

Geometric effects on EUV emissions in spherical and planar targets

M. S Tillack¹, K. L. Sequoia and Y. Tao

Mechanical and Aerospace Engineering Department and Center for Energy Research
University of California, San Diego

E-mail: mtillack@ucsd.edu

Abstract. We explored the radiation hydrodynamics of tin microsphere targets exposed to 1- μm , 8-ns laser pulses, and compared them with thick planar targets. Previous research [1] has shown that the conversion efficiency of laser light to in-band emissions around 13.5 nm is lower in microsphere targets. Our work was designed to elucidate the reasons for this drop in emission. Differences in plasma expansion, laser absorption and atomic emissions were measured in the UCSD Laser Plasma Laboratory and modeled using the 2D radiation hydrodynamic code h2d. Experimental data are compared with modeling and differences between emissions in planar and spherical targets explained.

1. Introduction

In order to maintain progress toward smaller features in semiconductor manufacturing, industry has been pursuing light sources for lithography in the extreme ultraviolet (EUV) part of the spectrum. One of the leading techniques to produce light around 13.5 nm uses laser-produced tin plasmas. The indirect process of laser irradiation and heating of a target, which subsequently emits radiation, is inherently more inefficient than direct illumination. The laser cost and requirements can be very challenging.

Because of the high cost and complexity of next-generation lithography tools, the conversion efficiency CE (defined as the ratio of energy produced in a 2% bandwidth around 13.5 nm to the incident laser energy) is critically important. Many factors contribute to the conversion efficiency, including the target and illumination geometry. In order to produce high average power in a commercial system, most concepts for a commercial EUV lithography light source utilize a microdroplet generator producing targets at a rate greater than 10 kHz. The spherical geometry of these microdroplets leads to a reduction in CE as compared with planar targets. Understanding and controlling this energy loss mechanism is the goal of the research described here.

Figure 1 shows a simplified depiction of the geometry of single-sided laser illumination of a train of microdroplets. The primary collector mirror subtends an angle up to 2π steradians, such that the angular distribution of emitted light will impact performance. Figure 2 shows a sample result from our calibrated in-band energy monitor (E-mon from JenOptik) taken at a 45° angle from the incident laser path. The integrated signal for a 150- μm diameter spherical target is 26 nVs as compared with 43 nVs for a planar target irradiated with the same laser conditions – a loss of 40%.

There are several possible reasons why CE might be reduced in spherical targets:

¹ To whom any correspondence should be addressed.

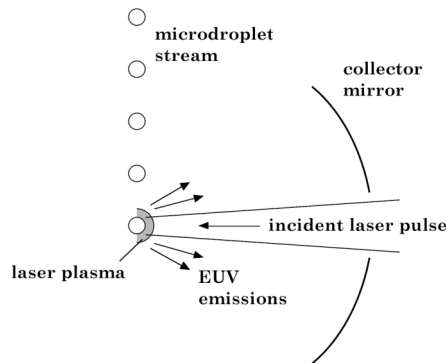


Figure 1. Geometry of an EUVL source.

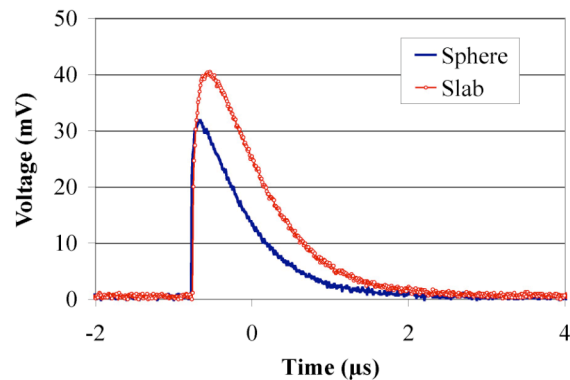


Figure 2. In-band energy measurement.

