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Efficient plasma EUV source and its application
プラズマEUV光源の高効率化とその応用

Takeshi Higashiguchi
東口武史

Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan
宇都宮大学 〒321-8585 宇都宮市陽東7-1-2

We demonstrate EUV and soft x-ray sources in the 2 to 7 nm spectral region related to the beyond EUV (BEUV) question at 6.*x* nm and a water window source based on laser-produced high-*Z* plasmas. Resonance emission from multiply charged ions merges to produce intense unresolved transition arrays (UTAs), extending below the carbon K edge (4.37 nm). An outline of a microscope design for single-shot live cell imaging is proposed based on a high-*Z* plasma UTA source, coupled to x-ray optics. We will discuss the progress and Z-scaling of UTA emission spectra to achieve lab-scale table-top, efficient, high-brightness high-*Z* plasma EUV-soft x-ray sources for *in vivo* bio-imaging applications.

1. Introduction

Development of shorter wavelength sources in the extreme ultraviolet (EUV) and soft x-ray spectral regions has been motivated by their application in a number of high profile areas of science and technology. Efficient, high-power extreme-ultraviolet (EUV) sources for semiconductor lithography at 13.5 and 6.7 nm based on laser-produced plasmas have been demonstrated in high-volume manufacturing of integrated circuits (IC) having node sizes of 22 nm or less [1]. Plasmas of the high-*Z* elements Sn and Gd produce strong resonant emission due to 4*d*–4*f* and 4*p*–4*d* transitions at 13.5 nm and 6.7 nm, respectively, which overlap in adjacent ion stages to yield an intense unresolved transition array (UTA) in their spectra. The in-band high-energy emission is thus attributable to hundreds of thousands of near-degenerate resonance lines lying within a narrow wavelength range [2].

All are based on $n = 4$–$n = 4$ (4*d*–4*f* and 4*p*–4*d*) transitions that overlap to generate an intense UTA. For efficient 13.5-nm operation, it is important to produce an optimum plasma electron temperature of 30-50 eV. The rare-earth elements of gadolinium ($_{64}$Gd) and terbium ($_{65}$Tb) produce strong emission near 6.7 nm, which is maximized at electron temperatures in the 100-120 eV range depending on initial focusing conditions [3]. Because it moves to shorter wavelength with increasing atomic number, *Z*, the $n = 4$–$n = 4$ UTA is expected to lie in the water window if higher *Z* elements from $_{79}$Au to $_{83}$Bi are used [4].

In this presentation, we report the efficient EUV-water window soft x-ray source by strong UTA band emission in laser-produced high-*Z* plasmas. Our proposed procedure for producing the water window soft x-ray emission is expected to be efficient and scalable in output yield. We have initiated a number of experiments to explore how this emission may be optimized in practice.

2. *Z*-scaling of efficient UTA emission: Quasi-Moseley's law

We show that the strong resonance UTAs of Nd:YAG LPPs for elements with $Z = 50$–83 obey a quasi-Moseley's law [5]. Figures 1(a)–1(k) show LPP emission spectra from high-*Z* metal targets. The main UTA peak at 8.17 nm in the case of Nd clearly shifts to shorter wavelength with increasing atomic number, 3.95 nm in the case of Bi. This movement indicates the availability of a wide wavelength range for a LPP light source. Optically thinner LHD plasma spectra are shown in Figs. 1(l)–1(q). It should be noted that the electron temperatures of LHD plasma were relatively low, ≤ 1 keV, but higher than in ps-LPPs. Comparing LPP and LHD spectra, the UTA widths in LHD spectra are relatively narrower than in LPPs especially for lighter elements. Self-absorption effects are clearly observed in the case of ns-LPP for Nd due to optical thickness. Although the $n = 4$–$n = 4$ UTA transition peak was observed at 8.05nm in the LHD spectrum, the strongest 4*d*–4*f* transitions essentially disappear in the ns-LPP owing to self-absorption. Because of their large transition probabilities, resonant lines that are strong in emission also strongly absorb in underdense ($n_e < n_c$, where n_c is the critical electron density) or optically thick plasma conditions. An optically thinner plasma reduces the self-absorption effects and increases the spectral efficiency of $n = 4$–$n = 4$ UTA emissions.

An approximated curve for ps-LPPs with a power-law scaling of the peak wavelength given by $\lambda = aR_\infty^{-1}(Z - s)^{-b}$ in nm where a = 21.86 ± 12.09, b = 1.52 ± 0.12, s = 23.23 ± 2.87 is the screening constant while Slater's rule gives s = 36−39.15 for 4d electrons, and R_∞ is the Rydberg constant. This empirical law is surprisingly similar to Moseley's law where a = 4/3, b = 2 and s = 1 were used to give the transition wavelength of the Kα-line of characteristic x-rays.

