EUV Source for Lithography:
Readiness for HVM and Outlook for
Increase in Power and Availability

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ASML Fellow

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Outline

• Background and History
• EUV Lithography with NXE:3400B
• Principles of EUV Generation
• EUV Source: Architecture
• EUV Sources in the Field
• Source Power Outlook
• Summary
Why EUV? - Resolution in Optical Lithography

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

Depth of focus:
\[ DOF = k_2 \times \frac{\lambda}{NA^2} \]

- **k**: process parameter
- **NA**: numerical aperture
- **\( \lambda \)**: wavelength of light

**KrF-Laser**: 248nm  
**ArF-Laser**: 193 nm  
**ArF-Laser (immersion)**: 193 nm  
**EUV sources**: 13.5 nm

**Theoretical limit (air)**: \( NA = 1 \)  
**Practical limit**: \( NA = 0.9 \)  
**Theoretical limit (immersion)**: \( NA \approx n \ (\approx 1.7) \)

- \( k_1 \): process parameter  
  - Traditionally: \( > 0.75 \)  
  - Typically: \( 0.3 – 0.4 \)  
  - Theoretical limit: \( 0.25 \)
EUV development has progressed over 30 years from NGL to HVM insertion.

- **'85** ASML starts EUVL research program
- **'86** ASML ships 2 alpha demo tools: IMEC (Belgium) and CNSE (USA)
- **'87** ASML ships 1st pre-production NA 0.25 system NXE:3100
- **'88** ASML ships 1st NA 0.33 system NXE:3300B
- **'89** ASML ships 1st HVM NA0.33 system NXE:3400B

- **1st lithography** (LLNL, Bell Labs, Japan)
- **Japan**
- **USA**
- **NL**
- **NL**
- **NL**
- **NL**

- **'90**
- **'91**
- **'92**
- **'93**
- **'94**
- **'95**
- **'96**
- **'97**
- **'98**
- **'99**
- **'00**
- **'01**
- **'02**
- **'03**
- **'04**
- **'05**
- **'06**
- **'07**
- **'08**
- **'09**
- **'10**
- **'11**
- **'12**
- **'13**
- **'14**
- **'15**
- **'16**
- **'17**
- **'18**

- 5 µm
- 160 nm
- 70 nm L&S
- 28 nm Lines and spaces
- 19 nm Lines and spaces
- 13 nm L/S
- 40nm 4.0nm WR
- 7 nm and 5 nm node structures
High-NA EUV targets <7nm resolution
Relative improvement: 5X over ArFi, 40% over 0.33 NA EUV

Resolution, nm
= \frac{k_1 \times \text{Wavelength}}{\text{NA}}

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

Wavelength, nm
436, g-line
365, i-line
248, KrF
193, ArF
13.5, EUV

Development systems
Production systems

Year of introduction

>10x
NA+45%
NA+67%
>2021
TWINSCAN EUV Product Roadmap

Supporting customer roadmaps well into the next decade

| Year  | EUV 0.55 NA 8nm | EUV 0.33 NA 13nm¹ | NXE:3350B 2.5|125wph | NXE:3400B 2.0nm|125wph | +OFP² 1.7nm | +PEP³ 145 | NXE:3400C 1.7nm|155wph | Next 1.1nm|≥ 170 wph |
|-------|-----------------|-------------------|-------------|-------------|-------------|------------|--------|-------------|-------------|
| 2016  | Product Matched Overlay, Throughput | 3400B uptime improving to >90% for 2018/2019 HVM, extending productivity to >150 W/hr @ 20 mJ/cm² | High NA 1.1nm|185wph |
| 2017  |                 |                   |             |             |             |            |        |             |             |
| 2018  |                 |                   |             |             |             |            |        |             |             |
| 2019  |                 |                   |             |             |             |            |        |             |             |
| 2020  |                 |                   |             |             |             |            |        |             |             |
| 2021  |                 |                   |             |             |             |            |        |             |             |
| 2022  |                 |                   |             |             |             |            |        |             |             |
| 2023  |                 |                   |             |             |             |            |        |             |             |
| 2024  |                 |                   |             |             |             |            |        |             |             |

Current Product status:
- Released
- Development
- Definition
- Study

High-NA platform designs learning from our 20-year EUV journey
High-NA Field and Mask Size productivity

