One Hundred Watt Class EUV Source Development for HVM Lithography

2014 EUVSource Workshop @ UCD, Dublin Ireland

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• Introduction

• LPP Light Source Concept and Component technology
  » Droplet Technology
  » Pre-pulse Technology
  » Driver CO2 laser
  » Debris Mitigation Technology
  » Collector Mirror and IR Reduction Technology

• Gigaphoton’s High Power LPP Light Source System Development
  » Output Power Update
  » Potential performance

• Power-up Scenarios of HVM EUV Light Sources
  » Construction of Pilot #1

• Summary
Technical Barrier of EUV Lithography

EUV light transmittance is only 2% with 11 reflection mirror systems

70% reflection

High power light sources for HVM exposure tools is the key issue

Demand is > 250W at first stage HVM
History of LPP Source Development (1)

Target Technologies
- Gas Jet
  - Single nozzle
  - Double nozzle
- Mechanical
  - Tape target
  - Cryogenic rotating drum target

Solid State Laser
- CO₂ Laser
  - CW-Osc
  - Pre-AMP1
  - Pre-AMP2
  - Main-AMP
- Double Pulse Solid State + CO₂ Laser
  - CO₂ laser
  - Pre-pulse laser
  - Main-pulse

Droplet target

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History of LPP Source Development (2)

Liquid Xe jet target experiment with YAG laser driver (2004)

Liquid Xenon Jet System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe Jet Velocity</td>
<td>30 m/s</td>
</tr>
<tr>
<td>Xe Jet Stability</td>
<td>10 μm@10mm</td>
</tr>
<tr>
<td>Xe Temperature</td>
<td>160K - 190K</td>
</tr>
<tr>
<td>Xe Pressure</td>
<td>&lt; 5MPa</td>
</tr>
</tbody>
</table>

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History of LPP Source Development (3)

LPP EUV light generation test (2004) with Xe Jet + YAG laser system

Nd:YAG Driver laser
[MOPA System]
Pulse: 6 - 30ns(FWHM)
Reprate: ~10kHz
Power: 300 - 420W

EUV chamber
MOPA YAG laser system

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**History of LPP Source Development (4)**

- EUV conversion efficiency (solid target) demonstrated in EUVA (2005)
- EUV conversion efficiency simulation by Osaka Univ. team (2006)
1. High ionization rate and CE EUV Sn plasma generated by CO$_2$ and solid laser dual shooting

2. Hybrid CO$_2$ laser system with short pulse high repetition rate oscillator and commercial cw-amplifiers

3. Accurate shooting control with droplet and laser beam control

4. Sn debris mitigation with a super conductive magnetic field

5. High efficient out of band light reduction with grating structured C1 mirror
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Droplet Technology (1)

- The **Droplet Generator** is one of the key technologies for achieving HVM level EUV light sources.
- **Requirement for droplet generator**
  - **Size of droplet** is $20\mu m$:
    - Smaller droplet is better
    - Debris mitigation
    - Longer lifetime of droplet generator
  - Technical barrier is higher
    - Clogging due to smaller nozzle
  - **Stability** is $\pm 20\mu m$:
    - Short and long term stability is necessarily to achieve stable dose control

![Diagram of Ar Pressurization ~ 10MPa, Tank, Tin (Sn), Heater, Droplet, Nozzle, Piezo Actuator]
Droplet Technology (2)

- 100 kHz, 20 μm droplet generation was confirmed
- Short & middle term stability was confirmed
  » Good margin compare to the target ±20 μm
  » No clogging / stability change even with cool down & re-start
Based on basic physical consideration and experiments, Gigaphoton has chosen to adopt the pre-pulse technology since 2009.

In 2012 Gigaphoton discovered that shortening the pre-pulses duration dramatically enhance the conversion efficiency in low repetition rate (2Hz).

