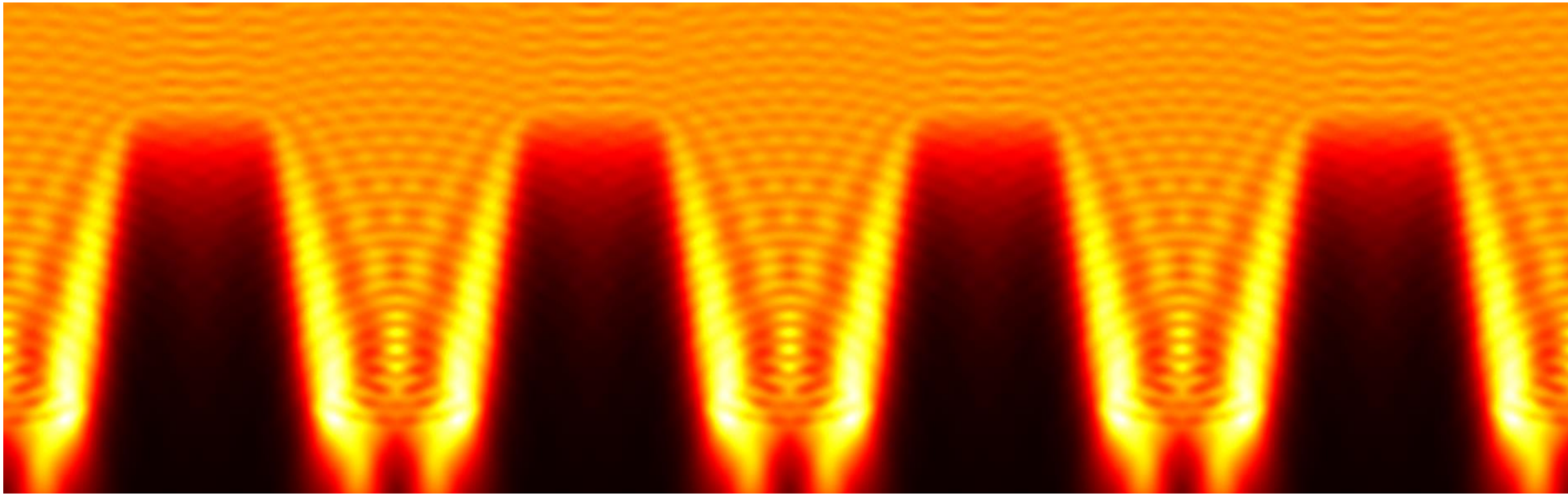
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

OCD Metrology for Advanced Lithography

B. Bodermann, Alexander Diener, Sebastian Heidenreich,
Frank Scholze, Victor Soltwisch, Matthias Wurm



Outline

1. Introduction
2. Common challenges in OCD metrology
3. PTB tools and analysis methods
4. Challenges of future applications
5. Future directions in OCD

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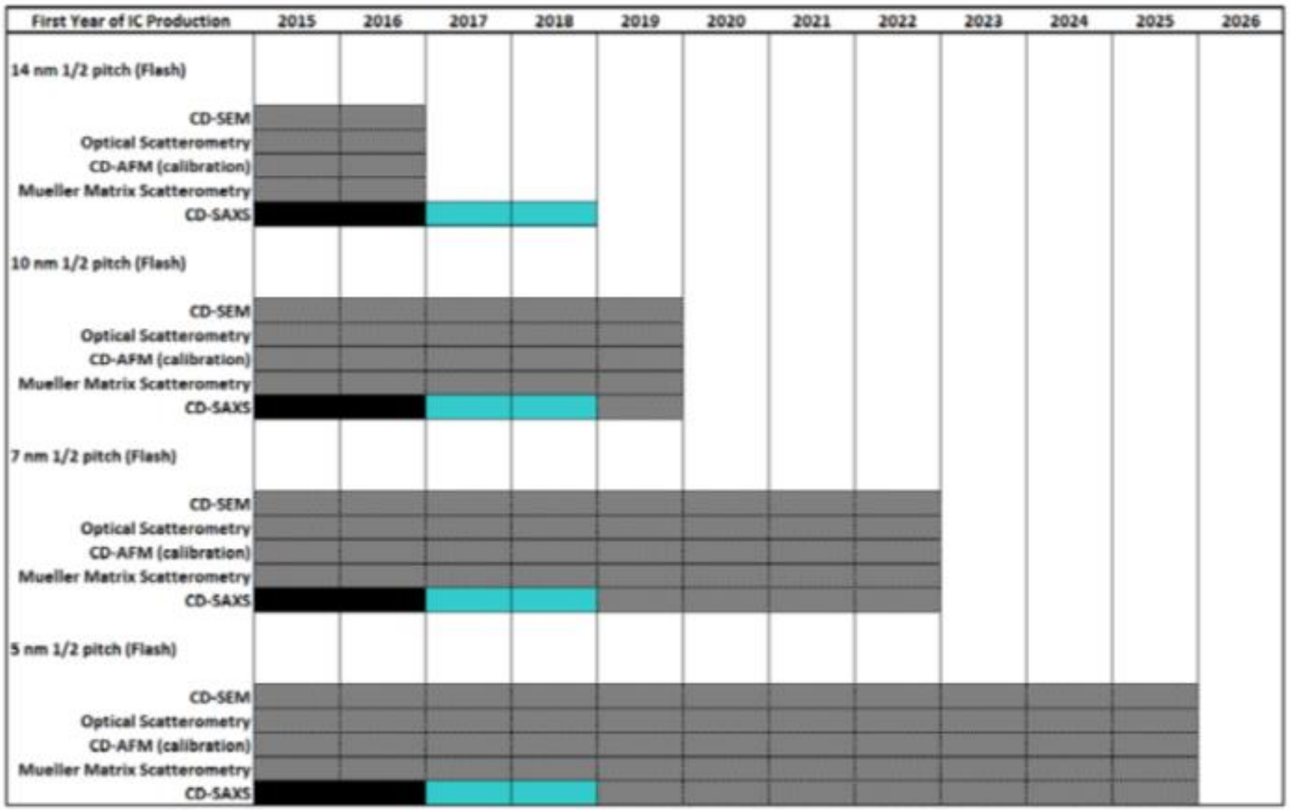
Introduction
CD Metrology for Advanced Lithography

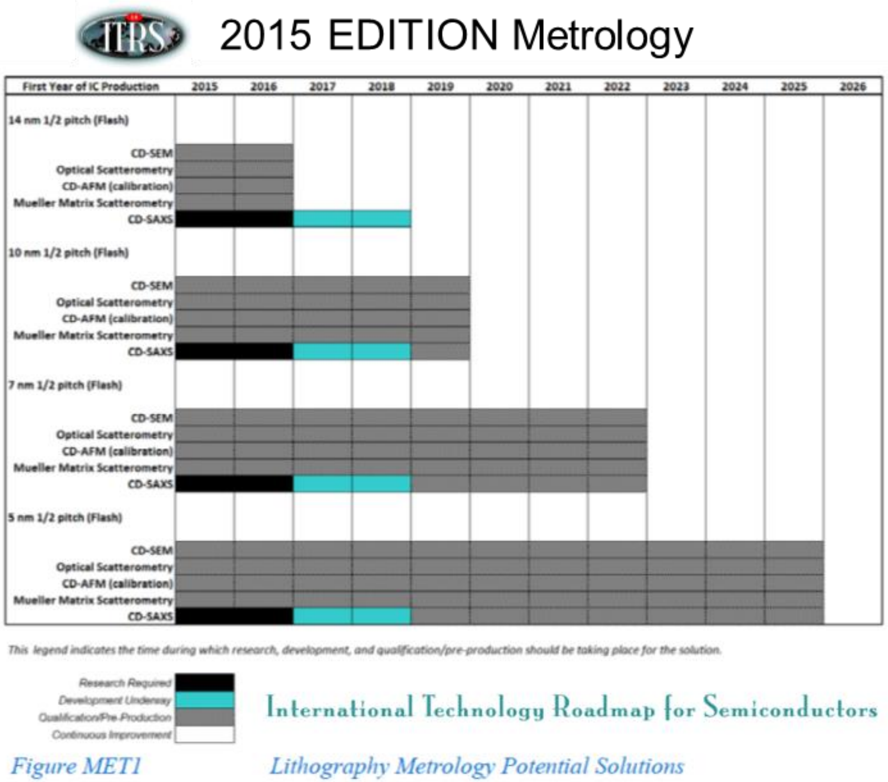
2015 EDITION Metrology

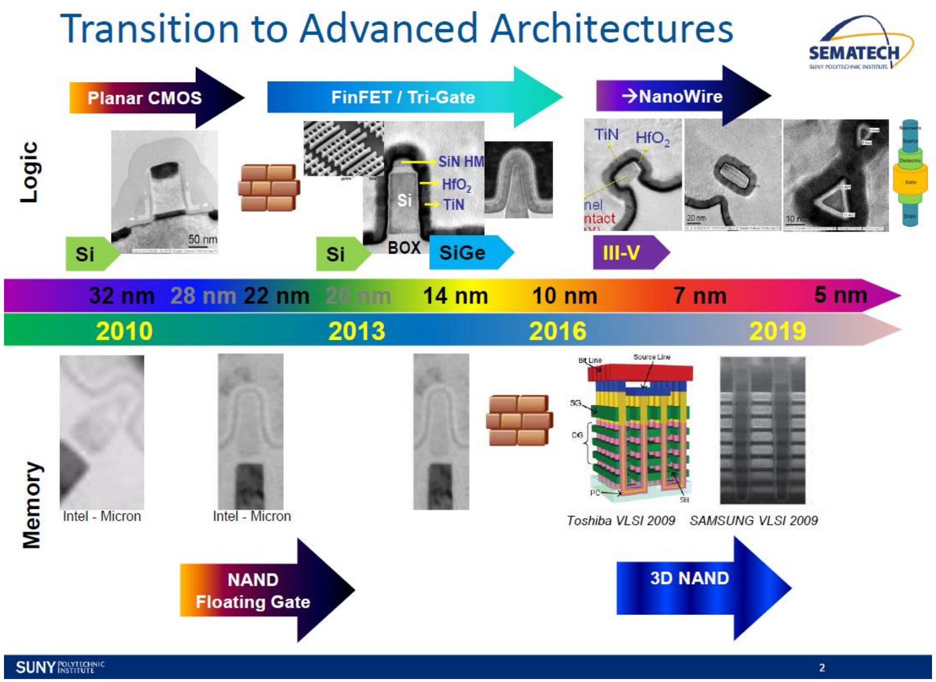


⇒ OCD (Scatterometry) and extensions (X-ray, hybrid,...) will retain its important role!

