OCD Metrology for Advanced Lithography

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

Critical Dimension CD: structure widths / size

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

Semiconductor people keep us busy in metrology!
Introduction

Why Scatterometry (OCD)?

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

\[ I_n = I_n^\text{ov} \]

-1 0 +1

10um x 10um

Film thickness

Porosity

Optical material parameters

Mask at-wavelength metrology

Diffraction Based Focus

40um x 40um

\rightarrow 10um x 10um

Sub-resolution structures

Oxide layer?

Widths?

Corner Rounding?

→ complex 3D multiparameter

→ complex 3D multiparameter

Physikalisch-Technische Bundesanstalt ■ Braunschweig und Berlin

Nationales Metrologieinstitut

22.03.2017

FCMN 2017, Monterey
Introduction
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 $\eta$)
  (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

$\lambda$: spectroscopic

$\Theta$: goniometric
Introduction
Scatterometry (Optical CD metrology)

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Current commercial OCD tools
Introduction
Model based analysis

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

rigorous calculation of diffracted E- and H-fields by numerical solution of Maxwell's equations: RCWA, FDTD, FEM, waveguide, ...

direct (forward problem)

surface parameters $p_i$

plane wave ($k$)

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

- U(CD) < 1 nm
- Two materials: Silicon and Si₃N₄ (dielectric)
- GISAXS reference target
- Characterised by scatterometry, Mueller ellipsometry, CD/tilt AFM, CD-SEM and GISAXS

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, stitching,…)
- geometrical structure model (binary, trapezoidal, corner rounding,…)
- 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 …
Common OCD Challenges
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
  size ~ wavelength/100
• Accuracy

• Increasing complexity
  ⇒ increasing parameter correlations
  ⇒ ambiguity issues
  ⇒ computations costs (time and memory issues)
Common OCD Challenges
Stochastic parameters, roughness

- Stochastic parameters ⇒ depolarisation & diffuse scattering
- Depolarisation & scattering usually not adequately described!
  ⇒ 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 Approach (EMA)
- Scattering theories (Born approximation, Beckmann-Kirchhoff, Rayleigh-Rice, Harvey-Shack (NP), ...)

Example Decomposition
\[ M = M_0 + \Delta M \]
- \( M \) - measured MM
- \( M_0 \) - best-fit Mueller-Jones matrix (no depolarisation)
- \( \Delta M \) - residuum

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PTB tools and methods
FEM Reconstruction: The Model

Rational Bézier curves, weighted

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

Ensures continuous profiles

Flexible curvature radii with gradients possible

Undercut

Pitch

Rigorous modelling for all 'optical' methods from NIR to X-ray
- Spectr. Ellipsometry / Mueller
- DUV Scatterometry
- EUV SAS
- GISAXS

Maxwell solver: FEM allows to model arbitrary structures

\[ \text{Downhill simplex method} \]
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 axeses positioning mount

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

M. Wurm, F. Pilarski, B. Bodermann:  

M. Wurm, S. Bonifer, B. Bodermann, J. Richter: *Deep ultraviolet scatterometer for dimensional characterization of nanostructures: system improvements and test measurements*  
PTB tools and methods
Goniometric Scatterometry & Reflectometry


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
- $\Theta_{\text{in}}$ und $\Theta_{\text{out}}$ independent, transmission
- Layers (thickness) and layer systems
- Complex permittivity
  (‘material parameters’ n&k)
- Depolarisation
- OCD metrology

Sentech SE 850 DUV

Ellipsometry

Mueller Ellipsometry (MME)

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


FCMN 2017, Monterey
**PTB tools and methods**

**X-ray-Scatterometry**

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

Circular shape: Ewald sphere section

Si grating

$\alpha_i \approx 1^\circ$

large interaction area

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

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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

