Aerial Imaging Technology for EUV Mask Making

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Carl Zeiss SMT, Germany

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Agenda

ZEISS

1 Company Overview

2 Introduction to Aerial Imaging Metrology

3 AIMS™ EUV and Application Examples

4 Summary

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SMT is a segment of ZEISS, a leading international enterprise operating in the fields of optics and optoelectronics

Semiconductor Manufacturing Technology

1.212 billion euros revenue

approx. 2,900 employees

Research & Quality Technology

1.538 billion euros revenue

approx. 6,300 employees

Medical Technology*

1.427 billion euros revenue

approx. 4,500 employees

Vision Care/Consumer Products

1.108 billion euros revenue

approx. 9,800 employees

As of 30 September 2017 *The values deviate from the published figures of Carl Zeiss Meditec AG as a result of different consolidation models.

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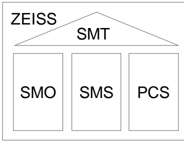
SMT covers a variety of processes in the production of microchips – with three strategic business units and as a segment of the ZEISS Group



ZEISS Group

Semiconductor Manufacturing Technology Business Group

Strategic Business Unit
Semiconductor Manufacturing Optics (SMO)

Strategic Business Unit
Semiconductor Mask Solutions (SMS)

Strategic Business Unit
Process Control Solutions (PCS)

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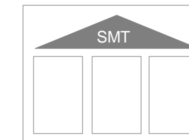
A place for innovation and growth: SMT fab in Oberkochen, Germany, is being further extended



Ongoing expansion with high-end equipment for R&D and production of High-NA EUV optics

700+ m€ anticipated as a total investment in High-NA EUV

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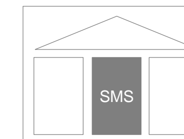
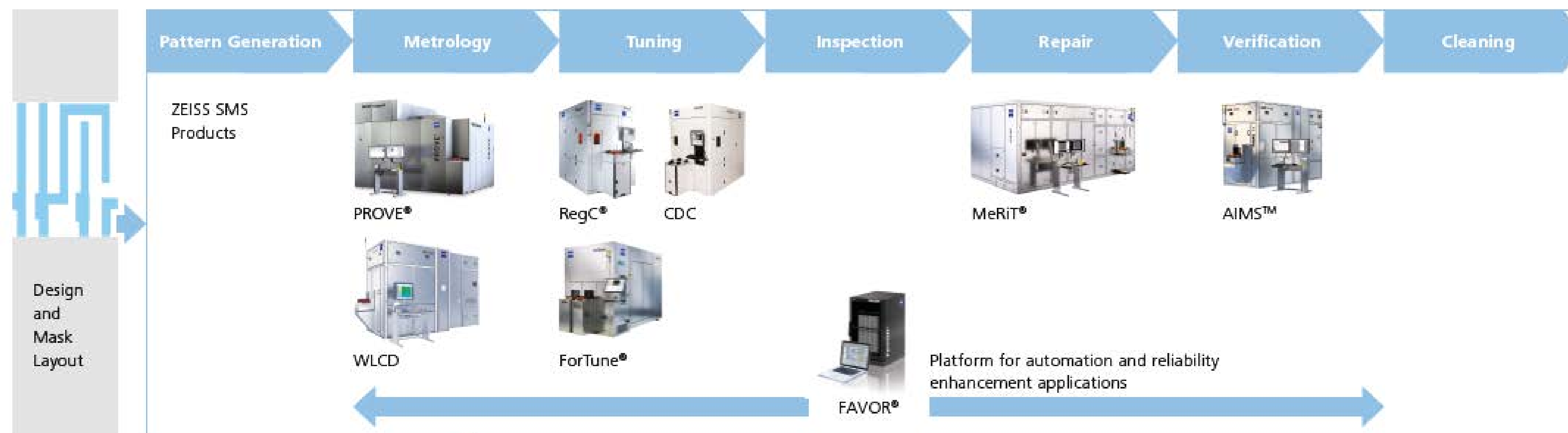
Semiconductor Mask Solutions (SMS) Overview about Product Offering





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AIMS™ Concept: Looking at the Mask with Scanner Eyes !

AIMS™ - Aerial Image Measurement System

Scanner / Exposure Tool

Illuminator

Mask

NA <0.35

0.25x

NA <1.4

Wafer

Wafer Print

equivalent image generation

AIMS™

Illuminator

Mask

NA 0.35

450x

NA ~ 0

CCD Camera

Aerial Image generated by mask

Field of View@mask
Large (“100mm range”, slit))

Field of View@mask
Small (“10µm range”, point-by-point measurement)

AIMS™ uses same wavelength, illumination condition and imaging NA as scanner

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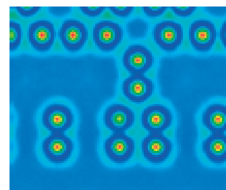
ZEISS celebrates 25 years of AIMS™ technology



1993
Optical platform developed in collaboration with IBM

1994
MSM 100 market introduction (365/248 nm)

1999
MSM 193 market introduction (193 nm)

2000
First fab tool AIMS™ fab (248 nm)

2003
First fab tool with automatic handling AIMS™ fab plus

2006
AIMS™ 45-193i market introduction (193 nm)

2009
AIMS™ 32-193i market introduction (193 nm)

2014
AIMS™ 1x-193i (193 nm)

2017
AIMS™ EUV (13.5 nm)

- Over the decades ZEISS has developed new AIMS™ generations to keep with the ongoing demands in mask making from i-line to EUV technology
- More than 100 AIMS™ systems have been delivered to the industry during that time
- AIMS™ has been established as an industry standard

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AIMS™ Main Application: Defect Disposition and Repair Verification

AIMS™

MeRiT® Repair Process

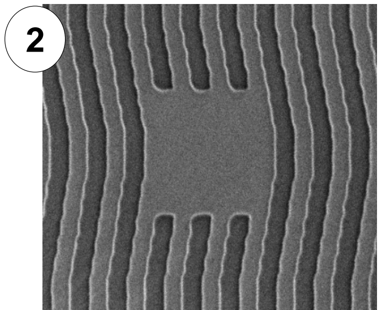
AIMS™

Printability test by AIMS™ technology

1

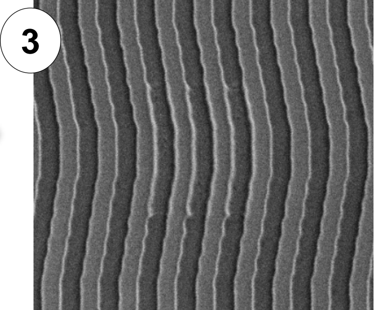
Detailed analysis by high resolution e-beam

2



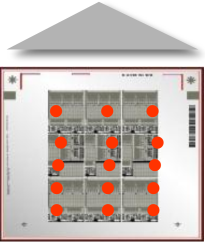
E-beam mask repair by MeRiT®

3



Printability check after repair by AIMS™

4



Input (from Mask Inspection Tool): Mask Defect coordinates:

Defect-free mask

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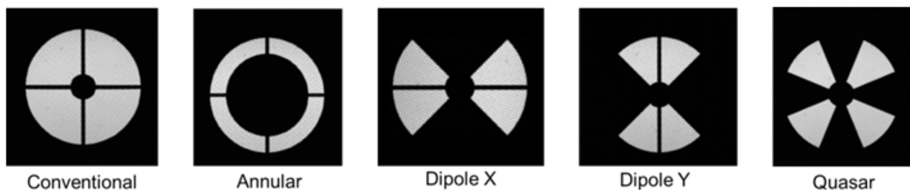
AIMS™ EUV actinic mask review tool