We are achieving this high Ce operation under high repetition rate, high duty cycle operation condition.
Pre-Pulse Technology (2)

Fragment distribution measurement and modeling

- The mist shape of a picosecond pre-pulse is different from the nanosecond pre-pulse (ps = dome vs. Ns=thin disk or ring)
- Fragment distribution could be a key factor for high CE

<table>
<thead>
<tr>
<th>Pulse energy</th>
<th>10 ps</th>
<th>10 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>delay</td>
<td>1 μs</td>
<td>2 μs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>60° view</th>
<th>20 ns</th>
<th>10 ps</th>
<th>10 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Liquid Tin moves to opposite of pre-pulse plasma expansion.

Liquid deformation speed ~1000 m/s (Sonic speed)

Thicker disk like fragment

~220 μm (~100 ns) km/s

Thinner isotropic Spherical fragment

~50 μm (~10 ps) km/s

All laser energy irradiated before plasma expansion

Pre-pulse plasma Expansion ~50 nm (~10 ps x 5 km/s)

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Pre-Pulse Technology (3)

Experiment shows picosecond pre-pulse dramatically enhances ionization rate and CE

Sn Droplet Smash

- Dome like target
- Flat disk like target

Data in 10 Hz Experimental Device

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CO$_2$ laser driver Technology (2)

CO$_2$ laser driver system test result

![Graph showing Proto#2 performance and Pulse waveform](image)

![Beam Profile images](image)

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Debris Mitigation Technology (1)

Gas mitigation method

EUV collector mirror

Droplet

Hydrogen Gas flow
100slm, 100Pa

CO2 Laser

Sn atom

Sn ion

Sn deposition

Figure 10: Hydrogen buffer gas pressure vs. ion energy and flux at the location of the collector surface

Debris Mitigation Technology (2)

- Issue with previous gas mitigation techniques

The Vicious Circle of Mitigation and Output Power

- Higher Power
  - Stronger shock wave
  - Droplet instability
  - Lower shooting accuracy
  - Increase fragment and deposition
  - Increase Hydrogen pressure to compensate

Gigaphoton has broken this vicious circle by developing the Magnetic Debris Mitigation system.
Debris Mitigation Technology (3)

Gigaphoton’s Magnetic Debris Mitigation concept

**Higher CE and Power**
- Optimum wavelength to transform droplets into fine mist
- Higher CE achievement with ideal expansion of the fine mist

**Long Life Chamber**
- Debris mitigation by magnetic field
- Ionized tin atoms are guided to tin catcher by magnetic field

- **Droplet (liquid)**
  - Pre-pulse laser
  - droplet <20μm

- **Fine-mist (liquid)**
  - main-pulse laser
  - mist size <300μm
  - 100% vaporization to atom
  - CO₂ laser irradiation ~100% ionization

- **Plasma (gas)**
  - Ions with low energy trapped by B field
  - Remaining atoms to mirror etched by gas

- **No Fragments**
- **Atom ~0**
- **Ion ~0**

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Debris Mitigation Technology (4)

Gigaphoton’s unique magnetic field + gas etching technology

- The collector mirror lifetime (i.e. debris mitigation technology) is one of the key items for reducing cost of consumables for HVM
- Gigaphoton’s unique technology for debris mitigation:
  » Magnetic field to catch Sn ion/atom
  » H* gas to etch out Sn atom

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Debris Mitigation Technology (5)

EUV Light Source for Debris Mitigation Testing

Mounting the collector mirror

Clean area is maintained during day level operation

After 27Mpulse/3days with P(I/F)=10W@20kHz

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Debris Mitigation Technology (6)

Debris mitigation: SEM image

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center of collector mirror SEM x10,000</td>
<td>0.1nm/MplS</td>
<td>0.075nm/MplS</td>
<td>0.003nm/MplS</td>
<td>0.002nm/MplS</td>
</tr>
<tr>
<td>Lower</td>
<td>8.7nm/MplS</td>
<td>1.1nm/MplS</td>
<td>0.62nm/MplS</td>
<td>0.67nm/MplS</td>
</tr>
<tr>
<td>Upper</td>
<td>4.1nm/MplS</td>
<td>0.16nm/MplS</td>
<td>0.012nm/MplS</td>
<td>0.008nm/MplS</td>
</tr>
<tr>
<td>C6 sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ion catcher side</td>
<td>25.1nm/MplS</td>
<td>18.8nm/MplS</td>
<td>25.9nm/MplS</td>
<td>9.9nm/MplS</td>
</tr>
</tbody>
</table>

