Important processes in modeling and optimization of EUV lithography sources

T. Sizyuk and A. Hassanein

Center for Materials under Extreme Environment, School of Nuclear Engineering
Purdue University, West Lafayette, IN, USA

Laser produced plasma (LPP) sources for extreme ultraviolet (EUV) photons are currently based on using small liquid tin droplets as target that has advantages in generation of stable continuous targets at high repetition rate, larger photon collection angle, and reduced contamination and damage to optical mirror system from plasma debris and energetic particles. The ideal target is to generate a source of maximum EUV radiation output and collection in the 13.5 nm range with minimum atomic debris. Based on our predictions, the smallest efficient droplets are of diameters in the range of 20-30 μm. In this study we analyzed detail plasma evolution processes in LPP systems using small spherical tin targets to predict the optimum droplet size yielding maximum EUV output. We identified several important processes during laser-plasma interaction that can affect conditions for optimum EUV photons generation. The importance of accurate description of modeling these processes increases with the decrease in target size and its simulation domain.

Keywords: EUV, LPP, HEIGHTS, CO_2 laser, mass-limited target, debris mitigation

1. INTRODUCTION

Accurate simulation of laser produced plasma (LPP) devices for extreme ultraviolet lithography (EUVL) requires advanced multidimensional physical models and numerical methods. Modeling of such devices should include description of all laser/target interaction processes. These include laser photons interaction with target material in all phases, thermal conduction in material and in plasma, vaporization, hydrodynamic evolution of vapor and plasma, ionization, plasma radiation, and details of photon transport in these media. We studied the influence and the importance of various processes and models, implemented in our comprehensive HEIGHTS package, on plasma evolution dynamics and as result on EUV source location, intensity, and size.

Plasmas in intense LPP sources have high gradients of radiation energy density at small spatial lengths and require special treatment. Therefore, accurate physical/mathematical models and appropriate numerical methods should be implemented and carefully benchmarked for correct calculation of plasma opacity, photons generation, and their transport and distribution. One of the most important processes in understanding plasma evolution and EUV source generation and location is photons transport in the complex plasma environment. We have implemented and compared two separate methods for radiation transport, i.e., direct integration of the radiation transport equation along photons path and Monte Carlo models with several novel weight factors to enhance the accuracy and the speed of calculations. These two methods agree well with each other and highlight the importance of accurate full 3D solution of radiation transport equations for the correct simulation of LPP sources [1]. Accurate description of laser energy absorption and dynamics of target vaporization are also quite important for various laser/plasma interaction regimes in EUVL devices. Hydrodynamic effects during plasma evolution and confinement can significantly influence EUV emission, which usually follows laser intensity profile in ideal LPP conditions. We analyzed the influence of the above processes on EUV source characteristics for various pre-plasma conditions and laser beam parameters, and compared results for different approaches and benchmarked with available experimental data.

2. LASER ENERGY ABSORPTION, REFLECTION, AND REABSORPTION

Models for self-consistent description of laser energy absorption combined with target material vaporization are critical parts in the simulation of LPP systems. This is more pronounced in the case of lower laser intensities, i.e., 10^8-10^{10} W/cm^2, and in plasma development from small targets with non-flat geometries. This becomes important because of the complex hydrodynamic flow near the target surfaces where one should take into account various energy input from laser radiation, i.e., absorption/reflection in solid/liquid target, in target vapor, and in plasma layer. The entire processes

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should consider various phases of transition from the laser interaction with material only (in vacuum chamber) to preferential absorption in the developed hot plasma. The conversion efficiency (CE) of the EUV sources depends on many parameters including the initial target preparation stage as well as the efficiency of laser energy absorption in the developed plasma plume. Optimum target preparation usually involves the use of dual laser pulse system, an initial low energy pulse to start generation of target plasma and then followed by a main pulse with larger spot to produce more efficient EUV photons. In this regard, taking into account laser photons absorption after reflection from the target surface can be very important in determining the CE.

For precise modeling of laser target interaction processes we implemented experimental data of the optical properties for laser reflection from liquid tin, verified with theoretical calculations [2]; then, modeled laser absorption in vapor based on the main feature of collision-induced absorption - quadratic dependence on density; and the inverse bremsstrahlung absorption was used for simulation of laser photons interaction with plasma.

Figures 1 and 2 demonstrate the efficiency of CO_2 laser energy absorption on the surface and in the developed plasma from small 30 µm droplet and in pre-plasma created by low intensity Nd:YAG pre-pulse from such size droplet and expanded during 450 ns. We should note that we used 266 nm wavelength laser for the pre-pulse with lower intensity. Laser with these parameters vaporized most of the droplet. This allowed simulation of vapor/plasma expansion before the main pulse and without concerns of processes for target fragmentation.

