The Effect of Critical Plasma Densities of Laser-Produced Plasma on Production of Extreme Ultraviolet Radiation

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***Abstract*—Accurate modeling and comprehensive understanding of laser-produced plasma (LPP) for various applications should consider details of spatial and temporal input power deposition from laser sources, absorption/reflection of laser light from the surface of the solid/liquid target, hydrodynamic evolution of the target, absorption/reflection of laser from the evolving target vapor, atomic physics and vapor ionization, absorption/reflection in a heated plasma layer, and photon generation and transport during the different phases of the evolving target. The high energy interaction with general heterogeneous target systems (HEIGHTS) simulation package for LPP incorporates detail models in full 3-D geometry of laser interactions with various target materials for different applications, including fusion, advanced lithography, directed energy lethality, and surface modifications of materials. HEIGHTS illustrates strong dependence of laser absorption/propagation on wavelength and the variation in hydrodynamic evolution of the produced plasma sources.**

***Index Terms*—CO_2 laser, critical density, nanolithography, plasma density, plasma simulation, plasma sources, radiation effects.**

THE HEIGHTS laser-produced plasma (LPP) simulation package was developed as a comprehensive tool for the investigation and optimization of radiation sources for the next generation of nanolithography, i.e., the extreme ultraviolet (EUV) lithography applications [1], [2]. Laser-produced plasma sources are currently being developed to generate photons at a 13.5-nm wavelength to continue the development of faster computer chips. Utilizing the smallest wavelength for projection–EUV lithography is the path to future progress in semiconductor technology.

This paper presents integrated multiphysics multiphase modeling of LPP devices that consider all involved processes, i.e., from the initial stage of solid/liquid target ablation by the laser photons up to final generation of EUV radiation [3], [4]. The developed models integrate several major subjects, namely, laser absorption in target materials, vapor/plasma evolution and magnetohydrodynamic (MHD) processes, thermal conduction in materials and plasma, atomic physics and resulting opacities, detailed photon radiation transport, and interaction between plasma/radiation and target materials in full 3-D geometry. The HEIGHTS package utilizes various numerical and solution methods to calculate energy deposition, MHD evolution, radiation transport, and heat conduction in solid/liquid/vapor/plasma target phases. Both Eulerian/Lagrangian and particle-in-cell methods are used for plasma evolution. Several models are developed and used to calculate opacity, such as collisional radiation equilibrium and nonstationary kinetic models, depending on the complexity of the problem. Radiation transport methods using both direct methods and weighted Monte Carlo models are developed to calculate both continuum and line transport with fine detailed spectral profiles. In addition, another weighted Monte Carlo model is used for laser energy absorption, reflection, and transmitted photons in various phases of evolving target materials [3].

The images shown in Fig. 1 demonstrate the mechanism of laser energy absorption in tin plasma for two laser wavelengths used for producing an efficient EUV photon source, i.e., 1.06 and 10.6 μm for Nd:YAG and CO_2 lasers, respectively. The intensity of the laser beams was chosen as 5×10^{10} W/cm^2, and laser pulses with 10- and 30-ns time durations were chosen for Nd:YAG and CO_2 lasers, respectively. Because of the longer wavelength, the CO_2 laser radiation cannot penetrate deep into the formed dense plasma compared to the Nd:YAG laser. This is due to the reflection of the radiation in plasma (radiation frequency approaches plasma frequency) that is achieved much sooner for the CO_2 laser wavelength. The overheating effect of the plume peripheral areas is a direct consequence of the CO_2 laser radiation absorption at a much lower critical plasma density compared with the Nd:YAG laser. This preferential absorption of the CO_2 laser photons in the peripheral region at the low plasma density causes a significant increase in the plasma temperature: the maximum electron temperatures exceed 100 eV for a laser intensity of 5×10^{10} W/cm^2, whereas in the case of the Nd:YAG laser, this value reaches only about 50 eV. Our previous studies showed that the optimum laser intensity for producing an efficient EUV source using 10.6 and 1.06 μm were 5×10^9 and 5×10^{10} W/cm^2, respectively, for the considered laser spot size [3]. We compared the properties of Sn plasma sources