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Debris Mitigation Technology (7)

Analysis: Tin Ion Catcher

- Tin depositions re-introduced from the ion catcher accumulates on the collector mirror
- We are improving the tin ion catcher mechanism to address this issue
Collector Mirror Technology (1)

Collector Mirror progress

IR Reduction Technology is Advancing

Gigaphoton is developing IR reduction mirror in co-operation with multiple mirror suppliers.

Gigaphoton’s Patent Pending IR Reduction Technology
Collector Mirror status

- Collector mirror with grating structure (V5 type) was successfully developed. Efficiency from plasma to clean would be improved from 21.6% to 26.7%.

<table>
<thead>
<tr>
<th>Appearance</th>
<th>EUV Reflectivity</th>
<th>IR Reflectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>V5-E002</td>
<td><img src="image1" alt="EUV reflectivity graph" /></td>
<td><img src="image2" alt="IR reflectivity graph" /></td>
</tr>
<tr>
<td>V5-E003</td>
<td><img src="image3" alt="EUV reflectivity graph" /></td>
<td><img src="image4" alt="IR reflectivity graph" /></td>
</tr>
</tbody>
</table>

*Values: 44.4%, 0.61%, 45.1%, 0.37%*
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High Power EUV Light Source of Gigaphoton

- Proto type of high power EUV light sources are in operation

  Proto 1 Exposure & Mitigation test
  Proto 2 High power Experiment
## Proto Systems in Operation

### Target System Specifications

<table>
<thead>
<tr>
<th>Operational Specification</th>
<th>Proto #1</th>
<th>Proto #2</th>
<th>Customer Beta Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Performance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EUV Power</td>
<td>25 W</td>
<td>100 W</td>
<td>250 W</td>
</tr>
<tr>
<td>CE</td>
<td>3%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>100 kHz</td>
<td>100 kHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Output angle</td>
<td>Horizontal</td>
<td>62° upper (matched to NXE)</td>
<td>62° upper (matched to NXE)</td>
</tr>
<tr>
<td>Availability</td>
<td>1 week operation</td>
<td>1 week operation</td>
<td>&gt; 75%</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Droplet generator</td>
<td>20 – 25 μm</td>
<td>20 μm</td>
<td>&lt; 20 μm</td>
</tr>
<tr>
<td>CO2 laser</td>
<td>&gt; 8 kW</td>
<td>&gt; 12 kW</td>
<td>25 kW</td>
</tr>
<tr>
<td>Pre-pulse laser</td>
<td>picosecond</td>
<td>picosecond</td>
<td>picosecond</td>
</tr>
<tr>
<td>Debris mitigation</td>
<td>validation of magnetic mitigation in system</td>
<td>10 days</td>
<td>15 days</td>
</tr>
</tbody>
</table>

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Driver Laser System Configuration

- **Proto#1**
  - 5kW CO2 power at 100kHz by 2 MA CO2 laser system.

- **Proto#2**
  - 17kW CO2 power at 100kHz by 3 MA CO2 laser + Mitsubishi pre-Amplifier system.

- **Pilot#1 (Designing)**
  - 25kW CO2 power at 100kHz by using Mitsubishi amplifier system.

