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Time and space resolved visible spectroscopic imaging CO2 laser produced extreme ultraviolet emitting tin plasmas

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Experiments involving laser produced tin plasma have been carried out using a CO2 laser with an energy of 800 mJ/pulse and a full width at half maximum (FWHM) of 80 ns in vacuum. Time-integrated extreme ultraviolet spectral measurement showed that the peak of the extreme ultraviolet lithography spectrum was located at 13.5 nm and the spectrum profile’s FWHM of the unresolved transition arrays was 1.1 nm. Plasma parameters of the electron temperature and density measurements in both axial and radial directions at later times had been obtained from a two-dimensional time and space resolved image spectra analysis. The axial spatial distribution of the electron density showed a $1/d^{2.6}$ decrease profile, and the radial spatial distribution of the electron density showed a $1/r^{1.1}$ profile, in which $d$ is the axial distance from the target surface and $r$ is the radial distance. The electron density was found to maintain symmetry across the radial distance at all delay times. Near the plasma plume center, the electron temperature $T_e$ varied slightly with increasing axial or radial distance, which was related to collisional decoupling and reheating of the ionized species in the plasma at distances longer than 3 to 4 mm. The space averaged electron temperature was measured in the range of 3.4–1.0 eV, and the space averaged electron density was measured in the range of $2.0 \times 10^{17}$ to $2.2 \times 10^{16}$ cm$^{-3}$, as the time delay varied from 1.6 $\mu$s to 3.6 $\mu$s with respect to the pulse discharge. Time evolutions of the plasma temperature and density were found to have an apparent rise at a delay time of 2.4 $\mu$s in the corresponding time of the laser pulse tail peak. This suggests that plasma parameters and extreme ultraviolet emission intensity can be controlled by a double pulse combined laser. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3698628]

I. INTRODUCTION

Recently, much effort has been devoted to developing an efficient and clean laser produced plasma (LPP) light source at 13.5 nm for next generation extreme ultraviolet (EUV) lithography in the semiconductor industries.1–3 The strong unresolved transition arrays of tin centered near 13.5 nm offer a promising source of EUV radiation for the next generation of lithography.4–7 Therefore, measurements of the plasma and space-averaged emission spectrum of the entire plasma. In this work, planar plates of pure tin were irradiated with 10.6 $\mu$m CO2 laser pulses. A novel two-dimensional optical emission spectroscopy (2D OES) method was chosen for the determination of the plasma parameters because it is a
powerful optical tool for remote material analysis and provides an effective and reliable determination between the produced excited neutral and ionized species. The image of the expanding laser produced plasma is focused on the entrance slit of a stigmatic spectrometer with a temporally resolved image readout. Analysis of the image spectra provides useful plasma parameters. The relative ion emission intensities provide the electron temperature, and Stark broadened line widths yield the electron densities. Precise spectral, spatial, and temporal measurements of the emission characteristics of CO₂ laser produced tin plasma are incorporated into a single imaging detector along the plume axial (normal to the target surface) and radial (along the central plane of the plasma plume) expansion directions. In addition, the photographs of the plasma plume and time-integrated extreme ultraviolet image spectra were also obtained and analyzed using a grazing incidence flat-field spectrograph coupled with an x-ray charge-coupled device camera.

