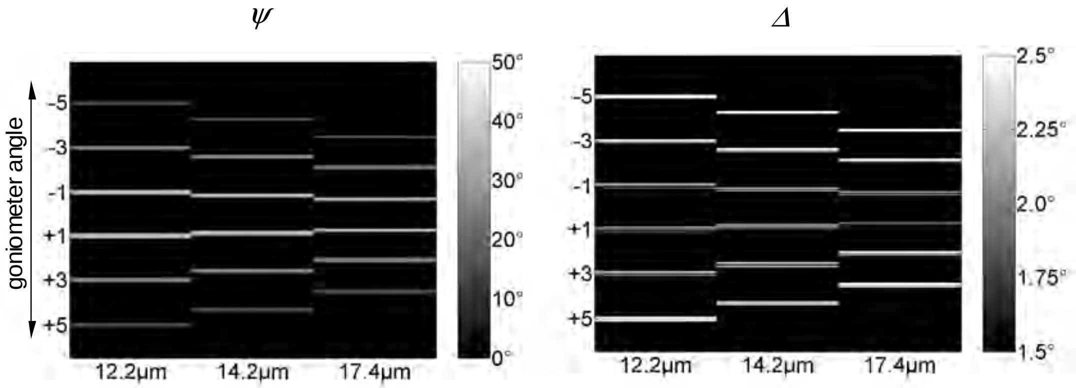
Instrumentation at ITO


JY UVISEL PEM spectroscopic ellipsometer


research diffractometer (double PEM)



diffraction orders of a 2 µm line grating, measured with the spectroscopic ellipsometer



polarization resolved diffractometry at line gratings for structure reconstruction

Scatterometry: Approach

Approach in CD-Metrology:

- **Measurement** of Spectra
- **Simulation** of Spectra with Maxwell-Solver (e.g. **MicroSim**)
- **Comparison** of measured and simulated data
- **Reconstruction** of structure data (CD, SWA, ...)

Question: - **Influence of LER/LWR?**

- **Influence of System Parameters?**

1.

Influence of LER on Scatterometry

Simulation Parameters

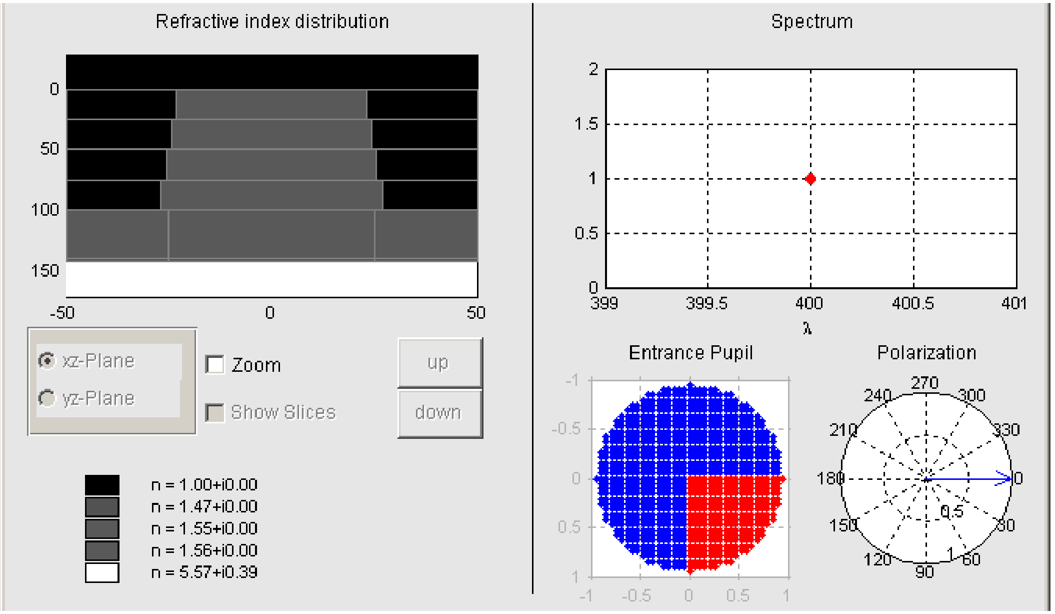
Fourier Scatterometry

- λ fix, vary angles
- RCWA
- NA=0.95
- Pupil sampling 37*37
- λ=400 nm (default)
  other λ's investigated
- reconstruction with real-time computation and iterative Gauss-Newton optimization available

Spectroscopic Ellipsometry

- angle fix, vary λ
- RCWA
- θ=71,6° (BA of Silicon)
- α=25° (analyzer angle)
- λ= 350..750 nm (increment 5nm)
- reconstruction using library search and parabolic sub-pixel interpolation

Simulated Structure and Approach



- Resist lines:
  dense: 50/100 nm
  iso: 50/350 nm
- height: 100nm
- BARC layer
- SWA 87° dense 84° iso
- 4 layers and ± 5 Fourier modes in x and y direction each yield deviations < 1%

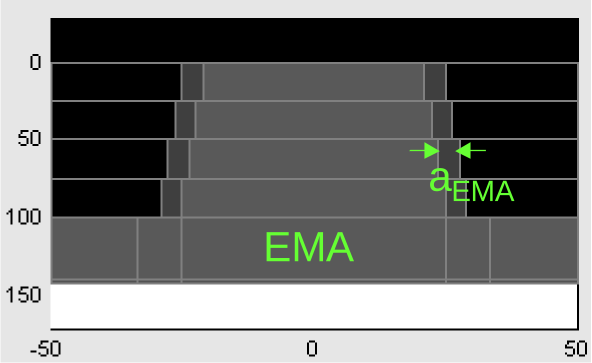
Approach:

- considering LER as a small perturbation of a perfect periodic structure

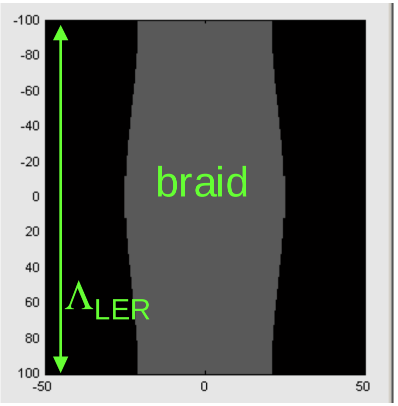
Restrictions:

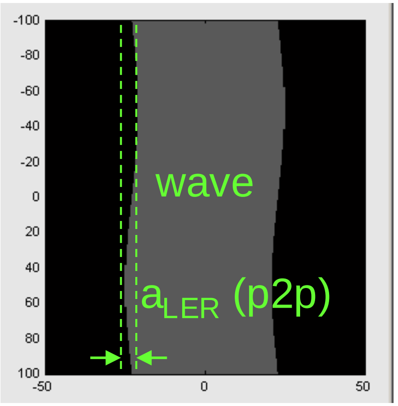
- computing time!
- periodic modeling of the LER instead of a truly random model

Modeling LER



"**EMA**": **Effective Medium Approximation**
(layer with averaged refractive index)





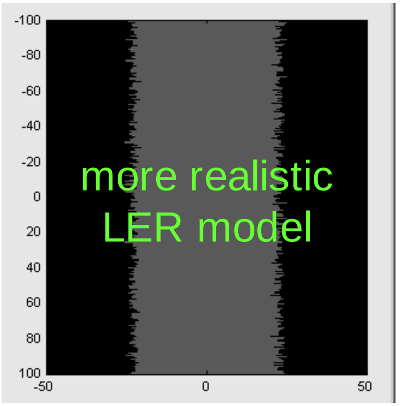
"**braid**": sinusoidal linewidth variation

"**wave**": sinusoidal line position variation

The periodic modeling keeps the computation time strongly tolerable!

