The Status and Future of Imaging Metrology Needs for Lithography.

Joost Sytsma
### International Technology Roadmap for Semiconductors 1999

<table>
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</thead>
<tbody>
<tr>
<td>Half Pitch DRAM (nm)</td>
<td>180</td>
<td>130</td>
<td>100</td>
<td>70</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>Development (nm)</td>
<td>90</td>
<td>35</td>
<td>45</td>
<td>-</td>
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</tbody>
</table>

**CD** = Controllable minimal linewidth

To be achieved via \( CD = k_1 \cdot \frac{\lambda}{NA} \)
Defining the challenge-1

\[ CD = k_1 \cdot \frac{\lambda}{NA} \]

Critical dimension (nm)

Time (years)

I-line

\( k_1 \)

NA

Contrast

Major Change

Paradigm Shift

and/or

DUV

193

157

EUV
Defining the challenge-2

- Major steps by λ and NA

- The process factor $k_1$ and contrast still decreases $\Rightarrow$
  Need for:
  - Improved System Dynamics
  - Improved System’s Imaging Capabilities

- Future Needs (EUVL)

“What you can not measure, you can not make, nor control”
Good System Dynamics
Even better System Dynamics
Improved System’s Imaging Capabilities

– Lower $k_1$:
  - Resolution enhancement techniques
  - Optics utilization improvement
  - Process improvement

system = scanner + reticle + process (+ SEM/ELM....)
The Status and Future of Imaging Metrology Needs for Lithography.

- Illumination enhancement techniques:
  - Off-axis illumination

- Optimal use of Projection Optics
  - Case Study $L_1$-$L_2$
  - Aberration measurements
  - Lithographic Correlation and Aberration control

- Reticles:
  - Optical Proximity Correction
  - Phase shifting mask
  - Reticle quality

- Process improvement

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Illumination enhancement techniques

(a) Two Huygen sources formed at S1 and S2

(b) More “isolated” S1 and S2

(c) “Densely” packed S1 and S2

Observations:

1) Diffraction patterns are not the same from dense to isolated

2) Lens act as “low-pass” filter, only lower diffraction order light beams can get through lens
Illumination enhancement techniques
Off-axis illumination (OAI)

220 nm
180 nm
150 nm

150 nm

Annular
Quasar
Dipole
Illumination enhancement techniques

OAI and Normalized Image Log Slope

\[ k_1 = CD \times \frac{NA}{\lambda} \]

“normalized CD”

NA = 0.7 \( \lambda = 248 \text{ nm} \)

simulation for L/S (1:1)

\( \sigma = 0.85 \) (conv.)

\( \sigma_0 = 0.85 \)

\( \sigma_i = 0.55 \) (ann, QUASAR)
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Optimal use of Projection Optics

Case study $L_1 L_5$

Target $0.180 \mu m$

$0.170 \mu m$

$0.190 \mu m$
Optimal use of Projection Optics

Case study $L_1L_5$

- Understanding $L_1$-$L_5$
  - Measured and calculated
  - two feature orientations
  - correlation 85%

Sample point
Optimal use of Projection Optics

Case study L₁L₅

- Correlation with coma aberration:
Optimal use of Projection Optics
Case study L₁L₅

\[ \Delta \Phi = |Q Q'| \]

Real Wave front

Gaussian reference sphere

Coma = 13 nm: \( \Delta \phi = (n-1)d \), \( d = 26 \text{ nm} \) on a track length of 1 meter, distributed over 50 to 60 surfaces.
Optimal use of Projection Optics

Aberration levels

- Quality in RMS wavefront aberration (Progler, 1998)
  - Gold: 0.025 λ (6.2 nm for 248 nm)
  - Silver: 0.04 λ
  - Bronze: 0.06 λ

Set a target at 5% CD change due to aberration

- Extract the RMS aberration level that results from the target
- Define an aberration sensitivity parameter as SA=RMS-1

More accurate description needed: Zernike fringe polynomials

Zeiss makes ‘golden’ lenses
Optimal use of Projection Optics

Aberration levels

Relative Performance

Starlith™ 500
Starlith™ 550
Starlith™ 700
Starlith™ 750

Zernike coefficients
Wavefront RMS
Focal Plane Deviation (integrated)
Astigmatism (integrated)
Distortion (integrated)
Optimal use of Projection Optics

Zernike Fringe Polynomials

\[ W(\rho, \theta) = \sum_{l,m} Z_l^m R_l^m e^{im\theta} \]

\( Z_n \): Zernike coefficients
Optimal use of Projection Optics
Aberration measurements

- All lens manufacturers use phase measuring interferometry (PMI) during manufacturing.