II. EXPERIMENTAL SETUP

The schematic of the experimental setup and the diagnostic technique are shown in Fig. 1. For producing plasmas, 10.6 μm radiation from a CO₂ laser (pulse energy of 800 mJ, pulse duration of 80 ns full width at half-maximum, and 1 Hz repetition rate) was used. The temporal profile of the laser pulse is given in Fig. 2. The inset of Fig. 2 shows the cross-sectional distribution of the peak energy of the incident laser beam recorded by heat-sensitive paper. It can be seen from Fig. 2 that both laser pulse waveforms and discharge waveforms for the experiment are presented, and the delay time between them is about 1.4 μs. The laser pulse also had a second peak energy of the tail at a delay time of about 2.4 μs. A 4 mm thick pure tin target in the form of a circular plate is mechanically rotated so as to provide a fresh surface for each shot in order to minimize the surface etching, and it is kept in a vacuum chamber. The laser beam, 45° to the target surface normal incidence, was focused onto the target using a ZnSe lens with a focal length of 9.525 cm placed inside the chamber, generating a plasma that expands along the normal to the target surface. The emitting plasma is imaged onto the entrance slit of a Princeton spectrograph equipped with 300 grooves/mm and 2400 grooves/mm gratings, which are blazed at 500 nm. The spectrograph used in the experiment was an Acton SP2750i with a focus length of 750 mm. The optimum resolution was obtained at a slit width of 20 μm; no improvement in resolution was obtained with a narrower slit. The spectrograph and intensified charge-coupled device (ICCD) combination provided a maximum resolution of 0.012 nm using a 2400 grooves/mm grating. The emission spectra from the plasma can be viewed normal to the expansion direction (radial direction r) or parallel to the plume expansion direction (axial direction d) by means of a periscope. The purpose of the periscope in Fig. 1 is to rotate the plasma image by 90° such that the axial direction of the plume lies along the orientation of the entrance slit of the spectrograph. At the output of the spectrograph, in the image plane, a time-gated ICCD camera was installed. The ICCD system was a PI-MAX-1300 (Princeton Instruments) and could control the delay between the trigger signal and the image acquisition. When the oscillograph (Tektronix TDS7154B) received an electromagnetic interfering signal generated from a pulsed discharge, the oscillograph generated a trigger signal to the ICCD system, which began to acquire an image in the time delay set before; then the image was sent to the computer and displayed. As its output, the spectrograph produces a one-dimensional spatial and spectral image of the expanding plasma in which the vertical axis corresponds to the radial or axial plume expansion direction and the horizontal axis corresponds to wavelength of the emission of the species. The intensity response of the ICCD was calibrated with a standard deuterium tungsten-halogen calibration light source (DH-2000-CAL, Ocean Optics Inc.). The wavelength calibration of the spectrometer was achieved with several standard atom lamps (Ar, Kr, Ne, Xe, and Hg). By varying the delay between the pulse discharge and the opening of the ICCD’s gate, we can track the temporal evolution of the plasma.

For the purpose of studying the EUV emission from laser produced plasmas, we have built a grazing incidence flat-field spectrograph with a mechanically aperiodically
ruled concave gold coated flat-field grating with a radius of curvature of 5649 mm (fabricated by Hitachi, Ltd.), as can be seen in Fig. 1. The detector is a 1340 \times 400 pixel array of back-illumination-type x-ray CCD (Princeton Instruments) and is used to record the EUV emission normal to the target surface. A 500 nm thick calibrated zirconium metal filter is used in the spectrometer to select wavelengths from 6.5 nm to 16.8 nm. The EUV spectrum was recorded by an x-ray CCD camera exposed for the duration of three laser shots with an automatic background subtraction. Fast imaging of the laser produced plasma plume is accomplished using a time gated intensified CCD camera.

III. RESULTS AND DISCUSSION

The experimental system described above was used to study the plasma characteristics of a CO2 laser produced plasma of tin. A CO2 laser energy of 800 mJ, with a power density of \(3 \times 10^{10}\) W/cm\(^2\), was used throughout the experiments. Figure 3 (background subtracted) shows the EUV emission spectrum measured from a plate tin target in vacuum (10\(^{-4}\) Pa), as well as the raw data registered by the x-ray CCD camera. The tin spectrum shows the expected broadband emission, originating from Sn\(^{12+}\) to Sn\(^{7+}\) ions with the ground configuration [Kr]4p\(^6\)4d\(^n\), in which \(n = 2\) to 7. Most of the lines in the spectral region around 13.5 nm come from the transitions between the excited configurations 4p\(^5\)4d\(^n+1\) and 4p\(^6\)4d\(^n-1\)d\(^1\). These energy levels are so close that the radiation they generate in the EUV regime can be considered as a continuum unresolved transition array. Using the spectrograph described above, the emission lines of the single transitions could not be separated. It can be seen in Fig. 3 that the peak of the EUV spectrum was located at 13.5 nm, and the profile width (FWHM) of the unresolved transition arrays was 1.1 nm. The conversion efficiency, i.e., the ratio of incident laser energy converted into 13.5 nm light within the 2% band-width over a solid angle of 2\(\pi\) sr, was estimated as around 1.2%, taking spectral shapes and angular distributions of the EUV emissions into account.

