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Systematic investigation of self-absorption property and conversion efficiency of 6.7-nm extreme ultraviolet sources

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Abstract

We have demonstrated rare-earth plasma extreme ultraviolet sources at 6.7 nm to investigate the spectral behavior and the conversion efficiencies to different laser wavelength and the initial target densities. The conversion efficiency was maximized to be 0.9% at laser intensity of 7×10^{12} W/cm² at its wavelength of 1064 nm, which is attributed to the minimum self-absorption effect by use of the low initial density target, together with the narrow spectrum. It is important to use a low initial density target and to produce low electron density plasmas for efficient EUV sources using the high-Z targets.

The development of sources of extreme ultraviolet (EUV) emission with a wavelength less than 10 nm is a challenging subject in next generation semiconductor lithography toward the final stage beyond the 13.5-nm EUV source [1] and for other applications, such as material science and biological imaging near the water window. EUV emission at the relevant wavelength is coupled with a Mo/B₄C multilayer mirror with a reflective coefficient of 40% at 6.5–6.7 nm [2]. Recently one of the reflective coefficients of about 70% has also been reported numerically [3].

The rare-earth elements of gadolinium (Gd) and terbium (Tb) produce strong narrow band emission, which is attributed to a $n = 4 - n = 4$ intense unresolved transition array (UTA), around 6.7 nm. The spectral behavior of Gd and Tb plasmas is expected to be similar to that of Sn plasmas for the 13.5-nm EUV sources [4-10], because of the similar atomic structure of 4d open-shell ions [11]. Previous work on rare-earth plasma EUV sources has been focused on absorption spectroscopy by generating quasicontinuum spectra at low laser power [12,13]. The UTA emitted from these plasmas have been investigated [14]. Recently, the Nd:YAG laser-produced plasma EUV sources based on Gd and Tb has been demonstrated for high power sources [15]. According to our previous study [15], the self-absorption effect in the Gd and Tb plasmas would be large, which is supported by the laser wavelength dependence and the dual laser pulse irradiation experiments. As a result, the emitted EUV spectrum and CE are the trade-off between its generation and the self-absorption in the dense Gd and Tb plasmas are optically thick at 6–7 nm. The spectra of these resonant lines around 6.7 nm suggest that the in-band emission increases with increased plasma volume by suppressing the plasma hydrodynamic expansion loss at an electron temperature of about 50 eV. In addition to this, to increase the conversion efficiency (CE) and the spectral purity, we have proposed the use of shorter pulse duration irradiation, a low initial density target and low

electron density plasmas (such as CO₂ laser-produced plasmas and/or discharge-produced plasmas) [15]. No fundamental research, however, has been reported for 6.7-nm focused spectral behavior and its dependence on various parameters, such as the laser wavelengths and the initial density of the target. In order to access the applicability of the efficient EUV generation, detailed emission property, which is included the self-absorption effect in the Gd plasmas, has to be clarified. In the semiconductor lithography point of view, the optimization of the laser irradiation condition and target material is expected to guide source development to realize powerful practical sources with high EUV conversion efficiency (CE) from the laser energy to the EUV emission energy. It is important to study plasmas produced by solid-state lasers operating at a typical wavelength at 1 μm as in future high power and high repetition rate operation fiber lasers would be used to produce the high temperature plasmas [16].

In this letter, we report and discuss fundamental property of the EUV spectra and the CE around 6.5–6.7 nm in the Gd plasmas produced by the fundamental wavelength (1064 nm) and its harmonics radiation of 532 and 355 nm of the Nd:YAG laser. To understand the self-absorption effect in the Gd plasmas, we observed the spectral behavior and the EUV CE and explored not only the laser wavelength effect, that is the high-density effect, but also the initial density effect of the target.

A Q-switched Nd:YAG laser operating at 1064, 532, and 355 nm produced maximum pulse energies of 2000, 1000, and 320 mJ with pulse duration of 10, 8, and 7 ns (full width at half-maximum (FWHM)), respectively. The laser was perpendicularly focused on planar Gd and Tb targets with a thickness of 1 mm with a 15-cm focal length lens. The focused intensity was varied from 10^{10} to 10^{13} W/cm² with focal spot sizes of 50 μm to compare with the laser wavelength effect and to achieve high laser intensity. The laser was operated in a single shot

mode. An absolute EUV energy was measured by use of a calibrated EUV energy meter equipped with a calibrated Mo/B₄C multilayer mirror [2] and a Zr filter. All EUV CE presented here were evaluated based on the emission energy at 6.7 nm within 2% bandwidth (BW) and a solid angle of 2π sr. A flat-field grazing incidence spectrometer with 1200 grooves/mm variable line space grating was positioned at 45° with respect to the incident laser axis. The time-integrated spectra were obtained by a thermoelectrically cooled back-illuminated x-ray CCD camera. The typical spectral resolution was better than 0.02 nm.

