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Potential of discharge-based lithium plasma as an extreme ultraviolet source

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Extreme ultraviolet (EUV) discharge-based lamps for EUV lithography need to generate extremely high power in the spectrum band of 13.5±0.135 nm. A model was developed to investigate the wavelength-integrated Lyman-α lines light outputs in hydrogen-like lithium ion. The analysis reveals that the commonly observed low conversion efficiency is largely due to a transient nature of Z discharge-based plasma and that a magnetically confined lithium plasma is an efficient EUV source even at low electron temperature. Calculation shows necessary confinement time that raises the conversion efficiency up to half the spectral efficiency. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2227560]

Recent advances in the field of extreme ultraviolet (EUV) lithography have revealed that laser-produced lithium,[1] and tin[2] plasmas or discharge-produced tin plasma[1] is a source candidate for next-generation microelectronics. In spite of impressive progress in the development of discharge EUV sources over the last several years,[3] only tin material demonstrated large conversion efficiency (CE) of input power to emission in 2% bandwidth centered at the wavelength $\lambda = 13.5$ nm, the so-called in-band radiation. On the other hand, there are significant motivations for the interest in lithium (Li) due to its pure spectrum and the lower energy ion generation. In addition, considerably lower electron temperature (T_e) satisfies the condition to generate required Li-charge state that makes possible the utilization of various sources.[4,5] Although there are many experimental results on Li, all of the previous works were performed in Z discharge-based plasmas,[6,7] which operate very far from equilibrium. However, calculation efforts to find out the optimal region of plasma electron density (n_e) and T_e, and the importance of the plasma lifetime for maximizing CE in conditions relevant to discharge EUV sources have not been reported. Herein using a simplified collisional-radiative model (CRM) and radiative transfer equation, we present results of a numerical investigation which reveal that a large CE of Li plasma could be achieved if the hydrodynamical behavior of the plasma is controlled.

The CRM involves all of the transitions in Li- and helium (He)-like ions based on unresolved transition arrays (UTAs) framework of the Hebrew University-Lawrence Livermore atomic code.[8] For hydrogen (H)-like Li, calculation was carried out using available relativistic transition probabilities[9] (or H-like ion approximation for high principal quantum number) and energy levels of fine structure cited in the database of the National Institute of Standards and Technology.[10] Opacity effects are considered among all of the transitions using the Doppler-profile escape factor normal to a plasma cylinder.[11] The effective ionization and recombination rate coefficients have been introduced in Ref. 12. Calculation of ion fractions is in agreement with Fig. 6 cited in Ref. 13. According to Lambert's law, the integrated radiant exitance M_λ (W cm^{-2})$=\pi L_\lambda$. L_λ is the integrated spectral radiance over the line profile (i.e., the power per unit area, per unit solid angle, integrated over the opacity-broadened Doppler-profile line in W cm^{-2} sr^{-1} units).[14,15]

Stem representations of M_λ vs λ are shown in Figs. 1(a) in logarithmic scale and in Fig. 1(b) in the spectrum range of 10–21 nm, for $n_e = 10^{18}$ cm^{-3}, T_e (ion temperature T_i) $= 10$ eV, and plasma radius of $R = 0.04$ cm. Out of band intensities are extremely low as shown in Fig. 1(a), viz., the plasma is optically thin for most of the transitions. The intensity of Lyman ratio ($\mathrm{Ly}_\alpha/\mathrm{Ly}_\beta \simeq 14$) in Fig. 1(b) is in agreement with results pointed out by Hutcheon and

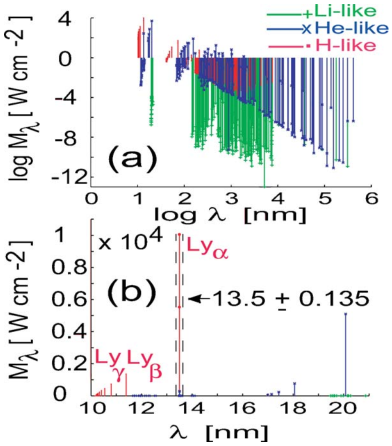

FIG. 1. (Color online) Stem diagram of M_λ vs λ: (a) Total transitions in logarithmic scale and (b) in spectrum band of 10–21 nm. Transitions in charge states marked by Li-(+), He- (×), and H-like ions (.).

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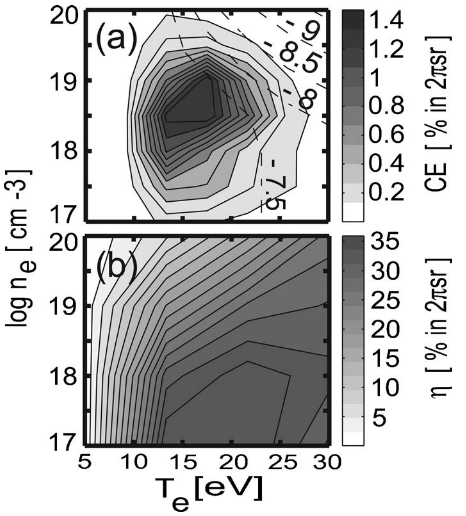

FIG. 2. (a) Contour of CE and log τ (dashed line, in s units) vs n_e and T_e for a cylinder plasma with 0.08 cm in diameter and 0.4 cm in length. (b) Spectral efficiency.