The plasma density can be inferred from the profile of the line spectra, because the shape and width of the spectral lines are governed by the collisional process perturbing the emitting atoms and ions. The FWHM of Stark broadened lines is related to the electron number density \(n_e\) by\(^{21-23}\)

\[
\Delta \lambda_{1/2} = 2W_p \left( \frac{n_e}{10^{16}} \right) \left[ 1 + 1.75G \left( \frac{n_e}{10^{16}} \right)^{1/4} \left( 1 - \frac{3}{4}N_D^{-1/3} \right) \right],
\]

in which \(N_D\) is the number of particles in the Debye sphere and is estimated from \(N_D = 1.72 \times 10^9 \rho^{1/3}/n_e^{1/2}\). \(W_p\) is the electron impact parameter in nanometers, and \(G\) is the ion impact parameter; \(W_p\) and \(G\) are functions of temperature and can be approximated by second-order polynomials. The highest resolution grating (2400 grooves/mm) was used for better resolution when measuring the Stark broadened transition lines; these lines are used to estimate the electron density. By increasing the gain to measure signal levels that are very close to the noise, the signal-to-noise ratio can be improved while maintaining the same integration time. The space resolved spectra used for density estimation were accumulated for 10 pulses so as to reduce the standard deviation and increase the signal to noise ratio. It should be noted in relation to the temporal measurements that the time origin is defined as the moment when the pulse charge is launched. For spatial resolved measurements, the emission from 5 pixels (corresponding to 100 \(\mu m\) of the plasma height) was averaged at various distances. For the determination of the electron density, we have selected lines with published broadening Stark widths that present small uncertainties, and thus the 6p\(^5\)3P\(^0\)-6d\(^2\)D transition (at \(\lambda = 553.2\) nm) attributed to Sn II ions was selected. Figure 4 shows a typical axial space-resolved raw image (left) and spectrum (inset) of tin plasma with a 2400 grooves/mm grating used for electron density estimation at a delay time \(t = 2.0\) \(\mu s\). Correspondingly, the photograph of the plume image can be seen in Fig. 4. In Fig. 4, the \(x\)-axis corresponds to the direction of wavelength dispersion, and the \(y\)-axis corresponds to the spatial distribution along the plasma plume expansion direction. A set of cells or a grid can be superimposed onto the image, and the image segment enclosed within each cell can be binned vertically. The binned lineouts are projected along the expansion direction as shown in Fig. 4, and a Lorentzian function is used to fit each spectrum for each spatial cell or box (see the inset in Fig. 4). Therefore, spectrally resolved plasma parameters such as the relative line intensity and Stark broadening can then be extracted from the time-resolved images.

As discussed before, a deuterium tungsten-halogen lamp is used to calibrate the spectral response of the system in the 400 nm to 700 nm wavelength range. The spectral efficiency of the system \(F(\lambda)\) is given by

\[
F(\lambda) = \frac{I(\lambda)}{P(\lambda)},
\]

in which \(P(\lambda)\) is the standard lamp intensity and \(I(\lambda)\) is the ICCD recorded spectral intensity. The relative efficiency curve obtained from the calibrated light source is shown in Fig. 5. As is well known, in optically thin plasma, the relative...
intensity $I_{ij,k}$ of the lines emitted from a given state of excitation can be used to calculate the electron temperature, if the transition probabilities $A_{ij}$ and the statistical weight of the upper level $g_j$ are known, via the expression

