EUV computational lithography to enable technology scaling below 10 nm

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Agenda

• Introduction: Need for EUVL for sub-10 nm node
• Modeling challenges for EUV specific effects
• FlexPupil and Source-mask optimization (SMO)
• EUV sub-resolution assist features (SRAF)
• Full field OPC and verification
• Summary
EUV improves post etch pattern fidelity vs. ArFi LE$^3$
NXE:3300 & Tachyon NXE OPC+ mask single exposure example

- 10 nm node logic 2D M1 evaluated in ASML-IMEC ‘Scaling project’
- SEMs show improved pattern fidelity & contact coverage for EUV vs. ArFi LE$^3$

ArFi LE$^3$ wafer after TiN etch
EUV single exposure wafer after TiN etch
Multi-patterning cost & complexity drive need for EUV

<table>
<thead>
<tr>
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# Multi-patterning cost & complexity drive need for EUV

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EUV litho improves metal interconnect resistance

EUV vs Multiple Patterning: variation

Cumulative distribution of Interconnect Resistance

- Electric test data: EUV single exposure patterning has tighter distribution compared to ArFi multi-patterning

Results from 10 nm technology learning vehicle

J. Shearer, (IBM), AVS 2014
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EUV modeling challenges addressed by Tachyon NXE

NXE scanner

- Multi-layer mirror
- Absorber
- Mask
- Projection optics
- Field

Φ = 90°  Φ = 71°

Modeling challenges

- Oblique Incidence (Chief Ray Angle at Object)
- 3D Mask Topology (absorber on ML mirror)
- Arc-shaped field (Chief ray phi)
- Residual mirror roughness

Imaging impact

- HV print bias (shadowing effect)
- Best focus shift and Bossung tilt
- Pattern shift non-telecentricity (impacting overlay)
- Flare (pattern/slit dep.)

Effects are pattern & slit position dependent: NXE SMO & full field OPC is required
3D Mask model enhancement for EUV applications
New Tachyon NXE M3D+ model captures the edge-to-edge interaction

- EUV mask is more susceptible to secondary scattering
  - $H \gg \text{wavelength}$
  - $S \sim H$ for dense patterns
  - Reflective mask

Illumination

M3D+ vs M3D Comparison
Conventional M3D model accuracy breaks down at tighter spaces

- 1D L/S, dark field mask
- Pitch: 100 nm, varying space width

Resolution limit based on rigorous model
NXE M3D+ enables accurate and fast EUV simulation

- Rigorous model (FDTD) used as reference
- Thin-mask model is fast but fails at smaller feature sizes
- Tachyon NXE M3D+ is fast and matches rigorous model
- Conclusion holds for HV bias, Bossung tilt, best focus shift, and for pattern shift
Model accurately predicts CD through-slit

- NXE 3300 IMEC 10 nm node metal layer calibration reticle
- NXE M3D+ model calibrated with 1D and 2D test patterns
- “Model-based” shadowing capability

**Pitch 48 CD 21 RMS: 0.40 nm**

- V wafer
- V model
- H wafer
- H model

**Pitch 48 CD 24 RMS: 0.38 nm**

- V wafer
- V model
- H wafer
- H model

**Pitch 50 CD 29 RMS: 0.40 nm**

- V wafer
- V model
- H wafer
- H model

**Pitch 94 CD 39 RMS: 0.31 nm**

- V wafer
- V model
- H wafer
- H model
Introduction: Need for EUVL for sub-10 nm node

Modeling challenges for EUV specific effects

FlexPupil and Source-mask optimization (SMO)

EUV sub-resolution assist features (SRAF)

Full field OPC and verification

Summary
EUV Imaging Performance meets 10 & 7nm node requirements
Tachyon SMO optimized FlexPupil improves Resolution

CD requirements by node

- Tip-to-tip
- Tip-to-line
- Lines / Spaces

CD performance OK for 7nm

0.33 NA, single expose
Dose ~20mJ/cm²

Tip-to-tip

0.33 NA, single expose
Dose ~32mJ/cm²
NXE illumination options roadmap
SMO optimizes FlexPupil enabling advanced EUV imaging