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Laser system: CO2 laser, Pre pulse laser, Optics

EUV Chamber system
- Vessel, Collector mirror, Droplet generator, Magnet

Driver Laser System Configuration

- Oscillator
- Isolator
- Pre-amplifier
- MA1
- MA2
- MA3

Beam transfer system
20kHz, 50% D/C: EUV Power Operation Data

- 42W in burst, 21W average (42W x 50%) output power for 3 hours (110Mpls)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep. rate</td>
<td>20kHz</td>
</tr>
<tr>
<td>EUV energy (ave.)</td>
<td>9.79mJ</td>
</tr>
<tr>
<td>IF power @ clean</td>
<td>42W</td>
</tr>
<tr>
<td>CO2 energy (ave.)</td>
<td>273mJ</td>
</tr>
<tr>
<td>CE</td>
<td>3.6%</td>
</tr>
<tr>
<td>EUV stability (3s)</td>
<td>14%</td>
</tr>
<tr>
<td>Pulse number</td>
<td>110Mpls</td>
</tr>
<tr>
<td>DLG</td>
<td>CJ1551-3</td>
</tr>
<tr>
<td>Droplet diameter</td>
<td>25um</td>
</tr>
<tr>
<td>Droplet spacing</td>
<td>500um</td>
</tr>
<tr>
<td>DL catcher</td>
<td>Type C</td>
</tr>
<tr>
<td>Ion catcher</td>
<td>Type D (L=200)</td>
</tr>
</tbody>
</table>

20KHz 50% duty (10000pls/0.5ms OFF)
60kHz, 70% D/C: EUV power operation data

- 118W output with 3.7% CE, 60kHz, 70% duty cycle (Clean power in burst)
- 83W (=118W x 70%) average power output.

**EUV clean power**

- 0.4sec ON, 0.167sec OFF

**Pulse data in burst**

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Potential: Higher Duty Cycle Operation

60kHz, 0.167sec OFF

80% duty

50% duty

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Potential: Higher Repetition Rate Operation

50% duty

- EUV clean power (W)
- Repetition rate (kHz)

70kHz

- EUV plasma energy (mJ)
- Pulse number

20kHz

- EUV plasma energy (mJ)
- Pulse number
# EUV average power improvement and potential

**Note:** C1 mirror was changed to V5 from V3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EUV average power</strong></td>
<td>3W</td>
<td>46W</td>
<td><strong>21W</strong></td>
<td><strong>83W</strong></td>
<td>(112W)</td>
</tr>
<tr>
<td><strong>EUV clean power</strong></td>
<td>60W</td>
<td>92W</td>
<td><strong>42W</strong></td>
<td><strong>118W</strong></td>
<td>(140W)</td>
</tr>
<tr>
<td><strong>Duty cycle</strong></td>
<td>5%</td>
<td>50%</td>
<td>50%</td>
<td>70%</td>
<td>80%</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>50kHz</td>
<td>50kHz</td>
<td>20kHz</td>
<td><strong>60kHz</strong></td>
<td>70kHz</td>
</tr>
<tr>
<td><strong>CE</strong></td>
<td>3.7%</td>
<td>4.2%</td>
<td>3.6%</td>
<td><strong>3.7%</strong></td>
<td>3.7%</td>
</tr>
<tr>
<td><strong>Operation time</strong></td>
<td>-</td>
<td>-</td>
<td><strong>3hour</strong></td>
<td>10min</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System parameter</th>
<th>Collector</th>
<th>Efficiency from plasma to clean</th>
<th>H2</th>
<th>CO2 power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>V3</strong></td>
<td>21.6%</td>
<td>21.6%</td>
<td>7Pa</td>
<td>7.6kW</td>
</tr>
<tr>
<td><strong>V3</strong></td>
<td>21.6%</td>
<td>21.6%</td>
<td>7Pa</td>
<td>10kW</td>
</tr>
<tr>
<td><strong>V3</strong></td>
<td>21.6%</td>
<td>21.6%</td>
<td>7Pa</td>
<td><strong>5.4kW</strong></td>
</tr>
<tr>
<td><strong>V5</strong></td>
<td><strong>31.6%</strong></td>
<td>31.6%</td>
<td>11Pa</td>
<td><strong>10.2kW</strong></td>
</tr>
<tr>
<td><strong>V5</strong></td>
<td><strong>31.6%</strong></td>
<td>31.6%</td>
<td>11Pa</td>
<td>12.0kW</td>
</tr>
</tbody>
</table>

**Remark:** EUV average power = EUV clean power x duty cycle, open loop F/B
Out of band DUV filter condition was revised since Oct.2014 data.
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Summary
EUV Power achievement and Target