$$\ln \left( \frac{I_{ij,k}}{F_{k}g_{i}A_{ij}} \right) = -\frac{1}{k_{B}T_{e}}E_{i} + \ln \left( \frac{\hbar c L_{z}}{4\pi P_{z}} \right)$$

for a transition from a higher state $i$ to a lower state $j$. The subscript $z$ refers to the ionization state of the species ($z=0$ and $z=1$ correspond to neutral and singly ionized atoms, respectively), $P_{z}$ is the partition function, $n_{i}$ is the number density of the emitting species, $L$ is the plasma characteristic length, $k_{B}$ is Boltzmann’s constant, $h$ is Planck’s constant, and $c$ is the speed of light in vacuum. If we were to plot $\ln(I/F_{k}g_{i}A)$ versus $E_{i}$, the resulting straight line would have a slope of $-1/k_{B}T_{e}$, and therefore the temperature could be obtained without knowledge of the total density of atoms or the atomic species partition function. The plasma temperature was estimated from the Boltzmann plot of 684.4 nm ($6p^{2}P_{3/2} \rightarrow 6s^{2}S_{1/2}$), 645.4 nm ($6p^{2}P_{3/2} \rightarrow 6s^{2}S_{1/2}$), 579.9 nm ($5d^{2}D_{5/2} \rightarrow 4^{2}F_{7/2}$), 558.9 nm ($4f^{2}F_{25/2} \rightarrow 5d^{2}D_{3/2}$), 556.2 nm ($6d^{2}D_{3/2} \rightarrow 6p^{2}P_{3/2}$), and 533.2 nm ($6d^{2}D_{3/2} \rightarrow 6p^{2}P_{1/2}$) line intensities of Sn II, for which the absolute transition probabilities are well known. The spectroscopic constants of Sn II lines used for the estimation of the electron temperature have been taken from the NIST database. With the six Sn II emission lines, the radial space integrated electron temperature obtained was $2.0 \pm 0.1$ eV for $\Delta E = 2.345$ eV using experimental data as shown in Fig. 6, discussed below at a delay time $t = 2.4 \mu s$, as can be seen in Fig. 6.

For the measurement of the electron temperature, a 300 grooves/mm grating was used. The determination of the plasma parameters during early times is difficult, because most of the emission at early times is contributed by continuum radiation attributed to Bremsstrahlung and photorecombination radiation depending strongly on the density of charged particles in the plume. At later times, the temperature can be estimated for the entire duration of the expansion of the plume with the aid of visible spectroscopy. Visible spectral measurements ranging from 500 nm to 700 nm were repeated at several delay times of 1.6 to 3.6 $\mu$s with respect to the pulse discharge and at a fixed gate time of 50 ns. In these measurements, the central wavelength of the spectrometer was set to 550 nm and 650 nm. Typical spectra and raw visible images of radial plasma covering the spectral regions from 500–600 nm and 600–700 nm belonging to neutral atoms and ions obtained from the plasma imaging system are shown in Figs. 7(a) and 7(b).

FIG. 4. Axial space-resolved image of tin plasma at a delay time $t = 2.0 \mu s$. The inset shows the spatial resolution emission from Sn II 533.2 nm. In the inset, the solid five-pointed stars represent the experimental data, and the smooth curve is the Lorentz fit. The photograph is of the plasma plume at a delay time $t = 2.0 \mu s$. (right) Integration times of 50 ns and accumulated for 10 pulses.

FIG. 5. Relative efficiency curve obtained from a calibrated deuterium tungsten-halogen light source. The data were normalized to unit at $\lambda = 400$ nm; the solid line is a guide for the eye only.

