Update of High Ce, High Power HVM LPP–EUV Source Development

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2013.11.05.
Agenda

- Introduction
- LPP source technologies progress
  - Concept of Gigaphoton LPP source
  - Droplrt generator
  - High CE Pre-pulse
  - Magnetic mitigation technology
  - High Power Laser
  - Corrector Mirror and IR Reduction
  - Extendibility to 1kW EUV power
- Update of LPP source development
  - High power EUV source systems
    - Device #1
    - Device #2
- Summary
Introduction

- LPP source technologies progress
  - Concept of Gigaphoton LPP source
  - Droplrt generator
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  - Magnetic mitigation technology
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Update of LPP source development

- High power EUV source systems
  - Device #1
  - Device #2

Summary
Finer patterning is realized by shorter wavelength

\[ R = K_1 \frac{\lambda}{n} \frac{1}{NA} \]

( Rayleigh Formula )

<table>
<thead>
<tr>
<th>Light Source</th>
<th>k₁</th>
<th>n</th>
<th>Medium</th>
<th>λ/n nm</th>
<th>NA</th>
<th>Power</th>
</tr>
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<tbody>
<tr>
<td>KrF dry</td>
<td>124</td>
<td>1</td>
<td>Air</td>
<td>248</td>
<td>0.8</td>
<td>40</td>
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<tr>
<td>ArF dry</td>
<td>103</td>
<td>1</td>
<td>Air</td>
<td>193</td>
<td>0.75</td>
<td>45</td>
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<tr>
<td>F₂ dry</td>
<td>84</td>
<td>1</td>
<td>N₂</td>
<td>157</td>
<td>0.75</td>
<td>–</td>
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<tr>
<td>ArF immersion</td>
<td>40</td>
<td>1.44</td>
<td>H₂O</td>
<td>134</td>
<td>1.35</td>
<td>90</td>
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<tr>
<td>EUV (λ=13.6nm)</td>
<td>18</td>
<td>1</td>
<td>Vacuum</td>
<td>13.6</td>
<td>0.3</td>
<td>&gt;250</td>
</tr>
<tr>
<td>EUV (λ=13.6nm)</td>
<td>9</td>
<td>1</td>
<td>Vacuum</td>
<td>13.6</td>
<td>0.6</td>
<td>&gt;500</td>
</tr>
<tr>
<td>EUV (λ=7.6nm)</td>
<td>4.5</td>
<td>1</td>
<td>Vacuum</td>
<td>7.6</td>
<td>0.6</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>
EUV Lithography and light source (2)

Light source issue in EUV lithography

EUV light transmittance is only 2% at 11 reflection mirror system

High power light source for HVM exposure tools is the KEY Issue

Demand: >250W at 1st stage HVM

SiO2, CaF2
>30 lenses and few mirrors
NA=0.85—1.35

Imaging (30)
0.98^{30}=0.55

Imaging (30) + Illumination (20)
0.98^{50}=0.36

Mo/Si multilayer
6-8 mirrors
NA=0.25—0.35

Imaging (6)
0.70^{6}=0.11

Imaging (6) + Illumination + Mask (5)
0.70^{11}=0.02

X-ray Bragg reflection by crystal
EUV reflection by multi-layer coating

70% Reflection

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- Corrector Mirror and IR Reduction
- Extendibility to 1kW EUV power

Update of LPP source development
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  - Device #1
  - Device #2

Summary
Concept of Gigaphoton LPP Light Source

1. Combined use of Sn droplets & pulsed CO$_2$ lasers
2. Stable 20mm droplet supply with Droplet Generator (DLG)
3. Dual wavelength (pre-pulse & main pulse) LPP plasma
4. Accurate shooting control with droplet and laser beam control
5. Perfect ionization and magnetic plasma mitigation
Pre-pulse & Magnetic Mitigation Technology

Ideal concept for High Power and Minimal Debris, suitable for HVM

**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

**Plasma (gas)**
- CO₂ laser irradiation
- ~100% ionization
- No Fragments
- Atom ~0

**Magnetic Field Ion Guiding**
- Ions with low energy trapped by B field
- Ion ~0

**Gas Etching**
- Remaining atoms to mirror etched by gas

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GPI is developing two types of tin droplet generators

- Droplet-on-Demand (DoD) technology is our goal for production tools
- Continuous Jet (CJ) is for the acceleration of system development except debris mitigation system
Droplet Generator Technology (2)

Over 70h operation was confirmed
- At Proto system with position control
- No deterioration found after 70h operation

Around 0 hr.