Default value: $a_{\text{LER}} = 3nm$

$\widehat{=} 1.06nm$ rms

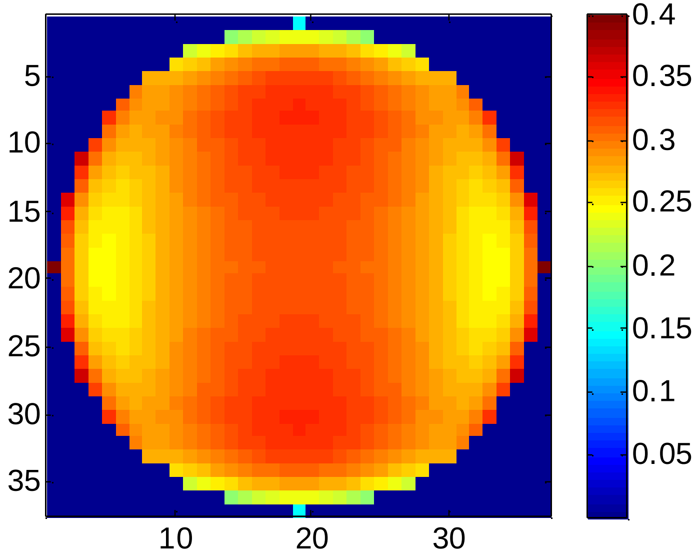


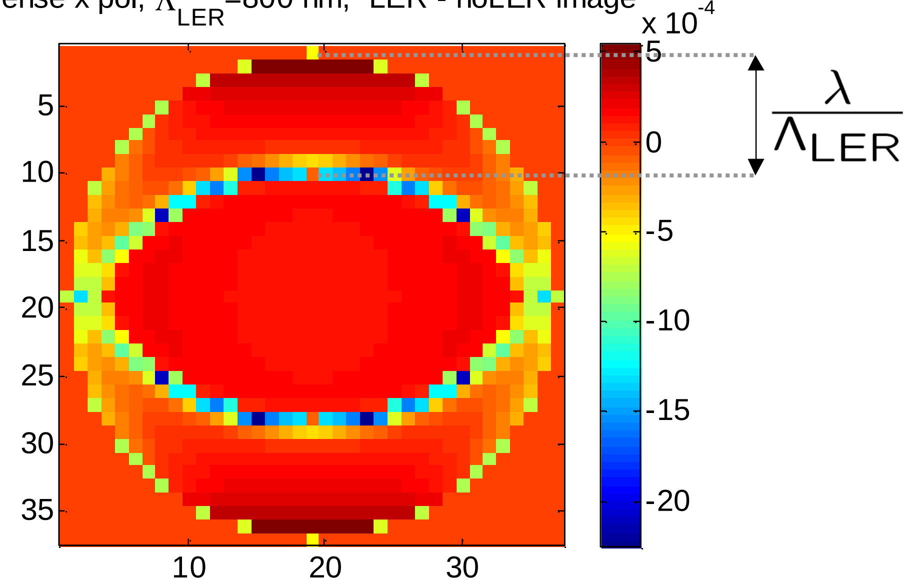
More realistic LER models cannot be computed with a few Fourier modes only. More advanced simulation techniques have to be applied for such studies.

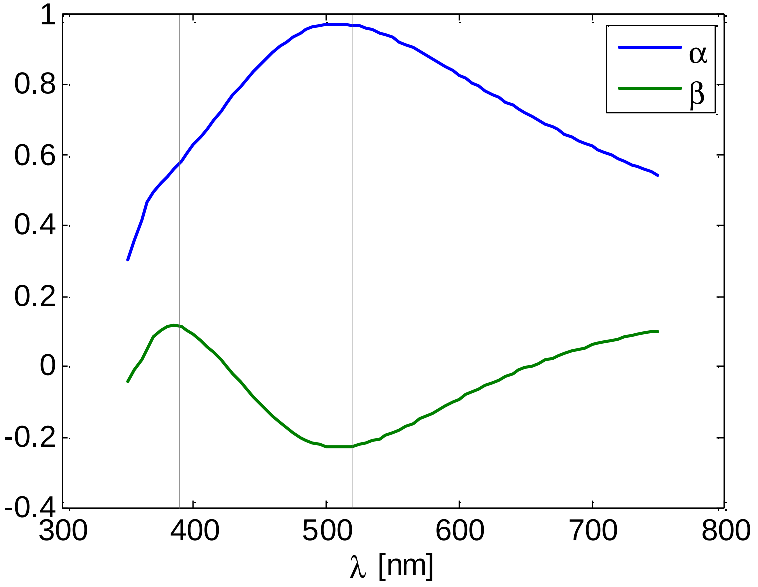
Procedure:

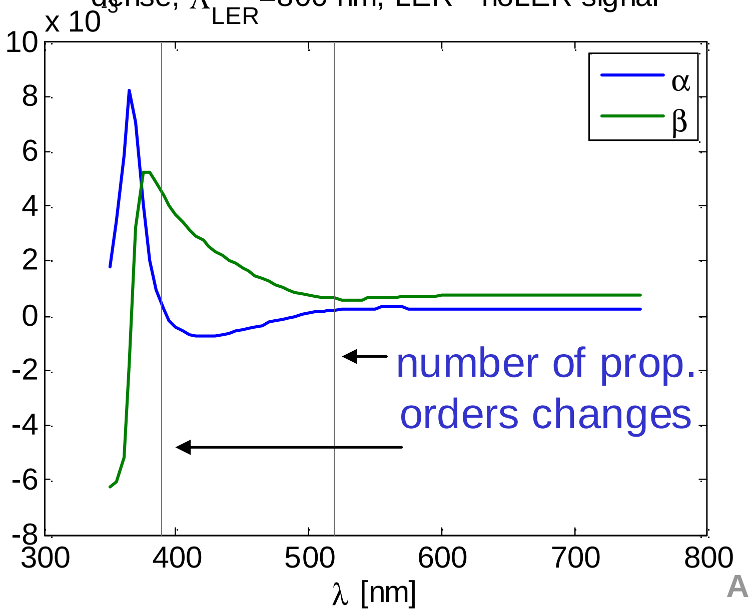
- **Simulation** of Spectra with various LER- parameters & considering them as pseudo measured data
- **Simulation** of Spectra without and with presence of LER (latter with EMA-approximation)
- **Reconstruction** of different parameters: CD & SWA
- **Reconstruction** with floating thickness of a_{EMA} (3nm)
- **Reconstruction errors** of the parameters as measures for the influence of LER

