1-1-2013

Laser-plasma source parameters for Kr, Gd, and Tb ions at 6.6 nm

Majid Masnavi

University of Central Florida

John Szilagyi

University of Central Florida

Homaira Parchamy

University of Central Florida

Martin C. Richardson

University of Central Florida

Find similar works at: <https://stars.library.ucf.edu/facultybib2010>

University of Central Florida Libraries <http://library.ucf.edu>

This Article is brought to you for free and open access by the Faculty Bibliography at STARS. It has been accepted for inclusion in Faculty Bibliography 2010s by an authorized administrator of STARS. For more information, please contact STARS@ucf.edu.

Recommended Citation

Masnavi, Majid; Szilagyi, John; Parchamy, Homaira; and Richardson, Martin C., "Laser-plasma source parameters for Kr, Gd, and Tb ions at 6.6 nm" (2013). *Faculty Bibliography 2010s*. 4381.

<https://stars.library.ucf.edu/facultybib2010/4381>

Laser-plasma source parameters for Kr, Gd, and Tb ions at 6.6 nm

Cite as: Appl. Phys. Lett. **102**, 164102 (2013); <https://doi.org/10.1063/1.4802789>

Submitted: 08 January 2013 . Accepted: 08 April 2013 . Published Online: 22 April 2013

Majid Masnavi, John Szilagyi, Homaira Parchamy, and Martin C. Richardson

View Online

Export Citation

CrossMark

ARTICLES YOU MAY BE INTERESTED IN

[Spectral irradiance of singly and doubly ionized zinc in low-intensity laser-plasma ultraviolet light sources](#)

Journal of Applied Physics **121**, 033303 (2017); <https://doi.org/10.1063/1.4973848>

[Estimation of optimum density and temperature for maximum efficiency of tin ions in Z discharge extreme ultraviolet sources](#)

Journal of Applied Physics **101**, 033306 (2007); <https://doi.org/10.1063/1.2434987>

[Rare-earth plasma extreme ultraviolet sources at 6.5–6.7 nm](#)

Applied Physics Letters **97**, 111503 (2010); <https://doi.org/10.1063/1.3490704>

Applied Physics Reviews
Now accepting original research

2017 Journal
Impact Factor:
12.894

AIP
Publishing

Laser-plasma source parameters for Kr, Gd, and Tb ions at 6.6 nm

Majid Masnavi, John Szilagyi, Homaira Parchamy, and Martin C. Richardson
*The Townes Laser Institute, College of Optics and Photonics, University of Central Florida,
 4000 Central Florida Blvd., Orlando, Florida 32816, USA*

(Received 8 January 2013; accepted 8 April 2013; published online 22 April 2013)

There is increasing interest in extreme-ultraviolet (EUV) laser-based lamps for sub-10-nm lithography operating in the region of 6.6 nm. A collisional-radiative model is developed as a post-processor of a hydrodynamic code to investigate emission from resonance lines in Kr, Gd, and Tb ions under conditions typical for mass-limited EUV sources. The analysis reveals that maximum conversion efficiencies of Kr occur at $5 \times 10^{10} \text{ W/cm}^2$, while for Gd and Tb it was $\simeq 0.9\%/2\pi \text{ sr}$ for laser intensities of $(2 - 5) \times 10^{12} \text{ W/cm}^2$. © 2013 AIP Publishing LLC [<http://dx.doi.org/10.1063/1.4802789>]

Progress in the field of extreme-ultraviolet (EUV) lithography based on 13.6 nm wavelength normal-incidence, Mo:Si multilayer mirror technology is advancing with the development of laser-based¹ and discharge-based² tin plasma sources. It is expected to be introduced into high-volume semiconductor chip production in the next few years. Shorter wavelengths permit higher imaging resolution at lower numerical apertures (NAs). So in seeking pathways towards still finer feature sizes, interest is rising in the possibility of fabricating high reflective EUV mirrors based in LaN and B or BC. Theoretical reflection efficiencies $\simeq 80\%$ have been postulated for these mirrors in the 6.6 nm region.³ The Feigl group³ estimates the highest efficiencies occurring in bands at $6.635 \pm 0.018 \text{ nm}$ or $6.675 \pm 0.015 \text{ nm}$, depending on whether LaN/B4C or LaN/B multilayer mirrors are used.