![Graph showing droplet position over operation time around 0 hr.]

Around 70 hr.

![Graph showing droplet position over operation time around 70 hr.]

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Pre-Pulse technology (1)

- 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.

![Diagram showing CO2 laser, pre-pulse laser, main-pulse, and droplet generator.]

**Graph: CO2 pulse energy vs. EUV-CE**

- Pre-pulse laser
- 10 ps
- 10 ns

**EUV-CE average (%)**

**CO2 laser pulse energy (mJ)**

0 50 100 150 200
Pre-Pulse Technology (2)

Fragment distribution measurement

- 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>2.0 mJ</td>
<td>2.7 mJ</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>delay</th>
<th>1 µs</th>
<th>2 µs</th>
<th>1 µs</th>
<th>2 µs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>500 µm</td>
<td></td>
<td>500 µm</td>
<td></td>
</tr>
<tr>
<td>90° view</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Modeling of pre-pulse plasma

- Liquid Tin move to opposite of pre-pulse plasma expansion
- Liquid deformation speed ~1000 m/s (Sonic speed)
- All laser energy irradiated before plasma expansion
- Pre-pulse plasma Expansion ~60 nm (~10 ps x 5 km/s)
- Thinner isotropic Spherical fragment
- Fragment expansion
Pre-Pulse Technology (3)

Neutral atoms measurement: ionization ratio is investigated
Pre-Pulse Technology (4)

Experiment shows pico-second pre-pulse dramatically enhances ionization rate and CE

Sn Droplet Smash

- Dome like target: psec laser, 300um
- Flat disk like target: nsec laser, 300um

Data in 10Hz Experimental Device

Ionization performance

- CO2 pulse energy on droplet vs. Ionization rate
  - ns-pulse laser
  - ps-pulse laser

Conversion efficiency (%)

- CO2 pulse energy (mJ) vs. Conversion efficiency (%)
  - ns-pulse laser
  - ps-pulse laser

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Pre-Pulse Technology (5)

Expanding distribution of Tin mist (10ns vs. 10ps)

Remarkable reduction of mist is demonstrated by the pico-second pre-pulse.

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Magnetic Mitigation Technology

Generated ion is corrected at Ion catcher

Magnetically guided ion are clearly corrected by ion catcher at both end of magnetic pole.

- 4.86Mpls (50kHz, 30% duty, 324sec)
- Pre-pulse 3.1mJ, CO2 laser 54mJ, DL=φ 30um,
Gigaphoton, in cooperation with CW-\(\text{CO}_2\) laser companies, has been jointly developing a unique high power pulsed \(\text{CO}_2\) laser system since 2004.

**Driver Laser System**

Gigaphoton Oscillator Laser

Amplifier Lasers

Pre-pulse Laser

Timing Controller

DLG

**Main Pulse \(\text{CO}_2\) Laser System**

**Reported by Dr. Krysztof M Nowak at P-SO-60**
High Power CO$_2$ Laser Technology (2)

Amplifier System A: experiment on present system using Trumpf amplifier laser

Performance data with 3x MA

- 10kW performance was confirmed during hour level operation
  - Pulsed CO$_2$ laser system experiment with Gigaphoton oscillator laser and Trumpf amplifiers x3 units laser system.