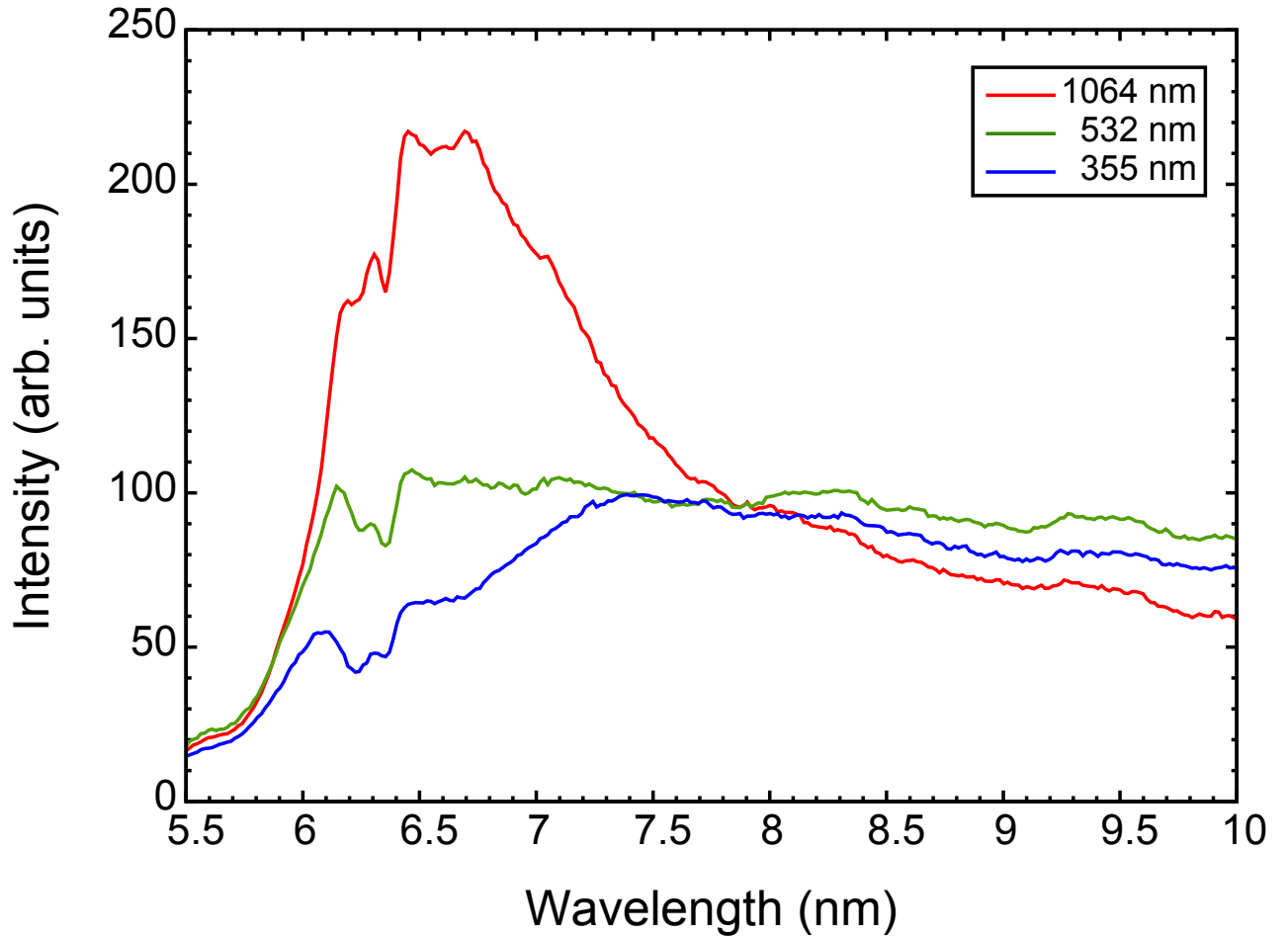


Fig 1: EUV spectra at the different laser wavelengths of 1064 (red), 532 (green), and 355 nm (blue) at same laser intensity of 1.6×10^{12} W/cm² (laser energy: 320 mJ per pulse and spot diameter: 50 μ m (FWHM)), respectively.