AIMS™ EUV prototype

Examples of Illumination Conditions



- Mirror optics based actinic mask defect aerial imaging
- NA 0.33 scanner illumination & projection emulation

Performance Specifications		
Scanner emulation	Up to 0.33 NA	
CD Reproducibility	≤1.5 nm (3σ, mask level)	
Run Rate standard 7 focus planes per site	≥ 27.5/hr ≥ 51/hr	> 38.5% pupil fill > 77% pupil fill
Run Rate fast mode* 7 focus planes per site *CD-repro = 1.8 nm (3σ)	≥ 55/hr	>38.5% pupil fill

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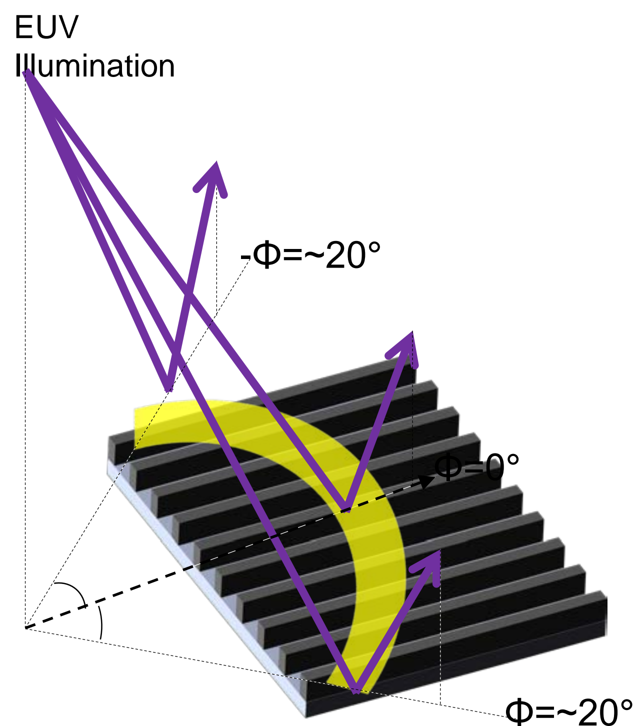
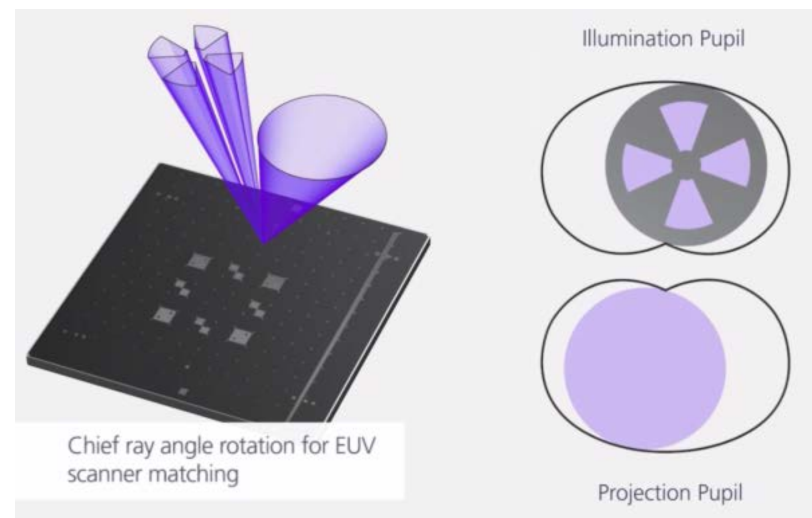
New: EUV Scanner Emulation
Scanner arc illumination

EUV illumination: **CRA with θ and ϕ components**

orientation & position dependent shadowing effects

OPC/bias compensation across X-axis





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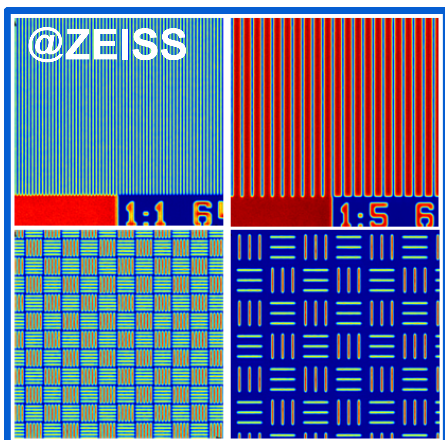
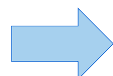
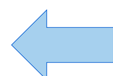
AIMS™ EUV at Intel: steps towards insertion into production

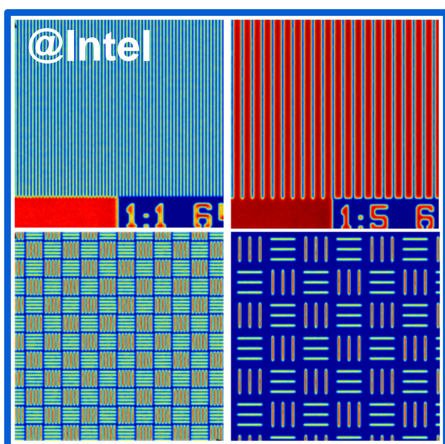
Following successful integration and acceptance, the tool has been handed over to customer in production



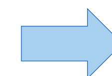
- Successful factory acceptance test
- Platform meets its performance specifications







- Successful final acceptance test
- Platform meets its target specifications
- Results obtained at Headquarter well reproduced



Tool in production

EUV Mask Challenges

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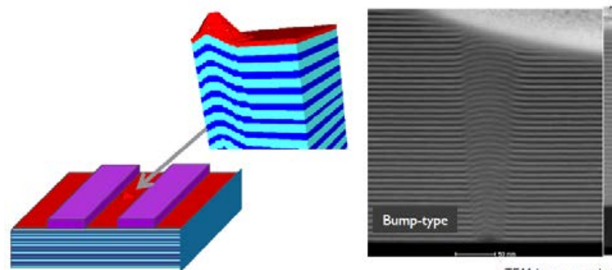
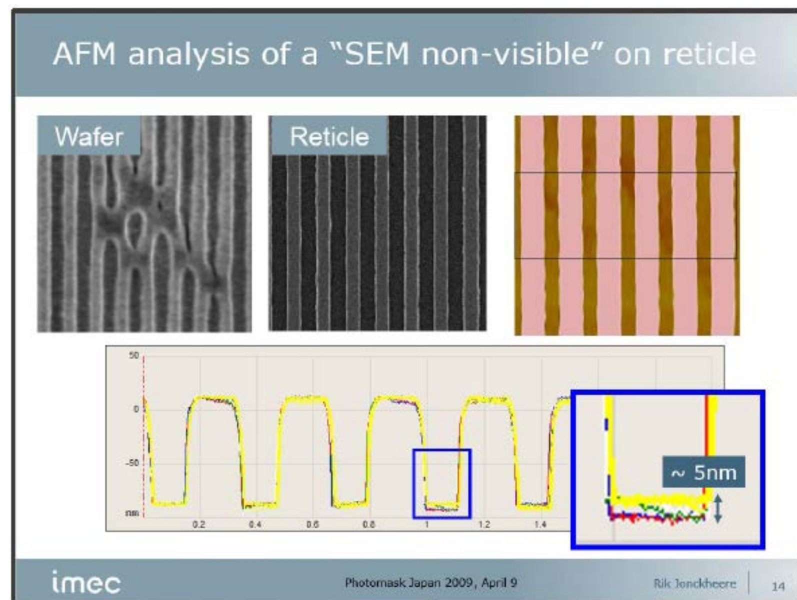
New Class of defects which is not visible in mask SEM and DUV inspection:

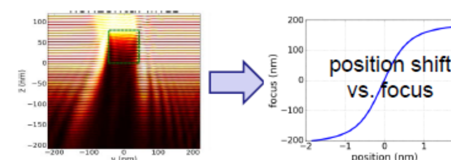




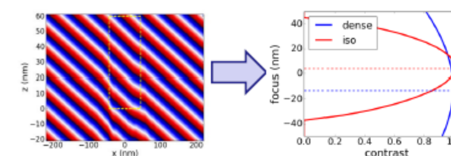
Mask 3D Effects impact the imaging performance of photomask

Introduction: 3D Mask Effects in EUV Lithography

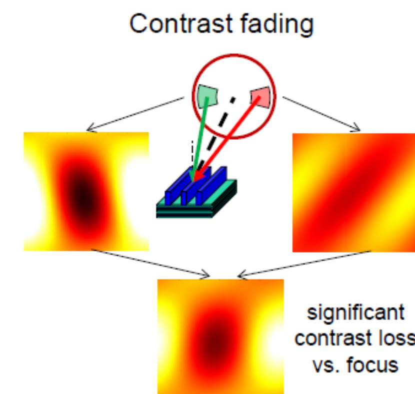
Shadowing & telecentricity error (TCE)



Phase deformation & best focus (BF) shifts



BF depends on pitch



A. Erdmann et al., Adv. Optical Technologies 6 (2017) 187

Lithography Simulation 3 Fraunhofer IISB

Andreas Erdmann SPIE 2018

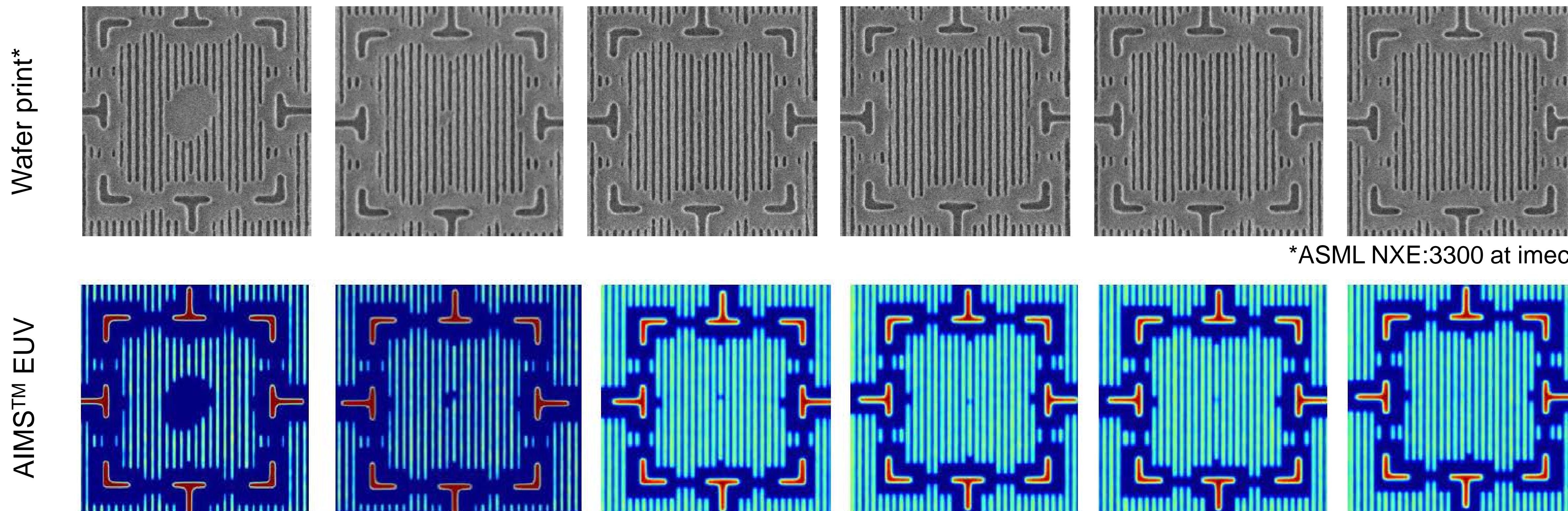
Multilayer defect printability with AIMS™ EUV

Imec through access with the support of all EMI members

Through-focus measurements of 146 native ML-defects as detected by ABI

- Correlation of AIMS™ EUV aerial image shows a good match to wafer prints over the range of printing impact
- Good correlation extends to defocus conditions within process window

Courtesy of Imec, **Rik Jonckheere**

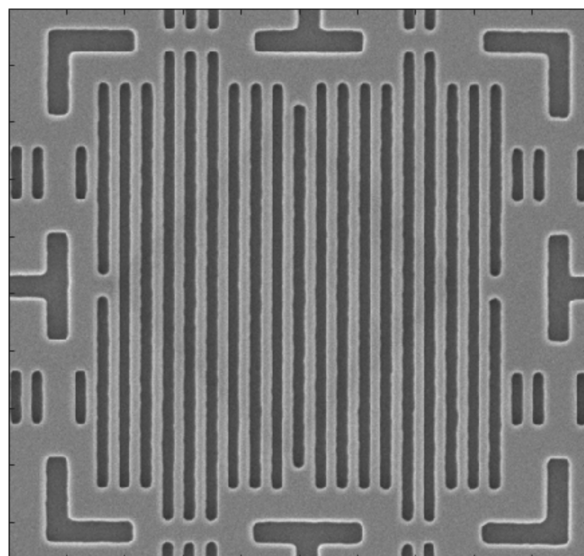


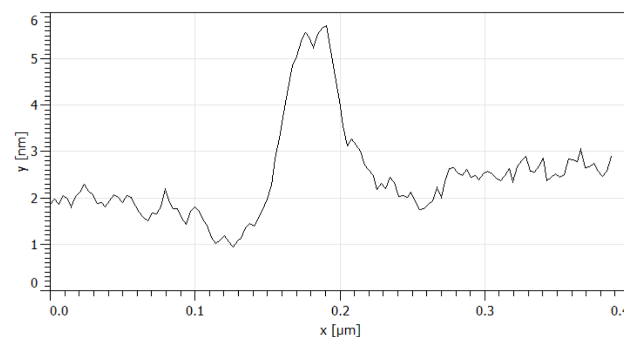
Multi-metrology printability assessment of buried blank defect

imec ZEISS

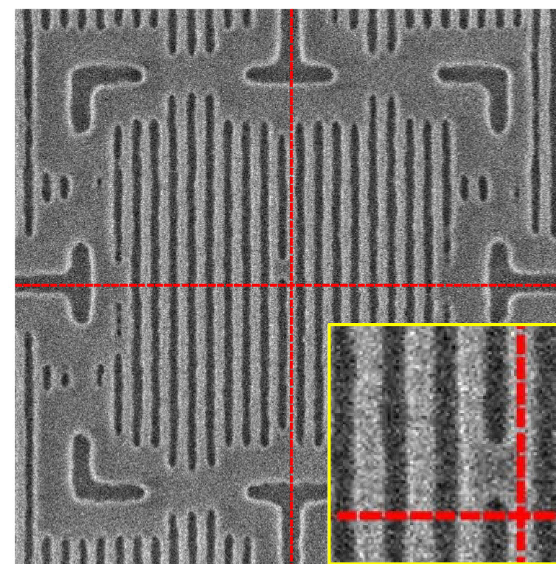
The AIMS™ EUV aerial image contains ALL relevant information to predict the impact of the defect on the wafer