- Next challenge
  - Confirm operation at target shooting
  - Further power improvement

Gigaphoton Oscillator Laser

<table>
<thead>
<tr>
<th>OSC</th>
<th>EO isolator</th>
<th>PA</th>
<th>MA#1</th>
<th>MA#2</th>
<th>MA#3</th>
</tr>
</thead>
</table>

Amplifier Lasers

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High Power CO$_2$ Laser Technology (3)

Amplifier System B: Laboratory level experiment with Mitsubishi electric amplifier laser

Performance data with 3x MA System-B

- 20kW performance was confirmed at minute level
  - Pulsed CO$_2$ laser system experiment with Gigaphoton oscillator laser and 4 Mitsubishi amplifier laser system
    (Data is reported EUV symposium 2013 in Toyama)

- Next challenge
  - Achieve 25kW level
  - Field level integration
  - Confirm operation while shooting at Sn target
Corrector Mirror Progress

**IR Reduction Technology is advancing:**
- Gigaphoton is developing IR reduction mirror co-operate with multiple mirror supplier.
- Rigaku demonstrated efficient and dramatic IR reduction by grating on the mirror surface – Prefabrication test is completed. (Data is reported EUV symposium 2013 in Toyama)
- Next step is prototype fabrication and evaluation.

**IR Reduction Technology**

![Graph showing out of band spectrum of LPP EUV source](image)

- Test Optic (no grating) S-Polarized AOI 5° avg = 66%
- Test Optic (no grating) Unpolarized AOI 7-35° avg = 54.9%
- Demo Optic with IR Rejection Unpolarized AOI 7-35° avg = 50.9%

(Patent pending by Gigaphoton)
Extendibility to 1kW EUV Power (1)

Feasibility study of EUV Output Power vs. CO2 Input Power

Feasibility study of extendibility to 1kW

- Conversion efficiency is Key. At least achievement of CE > 4% is essentially important. If not, CO2 laser will become > 100kW.

- At least > 50kW CO2 laser power must be realized. Even in best case of CE = 8%.

- I believe; 1000W EUV source is feasible in future, from the technical data (experiment of CE and CO2 laser) and technical expectation at present.
Extendibility to 1kW EUV Power (2)

Possible scale up scenario of EUV Output Power vs. CO₂ Input Power

<table>
<thead>
<tr>
<th>EUV ave.Power [W] @100kHz</th>
<th>Conversion Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>15</td>
<td>1.5</td>
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<tr>
<td>50</td>
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<td>100</td>
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<td>1000</td>
<td>100</td>
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<table>
<thead>
<tr>
<th>CO₂ laser ave. Power [kW]</th>
<th>Conversion Efficiency [%]</th>
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<tr>
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<td>1.5</td>
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<td>95</td>
</tr>
<tr>
<td>1000</td>
<td>100</td>
</tr>
</tbody>
</table>

HVM (1st) | HVM (2nd) | HVM (3rd)
---|---|---
EUV power | 250W | 500W | 1000W
CE | 4% | 5% | 6%
Pulse rate | 100 kHz | 100kHz | 100kHz
Pre-pulse laser | Pico-s | Pico-s | Pico-s
CO₂ laser power | 25kW | 40kW | 65kW
# of main amps | 3 | 5 | 8

Our possible scale-up scenario
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    - Device #2
- Summary
High Power EUV Source Systems (1)

Layout of 250W EUV light source

First HVM EUV Source

- We are developing 250W EUV source.
- Target timing 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>
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<tr>
<td>CE</td>
<td>&gt; 4.0%</td>
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<tr>
<td>Pulse rate</td>
<td>100kHz</td>
</tr>
<tr>
<td>Availability</td>
<td>&gt; 75%</td>
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</table>

<table>
<thead>
<tr>
<th>Technology</th>
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</thead>
<tbody>
<tr>
<td>Droplet generator</td>
<td>Droplet size</td>
</tr>
<tr>
<td>CO2 laser</td>
<td>Power</td>
</tr>
<tr>
<td>Pre-pulse laser</td>
<td>Pulse duration</td>
</tr>
<tr>
<td>Debris mitigation</td>
<td>Magnet, Etching</td>
</tr>
</tbody>
</table>

EUV Exposure Tool

Operational specification (Target) HVM Source
Performance
EUV Power > 250W
CE > 4.0%
Pulse rate 100kHz
Availability > 75%

Technology
Droplet generator Droplet size < 20mm
CO2 laser Power > 20kW
Pre-pulse laser Pulse duration psec
Debris mitigation Magnet, Etching > 15 days (>1500Mpls)

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## System Specification (Target)