- **2013:** Conventional illumination
- **2014:** Off-axis illumination option (6 pre-selected settings)
- **2015:** FlexPupil option (custom illumination)
- **2016:** Possible field HW upgrade
- **2017:** 3400 illuminator

NXE:3300B

NXE SMO optimizes FlexPupil

NXE:3350B

NXE:3400B*

Increasing EUV imaging requirements
Pattern placement aware SMO reduces non-telecentricity

Standard cost function $EPE^*$ evaluated through process variations

$$ CF = \sum_{pw,e} w_{pw,e} EPE^p $$

Placement-aware cost function $PPE^*$ evaluated at PPE gauges

$$ CF = \sum_{pw,e} w_{pw,e} (EPE^p + w PPE^v) $$

$\pm \Delta$ Focus (DOF)

$\pm \Delta$ Dose (EL)

$\pm \Delta$ Mask (MEEF)

PPE gauges enable PPE reduction at a specific location

$EPE^*$: Edge placement error

$PPE^*$: Pattern placement error

*EPE: Edge placement error

*PPE: Pattern placement error
Placement-aware SMO improves total process window

SMO: EPE only

SMO: EPE + PPE

7 nm node logic metal-1 case

<table>
<thead>
<tr>
<th>Process window DOF@10%EL</th>
<th>EPE only</th>
<th>EPE + PPE</th>
</tr>
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<tbody>
<tr>
<td>CD based</td>
<td>90</td>
<td>97</td>
</tr>
<tr>
<td>PPE based</td>
<td>65</td>
<td>97</td>
</tr>
<tr>
<td>CD and PPE combined</td>
<td>65</td>
<td>95</td>
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EPE = Edge placement error
PPE = Pattern placement error

45% improvement
SMO can optimize ILS to reduce LER

Factors impacting LER:
- Statistical local variation of absorbed photons
- Acid diffusion length
- Image log slope
- Dose (anchor mask bias)
- Target (litho) bias

L7 metal-1 logic design
- CD=16nm, pitch=32nm, $k_1=0.39$
- NXE:3350B, NA=0.33

Physical stochastic resist model contours or wafer data

Stochastic edge placement error (SEPE)

$\text{SEPE} = \frac{a}{\text{blurILS}^b}$

$a$ and $b$ calibrated to full stochastic resist model (SRM) or wafer data

RMS error = 0.19

Factors impacting LER:
- Statistical local variation of absorbed photons
- Acid diffusion length
- Image log slope
- Dose (anchor mask bias)
- Target (litho) bias

Focus of SMO application
SMO SEPE band reduction results
NXE:3350 FlexPupil optimization

- Pupil & mask optimization
- SEPE band
- CDU band
- SEPE = 4.0 nm

- Pupil & mask optimization with
  - Improves ILS
  - Optimal dose & target bias
- SEPE = 3.0 nm
- 25% SEPE reduction

- PPE spec @ +/-0.4nm

Graph:
- EL (%)
- DOF (nm)
- Pupil & mask optimization
- Pupil & mask + ILS optimization
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Asym. SRAF can be used to reduce Bossung tilt & shift

- Assist feature enhances the higher diffraction orders amplitude:
  \textit{improves contrast}

- Asymmetric AF introduces phase shift between 0\textsuperscript{th} and higher orders:
  \textit{balances m3d phase effect}

- Advantages: \textit{Local effect, Full-chip solution}
Asymmetric assist features reduce Bossung tilt

--- Symmetric assist features ---

--- Asymmetric assist features ---

Asymmetric AF

--- Asymmetric Bossung ---

--- Symmetric Bossung ---
SMO optimizes FlexPupil and asymmetric SRAF

- L7 metal 2 like design
  - Min CD: 15 nm, min pitch: 30 nm
  - Other pitches: 60/90/175 nm
- NXE 3300B, NA = 0.33
- $k_1 = 0.37$
- Assist feature width = 10 nm