In this paper, we examine the emission spectra of laser plasma sources that would be efficient in this region. In particular, the rare-earth elements of gadolinium (Gd) and terbium (Tb) emit as intense unresolved transition arrays around 6.6 nm. We report calculations using a model that includes a collisional-radiative (CR) solver⁴ and a modified one-dimensional hydrodynamic code MEDUSA⁵ coupled with an atomic code relevant to the conditions in mass-limited laser-based EUV sources.^{6,7}

The CR solver includes all of the electric dipole transitions among the most important singly excited-states configurations in the $\text{Kr}^{(0-13)+}$, $\text{Gd}^{(10-26)+}$, and $\text{Tb}^{(10-28)+}$ charge states using detailed atomic data obtained from the relativistic Flexible Atomic Code (FAC) including the effect of configuration interactions.⁸ The latter, primarily accounting for the effect of electron correlations among transitions with the same principal quantum number, causes a strong spectral narrowing. For other charge-states, we include only their ground states in the model. The in-band emission peaks arising mainly from the $3d-4f$ transitions belong to the charge states near the Kr^{10+} ion and the $4d-4f + 4p-4d$ transitions in the Gd^{20+} and Tb^{20+} charge states. Therefore, for example, $4p^6 4d^m$, $4p^6 4d^{m-1}nl$, and $4p^5 4d^{m+1}$ configurations with $n \leq 6$ and $l \leq 3$ are included for Tb^{19+} through Tb^{28+} charge states. The radiation transport is solved using the plane-parallel approximation for the case of a spatial grid, partitioning the plasma source into cells such that all their properties can be considered uniform within each cell. Thus, the

observed spectral radiance of plasma at a wavelength λ from a given cell i after successive loss by other cells j can be written as⁹

$$L_i^\lambda(\text{obs}) = S_i^\lambda [1 - \exp(-\tau_i^\lambda)] \exp\left(-\sum_j \tau_j^\lambda\right), \quad (1)$$

where S is the non-local thermodynamic equilibrium source function and τ is the optical depth including the continuum. This is the contribution from a single cell i for a photon at wavelength of λ . After summation over all cells along the line of sight, the total spectral radiance is estimated. The effect of radiation loss or opacity on the population distribution in Eq. (1) is evaluated using the photon escape probability factor for the Voigt line profile as¹⁰

$$p_i^\lambda = \beta_i^\lambda - \frac{1}{\tau_i^\lambda} \sum_{j=1, j \neq i} \frac{S_j^\lambda}{S_i^\lambda} M_{ij}, \quad (2)$$

where M is a function of optical depth.¹⁰ The function β is an escape factor for the cell i taking into account its own reabsorption effect. The second term on the right hand side describes the effect on the level populations in cell i due to radiation produced in all the other cells. Owing to a large number of excited states and iteration method to calculate opacity effect, we have removed a number of out-of-band transitions while keeping major in-band transitions in the CR solver.

