Interaction of a CO_2 Laser Pulse With Tin-Based Plasma for an Extreme Ultraviolet Lithography Source

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***Abstract*—The interaction of a CO_2 laser pulse with Sn-based plasma for a 13.5-nm extreme ultraviolet (EUV) lithography source was investigated. It was noted that a CO_2 laser with wavelength of 10.6 μm is more sensitive to surface impurities as compared with a Nd:YAG laser with wavelength of 1.06 μm. This reveals that a CO_2 laser is more likely absorbed in a thinner layer near the target surface. Compared with a Nd:YAG laser, a CO_2 laser shows higher in-band (2% bandwidth) conversion efficiency (CE) with a solid Sn target due to less reabsorption of the EUV emission induced by the plasma. However, with foam targets containing low concentrations of Sn, the in-band CE is lower than that with solid Sn. The CE can be enhanced with plasma confinement. These results suggest that a driving laser with wavelength between 1.06 and 10.6 μm may be an even better choice to generate higher CE from laser to 13.5-nm EUV emission.**

***Index Terms*—CO_2 laser, extreme ultraviolet (EUV) source, plasma.**

I. Introduction

EXTREME ULTRAVIOLET (EUV) lithography (EUVL) is the most promising candidate for the next generation lithography tools used in the semiconductor industry to produce microchips with feature size of 22 nm or smaller. Although deep ultraviolet lithography based on ArF lasers with wavelength of 193 nm has been extended to produce microchips with feature size of 32 nm by employing complicated technologies like liquid emersion and double patterns, EUVL is still believed to be a more cost-effective choice to produce the multilayer logical structures in future CPUs [1]. However, several critical issues must be addressed before its application to high-volume manufacturing (HVM). Among the issues, a powerful (115 W at intermediate focus), long lifetime (30 000 h at a repetition rate higher than 10 kHz), and affordable in-band (2% bandwidth) 13.5-nm EUV source has been considered the greatest challenge for a long time. The specific wavelength of the EUVL source is determined by the availability of EUV optics with high normal incidence reflectivity. Right now, a multilayer Mo/Si mirror with 70% reflectivity at normal incidence in a bandwidth of 2% (using 6–9 mirrors) centered at 13.5 nm is the only choice for the EUVL system. Hot plasmas heated either by an intense laser pulse or by an electric discharge are the main two candidates for the EUVL source used in HVM. The ability to scale to high power required by HVM makes laser-produced plasma more promising [2].

Various lasers, including Nd:YAG lasers with wavelength of 1.06 μm, discharge-pumped excimer lasers at 248 or 351 nm, newly developed fiber lasers, and infrared CO_2 lasers at 10.6 μm, have been studied to generate an efficient 13.5-nm EUV source. A diode-pumped Nd:YAG laser has been considered as the top candidate laser driver for HVM EUVL sources for a long time due to its compact footprint, easy manipulation, and ready availability at numerous universities and companies. However, a recent trend to replace the Nd:YAG laser with a CO_2 laser has emerged. Higher in-band conversion efficiency (CE) has been observed in CO_2 laser-produced Sn plasma under much more relaxed laser parameters [3], [4]. In addition, most importantly, high-power CO_2 lasers are cheaper and more reliable as compared with diode-pumped Nd:YAG lasers. A 100-kW CO_2 laser is commercially available and has good track record in high-duty industrial applications. Diode-pumped Nd:YAG lasers are limited by thermal loads in the laser medium that are difficult to manage.