Examplary Scatterograms


dense x, Λ_{LER}=800 nm, LER image


dense x pol, Λ_{LER}=800 nm, LER - noLER image


dense, Λ_{LER}=800 nm, LER signal


dense, Λ_{LER}=800 nm, LER - noLER signal

number of prop. orders changes

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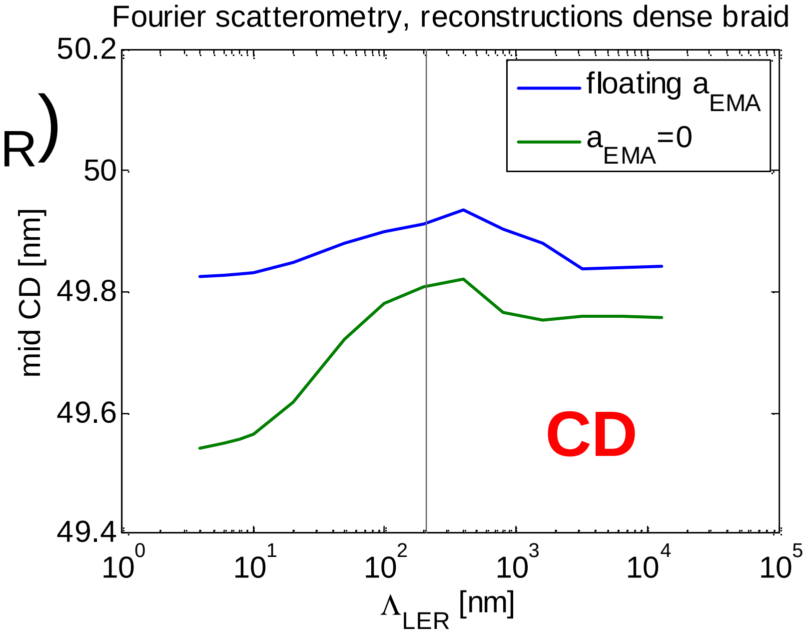
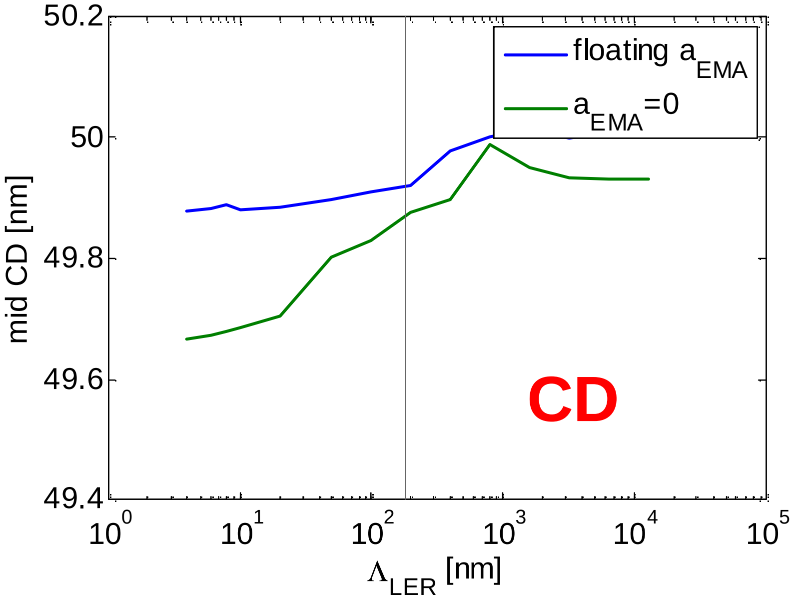
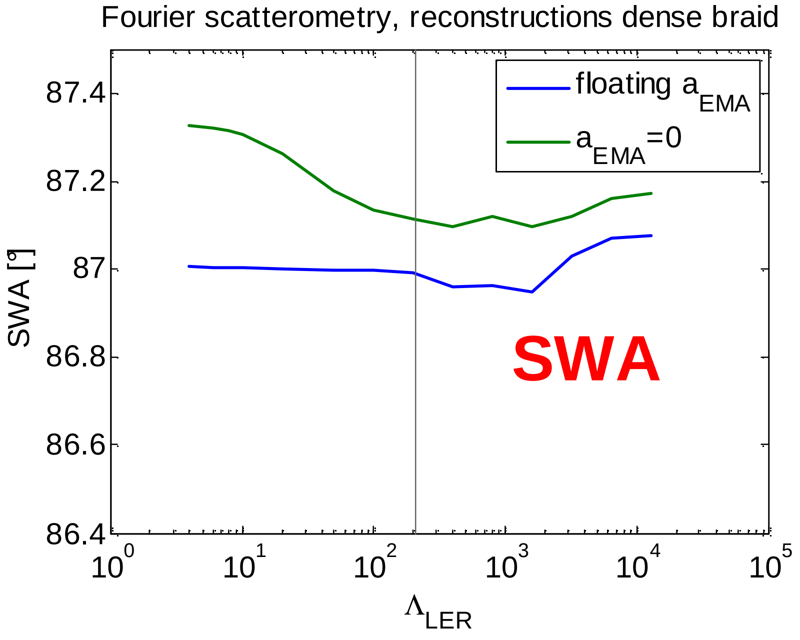
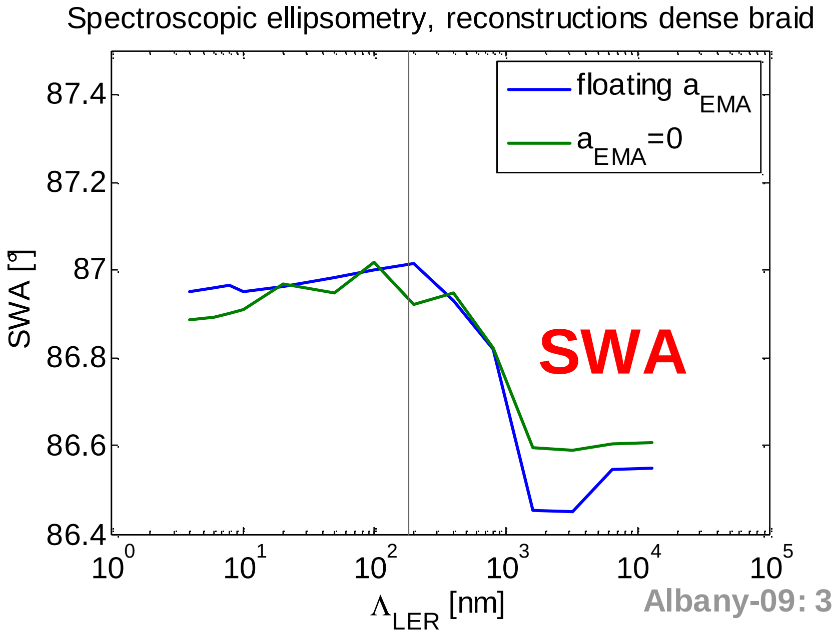
Reconstr. with & without floating EMA layer

$f(\Lambda_{LER})$


Fourier scatterometry, reconstructions dense braid


Spectroscopic ellipsometry, reconstructions dense braid


Fourier scatterometry, reconstructions dense braid


Spectroscopic ellipsometry, reconstructions dense braid

Conclusion 1

- The influence of LER decreases with increasing Λ_{LER}
- Reconstruction errors can be considerably reduced introducing a floating EMA layer, even in the regime $\Lambda_{\mathrm{LER}} > \lambda$, where the EMA is known to be invalid.
- The reconstructed EMA layer thickness is similar to the rms value 1.06 for $\Lambda_{\mathrm{LER}} \to 0$ and is getting small for large Λ_{LER}.
- The curves are "disturbed" when "roughness diffraction" sets in.
- The quasi-monochromatic noise with and without superlattice yields similar results as the purely sinusoidal model.
- More advanced models such as colored and white noise will be investigated with this approach.

2.

Parameter Sensitivity of Scatterometry

Motivation:

- Applicability of scatterometry towards smaller technology nodes

Questions/Directions:

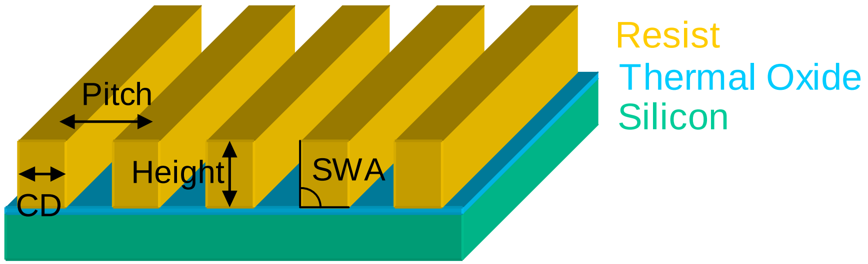
- How does Scatterometry perform for future (smaller) nodes?
- Possibilities of predicting parameter sensitivity (simulation based!)
- Investigate available degrees of freedom to optimize sensitivity
- Optimization of measurement configurations

Structures and Measurements

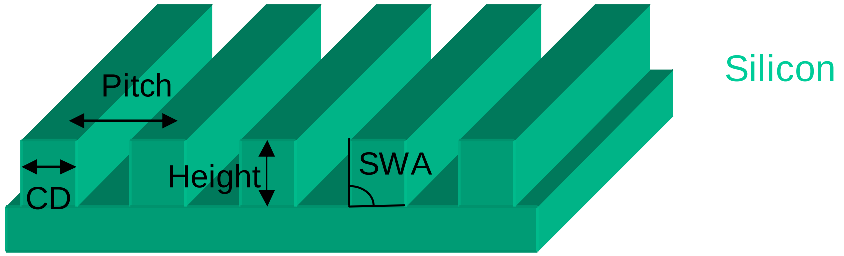
Analyzed Structures

Dense Lines, 3 Types:

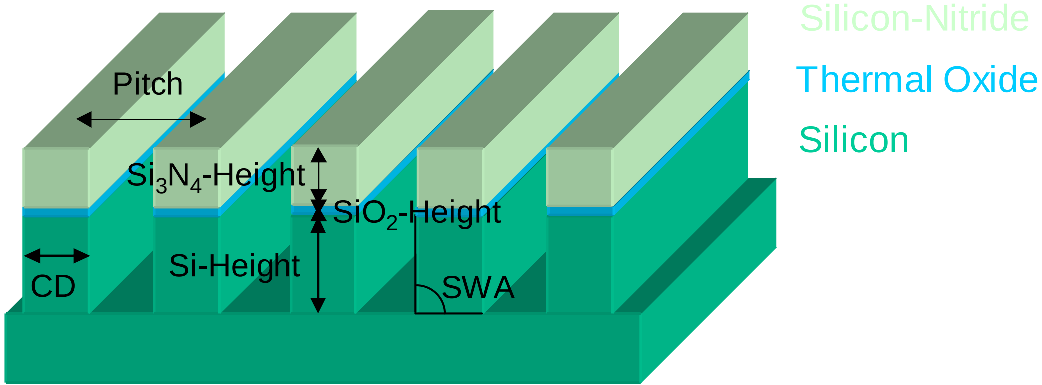
- E-beam written resist structures
  Nodes: CD 75 nm to 22 nm