In order to evaluate the self-absorption effect by changing the critical electron density, i.e., the laser wavelength, we observed the EUV spectra at same laser intensity of about $1.6 \times 10^{12} \text{ W/cm}^2$ (laser energy: 320 mJ per pulse and spot diameter: 50 μm (FWHM)), as shown in Fig. 1. This laser intensity is not the optimum intensity. (This condition is used to compare with the laser wavelength effect.) It is noted that the critical electron density is related to the laser wavelength: $n_c \propto 1/\lambda^2$, where, n_c and λ are the critical electron density and the laser wavelength, respectively. The critical densities are 1×10^{21} , 4×10^{21} , and $9 \times 10^{21} \text{ cm}^{-3}$ at the laser wavelength of 1064, 532, and 355 nm, respectively. The in-band emission at 6.7 nm, which is attributed to the resonant lines, increased with the decrease of the critical laser wavelength, resulting in the maximum emission at the laser wavelength of 1064 nm. The EUV CE ratio is observed to be 4:3:2 for the laser wavelength of 1064, 532, and 355 nm. The intensity ratio between the resonant line around 6.7 nm and the satellite lines longer than 7 nm decreased for the 532-nm and 355-nm laser pulses compared to the 1064-nm pulse. Satellite emission at wavelengths longer than 7 nm, on the other hand, is increased using the 532-nm and 355-nm wavelengths. The decrease of the 6.7-nm emission is attributed to self-absorption in the denser, short-wavelength plasma [17]. This behavior is supported by the dual laser irradiation experiment to control the electron density gradient, i.e., the absorption length [7,18]. The emission intensity of the Gd plasmas at 6.7 nm has been almost constant due to the large self-absorption effect [15].) These spectra contain resonant UTA lines around 6.7 nm and many satellite emission lines at wavelengths longer than 6.7 nm in sufficiently dense plasmas. The spectral behavior is similar to that of Nd:YAG laser-produced xenon (Xe) plasmas, with resonant lines around 11 nm and satellite emission at wavelengths longer than 11 nm, especially around 13.5 nm [19,20]. Figure 2(a) shows the laser intensity dependence on the EUV CE when the laser wavelength of 1064 nm is irradiated according to maximizing

the EUV emission in Fig. 1. The EUV CE increased with the increase of the laser intensity and the EUV CE was maximized to be 0.8% at the laser intensity of $(6-8) \times 10^{12} \text{ W/cm}^2$ when the solid Gd target was used. The electron temperature is evaluated to be 120 eV at this optimum laser intensity.