Figure MET1 Lithography Metrology Potential Solutions

Introduction
CD Metrology for Advanced Lithography





- Device shrinkage
- Planar to complex 3D architectures
- Novel materials
- Large diversity of NGL technologies
- Metrology solution required yesterday

⇒ OCD (Scatterometry) and extensions (X-ray, hybrid,...) will retain its important role!

⇒ **Semiconductor people keep us busy in metrology!**

Critical **D**imension **CD**: structure widths / size

Why Scatterometry (OCD)?

HVM Metrology Gap Analysis (simplified)*

	local (imaging)				ensemble ("spectroscopic")		
Application	CD-SEM	HV-SEM	HeIM	CD-AFM	OCD	T-SAXS	GI-SAXS
currently lim. node (mean)	7 nm modelling	5 nm modelling	≤ 5 nm modelling	10 nm (iso 5 nm)	7 nm n&k	≤ 5 nm	≤ 5 nm
Meas. time	okay	okay	okay	high	excellent	very high	high
Meas. area	excellent	excellent	excellent	excellent	okay	okay	very high
Destructiveness	okay	high	very high	excellent	excellent	excellent	excellent

*B. Bunday SUNY Poly SEMATECH
Proc. SPIE **9778** 97780E-1 (2016)

color code

color code
excellent
okay
high
very high

Advantages:

- fast, non-destructive and contamination free
- structure profile sensitive, good 3D capability, multi-parameter
- no "diffraction limit"
- process integrable
- high statistical significance
- characterisation of optical effects, "at-wavelength"-metrology
- comparison with local methods to eliminate systematic errors

Disadvantages:

- only integral measurements, relatively large interaction range
- parameter correlations, unambiguity ...

ITRS (2015): It is important to have both imaging and scattering techniques available for any given process control situation. (Table MET1)

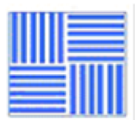
Introduction
Applications

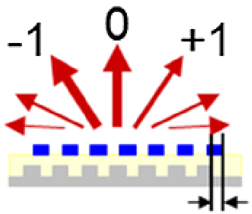
Samples: wafers, photomasks,...; many materials (Si, diel., high k, metals)

Measurands: 1D and 2D gratings

Diffraction Based Overlay

$I_n = I_n(\mathrm{ov})$



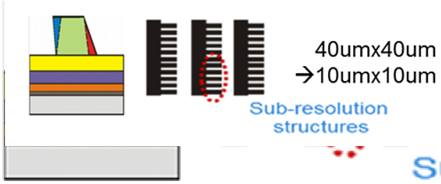


10umx10um

Film thickness
Porosity
Optical material parameters
Mask at-wavelength metrology

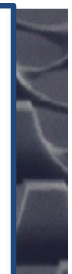
Film thickness
Porosity
Optical material parameters
Mask at-wavelength metrology
…

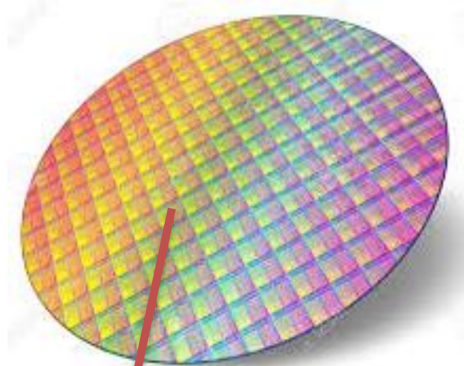
Diffraction Based Focus

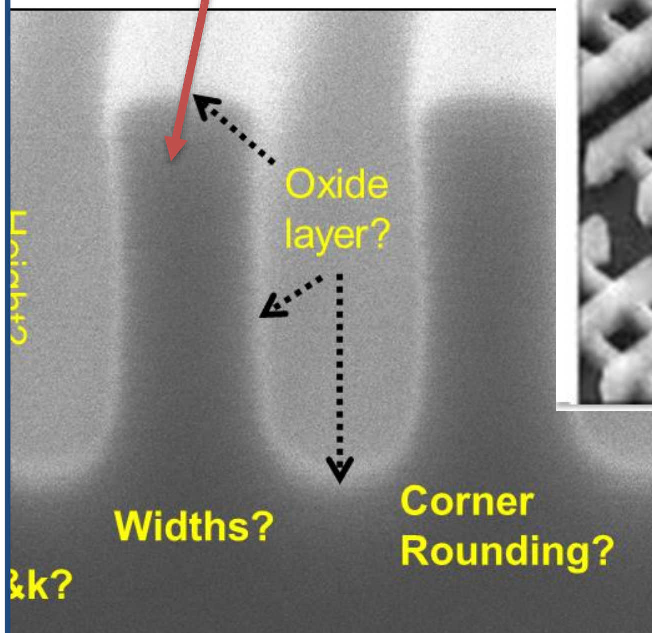


40umx40um
→10umx10um

Sub-resolution structures

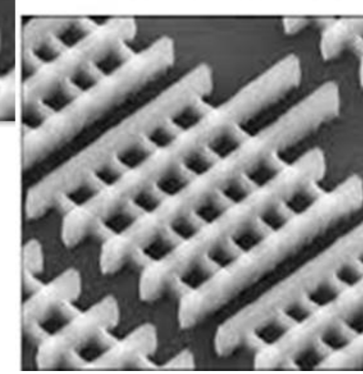






→ complex 3D multiparameter

22 nm Tri-Gate Transistors

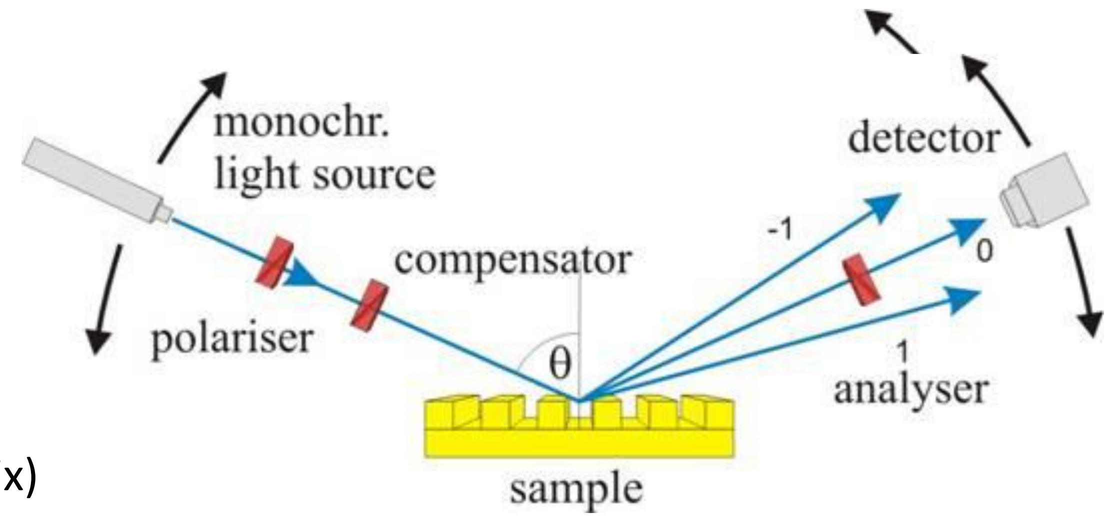


Scatterometry (Optical CD metrology)

Scatterometric methods measure property changes of the light caused by the interaction with the sample, use information to reconstruct the structures under test

Properties of light, that can be measured with scatterometric methods are:

- Radiant power (diffr. efficiency η)
  (type: reflectometer
  class. scatterometer)
- Direction of propagation
  (type: diffractometer)
- State of polarisation
  (type: ellipsometer, Mueller matrix)
- Phase information
  (type: interferometric scatterometer)



Classification after independent measurement variable

λ: spectroscopic

Θ: goniometric

Introduction
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  (type: **ellipsometer, Mueller matrix**)
- Phase information

  (type: interferometric scatterometer)

spectroscopic

Current commercial OCD tools

Model based analysis

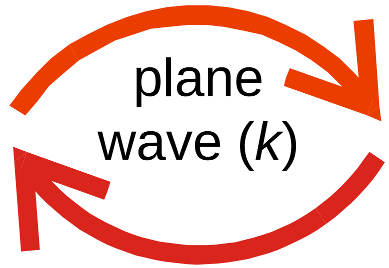
rigorous calculation of diffracted

By the way: any reasonable metrology is based on a model!

of Maxwell's equations: RCWA, FDTD, FEM, waveguide,...

direct (forward problem)

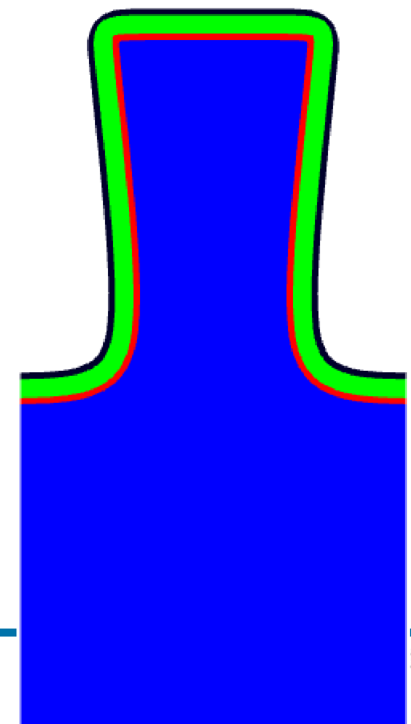
surface parameters p_i



scatterogram (prop. modes)

inverse (problem)

- library approach:
  - fast, robust, easy to use
  - long set-up time
  - large memory resources
- nonlinear optimisation:
  - more flexible, accurate
  - significantly slower
  - large computational resources



