Femtosecond laser pre-pulse technology for LPP EUV source


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International Workshop on EUV Sources, UCD Dublin, November 3-6, 2014
FS Laser

<table>
<thead>
<tr>
<th>Laser</th>
<th>Generator</th>
<th>Tsunami</th>
<th>Spectra Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regenerative amplifier</td>
<td>Spitfire</td>
<td>Spectra Physics</td>
<td></td>
</tr>
<tr>
<td>Autocorrelator</td>
<td>Pulse Scout</td>
<td>Spectra Physics</td>
<td></td>
</tr>
</tbody>
</table>

Laser parameters:
- Wavelength: 800 nm
- Pulse energy: 2.3 mJ
- Duration (FWHM): 50 fs ÷ 80 ps
- Gaussian beam energy profile
- Minimum focal spot size at F=200 mm (FWHM): 50 um
- Average power density in focal spot: $3 \times 10^{15}$ W/cm²
- PRD: 1 kHz

Droplet:
- Sn-In eutectic alloy (48%/52% atomic composition)
- Operating temperature: 140°C
- Size $\varnothing$: 40, 50, 60, 70 um
- Velocity: ≈ 2-4 m/s
- Interaction zone: ≈ 1 cm from nozzle.
In-Sn eutectic alloy can be used in modeling experiments for Sn droplet in pre-pulse technology of LPP EUV sources.

### Physical quantity

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>In</th>
<th>Sn</th>
<th>Δ, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>49</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>Atomic weight</td>
<td>114.82</td>
<td>118.71</td>
<td>3.3</td>
</tr>
<tr>
<td>Density (near r.t.), g*cm³</td>
<td>7.31</td>
<td>7.36</td>
<td>0.7</td>
</tr>
<tr>
<td>Liquid density (at melting point), g*cm³</td>
<td>7.02</td>
<td>6.99</td>
<td>0.4</td>
</tr>
<tr>
<td>Molar heat capacity, J<em>mol⁻¹</em>K⁻¹</td>
<td>26.74</td>
<td>27.11</td>
<td>1.1</td>
</tr>
<tr>
<td>Atomic radius, pm</td>
<td>142</td>
<td>139</td>
<td>2.1</td>
</tr>
<tr>
<td>Surface tension, din*cm⁻¹</td>
<td>559</td>
<td>554</td>
<td>0.9</td>
</tr>
<tr>
<td>Melting point, °C</td>
<td>156.6</td>
<td>231.9</td>
<td>16</td>
</tr>
</tbody>
</table>

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### Ionization potentials

<table>
<thead>
<tr>
<th>Ionization potentials</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>5.78</td>
<td>18.8</td>
<td>28.0</td>
<td>58</td>
<td>77</td>
<td>98</td>
<td>120</td>
<td>144</td>
<td>178</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>7.33</td>
<td>14.6</td>
<td>30.7</td>
<td>46.5</td>
<td>81</td>
<td>103</td>
<td>126</td>
<td>150</td>
<td>176</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>22</td>
<td>8.9</td>
<td>19.8</td>
<td>3.7</td>
<td>4.9</td>
<td>4.8</td>
<td>4</td>
<td>1.1</td>
<td>4.2</td>
</tr>
</tbody>
</table>

### Physical quantity

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Sn (300°C)</th>
<th>In–Sn alloy (200°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface tension, din/cm</td>
<td>538</td>
<td>534</td>
</tr>
<tr>
<td>Kinematic viscosity, cSt</td>
<td>0.24</td>
<td>0.25</td>
</tr>
</tbody>
</table>

- Main physical properties of In, Sn and In-Sn alloy are very similar.
- Replacement of Sn on In-Sn eutectic alloy allows to use much more reliable experiments because of lower work temperature.
- The alloy may be used as working substance in LPP EUV source. Conversion efficiency of LPP EUV source by using the alloy is about 70% from one by using pure Sn as working substances.

