High-NA EUV Lithography Exposure Tool
For EUV roadmap extension

ASML Veldhoven, The Netherlands
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Carl Zeiss SMT GmbH, Oberkochen, Germany
Paul Graeupner

22 January 2021, EUV-FEL Workshop, Japan / Cloud
### EUV product roadmap

#### EUV

<table>
<thead>
<tr>
<th>Year</th>
<th>NA</th>
<th>Pitch</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>0.33</td>
<td>13 nm</td>
<td>135 wph / 145 wph³</td>
</tr>
<tr>
<td>2021</td>
<td>0.33</td>
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<td>2025</td>
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</tbody>
</table>

1) 185wph@20mJ/cm² / 150wph@30mJ/cm²
2) 170wph@20mJ/cm²
3) Throughput upgrade

#### Throughput upgrade

<table>
<thead>
<tr>
<th>Product</th>
<th>Matched Machine Overlay (nm)</th>
<th>Throughput (wph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NXE:3600D</td>
<td>1.1 nm</td>
<td>160 wph</td>
</tr>
<tr>
<td>NEXT</td>
<td>&lt;1.1 nm</td>
<td>&gt;220 wph</td>
</tr>
</tbody>
</table>

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0.55NA enabling affordable scaling beyond current decade

0.33NA continuous imaging, overlay and productivity improvements in line with customers advanced node HVM requirements.
NXE productivity reached 170 wafers per hour
Productivity at higher exposure dose continues to increase

ATP test: 26x33mm², 96 fields, 20mJ/cm² / 30mJ/cm²
EUV collector transmission degradation meeting target
Average degradation rate 0.1%/GP on NXE:3400B/C

- NXE:3300B
  - Degradation rate [%/GP]: 0.6
  - Power [W]: 80
  - 2015

- NXE:3350B
  - Degradation rate [%/GP]: 0.4
  - Power [W]: 125
  - 2017

- NXE:3400B
  - Degradation rate [%/GP]: 0.15
  - Power [W]: 250
  - 2019

- NXE:3400B/C
  - Degradation rate [%/GP]: 0.1 (average)
  - Power [W]: 250
  - 2020

- NXE:3400C
  - Degradation rate [%/GP]: <0.05

>3x higher source power
>20% increase in average collector transmission
Improved availability due to longer collector lifetime
Wafers exposed on EUV systems grows exponentially

Cumulative wafers exposed on EUV

- Number of NXE:3400x systems shipped (cumulative)

Cumulative wafers exposed on EUV

- Number of NXE:3400x systems shipped (cumulative)

Q1 2019: 31 Mln
Q2 2019: 38 Mln
Q3 2019: 45 Mln
Q4 2019: 53 Mln
Q1 2020: 55 Mln
Q2 2020: 62 Mln
Q3 2020: 76 Mln
Q4 2020: 85 Mln

26 Mln

4 Mln

Public
Customer flagship products are powered by EUV

Outline

High-NA agenda
  • Why High-NA
  • Infrastructure
  • Architecture
  • High-NA manufacturing

Summary
Over 35 years 2 orders of magnitude resolution reduction by working on Wavelength, NA and $k_1$

$$CD = k_1 \frac{\lambda}{NA}$$

Resolution, nm

Wavelength, nm

- 436 g-line
- 365 i-line
- 248 KrF
- 193 ArF and Immersion

Over 35 years 2 orders of magnitude resolution reduction by working on Wavelength, NA and $k_1$
EXE platform to further enable affordable shrink (3 nm Logic)
Total patterning cost comparison: immersion, NXE, EXE

Source: Jan van Schoot et al. (ASML) ‘High-NA EUV lithography exposure tool progress’ SPIE 2019
High-NA contrast reduces Local CDU
key to continue Moore’s law: Resist, Dose, Contrast

\[ LCDU = 3 \cdot \sqrt{\frac{hv}{f \cdot \alpha \cdot \text{Area}}} \cdot \sqrt{\frac{1}{D_{\text{size}}}} \cdot \frac{2}{\text{ILS}} \]

Whereby:
- \( \sigma \) = resist blur
- \( D_{\text{size}} \) = dose to size
- ILS = image log slope
- \( p \) = pitch

• Minimize Local variation by
  - Improved resist: absorption ↑, blur ↓, chemical shot noise ↓
  - Maximize contrast: high-NA, advanced mask

