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Ahmed Hassanein
Tatyana Sizyuk
Valeryi Sizyuk
Sivanandan S. Harilal

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Ahmed Hassanein
Tatyana Sizyuk
Valeryi Sizyuk
Sivanandan S. Harilal
Purdue University
Center for Materials Under Extreme Environment
School of Nuclear Engineering
West Lafayette, Indiana 47907-2017
E-mail: tsizyuk@purdue.edu

Abstract. Laser produced plasmas (LPPs) are currently a promising source of an efficient extreme ultraviolet (EUV) photon source production for advanced lithography. Optimum laser pulse parameters with adjusted wavelength, energy, and duration for a simple planar or spherical tin target can provide 2% to 3% conversion efficiency (CE) in laboratory experiments. Additional effects such as targets with complex geometry and tin-doped targets using prepulsing of laser beams can significantly increase CE. Recent studies showed that such improvements in an LPP system are due to reduction in laser energy losses by decreasing photons transmission (higher harmonic of Nd:yttrium-aluminum-garnet laser) or photons reflection (for CO_2 laser). Optimization of target heating using prepulses or ablating low-density and nanoporous tin oxide can further improve LLP sources by creating more efficient plasma plumes and, as a result, increase CE, the most important parameter for EUV sources. We investigated the combined effects of prepulsing with various parameters and different target geometries on EUV conversion efficiency and on energetic ions production. The much higher reflectivity of CO_2 laser from a tin target leads to two possible ways for system improvement using prepulses with shorter laser wavelengths or using more complex targets geometries with special grooves as developed previously by the authors. [DOI: 10.1117/1.3609043]

Subject terms: nanolithography; extreme ultraviolet; laser produced plasma; HEIGHTS; debris mitigation; CO_2 lasers.

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1 Introduction

There are still several challenges in the development and production of the currently progressing laser produced plasma (LPP) sources for extreme ultraviolet lithography (EUVL), and in particular using CO_2 lasers and tin targets. Plasma sources using CO_2 lasers have a number of advantages over other LPP sources using Nd:yttrium-aluminum-garnet (YAG) lasers including higher laser efficiency, lower power needed to produce similar plasma conditions, less generated debris, etc. In addition to the extensive work on source optimization and collection of extreme ultraviolet (EUV) photons, the lifetime of the collecting mirror system is also very important and is under comprehensive development and investigation. Damage of multilayer Mo/Si mirrors by the debris products of laser beam interaction with target materials can significantly reduce their lifetime, and as a result, the efficiency and the economy of the entire EUVL system. For example, while debris production is more pronounced for Nd:YAG lasers, CO_2 laser beams produce more energetic ions at the optimum conditions for laser energy intensities needed for maximum EUV production.[1,2] Additionally the impact of plasma fast ions and the deposition of atomic debris and the deposition of EUV and out of band radiation can further cause surface erosion and damage at the required higher fluences of the 13.5 nm radiation needed for high volume manufacturing.[3]

The lower mass ablation rate by the CO_2 laser beams with the longer wavelength and comparatively low value of the critical density for absorption of these photons allow source operation using longer pulses (100 ns and more) without significant reduction in the efficiency of EUV output.[4] Increased pulse duration, however, leads to increasing debris producing and accumulation and therefore, decreasing mirror lifetime. Another disadvantage of longer pulses is the increase in EUV source size due to the large plasma expansion. While usually LPP devices provide smaller source sizes (compared to discharge produced plasma devices) that satisfy the optical system requirements for the etendue,[5] CO_2 laser systems using larger spot sizes and long pulse duration (tend to increase the source size) compared to Nd:YAG lasers may cause difficulties in EUV photons collection.

The above aspects and requirements determine the preferences in target geometry and size.[6] Currently tin droplets with sizes from 10 to 100 μm are under investigation. We extensively modeled tin droplets ablation by CO_2 laser and studied the dependence of laser energy losses on droplets and spots size, laser beam intensities, and time duration using our HEIGHTS (High Energy Interaction with General Heterogeneous Target Systems) full three-dimensional (3D) simulation package. We predicted the optimum parameters in certain combinations of a double-pulsed system to increase EUV production through the processes of the initial plasma

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creation by preheating the tin droplets with 532 nm and 1.064 μm wavelengths, and then followed by the main CO_2 laser pulse.