- Etched silicon structures
  Nodes: CD 75 nm to 22 nm

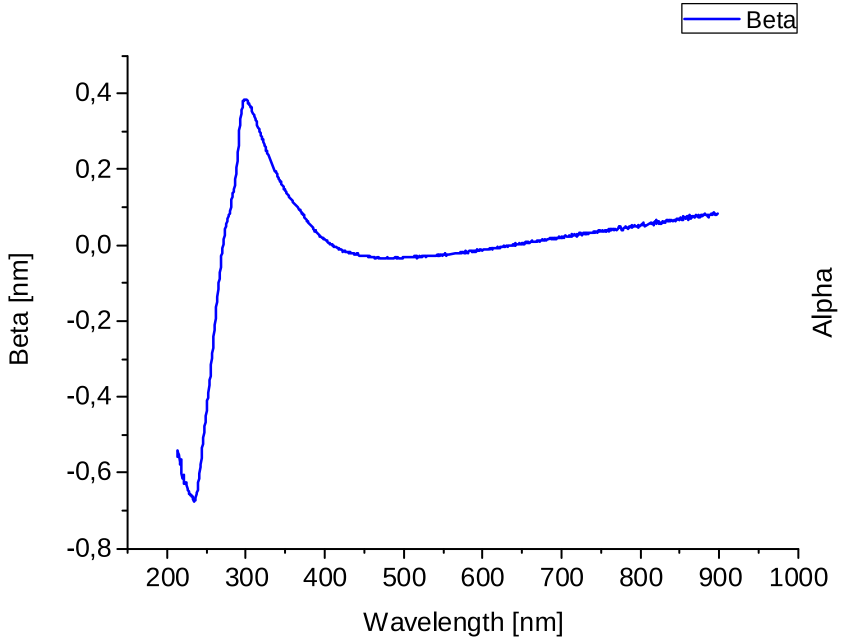


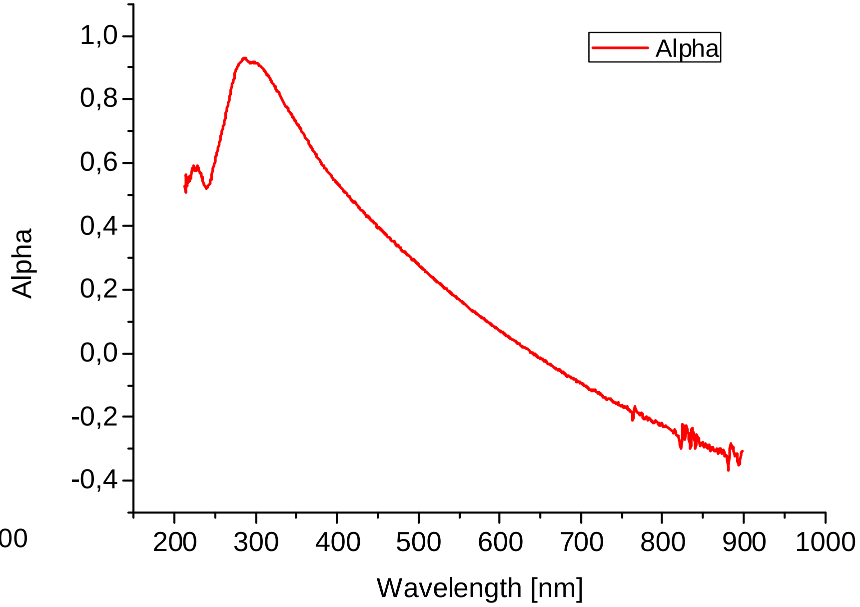
- STI structures



Measured Scatterometry Spectra

- Measured at Qimonda (industrial Scatterometry Tool)
- This means: fixed incident angle (near Brewster angle of Si)
- Spectrum 200 nm to 900 nm

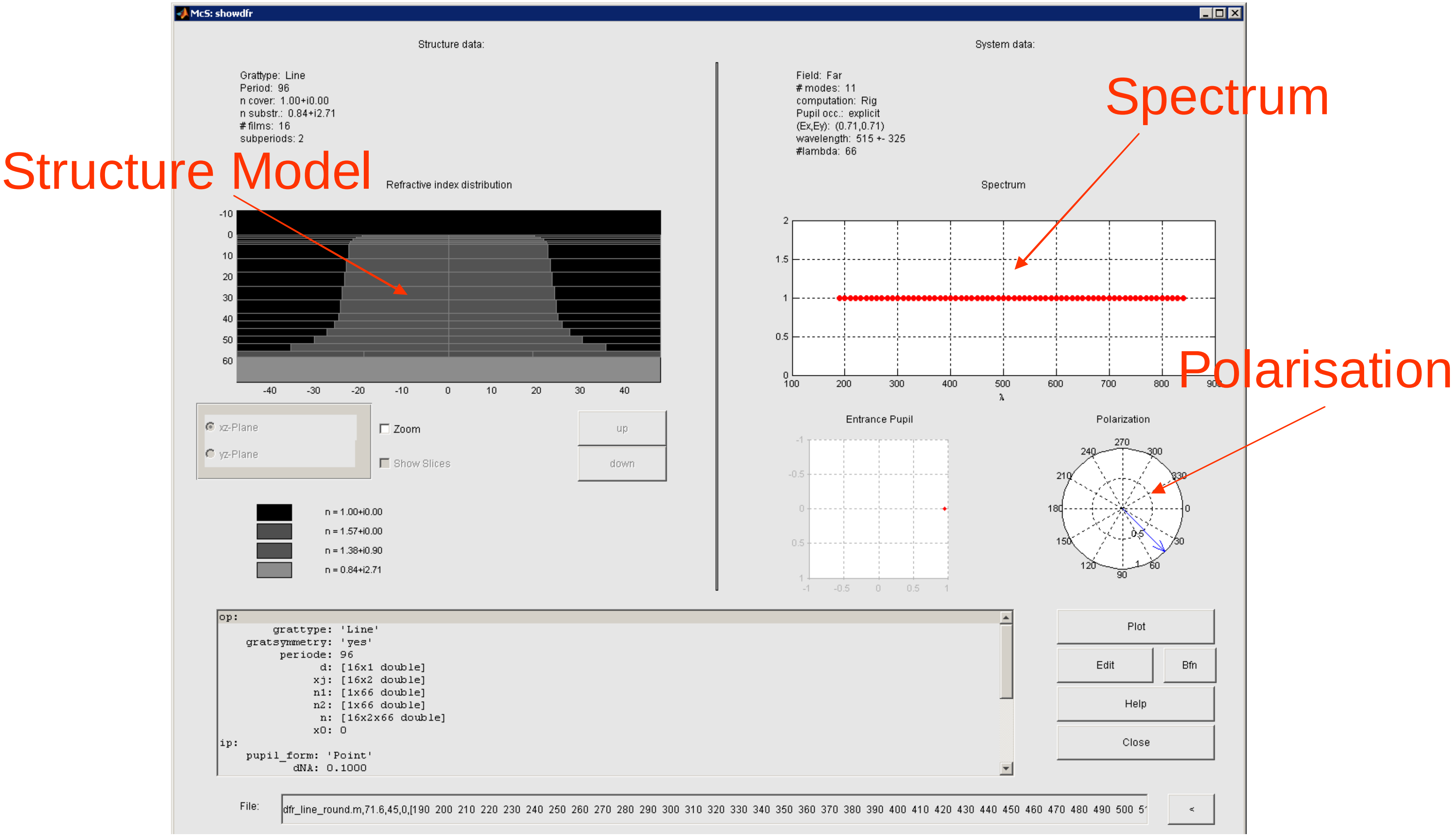




Example: Alpha and Beta for dense resist lines (CD 48nm, Pitch 96 nm)

Simulations

Simulations with Microsim



Structure Model

Spectrum

Polarisation

McS: showdfr

Structure data:

Grattype: Line
Period: 96
n cover: 1.00+i0.00
n substr.: 0.84+i2.71
films: 16
subperiods: 2

System data:

Field: Far
modes: 11
computation: Rig
Pupil occ.: explicit
(Ex,Ey): (0.71,0.71)
wavelength: 515 +- 325
#lambda: 66

● xz-Plane
○ yz-Plane
☐ Zoom
☐ Show Slices

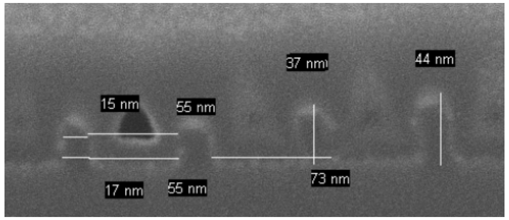
■ n = 1.00+i0.00
■ n = 1.57+i0.00
■ n = 1.38+i0.90
■ n = 0.84+i2.71