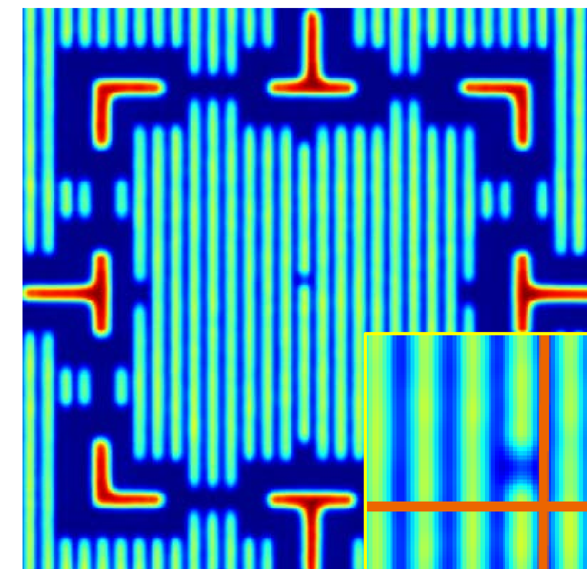
Assessment of alignment precision of mask pattern to blank inspection map
(see R. Jonckheere, Proc. SPIE Vol. 10807 - PMJ2018)





Averaged and smoothed AFM-Profile along Trench (ZEISS SMT)





- ABI inspection: detected
- SEM review on mask: not visible
- AFM review: detected
- AIMS™ EUV review: detected
- Wafer print: detected

Additional value of actinic review via AIMS™ EUV

Measurement of deviation of actual position from expected
What is expected to be under absorber, might end up printing!

The full qualification of printing behavior is only possible via AIMS™ EUV aerial image

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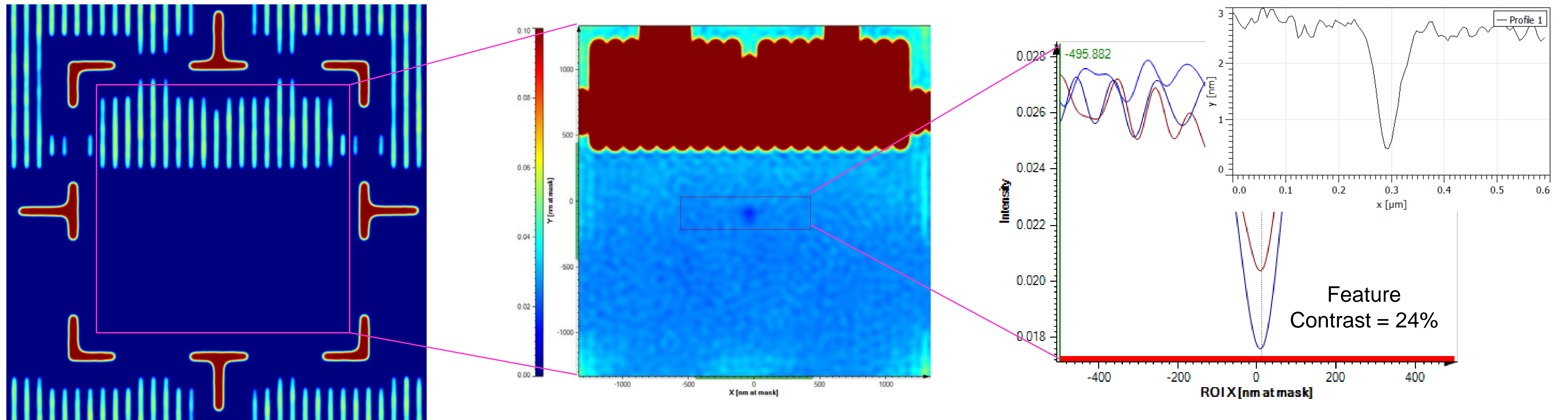
Aerial image based metrology of EUV masks

Defect detection below absorber, a door-opener to new applications

The AIMS^{TM} EUV platform capabilities go well beyond defect disposition and review

Also when underneath the absorber, a ML-defect is visible and its imaging impact can be qualified



AIMS^{TM} EUV sees all what's on the mask. Extremely sensitive to material and its changes in n,k.

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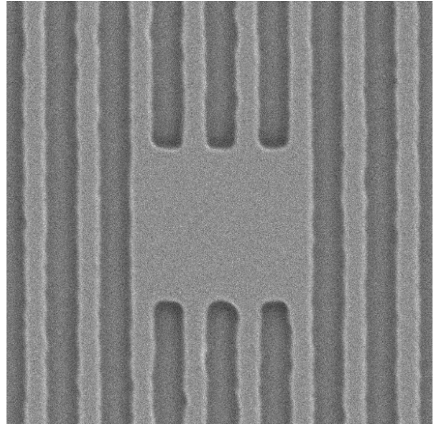
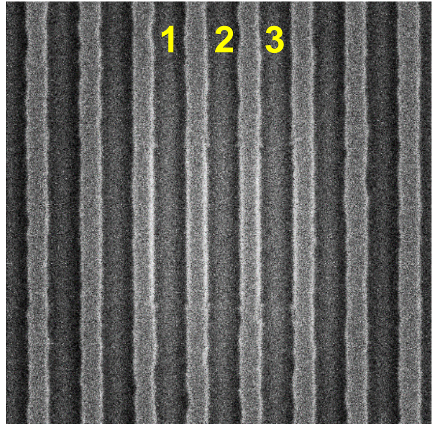
Repair Verification
Successful repair examples from ZEISS MeRiT neXT

ZEISS supports fully automated analysis of AIMS^{TM} EUV images via the FAVOR® platform