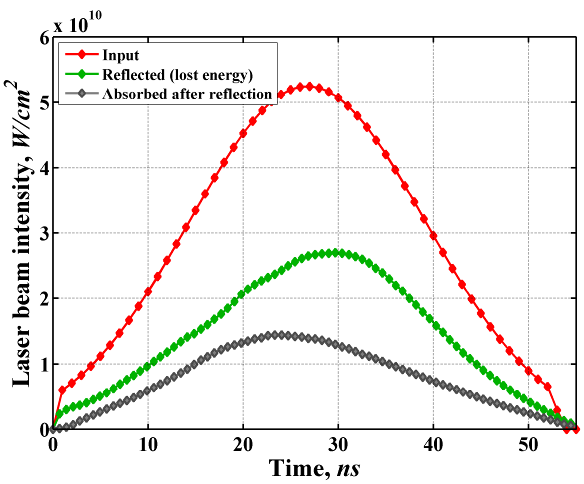

Figure 1. CO_2 laser energy absorption in material and in plasma from 30 µm droplet without pre-pulse – 0.45% CE.

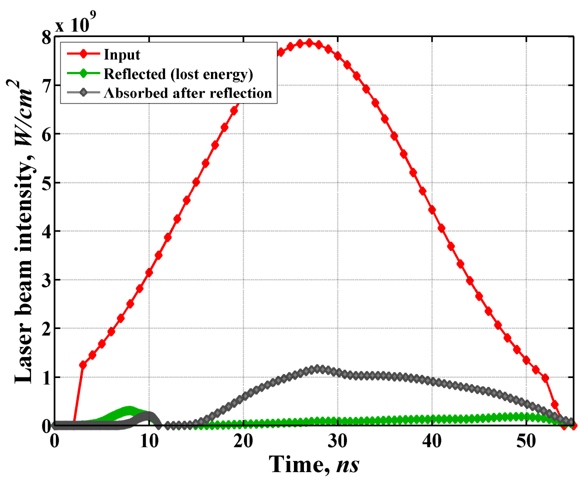

Figure 2. CO_2 laser energy absorption in pre-plasma created from 30 µm droplet by 266 nm laser and expanded during 450 ns – 2.9% CE.

More than half of the initial laser energy was reflected from the surface of small spherical targets (Fig. 1) – corresponding to the sum of both green and gray plots. However during increase of laser intensity, that caused plasma density and temperature increase, more of the reflected photons were absorbed in the evolving plasma. When laser intensity starts to decrease, plasma above the surface begins to cool down and density of the plasma is subsequently reduced because of plasma expansion and flow around droplet and lower evaporation rate in comparison with beginning of laser pulse. These processes resulted in lower absorption of the reflected photons that can affect and be an indicator for lower LPP source efficiency. It was shown in our previous analysis of comparing plasma behavior in LPP with planar and spherical targets using the same laser parameters [3] that laser absorption rate in plasma for planar target is 30% higher than from droplets. The CE of the planar target is two times larger in these cases. Simulation of laser photons absorption in plasma after reflection from the target can, therefore significantly influence the final EUV collected power. Not taking into account this effect in modeling of such small droplets and small spot sizes decreased the CE of this system in more than three times.

Fig. 2 shows time history of laser photons reflection and absorption after reflection during reheating of the pre-plasma by the main CO_2 laser. It illustrates evolution of processes in pre-plasma starting from cold vapor/plasma where almost all photons were transmitted through matter. Reflection processes and following absorption after reflection correspond to the time of the intense interaction of laser photons with the remained non-vaporized part of the droplet. When laser intensity increased almost all photons were absorbed in the heated pre-plasma, far from the target surface. Then due to hot plasma dynamics and compression toward the target location (specificity due to CO_2 laser interaction with pre-plasma), area of preferential laser absorption also moved closer toward the target. Laser photons then had more interactions with target surface and as a consequence more reflected and reabsorbed photons were occurred at this time. Figures 3 and 4 illustrate areas of accumulated laser energy absorption during the pulse with correspondent location of droplets.