1. Hydrodynamic losses. Mass and energy may be expelled from the interaction region before emitting useful light.
2. Angular distribution of light emission. The emitted light may be strongly dependent on angle, requiring careful measurements over a full range of angles.
3. Laser-target coupling. If the incident beam is larger than the target, then laser energy will be wasted. At the same time, the beam should not be much smaller than the target so that the target mass is more efficiently heated to the required temperature. Hydro expansion during the pulse changes the effective target diameter, so perfect matching is not possible.
4. Opacity effects. Ideally, the incident laser should be absorbed in a location where the EUV light can easily escape. In the presence of strong temperature and density gradients, it can be extremely difficult to optimize the opacity relative to the absorption scale length. Most likely the target geometry will play a strong role.
5. Spectral effects. The interaction of laser light with a spherical target may alter the spectrum of emissions. For example, if a wider range of plasma temperatures exist in a spherical target, then lower charge states will emit more of the plasma energy out-of-band.

We performed a set of experimental measurements using planar and spherical tin targets in order to better understand which of these effects may explain the loss of conversion efficiency in spherical targets. In the following section we describe the experimental setup, diagnostic techniques used and results obtained. We also performed numerical simulations of the radiation hydrodynamics; the computational tools and modeling results are described in Section 3.

2. Experimental studies

Figure 3 shows the experimental arrangement, described in more detail elsewhere [2]. Planar and microsphere targets are mounted in a vacuum chamber pumped below 10^{-6} Torr, and irradiated with a 1064-nm, 8-ns (full width, half maximum) Nd:YAG laser. Particles with $\sim 150\mu\text{m}$ diameter were selected from 100% dense powder, mounted on a precision translator and aligned using in-situ cameras and focal spot imaging. Plasma density is measured using a 150-ps time-resolved Nomarski interferometer to determine the plasma evolution and laser absorption location. Emission spectra are measured using a transmission grating spectrometer (TGS), and total in-band energy using a calibrated photodiode with multilayer mirror “filters”.

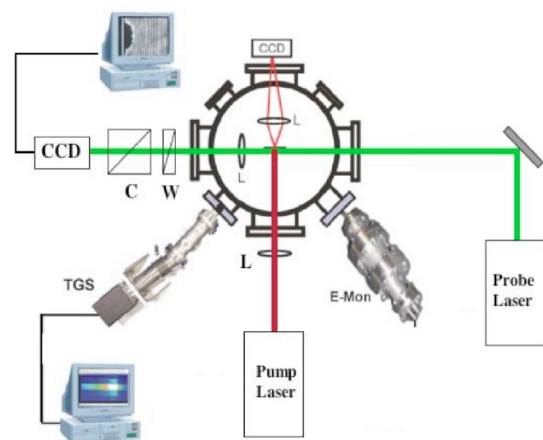


Figure 3. Experimental layout.

An example interferogram for a planar target is shown in Figure 4. The interferograms are processed and Abel inverted using the software package Interferometric Data Evaluation Algorithms (IDEA) from Graz University of Technology [3]. Figure 5 shows the result of this inversion at 4 ns past the peak for an incident beam with 70 μm diameter (full width half maximum) and average intensity of $5 \times 10^{11} \text{ W/cm}^2$. A comparison of the two cases shows that the plasma from the planar target is larger in extent and higher in density.

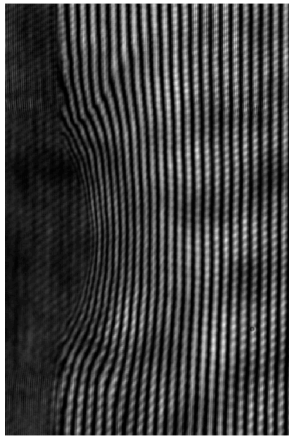


Figure 4. Raw interferogram from a planar target.

