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Spatial Profiles of Electron Density and Electron Temperature of Laser-Produced Sn Plasmas for EUV Lithography

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Abstract

Spatial profiles of the electron density (n_e), electron temperature (T_e), and averaged ionic charge (Z) of laser-produced Sn plasmas for EUV lithography, whose conversion efficiency (CE) is sufficiently high for practical use, were measured using collective Thomson scattering (TS) technique. For plasma production, droplet Sn with 26 μm diameter was used as a fuel. First, a picosecond-pulsed laser was used to expand the Sn target. Next, a CO_2 laser was used to generate plasmas. By changing the injection timing of the picosecond laser and the CO_2 laser, three different types of plasmas were generated. The CEs were different for the three-types of plasmas, and ranges of CEs were 2.8-4.0%. For the different plasma condition, spatial profiles of ne, Te, and Z were clearly different each other. However, for all plasma conditions, intense EUV was only observed for sufficiently high T_e (>25 eV) and adequate n_e range [10^{24}-(2×10^{25}) m^{-3}]. These plasma parameters lie in the efficient-EUV-light-source range, as predicted by simulations.

1. Introduction

EUV lithography (EUVL) is considered a promising technology for next-generation lithography systems. In this context, laser-produced Sn plasmas with moderate temperature and density have been utilized as EUVL light sources.[1] As regards practical application, the primary challenge involves the improvement of the conversion efficiency (CE) of the EUV light source with respect to the CO_2 laser, which is used as the driving laser to produce the plasma.[2] Consequently, controlling and understanding of Sn plasma behavior becomes essential, because EUV emission strongly depends on the ionic charge of the Sn plasma. Researchers have predicted the optimum values of electron temperature T_e, electron density n_e, and averaged ionic charge Z to lie in the range of 30-50 eV, 10^{24}-10^{25} m^{-3}, and 10-13, respectively, to realize high-power EUV light sources with excellent CEs.[3] However, direct measurements of these plasma parameters of laser-produced EUV light-source plasmas, whose CE is sufficiently high for practical use, have never been performed. This study reports results of TS measurements of laser-produced Sn plasmas for EUVL, whose CE range is 2.8-4.0%. In addition, the spatial profiles of the EUV emissions are correlated with the TS results.

2. Experimental setup

Figure 1 shows the top view of the experimental setup used in our study. A Sn droplet with a diameter of 26 μm was used as the fuel for the EUV light-source. The target was generated in a vacuum chamber (<10^{-4} Pa) by a droplet generator. Two different lasers were used to generate the plasma. The first was a picosecond Nd: YVO_4 laser (pulse width: 14 ps full width at half maximum (FWHM), laser energy: 2 mJ, wavelength: 1064 nm, typical spot diameter of 66 μm). The second laser was a CO_2 laser (pulse width: 15 ns FWHM, laser energy: 100 mJ, wavelength: 10.6 μm, typical spot diameter of 400 μm), which was used to heat the expanded Sn and generate EUV light sources. After the Sn droplet was heated by the CO_2 laser, a probing laser was injected into the plasma for TS measurements. The probing laser was a second-harmonic of Nd:YAG laser with injection seeding (spectral spread < 0.1 pm, pulse width: 6 ns FWHM, laser energy: 10 mJ, wavelength λ_0 = 532 nm, typical spot diameter of 50 μm). TS signals at an angle of 120° with respect to the

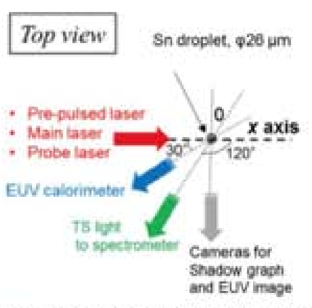

Figure 1. Top-view schematic of the experimental setup used in the study.

laser incident angle were collected by lenses and focused on the entrance slit of a spectrometer.