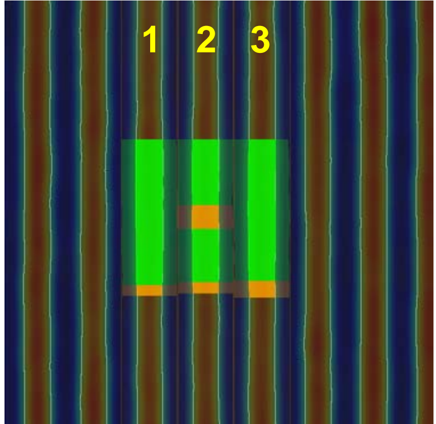
Etch



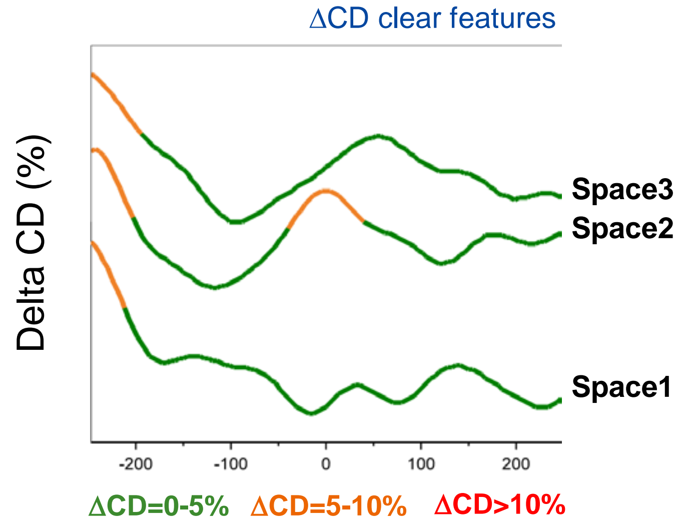
Pre repair SEM



Post repair SEM

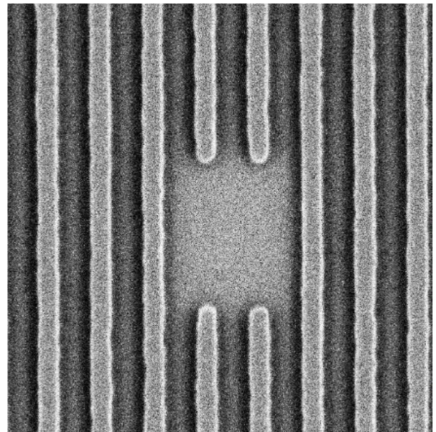


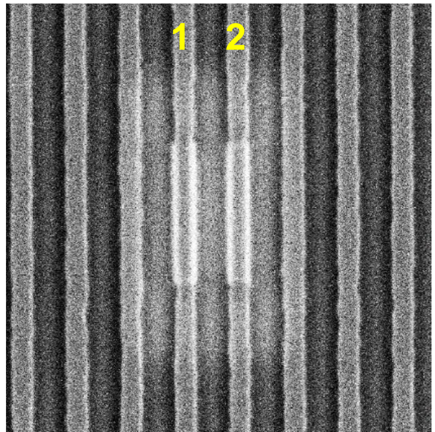
Single Slice Analysis of AIMS^{TM} EUV images

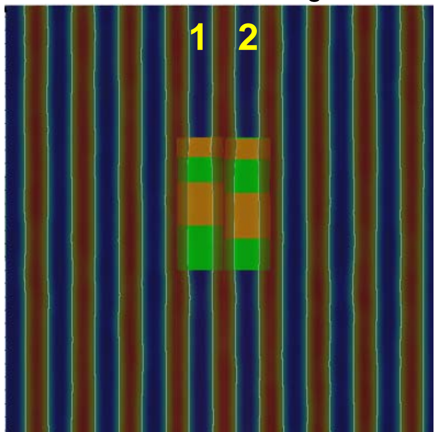


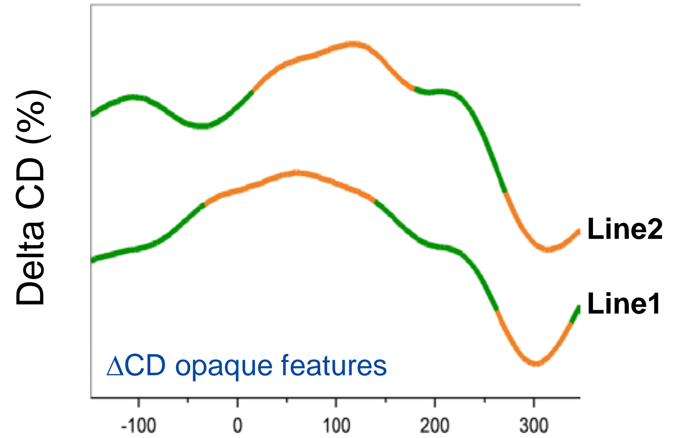
ΔCD=0-5% ΔCD=5-10% ΔCD>10%

Deposition









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AIMS™ EUV – Applications beyond repair
Printing Aware Metrology of Mask 3D Effects

Metrology AIMS based

Mask surface topology	Mask patterning	Mask Focus Shifts	Photon Stochastics

3σ = 1.6%

3σ = 16.2%

1.2

1

0.8

Mask LWR:

Horizontal	
Vertical	3.6nm

Aerial Image LWR:

horizontal

vertical

LWR (3 sigma, nm)

Threshold (a.u.)

Focus shift horizontal lines 16nm@WL, dipole-y

Best Focus position [nm@WL]

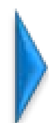
Pitch [nm@WL]

Local CDU: mask imaging stochastics

Local CDU 3σ@WL [nm]

dose [a.u.]

D. Hellweg et al., Proc. SPIE 10143, 101430J (2017).
M. Weiss et al., Proc. SPIE 9422, 942219 (2015).



- **Impact on wafer depends on structure, setting and focus**
- **Aerial Imaging specification usedfule for Euv masks**

AIMS™ EUV measurement of mask 3D focus shifts

Uses through focus aerial image acquisition capability

1. **Measure focus stacks for 16nm lines through pitch**

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AIMS^{TM} EUV measurement of mask 3D focus shifts

Significant pitch-, pattern- and setting-dependent focus-shifts

1. Measure focus stacks for 16nm lines through pitch
2. **Determine best focus shift**

Best Focus range [nm@WL]
50
40
30
20
10
0
Focus-Range 45nm

Best Focus position [nm@WL]
20
10
0
-10
-20
Horizontal lines 16nm@WL, dipole-y
32 48 64 128 256
Pitch [nm@WL]
Pronounced peak
at Semi-dense
Iso-dense bias 20nm

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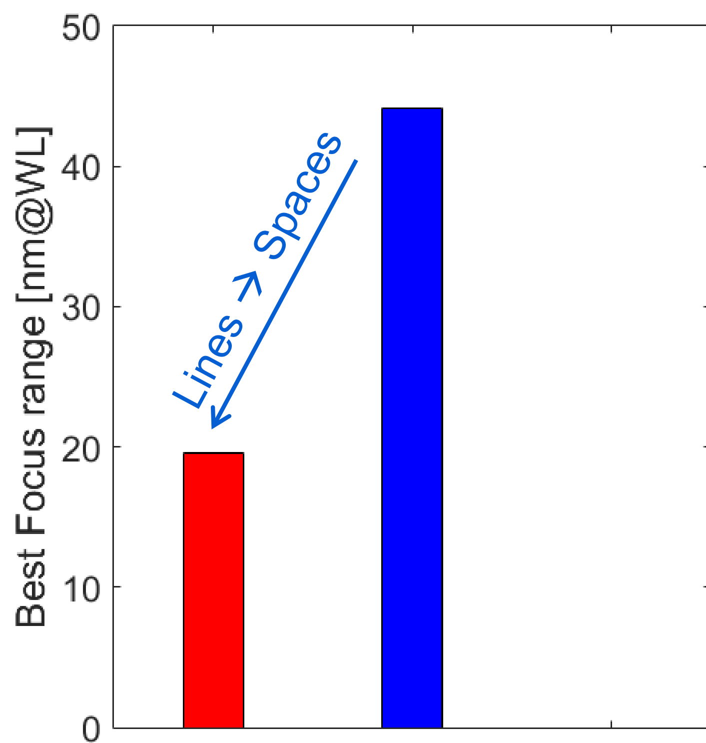
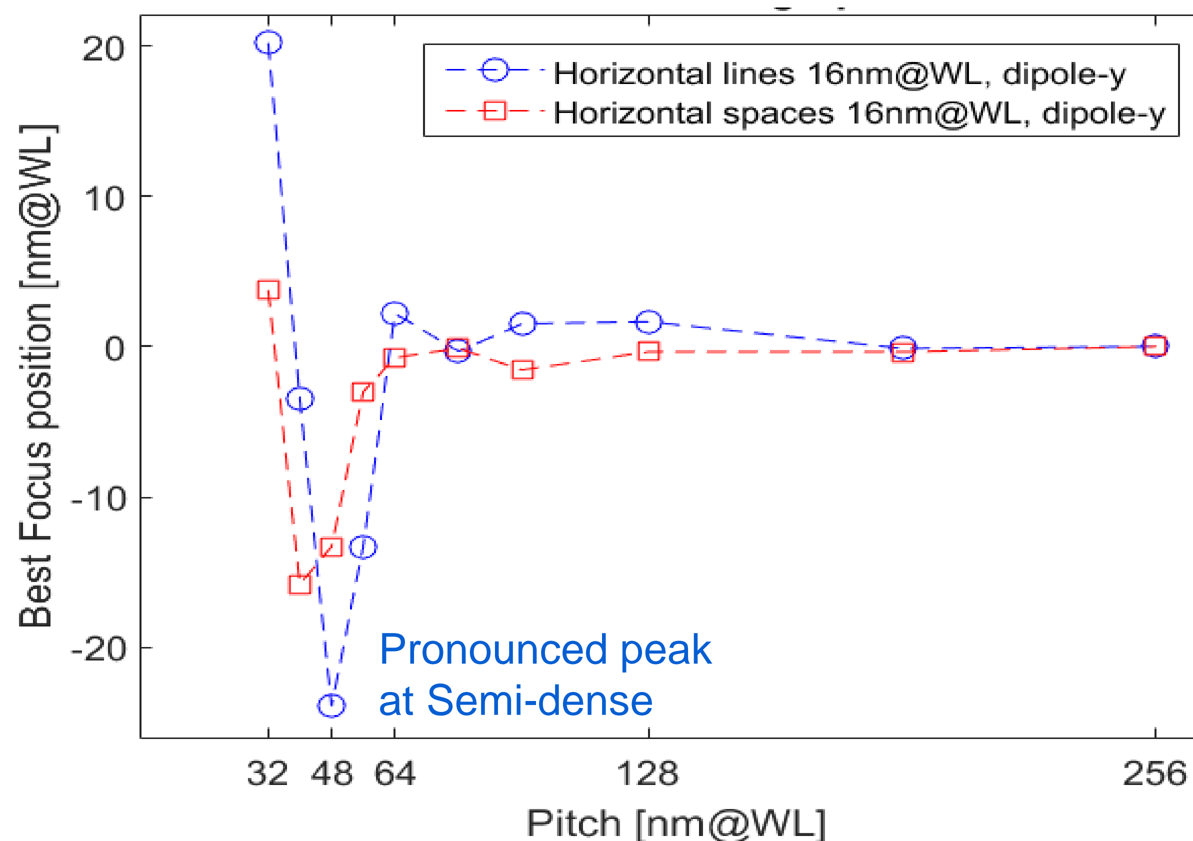
AIMS™ EUV measurement of mask 3D focus shifts