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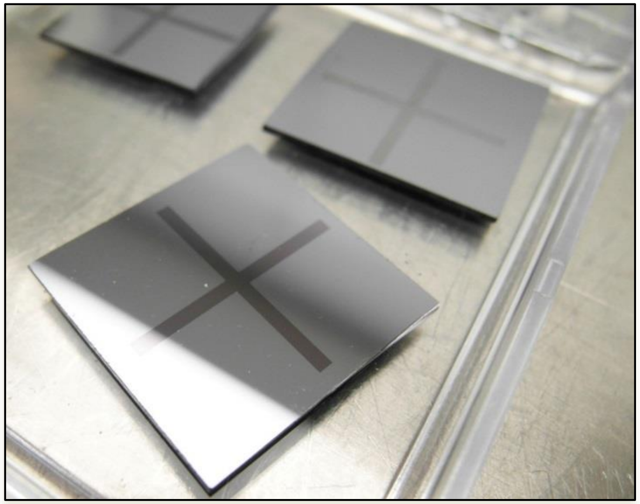
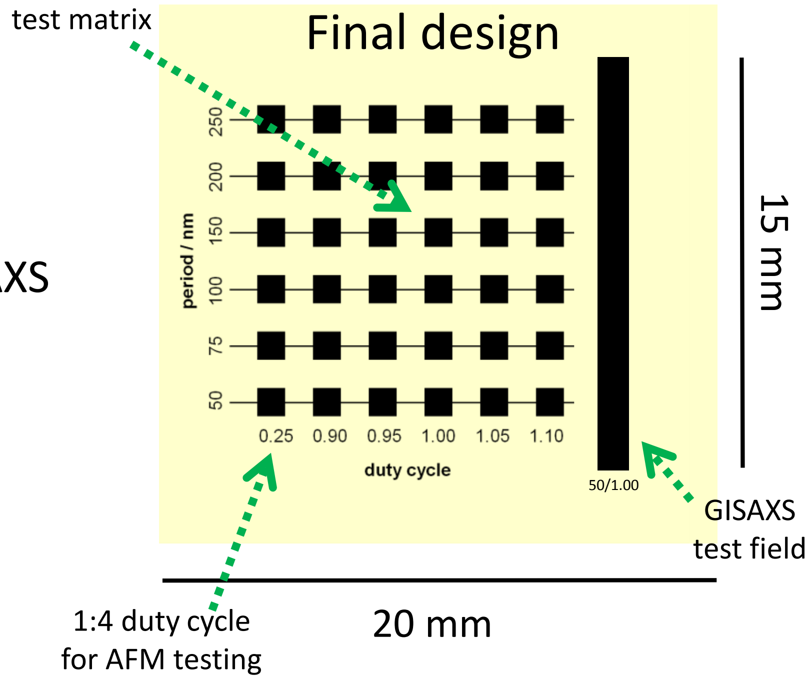
Common OCD Challenges
Traceability: Approximations & simplifications

Scatterometry reference standards to improve tool matching and traceability in lithographical nanomanufacturing, B. Bodermann et al. (2015), Proc SPIE **9556** 955610

- U(CD) < 1 nm
- Two materials: Silicon and Si_3N_4 (dielectric)
- GISAXS reference target
- Characterised by scatterometry, Mueller ellipsometry, CD/tilt AFM, CD-SEM and GISAXS





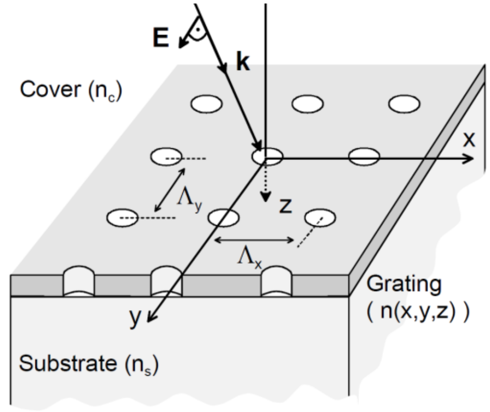
manufactured by HZB Helmholtz Zentrum Berlin

Dissemination: Development of a scatterometry reference standard

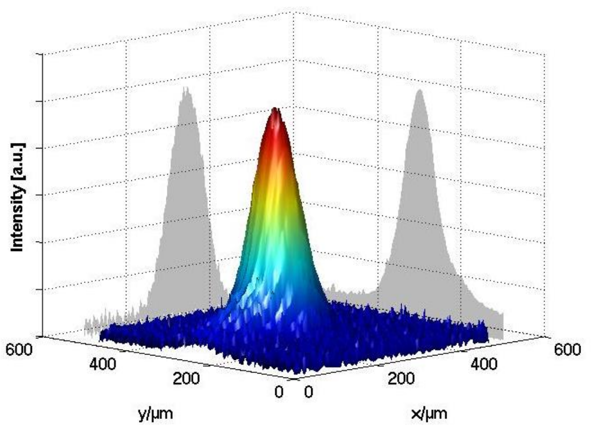
Common OCD Challenges
Approximations & simplifications

Examples:

- numerical approximations: periodic extension, computational volume and discretisation,...
- neglection of local parameter variations (CDU, stiching,...)
- geometrical structure model (binary, trapezoidal, corner roundling,...)
- monochromatic plane wave illumination
- infinite interaction area: finite spot size of illuminating beam, finite target (grating) size
- n & k: size dependent complex refractive indices gradients, EMA-interlayers (diffusion, roughness)
- roughness: surface, LER, LWR,...
- neglection of stray light ...

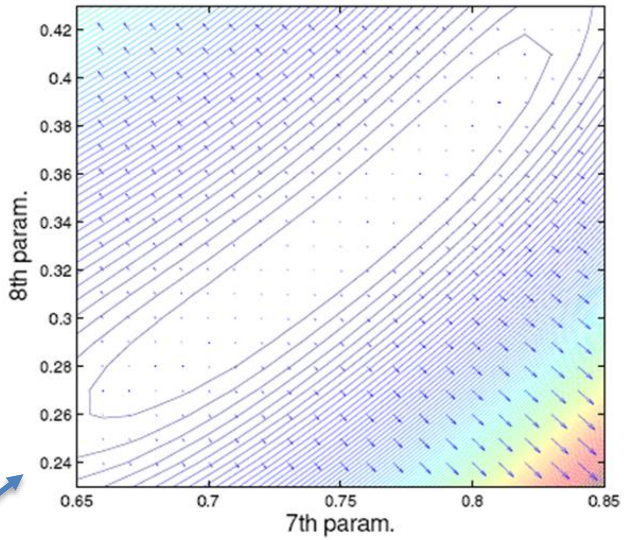


beam profile at sample



Solution of inverse problem

"severely ill-posed inverse problem"
⇒ direct inversion usually not possible
⇒ solution is in general not unique!
⇒ usually a-priory knowledge required
⇒ efficient global optimisation required

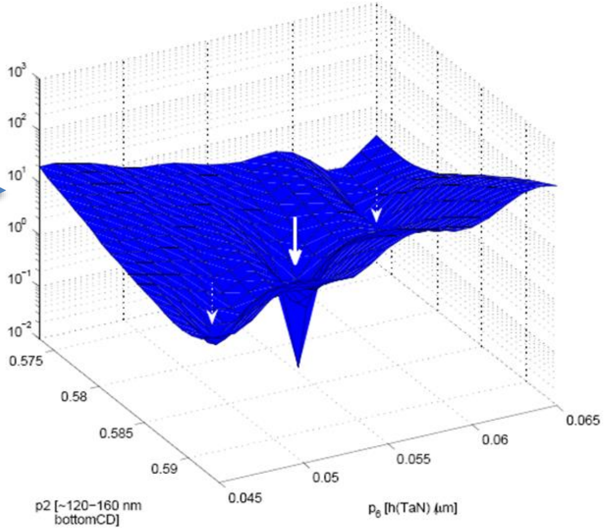


Specific challenges for optical methods:

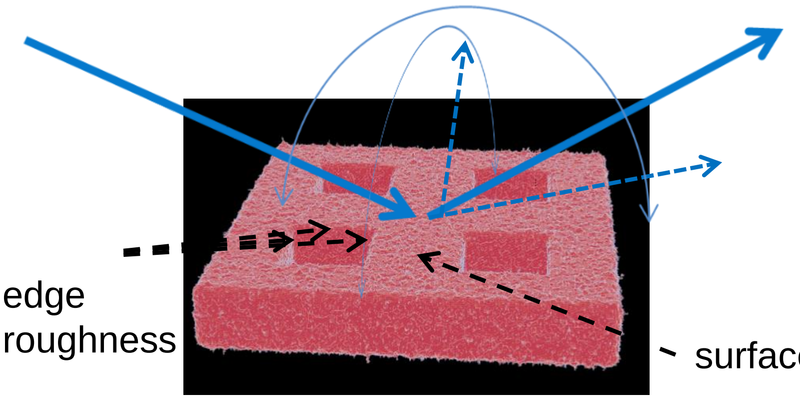
- Sensitivity
- Accuracy

} size ~ wavelength/100

- Increasing complexity
  ⇒ increasing **parameter correlations**
  ⇒ **ambiguity issues**
  ⇒ **computations costs** (time and memory issues)



Common OCD Challenges
Stochastic parameters, roughness



Example Decomposition

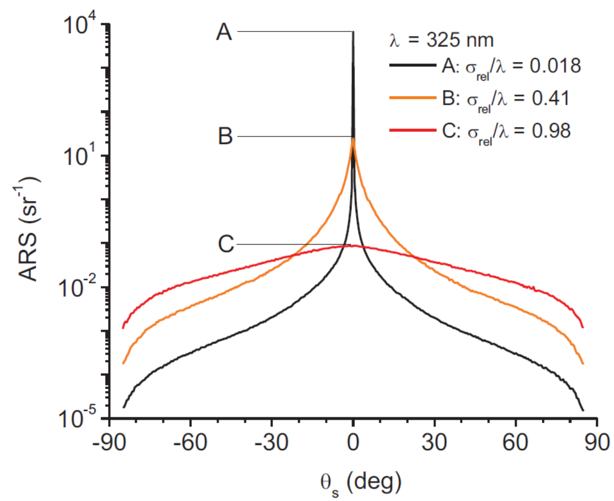
$$\mathbf{M} = \mathbf{M}_0 + \Delta\mathbf{M}$$

M - measured MM
$\mathbf{M}_0$ - best-fit Mueller-Jones matrix (no depolarisation)
Δ**M** - residuum

* J. J. Gil Perez, R. Ossikovski, *Polarized light and the Mueller matrix approach* CRC Press 2016

- Stochastic parameters $\Rightarrow$ depolarisation & diffuse scattering
- Depolarisation & scattering usually not adequately described!
  $\Rightarrow$ wrong uncertainty estimations, may introduce systematic bias
- Full rigorous modelling essentially impossible (very elaborate)
  Options:
- Mueller matrix ellipsometry: decomposition-techniques

Combined analytical and rigorous modelling for rough surfaces:
- Effective Medium Aproach (EMA)
- Scattering theories (Born approximation, Beckmann- Kirchhoff, Rayleigh-Rice, Harvey-Shack (NP), ...)