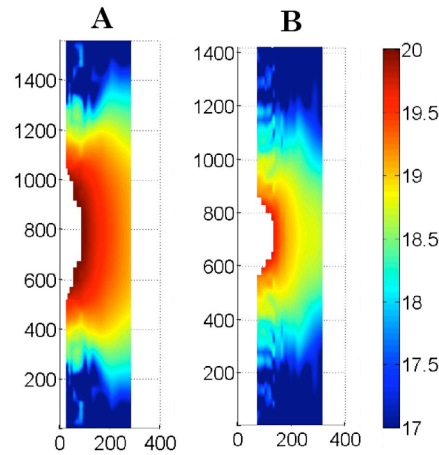


Figure 5. Electron density ($\log_{10}$) for A) planar and B) spherical targets.

The measured spectrum of emissions is shown in Figure 6. The spectra are normalized individually in order to highlight the different shapes; emissions from the spherical target are actually lower on an absolute scale. The spectrum from the spherical target is clearly narrower, suggesting a lower plasma density in the emitting region. We observed a similar spectral narrowing in experiments with doped foam targets [4]. Higher density leads to higher collisionality, which in turn results in more recombination and more ionization states. The long-wavelength tail is produced by these lower charge states.

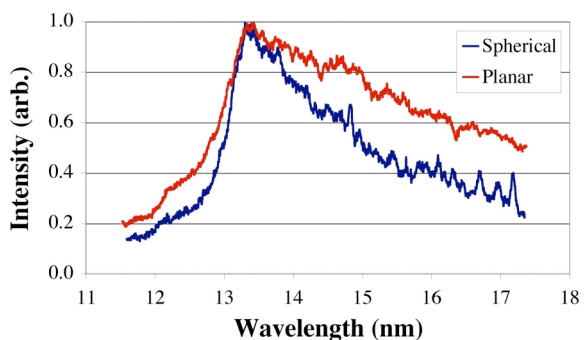


Figure 6. EUV spectra with planar and spherical targets.

3. Radiation-hydrodynamic modeling

Numerical modeling was performed using the Lagrangian radiation hydrodynamics code h2d [5]. Figures 7 and 8 show the computed electron density profiles at the time of peak laser intensity for a planar and spherical target respectively. In this case the laser spot is a flat-top with 100 μm diameter. The results are consistent with interferometry, showing a stronger density gradient and lower average electron density for a spherical target as compared with a planar target.

Figures 9 and 10 depict the energy balance results from h2d. Nearly all of the incident light is absorbed, and ends up either as hydrodynamic expansion energy, radiation or thermal energy. In the case of the slab target, a larger portion of the laser energy ($\sim 19\%$, as compared with 12% for the sphere) is retained in thermal energy of the electrons. With a spherical target, out-of-band radiation (h2d does not have the atomic physics required to compute in-band emission) is a larger contributor to the energy balance. The difference in radiation for the two cases is nearly equal to the difference in electron thermal energy. The larger, denser planar plasma is optically thicker, resulting in less radiation loss and more electron heating. We believe the reason for the reduction in CE is due to

higher out-of-band emissions and lower electron density. Although the spectrum is narrower, less light is emitted within the UTA.

The modeling results are consistent with experimental results, all of which suggest that the primary source of differences between planar and spherical targets stems from the electron density distribution.

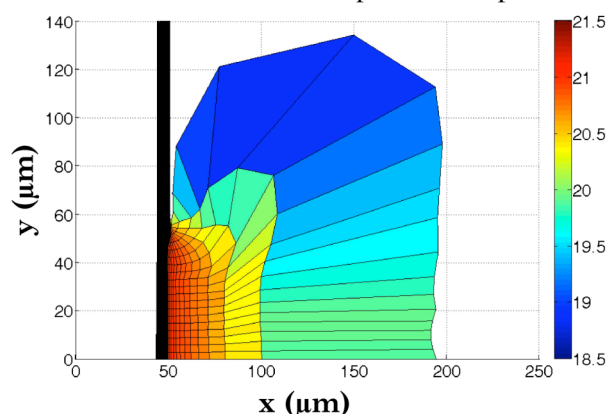


Figure 7. Computed h2d electron density in planar target ($\log_{10}$ scale).