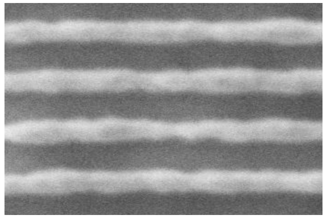
```
op:
        grattype: 'Line'
    gratsymmetry: 'yes'
         periode: 96
               d: [16x1 double]
              xj: [16x2 double]
              n1: [1x66 double]
              n2: [1x66 double]
               n: [16x2x66 double]
              x0: 0
ip:
    pupil_form: 'Point'
           dNA: 0.1000
```

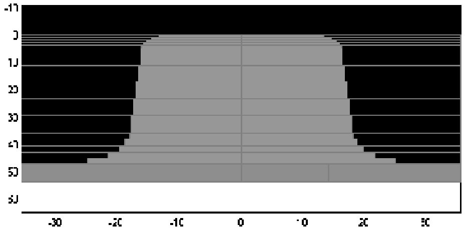
File: dfr_line_round.m,71.6,45,0,[190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 5

SEM vs. Model

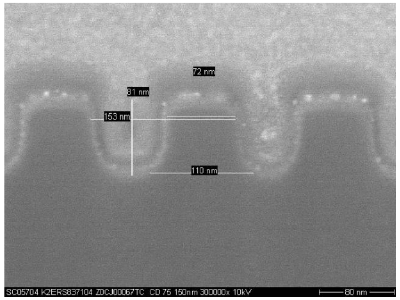
- **Resist Structure - Parameters**: CD, pitch, height, SWA, top- & bottom-rounding, SiO2-layer

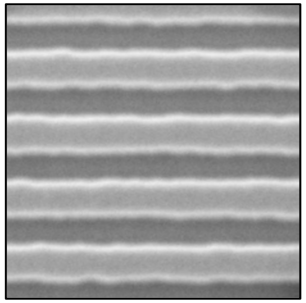


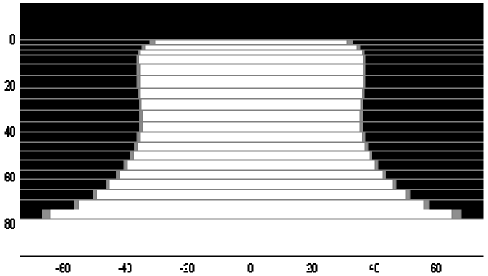




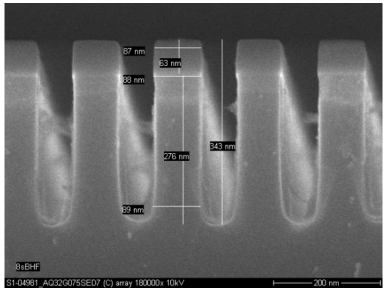
- **Etched Structure - Parameters**: CD, pitch, height, SWA, top- & bottom-rounding, bow, SiO_2

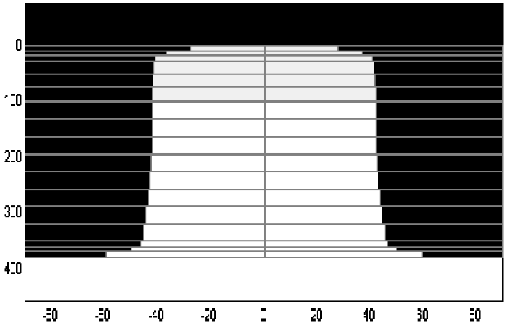






- **STI Structure - Parameters**: CD, pitch, height (Si_3N_4, $Si0_2$, Si), SWA, top & bottom-rounding

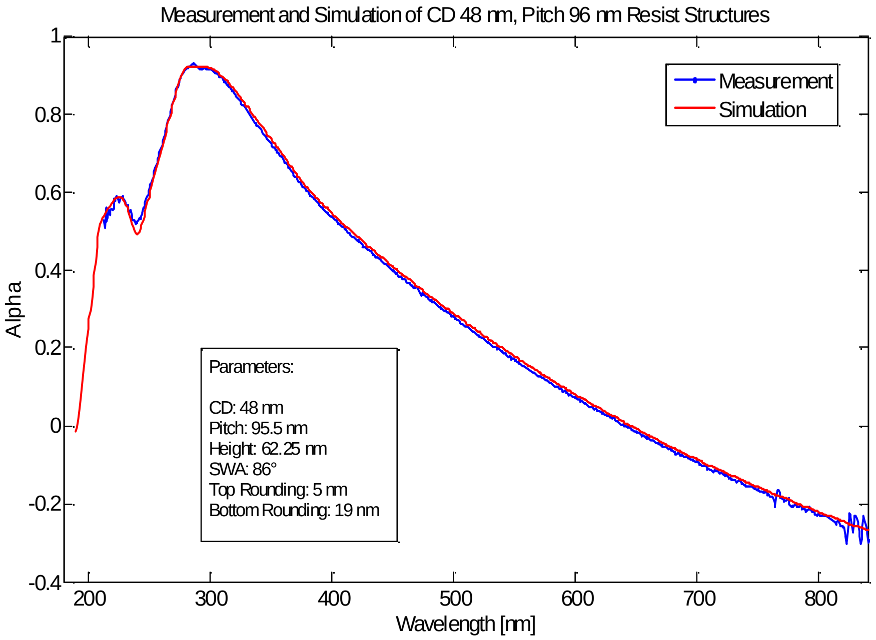


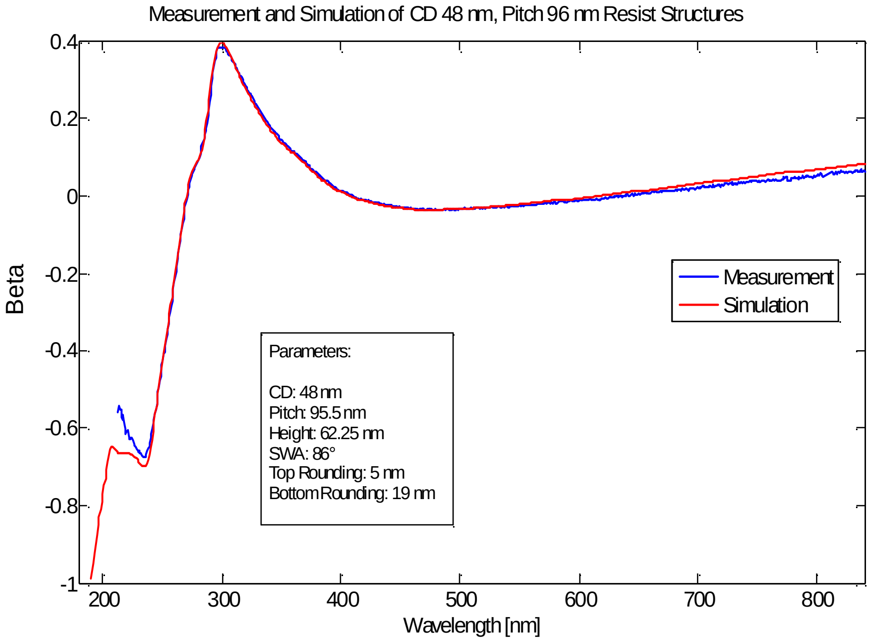


SEM (cross) **SEM (top-down)** **MicroSim**

Verification of simulations / Comparison to measurements

- Creation of pre-computed libraries for each structure
- Best match search (Measurement vs. Library)