High-Z target material, like Sn $(Z = 50)$, is considered as the primary candidate for the EUV plasma due to its high in-band CE from laser to 13.5-nm EUV emission. However, atomic data for Sn at the temperature of interest (30–60 eV) for efficient 13.5-nm EUV emission have rarely been benchmarked by experiments. Plasma physics of the Sn plasmas, including radiation transport and hydrodynamic expansion, have never been understood completely. It is difficult to accurately simulate the generation and transport of EUV light in Sn plasma even using the most state-of-art radiation hydrodynamic models. In particular, for a CO_2 laser, even though there has been a long history of research on its interaction with matter, most of the previous efforts either focused on intensities of $10^{12}\ \mathrm{W/cm^2}$

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or greater of interest to laser fusion or less than 10^9 W/cm^2 motivated by laser fabrication. Little effort has been made to investigate the fundamentals of the interaction of a CO_2 laser pulse with high-Z plasma at the intensity of interest to an EUVL source. In this paper, we present our efforts to further understand the interaction of CO_2 laser pulses with Sn plasma under the conditions favorable to efficient generation of 13.5-nm EUV light.

II. Experimental Arrangement

Experiments were carried out with a master oscillator and power amplifier (MOPA) CO_2 laser system operating at a wavelength of 10.6 μm. The MOPA laser system consists of a master oscillator, preamplifier, main amplifier, and plasma shutter. The oscillator is a transversely excited atmosphere CO_2 laser with a parallel-plane output coupler with reflectivity of 85%. The temporally cut CO_2 laser pulse (10–100 ns) is amplified by pre- and main amplifiers with single and double passes, respectively. Amplification of $6\times$ is achieved. Laser pulse energies of 60, 150, 400, and 550 mJ are obtained for the pulse durations of 10, 25, 60, and 110 ns, respectively. The laser is focused with an F/10 ZnSe plano-concave lens onto the target surface at normal incidence. The diameter of the focal spot is estimated at 200 μm.

High-purity planar Sn plate and Sn-doped foam are used as targets in the present experiments. The Sn-doped foam has a 1% concentration of Sn as compared with solid fully dense tin. The target is placed on a 3-D adjustable stage.

The in-band CE is measured with an absolutely calibrated EUV emission energy monitor (E-Mon from Jenoptik) [5]. The E-Mon is installed at an angle of 39° with respect to the target normal in the horizontal plane. The in-band CE is an integration of EUV emission over a solid angle of 2π. Soft X-ray spectra are observed with a transmission grating spectrometer with a spectral resolution better than 0.1 nm [5]. The spectrometer is installed in the horizontal plane at 45° with respect to the target normal. Time of flight of ions from the EUV plasma is observed with a Faraday cup (FC). The FC is placed at a distance of 15 cm away from the plasma and at an angle of 10° to the target normal. The FC is biased with -30 V to repel electrons. The signal from the FC is recorded with a digital oscilloscope (Tektronix TDS 5054B). Profiles of the target surface are measured with a surface profiler (Ambios Technology XP-1).

III. Results and Discussions

In-band CEs from CO_2 laser-produced Sn plasmas were investigated at various laser intensities from 1×10^9 to 1.5×10^{10} W/cm^2. It was found that within a wide range of intensities from 3×10^9 to 1.5×10^{10} W/cm^2, the in-band CE is almost constant around 2.5% to 3%, which is a little higher than that of a Nd:YAG laser [5]. At intensities of 1×10^9 W/cm^2 or lower, the in-band CE is much lower than the constant CE observed with higher intensities. Soft X-ray spectra were observed at various laser intensities from 1×10^9 to 1.5×10^{10} W/cm^2; typical results are shown in Fig. 1. It is shown

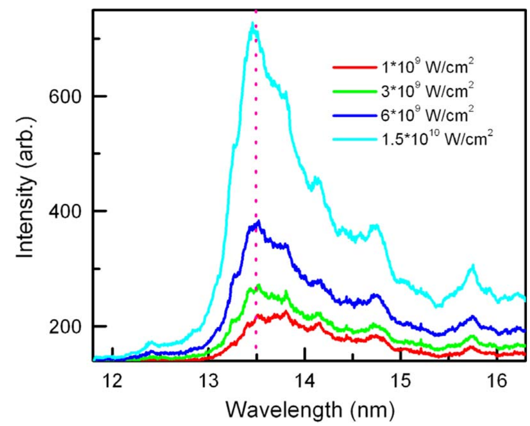

Fig. 1. (Color on line) Soft X-ray spectra from Sn plasma irradiated by CO_2 laser pulses with various laser intensities.

in Fig. 1 that when laser intensities are 3×10^9 W/cm^2 or higher, the spectral peaks are always located around 13.5 nm. At 1×10^9 W/cm^2, the spectral peak is located on the longer wavelength side.