We utilized a unique combination of our experimental facilities (CMUXE Laboratory) and our state-of-the art computer simulation (HEIGHTS package) at Purdue University for a detailed investigation, benchmarking, and optimization of LPP sources with various lasers, target parameters, geometries, and an optical collection system. Comparisons of various experiments with modeling results were discussed and detailed plasma characteristics for more efficient LPP sources were analyzed.

2 Model Description

The HEIGHTS simulation package is being developed as a comprehensive tool for the investigation and optimization of various radiation sources interacting with matter and that include both laser and discharge produced plasmas proposed for the next generation of nanolithography, i.e., the extreme ultraviolet lithography applications. We developed integrated multiphysics, multiphase models to simulate the interaction of intense energy sources with target materials. We used HEIGHTS to model in detail LPP devices that consider and integrate all interaction phases and various processes, i.e., from the initial stage of solid/liquid target ablation by the laser photons up to final generation of the EUV radiation.[7–10] The developed models address and integrate several major research areas, i.e., physics of laser absorption in target materials, vapor/plasma evolution, and magnetohydrodynamic (MHD) processes, thermal conduction in condensed material and plasma, atomic physics and resulting opacities, detailed photon radiation transport, and interaction between plasma/radiation and target material in full 3D geometry. The HEIGHTS package utilizes various models and numerical solution methods to calculate details of energy deposition, MHD evolution, radiation transport, and heat conduction in solid/liquid/vapor/plasma target phases. Radiation transport methods using both direct methods, as well as weighted Monte Carlo models, are developed to specifically calculate in fine detail both continuum and line transport with fine spectral resolutions and profiles. In addition, another weighted Monte Carlo model is used to calculate laser energy absorption, reflection, and transmission of photons in various phases of the dynamically evolving target material.

Accurate photon radiation transport calculations are very critical in the assessment and evaluation of EUVL devices and their efficiency. HEIGHTS uses two different approaches to calculate radiation transport: Direct integration of the radiation transport equation and Monte Carlo techniques with weight factors hierarchy. Each method has its own advantages and disadvantages. These different approaches provide significant insight and self-benchmarking on the appropriate numerical technique for multidimensional solution of such complicated physics problems. The radiant energy flux is calculated by integrating the differential radiation transport equation (RTE), which represents the conservation of emitted and absorbed photons energy along the direction of photons movement. Direct Gauss integration methods digitize the MHD domain in space, energy, and angles. The major limitations of this approach are time-consuming and computer resources, as well as numerical stability. An alternative to the direct resolution of the RTE, where we seek the continuous function of the radiation intensity, is the probabilistic model of the energy redistribution operates with discrete portions of the radiative energies, as shown in Fig. 1(a). Each energy portion is individually analyzed. The trajectory and number of emitted and absorbed energy portions are evaluated in each point of the plasma domain (or in the points which represent a major interest with fine details). The energy is then redistributed as a result of photons motion and interaction in each cell domain. The energy and the trajectory of photon movement can be determined by Monte Carlo techniques as well as by direct solution of photons transport equation as a way to check the accuracy of our calculations.

Laser absorption, reflection and resulting interaction/transport, and the reabsorption or transmission of laser