To verify the emission line positions, we have compared our calculated spectra for a homogeneous spherical Gd or Tb plasma having a radius of $50 \mu\text{m}$ ($\simeq$ laser spot size) with an electron temperature of 100 or 110 eV, respectively, and an ion density of $1.4 \times 10^{19} \text{ cm}^{-3}$ to experimental results created using planar-target laser-produced plasma¹¹ as shown in Figs. 1(a) and 1(b). For these conditions, the average ionic charge state for Gd is 18.5 and 19.2 for Tb plasmas. Using the FAC code, it is found that the calculated spectra are in approximately agreement with the experimental spectra around the mirror in-band region after a global displacement of 0.18 and 0.1 nm toward longer wavelength is introduced for Gd and Tb, respectively. The calculated spectra are slightly shorter in wavelength due to the configuration interaction effects and overestimation of the *ab initio* exchange

FIG. 1. Comparison between the calculated and measured spectra:¹¹ (a) the Gd and (b) the Tb spectra produced in laser-based EUV sources. Experimental spectra reproduced with permission from Churilov *et al.* Phys. Scr. **80**, 045303 (2009). Copyright 2009 Institute of Physics. The spectra calculated for homogeneous spherical Gd and Tb plasmas having a radius of $50\text{ }\mu\text{m}$, with an ion density of $1.4 \times 10^{19}\text{ cm}^{-3}$ and electron temperatures of 100 and 110 eV, respectively. In the experiment, each planar target is irradiated by 1064 nm laser pulse intensity $\simeq (5 - 8) \times 10^{11}\text{ W/cm}^2$.

Slater integrals, as investigated for a few elements including tin and xenon targets in 13.6 nm lithography tool.^{12,13} The effect of instrumental broadening in the Voigt line profile was not included. The calculations underestimate the out-of-band emission, in particular, on the longer wavelength side due to the limited number of emission lines treated in the model and the assumption of a single electron temperature and density for the transient plasma in experiment.

To investigate the in-band conversion efficiency (CE), the CR solver is used as a post-processor of the MEDUSA code. The space and time histories of the plasma are calculated for a $20\text{ }\mu\text{m}$ diameter liquid cylindrical Kr jet target and for spherical Gd or Tb solid targets having a radius of $10\text{ }\mu\text{m}$, each irradiated by a 1064 nm Gaussian laser pulse having full-width at half maximum (FWHM) of 8.5 ns. The ideal gas equation-of-state was used for liquid Kr and the modified Thomas-Fermi model for Gd and Tb. Typical ion densities and electron temperatures as a function of time and space obtained from these simulations of the interaction for a peak laser pulse intensity of $2 \times 10^{12}\text{ W/cm}^2$ for the spherical Gd target are shown in Figs. 2(a) and 2(b). In this simulation, the ionization process is calculated using the Saha model. The time and space histories of the plasma parameters are first calculated using the MEDUSA code and they were then used to recalculate electron density using the CR. The EUV spectrum, integrated over time and space, was obtained by allowing the CR solver to run for 50 ns, after which time there was little predicted emission.

The integrated spectral radiant energies for Kr, Gd, and Tb at different laser intensities are shown in Figs. 3(a), 3(b), and 3(c), respectively. The in-band region of a LaN/B4C mirror ($6.635 \pm 0.018\text{ nm}$) is shown for reference. The liquid density of Kr is assumed to be 2.4 g/cm^3 . Figure 3(a) shows integrated spectra per unit length of the Kr cylindrical target at intensities of (I) 5×10^{10} and (II) $3 \times 10^{11}\text{ W/cm}^2$.

FIG. 2. Surface plot of the ion density (a) in logarithmic scale and electron temperature (b) as a function of time and space obtained from the MEDUSA simulation of interaction of a Gaussian laser pulse having FWHM of 8.5 ns with peak intensity of $2 \times 10^{12}\text{ W/cm}^2$ for Gd spherical target having a radius of $10\text{ }\mu\text{m}$.

Although inert-gas targets are attractive since they produce negligible debris, however, these preliminary calculations show that the strongest spectral emission peaks of Kr are located outside the in-band region. However, comparison to experimental spectra may be necessary to verify the positions of these emission lines. Figures 3(b) and 3(c) show the integrated spectra for Gd and Tb spherical targets at intensities of (I) 2×10^{12} , (II) 6×10^{12} , and (III) 10^{13} W/cm^2 . These calculations show that the spectral emission from Gd target drops in the region of $\lambda \lesssim 6.7\text{ nm}$, while strongest emission peaks of Tb plasma are close to in-band mirror region for high laser intensities, which is for high plasma temperatures. The Tb spectrum becomes broader as the charge-state increases beyond Tb¹⁹⁺.