Significant pitch-, pattern- and setting-dependent focus-shifts

1. Measure focus stacks for 16nm lines through pitch
2. **Determine best focus shift**





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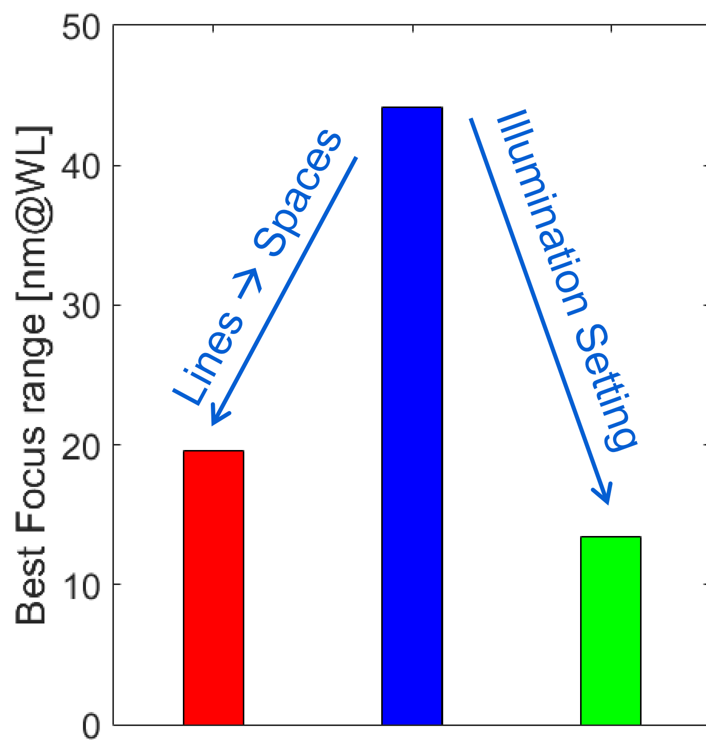
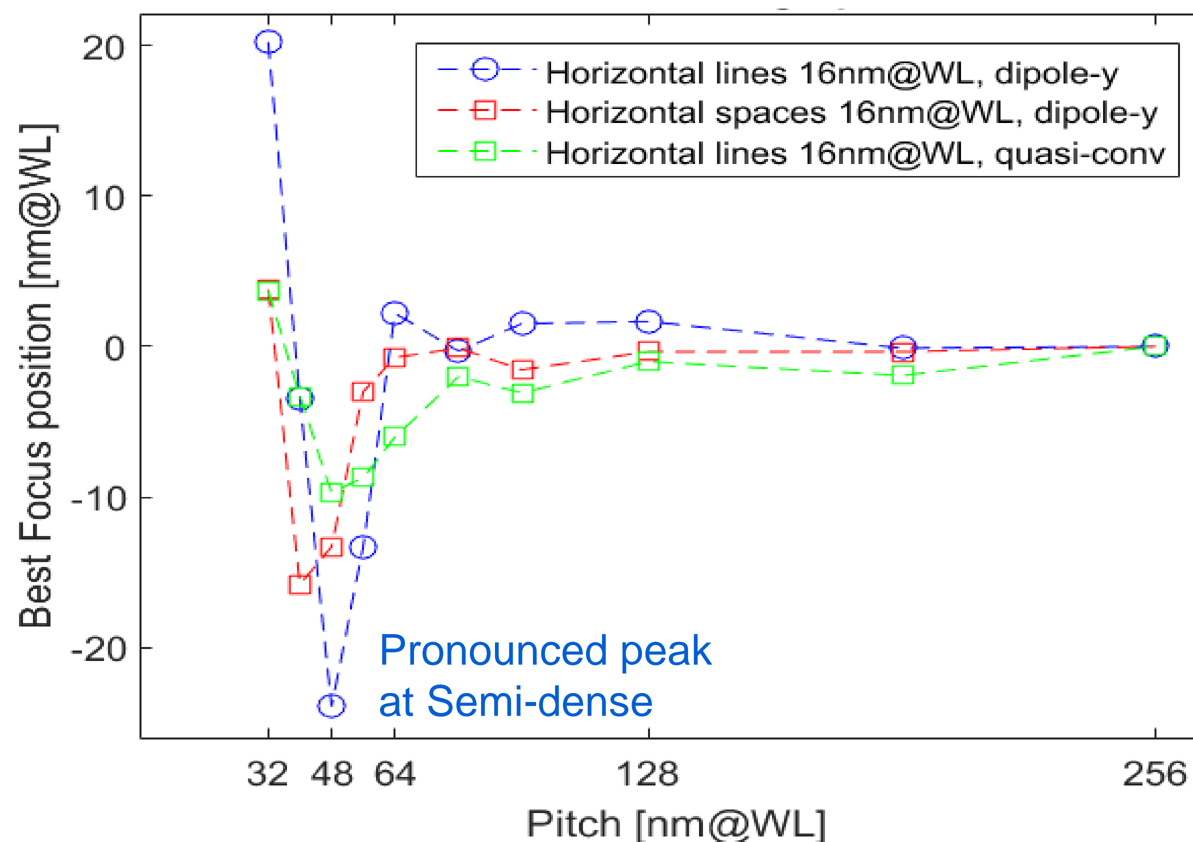
AIMS™ EUV measurement of mask 3D focus shifts