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

<table>
<thead>
<tr>
<th>Sample (nom. p, CD, h)</th>
<th>HZB_P100_CD35(100, 35, 100 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scatt.</td>
</tr>
<tr>
<td>CD [nm]</td>
<td>32.3 (1.8)</td>
</tr>
<tr>
<td>h [nm]</td>
<td>105.7 (2.3)</td>
</tr>
<tr>
<td>swa [°]</td>
<td>91.4 (1.9)</td>
</tr>
<tr>
<td>h_oxide [nm]</td>
<td>3.0 (0.6)</td>
</tr>
<tr>
<td>CR_top [nm]</td>
<td>14.9 (3.0)</td>
</tr>
<tr>
<td>CR_bottom [nm]</td>
<td>29.3 (2.8)</td>
</tr>
</tbody>
</table>

Results

<table>
<thead>
<tr>
<th>Results</th>
<th>CD / nm</th>
<th>h /nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUV-Scatterometry</td>
<td>25.9 (1.4)</td>
<td>50.0 (4.4)</td>
</tr>
<tr>
<td>Comb. With MME</td>
<td>26.4 (0.9)</td>
<td>50.5 (1.6)</td>
</tr>
<tr>
<td>GISAXS</td>
<td>25.1</td>
<td>48.2</td>
</tr>
</tbody>
</table>
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Challenges of future applications
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

High aspect ratio structures
- e.g. holes & trenches in single or multilayers
  - to many layers / parameters
  - waveguiding effects

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
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,…

\[ \frac{1}{\tau_f} = \frac{1}{\tau_{bulk}} \lambda = \left[ \frac{2(1-\beta)}{3\beta} \right] R_f \]

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

⇒ anisotropy
⇒ permittivity tensor

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

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

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

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

Small size or wavelength/size-ratio
is not the main issue!
Future directions
Application optimised OCD

Experiment:

Grat. structure:

Silicon with oxide-layer

CD=67 nm

Angle of incidence $\theta=80^\circ$

Meas. signal:

• free electrons in Si
• Maxwell currents in oxide

Light stimulated resonant E-field distribution

Local resonant charge oscillations at the surface

Localised Surface Plasmon Resonance (LSPR) $\rightarrow$ large sensitivity wrt. structure geometry
Adaption of field parameters ($\lambda$, AOI, pol.,...) can enhance sensitivity substantially exploiting nano-optical effects!

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

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)

<table>
<thead>
<tr>
<th>EUV 210 eV to 230 eV</th>
<th>GISAXS 5.5 keV to 5.6 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>pitch / nm</td>
<td>150</td>
</tr>
<tr>
<td>cd / nm</td>
<td>66.31 ± 0.57</td>
</tr>
<tr>
<td>height / nm</td>
<td>120.12 ± 0.19</td>
</tr>
<tr>
<td>top r / nm</td>
<td>12.64 ± 0.60</td>
</tr>
<tr>
<td>bot r / nm</td>
<td>10.29 ± 0.30</td>
</tr>
<tr>
<td>σr (rms)</td>
<td>1.89 ± 0.12</td>
</tr>
<tr>
<td>sidewall angle / °</td>
<td>83.48 ± 0.33</td>
</tr>
</tbody>
</table>

• Much reduced foodprint but
• Enhanced uncertainty
• S/N-issues
Future directions
Faster modelling/analysis

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

⇒ Faster numerical methods required:
smart interpolation of discrete sampling points in parameter space

Surrogate models

<table>
<thead>
<tr>
<th>Method</th>
<th>Function evaluations</th>
<th>FEM</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity Analysis</td>
<td>$3 \times 10^4$</td>
<td>41d</td>
<td>$20h + 0.1s$</td>
</tr>
<tr>
<td>Bayesian MCMC</td>
<td>$\sim 10^5$</td>
<td>139d</td>
<td>$20h + 47min$</td>
</tr>
<tr>
<td>Maximum Likelihood</td>
<td>30</td>
<td>1h</td>
<td>$20h + 0.84s$</td>
</tr>
<tr>
<td>Least squares</td>
<td>15</td>
<td>0.6h</td>
<td>$20h + 0.42s$</td>
</tr>
</tbody>
</table>

Reduced Basis Method

Fast Simulation Method for Parameter Reconstruction in Optical Metrology

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Frank Schmidt,$^b$ Bernold Bedermann,$^b$

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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 model!

• 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!