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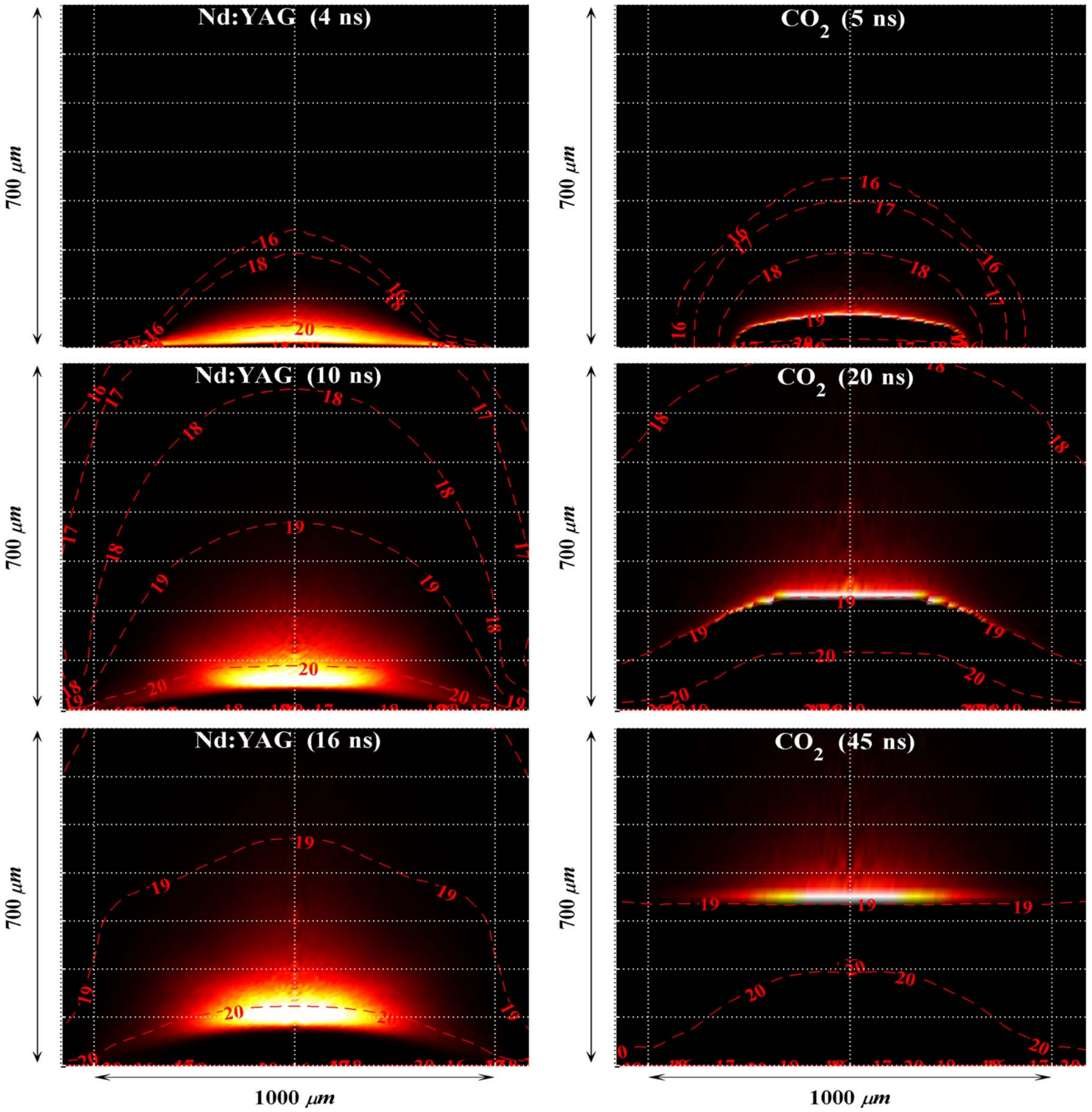

Fig. 1. Absorption of Nd:YAG and CO_2 laser energy values (in watts per square centimeter) in tin plasma at different times: a) at the beginning of the laser pulse; b) at the peak of the laser beam power; and c) at the end of the laser pulse. (Red contours) Plasma density distribution.

produced by 10.6 and 1.06 μm at the lower CO_2 power density of an order of magnitude. Our calculations showed that both produced plasma sources reach the same maximum temperature of around 50 eV, which is needed for efficient production of EUV photons.

The deposition and partition of the incident laser energy with the stronger absorption of the CO_2 laser in the upper region compared with the Nd:YAG laser explains the large difference in the erosion profile of the tin target under these conditions. The depth of the resulting erosion by the CO_2 laser is about 0.3 μm, whereas in the case of the Nd:YAG laser, this value is about 1.1 μm [4].

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