FIG. 6. Boltzmann plot for Sn II spectral lines from laser produced tin plasma, in vacuum, recorded at a 2.4 $\mu$s delay time from pulse discharge, with a linear coefficient of 0.9998.
For the measurements of plasma parameters, we considered LPP in this experiment to be in the local thermodynamic equilibrium (LTE) state, in which it was possible to find a temperature parameter for every point in a region of space that fits the Boltzmann and Saha relations for the population density of excited and ionic states and the Maxwell distribution of velocities among the electrons. In addition, we assumed that the plasma was optically thin, ignoring plasma self-absorption. The condition of LTE requires that collisional processes must be much more important than radiative processes, so that the deficit of radiative energy is extremely small. In other words, the probability of deexcitation by inelastic collision for an excited state must be very large compared to that of spontaneous emission. This is possible at very high electron densities in the plasma, such that

\[ n_e \geq 1.4 \times 10^{14} T_e^{1/2} (\Delta E)^3 \text{cm}^{-3}, \]

where \( T_e \) is the electron temperature in electron volts and \( \Delta E \) is the energy difference in electron volts between two neighboring states with an allowed transition. At Sn II 556.2 nm, \( \Delta E = 2.3 \text{ eV} \), and \( T_e = 3.4 \text{ eV} \), the minimum electron number density criteria is calculated as \( n_e > 3.1 \times 10^{15} \text{ cm}^{-3} \), justifying the LTE assumption, which is verified by the density measurements given afterward. With the aforementioned values of \( n_e \) and \( T_e \), we can calculate the absorption coefficient for the study lines using the following equation, expressed in m\(^{-1}\),

\[ \beta_\lambda = \frac{\pi e^2}{2 m_e c} f_{ij} n_i (1 - \frac{n_j g_j}{n_i g_i}) g(\omega), \]

where \( f_{ij} \) is the oscillator strength (absorption), \( g_i \) and \( g_j \) are the statistical weights of state, \( g(\omega) \) is the normalized profile of the line, \( c \) is the speed of light, \( e \) is the electron charge, and \( m_e \) is the electron mass. In the maximum, \( \omega = 0 \), and for a Lorentz profile, \( g(0) = 2/\pi \Gamma \), where \( \Gamma \) is the FWHM of the line. The parameters \( n_i \) and \( n_j \) are the population density of the lower-level energy and upper-level energy, respectively, and are estimated to be approximately equal to the electron density, this being a lower limit. A line may be considered optically thin if \( \beta_\lambda L \leq 0.05 \), such that the value of the optical depth \( \beta_\lambda L \) is not in excess of 0.05 (for example, 0.018 in the Sn II 533.2 nm line), and therefore the plasma can be considered optically thin.

Laser produced plasmas are spatially inhomogeneous, and the characteristic plasma parameters have spatial distributions with significant gradients. Figure 8 shows the dependence of the electron temperature \( T_e \) and the density \( n_e \) on the distance to the target surface for two time delays: \( t = 2.0 \mu s \) and \( 2.4 \mu s \). Near the target surface, the electron temperature \( T_e \) varied slightly when the axial distance was increased to 7 mm and then decreased rapidly for a time delay \( t = 2.4 \mu s \). The spatial distribution of the electron temperature for a time delay \( t = 2.0 \mu s \) is similar to that for a delay time of 2.4 \( \mu s \). The space slow-varying of \( T_e \) is related to collisional decoupling and reheating of the heavy species in the plasma for distances longer than 3 to 4 mm. As the plasma expands freely, the local temperature decreases (plasma cooling), and the maximum plasma electron density in the axial spatial distribution shifts farther from the target surface. The maximum electron density location shifted...
from 3 mm at a delay time \( t = 2.0 \, \mu s \) to 7 mm at a delay time \( t = 2.4 \, \mu s \). With increasing separation from the target surface, the electron density falls from \( 1.72 \times 10^{17} \, \text{cm}^{-3} \) at 3 mm to \( 4.34 \times 10^{15} \, \text{cm}^{-3} \) at 15 mm at a delay time of \( 2.0 \, \mu s \), which is also similar to that for a time delay of \( 2.4 \, \mu s \). For delay times from \( 2.0 \, \mu s \) to \( 2.4 \, \mu s \), an averaged expansion velocity of \( (1.0 \pm 0.1) \times 10^6 \, \text{cm/s} \) for the plasma plume was obtained by measuring the space shift in the maximum electron intensity point from the resolved images for different time delays. Their corresponding kinetic energy is about 61 eV. The velocity obtained in this study is in good agreement with the values reported by Namba et al.\(^{15}\) The dashed line is a \( 1/d^2 \) fit of the decreasing experimental data of electron density at a delay time \( t = 2.0 \, \mu s \), and the axial spatial distribution of the electron density showed a \( 1/d^{1.6} \) decrease profile. The electron temperature and density were slightly larger for a delay time \( t = 2.4 \, \mu s \) than for a delay time \( t = 2.0 \, \mu s \), due to the coupling of the later pulse tail energy into the laser produced plume, as is explained later.