EUV comes with less photons/J

<table>
<thead>
<tr>
<th>Resist (blur/chemistry)</th>
<th>Dose</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>10nm CH, 20mJ/cm² → 1000 photons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30% absorption → 300 photons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30% determines the edge → 100 photons</td>
<td></td>
<td></td>
</tr>
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</table>
High-NA contrast reduces Local CDU and defects
Key to continue Moore’s law: Resist, Dose, Contrast

\[ \text{LCDU} [3\sigma, \text{nm}] = 3 \cdot \frac{hv}{\sqrt{f \cdot \alpha \cdot \text{Area}}} \cdot \sqrt{\frac{1}{D_{\text{size}}}} \cdot \frac{2}{\text{ILS}} \]

Whereby:
- \( \alpha \) = resist absorption
- \( f \) = proportionality factor with, eg, QE
- \( D_{\text{size}} \) = dose to size
- \( \text{ILS} \) = image log slope
- \( \text{Area} \) = area containing photons contributing to LCDU

**High-NA: smaller CH’s at same dose**

- 1:1 CH Ta Mask
- MOR Annular scaled
- 45 mJ/cm²

**20nm 1:1 Contact Holes**

- Edge photons and contrast determine hole size variability
- Center photons open developer path to bottom “pipe cleaners”
- High-NA improves both aspects
20nm CH’s: Defects down by several orders
Impact of High-NA 2: more center photons

Gijsbert Rispens, SPIE AL (2020)

~ 2x photons

+ 10% photons ~ 1 order less defects
De Bisschop, JM3 (2018)
14nm CH’s: 0.55NA/SE expected to be better than 0.33NA/DE

Based on aerial images

**0.33 NA**
Double Expose

**0.55 NA**
Single Expose

Slope 1.35x and local photons 1.4x

Prediction: LCDU and defectivity better despite SE at smaller resolution
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  • High-NA manufacturing

Summary
Continuous resist improvement for multiple use cases
Progress is needed moving forward

<table>
<thead>
<tr>
<th>Resist type¹</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
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<tbody>
<tr>
<td>Non-CAR</td>
<td>57</td>
<td>45</td>
<td>39</td>
</tr>
<tr>
<td>LWR unb [nm]</td>
<td>3.1</td>
<td>3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Z-factor [10⁻⁶ mJ nm³]</td>
<td>1.2</td>
<td>0.9</td>
<td>0.7</td>
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Resolution: (P26 Lines and Spaces)

<table>
<thead>
<tr>
<th>Dose [mJ/cm²]</th>
<th>66</th>
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<th>53</th>
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<td>2.5</td>
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Resolution: (P40 Hexagonal Pillars/CH)

Lines and Spaces

Contact Holes

\[ Z\text{-factor} = \text{Res}^3 \times \text{LWR}^2 \times \text{Dose} \]

Z-factor comparison only valid at equal contrast

¹Resist system: CAR Chemical Amplified resist
Continuous resist improvement for multiple use cases
Progress is needed moving forward

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<td>2020</td>
<td>CAR</td>
<td>53</td>
<td>2.1</td>
<td>1.9</td>
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**HP12nm Lines and Spaces**

- **Non-CAR**
  - Dose [mJ/cm²]: 57
  - LWR [nm]: 3.1
  - Z-factor [10⁶mJ nm³]: 1.2

- **CAR**
  - Dose [mJ/cm²]: 66
  - LWR [nm]: 3.0
  - Z-factor [10⁶mJ nm³]: 0.9

**Resolution:**

- Non-CAR: (P26 Lines and Spaces)
- CAR: (P40 Hexagonal Pillars/CH)

**Z-factor comparison only valid at equal contrast**
<table>
<thead>
<tr>
<th>Resolution [hp]</th>
<th>13nm</th>
<th>12nm</th>
<th>11nm</th>
<th>10nm</th>
<th>9nm</th>
<th>8nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganic Resist</td>
<td>62 mJ/cm²</td>
<td>58 mJ/cm²</td>
<td>75 mJ/cm²</td>
<td>59 mJ/cm²</td>
<td>82 mJ/cm²</td>
<td></td>
</tr>
<tr>
<td>Chemically Amplified Resist (CAR)</td>
<td>58 mJ/cm²</td>
<td>52 mJ/cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resolution [hp]</th>
<th>24nm</th>
<th>22nm</th>
<th>20nm</th>
<th>18nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganic Resist</td>
<td>22 mJ/cm²</td>
<td>19 mJ/cm²</td>
<td>33 mJ/cm²</td>
<td></td>
</tr>
<tr>
<td>Chemically Amplified Resist (CAR)</td>
<td>16 mJ/cm²</td>
<td>17 mJ/cm²</td>
<td>21 mJ/cm²</td>
<td></td>
</tr>
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Ongoing imaging benchmarking of High-NA tools (PSI, BMET5, NXE)