The in-band EUV light centered at 13.5 nm mainly comes from the unresolved transition array of Sn^{6+} to Sn^{13+}, which has an optimum population distribution in Sn plasma with temperatures from 30 to 60 eV [6]. These spectral peaks located at 13.5 nm confirm the constant in-band CE over a wide range of laser intensities, and also show that with an laser intensity as low as 3×10^9 W/cm^2, the CO_2 laser can heat the material up to around 30 eV. It is worth noting that for a Nd:YAG laser with wavelength of 1.06 μm, the necessary laser intensity to obtain efficient 13.5-nm EUV emission is one order of magnitude higher, i.e., $\sim 10^{11}$ W/cm^2. One of the reasons for the efficient heating induced by a CO_2 laser may be the fact that a lower density of ions is involved in the interaction volume in CO_2 laser-produced Sn plasma as compared with that of a short wavelength laser. Two reasons may contribute to the low density of ions involved in CO_2 laser-produced Sn plasma: One is obviously the lower critical density of CO_2 laser with longer wavelength of 10.6 μm (we will discuss this and its impacts later) and the other may be the small penetration depth of a CO_2 laser into the target surface.

The smaller penetration depth is confirmed by an experimental finding about the sensitivity of the in-band CE on the impurities attached on the surface. It was noted that for a CO_2 laser pulse, a notable decrease of in-band CE—as much as half of the normal value—is observed in most shots with a fresh target surface. This decrease of CE was never found with a target surface after irradiation by a prepulse with small laser pulse energy of $\sim$5 mJ and intensity around 10^8 W/cm^2.

In order to clarify this CE decrease, time of flight (TOF) of ions from CO_2 laser-produced Sn plasma was observed. Typical results from Sn plate targets with fresh surface (red line) and exposed surface after prepulse irradiation (black line), both irradiated with a main CO_2 laser pulse with laser intensity of 1×10^{10} W/cm^2 are shown in Fig. 2. The fresh surface represents the surface of the new target placed in vacuum for at least 30 min, and the nonfresh surface means the surface irradiated by one prepulse but is still planar. The TOF from

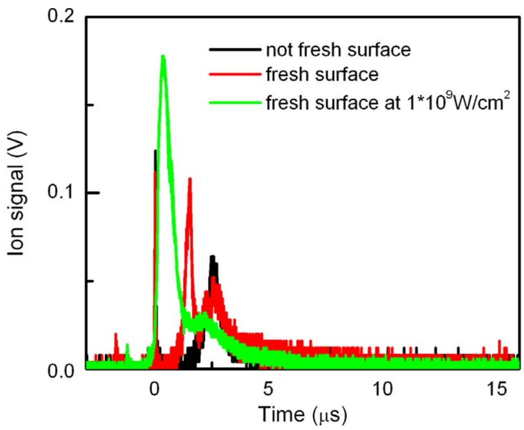

Fig. 2. (Color on line) Time of flights from Sn plate with (red line) fresh surface and (black line) exposed surface irradiated with a CO_2 laser pulse with a laser intensity of $1 \times 10^{10}\ \mathrm{W/cm^2}$, and (green line) fresh target surface irradiated with a CO_2 laser with laser intensity of $1 \times 10^{9}\ \mathrm{W/cm^2}$.