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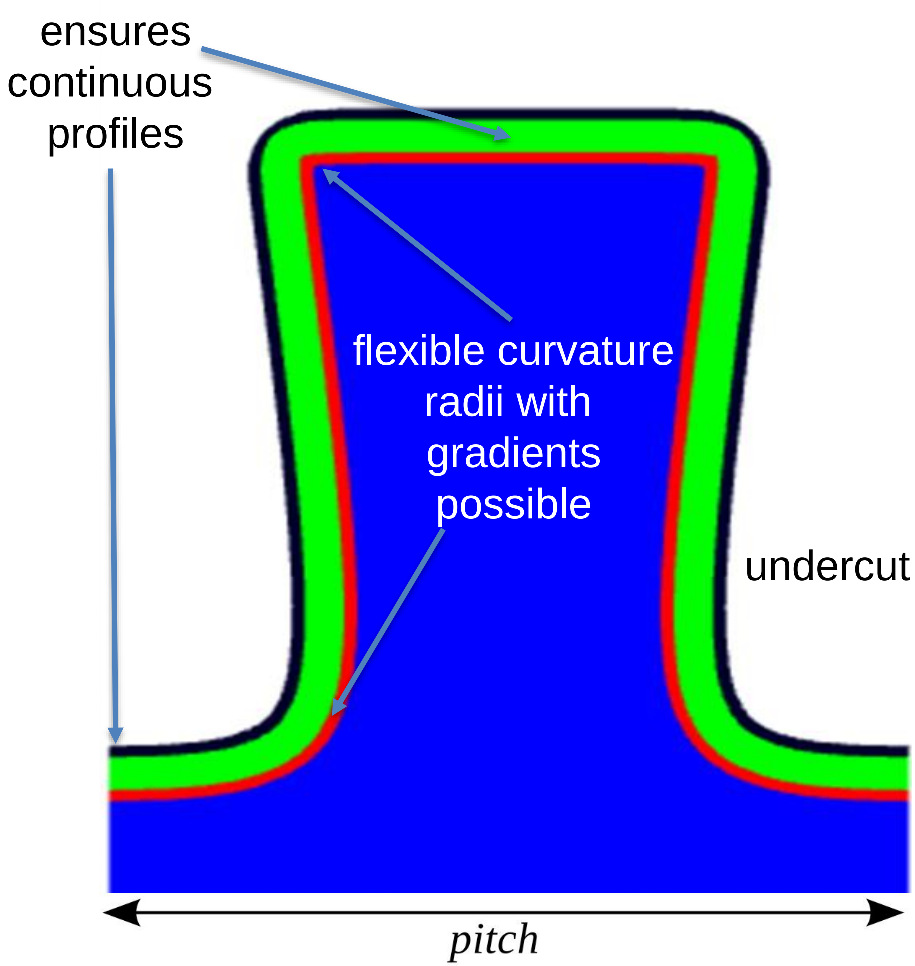
PTB tools and methods

FEM Reconstruction: The Model

Rational Bézier curves, weighted

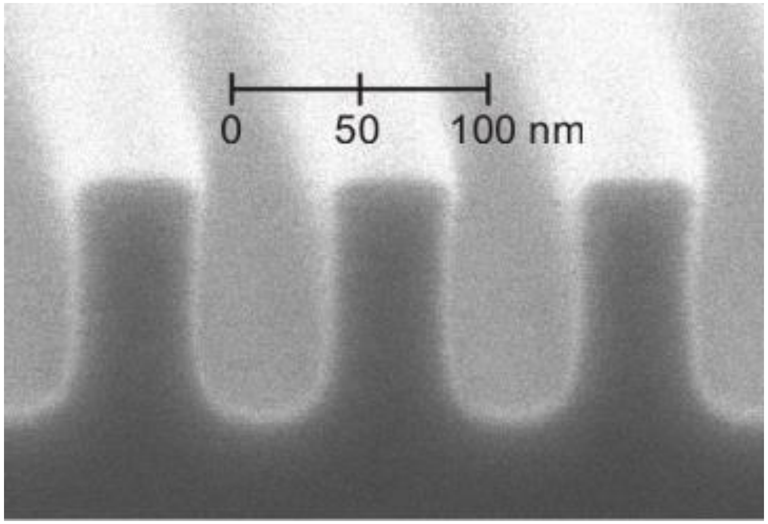
$$C(t) = \frac{\sum_{i=0}^{n} B_{i,n}(t) w_i P_i}{\sum_{i=0}^{n} B_{i,n}(t) w_i}$$



<u>Rigorous modelling</u> for all 'optical' methods from NIR to X-ray

- **Spectr. Ellipsometry / Mueller**
- **DUV Scatterometry**
- **EUV SAS**
- **GISAXS**

<u>Maxwell solver:</u> FEM allows to model arbitrary structures



Downhill simplex method

PTB tools and methods

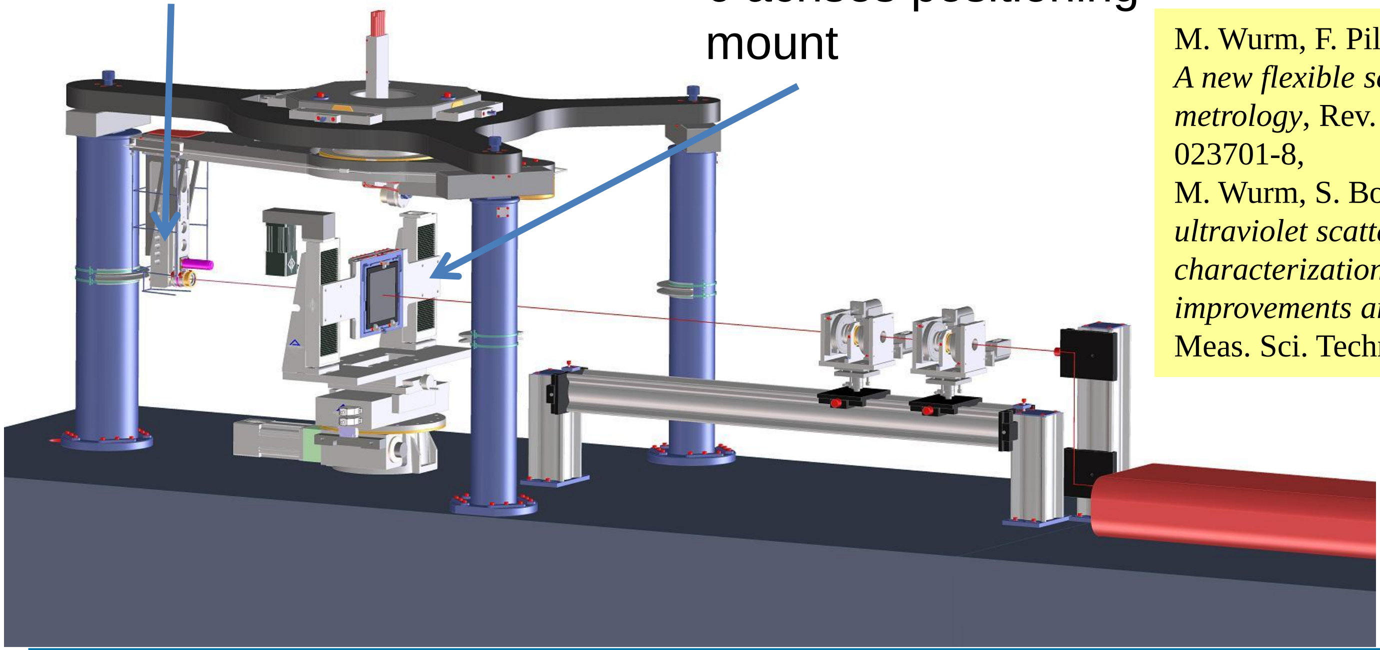
Goniometric Scatterometry & Reflectometry

DUV goniometric Scatterometer

- Reflectometry, diffractometry, scatterometry
- Polarised (any state of polarisation)
- At wavelength metrology (193 nm)
- Wafers and photomasks (mapping)

Detector on (nearly) 360° rotating arm: transmission & reflection

Sample holder: 6 achses positioning mount



M. Wurm, F. Pilarski, B. Bodermann: *A new flexible scatterometer for critical dimension metrology*, Rev. Sci. Instrum. **81** (2010), 2, 023701-1-023701-8,

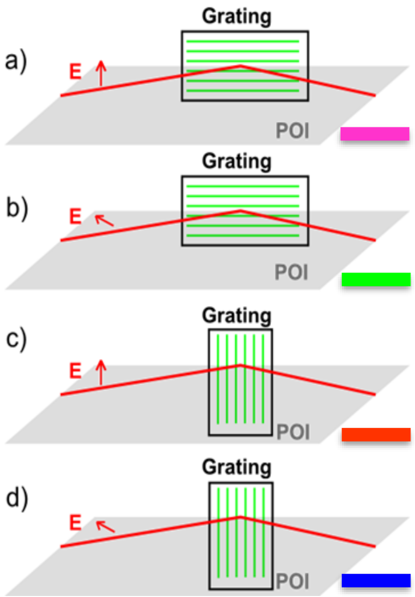
M. Wurm, S. Bonifer, B. Bodermann, J. Richter: *Deep ultraviolet scatterometer for dimensional characterization of nanostructures: system improvements and test measurements*