Reference:
Contrast-loss investigation for the characterization of resist and exposure tool performances Timothée Allenet, SPIE-AL, 11517-16
CXRO/LBNL shows resist capability for Lines and Pillars

<table>
<thead>
<tr>
<th>Resist &amp; Feature</th>
<th>Illumination</th>
<th>Resolution (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inpria Resist Lines</td>
<td>F2X frequency doubling</td>
<td>11nm 10nm 9nm 8nm</td>
</tr>
<tr>
<td>and Spaces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inpria Resist</td>
<td>F2X frequency doubling</td>
<td>13nm 12nm 11nm 8nm</td>
</tr>
<tr>
<td>Regular Pillars</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inpria Resist Tip-2-Tips</td>
<td>SMO</td>
<td>14P28 14P35</td>
</tr>
<tr>
<td>Lines and Spaces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAR Lines and Spaces</td>
<td>MP</td>
<td>13nm 12nm</td>
</tr>
</tbody>
</table>

C. Anderson et al., CXRO, SPIE 2020
Outline

High-NA agenda
• Why High-NA
• Infrastructure
• Architecture
• High-NA manufacturing

Summary
High-NA system architecture finalized

- **Lens & illuminator**
  - NA 0.55 for high contrast
  - High transmission

- **Mask Stage**
  - 4x increase in acceleration

- **Improved Source position**
  - Allows for larger transmission, compatible with 0.33 NA

- **Wafer Stage**
  - 2x increase in acceleration

- **Mask Stage**
  - 4x increase in acceleration

- **New Frames**
  - Improved thermal and dynamic control with larger optics

- **Improved metrology**
  - 2~3x improvement in overlay/focus
EUV High-NA requires an anamorphic lens

Note: for simplicity M3D effects are ignored, only multi-layer effect taken into account.
High-NA brings throughput >185 wph
Fast stages enable high throughput

Acceleration of mask stage ~4x

Acceleration of wafer stage ~2x

Throughput for various source powers and doses

Source Power/Dose [W/(mJ/cm²)]

Throughput [300/hr]

0 5 10 15 20 25 30 35

0 20 40 60 80 100 120 140 160 180 200

High-NA

0.33NA

WS, RS current performance

WS 2x, RS 4x

300W Watt 20mJ/cm²
Recent EUV power improvement allows higher dose
Servicing concept for high-NA identical to 0.33NA source

Continuous source improvements:
- Allow for more throughput
- Allow for more dose
  - Improved Local CDU

Modularity of the vessel reduces repair times

<table>
<thead>
<tr>
<th>Year</th>
<th>Source power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>100</td>
</tr>
<tr>
<td>2012</td>
<td>200</td>
</tr>
<tr>
<td>2014</td>
<td>300</td>
</tr>
<tr>
<td>2016</td>
<td>400</td>
</tr>
<tr>
<td>2018</td>
<td>500</td>
</tr>
<tr>
<td>2020</td>
<td>Future target</td>
</tr>
<tr>
<td>2022</td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td></td>
</tr>
</tbody>
</table>
High-NA projection optics design available
Larger elements with tighter specifications

Extreme aspheres enabling further improved wavefront / imaging performance

Obscuration enables higher optics Transmission

Big last mirror driven by High-NA

High NA optics design supports significant reduction in wavefront RMS

Design examples

NA 0.33

NA 0.55
Full wafer and tool-to-tool CD control well below 10% CD
Balanced performance budgets for many different use-cases and pupils
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Summary
Top Module Shift-in Shift-out test successful
18 tons moves at mm-level accuracy
Reticile stage short stroke module manufacturing progressing

- Manufacturing of cooling channels
- Finalized bottom plate
- First Reticle Stage short stroke
Long stroke motor mask stage risk build-down

Moving at NXE:3400 profile

Moving at EXE:5000 profile (4x)

Model verification

- modeled
- measured
Wafer stage cable slab guiding concept in test
Dynamical testing ok

Slab test Y-axes  Slab test X-axes  Crash test
Wafer stage modules being manufactured

