Radiative Hydrodynamic Simulation of Laser-produced Tin Plasma for Extreme Ultraviolet Lithography

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We have simulated EUV emission from the laser-produced tin plasmas for EUVL.

**Atomic physics**

**Brief theory of EUV conversion efficiency**

- Appropriate density and temperature for EUV emission

**LPP**

**Laser-produced Plasma**

Radiation Hydrodynamic simulation for EUV emission

**Two wavelength double laser irradiation for tin droplet**

We found that we can get more than 5% EUV conversion efficiency with the optimized droplet diameter, the delay time between pre-pulse and main CO2 pulse and the laser spot diameters.
EUV conversion efficiency consists of three factors.

1) EUV\textsuperscript{1)} Conversion efficiency (CE)

\[
\text{EUV\textsuperscript{1)} \left( CE \right) = \frac{\text{absorbed laser energy}}{\text{input laser energy}} \times \frac{\text{x-ray emission energy}}{\text{inputed energy into plasma}} \times \frac{\text{EUV emission energy}}{\text{x-ray emission energy}}
\]

1) 13.5nm wavelength with 2\% bandwidth

In order to get high EUV CE, we have to maximize the product of three factors.
Appropriate density and temperature can be found by the atomic physics.

EUV spectral efficiency

\[ \text{EUV opacity [cm}^{-1}\text{]} = 1 \times \text{plasma scale [cm]} \]

Plasma scale [cm] with optical thickness = 1

Etendue criterion (~0.1 cm)

\[ \frac{1}{\text{EUV opacity [cm}^{-1}\text{]}} \]

CO\textsubscript{2} laser can generate plasma with the density of \( n_e = 10^{19}\text{cm}^{-3} \)

\( n_i = 10^{18}\text{cm}^{-3} \text{ with } Z = 10 \)

After A. Sasaki et al., JAP(2010)

1) At optical thickness = 1, effective EUV spectral efficiency should be multiplied by 0.37.
We have simulated CO$_2$ laser irradiation on tin plate.

**CO$_2$ Laser intensity:** $10^{10}$ W/cm$^2$, duration: 110 ns, spot radius: 200 μm

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**Electron density**

- Electron density scale
- Electron critical density $n_{cr}$
- With single pulse irradiation, the density scale length keeps 25 μm with time due to lateral flow.

**Electron temperature**

- Electron temperature is constant in space.

**EUV emission**

- Measured laser absorption fraction
- Laser absorption fraction

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**Laser absorption fraction**

- Measured laser absorption fraction
- $1/e \times n_{cr}$

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- Electron temperature is constant in space.
We have simulated the double pulse irradiation on tin droplet.

**Sn droplet**
- Droplet diameter: 100 μm and 10 μm

**Pre-pulse**
- \( \lambda_L = 1.06 \mu m \)
- Pulse duration: 10 ns

**Main CO2 pulse**
- \( \lambda_L = 10.6 \mu m \)
- Intensity: \( 1 \times 10^{10} W/cm^2 \)
- Pulse duration: 20 ns

**Delay time**: 0 ns - 1.5 μs

**Mass-limited target**

**Pre-plasma**

**EUV emission**
Nd:YAG irradiation on tin droplet can change the shape of the droplet and expand it.

After irradiation of Nd:YAG laser on tin droplet, the change of shape, expansion and moving are observed.

Osaka Univ.(Leading Project)
Electron density

Electron temperature

Laser absorption fraction 65%

x-ray conversion fraction 41%

EUV CE 5.3%

Delay time 1.53μs

Laser spot radius 150μm
We can get relatively high EUV CE with the double pulse irradiation.

After optimization of the delay time, the laser spot diameter, and droplet diameter, we can get the high EUV conversion efficiency.
Conversion efficiency (CE)  
\[ CE = \text{Laser absorption fraction} \times \text{x-ray conversion fraction} \times \text{EUV spectral efficiency} \]

Droplet diameter 100μm  
Laser spot diameter  100μm, 200μm, 300μm  
Delay time  0~1.5μs

With large laser spot, the appropriate delay time is increased.

After optimization of the delay time, x-ray conversion increases compared to that with single irradiation.

With large laser spot, the EUV spectral efficiency increases.

With the appropriate delay time, and large spot > 200μm double pulse irradiation, the three important factors can be maximized compared to that with single irradiation.
After optimization of laser and target conditions, we can get 5% EUV CE.

<table>
<thead>
<tr>
<th>Simulation condition</th>
<th>EUV CE (%)</th>
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</thead>
<tbody>
<tr>
<td>Condition A</td>
<td>4.6</td>
</tr>
<tr>
<td>Condition B</td>
<td>5.9</td>
</tr>
<tr>
<td>Condition C</td>
<td>5.1</td>
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</tbody>
</table>

Osaka Univ.(Leading Project)
36μmφ droplet exp. showed 4%CE.

EUVA Hiratuska
20μmφ droplet exp. showed 3% CE.

Both simulation and experiments have showed the higher EUV CE.
In order to get the high EUV CE from the CO$_2$ laser-produced plasmas, the laser absorption fraction should be increased, and more than 100$\mu$m density scale length is required.

Two wavelength double pulse irradiation scheme is effective for obtaining the longer density scale length.

With the appropriate delay time, the large laser spot $> 200$ $\mu$m of CO$_2$ laser, and the droplet size, the three important factors [laser absorption fraction, x-ray conversion fraction and EUV spectral efficiency] can be maximized respectively, compared to that with single irradiation.

After optimization of droplet size, laser spot, delay time, laser intensity and pulse duration, we found that we can get more than 5% EUV CE with the double pulse irradiation scheme.
Acknowledgements

This research has been done under contract between ILT and ILE Osaka Univ. and EUVA-Hiratsuka.

This research has been supported by EUVA-Hiratsuka and Komatsu/Giga photon. We thank them for their great supports.