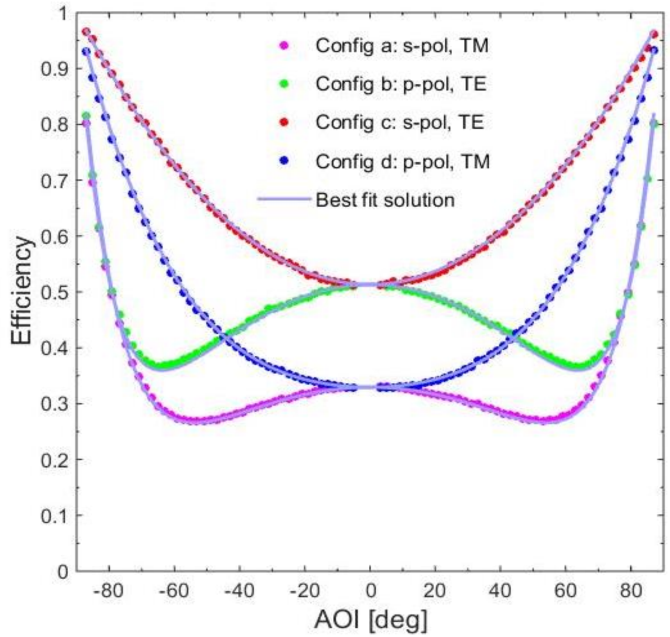
Meas. Sci. Technol. **22** (2011), 094024-1 - 094024-9

266 nm (Nd:YAG), or NIR (780 - 840 nm) to DUV (193 - 210 nm)

PTB tools and methods

Goniometric Scatterometry & Reflectometry

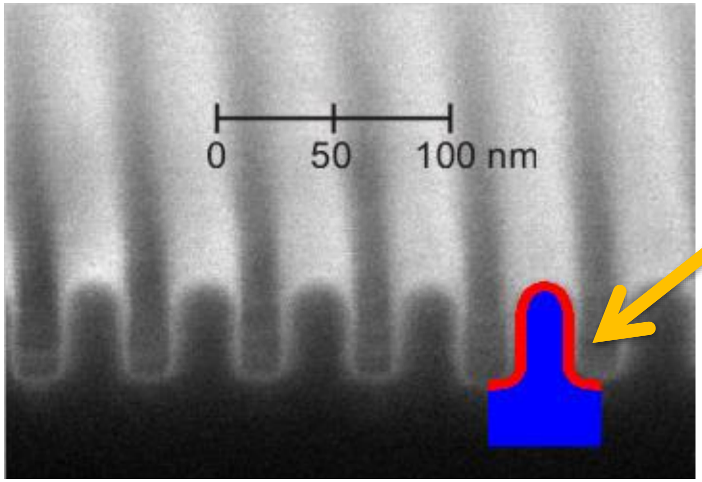


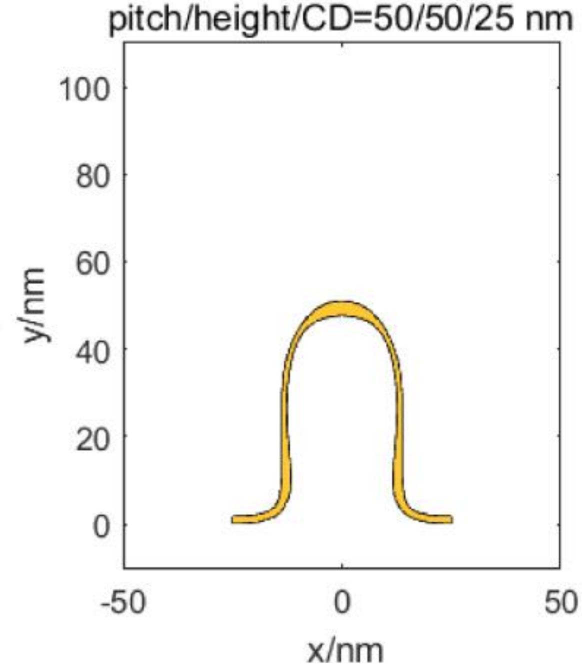


M. Wurm, J. Endres, J. Probst, M. Schoengen, A. Diener and B. Bodermann, *Metrology of nanoscale grating structures by UV scatterometry* Opt. Express **25**, (2017), 2460-2468

Full contour uncertainty! traceable, reference-free!

profile reconstruction

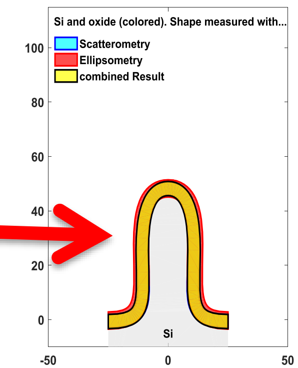




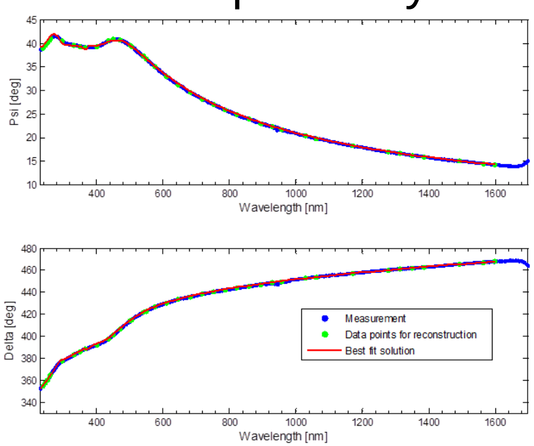
PTB tools and methods
Spectroscopic (Mueller) Ellipsometry

Spectroscopic Mueller polarimeter

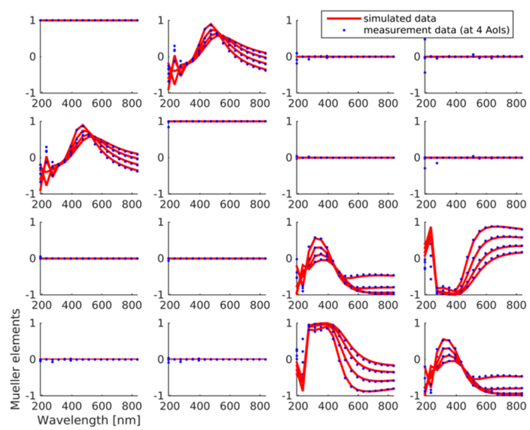
- Full Mueller matrix, 190 nm – 2500 nm
- Θ_{in} und Θ_{out} independent, transmission
- Layers (thickness) and layer systems
- Complex permittivity ('material parameters' n&k)
- Depolarisation
- OCD metrology



Ellipsometry



Mueller Ellipsometry (MME)

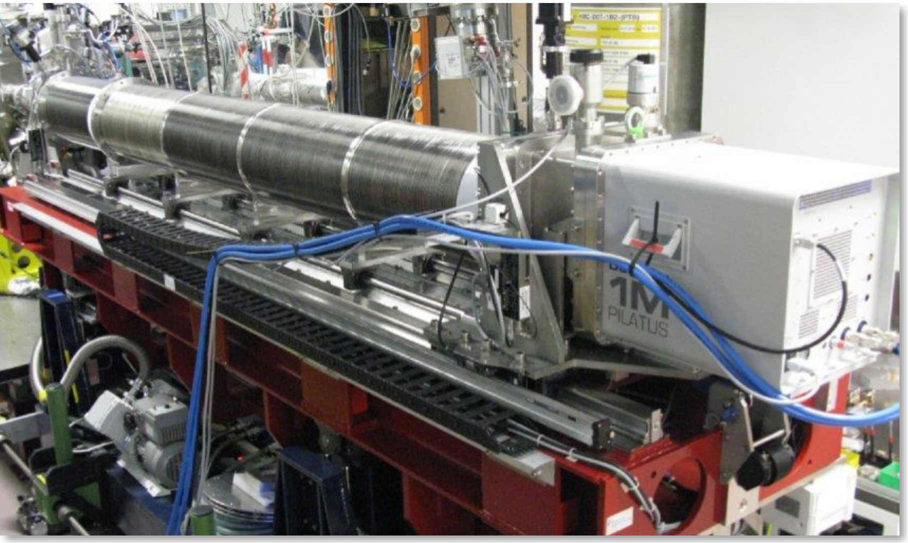


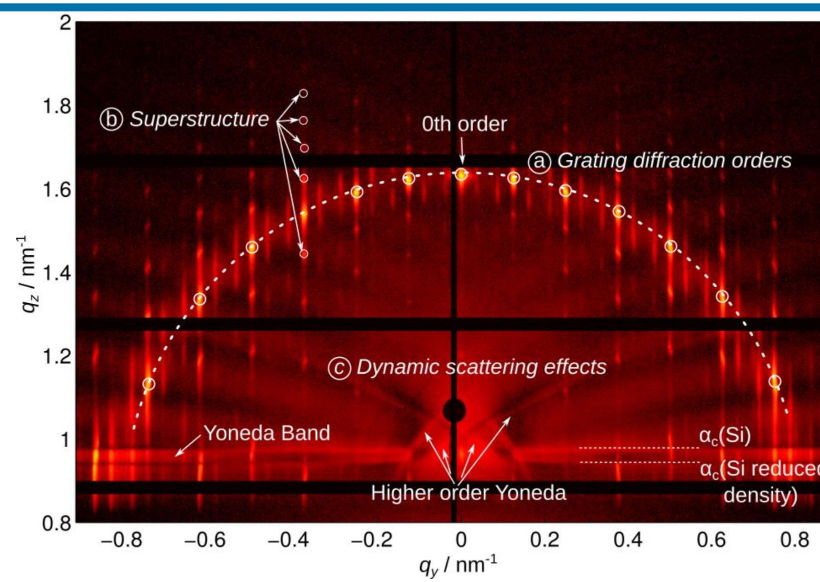
R&D on
- Reliable data analysis (MM decomposition*)
- Uncertainty evaluation and traceability
- Treatment of depolarisation and roughness

* J. J. Gil Perez, R. Ossikovski, *Polarized light and the Mueller matrix approach* CRC Press 2016

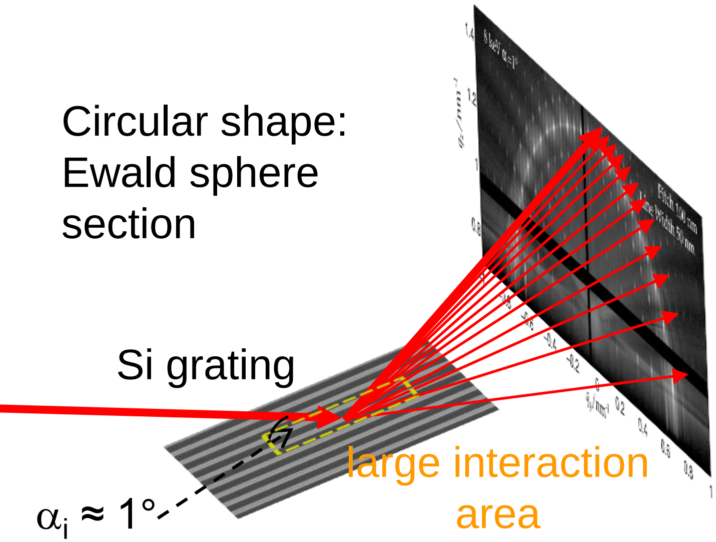
PTB tools and methods
X-ray-Scatterometry

