Laser-initiated discharge produced plasma ablated from liquid metal electrodes

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Laser-initiated discharge produced plasma system has been studied as a viable approach for the EUV lithography light source at 13.5 nm wavelength. The source is based on a discharge in tin or galinstan vapor produced by laser pulse between rotating disk electrodes. This paper focuses on results of the computer modelling of that laser-induced discharge with electrical circuit characteristics and laser beam parameters similar to the used in the experiment. Z*-code comprising recent advances in atomic physics and radiation-magnetohydrodynamics is used under international collaborative project FIRE in the framework of FP7 IAPP to model laser- and discharge-produced plasma dynamics and emission. Complex consideration of radiation from unresolved transition arrays includes the model of non-equilibrium ionization in plasma of multicharged ions based on detailed kinetic equations resolution with major electron-ion interaction processes taken into account. The radiation-plasma dynamics and the spectral effects of self-absorption in laser produced plasma and discharge produced plasma are considered. The simulation results are compared with experimental data. The detailed physics of the effects taking place in the laser-initiated discharge is discussed.
Radiation Sources for EUV Lithography

\[ r \geq k_1 \frac{\lambda}{NA} \]

Now EUV for HVM beyond 16 nm

\[ \lambda \Rightarrow 13.5\text{nm} \Rightarrow 6.X\text{nm} \]
\[ (h\nu=92\text{eV} \Rightarrow 185\text{eV}) \]
\[ \delta\lambda/\lambda \Rightarrow 2\% \]

The optics is made of multi-layer mirrors with reflection efficiency \( \sim \)70%

- For HVM: >> 200 W of in-band power at IF within < 3mm\(^2\)sr etendue
- For mask inspections ABI \(\rightarrow\) AIMS \(\rightarrow\) APMI: 30 \(\rightarrow\) >100 W/mm\(^2\).sr

Sn, Xe… High energy density plasma (\(T_e=20\text{-}40\text{eV}\)) radiates at EUV range

LPP & DPP
Laser Assisted Vacuum Arc (LAVA-lamp)

High-current discharge between two rotating electrodes covered with a thin liquid Tin or Galinstan film is triggered by local laser ablation of electrode material.

**Discharge**
- capacitance: 0.4 μF
- inductance: 19 nH
- voltages: 3 – 6 kV
- energies: 1.8 – 7.2 J
- current: 20 kA at 4.5 kV

**Trigger laser:**
- wavelength: 1064 nm
- beam diameter: 3 mm
- focal lens: 30 cm
- energy: 5 – 50 mJ
  (varied by means of rotatable half-wave plate and polarizing beam splitter)
Pinching peqularity on the current

Rogowski coil current characteristics

Current (uncorrected)

Time (μs)

Galinstan
Sn

Rogowski Coil (V)

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EUV images of galinstan plasma pinch

4 J (4.5 kV), trigger laser 5 mJ

Main pinching is near the cathode. The EUV source size is of 100μm diameter.

In Galinstan the pinch is not stable.
EUV spectra for various discharge energies

Galinstan:
68.5% Ga
21.5% In
10.0% Sn
EUV spectra for various discharge energies
ZETA → Z* RMHD Code → Z* BME → Z+
multi-physics model

Discharge plasma simulation in real geometry
Laser plasma

Data output:
\( r, z, \nu, T_e, i, \rho, E, B, Z, U, \omega \) etc;
visualization

Heat flux postprocessing

Spectral postprocessing

RMHD (2D, 3D) with:
- spectral multigroup radiation transport in nonLTE;
- nonstationary, nonLTE ionization;
- sublimation – condensation;
- energy supply (electric power, laser);
- etc

EMHD or 3D PIC with:
ionization of weekly ionized plasma, discharge triggering

Tables
nonLTE atomic & spectral data
\((T_e, \rho, U)\)
Next Generation Modelling Tools

knowledge transfer FP7 IAPP project FIRE

• FIRE - European FP7 Industry-Academia Partnerships and Pathways project

• The FIRE project aims to substantially redevelop the Z* code to Z+ to include improved atomic physics models and full 3-D plasma simulation of

  ✓ plasma dynamics
  ✓ spectral radiation transport
  ✓ non-equilibrium atomic kinetics with fast electrons
  ✓ transport of fast ions/electrons
  ✓ condensation, nucleation and transport nanosize particles.

• Modelling is essential in parametric scans in radiat source optimization, in fast particles and debris generation to solve current EUVL source problems as well as extending their application.
Ion fractions and average charge

Gallium ion fractions for $10^{18}$ 1/ccm electron density

Indium ion fractions for $10^{18}$ 1/ccm electron density

Tin ion fractions for $10^{18}$ 1/ccm electron density

Average ion charge for $10^{18}$ 1/ccm electron density
Ion fractions and average charge

Tin ion fractions for $1.5 \times 10^{19}$ 1/ccm electron density

Average ion charge for $1.5 \times 10^{19}$ 1/ccm electron density
Calculated EUV spectra

Tin line emission spectra

Wavelength, nm

Relative units

5 eV
10 eV
15 eV
20 eV
25 eV
30 eV
Calculated EUV spectra

Tin line emission spectra

Wavelength, nm

Relative units

20 eV
30 eV
40 eV
50 eV
60 eV
Z*: laser ablation dynamics

At focal spot diameter 300µm

To the time moment 210ns (174ns after laser power maximum) the plasma density near the anode and its conductivity become high enough for discharge ignition.
Z* modelling: pinch dynamics

- Pinch dynamics: R(cm) vs Z(cm)
  - Z(cm) values: -0.2, 0, 0.2, 0.4, 0.6
  - R(cm) values: 0.2, 0.4, 0.6, 0.8, 1
  - DENS(g/ccm) values: 0.000, 0.000342278, 0.000342278, 0.000342278, 0.000342278

- Cathode and Anode:
  - t = 2.4800E+02 ns
  - t = 2.8478E+02 ns
  - t = 3.2200E+02 ns
  - t = 3.3053E+02 ns
  - t = 3.3797E+02 ns

- EUV emission peak:
  - 4.5kV charge voltage (4J energy)

- Calculated dI/dt demonstrates pinching
**Z* modelling: EUV emission**

**Calculated discharge current**

4.5kV charge voltage (4J energy)

- **Discharge current, kA**
  - Time, ns

**Calculated EUV emission pulse**

- **EUV radiation source images**
  - In the emission maximum
    - \( N_e = 1.4-1.6 \times 10^{19} \text{ cm}^{-3} \)
    - \( T_e = 30-60\text{eV} \)
    - \( \langle Z\rangle = 10-13 \)

**In the emission maximum**

- EUV emission pulse
  - 40mJ (in 4\( \pi \)) emitted in 2\% band at 13.5nm WL
Conclusions

- EUV emission from Laser Assisted Vacuum Arc (LAVA-lamp) discharge in Galinstan and Tin vapor investigated experimentally is compared with simulations.
- EUV imaging – pinch is smaller ~100 µm in diameter
- Tin in-band emission is more efficient than from Galinstan (by a factor of 5x) mainly due to higher spectral efficiency.
- Gallium ions are mainly responsible for EUV emission below 13 nm whereas Indium ions emission dominates in the spectrum above 14 nm.
- Tin discharge is more reproducible than in Galinstan due to higher plasma conductivity at the breakdown.
- Pinching time matching to the current maximum is significant for the high EUV output and is sensitive to the trigger laser energy.
- Comparison with calculated discharge dynamics in Galinstan is ongoing.
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