In-Sn eutectic alloy can be used in modeling experiments for Sn droplet in pre-pulse technology of LPP EUV sources.
Multistage hit technology of laser beam into droplet

1- FS laser, 2- DG, 3- vacuum chamber, 4- driving generator, 5- frequency divider, 6- delay generator, 7- DG controller, 8- diode laser (IL30C, 850nm, 30ns), 9- long distance microscope (K2 DistaMax), 10- CCD camera (Manta MG-145B), 11- Faraday cup, 12- ion spectrograph, 13- pump, 14- tungsten filament, 15- beam formation optics (diffuser+lens), 16- band pass filter (850nm).
Droplet generator operation

DoD type nozzle based on annular piezoelectric actuator (MJ-SF-002 MicroFab Tech)

Shadow stroboscopic images 60um droplet

8 Hz, 10mm from nozzle

Pulse train at 5kHz run, \( v \approx 2.5 \text{ m/s} \)

\[ \sigma_z \approx 15 \text{ um} \]
\[ \sigma_r < 5 \text{ um} \]

Drive voltage pulse

Observed area 4.7 x 3.5 mm,
Spatial resolution 3.7 um
Exposure time (laser pulse duration) 30 ns

We have more than 6 controlled parameters of driving pulse!
## Sets of used experimental parameters

<table>
<thead>
<tr>
<th>Variable parameters:</th>
<th>Constant parameter:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Droplets size</td>
<td>PRR of DG</td>
</tr>
<tr>
<td>- Laser pulse durations</td>
<td>8 Hz</td>
</tr>
<tr>
<td>- Laser pulse energy</td>
<td>PRR of FS laser</td>
</tr>
<tr>
<td>- Focal spot sizes</td>
<td>1 kHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Droplets size</th>
<th>Laser pulse durations</th>
<th>Laser pulse energy</th>
<th>Focal spot sizes</th>
<th>Delay between FS and diagnostic lasers</th>
<th>&gt;160 images in each delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø40 um, $E_{\text{las}}=2.3 \text{ mJ}$</td>
<td>1. 50 fs, 50 um</td>
<td>2. 200 fs, 50 um</td>
<td>3. 400 fs, 50 um</td>
<td>4. 800 fs, 50 um</td>
<td>5. 1.5 ps, 50 um</td>
</tr>
<tr>
<td>Ø50 um, $E_{\text{las}}=2.3 \text{ mJ}$</td>
<td>1. 50 fs, 50 and 100 um</td>
<td>2. 100 fs, 50 and 100 um</td>
<td>3. 200 fs, 50 and 100 um</td>
<td>4. 600 fs, 50 and 100 um</td>
<td>5. 1.5 ps, 50 and 100 um</td>
</tr>
<tr>
<td>Ø50 um, $E_{\text{las}}=0.4 \text{ mJ}$</td>
<td>1. 50 fs, 50 um</td>
<td>2. 100 fs, 50 um</td>
<td>3. 200 fs, 50 um</td>
<td>4. 400 fs, 50 um</td>
<td>5. 1.5 ps, 50 um</td>
</tr>
<tr>
<td>Ø60 um, $E_{\text{las}}=1.3 \text{ mJ}$</td>
<td>1. 50 fs, 50 and 100 um</td>
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<td>4. 400 fs, 50 and 100 um</td>
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<td>1. 50 fs, 50 um</td>
<td>2. 100 fs, 50 um</td>
<td>3. 200 fs, 50 um</td>
<td>4. 400 fs, 50 um</td>
<td>5. 1.5 ps, 50 um</td>
</tr>
<tr>
<td>Ø70 um, $E_{\text{las}}=2.3 \text{ mJ}$</td>
<td>1. 50 fs, 50 um</td>
<td>2. 100 fs, 50 um</td>
<td>3. 200 fs, 50 um</td>
<td>4. 400 fs, 50 um</td>
<td>5. 1.5 ps, 50 um</td>
</tr>
</tbody>
</table>
Droplet deformation at $\tau_{\text{las}} = 50$ fs