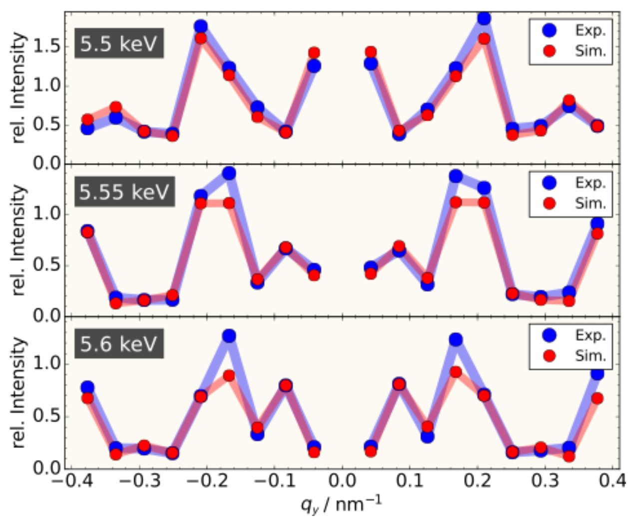
GISAXS: (0.12-0.73) nm, in-vacuum PILATUS 1M

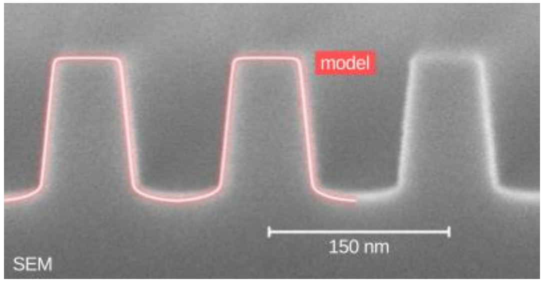




Circular shape: Ewald sphere section







- Structure geometry (CD, SWA,..)
- LER/LWR
- Surface roughness
- Stiching errors...

PTB tools and methods
Hybrid metrology

Combining measurements from multiple toolset types in order to enable or improve metrology for advanced structures.

Different approaches:

- (Weighted mean of multiple toolset measurements)
- Sequential
- Interpolating co-optimisation
- full parallel evaluation: usually requires to much computation costs, often issues of reasonable weighting

} **Bayesian approach** (Sequential, Interpolating co-optimisation)

Aims and advantages:

- Combine strengths and overcome individual weaknesses of different tools
- Break or minimize parameter correlations
- Improve sensitivity and accuracy beyond the sum of individual results

Results	CD / nm	h /nm
DUV-Scatterometry	25.9 (1.4)	50.0 (4.4)
Comb. With MME	26.4 (0.9)	50.5 (1.6)
GISAXS	25.1	48.2

Sample (nom. p, CD, h)	HZB_P100_CD35(100, 35, 100 nm)		
	Scatt.	MME.	comb.
CD [nm]	32.3 (1.8)	33.0 (1.5)	32.5 (1.1)
h [nm]	105.7 (2.3)	105.8 (2.2)	105.7 (1.6)
swa [°]	91.4 (1.9)	90.9 (1.6)	91.2 (1.2)
h_oxide [nm]	3.0 (0.6)	3.2 (0.7)	3.1 (0.4)
CR_{top} [nm]	14.9 (3.0)	13.8 (1.9)	14.0 (1.1)
CR_{bottom} [nm]	29.3 (2.8)	30.4 (1.4)	30.1 (1.2)

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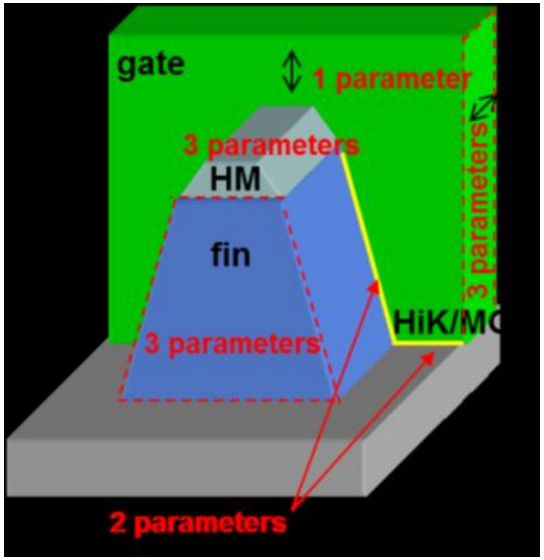
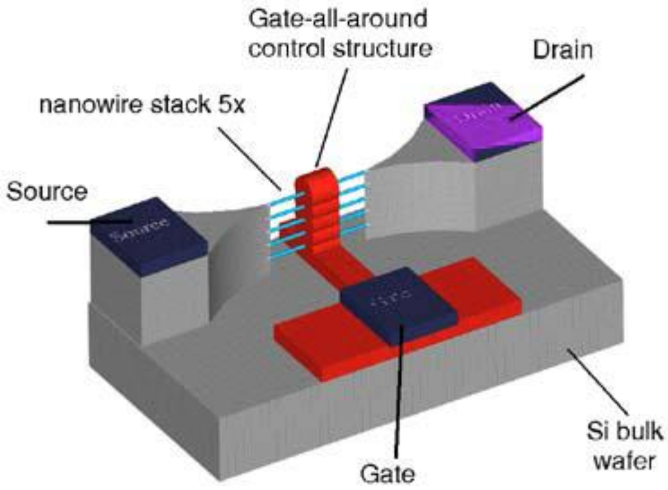
Complex 3D metrology

Substantially increasing **requirements** due to:

- decreasing dimensions
- complex 3D structures: FinFET, Nanowire / GAA,…
- requires multi parameter characterization (≥ 12)
  ⇒ **increasing correlation issues!**

  ⇒ increased variability required to break correlations: combined goniometric & spectroscopic or other hybrid approaches

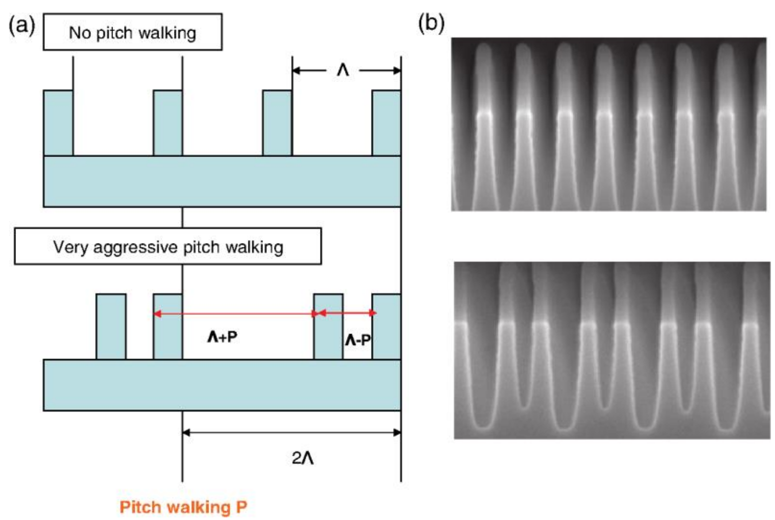




Challenges of future applications

Application specific challenges

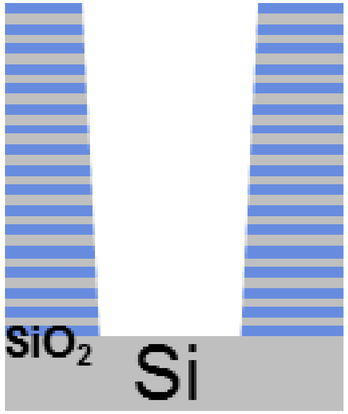
Double / multiple patterning: pitchwalk



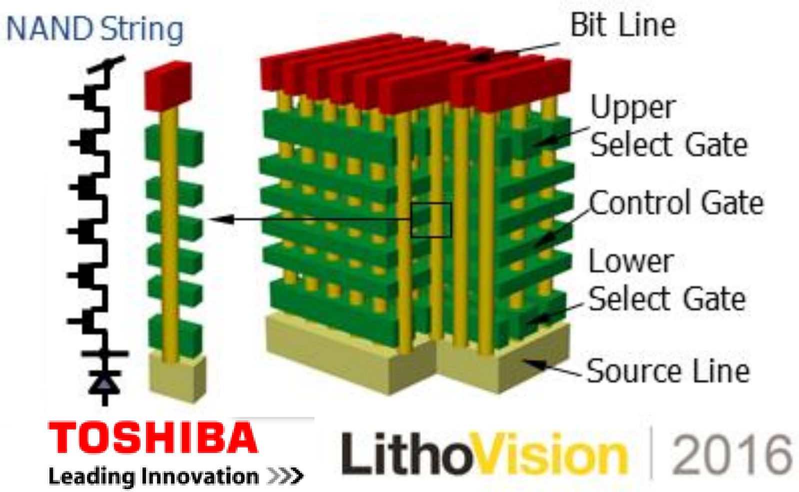
R. Chao et al. *Multitechnique metrology methods for evaluating pitch walking in 14 nm and beyond FinFETs* JM3 **13**, 041411 (2014)

low sensitivity of most common OCD methods

High aspect ratio structures
e.g. holes & trenches in single or multilayers

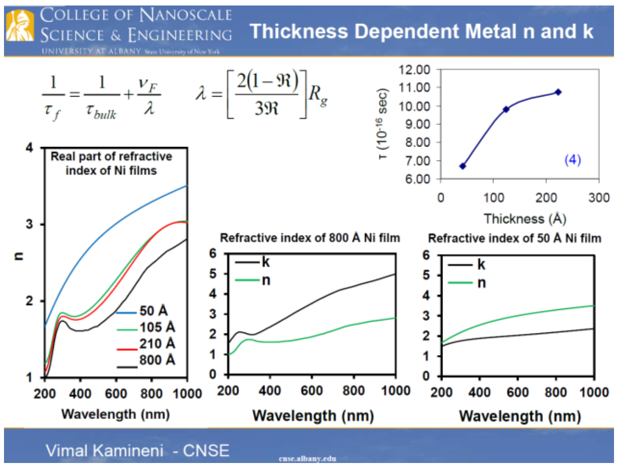


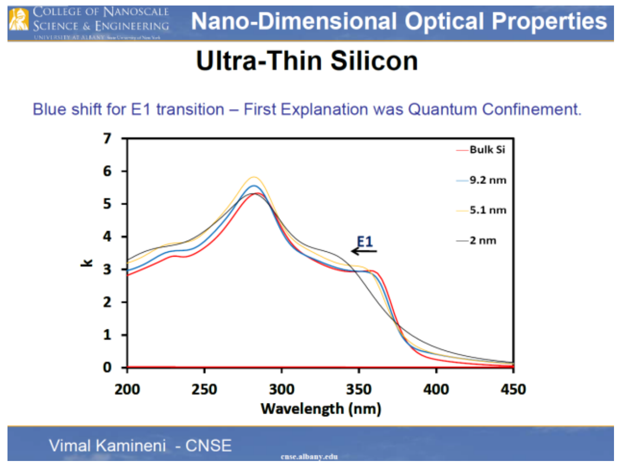
- to many layers / parameters
- waveguiding effects