- Wafer stage design ready
- Wafer stage position module manufactured
- Proto Actuator Coils for testing
- Mirror block manufacturing started
First images taken with High-NA ILIAS proto sensor
New ILIAS-sensor with improved marks for High-NA

High-NA ILIAS proto sensor installed in NXE:3400 WS

First image

First aberration scan results (@ 0.33NA)
Good progress with EXE frame development
Large frames modeled, improved welding

Traditional welding:
4 weeks / frame

Robotized E-beam welding:
3 days / frame

Ensure impact of Main Frame on POB in spec
Bottom Base Frame manufacturing has started

- Sub blocks pre-machined
- Welded to one piece with Electron Beam welding
- After welding the total frame is fine machined on large milling center
- Final machining planned later this year
Phase 1 (May 2020):
top frame mono rough machining

Above is a picture of the first top frame being prepped for rough machining.
First mirror ground
At this moment many more mirror in manufacturing
EXE:5000 mirror metrology is operational
Measuring a 1000kg anamorphic mirror with picometer accuracy
Mirror Metrology results

1st crosscheck with known NXE:3400 mirror

High-NA metrology

3400 metrology

difference

High-NA mirror

1st polishing loop

Part corrected during 1st polishing loop

12.4 nm RMS (w/o Z1-Z4)
Reproducibility tests
Air turbulences successfully eliminated by transition to vacuum

Further improve dynamics effects by

- Better mounting
- Rigid body movement correction
- Optimizing exposure time and number of images
EXE:5000 system global design completed
Solid progress on system design and optics development and – manufacturing

- Mirror manufacturing started
- Zeiss Oberkochen
  - Full-scale High-NA mirror ready for polishing
- CZO facility
- Building the optics assembly hall
- High-NA optics metrology equipment in cleanroom at Zeiss SMT
High-Na cleanroom constructions in progress

Wilton

Veldhoven

5000 Expansion

Wilton Factory EXE:5000 Addition

Current state

High-NA Cabins to be delivered according plan
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Summary
Summary

**EUV 0.33NA is used in volume production, adoption continues to grow**
- Adoption continues to grow to reduce patterning complexity and cost
- Used for 7nm and 5nm Logic nodes, 10nm-class DRAM
- Productivity is improving to beyond 3000 WpD capability

**High-NA is logical roadmap extension by improving contrast**
- LCDU and defect print rate reduced by improved contrast, dose and resist
- Contrast is improved by a new anamorphic lens; imaging well controlled
- Throughput at higher dose maintained by transmission and source power

**High-NA EUV Scanner realization is in full progress**
- Feasibility of stages, sensors and many more demonstrated
- System design available, manufacturing of modules ongoing
- Optics design finalized, mirror metrology in place, manufacturing has started
EUV 0.33NA is used in volume production, adoption continues to grow
• Adoption continues to grow to reduce patterning complexity and cost
• Used for 7nm and 5nm Logic nodes, 10nm-class DRAM
• Productivity is improved to reduce pattering complexity and cost

High-NA is logical roadmap extension by improving contrast
• LCDU and defect print rate reduced by improved contrast, dose and resist
• Contrast is improved by improved optical and dose control; well controlled

High contrast puts the photons where you need them

High-NA EUV Scanner realization is in full progress
• Feasibility of stages, sensors and many more demonstrated
• System design available, manufacturing of modules ongoing
• Optics design finalized, mirror metrology in place, manufacturing has started
Thank you for your attention

Special thanks goes to:
- Jara Garcia Santaclara
- Joost van Bree
- Gunes Nakiboglu
- Pieter de Groot
- Jason Steward
- Joost van Bree
- Chrysostomos Batistakis
- Bernardo Oyarzun
- Michael Renders
- Rob van Balleghijn
- Claire van Lare
- Rik Hoefnagels
- Lidia van Lent
- Zuhal Tasdemir, PSI
- Patrick Naulleau, CXRO
- Chris Anderson, CXRO
- Bram Slachter
- Gijsbert Rispens
- Gerardo Bottiglieri
- Jeannot Driedonkx

And the High-NA teams in Wilton, San Diego, Oberkochen, and Veldhoven

This work was funded by the European Commission and the Federal Ministry of Education and Research (Germany) by the ECSEL JU Grant Agreement SeNaTe (662338, FKz 16ESE0036K), TAKE5 (692522, FKz 16ESE0072K), TakeMi5 (737479), and TAPES3 (783247, FKz 16ESE0287K).