$E_{\text{las}} = 2.3 \text{mJ}$ $\varnothing 60 \text{ um}$

<table>
<thead>
<tr>
<th>Laser beam direction</th>
<th>Focal spot 50 um, $I = 3 \times 10^{15} \text{W/cm}^2$</th>
<th>Focal spot 100 um, $I = 7.5 \times 10^{14} \text{W/cm}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image1.png" alt="Image 1" /> $\Delta t = 2.0 \text{ us}$</td>
<td><img src="image2.png" alt="Image 2" /> $\Delta t = 3.0 \text{ us}$</td>
</tr>
<tr>
<td></td>
<td><img src="image3.png" alt="Image 3" /> $\Delta t = 4.0 \text{ us}$</td>
<td><img src="image4.png" alt="Image 4" /> $\Delta t = 7.0 \text{ us}$</td>
</tr>
</tbody>
</table>

$\Delta t$ – delay between FS laser and diagnostic diode laser.

The images at different delays belong to different droplets, but deformed images are reproduced very well.

Main difference from ns PP: deformed droplets have shape of hollow thin 3D shells!!
Droplet deformation at $\tau_{\text{las}} = 100$ fs

$E_{\text{las}}=2.3\text{mJ}$ $\varnothing 60\text{ um}$

Focal spot 50 um, $I=1.5\times10^{15}$ W/cm$^2$

Focal spot 100 um, $I=3.8\times10^{14}$ W/cm$^2$
Droplet deformation at $\tau_{\text{las}} = 200$ fs

$E_{\text{las}} = 2.3 \text{mJ}$  $\varnothing 60 \text{um}$

Focal spot 50 um, $I = 7.5 \times 10^{14} \text{ W/cm}^2$

$\Delta t = 1.0 \text{ us}$  $\Delta t = 2.0 \text{ us}$  $\Delta t = 3.0 \text{ us}$  $\Delta t = 4.0 \text{ us}$

Focal spot 100 um, $I = 1.8 \times 10^{14} \text{ W/cm}^2$

$\Delta t = 1.0 \text{ us}$  $\Delta t = 2.0 \text{ us}$  $\Delta t = 3.0 \text{ us}$  $\Delta t = 4.0 \text{ us}$
Droplet deformation at $\tau_{\text{las}} = 450$ fs

$E_{\text{las}} = 2.3 \text{mJ}$ $\varnothing 60 \text{ um}$

<table>
<thead>
<tr>
<th>Laser beam direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal spot 50 um, $I = 3.8 \times 10^{14} \text{ W/cm}^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta t$</th>
<th>1.0 us</th>
<th>2.0 us</th>
<th>3.0 us</th>
<th>4.0 us</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 um</td>
<td>500 um</td>
<td>500 um</td>
<td>500 um</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laser beam direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal spot 100 um, $I = 10^{14} \text{ W/cm}^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta t$</th>
<th>1.0 us</th>
<th>2.0 us</th>
<th>3.0 us</th>
<th>4.0 us</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 um</td>
<td>500 um</td>
<td>500 um</td>
<td>500 um</td>
<td></td>
</tr>
</tbody>
</table>
Droplet deformation at $\tau_{\text{las}} = 800$ fs

$E_{\text{las}}=2.3\text{mJ}$ $\varnothing 60\text{um}$

Focal spot 50 um, $I=1.8\times10^{14}$ W/cm$^2$

- $\Delta t = 1.0$ us
- $\Delta t = 2.0$ us
- $\Delta t = 3.0$ us
- $\Delta t = 4.0$ us

Focal spot 100 um, $I=0.45\times10^{14}$ W/cm$^2$

- $\Delta t = 1.0$ us
- $\Delta t = 2.0$ us
- $\Delta t = 3.0$ us
- $\Delta t = 4.0$ us
Droplet deformation at $\tau_{\text{las}} = 1.5$ ps

