Outline

• NXE3300 and NXE3350B progress and status
  • Roadmap, Layout, Performance
  • Imaging, Overlay, Defectivity
  • EUV pellicle status
• EUV source architecture and performance
• EUV source power scaling
  • EUV LPP technologies
  • Pre-pulse technology
  • EUV source drive laser
  • Droplet generator: performance, availability
  • Collector: protection, lifetime
• Summary
EUV technology roadmap, source architecture and performance
NXE extension roadmap to optimize capital efficiency

<table>
<thead>
<tr>
<th>Logic</th>
<th>DRAM</th>
<th>55 WpH</th>
<th>125 WpH</th>
<th>145 WpH</th>
<th>185 WpH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><em>NXE:3300B</em></td>
<td><em>NXE:3350B</em></td>
<td><em>NXE:3400B</em></td>
<td><em>NXE:3450C</em></td>
</tr>
<tr>
<td>2013</td>
<td>R&amp;D</td>
<td>250W LPP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>D1H</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>D1M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td>3.x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>2~2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Products under study:
- High NA
- 500W source
- Anamorphic lens
- Stages, handlers

Specifications:
- **Half pitch**
  - 55 WpH: 22 nm, 110 nm, 3.0/5.0 nm, 7.0 nm
  - 125 WpH: 16 nm, 70 nm, 1.5/2.5 nm, 3.5 nm
  - 145 WpH: 13 nm, 60 nm, 1.4/<2.0 nm, 2.5 nm
  - 185 WpH: 13 nm, 50 nm, 1.2/<1.7 nm, 2.0 nm
- **Focus**
  - 55 WpH: 7.0 nm
  - 125 WpH: 2.5 nm
  - 145 WpH: 7.0 nm
  - 185 WpH: <8 nm
- **DCO/MMO**
  - 55 WpH: 1.4/<2.0 nm
  - 125 WpH: 1.0/<1.4 nm
  - 145 WpH: 1.5/2.5 nm
  - 185 WpH: <40 nm
- **OPO**
  - 55 WpH: 110 nm
  - 125 WpH: 60 nm
  - 145 WpH: 50 nm
  - 185 WpH: 50 nm
NXE:3350B: 2x overlay improvement at 16nm resolution
Supporting 7nm logic, ~15nm DRAM requirements

- Overlay set up: Set-up and modeling improvements
- Reticle Stage: Better thermal control, increased servo bandwidth
- Projection Optics: Higher lens transmission, improved aberrations and distortion
- SMASH sensor: Improved alignment sensor
- Spotless NXE: Automated wafer table cleaning
- New UV level sensor
- Improved air mounts
- Off-Axis Illuminator FlexPupil
- Wafer Stage: Improved thermal control
- Resolution: 16nm
  - Full wafer CDU: ≤ 1.3nm
  - DCO: ≤ 1.5nm
  - MMO: ≤ 2.5nm
  - Focus control: ≤ 70nm
- Productivity: ≥ 125 WPH
Productivity, Availability, Source Power
>405k wafers exposed on NXE:3300B at customer sites

Currently 8 systems running in the field
Demonstrated 85 WPH on NXE:3350B
Achieved with 125W configuration

NXE:3300B at customers

Wafers per hour

2014 Q1 2014 Q2 2014 Q3 2014 Q4

NXE:3350B at customers

NXE:3350B ATP test: 26x33mm², 96 fields, 20mJ/cm²
NXE:3350B: 125W settings qualified being implemented at the customer

Mean pulse energy at Intermediate Focus ~3mJ

EUV power at Intermediate Focus 125W

Energy control Overhead ~20%
Progress in source power supporting productivity roadmap to >125 WPH

- 3100 NOMO (delivered)
- 3100 MOPA (not shipped)
- 3100 MOPA+PP (not shipped)
- 3300 MOPA+PP (delivered)
- 3400 MOPA+PP (development)

210W with dose in specifications obtained on development source

CE~5.5%
Three customer systems have achieved 80% availability.

*Best four-week average on systems in 80W configuration*

- System A: 76%
- System B: 85%
- System C: 85%
- System D: 75%
- System E: 83%

Uptime = productive time + standby time + engineering time

SD: Scheduled down • USD: Unscheduled down

+X% indicates change from Q4 2015
NXE:3300B multiple customers exposed >1,000 WPD;
NXE:3350B exposed 1,368 WPD at ASML factory

- **Best single day results**
  - NXE:3300B at customers
  - NXE:3350B at ASML factory

- **Best full week result**
  - NXE:3350B at ASML factory

- **Productivity [WPD]**
  - WPD: maximum number of wafers exposed in a 24 hour period
  - Each bar represents an individual system

- **Best single day results**
  - NXE:3350B with S2 source config. at ~80W EUV power.
  - TPT job: 26x33mm field @ 20 mJ/cm², full wafer coverage (96 fields)
Source power, availability, productivity summary