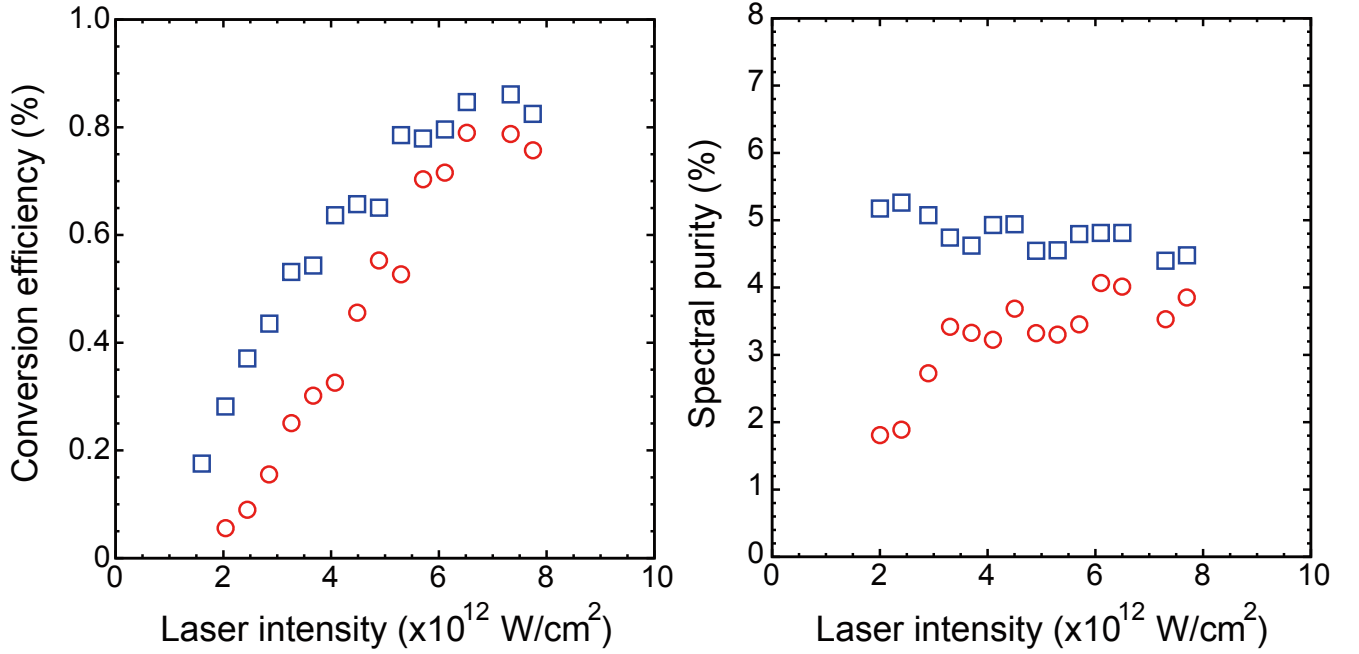


Fig 2: Laser intensity dependences on the EUV CE (a) and the spectral purity (b) by use of different target of low-density target (blue, rectangles) and the solid density target (red, circles) at the laser wavelength of 1064 nm.

In the self-absorption effect reduction point of view, it is important to study the effect of the initial density of the target. In order to increase of the spectral purity and the EUV CE, we use the low-density Gd target, such as the low-density Sn target for 13.5-nm EUV sources [7,9,21]. The laser intensity dependence on the EUV CE in Fig. 2(a) and the spectral purity in Fig. 2(b) are shown at the laser wavelength of 1064 nm and the laser spot diameter of 50 μm

by use of different targets of solid and low-density. The EUV CE was evaluated with an estimated angular distribution of 2π sr. The EUV CE increased with the increase of the incident laser intensity and reached its maximum value of 0.8% at a laser intensity of around $(6-8) \times 10^{12}$ W/cm². The EUV CE was also saturated at the laser intensity higher than $(6-8) \times 10^{12}$ W/cm², which is attributed to the widely electron temperature window to produce the related multi charged state Gd ions [15]. In the case of low-density target, the EUV CE was observed to be 0.9% (little increment) higher than that of solid target due to the reduction of the self-absorption effect in Gd plasmas. The spectral efficiency in the case of solid target within the 2% bandwidth around 6.7 nm against the spectral range from 5.5 to 10 nm increased with the increase of the laser intensity and reached to be about 4%. Its purity, on the other hand, was about 5% and almost constant over the intensity range examined and was higher than that of the use of the solid target.

Figure 3 shows the spectral comparison with the low- and the solid-density targets at different laser intensities of 4×10^{12} and 7×10^{12} W/cm², respectively. The resonant line emission is relatively higher than that of the longer wavelength due to satellite lines, which is attributed to the reduction of the self-absorption effect. It is seen that the emission intensity increased with the use of the low-density target at the laser intensity of 4×10^{12} W/cm². The spectral efficiency within the 2% bandwidth around 6.7 nm to the spectral range from 5.5 to 10 nm was observed to be 5% for the low-density target as compare with the case of the solid target of 3.5% at an intensity of 4×10^{12} W/cm². As a result, the CE is measured to be about 0.5% for the use of the low-density target. To increase the CE and the spectral purity these data suggest that it is important to use shorter pulse duration irradiation, and low electron density plasmas (such as CO₂ laser-produced plasmas or discharge-produced plasmas) [15]