fresh surface irradiated by a CO_2 laser pulse with a laser intensity of $1 \times 10^{9}\ \mathrm{W/cm^2}$ is also shown in Fig. 2 (green line). Comparison of the TOFs of the cases with fresh and exposed (prepulse irradiated) surfaces in Fig. 2 shows an additional faster ion peak in the case of a fresh surface. This additional fast ion peak comes from impurities attached on the fresh surface, like moisture (O, H), and vacuum pump oil (C, H, O, N) in the ambient vacuum. Since O, H, C, and N are much lighter than Sn, higher velocity can be achieved under the same laser intensity as compared with that of Sn. The drop of in-band CE and the additional faster ion peak were never observed with a Nd:YAG laser pulse with fresh target surface in the identical vacuum environment. However, very weak signals of O, H, C, and N were detected from Nd:YAG laser-produced Sn plasma with more sensitive diagnostics (i.e., an electric energy analyzer) [7]. This means that there are impurities attached on the target surface in both cases; however, for Nd:YAG laser, there is no significant laser pulse energy deposited within the surface impurity layer. It is also shown in Fig. 2 that for a CO_2 laser pulse with a lower intensity, more laser pulse energy goes into the impurities as compared with that of higher intensity. Now, we can conclude that longer wavelength and lower intensity make CO_2 laser more likely to be absorbed within a thinner layer near the target surface. This small penetration depth could lead to less ablation material with a CO_2 laser pulse as compared with that of a Nd:YAG laser, and a lower density of ions is involved in the EUV plasma.

Although accurate plasma diagnostics are required to obtain information about laser deposition depth and plasma density profile, it is reasonable to conclude that a small and steep plasma density profile should be found in CO_2 laser-produced Sn plasma due to the shallow deposition of CO_2 laser energy. A steep plasma density profile should help reduce the reabsorption of in-band EUV light by the plasma itself.

It is known that laser light can only propagate in plasma with density less than the critical density. The critical density can be described as $n_c\ [\mathrm{cm}^{-3}] = 1.1 \times 10^{21}\ (1/\lambda\ [\mu\mathrm{m}]^2)$, where λ is the light wavelength. The dominant mechanism of laser absorption in the plasmas of interest to an EUVL source is inverse bremsstrahlung (IB). The IB absorption coefficient can be described as [8]

$$f_A = 1 - \exp\left(-\frac{8}{3}\frac{v_{ei} l_s}{c}\cos^3\theta\right) \qquad (1)$$

where $v_{ei} \approx 3 \times 10^{-6} \ln\Lambda\ (Zn_e/T_e^{3/2})$ is the electron-ion collision frequency, l_s is the scale length of plasma, c is the velocity of light in vacuum, θ is the incidence angle, n_e is plasma density, and $\ln\Lambda$ is the Coulomb logarithm. IB is more efficient near the critical density. Longer wavelength lasers have a lower critical density; for example, for 1.06 and 10.6 μm lasers the critical densities are 10^{21} and $10^{19}\ \mathrm{cm}^{-3}$, respectively. Ions in a low-density plasma are involved in the plasma irradiated by a CO_2 laser as compared to that of Nd:YAG laser.

However, it is found from equation (1) that IB occurs more efficiently in the dense plasma region, and particularly near the critical density. Therefore, better laser absorption can be expected for a shorter wavelength laser. In addition, since there are more ions in the plasma to emit EUV light, higher CE should be expected for a short wavelength laser. However, as previously mentioned, a CO_2 laser with a longer wavelength shows a higher in-band CE as compared with a Nd:YAG laser. The reason is the opacity effect of the EUV plasma. For a short wavelength laser, the regions of laser pulse energy deposition and the generation of the in-band EUV are located in denser plasma regions as compared with a longer wavelength laser. The dense Sn plasma is optically thick for 13.5-nm EUV light and the reabsorption of the EUV emission induced by the plasma itself cancels the higher generation of EUV emission. For CO_2 laser-produced Sn plasma, there are fewer Sn ions in the dominant region of EUV generation, so less laser pulse energy deposition and less EUV generation result. However, most of the EUV emission can escape from the plasma. Therefore, the final output of the EUV plasma is the result of the tradeoff between generation and reabsorption of the EUV emission.