**Source power**

- 80W configuration rolled out to customer sites, 125W configuration qualified
- 210W of dose-controlled EUV power demonstrated at ASML

**Availability**

- Three customer systems achieved more than 80% average availability over four weeks
- While overall average availability has increased, consistency still needs to be further improved

**Productivity**

- More than 1000 wafers per day exposed on NXE:3300B at customer sites, further improved to more than 1,350 wafers per day on NXE:3350B at ASML
- In a manufacturing readiness tests at a customer site an average of 800 wafers per day over two weeks was achieved
EUV single exposure replaces immersion multiple patterning

2D-Metal at **32nm pitch** achieved with Quasar illumination

**ArFi LE^3**
(triple patterning)

EUV Single Exposure

**32nm pitch / 16nm CD**

**48nm pitch / 24nm CD**

Dose: 20 mJ/cm^2

In cooperation with IMEC
NXE:3350B imaging: 16nm dense lines and 20nm iso space consistently achieve <1.0nm Full Wafer CDU

Tested with new ATP – 0mm field spacing and 15x9 grid
Progress resist materials: towards 16nm resolution at 125 WPH
19% EL, 4.4nm LWR @18.5mJ/cm². Also 13nm resolved with 17% EL and 4.2nm LWR @31mJ/cm²

<table>
<thead>
<tr>
<th>NXE:3350B</th>
<th>16nm Horizontal Dense lines/spaces</th>
<th>13nm Horizontal Dense lines/spaces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference CAR</td>
<td>New formulation CAR</td>
</tr>
<tr>
<td>SEM image @BE/BF</td>
<td><img src="image" alt="SEM image" /></td>
<td><img src="image" alt="SEM image" /></td>
</tr>
<tr>
<td>Dose</td>
<td>40 mJ/cm²</td>
<td>25 mJ/cm²</td>
</tr>
<tr>
<td>Exposure Latitude</td>
<td>16 %</td>
<td>16 %</td>
</tr>
<tr>
<td>DoF</td>
<td>145 nm</td>
<td>100 nm</td>
</tr>
<tr>
<td>LWR</td>
<td>4.6 nm</td>
<td>5.2 nm</td>
</tr>
</tbody>
</table>

LWR = Line Width Roughness  
DoF = Depth of Focus  
EL = Exposure Latitude  
CAR = Chemically Amplified Resist  
BE/BF = Best Energy/Best Focus
NXE:3350B **overlay** and **focus** performance

*Well in specification due to HW improvement and new calibrations*

Dedicated chuck overlay [nm]

Matched machine overlay [nm]

Focus uniformity [nm]
NXE:3350B matched machine overlay with NXT:1980Di <2.8nm

Lot (x: 2.8nm, y: 2.5nm)

Overlay 99.7% (nm)

Wafer number

0 1 2 3 4 5 6

10 nm

99.7%
x: 2.8 nm
y: 2.5 nm
Front-side reticle defectivity: 10x reduction/year realized

Key improvements

Optimization of flow around reticle stage using new hardware

Optimized maintenance sequence to flush out particles
Imaging, overlay, focus, defectivity summary

Status April 2016

**Imaging**

- NXE:3350B imaging and overlay results for 7nm Logic are good
- 16 nm dense lines and 20 nm iso space consistently achieve full-wafer CDU below 1 nm

**Overlay and focus**

- NXE:3350B: 2x overlay improvement over NXE:3300B
- Matched-machine overlay below 2.5 nm, focus uniformity below 10 nm

**Defectivity**

- Front-side reticle defectivity: 10x reduction/year realized
Pellicle film must simultaneously fulfill all key requirements

Polycrystalline silicon based films meet the key requirements

**Pellicle robustness**

- Chemical resistance (EUV+H₂)
- Thermal resistance
- Mechanical compatibility

**Scanner (imaging) performance**

- Defect free
- Low transmission nonuniformity
- High transmission
NXE Pellicles are being mounted and used in scanners

Prototype pellicle on early integration mounting tooling
Pellicle technology: durability proven to at least 125 W

Heat load test results

<table>
<thead>
<tr>
<th>Film stack</th>
<th>Equivalent source power</th>
<th>Sample survivability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>40 W</td>
<td>9/9</td>
</tr>
<tr>
<td>Uncoated</td>
<td>125 W</td>
<td>3/5</td>
</tr>
<tr>
<td>Coated</td>
<td>125 W</td>
<td>33/33</td>
</tr>
</tbody>
</table>

ASML pellicle integration Work Center at our Veldhoven production facilities

* Duration of tests: equivalent with exposure of 1000 wafers
EUV source power scaling
EUV Source Architecture, Sn LPP MOPA with Pre-pulse