3. Results

Figure 2(a) shows the shadowgraph of the Sn droplet before injection of the pre-pulsed laser. Figures 2(b)-(d) show the shadowgraphs of the expanded Sn at time instants of 1.3, 2.0, and 2.5 μs after injection of the pre-pulsed laser (t = 1.3, 2.0, and 2.5 μs). The main laser was focused on these expanded droplets to generate the plasmas. For convenience, we refer to the generated plasma based on the time instant at which the shadowgraphs were acquired, e.g., the plasma in Fig. 2(b) is the 1.3-μs-plasma. Figures 3(a)-(c) depict the time integrated images of EUV emissions of the 1.3-μs-plasma, 2.0-μs-plasma, and 2.5-μs-plasma, respectively. The corresponding absolute CEs are mentioned in Figs. 3(a)-(c), whose values were 3.1, 4.0, and 2.8%, respectively. Figures 4 (a)-(c) illustrate the spatial profiles of n_e and T_e, and Fig. 4(d) depicts the spatial profiles of Z.

4. Conclusion

In this study, we performed direct measurements of ne, Te, and Z of laser-produced Sn plasmas for EUVL, whose CE range is 2.8-4.0%, by using a collective TS technique. As the results of the collective TS measurements, it becomes possible to compare the EUV emission profiles with the plasma parameters directly, for the first time. The collective TS results clearly shows that intense EUV emissions were obtained from the positions where the plasma conditions are adequate for EUV emissions, which are predicted by the previous simulation studies.

Reference

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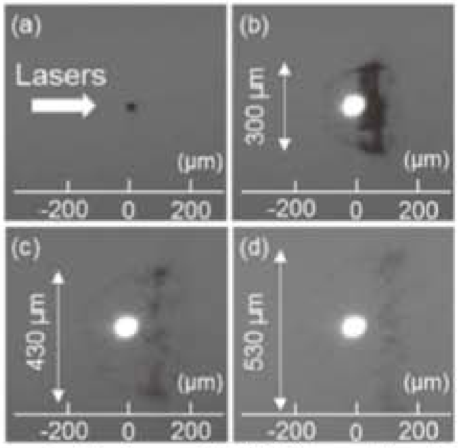

Figure 2. Shadowgraph of (a) target Sn-droplet with diameter of 26 μm, and expanded Sn droplet at (b) 1.3 μs, (c) 2.0 μs, and (d) 2.5 μs after injection of the pre-pulsed laser.

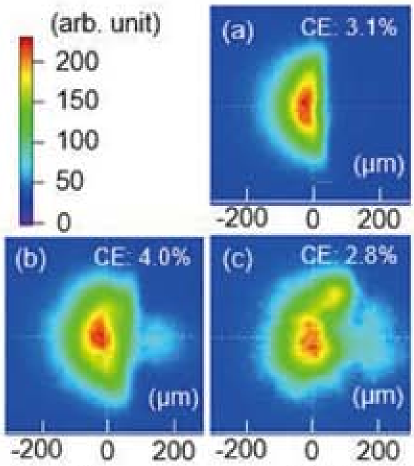

Figure 3. Extreme ultraviolet (EUV) emission images of (a) 1.3-μs-plasma, (b) 2.0-μs-plasma, and (c) 2.5-μs-plasma.

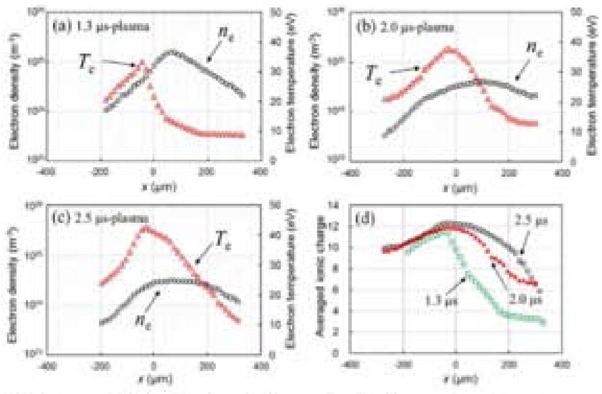

Figure 4. Spatial profiles of electron density n_e and electron temperature T_e of (a) 1.3-μs-plasma, (b) 2.0-μs-plasma, and (c) 2.5-μs-plasma. (d) Spatial profiles of average ionic charge Z for the three plasma conditions.