$E_{\text{las}}=2.3\text{mJ} \ 60\text{ um}$

Laser beam direction

Focal spot 50 um, I=$10^{14}$ W/cm²

$\Delta t = 1.0$ us

$\Delta t = 2.0$ us

$\Delta t = 3.0$ us

$\Delta t = 4.0$ us

Focal spot 100 um, I=$2.7\times10^{13}$ W/cm²

$\Delta t = 1.0$ us

$\Delta t = 2.0$ us

$\Delta t = 3.0$ us

$\Delta t = 4.0$ us
Droplet deformation at $\tau_{\text{las}} = 3$ ps

$E_{\text{las}}=2.3\text{mJ}$ $\varnothing 60 \text{um}$

Laser beam direction

Focal spot 50 um, $I=5\times10^{13}$ W/cm$^2$

Focal spot 100 um, $I=1.3\times10^{13}$ W/cm$^2$

$\Delta t = 1.0$ us

$\Delta t = 2.0$ us

$\Delta t = 3.0$ us

$\Delta t = 4.0$ us
Droplet deformation at $\tau_{\text{las}} = 5.3$ ps

$E_{\text{las}} = 2.3\text{mJ}$  $\varnothing 60$ um

Laser beam direction

Focal spot 50 um, $I = 2.8 \times 10^{13}$ W/cm$^2$

$\Delta t = 1.0$ us  $\Delta t = 2.0$ us  $\Delta t = 3.0$ us  $\Delta t = 4.0$ us

Focal spot 100 um, $I = 7.4 \times 10^{12}$ W/cm$^2$

$\Delta t = 1.0$ us  $\Delta t = 2.0$ us  $\Delta t = 3.0$ us  $\Delta t = 4.0$ us
Droplet deformation at $\tau_{\text{las}} \approx 80$ ps

$E_{\text{las}} = 2.3\text{mJ}$ \(\varnothing 60\text{ um}\)

Focal spot 50 um,
$I = 1.9 \times 10^{12} \text{W/cm}^2$

Laser beam direction

\begin{align*}
\Delta t &= 1.0 \text{ us} \\
\Delta t &= 2.0 \text{ us} \\
\Delta t &= 3.0 \text{ us} \\
\Delta t &= 4.0 \text{ us} \\
\Delta t &= 5.0 \text{ us} \\
\Delta t &= 6.0 \text{ us} \\
\Delta t &= 7.0 \text{ us}
\end{align*}
Shell expansion velocity vs pulse duration

$V_Z \approx 300 \text{ m/s}$
$V_{-Z} \approx 80 \text{ m/s}$
$V_R \approx 120 \text{ m/s}$

There is weak dependence of droplet expansion velocity on pulse duration at more than 1 ps. Dependence velocity on laser power density for ns lasers $V_Z \approx I^{2/3}$ is not working in this case!
Changing experimental parameters (size of droplet and focal spot, laser pulse duration, laser energy, delay) we can choose the optimal target shape for LPP EUV source from point of view max CE, min debris and high energy ions.

All shapes have been stable from pulse to pulse.

- **Dome**
  - $E_{\text{las}} = 2.3 \text{ mJ}$
  - SpotSize = 50 um
  - $\tau_{\text{las}} = 100 \text{ fs}$
  - $\Delta \tau = 3 \text{ us}$

- **Nut**
  - $E_{\text{las}} = 2.3 \text{ mJ}$
  - SpotSize = 50 um
  - $\tau_{\text{las}} = 200 \text{ fs}$
  - $\Delta \tau = 1 \text{ us}$

- **Medusa**
  - $E_{\text{las}} = 2.3 \text{ mJ}$
  - SpotSize = 100 um
  - $\tau_{\text{las}} = 200 \text{ fs}$
  - $\Delta \tau = 4 \text{ us}$

- **Blot**
  - $E_{\text{las}} = 1.3 \text{ mJ}$
  - SpotSize = 100 um
  - $\tau_{\text{las}} = 50 \text{ fs}$
  - $\Delta \tau = 10 \text{ us}$

- **Heart**
  - $E_{\text{las}} = 0.4 \text{ mJ}$
  - SpotSize = 50 um
  - $\tau_{\text{las}} = 50 \text{ fs}$
  - $\Delta \tau = 10 \text{ us}$

- **Mist**
  - $E_{\text{las}} = 0.4 \text{ mJ}$
  - SpotSize = 50 um
  - $\tau_{\text{las}} = 50 \text{ fs}$
  - $\Delta \tau = 4 \text{ us}$