In order to clarify the reabsorption of the EUV emission, typical spectra observed from a pure Sn plate irradiated with Nd:YAG and CO_2 lasers, represented by blue and red lines, respectively, are shown in Fig. 3. The spectral dip in the Nd:YAG's spectrum is due to heavy reabsorption of the EUV light induced by the plasma itself. Now, we can conclude that the critical density of a 1.06 μm laser is too high for 13.5-nm EUV emission and 1.06 μm is near the lower limit to produce the optimum plasma density that enables efficient emission of EUV light. However, until now, we cannot conclude if 10.6 μm is the optimum wavelength or an upper limit.

Unfortunately, an intense laser with wavelength longer than 10.6 μm is not available up to date. In order to clarify the upper limit of the optimum wavelength, the method of reduction of the concentration of Sn was used [10]. It has been shown that using a target with a low concentration of Sn could significantly reduce the reabsorption of the EUV light for a Nd:YAG laser. In the present experiment, a foam target with 1% concentration of Sn as compared with fully dense solid Sn was irradiated with a CO_2 laser pulse with intensity of $1 \times 10^{10}\ \mathrm{W/cm^2}$. It was found that the in-band CE from the foam target is less half of that with a solid Sn target. This is different from the

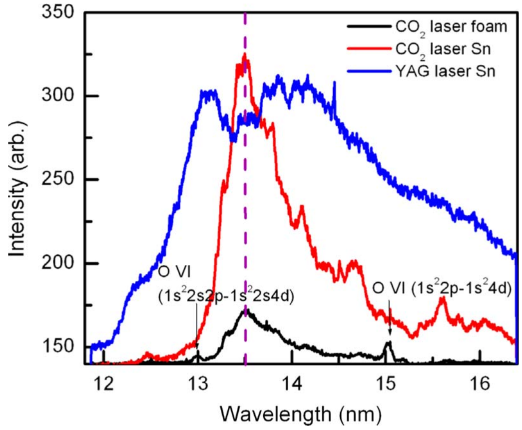

Fig. 3. (Color on line) Soft X-ray spectra from pure Sn target irradiated with (blue line) 1.06 and (red line) 10.6 μm lasers, and from (black line) foam target with 1% concentration of Sn.

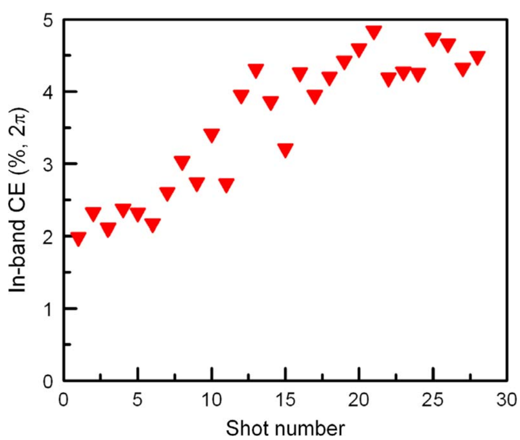

Fig. 4. (Color on line) In-band CE as a function of laser shot number accumulated at the same position.

result obtained with a Nd:YAG laser. In that case, a target with a low concentration of Sn showed a comparable or even slightly higher in-band CE as compared with that of a solid tin target [9]. A typical soft X-ray spectrum from the foam target is shown in Fig. 3, which is much lower than that of a pure solid Sn target.