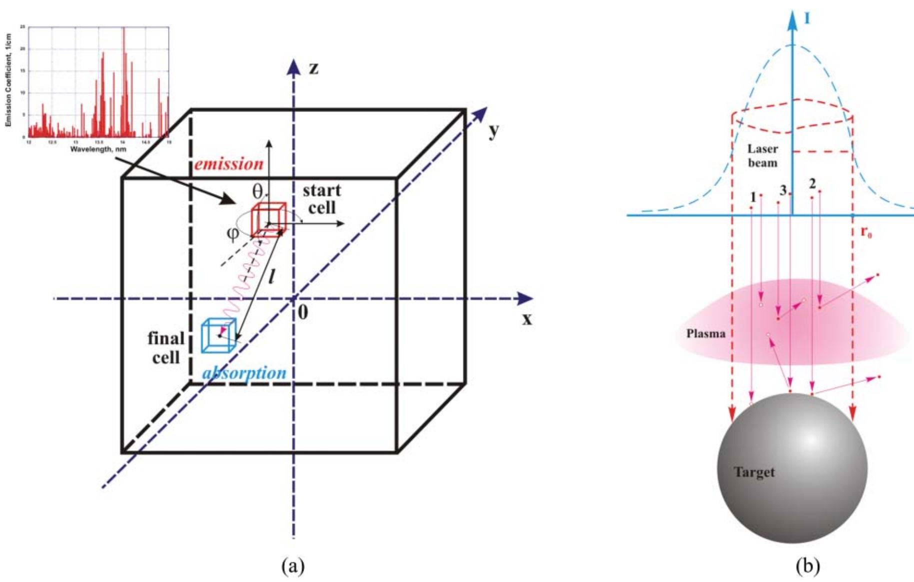

Fig. 1 (a) Monte Carlo illustration of emission-absorption process for the radiation transport and (b) interaction of the laser energy photons with target.

photons energy are modeled similar to the plasma photon radiation transport with weighted Monte Carlo techniques. Figure 1(b) illustrates three possible events for laser photons: 1. absorption in solid matter or plasma; 2. reflection and reabsorption in plasma; 3. reflection and transmission out of the area of potential absorption. Our Monte Carlo method allows redistribution of laser photons energy in all directions that can be important in the domain of the plasma plume with nonuniform conditions in two-dimensional or 3D configurations.

The absorption/reflection of laser photons in solid/liquid phases of the target in our models is based on experimental data and models of absorption/reflection in plasma utilize inverse bremsstrahlung mechanism since the electrons are the main interaction particles of the laser photon radiation energy.[9]

For correct modeling and higher accuracy of the radiation transport processes, we considered two important features in our calculations. Radiation fluxes should first be determined with the correction of the plasma thermal energy and, as a result, the correction of plasma evolution and motion in the device domain and second, following the use of detail analysis of the final useful part of the very narrow EUV plasma radiation flux. These problems involve different requirements for determining the radiation flux and therefore require different numerical techniques for solving the photon transport problem. Correct calculation of the spatial energy redistribution in the full spectrum plays an important role in the accurate solution of the first problem. A model that adequately describes radiation transport is only correct if it takes into account the optical thickness of the plasma over a wider spectral range that exists in plasma domain. The total spectral range must be optimized to sufficiently and accurately describe the radiation energy redistribution using reasonable computational capability. These opacities, however, will be inadequate for detailed investigations of the EUV photons in the required spectral band of $13.5 \pm 2\%$ nm. Therefore, two sets of optical opacities are developed, i.e., a general one (for full energy redistribution calculations) and a specific detailed one (for a specific spectral band).

The equations-of-state (EOS) and opacities are calculated independently for a wide range of temperatures and densities. Tabulated opacities are used during the numerical simulation by interpolating plasma density and temperature parameters.

The structure of atomic energy levels, wavefunctions, transition probabilities, ionization potentials, oscillator strengths, broadening constants, photoionization cross sections, and other atomic characteristics are calculated using the self-consistent Hartree–Fock–Slater method.[11] The collisional-radiative equilibrium (CRE) model[12] is used to calculate the populations of atomic levels and the ion and electron plasma concentrations. The ion and electron concentrations calculated from the CRE model are used in the EOS to calculate plasma pressure and internal energy.

First, we calculated the emission and absorption coefficient in the full energy spectrum with resolution of up to 100,000 spectral points. Then we analyzed the full spectrum, determined strong spectral lines, and integrated into spectral groups for accurate modeling and transport of these critical EUV photons.