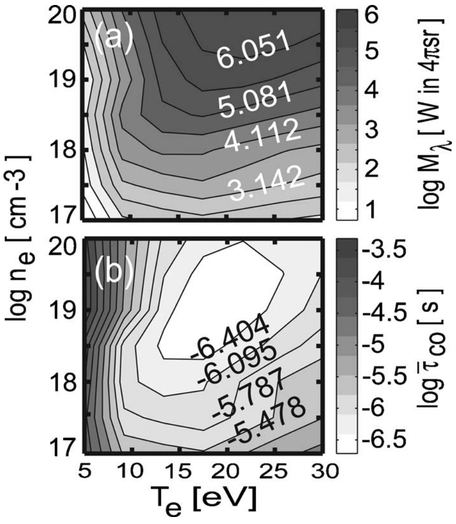

FIG. 3. The natural logarithm of (a) radiative loss power by line radiations and (b) mean radiative cooling time $\bar{\tau}_{\mathrm{co}}$ (s).

McWhirter.[16] With increasing density, Lyman ratio continuously drops down since the spectral intensity distributions for all of the transitions approach their intrinsic spectral radiance.[15] Note that the transitions in Li- and He-like ions, for instance, near $\lambda \simeq 20$ nm represent the total emission in the UTA model.[17] We ignored a possible contribution of the He-like ion to the in-band region via stabilizing transitions[12] as shown in Fig. 1. Calculation was performed for Gaussian line shape because the Stark broadening of Ly$_\alpha$ lines are negligible in low n_e. For conditions considered in Fig. 1, the full-width at half-maximum (FWHM) Stark widths (Δ_S) of Ly$_\alpha$ lines within the framework of Griem's semiemprical approach[18] are approximated to be 5×10^{-5} nm, whereas FWHM Doppler widths (Δ_D) are 1.3×10^{-3} nm. The actual linewidth will be further broadened by opacity broadening, which yields $\simeq 2.4 \times \Delta_D$. Thereby in a discharge EUV source, FWHMs of Ly$_\alpha$ lines are much more narrow than the bandwidth of the Mo/Si mirror.

The maximum CE can be written as[14,19]

$$\mathrm{CE}(\mathrm{in}\ 4\pi\ \mathrm{sr}) = \frac{\sum M_{\lambda 2\%} S_p \tau}{\sum M_\lambda S_p \tau + E}, \tag{1}$$

where $M_{\lambda 2\%}$ denotes the integrated radiant exitance of transition in 2% bandwidth, S_p is plasma surface, τ is emission duration, and E is the minimum energy needed to heat and ionize a plasma to a given ionization state (internal plasma energy) and the cohesive energy (1.63 eV/atom for Li).[20] Equation (1) clearly implies that τ is of key importance in the optimization of CE. It should be noted that Eq. (1) does not take into account the electrical coupling efficiency from pulsed power generator to the internal plasma energy. In other words, we restricted our analysis to the inherent CE of Li plasma.[21]

Figure 2(a) represents a contour of CE vs n_e and T_e. Plasma conditions span for $n_e = 10^{17} - 10^{20}$ cm^{-3} and $T_e = 5-30$ eV, while keeping photon path length ($R = 0.04$ cm) constant. According to étendue limit ($\leqslant 3.3$ mm^2 sr),[22] the plasma length is assumed to be 0.4 cm. Moreover, Fig. 2(a) shows the contour of τ in logarithmic scale (dashed line) in seconds. In Z discharge type transient plasma τ is governed by (i) the characteristic time scale of the plasma hydrodynamic behavior, and (ii) ionization (τ_i) and recombination times of given ionization state at pinching phase (maximum compression). Thereby to estimate τ in Fig. 2(a), we have considered a shorter time between (i) inertial confinement time ($\tau_c = 2R/V_t$, where V_t is the ion thermal velocity) and (ii) ionization time of H-like Li ($\tau_i = 1/n_e S_i$, where S_i is the ionization rate coefficient). For example, the values of $n_e = 10^{18}$ cm^{-3}, $T_e = T_i = 10$ eV, and $R = 0.04$ cm yield $\tau_c \simeq 4 \times 10^{-8}$ s and $\tau_i \simeq 4 \times 10^{-4}$ s from the ground state of H-like Li (Ref. 23) and $\simeq 2 \times 10^{-5}$ s in our calculation, which includes effect of excited states and ionization potential lowering.[12] Thus for this condition CE in Fig. 2(a) is estimated based on τ_c, i.e., for a short-lived plasma when the hydrodynamic behavior is dominant.[24]

The spectral efficiency (η), i.e., when E is set to zero in Eq. (1), is shown in Fig. 2(b). Figures 2(a) and 2(b) reveal that E is the dominant term in Eq. (1) for a short-lived plasma. Keep in mind that τ is also device dependent, that is, it is affected by cooling time due to the plasma expansion in pulsed discharge plasmas.