The CE calculated as a percentage [(%) of the incident laser energy, emitted into 2π steradian] = $(\sum_{\text{in-band}} \text{radiant energy in } 2\pi\text{sr} / \text{total input laser energy}) \times 100$ against 1064 nm

FIG. 3. The integrated spectral radiant energy: (a) a cylindrical liquid jet Kr target having a diameter of $20\text{ }\mu\text{m}$ irradiated with 1064 nm Gaussian laser pulse intensities of (I) 5×10^{10} and (II) $3 \times 10^{11}\text{ W/cm}^2$. (b) The spherical Gd target having a radius of $10\text{ }\mu\text{m}$ irradiated with 1064 nm laser pulse intensities of (I) 2×10^{12} and (II) $6 \times 10^{12}\text{ W/cm}^2$. (c) The spherical Tb target having a radius of $10\text{ }\mu\text{m}$ irradiated with 1064 nm laser intensities of (I) 2×10^{12} , (II) 6×10^{12} , and (III) 10^{13} W/cm^2 . The in-band region of a LaN/B4C mirror ($6.635 \pm 0.018\text{ nm}$) is shown for reference.

FIG. 4. The CE (% in $2\pi\text{sr}$) for the Kr (circle), the Gd spectra shifted by 0.18 nm to longer wavelength (square), the Tb (solid line) against a 1064 nm Gaussian laser pulse intensity having FWHM of 8.5 ns: (a) calculated for in-band region of a LaN/B4C mirror ($6.635 \pm 0.018 \text{ nm}$) and (b) for in-band region of a LaN/B mirror ($6.675 \pm 0.015 \text{ nm}$).

laser intensity is shown in Fig. 4. The CE in Fig. 4(a) is calculated for the LaN/B4C mirror ($6.635 \pm 0.018 \text{ nm}$) and in Fig. 4(b) for the LaN/B mirror ($6.675 \pm 0.015 \text{ nm}$). A maximum conversion efficiency of $\approx 0.2\%/2\pi\text{sr}$ is expected for the krypton plasma at a laser intensity of $5 \times 10^{10} \text{ W}/\text{cm}^2$. The calculation shows that the strongest peaks of the Gd spectra do not match the in-band mirror regions. However, a comparison between calculated Gd spectra to a sophisticated experimental spectra against thickness of target¹⁴ reveals that we may need only a global displacement of our calculated spectra by 0.1 nm toward longer wavelength instead of 0.18 nm as shown in Figs. 1(a) and 3(b). In this case, the CE of Gd increases as shown by the hollow squares in Figs. 4(a) and 4(b). The calculated optimum laser intensity region to maximize CE of Gd is in approximately agreement to the experimental result presented in Ref. 16. It is expected that with a decrease in initial density of Gd or Tb, the maximum CE enhances compared to the solid density targets due to the lower opacity effects as investigated for tin in 13.6 nm lithography tool.^{6,15} To better characterize features of Gd spectra, a detailed comparison between calculation and the

experimental spectra¹⁴ will be published elsewhere. Figure 4 shows that the mass-limited spherical Tb target irradiated by a 1064 nm Gaussian laser pulse intensity of $5 \times 10^{12} \text{ W}/\text{cm}^2$ gives the CE as high as $\approx 0.9\%/2\pi\text{sr}$.

One of the authors (M.M.) gratefully acknowledges Professor A. N. Ryabtsev for providing us the experimental data presented in Figure 1.