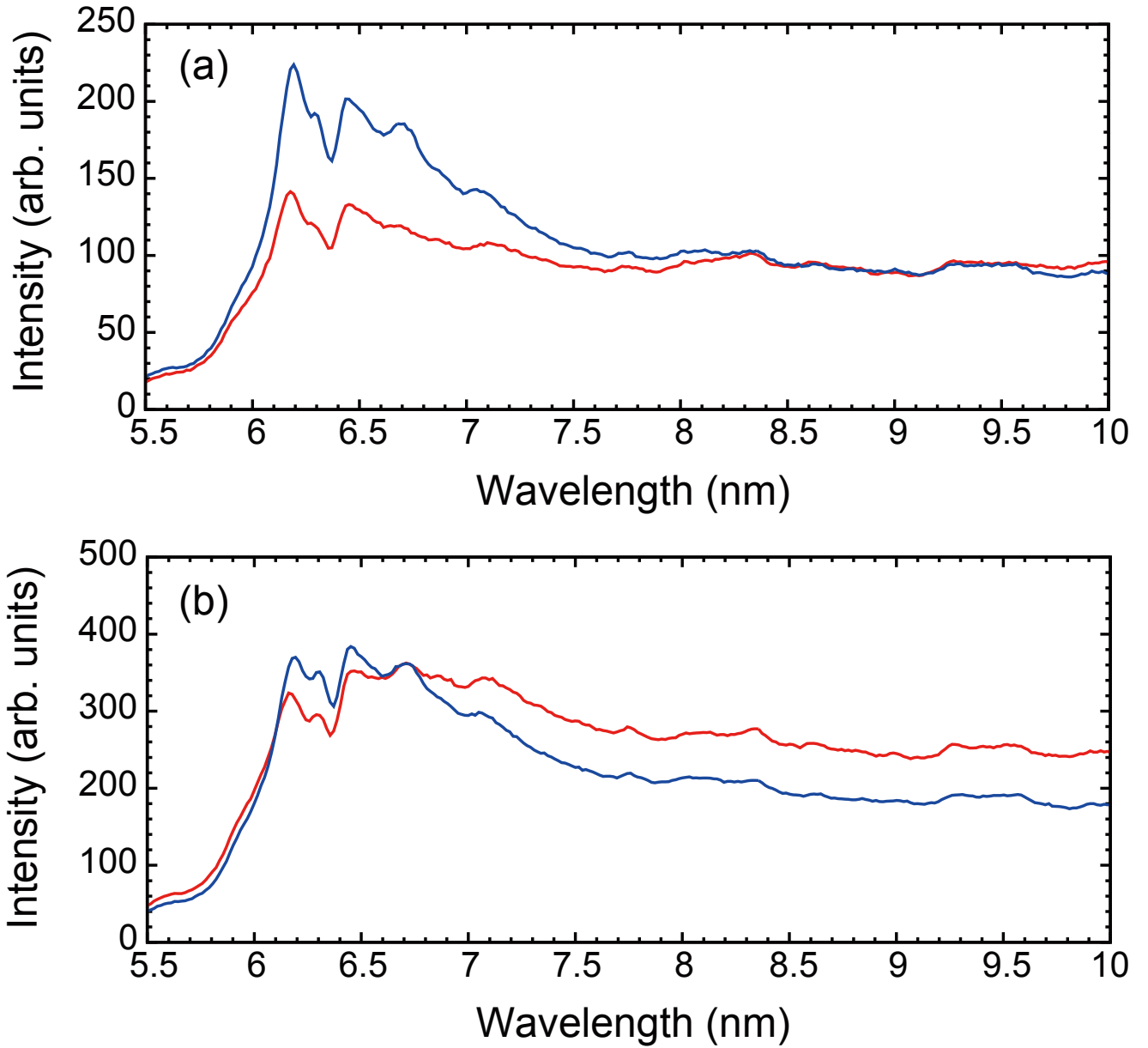


Fig 3: Spectral comparison with the low- (blue) and the solid-density target (red) at different laser intensities of 4×10^{12} (a) and $7 \times 10^{12} \text{ W/cm}^2$ (b), respectively.

In summary, we have observed the spectral behavior around 6.7 nm due to the resonant lines when different laser wavelength laser beams have been irradiated to change the critical electron densities. As the effect of the self-absorption effect of the resonant lines in

the Gd plasmas are large, it is important to produce the low density by use of long laser wavelength and/or low-initial target. The spectrum based on the low initial density target was narrower than that of the pure solid target. As a result, the maximum CE was observed to be 0.9%.

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