Collector
Laser Metrology, MP PP Focusing
Collector
Tin catch
Vaness
Intermediate Focus Unit
Scanner
metrology for source to scanner alignment
Beam Transport
High Power Amplification Chain
On-droplet Gain Optimization
Source Pedestal
Fab Floor
Scanner Pedestal
High Power Seed System
CO2 system
Power Amplifiers
PP&MP Seed unit
Laser / EUV dose Controls
Sub-fab Floor
EUV LPP Source Key Technologies

1. Optics Protection (Debris Management)
   - Collector protection by gas flow
   - In-situ collector cleaning
   - Collector capping layers
   **Availability / CoO**

2. Targeting Dynamics
   - Target conditioning
   - Focus Control
   - x,y,z, E & t control
   **Dose Control / Yield**

3. CO₂ Laser Power
   - High power drive laser
4. Conversion Efficiency
   - Prepulse

**EUV Power / Throughput**
Source power and availability drive productivity

Technology development work is ongoing to improve all aspects

Productivity = Throughput(\(\propto\) EUV Power) \times Availability

EUV Power = \((\text{CO}_2 \text{ laser power} \times \text{CE} \times \text{transmission}) \times (1 - \text{dose overhead})\)

<table>
<thead>
<tr>
<th>Source power</th>
<th>Drive laser power</th>
<th>from 20 to 40 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>from 10 W to &gt; 250 W</strong></td>
<td>Conversion efficiency (CE)</td>
<td>from 1 to 6%</td>
</tr>
<tr>
<td></td>
<td>Dose margin</td>
<td>from 50 to 10%</td>
</tr>
<tr>
<td></td>
<td>Optical transmission</td>
<td></td>
</tr>
<tr>
<td>Source availability</td>
<td>Automation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Collector protection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Droplet generator reliability &amp; lifetime</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drive laser reliability</td>
<td></td>
</tr>
</tbody>
</table>

Raw EUV power
EUV power scaling through 2016

EUV power ~ CO$_2$ power * Conversion Efficiency * (1-Dose Overhead)

- NOMO and NXE:3100 drive laser
- MOPA+PP and NXE:3100 drive laser
- MOPA+PP and NXE:3300B Drive Laser
- MOPA+PP High Power Amplification Chain

Conversion Efficiency (CE) values:
- CE=0.8%
- CE=2.5%
- CE=3.5%
- CE=5.5%

Power levels:
- Laser Power (kW): 8kW, 12kW, 15kW, 20kW
- EUV Power (W): 10W, 50W, 100W, 210W
- Dose Overhead (%): 45%, 30%, 17%, 10%
Pre-pulse technology
Conversion efficiency: Optimizing pre-pulse to create a more efficient target

Target expansion fills main pulse beam waist

Droplet Trajectory

Prepulse (low energy)

Mainpulse (high energy)

Target shape changes from droplet to disk
Increased conversion efficiency with Pre-pulse

by optimization of target size, shape and density

EUV CE ~6% demonstrated on development platforms
Plasma scale length \((Z)\) is the key to increase its volume

*Volume-distributed laser absorption enhances \(CO_2\) laser deposition in plasma*

Schematic diagram of traditional LPP

Hydrodynamic simulation of \(CO_2\) Sn LPP

SPIE 2016, 97760K-1, Michael Purvis

“Advances in predictive plasma formation modelling”
EUV Source, Drive Laser Development Progress
CO\textsubscript{2} laser power scaling to scale EUV power

Efficient CO\textsubscript{2} laser pulse amplification

<table>
<thead>
<tr>
<th>Throughput, WPH</th>
<th>125</th>
<th>145</th>
<th>185</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUV power (W)</td>
<td>250</td>
<td>350</td>
<td>500</td>
</tr>
<tr>
<td>CO\textsubscript{2} laser power (kW)</td>
<td>27</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

3300 CO\textsubscript{2} drive laser
CO₂ drive laser power scaling

Key technologies:
1. Drive laser with higher power capacity
2. Gain distribution inside amplification chain
3. Mode-matching during beam propagation
4. Isolation between amplifiers
5. Metrology and automation
Droplet Generator, Principle of Operation

- Tin is loaded in a vessel & heated above melting point
- Pressure applied by an inert gas
- Tin flows through a filter prior to the nozzle
- Tin jet is modulated by mechanical vibrations

**Fig. 1.** Images of tin droplets obtained with a 5.5 μm nozzle. The images on the left were obtained in frequency modulation regime; the image on the right – with a simple sine wave signal. The images were taken at 300 mm distance from the nozzle.

Short term droplet position stability $\sigma \sim 1 \mu m$
Forces on Droplets during EUV Generation

High EUV power at high repetition rates drives requirements for higher speed droplets with large space between droplets.