3 Dependence of Laser Energy Absorption Efficiency on Plasma Conditions

We studied the effect of initial prepulses of laser energy and the dependence of laser wavelengths on the conversion efficiency (CE) for various target and laser beam conditions. First we evaluated the percentage of useful laser energy which is absorbed in matter for the optimum intensity of a CO_2 laser beam with 100 μm spot size (FWHM) and 30 ns pulse width on 30 μm tin droplet. These values correspond to a mass-limited source that can reduce chamber contamination and have reasonable laser beam parameters for an efficient EUV source. Figure 2 shows HEIGHTS comparison of the input laser power and the lost power, i.e., escaped and reflected energy as a function of time. Since the spot size of the laser exceeded the droplet diameter more than three times, major part of laser photons did not interact with the target until a plasma plume was formed with sufficient density needed for the absorption of laser photons at this wavelength. The conditions at which the evolving target plasma started to interact with the laser beam are at about 20 to 25 ns from the start of irradiation. The corresponding mass density distribution of the initial plasma is shown in Fig. 3 at the time of 20 ns.

Preheating the droplet by a laser with a shorter wavelength and the resulting initial plasma plume formation can reduce energy losses of the main pulse. A second harmonic of Nd:YAG laser was used in our numerical simulations for the heating, evaporation, and initial ionization of the droplet target. Figure 4 shows a comparison of laser energy absorption for Nd:YAG (second harmonic of 532 nm) at intensity of 5×10^{11} W/cm^2 during 10 ns and CO_2 at intensity of 10^{10} W/cm^2 for two cases with and without prepulse interacting with 30 μm initial droplet size. Figure 5 shows the mass density distribution as a result of the prepulse laser that expanded during 80 ns. In both cases the CO_2 laser heated the plasma up to a maximum temperature of 50 eV; this temperature indicates that plasma plume with optimum conditions for EUV production was created.[10] The improved absorption of the laser energy increased the CE value up to 50%.

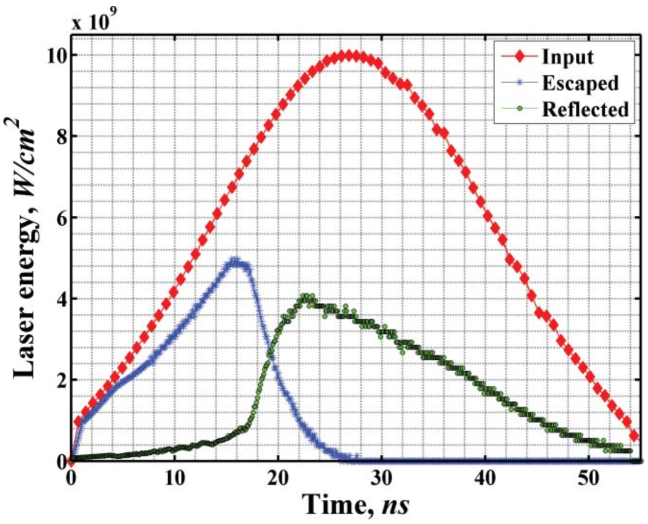

Fig. 2 Laser energy distribution for 100 μm spot size (FWHM), 30 ns duration (FWHM), and 1×10^{10} W/cm^2 intensity; droplet diameter 30 μm.

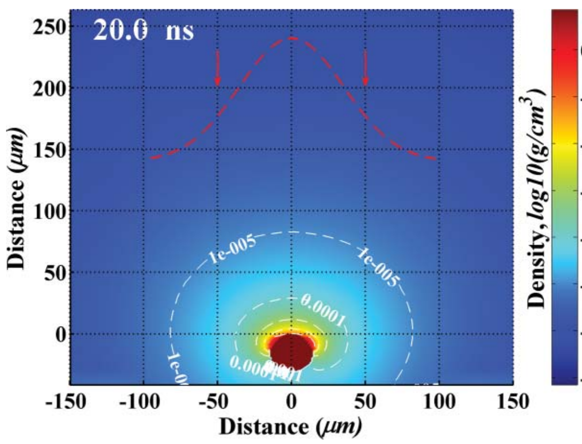

Fig. 3 Mass density distribution of plasma plume from tin droplet of 30 μm diameter.