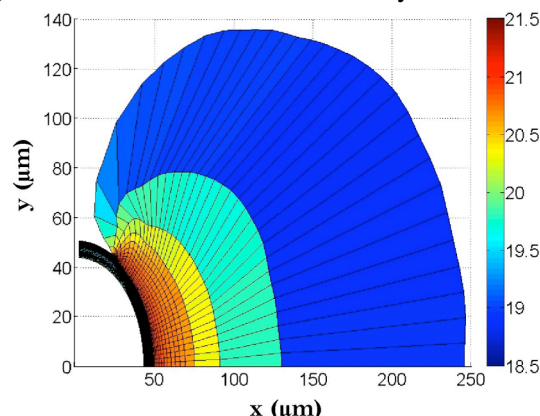


Figure 8. Computed h2d electron density in spherical target ($\log_{10}$ scale).

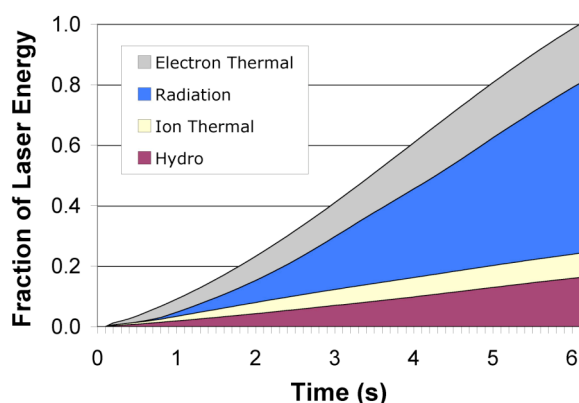


Figure 9. h2d energy balance in planar target.

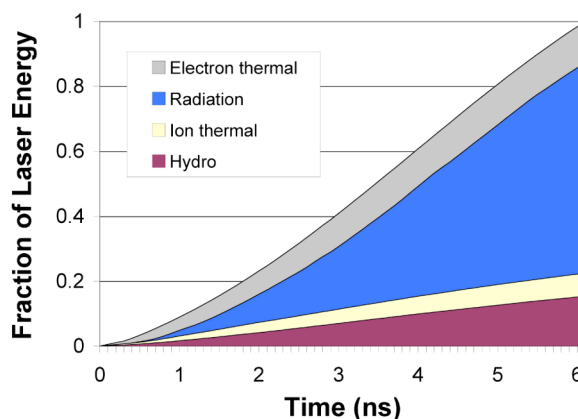


Figure 10. h2d energy balance in sphere target.

References

- [1] Brandt D C 2006 "LPP EUV Source Development for HVM" (SEMATECH EUVL Symposium 2006, Barcelona Spain).
- [2] Tao Y, Tillack M S, Harilal S S, Sequoia K L, and Najmabadi F 2007 "Investigation of the interaction of a laser pulse with a preformed Gaussian Sn plume for an extreme ultraviolet lithography source," *Journal of Applied Physics* **101** (2), 023305.
- [3] Hipp M, Woisetschlger J, Reiterer P and Neger T 2004 "Digital evaluation of interferograms," *Measurement* **36** 53-66.
- [4] Harilal S S, O'Shay J, Tillack M S, Tao Y, Paguio R, Nikroo A and Back C A 2006 "Spectral control of emissions from Sn-doped targets for EUV lithography," *J. Phys. D: Applied Physics* **39** 484-487.
- [5] h2d is a commercial product of Cascade Applied Sciences Incorporated, 6325 Trevarton Drive, Longmont, CO 80503. Electronic mail: larsen@casinc.com.
- [6] Private communication with Stephanie Hansen, LLNL.
- [7] Gu M F 2003 "Indirect X-Ray Line-Formation Processes in Iron L-Shell Ions," *The Astrophysical Journal*, **582**:1241-1250.