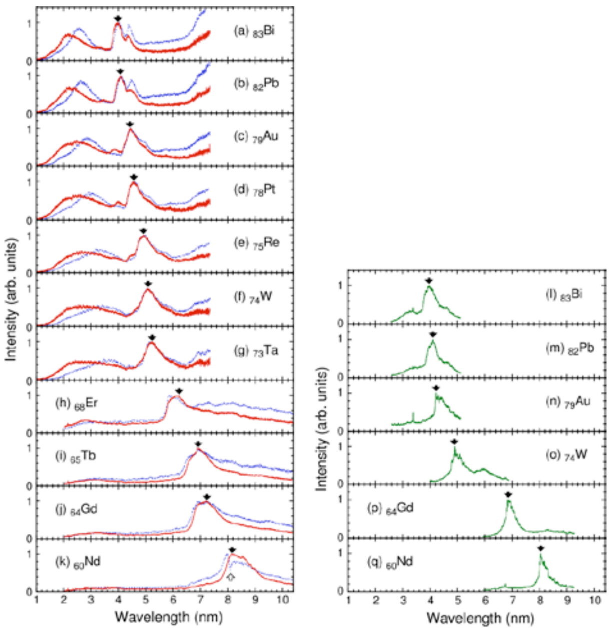

Fig. 1. Time-integrated EUV emission spectra of the Nd:YAG LPPs for (a) $_{83}$Bi, (b) $_{82}$Pb, (c) $_{79}$Au, (d) $_{78}$Pt, (e) $_{75}$Re, (f) $_{74}$W, (g) $_{73}$Ta, (h) $_{68}$Er, (i) $_{65}$Tb, (j) $_{64}$Gd and (k) $_{60}$Nd targets with 150-ps laser (red, solid line) and 8-ns laser (blue, dotted line), respectively. The measured LHD spectra (green, solid) for (l) Bi, (m) Pb, (n) Au, (o) W, (p) Gd and (q) Nd targets, respectively. An emission line at 3.4 nm is from impurity carbon ions. Intensities were normalized at each maximum of the n = 4−n = 4 UTAs. Solid arrows indicate peak position of n = 4−n = 4 UTAs of ps-LPP and LHD spectra. An open arrow indicates structure due to self-absorption.

3. Efficient BEUV source at 6.7 nm

Lateral expansion of the plasma causes kinetic energy losses which reduce the energy available for radiation and is particularly important for small focal spot diameters. For practical light source development, it is important to establish the optimum plasma parameters related to laser irradiation conditions and construct a database of characteristics of the plasma EUV sources. In addition, to compare with one-dimensional (1D) numerical simulation, it is important to produce 1D expanding plasmas by use of multiple laser beams based on the laser inertial confinement fusion (ICF) geometry. Laboratory scale experiments have, to date, only been studied under 2D conditions due to the use of a single laser beam and small focal spot diameters. Under multiple laser irradiation, it is expected that the highest CE will be achieved as plasma expansion loss can be neglected in plasmas from targets irradiated by solid-state laser pulses.

We demonstrate a high conversion efficiency for EUV emission around 6.5−6.7 nm from multiple laser beam-produced 1D spherical plasmas. Multiply charged-state ions produce strong resonance emission lines, which combine to yield intense unresolved transition arrays (UTAs) in the elements Gd, Tb, and Mo. The maximum in-band EUV conversion efficiency (CE) was observed to be 0.8%, which is one of the highest values ever reported due to the reduction of the plasma expansion loss, as shown in Fig. 2 [6].

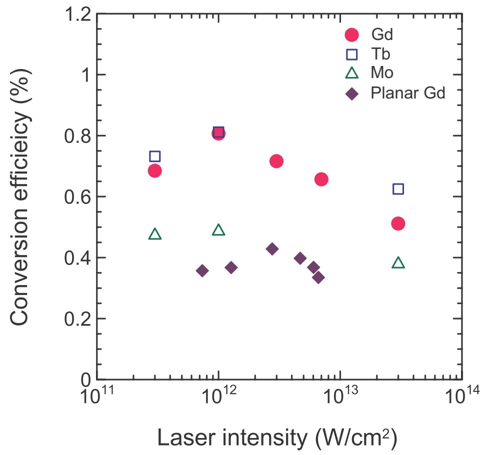

Fig. 2. Dependence of CEs on laser intensities and target elements for Gd (circles), Tb (rectangles), and Mo (triangles) with planar Gd targets (rhombuses) in Ref. [4]. The maximum CEs of 0.8% from Gd at 6.7 nm and Tb at 6.5 nm.

Acknowledgments

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