- In situ by sampling the pupil
  - Select angles (Litel)
  - Use structures with different diffraction patterns
  - Use Multiple Illumination Settings (NA/s)
    - Quick and extension on established methods: FAMIS/DAMIS
    - Full lens qualification: Artemis
Optimal use of Projection Optics

Aberration measurements At Multiple Illumination Settings

- **FAMIS: Focal At Multiple Illumination Settings**
  - Best Focus changes due to spherical aberration: $Z_4, Z_9, Z_{16}, \ldots$
  - Sensitivity depends on $\frac{\text{NA}}{\sigma}$ and can be calculated
  - Solve linear matrix equation:

\[
\begin{bmatrix}
BF_{\text{meas}}(1) \\
BF_{\text{meas}}(2) \\
\vdots \\
BF_{\text{meas}}(n)
\end{bmatrix}
= Z_4 \cdot \begin{bmatrix} 1 \\ 1 \end{bmatrix} + Z_9 \cdot \begin{bmatrix} BF_{\text{sim@1nm}}(1) \\
BF_{\text{sim@1nm}}(2) \\
\vdots \\
BF_{\text{sim@1nm}}(n)\end{bmatrix} + Z_{16} \cdot \begin{bmatrix} BF_{\text{sim@1nm}}(1) \\
BF_{\text{sim@1nm}}(2) \\
\vdots \\
BF_{\text{sim@1nm}}(n)\end{bmatrix}
\]

- **Generalized:** $C = W \cdot Z$
Optimal use of Projection Optics

Aberration measurements at Multiple Illumination Settings

- **Famis:**
  - Spherical aberration,
  - Astigmatise: $Z_{9,16}, Z_{12,21}$

- **Damis:** Distortion at MIS
  - Coma: $Z_{7,8}, Z_{14,15}$

- **Artemis:** ART at MIS (Philips)
  - Full set, $Z_{5-37}$,

- **Artemis:** Prints a phase dot

- **MIS** allows separation of radial terms

- **Deformation is written as a Fourier series.**

- **Order of Fourier components correspond to angular Zernike coefficients**

- **ASML**
Optimal use of Projection Optics

Lithographic Correlation and Aberration control

- Controlling Iso-dense bias
  - Related to Spherical Aberration, measurable with FAMIS
  - Process optimization reduces Iso-dense bias

![Graph showing Iso-Dense bias and Zernike Z9 relationship](image)
Optimal use of Projection Optics

Lithographic Correlation and Aberration control

- Controlling $L_1L_2$
  - Caused by coma, measurable by DAMIS
  - Wavelength shift reduced coma
  - $L_1L_2$ reduced from 50 to 10 nm
Optimal use of Projection Optics

Lithographic Correlation and Aberration control

- Isolation properties of DRAM cells at $k_1 = 0.37$
  - C-D is critical metric, Threewave and coma sensitive
  - Predicted performance of a ‘golden’ lens
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“What you can not measure, you can not make, nor control”
Reticles

Resolution Enhancement Techniques

Masks

Mask Type

Structure(s)

Challenges

Binary or Chrome on Glass

Low k1 Imaging

OPC & Assist Features

Writing, Inspection

Half Tone or Attenuated PSM

Material, Repair

Levenson or Alternating PSM

CoO, Phase errors, inspection & repair

Imaging 28
version 2.0
Joost Sytsma / ULSI Characterization and Metrology 2000
Reticles

Optical Proximity Correction

Scatter Bars

Serifs

Scatter Bars

Serifs

Scatter Bars
Reticles

Phase Shifting Masks

Binary Mask

Quartz

Chrome

Multi-Phase Shift Mask

Quartz

Etched Quartz

Chrome
### Reticles

#### Quality: CD-uniformity

<table>
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<tr>
<th>Feature</th>
<th>Setting</th>
<th>CD-uniformity [3σ, nm]</th>
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<tbody>
<tr>
<td></td>
<td>@BF</td>
<td>MEF</td>
</tr>
<tr>
<td>180nm DL</td>
<td>NA=0.60</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>σ=0.70/0.40</td>
<td></td>
</tr>
<tr>
<td>180nm iso</td>
<td>NA=0.56</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>σ=0.60/0.30</td>
<td></td>
</tr>
<tr>
<td>150nm DL</td>
<td>NA=0.66</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>σ=0.75/0.45</td>
<td></td>
</tr>
<tr>
<td>150nm DL*</td>
<td>NA=0.70</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>σ=0.85/0.55</td>
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</tr>
<tr>
<td>150nm iso</td>
<td>NA=0.62</td>
<td>11</td>
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<tr>
<td></td>
<td>σ=0.85/0.55</td>
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* Quadrupole

20 points per field, 2 orientations
Averaged over 6 dies
AMAT 7830SI CD-SEM
Reticles

Why is MEF ≠ 1?

- Lower Aerial Image Contrast -> Higher MEF
- Position of Resist Threshold strongly affects MEF
Acknowledgements

- Projection Lenses group, especially Hans van der Laan, Marco Moers, Rob Willekers

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- Christian Wagner of Carl Zeiss

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