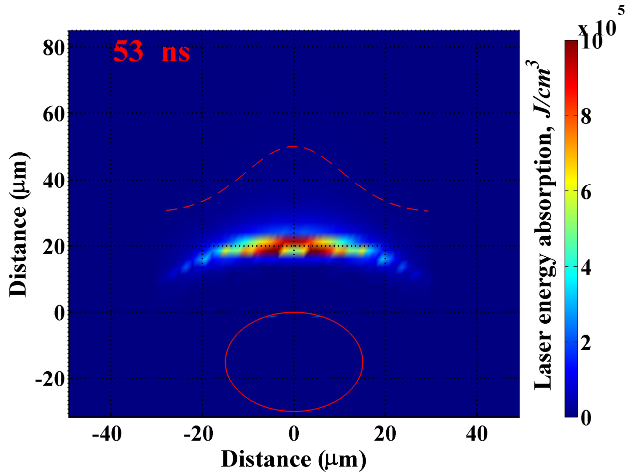

Figure 3. CO_2 laser energy absorption during pulse in material and plasma from 30 μm droplet without pre-pulse.

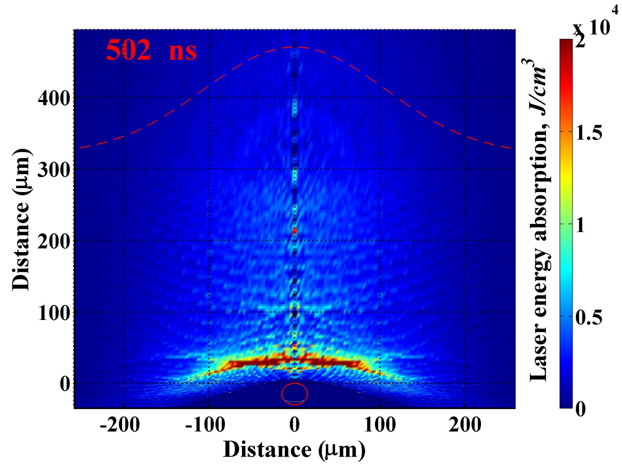

Figure 4. CO_2 laser energy absorption during pulse in pre-plasma created from 30 μm droplet by 266 nm laser and expanded during 450 ns.

3. RADIATION TRANSPORT IN FULL AND EUV RANGE

Self-consistent modeling of processes during target ablation is necessary for accurate predictions of plasma evolution and CE estimation. Initially laser photons start to heat target surface initiating target vaporization. Subsequent laser interaction with the developed vapor/plasma results in reducing laser penetration to the target, however it initiates heating of the target by plasma radiation. Thermal conduction in plasma distributes energy of absorbed laser photons that also can affect dynamics of target vaporization through the radiation from the warm plasma around the target surface. Hydrodynamic effects such as spherical expansion of plume and plasma motion around the droplet result in density distribution that changes dynamics of laser photons absorption as well as plasma radiation emission and absorption in plasma and on the target surface.

Radiation transport can be one of the main mechanisms responsible for the target heating and vaporization. Figures 5 and 6 show simulation results of tin foil ablation by CO_2 and Nd:YAG laser with the same pulse parameters, i.e., 10^{11} W/cm^2 intensity, 100 μm spot, and 10 ns duration. This intensity of lasers created plasmas with temperatures up to 65 eV in case of Nd:YAG and up to 120 eV by CO_2 laser. Most of laser photons were absorbed in the hot plasma. The temperature distributions in the target and erosion profile are attributed to the plasma radiation. Temperature profile on the surface demonstrates processes of plume expansion in LPP source with planar target, i.e., with denser plasma at the center of laser spot and with more hot less dense plasma correspondent to the wings of surface temperature.

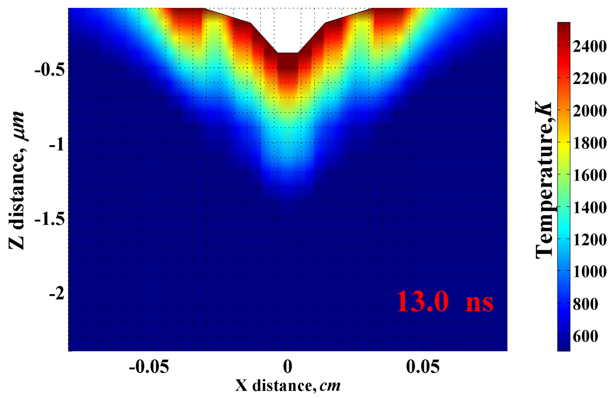

Figure 5. Sn erosion by CO_2 laser with 100 μm spot and 10^{11} W/cm^2 intensity.