Compare:
- OPW
- PW limiters
- best focus range
Asymmetric AFs improve OPW by correcting Bossung tilt

- Without assist features (AF), large best focus range and poor contrast limits overlapped process window (OPW)
- Symmetric AFs improve contrast, but cannot correct best focus shift and introduce Bossung tilt limits OPW
- Asymmetric AFs reduce best focus shift (-54%), correct Bossung tilt, and increase OPW (DOF @ 10% EL increases by 51%)

**Best focus shift Range (nm)**

- No AF: 24 nm
- Symmetric AF: 23 nm
- Asymmetric AF: 11 nm

**BF limiter**
- No AF
- CD PW limiter

**Dose**
- asymmetric AF: 82 nm @ 10% EL
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Full field OPC needed to compensate Shadow effect

- Shadow effect is long range with slit location dependency \(\rightarrow\) requires full field correction
- Slit specific OPC required \(\rightarrow\) need more computation resources and larger data storage

Both Model Based (M3D+) and Rule Based Shadowing (Cosine2) Correction is available

Shadowing: CD difference caused by 6 degree Incident angle on mask for patterns of different directions and slit position
Full field OPC required to compensate for Flare

- Flare has a very long range effect and location dependency → requires full field correction
- Slit position specific OPC required → need more computation resources and larger data storage

Flare: CD difference caused by combination of stray light and pattern density on mask

Flare Mapping and OPC correction based on Flaremaping
Full field OPC required to compensate Black Border

- Black Border effect is long range → requires full field correction
- OPC can correct the Black Border introduced CD error
Tachyon NXE HScan solution addresses computation and memory challenges in full field OPC

**HScan Functions**

HScan:
1) Analyze GDS Hierarchy based on
   (1) flare amount
   (2) Slit position (shadowing)
2) Analyzed result is used to group different cells together
3) OPC is ran for each different cell, then result is pasted to minimize runtime

**HScan reduces runtime and output file size**

HScan shows significant improvements in runtime (10x~70x) as well as output data size (10x) for both logic and memory devices
Tachyon NXE OPC with M3D+ model enables robust imaging with large process window

- IMEC N10 metal-1 logic cell: NXE:3300B exposure, Quasar45
- Mask tape-out using Tachyon NXE OPC with M3D+ model
- Predicted contours (green) match well SEM contours
Logic 7 nm node early results: Mask taped out using Tachyon NXE OPC and exposed on NXE:3300

- Good L7 M1 logic cell imaging results
- Fully routed 2D non-gridded M1 logic cell 18 nm trench CD, 36nm pitch

White is absorber
Blue is multilayer (mirror)
Tachyon NXE SMO and OPC optimize scanner and mask for best full field process window

**EUV design & process optimization**
- Target clips
- Tachyon NXE SMO w/M3D+
- Verify using full-chip applications
  - Tachyon NXE:OPC+
  - Tachyon NXE:LMC

**EUV model calibration**
- Optimized NXE:33x0 FlexPupil
- Tachyon NXE w/M3D+ FEM+ calibration
- Metrology data

**EUV OPC & verification**
- Tachyon NXE:OPC+
- Tachyon NXE:LMC
- Optimized mask
- LCP

- NXE:33x0 w. FlexPupil
- Fab

- .xml file
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- ASML/Brion has developed solutions to accurately model various EUV specific effects

- NXE SMO optimizes FlexPupil to minimize the pattern placement error through defocus for best placement aware process window

- Developed compact LER model to evaluate the stochastic edge placement error (SEPE) and NXE SMO to optimize Flexpupil to enhance image log slope to reduce stochastic effect

- Optimize asymmetric assist feature placements to enlarge common process window, reduce Bossung tilt and minimize best focus shift

- Full field RET and OPC solutions are validated and ready for EUV lithography deployment below 10 nm
Thank you for your attention!