The spatial resolved profile of the electron density and temperature along the radial direction at a delay time of \( t = 2.0 \, \mu s \) from the pulse discharge is shown in Fig. 9. The radial distribution of the plasma electron density and temperature along the central plane of the plasma plume has good symmetry at all times and distances, which indicates that the expansion of the laser produced tin plasma plume is axial symmetric. The dashed line is a \( 1/r^2 \) fit of the experimental data at a delay time \( t = 2.0 \, \mu s \), and the radial spatial distribution of the electron density showed a \( 1/r^{1.1} \) decrease profile, as shown by the fitted curve in Fig. 9. The leveling off of the electron density after 4 mm was expected and can be attributed to a reduced rate of three-body recombination. The electron density gradient along the axial direction was larger than that in the radial direction. This can be explained by the fact that the flow of the plasma has a maximum velocity perpendicular to the surface and is independent of the angle at which the laser beam is incident on the surface.

Time gated images of the plasma expanding from the surface of a tin target were obtained via irradiation with ten laser pulses using the 2D spatial imaging spectra mode. At a delay time of \( t < 1.6 \, \mu s \) with respect to pulse discharge, intense continuum emission was observed. At later times, the continuum vanished and a prominent line became observable. Using the singly ionized (Sn II) spatial integrated emission spectra recorded at different delay times in the span of 1.6–3.6 \( \mu s \), we have characterized the LPP in terms of its transient electron temperature and density. The results of this measurement are given in Fig. 10. Within 2 \( \mu s \) of plume evolution, the axial space-averaged electron temperature decays from 3.4 eV to 1.0 eV. However, the plasmas generated in the present studies at earlier times are emitting in the EUV region (see Fig. 3), and thus the initial temperatures might approach 30 eV during the laser pulse. In the delay time span of 1.6–3.6 \( \mu s \), EUV emission was impossible in the plasma. It can be seen from Fig. 10 that the electron temperature significantly increases at a time delay of 2.4 \( \mu s \), which might be due to the coupling of the later portion of the laser pulse into the plasma plume via inverse Bremsstrahlung (IB) absorption (see Fig. 2). The laser intensity absorbed by expanding plasma via the IB process from the incident laser beam at any time is given by 

\[
\beta(\text{cm}^{-1}) = 1.37 \times 10^{-35} \lambda^2 n_e^2 T_e^{1/2}
\]

where \( \lambda \) is the wavelength of the incident laser beam, \( n_e \) is the electron density, and \( T_e \) is the electron temperature. The absorbed energy is converted into internal energy of the plasma and thereby increases the plasma temperature. It is indicated that the coupling of the second laser beam with the laser-ablated plume causes changes in both plume dynamics and the intensities of plasma emissions.