¹D. C. Brandt, I. V. Fomenkov, M. J. Lercel, B. M. La Fontaine, D. W. Myers, D. J. Brown, A. I. Ershov, R. L. Sandstrom, A. N. Bykanov, G. O. Vaschenko, N. R. Bawering, P. Das, V. B. Fleurov, K. Zhang, S. N. Srivastava, I. Ahmad, C. Rajyaguru, S. D. Dea, W. J. Dunstan, P. Baumgart, T. Ishihara, R. D. Simmons, R. N. Jacques, R. A. Bergstedt, P. I. Porshnev, C. J. Wittak, M. R. Woolston, R. J. Rafac, J. Grava, A. A. Schafgans, and Y. Tao, *Proc. SPIE* **8322**, 83221I (2012).

²H. Meiling, W. de Boeij, F. Bornebroek, N. Harned, I. de Jong, P. Kürz, M. Lowisch, H. Meijer, D. Ockwell, R. Peeters, E. van Setten, J. Stoeldraijer, C. Wagner, S. Young, and R. Kool, *Proc. SPIE* **8322**, 83221G (2012).

³S. Yulin, T. Feigl, V. Nesterenko, M. Schurmann, M. Perske, H. Pauer, T. Fiedler, and N. Kaiser, in *Proceedings of the International EUVL Symposium*, Miami, 17 October 2011, International SEMATEC, <http://www.semtech.org/meetings>.

⁴M. Masnavi, M. Nakajima, E. Hotta, and K. Horioka, *J. Appl. Phys.* **103**, 013303 (2008).

⁵J. P. Christiansen, D. E. T. F. Ashby, and K. V. Roberts, *Comput. Phys. Commun.* **7**, 271 (1974).

⁶S. A. George, K. Hou, K. Takenoshita, A. Galvanauskas, and M. C. Richardson, *Opt. Express* **15**, 16348 (2007).

⁷M. Richardson, C. S. Koay, K. Takenoshita, C. Keyser, S. George, M. Al-Rabban, and V. Bakshi, in *EUV Sources for Lithography*, edited by V. Bakshi (SPIE, Bellingham, WA, 2005).

⁸M. F. Gu, *Astrophys. J.* **582**, 1241 (2003).

⁹P. K. Patel, J. S. Wark, D. J. Heading, A. Djaoui, S. J. Rose, O. Renner, and A. Hauer, *J. Quant. Spectrosc. Radiat. Transf.* **57**, 683 (1997).

¹⁰M. Elitzur and A. A. Ramos, *Mon. Not. R. Astron. Soc.* **365**, 779 (2006).

¹¹S. S. Churilov, R. R. Kildiyarova, A. N. Ryabtsev, and S. V. Sadovsky, *Phys. Scr.* **80**, 045303 (2009).

¹²C. Bauche-Arnoult, J. Bauche, J. F. Wyart, and K. B. Fournier, *J. Quant. Spectrosc. Radiat. Transf.* **65**, 57 (2000).

¹³R. D'Arcy, O. Morris, H. Ohashi, S. Sudo, H. Tanuma, S. Fujioka, H. Nishimura, K. Nishihara, C. Suzuki, T. Kato, F. Koike, and G. O'Sullivan, *Phys. Scr.* **T144**, 014026 (2011).

¹⁴S. Fujioka, H. Nishimura, M. Miyake, T. Ugomori, M. Yoshida, and H. Azechi, in *Proceedings of the International Workshop on EUV and Soft x-ray Sources*, Dublin, Ireland, 2011.

¹⁵A. Sasaki, K. Nishihara, A. Sunahara, H. Furukawa, T. Nishikawa, and F. Koike, *Appl. Phys. Lett.* **97**, 231501 (2010).

¹⁶T. Cummins, T. Otsuka, N. Yugami, W. Jiang, A. Endo, B. Li, C. O'Gorman, P. Dunne, E. Sokell, G. O'Sullivan, and T. Higashiguchi, *Appl. Phys. Lett.* **100**, 061118 (2012).