Consistent results have been demonstrated for the last 9 quarters
Next target is 12 kW by upgrading the pre-amplifier (installation is on going now)

<table>
<thead>
<tr>
<th>Target at Plasma</th>
<th>System</th>
<th>Oscillator</th>
<th>Pre-Amplifier</th>
<th>Main Amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>5kW</td>
<td>Endurance Testing Platform</td>
<td>GPI</td>
<td>R</td>
<td>T</td>
</tr>
<tr>
<td>8kW</td>
<td>Power Up Testing</td>
<td>GPI</td>
<td>R</td>
<td>T</td>
</tr>
<tr>
<td>14kW</td>
<td>Power Up Testing</td>
<td>GPI</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>&gt;20kW</td>
<td>Customer Beta Unit</td>
<td>GPI</td>
<td>M</td>
<td>M</td>
</tr>
</tbody>
</table>

Validated performances at system
### Power-up Scenario of HVM Sources

We are achieving **solid** and **steady** progress towards realizing our HVM EUV source.

<table>
<thead>
<tr>
<th></th>
<th>EUV clean power</th>
<th>25W</th>
<th>43W</th>
<th>118W</th>
<th>150W</th>
<th>250W</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
<td>2013, Q4</td>
<td>2014, Q1</td>
<td>2014, Q3</td>
<td>2014, Q4</td>
<td>2015, Q2</td>
<td></td>
</tr>
<tr>
<td><strong>CO₂ power at plasma</strong></td>
<td>5kW</td>
<td>8kW</td>
<td>10.2kW</td>
<td>&gt;14kW</td>
<td>&gt; 20kW</td>
<td></td>
</tr>
<tr>
<td><strong>CE</strong></td>
<td>2.5%</td>
<td>3%</td>
<td>3.7%</td>
<td>&gt;4.2%</td>
<td>&gt; 4.5%</td>
<td></td>
</tr>
<tr>
<td><strong>Plasma to IF clean</strong></td>
<td>21.7%</td>
<td>21.7%</td>
<td>31.6%</td>
<td>31.6%</td>
<td>35.1%</td>
<td></td>
</tr>
<tr>
<td><strong>CO₂ laser</strong></td>
<td>2 main amp.</td>
<td>3 main amp.</td>
<td>Mitsubishi pre. amp.: Proto#2</td>
<td>Mitsubishi pre. amp.: Proto#2</td>
<td>Mitsubishi main amp. system</td>
<td></td>
</tr>
<tr>
<td><strong>system</strong></td>
<td>system: Proto#1</td>
<td>system: Proto#2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Collector mirror</strong></td>
<td>Normal Type</td>
<td>Normal Type</td>
<td>Grating Type</td>
<td>Grating Type</td>
<td>Grating Type</td>
<td></td>
</tr>
</tbody>
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Summary

• Progress of component technology;
  » Improvement of debris mitigation is reported; 4 hrs. continuous operation, deposition sampled at mirror center area was less than 0.006nm/MPLs.
  » Improvement data of IR reduction corrector mirror is reported
  » Driver CO2 laser power at plasma point is improved from 10kW to 17kW

• Verified high output EUV light on Proto#2 unit
  » New Data: 118W (CE3.7%) x 70%duty, 83W average power x10min
  » and 42Wx3hours, clean output at IF under 50%Duty* were reported.
  » Next step is to enable higher duty cycle and higher repetition rate operations. Potential data is reported.

• Design of the development pilot#1 is reported.

* Percentage of EUV emission during operation
Acknowledgements

Thanks for your co-operation:

Mitsubishi electric CO₂ laser amp. develop. team: Dr. Yoichi Tanino*, Dr. Junichi Nishimae, Dr. Shuichi Fujikawa and others.

* The authors would like to express their deepest condolences to the family of Dr. Yoichi Tanino who suddenly passed away on February 1st, 2014. We are all indebted to his incredible achievements in CO₂ amplifier development. He will be missed very much.

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