Significant pitch-, pattern- and setting-dependent focus-shifts

1. Measure focus stacks for 16nm lines through pitch
2. **Determine best focus shift**

Focus shift dependency can be verified using AIMS™ EUV



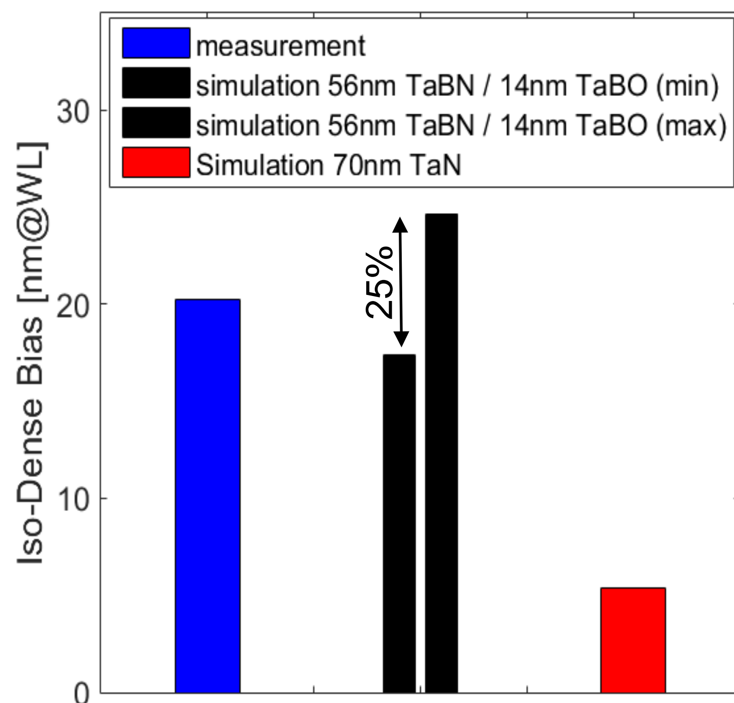


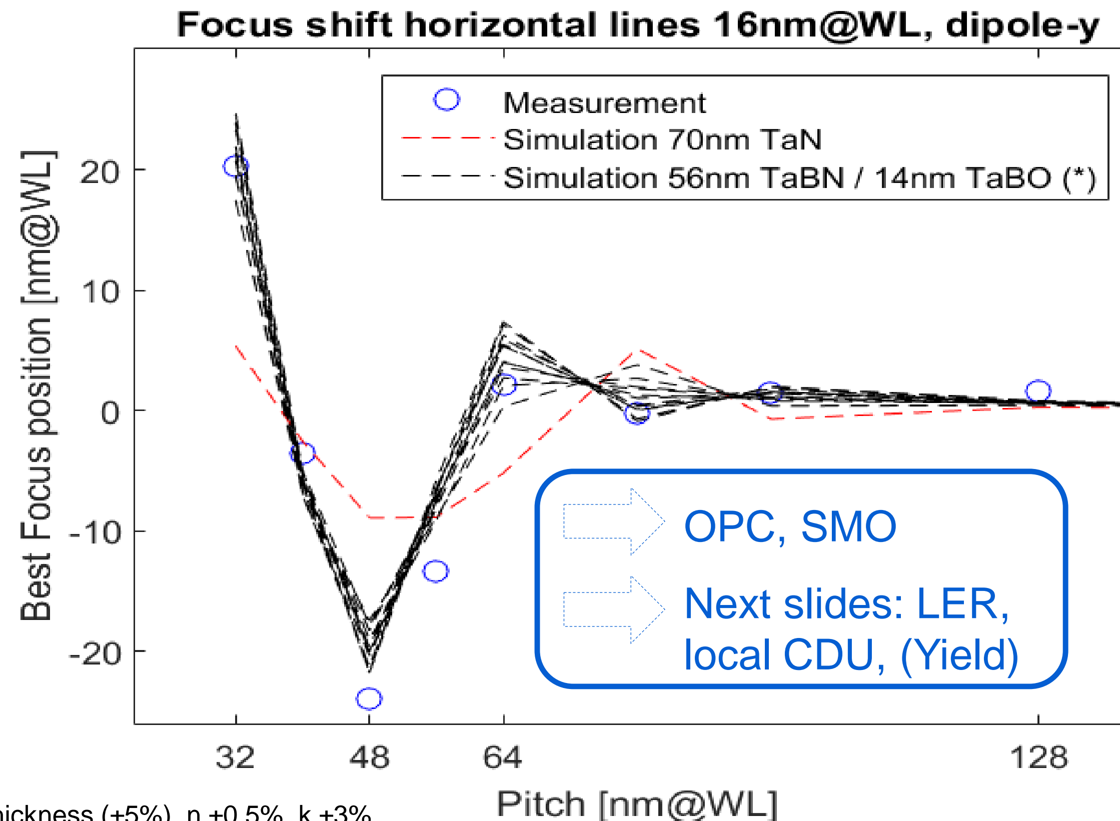
AIMS™ EUV measurement of mask 3D focus shifts

Does not require knowledge of mask structure

1. Measure focus stacks for 16nm lines through pitch
2. Determine best focus shift
3. **Compare to simulation**

Can be used for OPC/SMO verification / optimization





(*): side wall angle (86°-90°), absorber thickness (±5%), n ±0.5%, k ±3%

Stochastic Effects

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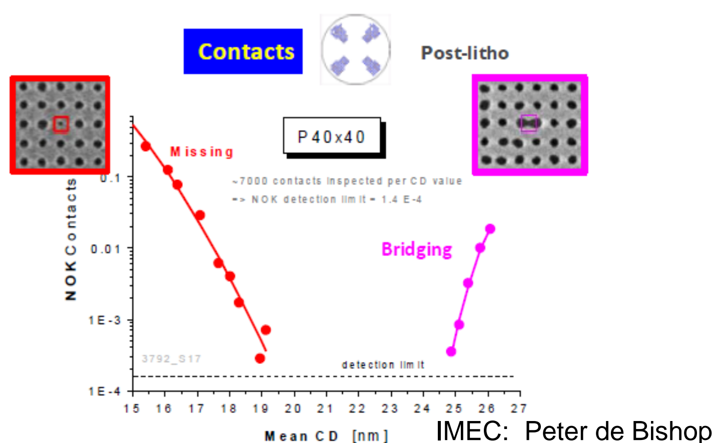
Paradigm change DUV- to EUV-Lithography

DUV: Photon stochastics not important

EUV: Higher photon energy, smaller lithography feature

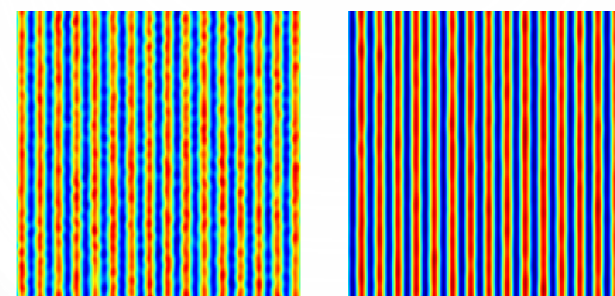
- Major contribution to wafer local CDU & LWR
- Stochastic printing defects on wafer
- Noisy wafer wafer SEM images