<table>
<thead>
<tr>
<th>Operational Specification (target)</th>
<th>#1 in PROTO-2</th>
<th>#2 in PROTO-2</th>
<th>PILOT HVM Source</th>
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<tbody>
<tr>
<td><strong>Performance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EUVPower</td>
<td>25W</td>
<td>&gt; 50W</td>
<td>250W</td>
</tr>
<tr>
<td>CE</td>
<td>3%</td>
<td>4%</td>
<td>4%</td>
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<tr>
<td>Pulse rate</td>
<td>100kHz</td>
<td>100kHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Output angle</td>
<td>horizontal</td>
<td>62 degrees upper (matched to NXE)</td>
<td>62 degrees upper (matched to NXE)</td>
</tr>
<tr>
<td>Availability</td>
<td>1 week (operation time)</td>
<td>1 week (operation time)</td>
<td>&gt; 75%</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dloplet generator</td>
<td>20 – 25 μm</td>
<td>20 μm</td>
<td>&lt; 20 μm</td>
</tr>
<tr>
<td>CO2 laser</td>
<td>&gt; 8kW</td>
<td>&gt; 12kW</td>
<td>25kW</td>
</tr>
<tr>
<td>Pre-pulse laser</td>
<td>picosecond</td>
<td>picosecond</td>
<td>picosecond</td>
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<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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High Power EUV Source Systems (3)

Status of proto light sources, #1 and #2

- System #1 : For EUV irradiation experiment (Operational)
  - The whole system (lasers and chambers) is working now
  - There are some issues and improvement activity is in progress

- System #2 : For high power development (Under construction)
  - The design and procurement was finished
  - The assembly will be finish soon
  - After the initial adjustment, the first EUV emission will be in this Q4
High Power EUV Source Systems (4)

In-burst Power performance improvement at proto #1

Nov. 2012

1.0mJ

1.0mJ

30000pls

Mar. 2012

30000pls

Aug. 2013

30000pls

50000pls

4.3W*, 100kHz
*:EUV Clean power @I/F

6.5W*, 50kHz
*:EUV Clean power @I/F

15W*, 100kHz
ON/OFF=0.5s/0.5s
Duty=50%, CE=1.5%
*:EUV Clean power @I/F

Shooting control and stabilization A

Shooting control and stabilization B

Improve pre-pulse laser

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High Power EUV Source Systems (5)

Latest update on power and conversion efficiency (CE)

• 15W* (100kHz) EUV power in burst (50% duty) was achieved.
• CE is 1.5%. Now we are improving CE >2.5% by optimizing shooting conditions.
• Higher CE gives high ionization rate to activate magnet mitigation properly.

* EUV Clean power at I/F[W]
High Power EUV Source Systems (6)

Status of proto light sources, #1 and #2

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Extendibility of LPP-EUV source power is discussed

- High CE technology
  - Demonstrated remarkable reduction of mist after the pico-second pre-pulse.
- Magnetic mitigation is working well in proto-2
- High power CO2 driver laser technology
  - For >500W EUV source, New 40kW CO2 laser amplifier development project started co-operation with Mitsubishi electric.
  - Target is 25kW until Q1 2013.6 20kW@S/L output is observed after 4-amplifier
- Progress of corrector mirror and IR reduction technology is reported.
- Possible scenario of 1000W EUV source is reported

- Gigaphoton LPP source:
  - Droplet generator is improved dramatically, stable operation >100h is demonstrated.
  - CO2 laser achieved 10kW operation with 75% duty.
  - EUV light emission 15 W (@1/F Clean power in 50% duty burst 100kHz) is achieved.
  - Proto-2 #2 is under construction
  - Proto-2 target is 25W level one week operation demonstration by Q4 2013.

- Gigaphoton’s shipment target of pilot is 2015.
Acknowledgement

- Thanks for co-operation
  Dr. Akira Endo, Waseda University (Tokyo) & HiLase Project (Prague)
  Prof. Masakazu Washio, Waseda University

- Thanks for my colleagues in Hiratsuka facility
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  Tatsuya Yanagida, Tsuyoshi Yamada, Taku Yamazaki and Takashi Saitou

- Thanks for technical advice
  Dr. Shinji Okazaki

- Thanks for Cooperation of Mitsubishi electric CO2 laser amplifier development team

- EUV source development funding is partially support by NEDO in JAPAN.
THANK YOU