*Throughput >185wph with Half Fields*

Throughput for various source powers and doses

- **0.33NA**
  - WS, RS, current

- **High-NA**
  - WS 2x, RS 4x

- **250 Watt 20 mJ/cm²**
- **500 Watt 30 mJ/cm²**

Source Power/Dose [W/(mJ/cm²)]

- **0**
- **20**
- **40**
- **60**
- **80**
- **100**
- **120**
- **140**
- **160**
- **180**
- **200**

Throughput [300mm/hr]

- **0**
- **20**
- **40**
- **60**
- **80**
- **100**
- **120**
- **140**
- **160**
- **180**
- **200**

Acceleration of mask stage ~4x

Acceleration of wafer stage ~2x

Fast stages enable high throughput despite half fields
EUV HVM introduction targeted at 7nm

*Installed base of EUV systems expected to ~double in 2018*

NXE:33x0 and NXE:3400

- **Installed Base**
- **Planned**
- **Shipments**

<table>
<thead>
<tr>
<th>Year</th>
<th>Installed Base</th>
<th>Planned</th>
<th>Shipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>'13</td>
<td>3</td>
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<tr>
<td>'14</td>
<td>4</td>
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<td>'15</td>
<td>7</td>
<td></td>
<td>2</td>
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<tr>
<td>'16</td>
<td>9</td>
<td></td>
<td>3</td>
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<tr>
<td>'17</td>
<td>12</td>
<td></td>
<td>10</td>
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<td>'18</td>
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<td>'19</td>
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<td>30</td>
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<tr>
<td>'20</td>
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<td></td>
<td>40</td>
</tr>
</tbody>
</table>

HVM ramp and HVM phases for NXE:33x0 and NXE:3400 systems.
EUV Lithography, NXE:3400B
NXE:3400B: 13 nm resolution at full productivity
Supporting 5 nm logic, <15nm DRAM requirements

Reticle Stage
Improved clamp flatness for focus and overlay

Projection Optics
Continuously improved aberration performance

New Flex-illuminator
outer sigma to 1.0
Inner sigma to 0.06
reduced PFR* (0.20)

Overlay set up
Set-up and modelling improvements

125WPH
Reduced overhead
Improved source power

Wafer Stage
Flatter clamps, improved dynamics and stability

Resolution 13 nm
Full wafer CDU ≤ 1.1 nm
DCO ≤ 1.4 nm
MMO ≤ 2.0 nm
Focus control ≤ 60 nm
Productivity ≥ 125 WPH

*PFR = pupil fill ratio
NXE productivity above 140 wafers per hour
NXE:3400B, 140 WPH at 246W

Overlay in spec at 125 WPH throughput
~200W power at IF with proto version SIM

Throughput of 140 WPH achieved at 246W

- Actual: 195W, Target: 205W
  - Throughput without pellicle
  - Full field, 96 fields at 20 mJ/cm²

- Actual: 246W, Target: 250W
  - Throughput without pellicle
  - Full field, 96 fields at 20 mJ/cm²
  - Throughput with pellicle+DGLm
  - Full field, 96 fields at 20 mJ/cm²

*Measured 116 WPH using pellicle with >83% transmission without DGL membrane. Throughput with membrane is calculated.
**Improvement plan for pellicle transmission to 88% and DGL membrane transmission to 90% included
NXE productivity above 125 wafers per hour
NXE:3400B, 140 WPH at 246W

NXE:3400B ATP test: 26x33mm2, 96 fields, 20mJ/cm2

Throughput [Wafers per hour]

- 2014 Q1: NXE:3300B at customers
- 2014 Q2: NXE:3300B at customers
- 2014 Q3: NXE:3300B at customers
- 2014 Q4: NXE:3300B at customers
- 2015 Q3: NXE:3350B at customers
- 2015 Q4: NXE:3350B at customers
- 2016 Q2: NXE:3400B ASML factory
- 2016 Q4: NXE:3400B at customers
- 2017 Q1: NXE:3400B ASML factory (proto)
- 2017 Q3: NXE:3400B at customers
- 2017 Q3: NXE:3400B at customers
- 2018 Q1: NXE:3400B at customers

NXE:3400B ATP test: 26x33mm2, 96 fields, 20mJ/cm2
>3.2M wafers exposed on NXE:3xx0B at customer sites
Currently 34 systems running in the field. First system was shipped Q1 2013