IMEC: Peter de Bishop

New AIMS™ Imaging Mode

- Stochastics emulation capability*



8 mJ/cm²* AIMS™ mode

* experimental mode

*Equivalent of 40mJ&/cm2 with 20% resist absorption

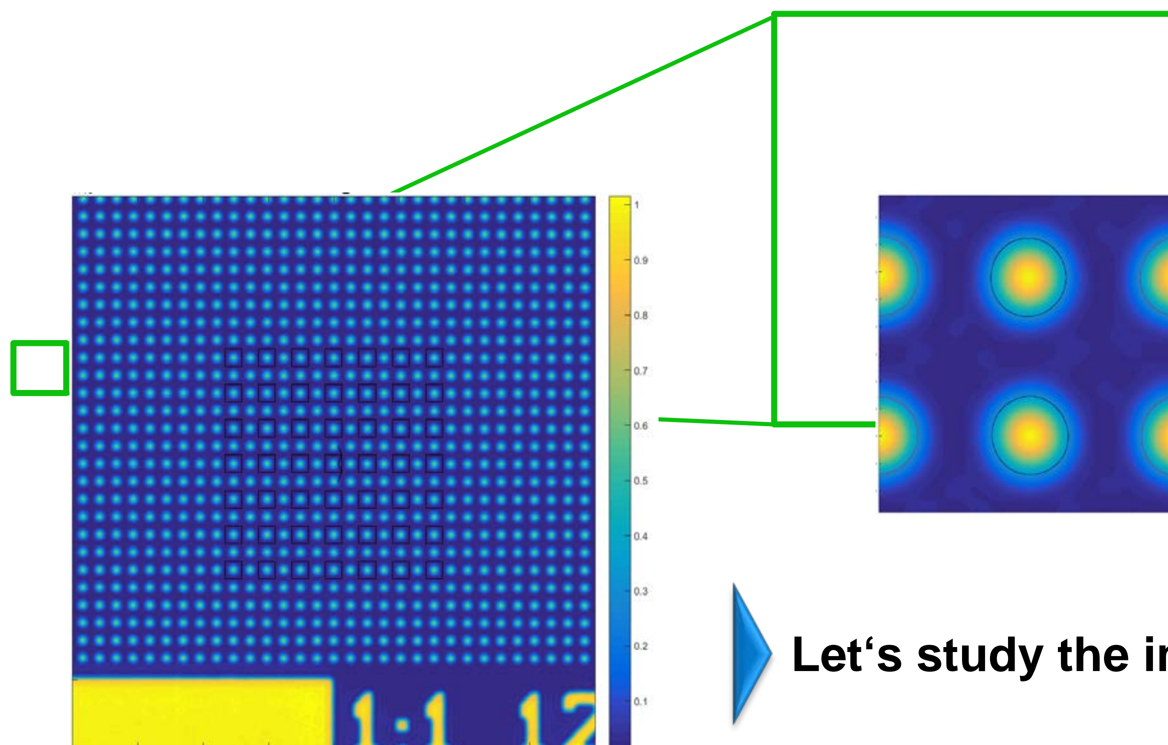
- Impact of photon stochastics on imaging can be studied

→ LCDU, LWR in aerial image

AIMS™ EUV allows to separately measure mask making contribution and aerial imaging stochastics

Repeated measurement of contact hole arrays with varying number of photons:

Determine CD (by area of CH):
$CD(CH, rep)$



22nm (@wafer level) dense contacts
Field of view: 2 x 2µm (@wafer level)

Determine statistical contribution to local CDU:

1. Subtract mean CD of each CH
2. Calculated local CDU

Let‘s study the impact of photon statistics on LCDU

AIMS^{TM} EUV measurement of aerial image stochastics
- 1/NILS and 1/sqrt(dose) scaling confirmed
- AIMS^{TM} EUV can range from mask making quality to stochastics regime

Local CDU: mask imaging stochastics

Best focus
Defocus 60nm@WL
c / sqrt(dose)
c / sqrt(dose) * NILS(BF)/NILS(def)
Local CDU 3σ@WL [nm]
1.5
1
0.5
0
0.2
0.4
0.6
0.8
dose [a.u.]

AIMS^{TM} EUV standard mode: Mask making quality

New AIMS^{TM} EUV stochastic mode
Photon stochastics in wafer exposure

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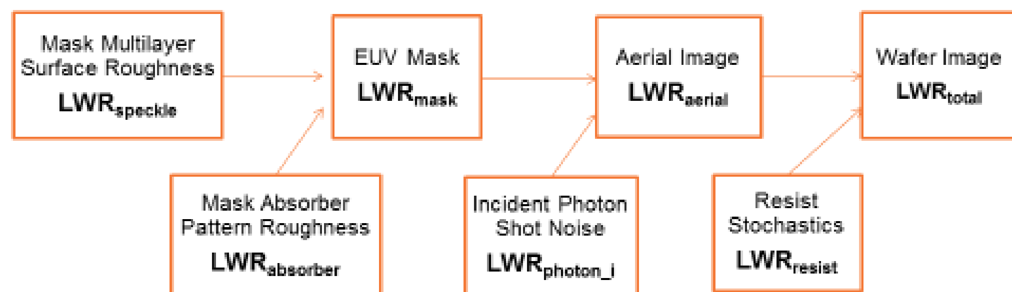
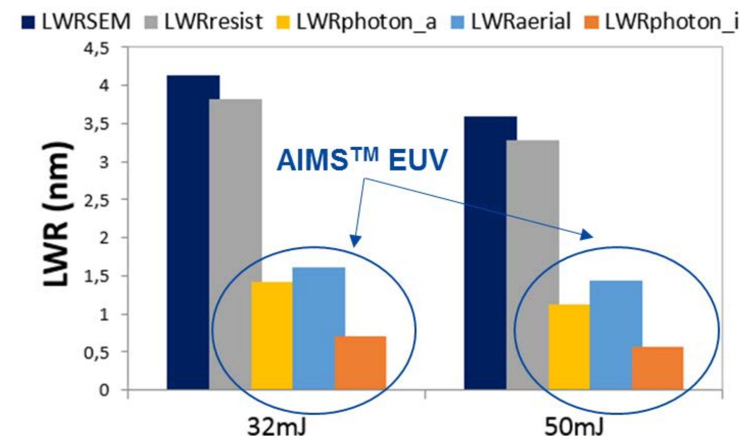
Evaluation of phton stochastics on wafer linewidth roughness AIMS™ stochastic mode



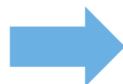
- Goals of this study
  - Measure, quantify, and correlate the variance and spectral components of aerial LWR and resist LWR
  - Assess the relative contributions to resist LWR from mask absorber and multilayer roughness

SPIE 2018 EUV Lithography IX 2/27/2018 2

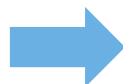
SPIE 2018



- Resist effects dominate wafer LWR
  - Mask qualification is only possible within the actinic aerial image



AIMS™ EUV enables separation of mask effects from wafer process effects



Beneficial for root cause analysis of EUV specific mask 3D and stochastic effects

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Agenda

ZEISS

1	Company Overview
2	Introduction to Aerial Imaging Metrology
3	AIMS™ EUV and Application Examples
4	Summary

Summary

ZEISS

- Aerial Imaging Metrology is Industry Standard since more than 20 years:
- “See the mask with scanner eyes”
- AIMS™ EUV: First system installed and released by customer
- EUV mask repair verification
- Printing Aware Mask Metrology:
  - Accurate measurement of EUV mask 3D effects
  - Separation of mask effects from lithographic process effects
  - Impact of photon stochastics on imaging
- Enabling for EUV mask development and HVM production

ZEISS