In a previous work by Shaikh,\(^{18}\) lower temperatures and electron densities were measured using a CO\(_2\) laser than in the work presented here. The laser pulse duration, focal spot size diameter, pulse energy, and resultant laser intensity in Ref. 18 are 84 ns, 200 \( \mu \text{m} \), 130 mJ, and \( 10^{10} \, \text{W/cm}^2 \), respectively. In the same paper, the measured electron temperature and density were within 1.13 eV to 0.53 eV and \( 5.3 \times 10^{16} \, \text{cm}^{-3} \) to \( 1.4 \times 10^{16} \, \text{cm}^{-3} \), respectively, for delay times between 200 ns and 1100 ns at distances of up to 5 mm.
along the target normal. The most important factor is the laser intensity, which directly affects the mass ablation rate. The mass ablation rate of the target in a LPP is given by

\[
\frac{dm}{dt} \approx (3.0 \times 10^5) \left( \frac{I_{\text{laser}}}{10^{11} \text{W/cm}^2} \right)^{5/9} \left( \frac{\lambda_{\text{laser}}}{1 \mu\text{m}} \right)^{-4/9} \times Z^{3/8} (\text{g/cm}^2\text{s}),
\]

in which \(I_{\text{laser}}\) is the laser pulse intensity, \(\lambda_{\text{laser}}\) is the laser wavelength, and \(Z\) is the atomic number. For the CO\(_2\) laser in Ref. 18, the mass ablation rate was calculated as 1.27 \(\times\) 10\(^3\) g/cm\(^2\) s for Sn. Correspondingly, the ablation mass was calculated as 3.3 \(\times\) 10\(^{-8}\) g for one shot. In the same way, the ablation mass was calculated as 9.8 \(\times\) 10\(^{-8}\) g in the present experiment, which is about three time larger than that in Ref. 18. As for a long pulse laser, the energy density of which can cause liquid mass transfer, a laser beam with a higher energy density can yield a greater ablation ratio. This difference in laser ablation mass and thermal energy due to the energy deposition in the plasma might explain the higher measured electron density and temperature, the longer duration time, and the further plasma plume distribution in our experiment than in that of Ref. 18.

**IV. SUMMARY AND CONCLUSIONS**

Conventional 1D OES generates a line-of-sight averaged intensity versus wavelength plot for a segment in plasma along the plume expansion direction. In this paper, a novel 2D image spectrump technique that allows precise measurement of the spectral, spatial, and temporal emission characteristic of LPP is applied to the study of tin via the use of a single detection system. In the 2D image spectra, an ICCD detector is operated in the imaging mode and generates an intensity-wavelength plot for each pixel of the detector at different points in space along the plume expansion direction. The plasma temperature is inferred via the Boltzmann plot method from six singly ionized Sn emission lines, and electron density measurements are made using the Stark broadening method by assuming the conditions of LTE and optically thin plasma in both radial and axial directions. A grazing-incidence flat-field spectrometer using a concave grating with varied groove spacing coupled with an x-ray CCD camera was also constructed to measure EUV spectra emitted from a CO\(_2\) laser produced tin plasma light source in the 6.5–16.8 nm wavelength region. The plasma parameter evolution and profile retrieved from the measurements are discussed and compared with the laser pulse waveform. These measurements show that the plasma electron density decreases along the radial direction and maintains symmetry across the radial distance at all times and distances. However, the maximum plasma electron density in the axial spatial distribution shifts farther from the target surface. For delay times from 2.0 \(\mu\)s to 2.4 \(\mu\)s, an averaged expansion velocity of (1.0 \(\pm\) 0.1) \(\times\) 10\(^6\) cm/s for singly charged Sn ions was obtained by measuring the space shift in the maximum electron intensity point from the resolved images for different time delays. Time evolutions of the electron temperature and electron density were found to have an appreciable rise at the delay time of the CO\(_2\) laser pulse tail peak. This suggests that plasma parameters and extreme ultraviolet emission intensity can be controlled by a double pulse combined laser. The enhancement of EUV light emission and the reduction of ion debris with pre-pulse from a tin target via the optimization of many parameters such as the energy of the pre-pulse and the main pulse, the pulse duration, and delay times between pulses still deserves further investigation.

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