**EUV Availability**

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uptime</td>
<td>0%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Planned upgrades</td>
<td></td>
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</tbody>
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**Cumulative EUV wafer exposures**

NXE:3xxx, Wafers

- 2011: 0.6M
- 2012: 1.1M
- 2013: 2.0M
- 2014: 3.2M

Uptime %

- 2016: 0%
- 2017: 100%
- 2018: 100%
Productivity increases via source availability

*Secured EUV power is matched with increasing availability*

Productivity = Throughput(∝EUV Power) × 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 from 10 W to &gt; 250 W</th>
<th>Drive laser power</th>
<th>from 20 to 40 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive laser power</td>
<td>Conversion efficiency (CE)</td>
<td>from 2 to 6% (Sn droplet)</td>
</tr>
<tr>
<td>Dose overhead</td>
<td>Optical transmission</td>
<td>from 50 to 10%</td>
</tr>
<tr>
<td>Source availability</td>
<td>Automation</td>
<td></td>
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<tr>
<td></td>
<td>Collector protection</td>
<td></td>
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<tr>
<td></td>
<td>Droplet generator reliability &amp; lifetime</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drive laser reliability</td>
<td></td>
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</table>
Two-fold approach to eliminate reticle front-side defects

1. Clean scanner

2. EUV pellicle

EUV Reticle (13.5nm)

Without Pellicle

With Pellicle
Clean Scanner

Reticle front-side defectivity ~1/10k

Each data point represents between 1,000 and 10,000 wafer exposures in ASML factory or at a customer.

Improvements on hydrogen gas curtain, parts cleanliness, in-situ cleaning, factory way-of-working.

Continuous fine-tuning and reduction of electrostatic effects

Improvement roadmap in place to consistently meet HVM target. Addressing particle generation, release, and transport.

HVM target <1/10k
EUV pellicle industrialization

Pellicle infrastructure in place and 100 WPH throughput achieved

**Pellicle Film**
EUV Transmission

83% transmission
Target 90%

**Pellicle Mounting**
Automated Equipment

**Pellicle Performance**
# defects, Max Power

125 WPH

>100 WPH

Offline tests confirm > 10k durability at 300W and beyond
Measured at 83% transmission pellicle

Actual: 246W
Target: 250W

Throughput with pellicle+DGLm

20,000 equivalent wafers exposed
300W

22,000 equivalent wafers exposed
400W

Tested at temperatures corresponding to 300-400W EUV on 83% transmission pellicles
DGL membrane as spectral filter

Located at Dynamic Gas Lock (DGL) suppresses DUV and IR, plus removes outgassing risk to POB

DGL membrane (~ 50 x 25 mm)

Effective DUV and IR suppression

>100x DUV suppression

>4x IR suppression
EUV: Principles of Generation
Laser Produced Plasma Density and Temperature

Ion density $\sim 10^{17} - 10^{18} \text{#/cm}^3$

Temperature $\sim 30 - 100 \text{ eV}$

Nishihara et al. (2008)
Fundamentals: EUV Generation in LPP

Laser produced plasma (LPP) as an EUV emitter

1. High power laser interacts with liquid tin producing a plasma.
2. Plasma is heated to high temperatures creating EUV radiation.
3. Radiation is collected and used to pattern wafers.
Modelled EUV CE of LPP Sn Plasma vs. Wavelength

Simulation Assumptions:

- 1D modeling
- Sn flat target (50um thickness)
- Laser Pulse: 10ns duration (rectangular)
- Uniform radial distribution of intensity in beam spot
- Prizm Computational Sciences, Inc., 2005

EUV CE defined into 2% bandwidth, $2\pi$ sr solid angle
Peak of EUV spectrum matches the MoSi multilayer reflectivity band at 13.5 nm
**LPP Target Material and Laser Wavelength Options**

High Efficiency is the Key to a Low Cost Architecture

<table>
<thead>
<tr>
<th></th>
<th>Xe</th>
<th>Sn</th>
<th>Li</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excimer (351nm)</td>
<td>-</td>
<td>0.5-1.0%</td>
<td>2.0-2.5%</td>
</tr>
<tr>
<td>Solid State (1064nm)</td>
<td>0.5-1.0%</td>
<td>2.0-2.5%</td>
<td>2.0-2.5%</td>
</tr>
<tr>
<td>CO₂ (10.6μm)</td>
<td>0.5-1.0%</td>
<td>4.0-5.0%</td>
<td>1.0-1.5%*</td>
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- Best high efficiency options of laser/target combinations for future HVM sources

CO₂ Laser with Sn target was selected for industrialization in 2006
Plasma simulation capabilities

**Main-pulse modeling using HYDRA**

1D simulations are fast and useful for problems that require rapid feedback and less accuracy.