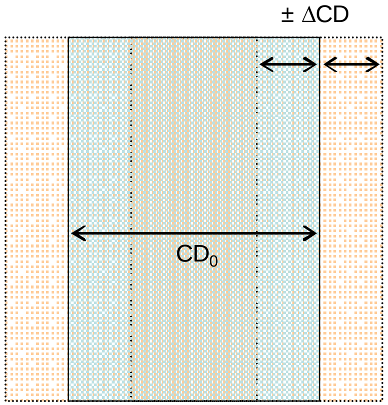


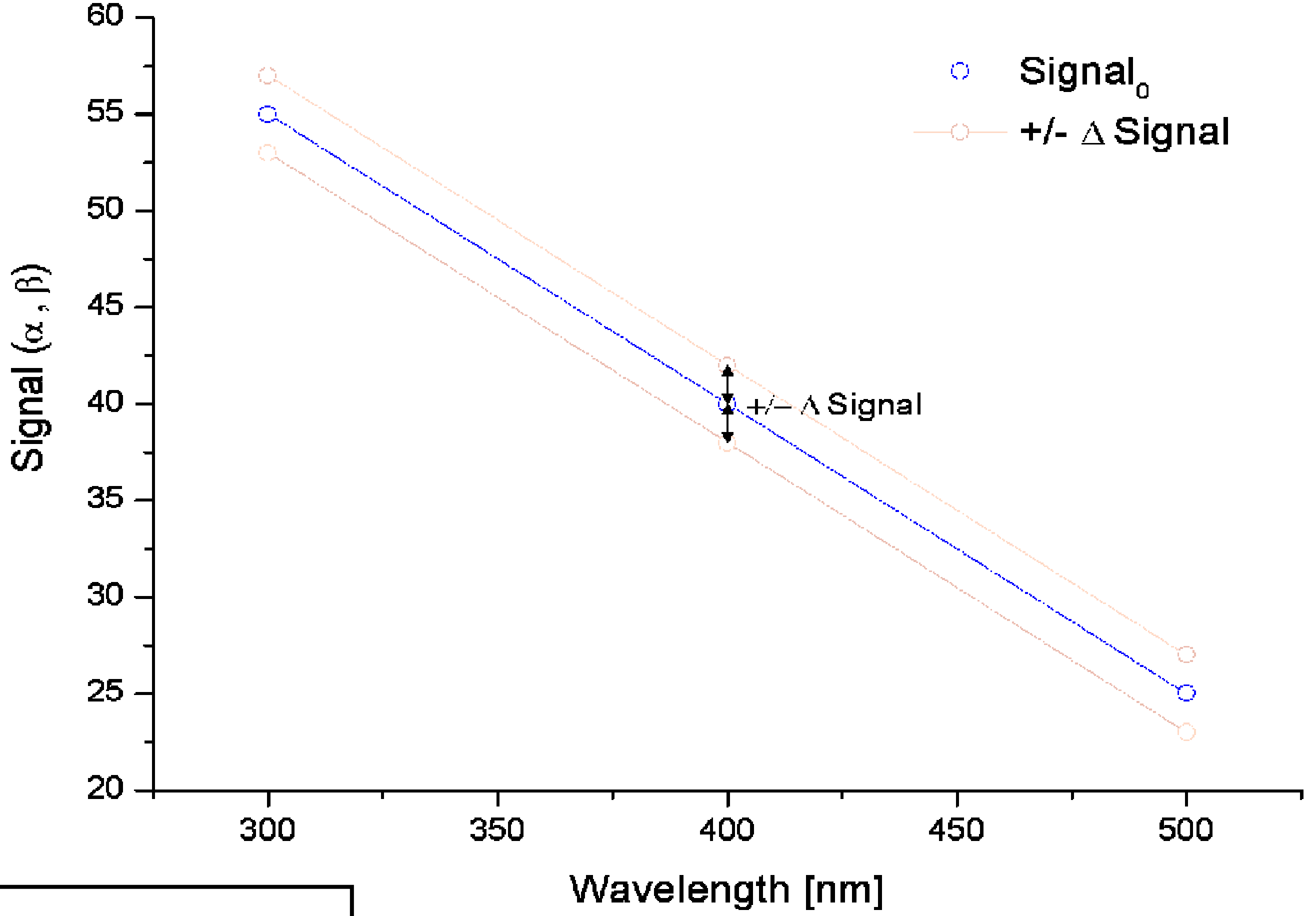
<u>Example</u>: Resist structures CD 48nm, Pitch 96 nm

Sensitivity of Scatterometry

Sensitivity Definition

Example: CD





$$\text{Sensitivity} = \frac{|\Delta \text{Signal}|}{|\Delta \text{Var}| / |\text{Var}_0|}$$

Signal-Variation ⌧ Input-Variation

Performed Sensitivity Analysis

- **wavelength**: 190 nm – 840 nm in 1 nm steps
- **incident-angle:** 0° – 90° in 0.5° steps
- for all 3 structure types (dense lines: resist, etched, STI)
- parameters (CD, pitch, height, SWA,…)
- nodes: CD 75 nm ... CD 18 nm, in max. 6 nm steps

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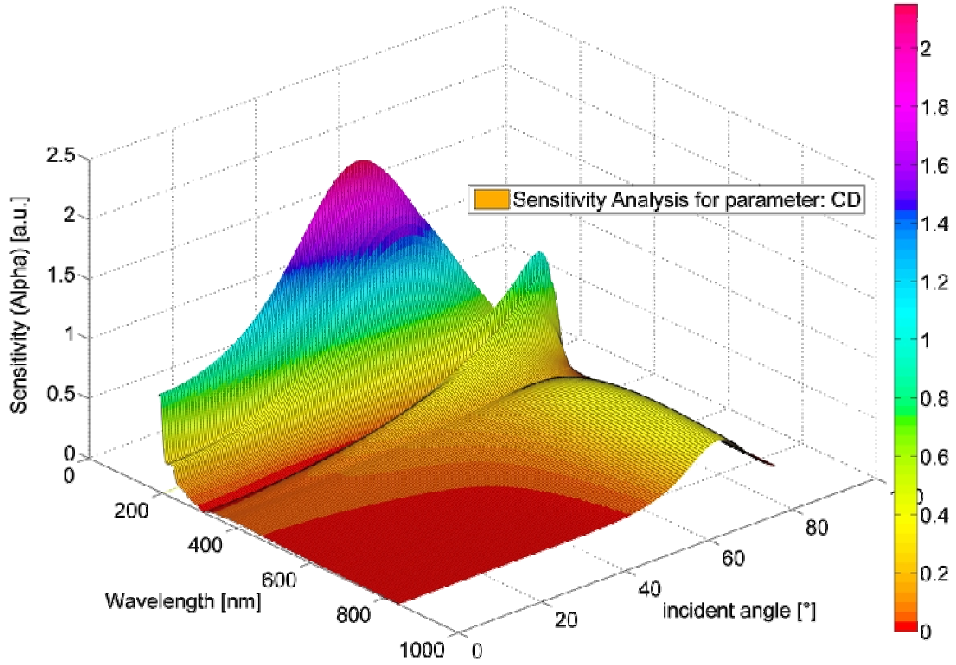
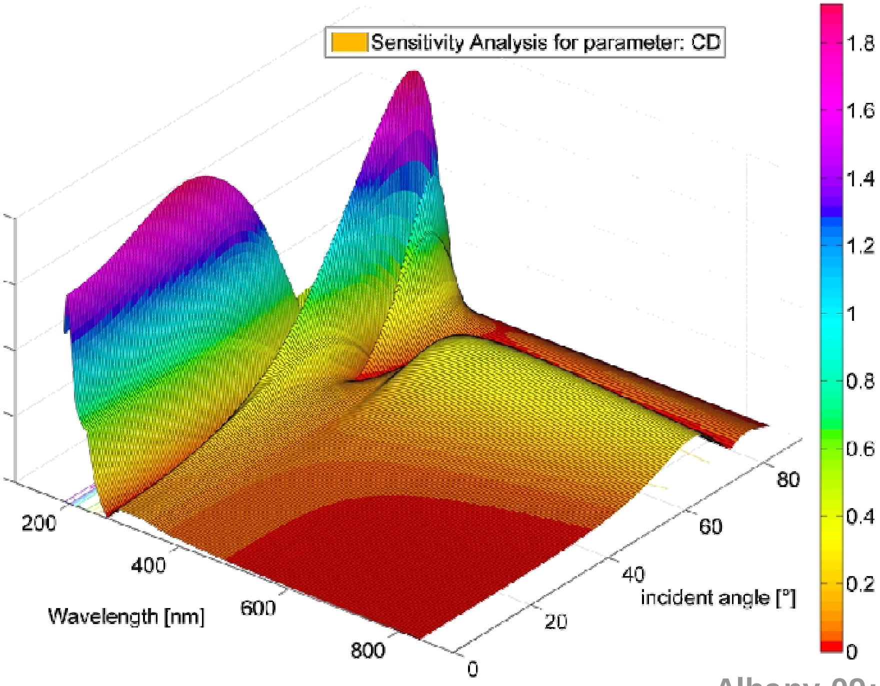
Sensitivity Analysis: Results