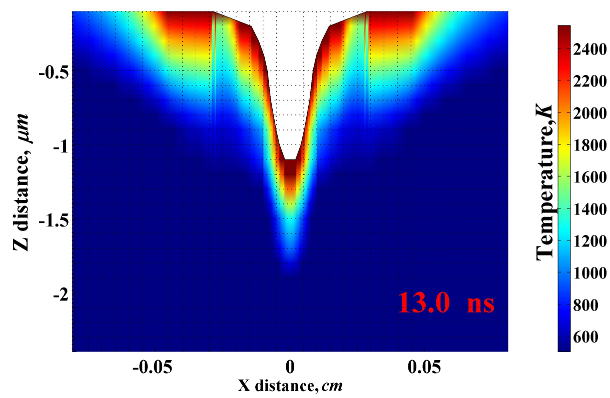

Figure 6. Sn erosion by Nd:YAG (1064 nm) laser with 100 μm spot and 10^{11} W/cm^2 intensity.

While accurate modeling of radiation transport in full energy range is critical for understanding plasma evolution to optimize LPP source, calculation of radiation output in 13.5±1% nm region requires accurate atomic data with detailed resolution of spectra in this energy range. We used separate detailed resolution of energy groups in 1.84 eV interval for simulation of EUV photons emission and absorption. Figures 7 and 8 show the difference in EUV source location and intensity collected in 2π sr from plasma heated by CO_2 laser with different initial plasma conditions. In the first case plasma was created in vacuum chamber from droplet using single CO_2 laser during 15 ns of exposure (Fig. 7). In the second case plasma was prepared using pre-pulse laser, expanded during 500 ns, and then heated by main laser during 15 ns (Fig. 8). Larger plasma plume allowed efficient utilization of laser energy and extended area for EUV photons emission. Even higher intensity of EUV power from single pulse did not compensate EUV collection from larger volume. We obtained less than 1% CE from single pulse and more than 3% in the second case. Reducing spot size to match the droplet diameter did not significantly increase the efficiency of single CO_2 devices.

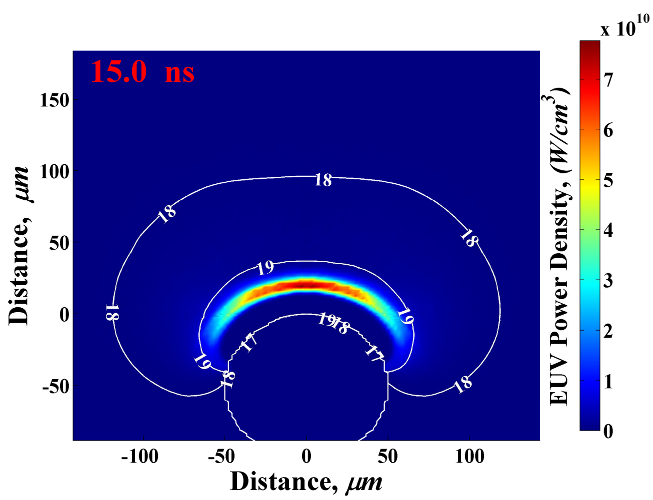

Figure 7. EUV Source strength and location from 100 μm droplet without pre-pulse; CO_2 laser with 300 μm spot, 30 ns pulse.

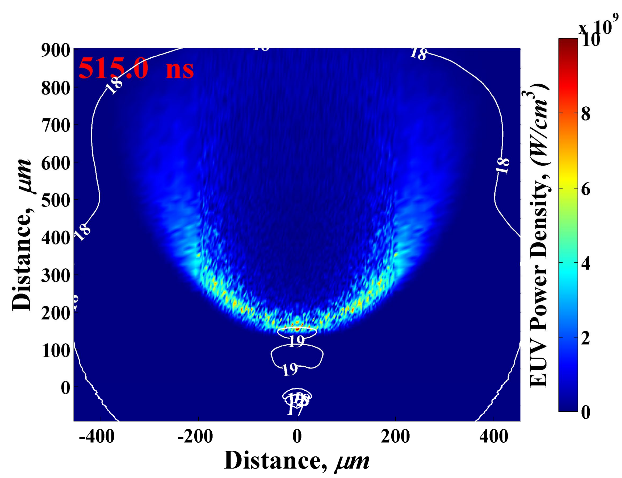

Figure 8. EUV Source strength and location due to pre-plasma created from 50 μm droplet and expanded during 500 ns; CO_2 laser with 300 μm spot, 30 ns pulse.

4. HYDRODYNAMIC CONFINEMENT

Hydrodynamic plasma evolution also requires accurate treatment and advanced modeling especially in the simulation of smaller laser spots and targets.