- **1D**: real pulse shape
- **2D**: + symmeterized beam profile
- **3D**: + real asymmetric profile

**Sn target using a real irradiance distribution**

- Electron density (top half) with laser light (bottom half)
- 2D and 3D simulations are run for the full duration of the Main pulse. Results include temperature, electron density, spectral emission, etc.
Simulation of the EUV source

The plasma code’s outputs were processed to produce synthetic source data. The comparison to experiments helps to validate the code and understand its accuracy.
EUV Source: Architecture and Operation Principles
EUV Lithography System Schematic

- LPP Source
- Collector
- Drive Laser
- Tin Catch
- Plasma
- Intermediate focus
- Reticle-stage
- Illuminator
- Projection optics
- Wafer stage
LPP: Master Oscillator Power Amplifier (MOPA) Pre-Pulse Source Architecture

- Key factors for high source power are:
  - High input CO$_2$ laser power
  - High conversion efficiency (CO$_2$ to EUV energy)
  - High collection efficiency (reflectivity and lifetime)
  - Advanced controls to minimize dose overhead

![Diagram of LPP: Master Oscillator Power Amplifier (MOPA) Pre-Pulse Source Architecture](image-url)
EUV System overview

Drive Laser
Common Housing
[Power Amplifiers]

Beam Transport System

Scanner

Vessel

Final Focus Assembly

Drive Laser Ancillaries
Industrial high power CO$_2$ laser

High beam quality for gain extraction and EUV generation

- 4 cascaded power amplifiers (PAs) in HPAC
- Individually optimized geometry and settings
- Connected by relay optics
- Extensive metrology between amplifiers & at DL exit
NXE:3XY0 EUV Source: Main modules

*Populated vacuum vessel with tin droplet generator and collector*
EUV Source: MOPA + Pre-Pulse

- Pre-pulse transforms tin droplet into “pancake/mist” that matches CO₂ main pulse beam profile

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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

Short term droplet position stability $\sigma \sim 1 \mu m$
Droplet Generator: Principle of Operation

Large separation between the droplets by special modulation

Multiple small droplets coalesce together to form larger droplets at larger separation distance
High EUV power at high repetition rates drives requirements for higher speed droplets with large space between droplets.
Droplet Generator: Principle of Operation

*Large separation between the droplets by special modulation*

Tin droplets at 80 kHz and at different applied pressures. Images taken at a distance of 200 mm from the nozzle.
Increase of droplet spacing

Larger separation between the droplets needed for higher pulse energies

Droplet spacing of 1.5 mm demonstrated at 80 Khz
Collector Protection by Hydrogen Flow

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

- Hydrogen buffer gas (pressure ~100 Pa) 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
EUV Collector: Normal Incidence

- Ellipsoidal design
  - Plasma at first focus
  - Power delivered to exposure tool at second focus (intermediate focus)
- Wavelength matching across the entire collection area

Normal Incidence Graded Multilayer Coated Collector
EUV Sources in the Field
Progress for in EUV power: 250W

Increase average and peak laser power
Enhanced isolation technology
Advanced target formation technology
Improved dose-control technique

>250W is now demonstrated, Shipping started in the end of 2017

EUV power (source/scanner interface, [W])

\[ \propto \text{CO}_2 \text{ power [W]} \]

1 – Dose Overhead

Conversion Efficiency

Dose controlled EUV power (W)

Year

Shipments in 2017
Research
Shipped

08 09 10 11 12 13 14 15 16 17 18

0 25 50 75 100 125 150 175 200 225 250
250W demonstrated multiple times in 2017
Including industrialized version of SIM, field upgrades in progress

Proto 1
May 2017
@ 250W

Pre-Pilot
July 2017
@ 250W / 125wph

Industrialized module
December 2017
@ 250W

Proto SIM – 250W 1hr RFCM 98.1% Die Yield (7/18)
Pre-pilot SIM – 250 W 10 minutes run
20170726-163655 L20V + 7 um
250W achieved with industrialized SIM in San Diego
99.97% Die Yield
EUV Source operation at 250W
with 99.90% fields meeting dose spec

Source power (W)

Die yield (%)

May 2018  June 2018  July 2018  August 2018
Performance at customers sites at 250W

On multiple systems

- Source Power >250W
- Power fluctuations corrected by scanner dose control

Operational power performance

Operational dose performance

- At 250W, Average dose performance well above >99.99%
NXE:3400B productivity of average >1000 WPD

Wafers per day for 6 consecutive weeks

At a customer site
Dose Performance and Slit uniformity show stable results.

