HIGH POWER LPP-EUV SOURCE WITH LONG COLLECTOR MIRROR LIFETIME FOR HIGH VOLUME SEMICONDUCTOR MANUFACTURING

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Agenda

- Motivation
- HVM Ready System Performance Progress and Target
- HVM Ready Long-lifetime Collector Mirror
- Summary
MOTIVATION
Requirement for a Light Source in EUV Lithography

EUV light transmittance is less than 2% at 11-reflection mirror system

The development of a high power EUV light source for HVM exposure tools is the KEY Issue.

Requirement: >250W at IF (1st stage HVM)

11 reflections (Maximum)

Transmittance: \(0.70^{11}=0.02\)
### EUV extension roadmap

<table>
<thead>
<tr>
<th></th>
<th>55 WPH</th>
<th>125 WPH</th>
<th>145 WPH</th>
<th>185 WPH</th>
<th>Overlay [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>2017-2019</td>
<td></td>
<td></td>
<td>NXE:3300B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NXE:3350B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NXE:3400B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source: 250W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>products under study</td>
<td></td>
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<td></td>
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<tr>
<td>NXE:next</td>
<td></td>
<td></td>
<td></td>
<td>&lt;3</td>
<td></td>
</tr>
<tr>
<td>High NA</td>
<td></td>
<td></td>
<td></td>
<td>&lt;2</td>
<td></td>
</tr>
</tbody>
</table>

Source: 500W

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Jan van Scoot (ASML); “The future of EUV lithography: enabling Moor’s Law in the next decade”, EUVL symposium 2017, 2017/9/11-14, Monterey, USA
Motivation

According to ASML roadmap*, EUV lithography will be released with 145wph throughput by 2019 for HVM.

- EUV source power is increasing, but has not yet reached sufficient power levels, required **250W is Ready?** Q1
- In order to reach 145wph, it requires high **Availability**, and also one key element such as **Collector Life are Ready?** Q2

Gigaphoton has been integrating an architecture of LPP with CO₂ laser plus Pre-pulse since 2002, and has the longest development history in EUV.
- Will **Gigaphoton’s** source be in time to meet 145wph HVM by **2019** ? Q3

* Reference: Christophe Smeets (ASML)@ EUVL Symposium - 2016
HVM READY
PERFORMANCE PROGRESS
AND TARGETS
How to generate EUV light

**Structure**

- Sn droplet 20um Dia. 100kHz ejection with 300km/h
- Pre and main lasers shoot every single droplets.
- Collector transfer EUV light to the IF point.

**Sn life cycle**

1. Pre-pulse laser (liquid)
2. Main-pulse laser (CO₂)
3. EUV light Emission
4. Plasma (gas)
5. Debris Mitigation: Tin ionized 100%
6. Ions trapped
7. Exhaustion
8. Magnetic Field
Gigaphoton’s LPP Source Concept

1. **Dual-wavelength shooting concept**
   High CE attained with CO₂ and pre-pulse solid-state lasers

2. **EUV specific Hybrid CO₂ laser system**
   Short pulse/High repetition rate oscillator combined with commercial cw-amplifiers

3. **Debris mitigation with Super conductive magnets (SM3)**

4. **Accurate shooting system**
   Stable droplet generation and shooting beam control

5. **Out-of-band light reduction**
   Grating structured collector mirror
Current EUV Sources at Gigaphoton

Proto#1
Operational since October 2012
Elemental technology research and proof of concept

Proto#2
Operational since November 2013
Key technology development for HVM

NEW
Pilot#1
Operational since 2015
First pilot EUV system designed for ASML NXE integration and HVM operations
**Pre-pulse Technology**

**Higher CE and Power**
- Optimum wavelength to transform droplets into fine mists
- High CE is achieved with ideal expansion of the fine mists to match the CO$_2$ laser beam diameter

**Long Life Chamber**
- Debris mitigation by superconducting magnets
- Ionized tin atoms are guided to tin catchers by the magnetic field

**Pre-pulse enables the size matching between a droplet and CO$_2$ laser beam to achieve high CE.**
Droplet Generator and Shooting System

LPP EUV Source Shooting Control System

20um diameter-droplets with 900 um interval are ejected at 100kHz.

<table>
<thead>
<tr>
<th></th>
<th>Proto#2</th>
<th>Pilot#1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet Speed (m/s)</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Back Pressure (MPa)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Max Repetition Rate (kHz)</td>
<td>80</td>
<td>100</td>
</tr>
</tbody>
</table>
## Pilot System Driver Laser and PPL System

<table>
<thead>
<tr>
<th>OSC</th>
<th>OSC</th>
<th>PA1</th>
<th>MA1</th>
<th>MA2</th>
<th>MA3</th>
<th>Plasma Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot #1</td>
<td>OSC</td>
<td>Pre-Amp</td>
<td>Pre-Amp</td>
<td>AMP</td>
<td>AMP</td>
<td>AMP</td>
</tr>
<tr>
<td>Proto #2</td>
<td>OSC</td>
<td>Pre-Amp</td>
<td>Pre-Amp</td>
<td>AMP</td>
<td>AMP</td>
<td>AMP</td>
</tr>
</tbody>
</table>

### CE performance

<table>
<thead>
<tr>
<th>Conversion Efficiency (%)</th>
<th>CO2 pulse energy (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>250</td>
</tr>
<tr>
<td>5.5</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>4.5</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
</tr>
<tr>
<td>3.5</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Pilot #1**: Due to EO isolator damage from back reflection.
- **Proto #2**: CO2 pulse energy is shown with different colors representing different efficiencies.

Specially designed new CO2 lasers have improved beam quality to give higher CE.
## Target System Specification

<table>
<thead>
<tr>
<th></th>
<th>Proto#1</th>
<th>Proto#2</th>
<th>Pilot#1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Performance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EUV Power</td>
<td>25W</td>
<td>&gt;100W</td>
<td>250W</td>
</tr>
<tr>
<td>CE</td>
<td>3%</td>
<td>&gt; 4%</td>
<td>&gt; 5%</td>
</tr>
<tr>
<td>Pulse Rate</td>
<td>100kHz</td>
<td>100kHz</td>
<td>100kHz</td>
</tr>
<tr>
<td>Output Angle</td>
<td>Horizontal</td>
<td>62°upper</td>
<td>62°upper</td>
</tr>
<tr>
<td>Availability</td>
<td>~1 week</td>
<td>~1 week</td>
<td>&gt;80%</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Droplet Generator</td>
<td>20 - 25μm</td>
<td>&lt; 20μm</td>
<td>&lt; 20μm</td>
</tr>
<tr>
<td>CO₂ Laser</td>
<td>5kW</td>
<td>20kW</td>
<td>27kW</td>
</tr>
<tr>
<td>Pre-pulse Laser</td>
<td>picosecond</td>
<td>picosecond</td>
<td>picosecond</td>
</tr>
<tr>
<td>Collector Mirror Lifetime</td>
<td>Used as development platform</td>
<td>10 days</td>
<td>&gt; 3 months</td>
</tr>
</tbody>
</table>
## Key Performance Status and its target

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
<th>2017 Current</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-band power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Average Power)</td>
<td>87W</td>
<td>113W</td>
<td>113W (91W)</td>
<td>250W</td>
</tr>
<tr>
<td></td>
<td>(83W)</td>
<td>(111W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Collector lifetime</strong></td>
<td>No data</td>
<td>-10%/Bpls *3</td>
<td>-0.4%/Bpls</td>
<td>-0.2%/Bpls</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>15%</td>
<td>44%</td>
<td>53%</td>
<td>&gt; 80%</td>
</tr>
</tbody>
</table>

*1, Collector lifetime estimation has been started from 2017

*2, Max availability in 4 week operation.

*3, Main issue was capping layer performance.

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Proto #2

Pilot #1

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2nd EUV-FEL Workshop

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Power and Stability at Continuous Operation

Performance

- Average power at IF: 85W
- Dose error (3 sigma): 0.04%
- Die yield (< 0.16%): 99.4%
- Operation time: 143h
- Pulse Number: 19Bpls
- Duty cycle: 75%
- In-band power: 113W
- Dose margin: 35%
- CE: 4.4%
- Availability 4wk: 32%
- Collector lifetime: -10%/Bpls
- Repetition rate: 50kHz
- CO2 power: 12kW

Note:
Dose error was mainly due to droplet combination failure and it was improved by droplet generator improvement (but not perfect).
EUV power: 250W achieved

Proto#2: 250W with 4% CE at 100KHz

Open loop, 50% duty cycle

- 301W with 4% CE
- 268W with 3.5% CE

Closed loop, 50% duty cycle

- 256W with 15% Dose Margin

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The potential availability is 89%.
(Availability: 64% / Idle time: 25%)

Dose error: System stopped at > 2% dose error (3 sigma) /10kplsl slit and error was not recovered by automatic function
Idle time: Time for waiting operators.

24 hour x 7 days definition:
Unmanned operation between 9pm thru 8am

Downtime breakdown

- CO2 Laser: 29%
- Vessel: 28%
- Pre-pulse Laser: 5%
- Others: 16%
- Droplet generator: 22%
- Beam Steering System: 0%
### High Power EUV Source for High NA EUV Exposure Tool

#### CO2 Laser Average Power [kW] @100kHz

<table>
<thead>
<tr>
<th>EUV ave.Power [W]</th>
<th>Conversion Efficiency [%]</th>
<th>@100kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2% 3% 4% 5% 6% 7% 8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>46.4</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>101.0</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>128.3</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>155.6</td>
</tr>
<tr>
<td>100</td>
<td>35</td>
<td>182.9</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>210.2</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>237.5</td>
</tr>
<tr>
<td>250</td>
<td>50</td>
<td>264.8</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>292.1</td>
</tr>
<tr>
<td>500</td>
<td>60</td>
<td>319.4</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>346.7</td>
</tr>
<tr>
<td>700</td>
<td>70</td>
<td>374.0</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>401.3</td>
</tr>
<tr>
<td>800</td>
<td>80</td>
<td>428.6</td>
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<tr>
<td></td>
<td>85</td>
<td>455.9</td>
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<tr>
<td>900</td>
<td>90</td>
<td>483.2</td>
</tr>
<tr>
<td>950</td>
<td>95</td>
<td>510.5</td>
</tr>
<tr>
<td>1000</td>
<td>100</td>
<td>537.8</td>
</tr>
</tbody>
</table>

#### CO2 Laser Energy [mJ]

<table>
<thead>
<tr>
<th>CO2 laser average Power [kW]</th>
<th>HVM1</th>
<th>HVM2</th>
<th>HVM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25kW</td>
<td>250W</td>
<td>300W</td>
<td>500W</td>
</tr>
<tr>
<td>40kW</td>
<td>100kHz</td>
<td>100kHz</td>
<td>100kHz</td>
</tr>
<tr>
<td>5%</td>
<td>4.5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>25W</td>
<td>25W</td>
<td>25W</td>
<td>40kW</td>
</tr>
</tbody>
</table>

Our LPP system has capability to give 300~500W output power.
HVM READY LONG-LIFETIME COLLECTOR MIRROR
Pilot System EUV Chamber
HVM Collector Mirror Specifications

- Size Φ412mm
- Weight 22kg
- Collector efficiency >74%
- Collector reflectivity >48%
- Grating structure

- Measured IR reflectivity: 0.37%
"SM3": Superconducting Magnet Mitigation Method

Higher CE and Power
- Optimum wavelength to transform droplets into fine mists
- High CE is achieved with ideal expansion of the fine mists to match the CO₂ laser beam diameter

Long Life Chamber
- Debris mitigation by superconducting magnets
- Ionized tin atoms are guided to tin catchers by the magnetic field

Droplet (liquid) → Fine-mist (liquid) → Plasma (gas)

Magnetic Field Ion Guiding
- Ions with low energy are trapped by B field

Gas Etching
- Remaining atoms to the mirror are etched by gas

KEY TECHNOLOGY 2

SM3 is the basis of debris mitigation system.
“SM3”: Superconducting Magnet Mitigation Method

- Minimum amount of Sn
  - 20um diameter droplet
- 100% ionization in plasma emission
  - Pre pulse technology
  - Precise shooting control
  - Solid beam profile of laser
- Sn ion trap by magnetic field
  - Not to reach the collector surface
- Sn etching even after deposition
  - \( \text{Sn} + 2\text{H}_2 + \text{EUV} \rightarrow \text{SnH}_4 \)
Debris Mitigation and Capping Layer Evaluations with a Dummy Mirror