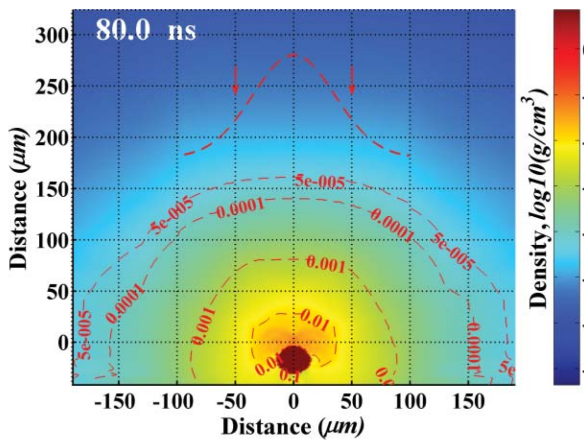

Fig. 5 Mass density of plasma plume from the droplet of 30 μm created by 532 nm laser and expanded during 80 ns.

In this numerical simulation the initial plasma was created by a 532 nm laser with the intensity of 10^{10} W/cm^2, which did not create plasma with conditions suitable for EUV emission during pre-pulse.

4 Dependence of EUV Emission on Target Mass and Spot Size

Increasing the delay time between the prepulse and the main pulse did not influence much on the EUV production by the main CO_2 laser. After the time moment when the mass density of about 10^{-4} g/cm^3 reaches the borders of the spot radius (around 30 ns for this droplet size and the prepulse energy), additional plasma expansion does not significantly improve EUV production. The change in the CE for 30 and 80 ns delay times was only about 10%. A more important parameter in this case is the spot size of the main laser beam, which can be adjusted to the delay duration and, as a result, to the evolving plasma size. A double increase in spot size of the CO_2 laser led to an increase in CE of more than two times with a conversion efficiency that is comparable to that received for planar targets, i.e., of about 1.8%.

There are several ways for optimizing LPP sources with mass-limited targets: 1. preparing an initial plasma by a prepulse; 2. adjustment of target size and spot size; and 3. increasing the time of laser pulse duration. We studied the above options in our optimization analysis. Since the time dependence of EUV output always follows the time profile of the laser beam, it is also reasonable to use prepulse laser intensity suitable for in-band emission at this stage. To achieve the maximum EUV output we used optimized parameters for the prepulse beam, i.e., 10^{11} W/cm^2 of 1064 nm with 100 μm spot on the same diameter of a tin droplet. We obtained a conversion efficiency of about 1.7% for this pulse. Next, we allowed the plasma plume to expand during 40 ns and then applied a main CO_2 laser pulse with 30 ns duration and an intensity of 10^{10} W/cm^2 with various spot sizes. Figure 6 shows the influence of the spot size on EUV production at the above stated conditions.

For mass-limited target systems, two parameters can influence the efficiency of an EUV source: a comparatively larger spot size and sufficiently prepared mass density to absorb the incident laser energy with such a spot size. Mainly lasers with short wavelengths (harmonics of Nd:YAG) can

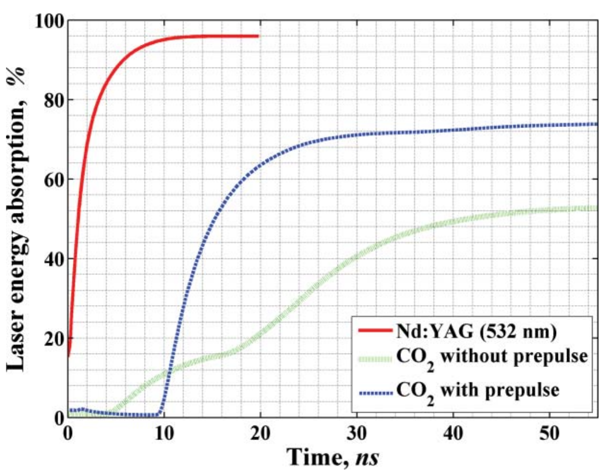

Fig. 4 Laser energy absorption at optimized intensities of: 1. 532 nm laser; 2. CO_2 without prepulse; 3. CO_2 after prepulse.