Challenges of future applications
Material parameter challenges

- Complex refractive index process dependent!
- Many novel materials (advanced litho & beyond CMOS)
- **Interplay of dimensions and refractive index**: quantum confinement, el.-phonon interactions,…





Electron-phonon interaction effects on the direct gap transitions of nanoscale Si films
V. K. Kamineni and A. C. Diebold, Appl. Phys. Lett. **99**, 151903 (2011)

- Strain / stress induced birefringence
- Beyond CMOS: many 1D & 2D materials discussed (Si NW, CNT, graphene…)

$\Rightarrow$ anisotropy
$\Rightarrow$ permitivity tensor

$$\varepsilon \rightarrow \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}$$

affects in particular goniometric methods

Size-dependent permittivity and intrinsic optical anisotropy of nanometric gold thin films: a density functional theory study.
Laref S[1], et al., Opt Express. 2013, 21 11827-38.

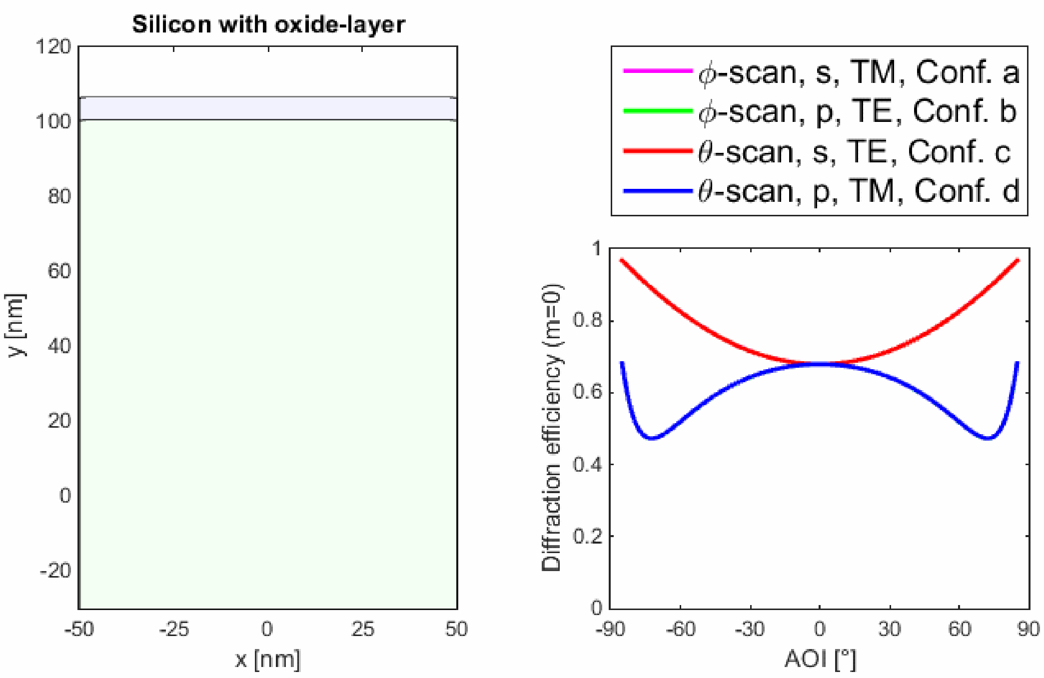
Requires additional metrology steps (time and effort issues) and/or fitting of corresponding material parameters (multi parameter, correlation issues)

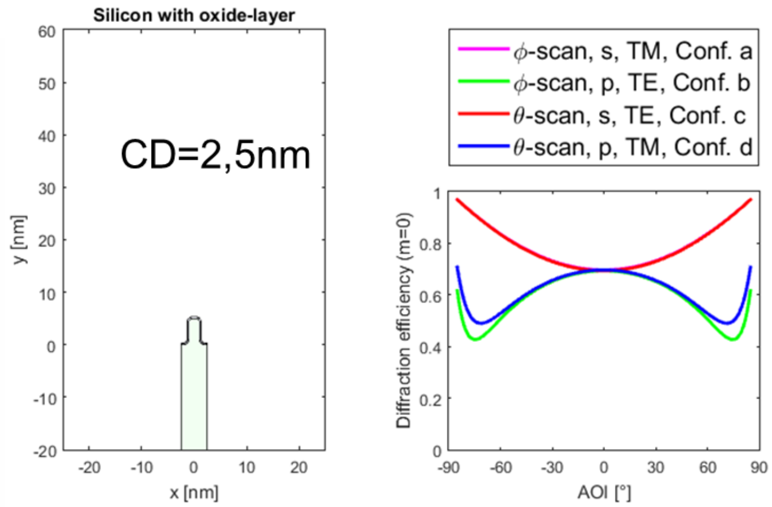
Outline

1. Introduction
2. Common challenges in OCD metrology
3. PTB tools and analysis methods
4. Challenges of future applications
5. Future directions in OCD

Application optimised OCD

Num. simulation of reflectance for a gratings
with a period of 100 nm and varying CD





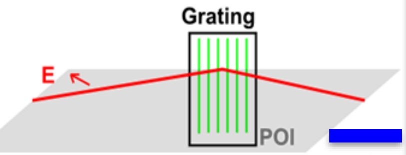
Small size or wavelength/size-ratio is not the main issue!

Very large dynamics in reflectivities
→ Excellent sensitivity with respect to linewidth

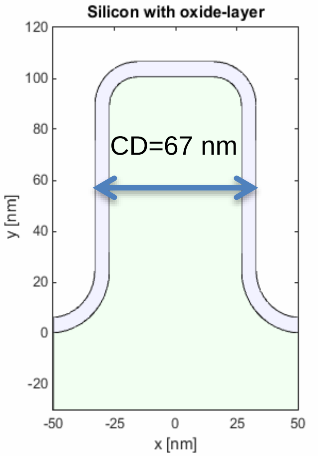
Future directions

Application optimised OCD

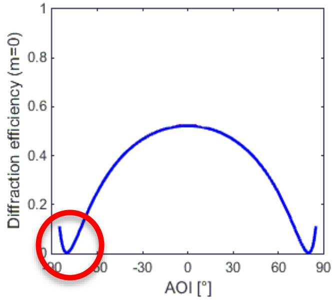
Experiment:

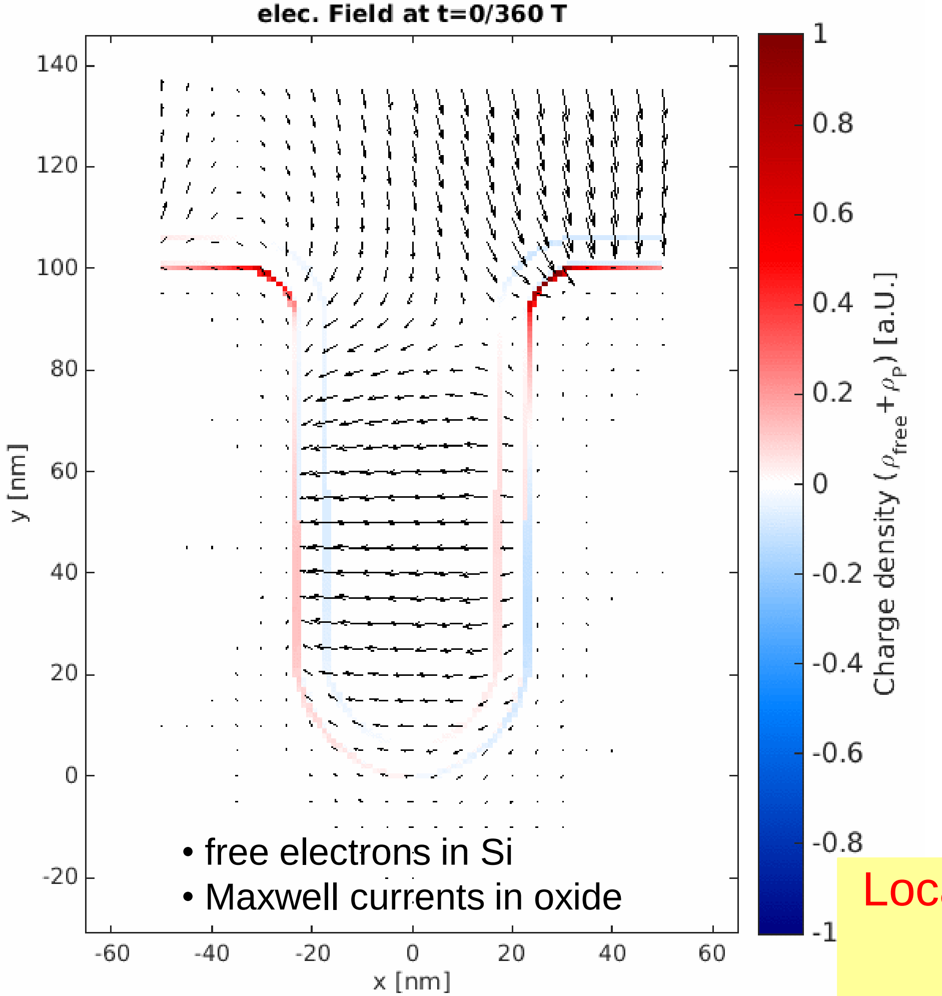


Grat. structure:



Meas. signal:





Angle of incidence θ=80°

Light stimulated resonant E-field distribution

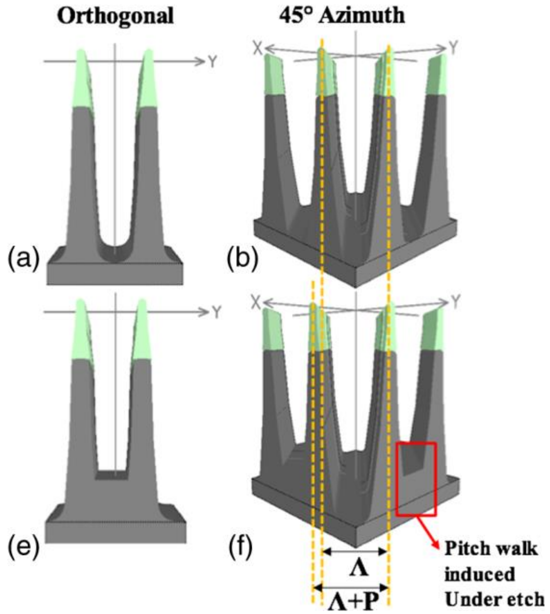
Local resonant charge oscillations at the surface

Localised Surface Plasmon Resonance (LSPR)
→ large sensitivity wrt. structure geometry

Application optimised OCD

⇒ Adaption of field parameters (λ, AOI, pol.,...) can enhance sensitivity substantially exploiting nano-optical effects!

⇒ Another example: nonorthogonal azimuth angle reflectometry or/and MME for enhanced pitchwalk sensitivity



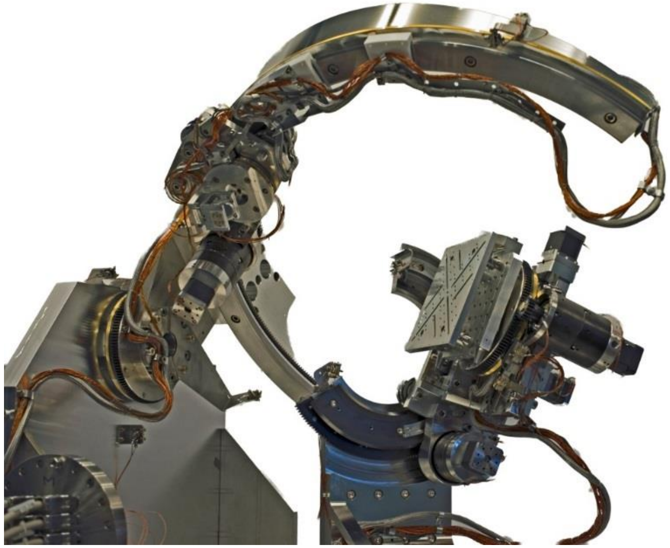
R. Chao et al.,*Multitechnique metrology methods for evaluating pitch walking in 14 nm and beyond FinFETs*, J. Micro/Nanolith. MEMS MOEMS. (2014) **13**, 041411

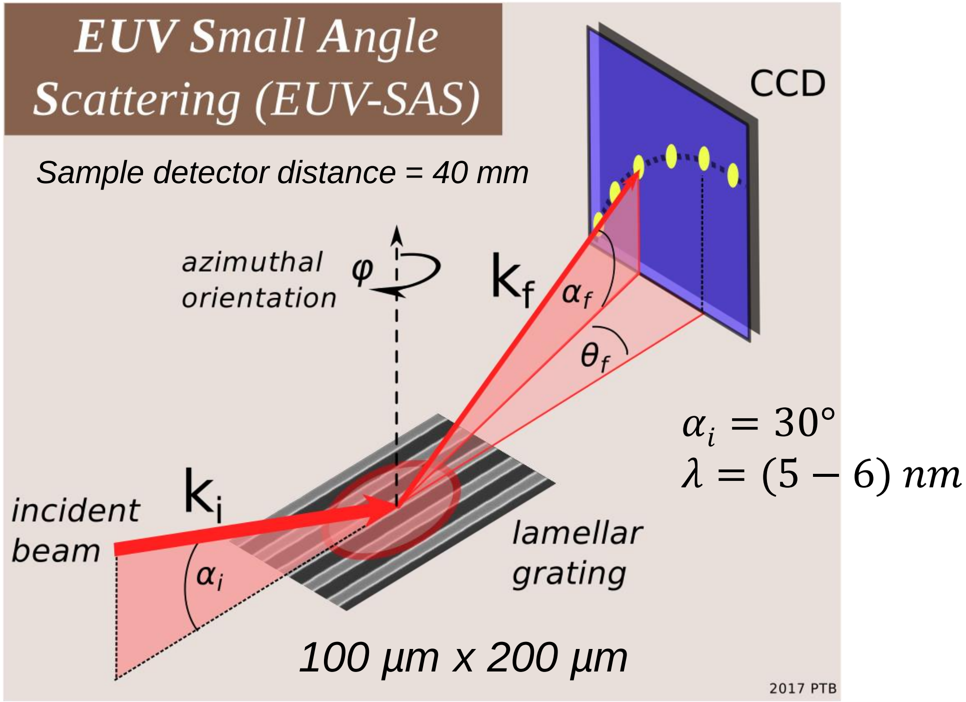
Future directions

Advanced X-ray / EUV scatterometry

SX700 Soft X-ray reflectometer

- (0.7 - 25) nm
- Soft X-ray reflectometry (EUV)
- EUV-scatterometry
- Polarisation sensitive (s, p)





	EUV 210 eV to 230 eV	GISAXS 5.5 keV to 5.6 keV
pitch / nm	150	150
cd / nm	66.31 ± 0.57	67.18 ± 0.16
height / nm	120.12 ± 0.19	119.66 ± 0.06
top r / nm	12.64 ± 0.60	7.46 ± 0.19
bot r / nm	10.29 ± 0.30	14.26 ± 0.32
σ_r (rms)	1.89 ± 0.12	2.14 ± 0.08
sidewall angle / °	83.48 ± 0.33	84.53 ± 0.19

- Much reduced foodprint but
- Enhanced uncertainty
- S/N-issues

Future directions
Faster modelling/analysis

Speed-challenge!

- Uncertainty evaluation
- 3D-modelling; complex structures
- Hybrid metrology
- Analysis of Mueller matrix measurements
- stochastic structure parameters (roughness)

$\Rightarrow$ Faster numerical methods required:
smart interpolation of discrete sampling points in parameter space

Surrogate models

Method	Function evaluations	FEM	PC
Sensitivity Analysis	3×10^4	$41d$	$20h + 0.1s$
Bayesian MCMC	$\sim 10^5$	$139d$	$20h + 47min$
Maximum Likelihood	30	$1h$	$20h + 0.84s$
Least squares	15	$0.6h$	$20h + 0.42s$

ZIB

JCMwave

Reduced Basis Method

Fast Simulation Method
for Parameter Reconstruction
in Optical Metrology

Sven Burger,[a,b] Lin Zschiedrich,[b] Jan Pomplun,[b]
Frank Schmidt,[a,b] Bernd Bodermann[c]

[a] Zuse Institute Berlin (ZIB), Takustraße 7, D-14195 Berlin, Germany
[b] JCMwave GmbH, Bolivarallee 22, D-14050 Berlin, Germany
[c] Physikalisch-Technische Bundesanstalt Braunschweig (PTB), Bundesallee 100, D-38116 Braunschweig, Germany

Proc. SPIE **8681**, 868119 (2013)

Future directions
Advanced hybrid metrology

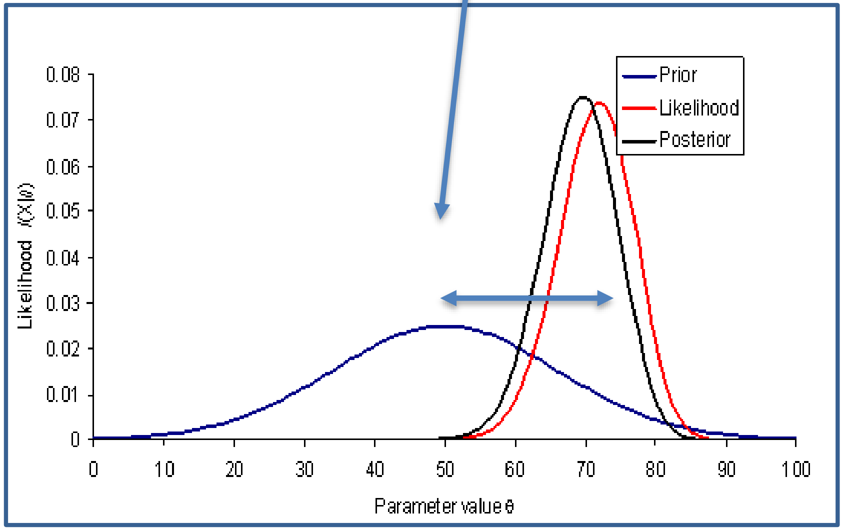
In-line metrology: ≥ 2 tools combined

High resolution imaging (HV-SEM, TEM,...) ↔ Versatile OCD (application optimised!) (MME, maybe EUV-SAS or T-SAXS)

supported by a-priory knowledge from off-line metrology:

CD-AFM or GISAXS/T-SAXS on special suitable test structures/targets

Interpolating co-optimisation (advanced Bayes), or full parallel evaluation applying surrogate modelling;
Automation (Markus talk)
Machine Learning (Johanns talk)



Conclusions

- Scatterometry (OCD and/or X-ray based) will play an essential role in CD metrology down to 5 nm and beyond!
- Here the challenges increase dramatically, some of them critical
- Most critical: Material parameters, parameter correlations & choice of geometry modell!
- Thus essential R&D is required and significantly enhanced or novel approaches are required (hybrid, X-ray based, exploitation of nano-optical effects)

Thank you for your Attention!

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Bundesallee 100
38116 Braunschweig
Bernd Bodermann
Telefon:0531 592-4222
E-Mail: bernd.bodermann@ptb.de
www.ptb.de/OptNanoMet

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