- **Purpose**
  - Evaluation of tin deposition distribution on the collector mirror

- **Method**
  - Dummy collector mirror (no coating)
  - Sampling plate (sample coupon)
    - Size: 15mmx15mmx0.7mm
    - Material: Si plate (46 pieces) + multi layer (Si/Mo) + Capping layer

- **Analysis after test**
  - Surface condition: SEM
  - Deposited tin thickness: XRF
  - Capping layer thickness: TEM
Difference of Deposition on the Sample Coupons of a Dummy Mirror

Capping layer disappearance
Blister generation

Capping layer deformation
Blister generation

Capping layer survived
No blister generation

The capping layer material has great influence on ML durability.
Debris Mitigation Concept; Tin Stopping

- **Tin stopping**
  1. Tin is ionized effectively by double pulse irradiation and precise shooting control
  2. Tin ions are confined by magnetic field and stopped by H₂ gas to prevent the sputtering to the coating of mirror.
  3. Confined tin ions are guided and exhausted by H₂ flow from vessel.
Debris Mitigation Concept; Tin Cleaning

**Tin cleaning**

1. Tin, not confined by magnetic field, are stopped by H\textsubscript{2} gas in order to prevent the sputtering to the coating of collector.
2. Deposited tin on the collector is etched by H radical gas.

3. **Cooling and gas flow systems for preventing decomposition of SnH\textsubscript{4}**

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**Radical Etching**

Sn + 4H\textsuperscript{+} → SnH\textsubscript{4}

**Decomposition**

SnH\textsubscript{4} → Sn + 2H\textsubscript{2}

**SnH\textsubscript{4} → Sn + 4H**

Decomposition speed

\[ k = A \cdot \exp\left(\frac{-E_a}{RT}\right) \]
Collector lifetime status after improvement

- Power level of EUV: 100W in Burst, (= 2mJ x 50kHz), 33% duty cycle, 30W in average.
- Collector lifetime was improved to -0.4%/Bpl\textsubscript{s} by magnetic debris mitigation technology optimization.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Heat Load</th>
<th>Collector Reflectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot#1</td>
<td>85W high heat load with condition B</td>
<td>0.1Bpl\textsubscript{s}</td>
</tr>
<tr>
<td>Proto#2</td>
<td>31W low heat load with condition C</td>
<td>9.6Bpl\textsubscript{s}</td>
</tr>
<tr>
<td>Pilot#1</td>
<td>85W high heat load with condition B</td>
<td>15.8Bpl\textsubscript{s}</td>
</tr>
</tbody>
</table>

Far field pattern in test condition C

Proto#2
31W Low heat load with condition C

-0.4%/Bpl\textsubscript{s}

Edge Tin deposition by H\textsubscript{2} flow convection
Summary

Pilot#1 for HVM is now under construction, and shows promising results;
  ▶ Demonstrated 113W in-burst power at 75% duty (85W average) for 143 hours based on the preliminary results of CE 5%, 250W power with Proto#2
  ▶ Next target: 250W full specification operation with long term by 1H 2018.

Pilot#1 Collector Mirror test shows HVM capable lifetime;
  ▶ Superconducting Magnet Mitigation Method “SM3” realized the reflectance degradation rate of 0.4%/Bpλs at over 100W level operation (in burst mode, up to 30Bp).

Pilot#1 shows HVM ready availability;
  ▶ Pilot#1 system achieved the potential availability of 89% (2week-average).

Will Gigaphoton’s Source be in time to meet 145wph HVM by 2019?
Yes, Gigaphoton’s Source will be in time to meet 145wph HVM by 2019.
Thank you for co-operation:

Dr. Akira Endo :HiLase Project (Prague) and Prof. Masakazu Washio and others in Waseda University
Dr. Kentaro Tomita, Prof. Kiichiro Uchino and others in Kyushu University
Dr. Jun Sunahara, Dr. Katsunori Nishihara, Prof. Hiroaki Nishimura, and others in Osaka University

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