Imaging a magnetically confined plasma when τ is longer than τ_c in Z discharge is possible. At low $n_e - T_e$ region at which τ_i of H-like Li becomes longer than the confinement time (τ_m) when E in Eq. (1) converts to radiation, i.e., when condition $\tau = \tau_m = E / \Sigma M_\lambda S_p \leqslant \tau_i$ is fulfilled, we expect CE to approach $0.5 \times \eta$. The radiative loss power due to line emissions $P(\mathrm{W}) = \Sigma M_\lambda S_p$ is shown in Fig. 3(a). The values of $T_e = T_i = 10$ eV, ion density $n_i = 5 \times 10^{17}$ cm^{-3}, mean ionic charge state $\bar{Z} = 2$, and the aforementioned plasma dimension give $E \simeq 0.023$ J and $P \simeq 8 \times 10^3$ W. Consequently, for this condition, mean confinement time $\bar{\tau}_m = E/P \simeq 3$ μs. If we consider additional heating to compensate for radiation loss, for instance, Joule heating, we expect that CE for this input energy approaches η, that is, putting $E = 0$ in Eq. (1). It may be interesting to notice here that the maximum η of tin-based discharge source is estimated to be less than one-third compared to that of Li plasma. The details will be published elsewhere. The mean radiative cooling time $[\bar{\tau}_{\mathrm{co}} = E_t / P$,[25] where $E_t = 3 n_e (T_i / \bar{Z} + T_e) V_p / 2]$ is the sum of the thermal energies of ions and electrons for the aforementioned

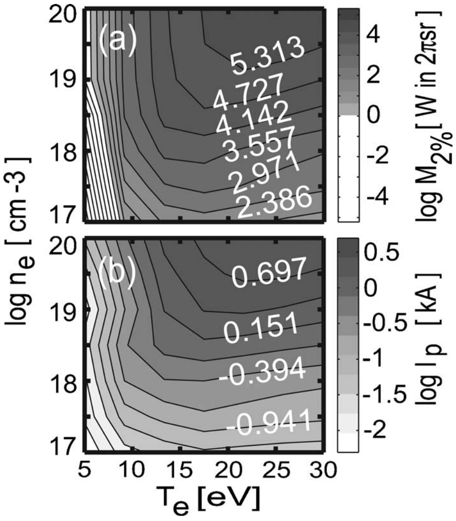

FIG. 4. The natural logarithm of (a) total in-band power and (b) the necessary plasma current I_p (kA), in which Joule heating compensates for the total radiation loss. The Joule heating is calculated for unmagnetized plasma using the Coulomb logarithm as a function of n_e and T_e for a constant plasma dimension.

plasma volume V_p, i.e., the time that the plasma needs to radiate away its thermal energy is shown in Fig. 3(b). Note that this is the mean value due to the steady-state nature of the model. Also, a contour of total in-band power ($M_{2\%}$) vs n_e and T_e is shown in Fig. 4(a). At low $n_e - T_e$ region, in which $\bar{\tau}_{\text{co}}$ is on the order of microseconds, a steady-state H-like Li plasma has a potential to radiate up to 1 kW as can be seen in Fig. 4(a). A contour plot of the necessary plasma current $[I_p(\text{kA})]$, which compensates for the radiation loss by Joule heating in an unmagnetized plasma[21] is shown in Fig. 4(b). At $n_e = 10^{18}$ cm^{-3} and $T_e = 10$ eV, the necessary plasma current for the energy balance is $\simeq 250$ A.

In the quest for enhancing CE of Li plasma, it is crucially important to prolong emission duration. Calculation shows that when the Li plasma is sustained for more than the confinement time, CE would be an order of magnitude greater than the conventional Z discharge source.

A possible interesting venue where these results find application will be in arc discharge-based plasmas. Although the nature of arc plasmas is extremely complicated, an analytical estimation[26] based on a steady-state current-carrying plasma predicts $T_e \simeq 5-10$ eV and $n_e \simeq (3-30) \times 10^{17}$ cm^{-3}, for values of arc current over the range $\simeq 1-4$ kA, a group spot with a diameter $\simeq 0.05$ cm, $\bar{Z} \simeq 1.5$, a typical jet velocity $\simeq 10^6$ cm/s, and a net erosion rate $\simeq 7-20$ μg/C.[27] Moreover, it is well known that n_e, T_e, charge state, and plasma radius in arc plasmas could be controlled by a variety of methods, in particular, in the presence of a strong axial magnetic field combined with additional heating of the plasma and/or auxiliary cooling of the cathode. However, a complete picture of arc plasmas would require a full account of the magnetohydrodynamic behavior self-consistently coupled to the ionization dynamics, and plasmas-surface interaction including energy loss to the electrodes, which are beyond the scope of the present study.

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