Optimization of high average power FEL for EUV lithography application

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Outline

• EUV lithography source
• Power scaling of SASE FEL technology
• EUV resist under FEL pulses
• Spatial coherence and EUV homogenizer
• Temporal smoothing and HGHG
• Laser seeding technology at MHz
• Perspective
Trends of optical lithography

Wavelength (nm)

- 400
- 300
- 200
- 100
- 0

- Mercury lamp
- Excimer laser
- EUV Source

- G-line (436nm)
- I-line (365nm)
- KrF excimer laser (248nm)
- ArF (193nm)
- ArF immersion (193nm/1.44)
- EUV (13.5nm)

- DRAM ½ pitch
- 250-130nmHP
- 90nmHP
- 65nmHP
- 45nmHP
- 32nmHP
- 22nmHP
- 16nmHP

FEL Conference 2014 Basel, Switzerland
Typical configuration of EUV source

CO2 laser
>20kw 100kHz

Sn droplet (10μm, 100m/s)

EUV power at plasma
> 1kW

EUV C1 mirror

lifetime : > 12months (800Bpls)
(R10%loss=Sn deposition < thickness 1nm)

EUV power at IF
> 250W
13.5nm 2%BW
(fwhm:0.27nm)
Power-up Scenario of HVM Sources

Layout of 250W EUV light source

First HVM EUV Source

- Gigaphoton is developing 250W EUV source
- Target is 2015

<table>
<thead>
<tr>
<th>Operational specification (Target)</th>
<th>HVM Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUV Power</td>
<td>&gt; 250W</td>
</tr>
<tr>
<td>CE</td>
<td>&gt; 4.0 %</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>100kHz</td>
</tr>
<tr>
<td>Availability</td>
<td>&gt; 75%</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
<th>HVM Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet generator</td>
<td>&lt; 20mm</td>
</tr>
<tr>
<td>CO2 laser</td>
<td>&gt; 20kW</td>
</tr>
<tr>
<td>Pre-pulse laser</td>
<td>psec</td>
</tr>
</tbody>
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Debris mitigation: Magnet, Etching > 15 days (>1500Mps)

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High Power EUV Light Source

Proto #2 System

Driver Laser Beam

Droplet Generator

EUV Light Beam

Intermediate Focus

EUV Plasma Point
Scaling to shorter wavelength, multi kW operation

Scaling to 6.xnm, kW source

<table>
<thead>
<tr>
<th>EUV IF power</th>
<th>1kW (6.xnm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 laser power</td>
<td>160kW</td>
</tr>
<tr>
<td>Conversion efficiency</td>
<td>1.5%/0/6%b.w. *</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>40%</td>
</tr>
<tr>
<td>Mirror reflectivity</td>
<td>70% **</td>
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</table>
## GENESIS Calculation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Charge</td>
<td>300pC</td>
</tr>
<tr>
<td>Emittance</td>
<td>1 mmmrad</td>
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<tr>
<td>Energy Spread</td>
<td>1 E-4</td>
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<tr>
<td>Bunch length</td>
<td>200fs</td>
</tr>
<tr>
<td>Energy</td>
<td>331.13MeV</td>
</tr>
<tr>
<td>Undulation Period</td>
<td>9mm</td>
</tr>
<tr>
<td>K Value</td>
<td>1</td>
</tr>
</tbody>
</table>
175\mu J pulse energy
With 30m long undulator

FEL power can be increased by using tapering undulator
REF : SLAC-PUB-15900
Scaling of SASE-FEL power

- MHz >100W
- 10MHz >1kW
Chemically amplified resist

Resist sensitivity > 10mJ/cm$^2$ (10ns, 13.5nm)
Second moment beam diameter from PMMA

Ablative PMMA imprint, white-light interferometer

- Bulk PMMA sample at same position as phosphor
- Single pulses
- Assuming Lambert-Beer’s law with
  - Ablation threshold 7.2mJ/cm²
  - Attenuation length 55.2nm
- Second moment beam diameter

Issue 1: ablation threshold < resist sensitivity

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Spatial coherence

K of SASE FEL

\[ \sim 0.5 \]

K of plasma source

\[ \sim 3.2 \times 10^{-9} \]

Issue 2: interference pattern
Beam homogenizer by reflective optics

- Low roughness surface to avoid speckle pattern generation
- Higher transmission for low loss
Temporal pulse structure

SASE FEL (FLASH)  Sn laser plasma

E.A. Schneidmiller and M.V. Yurkov, Coherence properties of the radiation FLASH, FLASH Seminar, September 17, 2013
Fresh bunch injection HGHG

324nm, 100fs, 20μJ

40.5nm

13.5nm

Fresh bunch injection HGHG
Development of CW seeded picosecond mid-IR parametric light source pumped
By the high average power Yb:YAG thin disc laser, Ondreji Nowak
Conclusion

• Scaling of EUV source over kW
• SASE FEL can generate over kW power at 13.5nm
• Matching of FEL pulse for lithography
  1. Resist sensitivity & ablation
  2. Spatial coherence reduction
  3. Temporal smoothing