Measured
Angular dependence of Forces on the droplets

Function fit: Force $\sim$ EUVn $\times A \times (1 + \cos\theta + B) / R^2$
High Speed Droplet Generation

<table>
<thead>
<tr>
<th>Pressure (Speed)</th>
<th>Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 MPa</td>
<td>26</td>
</tr>
<tr>
<td>6.9 MPa</td>
<td>40</td>
</tr>
<tr>
<td>13.8 MPa</td>
<td>58</td>
</tr>
<tr>
<td>27.6 MPa</td>
<td>84</td>
</tr>
<tr>
<td>41.4 MPa</td>
<td>104</td>
</tr>
<tr>
<td>55.2 MPa</td>
<td>121</td>
</tr>
</tbody>
</table>

Tin droplets at 80 kHz and at different applied pressures. Images taken at a distance of 200 mm from the nozzle.
5x improvement in Droplet Generator run time demonstrated

Data based on ASML internal testing; Field qualification started

- Bundle I DGen (field avg.)
- Bundle II DGen (field avg.)
- Bundle III DGen (ASML internal)
- Bundle III DGen (Beta Test)

Runtime [Hours]

Field Droplet Generator still operational >350hrs

Droplet Generator still operational >1000hrs

Run time improvements:
- Field avg. Bundle I: 1000 hrs
- Field avg. Bundle II: 300 hrs
- ASML internal Bundle III: >350 hrs
- Beta test Bundle III: >1000 hrs
EUV Collector: Normal Incidence

- Ellipsoidal design
  - Plasma at first focus
  - Power delivered to exposure tool at second focus (intermediate focus)
- 650 mm diameter
- Collection solid angle: 5 sr
- Average reflectivity: > 40%
- Wavelength matching across the entire collection area

5sr Normal Incidence Graded Multilayer Coated Collector
Collector Protection

- Reaction of H radicals with Sn to form SnH₄, which can be pumped away.
  \[ \text{Sn (s)} + 4\text{H (g)} \rightarrow \text{SnH}_4 \text{ (g)} \]

- Hydrogen buffer gas causes deceleration of ions
- Hydrogen flow away from collector reduces atomic tin deposition rate

- Vessel with vacuum pumping to remove hot gas and tin vapor
- Internal hardware to collect micro particles
Collector Lifetime on NXE:3300 Sources
UP2 configuration operating at 60-80W

- Collector lifetime ~3 months (~80Gp) on sources in the field
- Customer Demo (Q1’16): >100 Gpulse

Transmission loss ~0.5%/Gp
Transmission loss ~0.6%/Gp
250W feasibility proven without increase in protective Hydrogen flow.
No rapid collector contamination, allowing stable droplets and >125 w/hr@20 mJ/cm².
In-situ collector cleaning
Effectiveness of product configuration confirmed

Field collector cleaned in NXE:3300 source vessel test rig

Reflectivity restored within 0.8% of original
Cleaning in off-line MOPA Prepulse development vessel

Off-line cleaning using NXE:3300B source vessel with product configuration hardware
Summary: EUV readiness for volume manufacturing

- 8 NXE:3300B systems operational at customers
- Completed qualification of five NXE:3350B, the 4th generation EUV exposure tool, one system qualified at 75 wph
- Multiple systems demonstrated >1,000 wafers per day capability, with one system exceeding 1,350 wpd
- 80W configuration operational in the field, 125W configuration qualification completed
- 80% source availability capability demonstrated
- Excellent NXE:3350B imaging and overlay performance at >80W power
- Continuous progress in resist formulation promising towards enabling 13nm half pitch at high throughput
Summary

Significant progress in EUV power scaling,
- CE is up to 6 %
- Dose-controlled power is up to 210 W

CO$_2$ developments support EUV power scaling,
- Clean (spatial and temporal) amplification of short CO$_2$ laser pulse
- High power seed-table enables CO$_2$ laser power scaling

Significant progress made in Source Availability
- >80% source availability in the field
- >1000 hrs droplet generator runtime
- >100 Gp collector lifetime
Acknowledgements:

David Brandt, Daniel Brown, Rob Rafac, Alexander Schafgans, Yezheng Tao, Michael Purvis, Alex Ershov, Georgiy Vaschenko, Slava Rokitski, Michael Kats, Daniel Riggs, Wayne Dunstan, Michael Varga, Mathew Abraham, Matthew Graham

Cymer LLC, 17075 Thornmint Ct, San Diego, CA 92127 USA

Rudy Peeters, Daniel Smith, Uwe Stamm, Sjoerd Lok, Arthur Minnaert, Martijn van Noordenburg, Joerg Mallmann, David Ockwell, Henk Meijer, Judon Stoeldraijer, Christian Wagner, Carmen Zoldesi, Eelco van Setten, Jo Finders, Koen de Peuter, Chris de Ruijter, Milos Popadic, Roger Huang, Roderik van Es, Marcel Beckers, Hans Meiling

ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands
Acknowledgements: