# Design and Optimization of Laser Produced Plasma Devices for Nanolithography

**Ahmed Hassanein and Tatyana Sizyuk**

**Center for Materials Under eXtreme Environment, School of Nuclear Engineering**
**Purdue University, West Lafayette IN, 47907, USA**

**ABSTRACT**

*Laser Produced Plasma (LPP) devices with Sn targets are currently the leading design in the development of extreme ultraviolet (EUV) photon sources for the advanced lithography in future manufacturing of computer chips. The developments and optimizations of LPP sources for EUV lithography include research starting from simple planar targets to high frequency droplet targets. Investigation of Sn-doped materials for producing optically thin plasma was conducted to reduce EUV photons loss due to self-absorption and minimize tin debris. Recent utilization of small Sn droplets with pre-pulse technique promises achieving high volume manufacturing of this advanced nanolithography systems. Optimization of commercial devices using liquid droplets requires consideration of two major objectives: minimum debris production and maximum conversion efficiency (CE) and EUV power. We studied various laser beam parameters along with droplet sizes to determine conditions that influence EUV emission and absorption as well as debris development. The process of optimization included simulation and benchmarking of LPP devices with single and dual-beam pulses, producing enough volume of vapor/plasma mix that can be efficient source of EUV photons emission, optically thin for EUV photons collection and, at the same time, relatively dense to reduce energetic ions production. We used our comprehensive HEIGHTS package for modeling analysis, optimization, and LPP system design.*

**KEYWORDS:** EUVL, LPP, Tin Droplets, HEIGHTS

## 1. INTRODUCTION

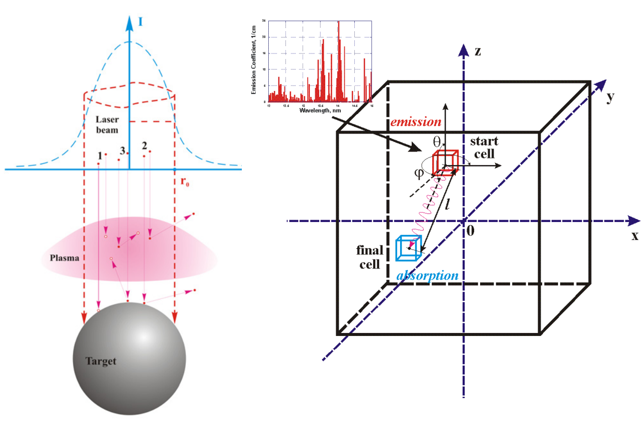
The history of 13.5 nm photons source development for EUV lithography includes investigation of several devices using discharge produced plasma (DPP) as well as devices using LPP utilizing several target materials, i.e., xenon, lithium, and tin [1]-[3]. The most promising devices, LPPs with various tin target configurations, allowed producing the most efficient sources showing the highest rate of laser energy conversion to EUV photons output. Several criteria were considered for the optimization of LPP systems including efficient EUV output and collection, minimized debris production and mitigation, components lifetime, and source brightness for the high volume manufacturing (HVM) devices. From the most points of view, small liquid tin droplets, fragmented and evaporated by an initial pre-pulse laser for the following subsequent heating and ionization by the main laser pulse, showed the best results and currently have highest priority for further investigation and optimization. We analyzed several tin targets geometries and sizes heated by various lasers with different parameters to predict EUV photons emission, collection, source size and intensity, atomic and ionic debris producing, as well as effect of debris on LPP device components lifetime. We utilized HEIGHTS LPP package for the modeling analysis and benchmarking with experimental results obtained in our CMUXE Lab and with experiments of other groups in EUVL field [4],[5].

## 2. HEIGHTS MODELING OF LPP

Accurate simulations of laser interaction with targets in different configurations and plasma evolution in various design geometries require multidimensional comprehensive and advanced models for the description of all plasma physics processes. Our HEIGHTS package contains detailed models for energy deposition, vapor/plasma formation/evolution and magneto hydrodynamic (MHD), thermal conduction in material and in plasma, atomic physics and resulting opacities, detailed photon radiation transport, and interaction between plasma/radiation and target material[1],[6].

For accurate modeling of various energy inputs from laser radiation, i.e., absorption/reflection in solid/liquid target, in target vapor, and in plasma layer, we used experimental optical properties for laser reflection from liquid tin. Simulation of laser photons absorption in vapor was based on the experimental results where quadratic dependence of the absorption coefficient on the density and a weak dependence on the temperature were shown. Inverse bremsstrahlung absorption was used for simulation of laser photons interaction with plasma [7].

Self-consistent simulation of all LPP processes in HEIGHTS package further showed importance of detail models description. Monte Carlo modeling of laser photons absorption and reflection (**Fig.1a**) as well as plasma radiation and transport (**Fig.1b**) interplays with and influences surface vaporization processes. The vaporized layer above the target surface initializes the processes of laser photons absorption in vapor/plasma that prevents their penetration to target surface. At the same time, radiated plasma photons add their energy to further heating of the droplet and this energy load to the target can be significant from the well-developed hot plasma plume. Implemented in HEIGHTS model for target vaporization establishes the connection between the surface temperature and the net atom flux leaving the surface taking into account the possibility of recondensation [8].




a) b)

**Fig. 1** Monte Carlo modeling of a) laser photons interaction with target; b) plasma photons emission, transmission, and absorption [7]

Combination of plasma temperature and density distribution determines EUV photons emission, absorption, and resulting collection in the specified solid angle. Hence advanced models for hydrodynamics of vapor/plasma plume are required to consider the difference of these parameters dynamics in various device geometries. The Eulerian/Lagrangian description of vapor/plasma plume expansion with finite volume approximation is implemented in HEIGHTS. Model for energy redistribution due to heat conduction by electrons and ions utilizes sparse solvers of linear equations system.

Simulations and predictions for complex target geometries require multidimensional description of all processes in LPP devices. Such modeling is time consuming that requires moreover code optimization to achieve detail results in acceptable time. HEIGHTS Monte Carlo method for modeling of laser beam as well as plasma radiation transport has implemented several weight factors for increasing accuracy and speedup of the simulations.

## 3. RESULTS AND DISCUSSION

### 3.1 Details of laser interaction with small targets

Optimization of LPP sources for EUV photons production requires simultaneous analysis of combination of several laser beam parameters such as laser beam wavelength, intensity, duration, and spot size. Effect of target material, geometry, and size on the requirements to energy source characteristics adds complexity to the optimization process. Our modeling considered different target geometries for tin, starting from simple planar case, then grooved plates and, finally, small spherical targets. Modeling results showed different tendencies in laser parameters optimization for the above various geometries.

For example, Nd:YAG laser with 1064 nm wavelength and $CO_2$ laser with 10.64 μm wavelength

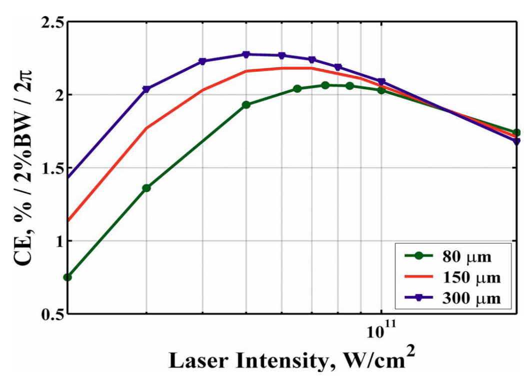



**Fig. 2** Effect of spot size on CE of source with Nd:YAG laser and tin foil; pulse duration is 9 ns [5]

can produce plasma from tin foil with approximately the same efficiency of EUV output. These lasers have different intensities range and pulse duration for efficient EUV source; however, they showed the same tendency in increasing conversion efficiency (CE) with increasing spot size. **Figure 2** illustrates this tendency for Nd:YAG laser with 9 ns duration. While the CE decrease for smaller spot size is not so significant in the case of this laser, decrease of $CO_2$ laser efficiency for EUV photons output is more dramatic. For example, LPP device with 10 μm $CO_2$ wavelength, 220 μm spot diameter and 35 ns duration produces EUV source with CE of 2.15%. This value agrees well with our recent CMUXE experimental results for similar conditions [9]. A decrease of spot size to 100 μm leads to the decrease in CE to 1.8%. Further reduction of spot diameter to 30 μm results in CE decrease up to 1%.

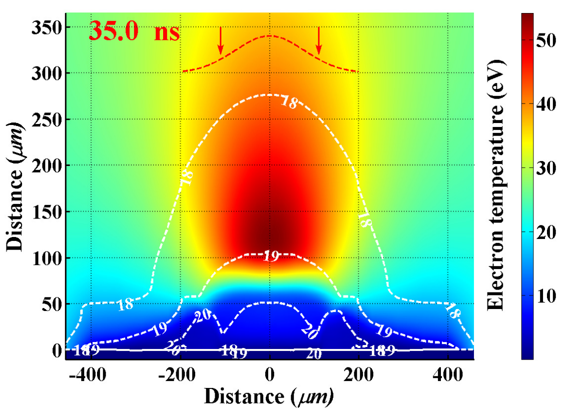



**Fig. 3** Plasma temperature and density (white contours) distribution at 35 ns of $CO_2$ laser pulse with 220 μm spot diameter

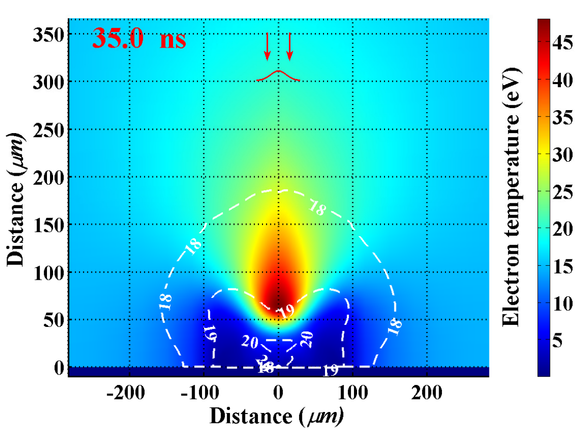



**Fig. 4** Plasma temperature and density (white contours) distribution at 35 ns of $CO_2$ laser pulse with 30 μm spot diameter

**Figures 3** and **4** illustrate the difference in density and temperature distribution in plasmas created by $CO_2$ laser with large and small spot diameters. We used optimized laser intensities for the considered spot sizes, $5x10^{10}$ W/cm$^2$ for smaller spot and $7x10^9$ W/cm$^2$ for the larger one. The EUV source in tin plasma is determined by 30-40 eV temperatures and utilizing of these intensities allowed achieving approximately the same plasma temperatures range for both beams. The difference in plasma conditions in these two cases is related to the density distribution. Laser with larger spot created larger volume of plasma that provided better confinement. This results in extended area with densities relevant to EUV photons emission correspondent to the ionic species of $Sn^{8+}$-$Sn^{14+}$.

Low efficiency of sources created by $CO_2$ lasers with small spots is more expressed in devices with small, i.e., 10-50 μm droplets. These devices have several advantages for the development of systems with high volume manufacturing such as possibility of efficient mechanism for target delivery and longer optical system and components lifetime due to reduced target mass and, therefore, reduced debris production. However, they require significant efforts for analysis and optimization to provide CE comparable with planar targets.

Our modeling for small spherical targets showed another tendency in the effect of spot size on source efficiency for Nd:YAG and $CO_2$ lasers. In the case of Nd:YAG laser, reasonable reduction in spot diameter (FWHM) to the size smaller than droplet diameter allows producing more efficient EUV source. This is due to relatively high absorption of 1.064 μm wavelength on the target surface and in dense plasma above. Therefore, reducing spot size prevents laser photons loss due to target missing. Opposite situation appears for $CO_2$ laser. Laser photons with 10.64 μm wavelength are preferentially absorbed in relatively low density region. Hence larger volume with low dense plasma provides better conditions for the laser photons absorption. Therefore, laser beam with spot diameter even exceeding the droplet size can produce more efficient EUV source.

**Figures 5** and **6** show EUV source size and intensity in plasmas created from 30 μm tin droplet by $CO_2$ laser with 30 μm (**Fig. 5**) and 50 μm spot diameters (**Fig. 6**). EUV photons were collected in $2\pi$ sr during 50 ns laser pulse. Increase of spot size in these cases allowed increase in CE from 0.45% to 0.67%. These values are still much lower than the efficiency from a foil heated by laser with large spot;

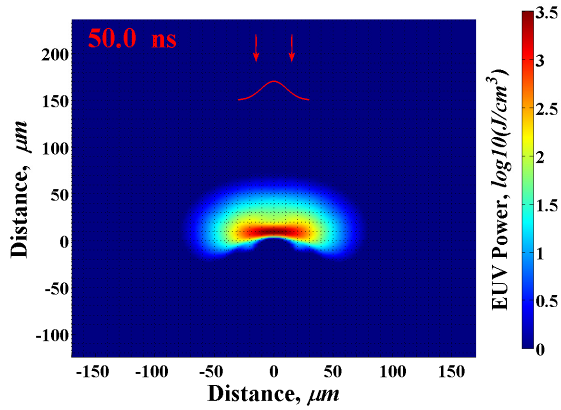



**Fig. 5** EUV source from 30-μm droplet heated by $CO_2$ laser with 30 μm spot size

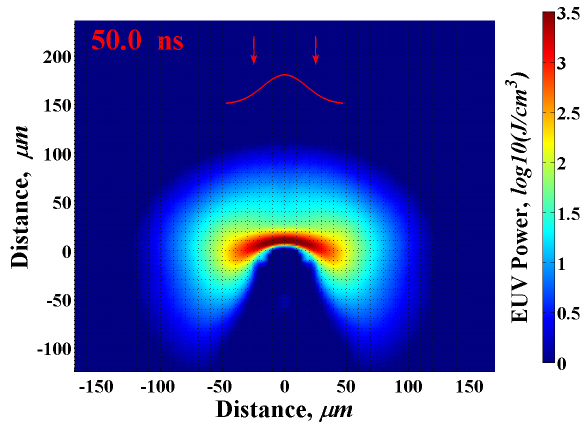



**Fig. 6** EUV source from 30-μm droplet heated by $CO_2$ laser with 50 μm spot size

however, this example illustrates the way for such devices optimization that is a preparation of large volume of low dense plasma. Red plots and arrows in Figures 3-6 show laser footprint and beam direction.

### 3.2 Dual-beam lasers for optimization

The utilization of pre-pulses for target preparation prior to the main pulse can significantly increase CE of LPP sources with small droplets. We modeled various combinations of laser beams parameters for pre-plasma creation and for the following plasma ionization to achieve efficient EUV photons output. Our analysis showed, for example, that forth harmonic of Nd:YAG laser is more suitable for the first, preparation stage, while $CO_2$ laser is more efficient for interaction with prepared plasma. We studied ways of maximizing EUV emission based on vaporization processes and adjustments of delay time and main spot size for specific created pre-plasma[10],[11]. Our analysis showed that 20 μm is about the smallest size of droplet for efficient EUV source [10]. We demonstrated also that dual-beam systems produce less energetic ions that result in reducing damage of collecting mirrors system. In the dual pulse case, the interaction of the $CO_2$ main laser pulse with the plasma created by the pre-pulse laser helps dissipate the $CO_2$ energy deeper into the pre-pulse plasma [12].

## 4. CONCLUSION

We used our multi-physics HEIGHTS package for the modeling analysis and optimization of LPP systems for efficient photons source for EUVL. The processes of optimization of LPP devices with small tin droplets included simulation and benchmarking of LPP devices with single and dual-beam pulses. Efficient EUV sources depend on combination of various parameters including pre-pulse laser wavelength/intensity, size of target/vaporization rate, and delay time/spot size. We showed that devices with dual-beam pulses and small tin droplets can produce efficient EUV sources starting from the droplet sizes of 20 μm. The requirements for the desired increase of EUV power for HVM will require detail analysis of larger droplets of 25 μm and more.

## ACKNOWLEDGEMENTS

This work is partially supported by the College of Engineering, Purdue University.

## REFERENCES

[1] A. Hassanein et al., in EUV Sources for Lithography, edited by V. Bakshi (SPIE, Bellingham, Washington, USA, 2006), Chap. 9, pp. 277–298.
[2] U. Stamm et al., Proc. SPIE 5037, 2003, 119.
[3] T. Higashiguchi, Appl. Phys. Lett. 88, 2006, 161502.
[4] V. Sizyuk, A. Hassanein and T. Sizyuk, Laser and Particle Beams 25, 2007, 143-154.
[5] A. Hassanein, V. Sizyuk, T. Sizyuk and S.S Harilal, J. Micro/Nanolith. MEMS MOEMS 8, 2009, 041503.
[6] V. Sizyuk, A. Hassanein, V. Morozov, V. Tolkach, T. Sizyuk, and B. Rice, Numerical Heat Transfer Part a-Applications 49, 2006, 215-236.
[7] A. Hassanein, T. Sizyuk, V. Sizyuk and S.S. Harilal, J. Micro/Nanolith MEMS MOEMS 10, 2011, 033002.
[8] A. Hassanein, G. L. Kulcinski, and W. G. Wolfer, Nucl. Eng. Des. Fusion 1, 1984, 307–324.
[9] J. R. Freeman, S. S. Harilal, A. Hassanein, and B. Rice, Appl. Phys. A 110, 2013, 853.
[10] T. Sizyuk and A. Hassanein, Journal of Applied Physics 112, 2012, 033102.
[11] T. Sizyuk and A. Hassanein, Physics of Plasmas 19, 2012, 083102.
[12] A. Hassanein and T. Sizyuk, Physics of Plasmas 20, 2013, 053105.