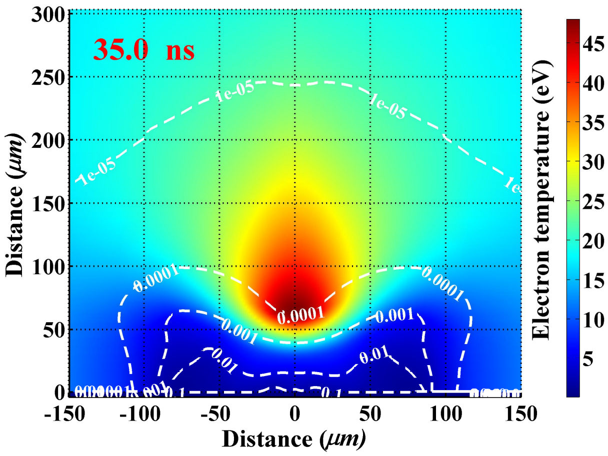

Figure 9. Temperature and mass density distribution at 35 ns in plasma created from Sn foil by CO_2 laser with 30 μm spot.

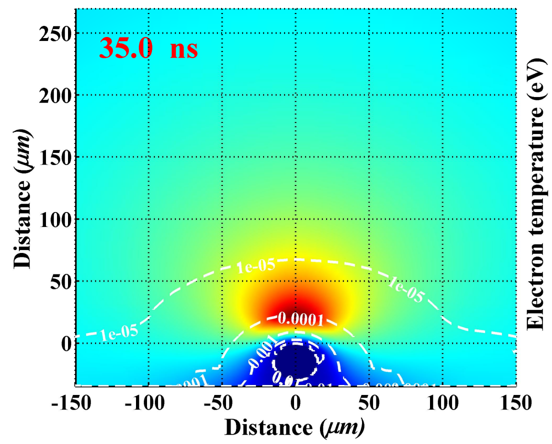

Figure 10. Temperature and mass density distribution at 35 ns in plasma created from 30 μm droplet by CO_2 laser with 30 μm spot.

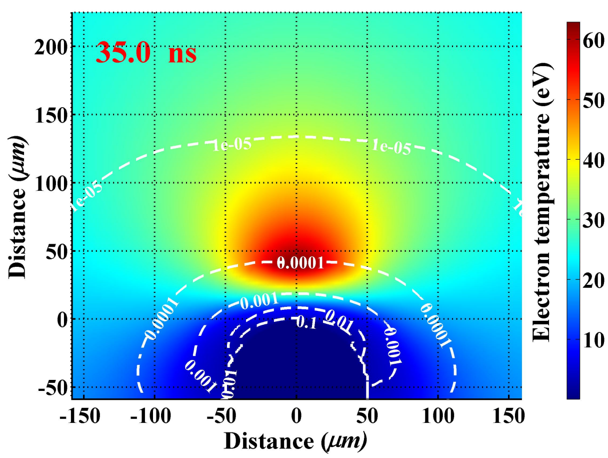

Figure 11. Temperature and mass density distribution at 35 ns in plasma created from 100 μm droplet by CO_2 laser with 50 μm spot.

The difference in combination of plasma density and temperature in most emissive areas and in surrounding plasma determines photons source efficiency. Distribution of these parameters depends also on hydrodynamic expansion and confinement, which can be controlled by lasers [4], [5], target geometry [6], or combination of both. For example, planar target yields two times higher CE for the same CO_2 laser parameters. Comparative analysis of plasma temperature and mass density distribution (Figs. 9 and 10) shows larger potential area for EUV photons emission in the planar target geometry. Figure 11 shows the distribution of plasma parameters for a medium case between planar and spherical targets where larger droplet was used and the laser spot size was smaller than droplet diameter. The efficiency of this system was comparable with the efficiency of planar geometry.

5. CONCLUSION

We studied the effect of various processes on plasma evolution in LPP sources in regards to the efficiency of these sources for emission and collection of EUV power. Radiation transport and hydrodynamic processes play critical role in determining the conversion efficiencies of laser-produced plasma for EUV sources. The complex hydrodynamic flow near target surfaces should take into accounts various energy input from laser input source, i.e., absorption/reflection in solid/liquid target, in target vapor, and in plasma layer. Calculation of radiation output in the EUV region also requires accurate atomic data with detailed resolution of spectra in this energy range. HEIGHTS integrated models in full 3D geometry were extensively benchmarked against various experimental results in various fields of science during many years. Computer simulation can therefore be used with confidence to simulate and optimize EUV sources for advanced lithography and reduce the need for numerous expensive experiments to identify regimes where optimum target/laser system can be designed.

ACKNOLEDGMENTS

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