Another way to verify whether the ion density in CO_2 laser-produced Sn plasma is higher or lower than the optimum value is to enhance the plasma density. Ueno *et al.* [3] have shown that with a short pulse CO_2 laser the in-band CE could be enhanced significantly by confining the plasma within a crater formed by accumulating 100 laser shots at the same position on the target surface, or with a prefabricated V-shaped target. A similar experiment with longer laser pulse duration, i.e., 100 ns, was carried out here. Typical in-band CEs as a function of laser shot number are shown in Fig. 4. It is shown that the in-band CE can be doubled by accumulating 20 shots at the same position on the target surface. The surface profile to obtain the higher CE was checked with a surface profiler. The profile of the target surface after 20 shots is shown in Fig. 5. A crater with diameter of 500 μm and a height of ~ 100 μm was measured. This crater could help confine the plasma, to form larger volume plasma with longer plasma density scale length. The longer plasma scale length could help improve laser absorption and provide

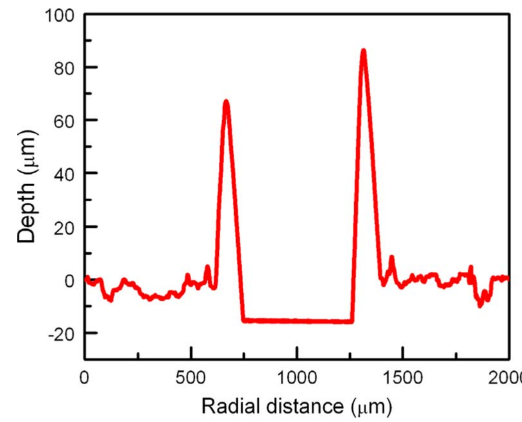

Fig. 5. (Color on line) Profile of the target surface after accumulating 20 laser shots.

more Sn ions to emit EUV radiation, which results in more generation of EUV light. Even though reabsorption of the EUV emission could also be enhanced with the extended plasma scale length, the in-band CE can still be enhanced due to the fact that the increased generation of EUV light is much more than its reabsorption. This clearly shows that the wavelength of a CO_2 laser, i.e., 10.6 μm, is too long to ensure good laser pulse deposition and sufficient ions to generate efficient 13.5-nm EUV emission. The value of 10.6 μm is near the upper limit of the optimum laser wavelength. A laser with wavelength between 1 and 10 μm may be a better choice to obtain more efficient in-band 13.5-nm EUV emission.

A preliminary idea about the specific optimum plasma density can be deduced from previous research to identify the dominant EUV emission region under optimized conditions for a Nd:YAG laser-produced Sn plasma [10]. It has been shown in [10] that for a Nd:YAG laser, under optimum conditions the peak of the EUV emitting region is located in the plasma region with plasma density around 4×10^{19} cm^{-3}. This peak density is the best balance point between the generation and reabsorption of the EUV light induced by the plasma itself. If the dominant laser deposition region can be assumed to be localized near the critical density, then the corresponding laser wavelength is around 5 μm. One laser with wavelength 5–6 μm is the carbon monoxide (CO) laser, and its power can be scaled up to kilowatt levels [11]. More experiments and numerical simulations are still necessary to clarify the optimum laser driver for an EUVL source.

IV. Summary

In summary, the interaction of a CO_2 laser pulse with Sn plasma was investigated under the conditions of interest to an efficient in-band 13.5-nm EUV source. The low critical density and possible smaller penetration depth of the CO_2 laser result in results in that ions from a low plasma density are involved in the interaction volume of CO_2 laser-produced Sn plasma, which leads to a lower necessary CO_2 laser intensity to heat Sn plasma up to the temperature of interest to in-band 13.5-nm EUV emission. Less reabsorption of the EUV emission induced by the EUV plasma itself leads to higher in-band CE from CO_2

laser-produced Sn plasma as compared with that of Nd:YAG laser. It was shown that a drive laser with wavelength between 1.06 and 10.6 μm might be a better choice for EUVL source due to the better balance between the generation and reabsorption of EUV emissions.