Slide 17

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Ion flux measurements
• Total charge of ions flying against laser beam for 70 um droplets is much more than one for 40 um droplet.
• Total charge of ions flying against laser beam is much more than ones flying in along laser beam.
• There is min total charge at 800 fs pulse duration which correlates with max of shell expansion velocities.
High-energy ions fly only in the opposite direction to the propagation of the laser beam.
- Maximum number of the high-energy ions observed at 50 fs pulse.
- There is minimum of the high-energy ions at 800 fs pulse.
Ion spectrum measurements

Electrostatic ion energy analyzer based on a cylindrical capacitor

\[ E_{\text{ion}} = 1.25 \times Z \times U, \quad U - \text{deflection voltage}, \]
\[ 1.25 - \text{energy scaling factor} \]

- Detector
  - Faraday cup
- Input aperture
  - 1 mm
- Azimuth angle between laser beam and IS
  - 30°
- Angle in vertical plane to the laser beam
  - 17°
- Distance to the droplet
  - 500 mm

Ion source

\[ +U_a/2 \]

Axis path for specific energy ions

Grid

5mm aperture

Faraday cup

Transimpedance amplifiers
Oscillograms of ion beam current

Droplet \( \varnothing 50 \text{ um} \), focal spot size 50 um

\[ \tau_{\text{laser}} = 50 \text{ fs}, \ P=1.5 \times 10^{15} \text{ W/cm}^2 \ U = 800 \text{ V} \]

\[ \tau_{\text{laser}} = 400 \text{ fs}, \ P=3.8 \times 10^{14} \text{ W/cm}^2 \ U = 200 \text{ V} \]

Ion multiplicity for 50 fs pulse much more than for 400 fs pulse
Debris deposition

Number of pulses ≈ 25 000

Minimal size of observed debris = 90 nm

Electron microscope photos

Sample A (along laser beam direction)
60 um, 50 fs Mag 9KX
60 um, 50 fs Mag 1KX
55 um, 5.3 ps Mag 1KX

Sample B (against laser beam direction)
60 um, 50 fs

1 um 2 um 2 um

2 um 2 um 1 um

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Debris distribution
For particles >250nm, step of particle sizes 100nm

1. Distribution for all modes and both directions are close.
2. Mass of particles flying along laser beam direction are much more than ones flying against laser beam direction

Number and mass of debris from single droplet in 1 sr

<table>
<thead>
<tr>
<th></th>
<th>60 um, 50 fs</th>
<th>40 um, 5.3 ps</th>
<th>55 um, 5.3 ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>≈ 16 300 (4.9*10^{-8} g/sr)</td>
<td>≈ 6 400 (2.6*10^{-8} g/sr)</td>
<td>≈ 2 600 (1.5*10^{-8} g/sr)</td>
</tr>
<tr>
<td>Sample B</td>
<td>≈ 9 400 (10^{-8} g/sr)</td>
<td>≈ 2 400 (0.2*10^{-8} g/sr)</td>
<td>≈ 1 600 (0.37*10^{-8} g/sr)</td>
</tr>
</tbody>
</table>

At isotropic scattering of debris masses would be:
For 60um 6.6*10^{-8} g/sr
For 55 um 5*10^{-8} g/sr
For 40 um 1.9*10^{-8} g/sr

Where is difference? Vapor?
Summary

- In-Sn droplet deformation and fragmentation dynamic at the action of femto- and picosecond laser in wide band pulse duration from 50 fs up to 80 ps at power density up to $P=3\times10^{15} \ W/cm^2$ were studied by ultrafast shadowgraph method. Changing experimental parameters it is possible choose the optimal shape of target for LPP EUV source.
- Total ion charge and ion spectrum measurements at action of laser with femto- and picosecond pulse duration on In-Sn droplets were carried out. It is established that high-energy ions up to 8 keV are present only in the opposite direction to the laser beam.
- Debris distributions at interaction of femto- and picosecond laser with In-Sn droplets. It is established that particles flying along laser beam are much more than ones flying against laser beam.
Acknowledgements

We thank ASML company for technical support our experiments.

Thank You for Your Attention