Supporting requirements for 5 nm node CD control.

**NXE:3400B**

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

**Legend:**
- Light blue: Dose System Performance, DSP
- Dark blue: Slit uniformity
NXE:3400B availability plan to 88% availability EoY ‘18
Roadmap in place to 95% availability for 95% of fleet

NXE:3400 combined scanner/source availability

- Best data on 3400 comes from dedicated effort on small number of systems – little bit of luck and lots of focus
- Need to scale to install fleet

NXE:3400B availability, in final configuration, climbing steadily from 40% end of Q1 to 70-80% worldwide (4 weeks average), variation reduction is key
Collector lifetime improvement at 250 W
Longer collector lifetime confirmed at full power

Far Field EUV intensity
(image of the collector)

Relative Collector reflectivity

Collector reflectivity loss over time reduced to <0.3%/Gp
EUV Source Power Outlook
EUV Source operation at 250W with 99.90% fields meeting dose spec

**Operation Parameters**
- Repetition Rate: 50kHz
- MP power on droplet: 21.5kW
- Conversion Efficiency: 6.0%
- Collector Reflectivity: 41%
- Dose Margin: 10%
- EUV Power: 250 W

**Graphs:**
- EUV Power vs. Time [sec]
- Overhead [%] vs. Time [sec]
- Good Dies (Exposures) [%] vs. Dose Error [%]
- Open Loop Performance: Improved Isolation
Hydrogen gas central to tin management strategy

Requirements for buffer gas:
- Stopping fast ions (with high EUV transparency)
- Heat transport
- Sn etching capability

Hydrogen performs well for all these tasks!
Debris in the tin LPP EUV source

Primary debris – directly from plasma and before collision with any surface:

- Heat and momentum transfer into surrounding gas
  - Kinetic energy and momentum of stopped ions
  - Absorbed plasma radiation
- Sn flux onto collector
  - Diffusion of stopped ions
  - Sn vapor
  - Sn micro-particles
3D measurement of fast tin ion distributions

Faraday cups measure tin ion distributions

Ion measurements inform $H_2$ flow requirements for source
Tin ion distributions

Data are used for optimization of H$_2$ flow in the source
Measurement of fast tin ion and radiation distributions

*Multiple sensors on a rotating frame*

**Sensors**

- Faraday Cups: ion energy and charge distributions
- CO$_2$ PEMs: scattered infrared radiation
- EUV PDs: EUV emission and anisotropy

**Applications**

- Input to Plasma-Gas Interaction / Computational Fluid Dynamics model
- Evaluation of collector protection capability
- Improvement of Conversion Efficiency
Improved debris mitigation
At 250 watt of EUV power

Data from the EUV source development system
450W in-burst EUV power demonstration
Demonstrated IF EUV pulse energy of 9 mJ at 50 kHz

EUV data over 8 EUV LPP source architectures

Open loop, EUV pulse energy histograms

Open loop, 15 ms Bursts, 3% duty cycle
On the development system
Summary: EUV readiness for volume manufacturing

- 34 NXE:3XY0B systems operational at customers
- Dose-controlled power of 250W on multiple tools at customers

Progress in EUV power scaling for HVM
- Dose-controlled power of 250W on multiple tools at customers
- Collector lifetime ~ 150 Billion Pulses in the field

CO$_2$ development supports EUV power scaling
- Clean (spatial and temporal) amplification of short CO$_2$ laser pulse
- High power seed system enables CO$_2$ laser power scaling

Droplet Generator with improved lifetime and reliability
- >700 hour average runtime in the field
- >3X reduction of maintenance time

Path towards 500W EUV demonstrated in research
- CE is up to ~ 6 %
- In-burst EUV power is up to 450W
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