Brilliance Scaling of Discharge based EUV and soft X-Ray Sources

Klaus Bergmann, Fraunhofer Institute for Laser Technology, Aachen, Germany
Source Workshop, 13-15 November, Dublin
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Overview

- Introduction
- Investigations on brilliance for pseudo-spark based discharge source at ILT
- State of the art for:
  - 2.9 nm into single line: soft x-ray microscopy
  - 10.9 nm into 4% b.w.: interference lithography
  - 13.5 nm into 2% b.w.: environment of EUV lithography
- Outlook on brilliance scaling potential
- Conclusions
Current XUV activities at ILT

- Development of sources for EUV lithography based on tin vacuum arc (together with Xtreme)
- Sources for metrology in the range soft x-ray and EUV
- XUV-Applications (*)
  (Support of TOS, RWTH Aachen University)

EUVL source development

Interference lithography

(*) see also posters on “Defect Inspection”, “Reflectometry” and “Interference Lithography” by Larissa Juschkin
Discharge XUV sources are in commercial use . . .
…and also already in museum

Pseudospark based discharge source

Typical device parameters

- capacity: 100 nF to few µF
- pulse energy: 2 - 20 J
- inductance: ~ 10-14 nH
- peak current: up to 40 kA
- pulse duration: few 100 ns
- pressure: several 10 Pa (dependent on gas)

Scheme of electrode system
Emission spectra (soft x-ray)

Argon (4.9 nm)

Argon (broadband)

Oxygen

Nitrogen (2.9 nm)
Soft x-ray microscopy

Nitrogen emission spectrum

- Brilliance: $2 \times 10^9$ Ph/(µm² sr s)
- Total emission: 15 W/(2πsr)
  at 2.88 nm (430 eV)
- Input power: 20 kW at 1 kHz
Platform for brilliance measurements (EUV)

- Xenon based technology developed by Philips for EUV lithography
- input power : max. 10 kW
- pulse energy : max. 3 J
- repetition rate : max. 3 kHz
- operational with different gases
Brilliance for optimization around 11 nm

- suppression of optically thin Xe transitions by dilution with Argon:
  - ~ 11 nm: optically thick 4f-4d transitions
  - ~ 12-16 nm: optically thin 5p-4d transitions
- increase of brightness at 11 nm due to better discharge conditions with Argon
- discharge parameters:
  - frequency: 2000 Hz
  - pulse energy: 2.8 J
  - input power: 5.6 kW
- emission around 11 nm into 4% b.w.:
  - radius (FWHM): 100 μm
  - near Gaussian shape
  - total power: \(40 \text{ W/(2}\pi\text{sr)}\)
  - brilliance: \(100 \text{ W/(mm}^2\text{sr)}\)
Measurements around 13.5 nm: Radial Profile

- pulse energy: 3.1 J
- input power: up to 8.7 kW
- no increase of radius with increase of input power
- maximum pulse brilliances at highest input power
- no change of radial profile with input power
- radius (FWHM): ~ 210 µm
Measurements around 13.5 nm: Brilliance Scaling

- increase of peak brilliance with higher input power due to higher conversion efficiency

- discharge parameters:
  - frequency: 2800 Hz
  - pulse energy: 3.1 J
  - input power: 8.7 kW

- emission around 13.5 nm into 2% b.w.:
  - radius (FWHM): 210 µm
  - close to Lorentzian shape
  - total power: 48 W/(2πsr)
  - brilliance: 12.9 W/(mm²sr)
Xenon discharge: Soft x-ray contribution (1)

- Pulse energy: 3.1 J
- Pinhole images for:
  - Soft x-rays (Ti): ~3 nm
  - EUV (Si$_3$N$_4$ + Zr): 12-16 nm
- Observed hot spot:
  - Length: ~1 mm
  - Radius: ~100 µm

Simulated distribution of EUV (red) and soft x-ray (blue)
Xenon discharge: Soft x-ray contribution (2)

- Emission spectra observed with pinhole grating spectrograph (low resolution)
- Control measurement with Ar
- Broadband Xenon emission in water window range
- Line emission around 1.4 nm
- Hint for highly ionized Xenon and processes leading to small hot spots
Brilliance of standard Xenon source at Xtreme

Brilliance B:
16.5 W / (mm² sr)
into 2% b.w. for 13.5 nm
4 kHz operation, dc ~ 10%
Radial profile (on-axis)
radius (FW1/e²) : ~ 0.8 mm

\[ \int B(x,y) \, dA = \frac{146 \, W}{2\pi} \]
Scaling considerations for 13.5nm (2% b.w.)

<table>
<thead>
<tr>
<th>Table</th>
<th>today</th>
<th>extrapolated</th>
<th>Remark</th>
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<tbody>
<tr>
<td>Input Power</td>
<td>kW</td>
<td>8,7</td>
<td>15</td>
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<tr>
<td>Conversion efficiency</td>
<td>%/(2πsr 2%bw.)</td>
<td>0,48</td>
<td>0,6</td>
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<tr>
<td>Pinch radius (end-on)</td>
<td>μm</td>
<td>210</td>
<td>170</td>
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<td>Pinch Profile</td>
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<td>appr. Lorentz</td>
<td>Gauss (gain of ~2)</td>
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<td>Loss due to axial extension</td>
<td></td>
<td>0,8</td>
<td>0,8</td>
</tr>
<tr>
<td>Brilliance</td>
<td>W/(mm²sr)</td>
<td>12,9</td>
<td>84.0</td>
</tr>
</tbody>
</table>

Including technical constraints: \( \sim 40 \text{ W/(mm}^2 \text{ sr)}\)
at 13.5 nm into 2% b.w.
Next Generation XUV sources at ILT

- same design for covering the range from soft x-rays to extreme ultraviolet
- power supply developed by ILT matched to special requirements for XUV sources
- push-button operation (no special trained personal required)
Conclusions and Summary

- discharge sources exhibit high maturity and are in commercial use
- a range from soft x-ray to extreme ultraviolet can be covered with the same discharge concepts
- work on brilliance scaling just has started
- demonstrated:
  
  >100 W/(mm² sr) into 4% b.w. for 10.9 nm (ILT)
  12.9 W/(mm² sr) into 2% b.w. for 13.5 nm (ILT)
  16.5 W/(mm² sr) into 2% b.w. for 13.5 nm (Xtreme Tech.)

- optimization potential for up to 100 W/(mm² sr) for 13.5 nm is identified
- discharge sources are worth for further work on brilliance scaling