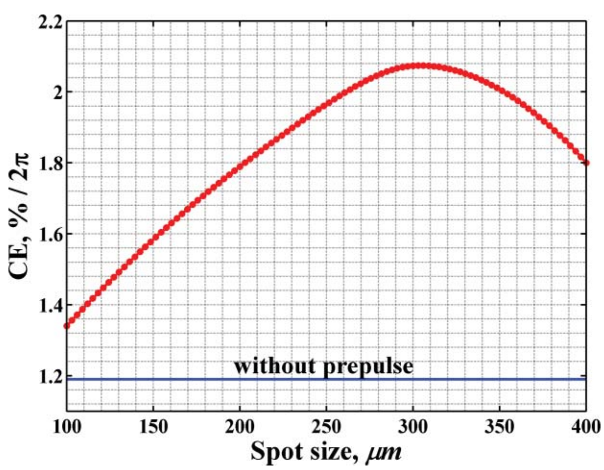

Fig. 6 The dependence of CE on CO_2 spot size applied after prepulse on tin target. For comparison. CE of a CO_2 laser with 100 μm spot size and 100 μm droplet without prepulse is given.

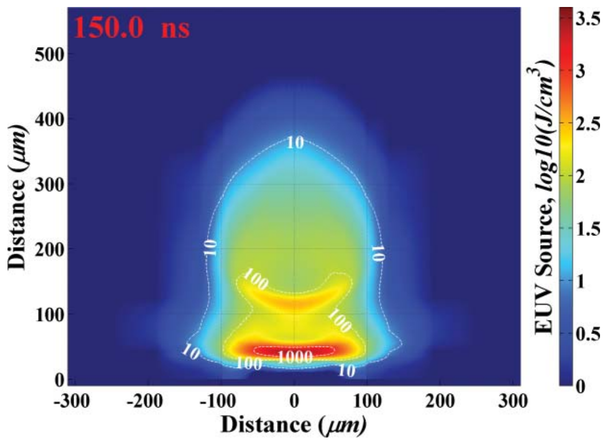

Fig. 7 Location and intensity of the EUV power collected during 150 ns in 2π sr in planar target.

be used for the first stage since they have better absorption in solid and liquid matter. The CO_2 laser can then be the best choice for the second stage, i.e., EUV production stage, since the evolving plasma plumes are more suitable for the absorption of a longer laser wavelength.

5 Hydrodynamic Effects on EUV Production by CO_2 Laser in Planar and Spherical Targets

We analyzed the EUV source size and intensity from a tin plasma produced from both plate and droplet targets with the same parameters of a CO_2 laser. We used a 100 μm spot size (FWHM) and long pulse duration of 90 ns. The difference in the hydrodynamics of plasma motion in these two systems determines the differences in the EUV source size and shape. Figures 7 and 8 show the areas of emitting EUV photons that are collected in 2π sr during 150 ns. The expanded source in the planar case is explained by the changes in the source location with time, and this is related to the movement of plasma plume with the optimal combination of temperature and density values. This is specifically related to the CO_2 laser system, where EUV radiation is produced in a low-density region that moves and expands more easily. Plasma motion around the droplet in the spherical target case prevents plasma accumulation above the target. The planar target provided a more efficient source with increasing CE of more than 30% for these conditions. This is a consequence of the hydrodynamic evolution where the plasma geometrical confinement can play an important role.[9]

Because the evolving plasma plume above the droplet surface, created by the prepulse laser beam, can change the EUV production area during the main pulse similar to the planar target, the spatial distribution of the EUV source will have the same tendency in the size expansion. Therefore, in the optimization processes, one needs to further adjust the spot and droplet sizes as well as prepulse/delay/pulse times. The resulting source size should be evaluated to satisfy the optical etendue system requirements.[13]