Example:
Resist Structures CD 36 nm



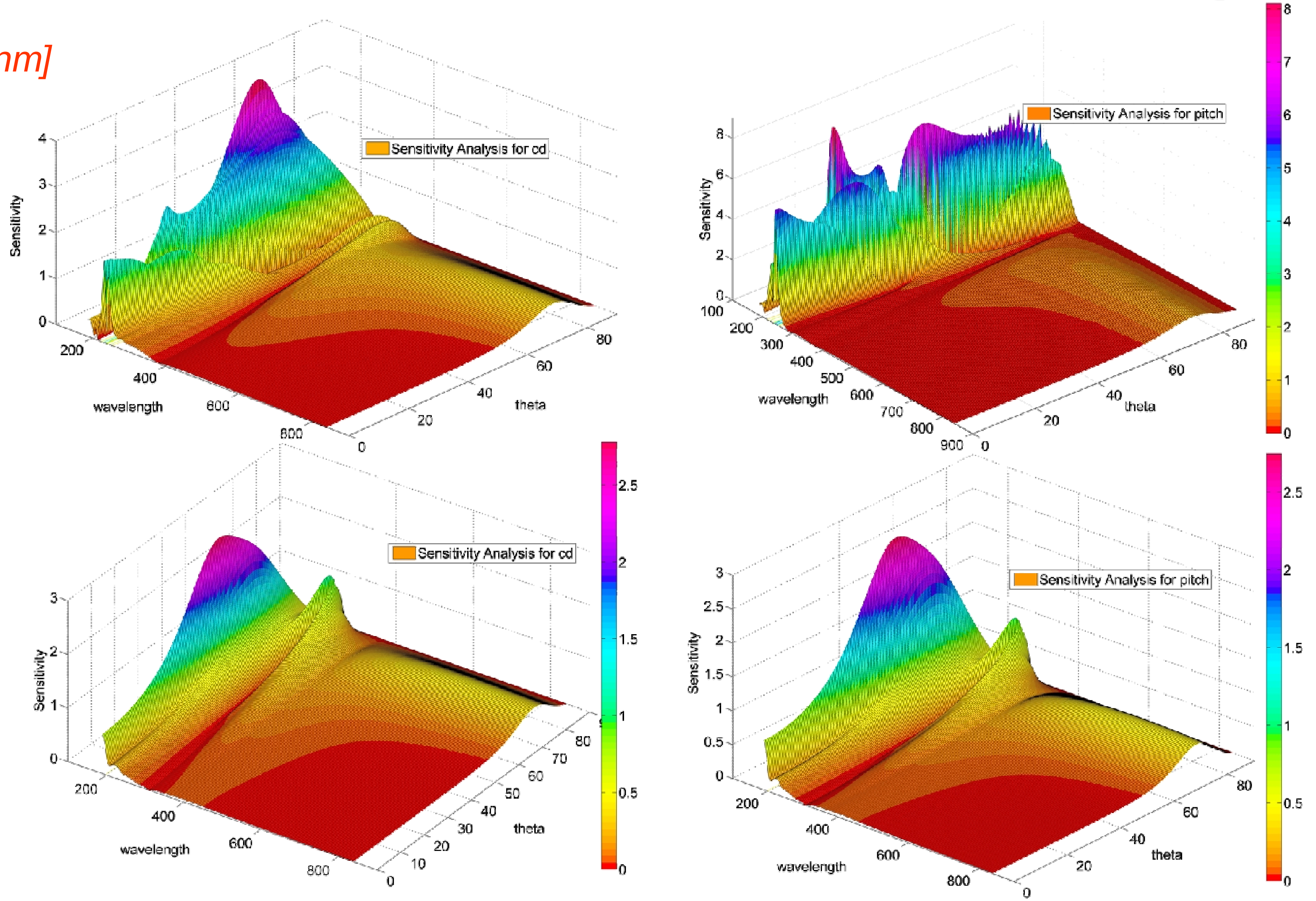
Alpha

Beta



Resist Structures – CD alpha sensitivity vs. parameters

CD [nm]



75

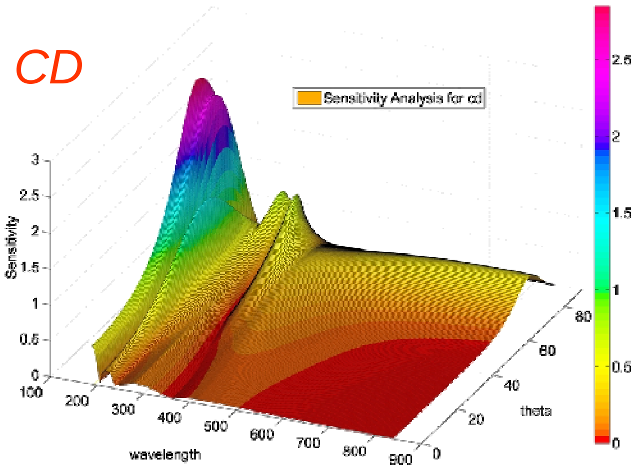
22

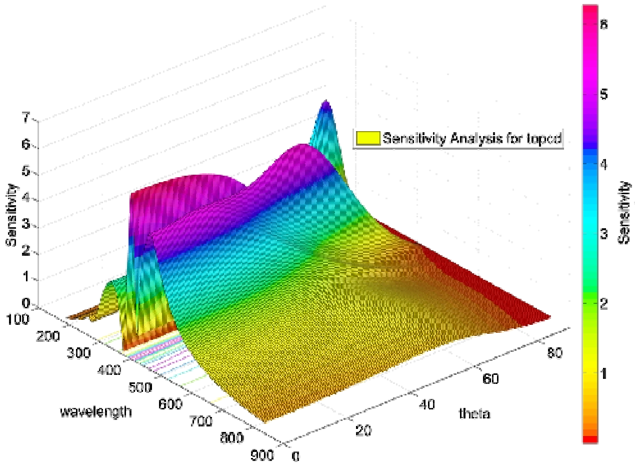
CD

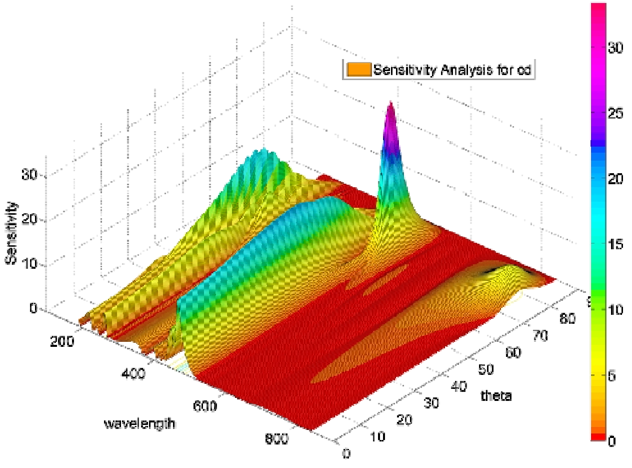
pitch

Comparison of different structures (i.e. 48 nm node)