REFERENCES

[1] H. Meiling, N. Buzing, K. Cummings, N. Harned, B. Hultermans, R. de Jonge, B. Kessels, P. Kürz, S. Lok, M. Lowisch, J. Mallman, B. Pierson, C. Wagner, A. van Dijk, E. van Setten, and J. Zimmerman, "EUVL system: Moving towards production," *Proc. SPIE*, vol. 7271, p. 727 102, Mar. 2009.

[2] D. C. Brandt, I. V. Fomenkov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, N. R. Farrar, G. O. Vaschenko, O. V. Khodykin, A. N. Bykanov, J. R. Hoffman, C. P. Chrobak, S. N. Srivastava, I. Ahmad, C. Rajyaguru, D. J. Golich, D. A. Vidusek, S. De Dea, and R. R. Hou, "LPP source system development for HVM," *Proc. SPIE*, vol. 7271, p. 727 103, Mar. 2009.

[3] Y. Ueno, G. Soumagne, A. Sumitani, A. Endo, and T. Higashiguchi, "Enhancement of extreme ultraviolet emission from a CO_2 laser-produced Sn plasma using a cavity target," *Appl. Phys. Lett.*, vol. 91, no. 23, p. 231 501, Dec. 2007.

[4] Y. Tao, M. S. Tillack, K. L. Sequoia, R. A. Burdt, S. Yuspeh, and F. Najmabadi, "Efficient 13.5 nm extreme ultraviolet emission from Sn plasma irradiated by a long CO_2 laser pulse," *Appl. Phys. Lett*, vol. 92, no. 25, p. 251 501, Jun. 2008.

[5] Y. Tao, M. S. Tillack, S. S. Harilal, K. L. Sequoia, and F. Najmabadi, "Investigation of the interaction of a laser pulse with a preformed Gaussian Sn plume for an extreme ultraviolet lithography source," *J. Appl. Phys.*, vol. 101, no. 2, p. 023 305, Jan. 2007.

[6] K. Nishihara, A. Sunahara, A. Sasaki, M. Nunami, H. Tanuma, S. Fujioka, Y. Shimada, K. Fujima, H. Furukawa, T. Kato, F. Koike, R. More, M. Murakami, T. Nishikawa, V. Zhakhovskii, K. Gamata, A. Takata, H. Ueda, H. Nishimura, Y. Izawa, N. Miyanaga, and K. Mima, "Plasma physics and radiation hydrodynamics in developing an extreme ultraviolet light source for lithography," *Phys. Plasmas*, vol. 15, no. 5, p. 056 708, May 2008.

[7] R. A. Burdt, S. Yuspeh, K. L. Sequoia, Y. Tao, M. S. Tillack, and F. Najmabadi, "Experimental scaling law for mass ablation rate from a Sn plasma generated by a 1064 nm laser," *J. Appl. Phys.*, vol. 106, no. 3, p. 033310, Aug. 2009.

[8] W. L. Kruer, *The Physics of Laser Plasma Interaction*. New York: Addison-Wesley, 1988.

[9] S. S. Harilal, M. S. Tillack, Y. Tao, B. O'Shay, R. Paguio, and A. Nikroo, "Extreme-ultraviolet spectral purity and magnetic ion debris mitigation by use of low-density tin targets," *Opt. Lett.*, vol. 31, no. 10, pp. 1549–1551, May 2006.

[10] Y. Tao, H. Nishimura, S. Fujioka, A. Sunahara, M. Nakai, T. Okuno, N. Ueda, K. Nishihara, N. Miyanaga, and Y. Izawa, "Characterization of density profile of laser-produced Sn plasma for 13.5 nm extreme ultraviolet source," *Appl. Phys. Lett.*, vol. 86, no. 20, p. 201 501, May 2005.

[11] J. Xin, W. Zhang, and W. Jiao, "Radio frequency discharge excited diffusively cooled kilowatt carbon monoxide slab waveguide laser with a three mirror resonator," *Appl. Phys. Lett.*, vol. 75, no. 10, p. 1369, Sep. 1999.

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