High-brightness Light Source Based on a New Concept of LPP for Actinic EUV microscopy and Metrology Applications

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Outline

1. Source requirements and how to achieve them
2. New concept of LPP source: the key idea
3. EUV source parameters
4. Examples of source operation
5. Conclusions
Source requirements and how to achieve them

General source requirements

- EUV “inband” emission, i.e. 13.5 nm ± 1%
- High inband brightness (100 ..500 W/mm²-Sr)
- Etendue 5e-4…1e-2 mm²-Sr
- Energy stability <3.5%(3σ) pulse-to-pulse
- Stability of plasma position < 3% of the source size
- High rep-rate, >10 kHz
- Cleanliness 100% (debris containment must be included in the source)
- Safe, full automation
- Availability / Reliability (> 90% uptime)

Rotating liquid metal target

- Renewable target
- Extremely stable
- Continuous target → no synchronization needed
High rotation speed allows high rep-rate operation.

Perturbed target surface

Unperturbed target surface

Target rotation frequency

@30kHz laser

3 mm
High rotation speed allows completely suppress droplet debris

Droplets are being dragged by the target motion ($V_{\text{target}}$)
New concept of LPP source: advantages

- High rotation frequency allows high rep-rate operation
- Extremely high target speed provides the protection from droplet debris
- Protection from plasma debris (fast ions and neutrals) is provided by counter gas flows and magnetic field
- The use of tin, its alloys and also lithium as target material ensures high values of conversion efficiency
The recent results: summary table

Ytterbium pulsed fiber laser, IPG Photonics, YLPP-1-150V-30
Target Sn/In eutectic alloy

<table>
<thead>
<tr>
<th>Laser</th>
<th>Frequency, kHz</th>
<th>Duration, ns</th>
<th>Energy, mJ</th>
<th>CE, %</th>
<th>Source size, µm</th>
<th>B, W/mm²sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4</td>
<td>30</td>
<td>3.99</td>
<td>0.89</td>
<td>0.6</td>
<td>26</td>
<td>50</td>
</tr>
<tr>
<td>T3</td>
<td>60</td>
<td>1.85</td>
<td>0.44</td>
<td>0.5</td>
<td>22</td>
<td>60</td>
</tr>
<tr>
<td>T2</td>
<td>100</td>
<td>1.07</td>
<td>0.27</td>
<td>0.3</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>T1</td>
<td>600</td>
<td>0.18</td>
<td>0.04</td>
<td>0.05</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

30 W average power
Examples of source operation: dose stability

Pulse trains

T4, 30 kHz

T3, 60 kHz

T2, 100 kHz

Dose stability, T4

Dose – 128 pulses, for each dose the average CE is calculated. \( \delta \text{CE}/\text{CE} \sim 0.5\%. \) Recording rate 1/s.
Examples of source operation: debris mitigation

The witness samples (Si wafer) at output window

Before operation

After 2·10^8 shot

Input window, high rotation frequency

Before operation

After 2·10^8 shot

No noticeable contamination, no changes in transparency

Target rotation frequency

10 Hz

100 Hz

Examples of source operation: debris mitigation

In progress: long term runs, 24/7

2018 Source Workshop, November 5-7, 2018, HiLASE, Prague, Czech Republic
Examples of source operation: spatial stability

- 45° Zr/Si multilayer mirror
- Laser
- 33°
- Zr/Si filter
- Pinhole

Pinhole EUV image, integrated over ~21k pulses

Corresponds to 22 µm source size

Center of mass displacement, STD <1% of plume size

Plasma plume image in visible range (recorded by CCD with telescope)

Andor DX440-BN

300 µm
The recent results and optimal laser parameters

Ytterbium pulsed fiber laser, IPG Photonics, YLPP-1-150V-30
Target Sn/In eutectic alloy

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<tr>
<th>Laser</th>
<th>Duration, ns</th>
<th>Energy, mJ</th>
<th>CE, %</th>
<th>Power density, W/cm²</th>
<th>B, W/mm²sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4</td>
<td>3.99</td>
<td>0.89</td>
<td>0.6</td>
<td>4.9e10</td>
<td>50</td>
</tr>
<tr>
<td>T3</td>
<td>1.85</td>
<td>0.44</td>
<td>0.5</td>
<td>5.2e10</td>
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<tr>
<td>T2</td>
<td>1.07</td>
<td>0.27</td>
<td>0.3</td>
<td>5.5e10</td>
<td>30</td>
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<tr>
<td>T1</td>
<td>0.18</td>
<td>0.04</td>
<td>0.05</td>
<td>5.7e10</td>
<td>10</td>
</tr>
</tbody>
</table>

CE to be increased by power density

Emission spectrums at different power densities

Nd:YAG, 3e11 W/cm²
CE = 2%

T4, T3, T2, T1, ~5e10 W/cm² low CE
Conclusion

• We have proposed the new concept of LPP based on extremely fast-rotating liquid target.
• High rotation frequency (up to 400 Hz) of the target provides protection from droplet debris.
• Employing proven protection from ions and neutrals, we have demonstrated that optical windows (input laser and output EUV) stay clean after $2 \times 10^8$ shots.
• Stability of plasma position and the dose lie in the range of required specification for inspection applications.

• Brightness scaling with power:

$$B = \frac{P_{\text{laser}} \cdot CE}{2\pi \cdot (\pi d^2 / 4)}$$

where $P_{\text{laser}}$ – average laser power, conversion efficiency $CE$, and $d$ is source size; assuming laser provides power density $>1\times10^{11}$ W/cm$^2$, i.e. $CE = 2\%$.

Then brightness would be:

- $10 \cdot P_{\text{laser}}$ @ 20 $\mu$m source
- $4.5 \cdot P_{\text{laser}}$ @ 30 $\mu$m source
- $1.6 \cdot P_{\text{laser}}$ @ 50 $\mu$m source
Thank you for attention

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