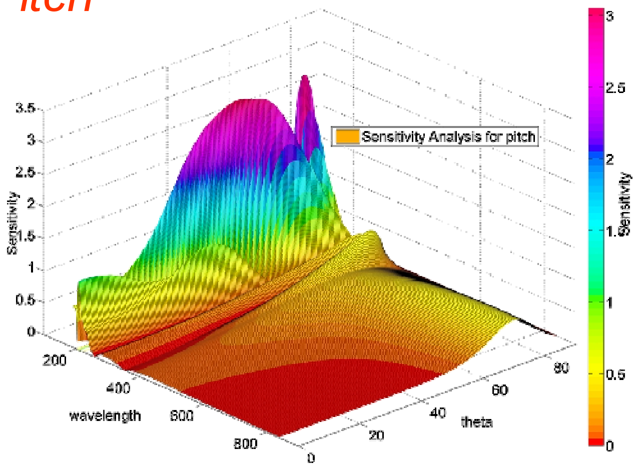
CD

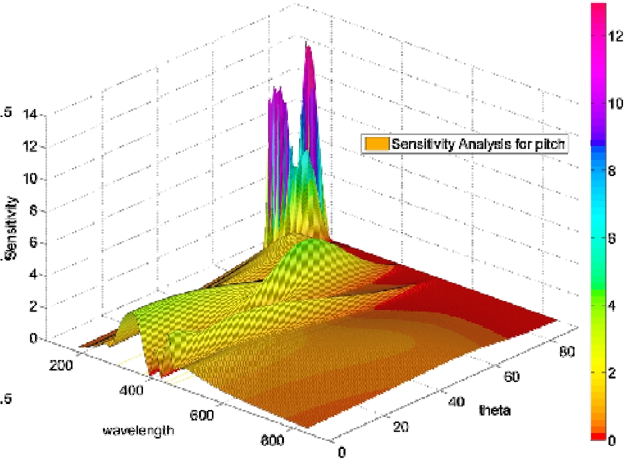


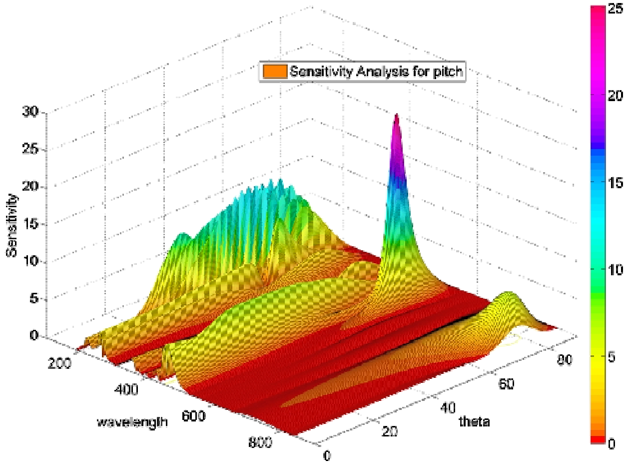




Pitch



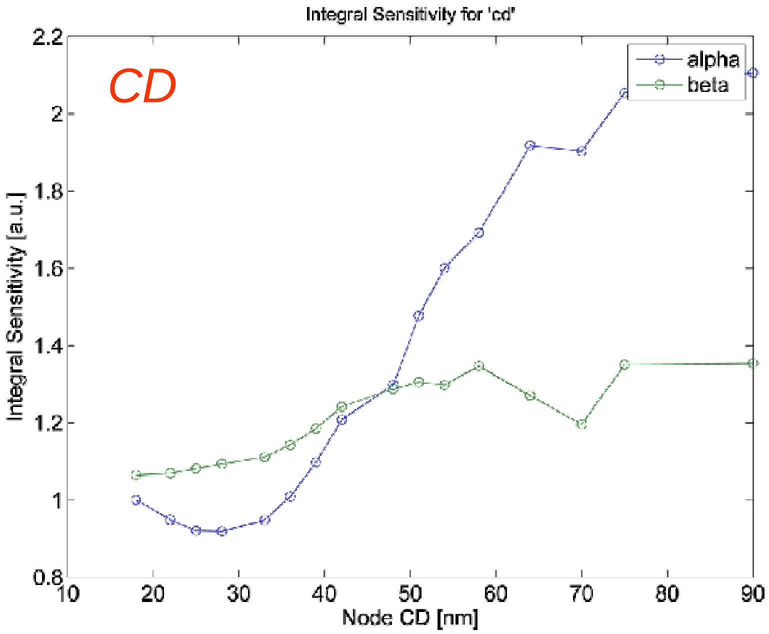


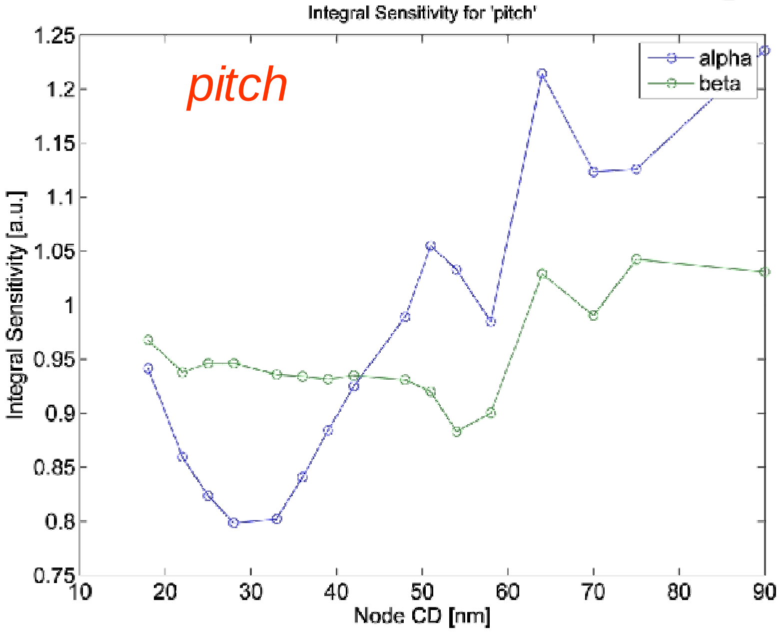


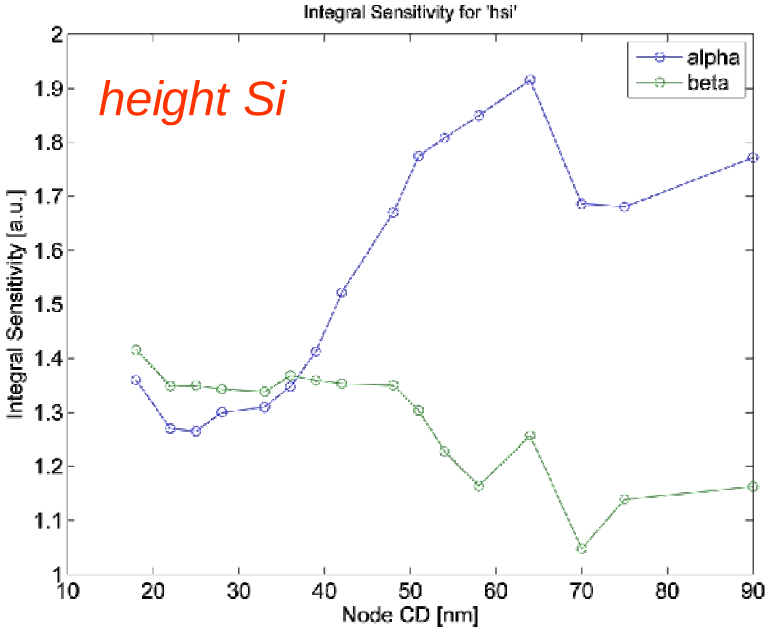
Resist Etched STI

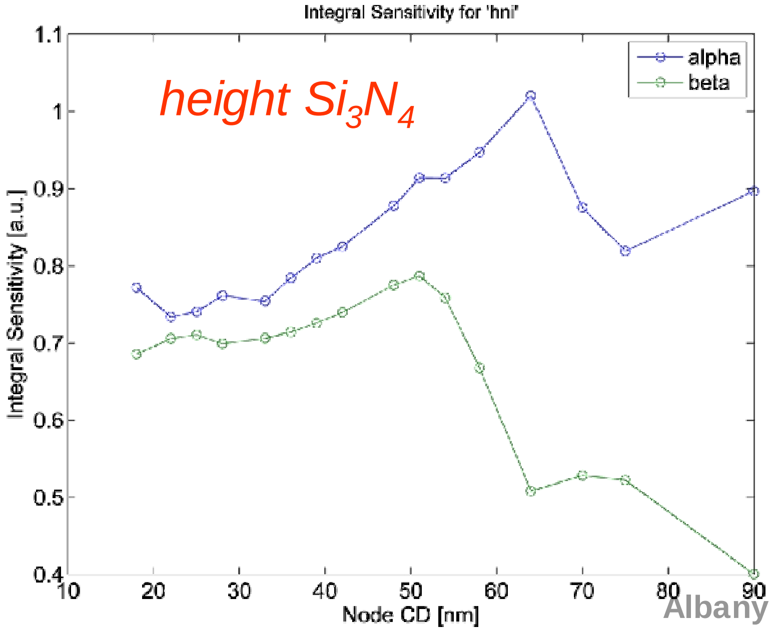
Sensitivity Trend Analysis

Sensitivity-Trends vs. Node (STI structures)


Integral Sensitivity for 'cd'


Integral Sensitivity for 'pitch'


Integral Sensitivity for 'hsi'


Integral Sensitivity for 'hni'

Conclusion 2

- Optimising the incident-angle can improve sensitivity compared to fixed incident angle configurations
- Optimal incident angle depends on parameter of interest and structure size
- Simulation based Sensitivity analysis can help to find optimized measurement configurations for future technology nodes and help to setup measurement recipes
- Sensitivity towards most parameters decreases as expected with smaller nodes

the staff

FRINGE´09

6. International Workshop on **Advanced Optical Metrology**

Stuttgart, September 14. - 16., 2009

organized by ITO Institute of Applied Optics

www.fringe09.de

I t´s Fringe Time

Thanks!

Method: Terminology

When What?

Strukturen >> Wellenlänge ⇧ reine Diffraktometrie mit Intensitätsmessung

Strukturen T Wellenlänge ⇧ polarisationsaufgelöste Diffraktometrie

Strukturen << Wellenlänge ⇧ Scatterometrie