6 Comparison of HEIGHTS Results with Experiments

We tested various models and components of the HEIGHTS package to simulate EUV production at various experimental conditions directly without any adjustments in the package and benchmarking with different experimental results and conditions.[14] We considered several parameters that can influence the in-band photons production, i.e., laser beam wavelength, pulse duration, and spot size. Figure 9 compares the results of HEIGHTS modeling with the experimental results, where tin droplets with 100 μm diameters were irradiated by a CO_2 laser beam with 100 μm spot size and with different intensities.[14] HEIGHTS showed very good agreement with the data over a wide range of laser intensities. Since Nd:YAG laser is more suitable for the prepulse irradiation, and the prepulse stage can also be used for EUV production, we compared the efficiency of this laser with different wavelengths. The dependence of the CE on the laser beam wavelength using HEIGHTS simulation was studied in detail.[8] HEIGHTS results showed that the CE exhibits similar peaking behavior to the experimental data with laser intensity and laser wavelength, with maximum CE predicted at the longer wavelength and relatively lower intensity for the conditions studied in this case. Experimental data showed HEIGHTS similar behavior on wavelength intensities of Nd:YAG lasers.[15]

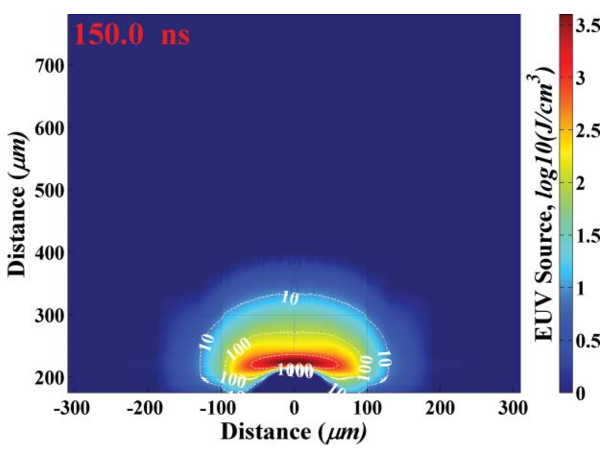

Fig. 8 Location and intensity of the EUV power collected during 150 ns in 2π sr in spherical target.

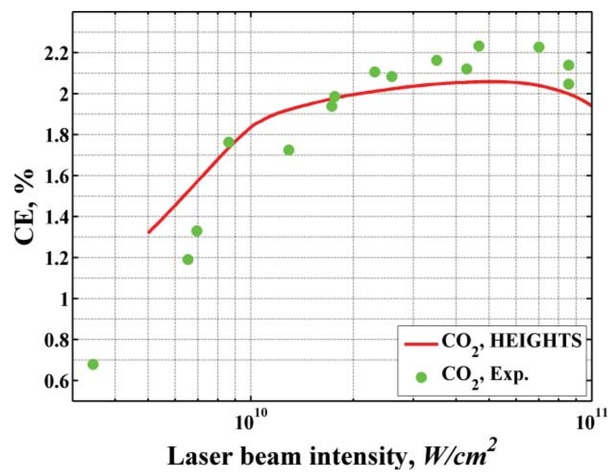

Fig. 9 Dependence of CE on laser beam intensity in experiments (Ref. 14) and HEIGHTS modeling.

7 Conclusion

Further development of LPP sources for EUV lithography should be based on mass-limited targets such as tin droplets with 10 to 100 μm diameter using CO_2 lasers. However, the CO_2 lasers have high reflectivity from the solid and liquid tin that reduces efficiency of such small targets and result in low CE. To optimize and enhance the CE of LPP sources, several factors need to be taken into account, i.e., evaluation of Nd:YAG laser parameters needed for the prepulse to create sufficient mass density of a plasma plume suitable for the main CO_2 pulse, adjustment of the delay time between the two pulses and the laser spot size of main pulse, prediction of EUV source size at different combinations of laser beam characteristics, and target evolution dynamics. We utilized our HEIGHTS package to simulate several of the above combinations to determine the critical values that influence the CE of EUV protons and their collection, and identified an optimum spot size for the evolving plasma plume created at specific prepulse conditions. Computer simulation analysis can provide great guidance to predict the optimum conditions of LPP devices to enhance their performance and extend their lifetime.

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Biographies and photographs of the authors are not available.