EUV lithography research at UCSD using laser-produced plasma

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At UCSD we are developing techniques to control LPP light sources using Sn targets

- Key challenges:
  - Maximize in-band emissions, Minimize debris damage

- Recent research performed at UCSD:
  - Targets: low-density, mass-limited, planar and spherical
  - Lasers: pulse length, double-pulse, *wavelength*
  - Debris mitigation: gas, magnetic fields

*UCSD Laser Plasma & Laser-Matter Interactions Lab*
Diagnostic capabilities:

- Nomarski interferometer
- Transmission grating EUV spectrometer
- In-band energy monitor
- Faraday cup, energy analyzer
- 2 ns visible imaging
- Spatially-resolved visible spectroscopy (2 ns)
- EUV imaging at 13.5 nm
Modeling tools

- **Hyades and h2d**
  - 1d and 2d Lagrangian radiation hydrodynamic codes
  - Distributed & maintained by Jon Larsen, Cascade Applied Sciences
  - Tabular EOS and opacity, hydrogenic model, mesh refinement in h2d

- **Cretin**
  - Multidimensional non-LTE collisional-radiative solver
    (*population kinetics, ionization balance, radiative transfer*)
  - Distributed & maintained by Howard Scott, LLNL
  - Sn data generated by FAC atomic code
  - 1d hydro capability

- **Helios**
  - 1d Lagrangian radiation hydrodynamic code
  - Distributed & maintained by Joe MacFarlane, Prism Comp. Sciences
  - Computed EOS and spectral opacity data (from Propaceos)
Part I: Studies of conversion efficiency

1. Target density
2. Pulse length
3. Spot size
4. Target geometry
Our early work on low density targets showed a narrower UTA

- We attempted to reduce debris by reducing the target density.
- The optical depth at 13.5 nm is only ~7 nm of full density Sn. Beyond that, light is reabsorbed.
- An advantage of low density is a narrower spectrum.

- 100 mg/cc RF foam
- 0.1-1% solid density Sn
- e.g., $0.5\%$Sn = Sn$_{1.8}$O$_{17.2}$C$_{27}$H$_{54}$
Laser pulse length affects conversion efficiency in a complex way

Each CE value is chosen at the optimum intensity

Our results extend those of Ando, showing high CE is possible at longer pulselengths

2 ns gives better CE, but longer pulses may be more cost-effective.
Density profiles and spectra suggest that short-pulse emission occurs at higher $n_e$

- Steeper gradient with short pulse, deeper penetration
- Broader spectra with short pulse (more collisional)
- Longer pulse has hydro losses, but less opacity helps recover emission
- Work is ongoing to extend pulse length even further
Spot size also involves a tradeoff between hydro loss and self-absorption

CE depends on a balance between emission and opacity

In a smaller spot:
- Lateral expansion wastes laser energy → less emission
- Lateral expansion reduces plasma scale length → less opacity
Why is conversion efficiency lower in spherical targets as compared with planar?

**Possible reasons for lower CE**

- Higher losses due to hydro expansion
- Mismatch of laser spot with target
- Different angular distribution of EUV emissions
- Spectral differences (out-of-band emissions)
- Opacity effects

(Koay et al, SPIE 5751, 2005)
The plasma density profile was found to be very different in the two targets

- Planar targets have a wider plasma (the tails of the laser beam miss the spherical target)
- Planar targets have a larger corona with higher density

Before pulse

During pulse
Comparison of h2d model and experiments

t = 3 ns past peak laser irradiance
The differences all can be explained by higher electron density in planar targets

Narrower EUV spectrum results from lower electron density

$h_2d$ predicts more radiation loss and less thermal energy retained in spheres
Part II: Studies of debris mitigation

1. Gas stopping
2. Magnetic stopping
3. Gas plus magnets
4. Double-pulsing
   - Full density
   - Mass-limited
   - Mass-limited plus gas
Gas stops ions, but also stops EUV photons

- Hydrogen is best, but not good enough (and nasty)
- Collisionality in plumes also affects their range
Magnetic diversion was found to be partially effective

0.6 T transverse field was not sufficient
A magnetic field produces a synergistic effect in combination with background gas.

Faraday cup time-of-flight measurements at 10°, 15 cm from target.

Photoionization peak appears when gas is present.

**Sn Slab 100% dense**

- noB-vacuum
- B-vacuum
- noB-58mT He
- B-50mT He
We recently discovered a technique that dramatically reduces the ion emission energy

- Low-energy short pre-pulse forms target; main pulse interacts with pre-plasma.
- Degrees of freedom to control performance.

### Pre-pulse:
- Wavelength: 532, 1064 nm
- Pulse length: 130 ps
- Energy: 2 mJ
- Intensity: \( \sim 10^{10} \) W/cm\(^2\)
- Spot size: 300 \( \mu \)m

### Main pulse:
- Wavelength: 1064 nm
- Pulse length: 7 ns
- Energy: 150 mJ
- Intensity: \( 2 \times 10^{11} \) W/cm\(^2\)
- Spot size: 100 \( \mu \)m
Ion energy was reduced by a factor of 30!

\[ v = \frac{L}{t}, \quad E = \frac{1}{2}mv^2 \]
The main pulse interacts with a pre-formed gas target on a gentle density gradient

**Pre-plume density profile**
840 ns after the pre-pulse

![Graph showing atom density](image)

130 ps pre-pulse, 2 mJ, 532 nm

![Images of thermal plasma and cold plume](image)

500 µm
At the optimum delay time, no loss of conversion efficiency is observed
Gas is more effective at stopping ions that already have their energy degraded

In both cases, the predicted transmission of 13.5 nm light is >95%
“Mass-limited” targets should reduce the debris loading, without loss of light output

- Thin films were fabricated using e-beam evaporative coating of Sn on plastic or glass
- Film thicknesses 20 to 100 nm, as well as foils from 1 to 10 μm were tested

Results are consistent with 7 nm expected optical depth at 13.5 nm
Unlike single-pulse results on mass-limited targets, ion energy was reduced with pre-pulse.

- Acceleration with single pulse likely due to low-Z substrate
- Double-pulse pump beam never reaches the substrate
Pre-pulse + gas + mass-limited target could satisfy requirements of a practical EUVL source

We are now working on better diagnostics to measure smaller yields
Summary

- Our research has found many ways to control laser-produced plasma for EUV lithography, e.g.
  - Plasma density
  - EUV opacity
  - Target density profile
  - Gas and magnetic interactions

- We are anxious to collaborate with industry to help improve products for next-generation semiconductor fabrication
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ありがとうございます！