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Progress of high-power, UTA based EUV sources for next generation lithography and short wavelength imaging below 10 nm

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A high average power 13.5-nm engineering prototype source has been shipped to semiconductor facilities to permit commencement of high volume production at a 100W power level in 2011. In this source, UTA (unresolved transition array) emission of highly ionized Sn is optimized for high conversion efficiency and full recovery of the injected fuel is realized through ion deflection in a magnetic field. By use of a low-density target, satellite emission is suppressed and full ionization attained with short pulse CO_2 laser irradiation. Recently, the possibility of switching to an even shorter EUV wavelength of 6.X nm has been pointed out [1]. In fact, the 6.X-nm beyond EUV (BEUV) emission can be coupled with a Mo/B_4C or La/B_4C multilayer mirror whose reflectivity is currently 40% at 6.5-6.7 nm, (theoretical maximum >70%). The UTA emission exploited in Sn is scalable to shorter wavelengths, and Gd has a similar conversion efficiency to Sn, though at a higher plasma temperature, within a narrow spectral range centered near 6.7nm.

In a proof-of-principle experiment to generate shorter wavelength EUV emission, we demonstrated a source with peak emission around 6.5-6.7 nm[2,3]. The rare-earth elements gadolinium (Gd) and terbium (Tb) produce strong narrow band emission, again attributable to thousands of resonance lines which merge to yield a n=4-n=4 UTA, near 6.7 nm. The spectral behavior of Gd and Tb plasmas is largely similar to that of Sn plasmas, because 4d open-shell ions are involved in each case. Figure 1(a) shows the ion population of a Gd plasma as a function of electron temperature, calculated in the steady-state collisional-radiative (CR) regime at an electron density of 1×10^{21} cm^{-3}. In such a plasma, the 4 -4 transitions in Gd^{12+} and Gd^{25+}ions form UTAs at electron temperatures of 50 eV and 120 eV, respectively. Theoretical weighted oscillator strength spectra are presented in Figs. 1(b) and 1(c) to show the resonant emission from ions ranging from Gd^{12+} to Gd^{25+} which combine to produce the intense UTA.

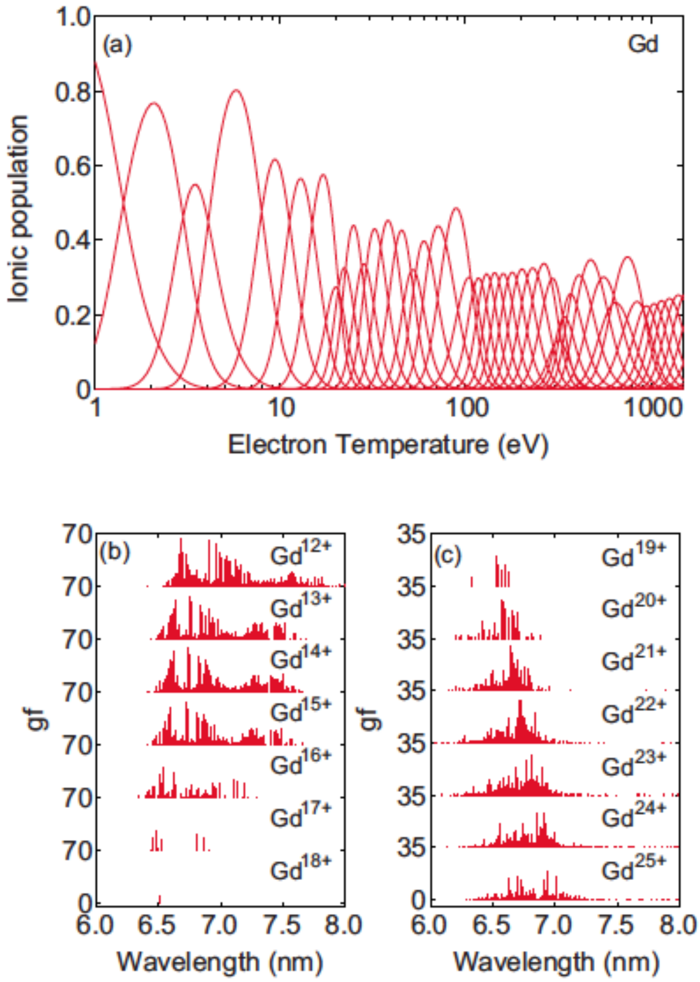

Figure 1.*Electron temperature dependence of the Gd (a) ion population according to the steady-state CR model. The weighted oscillator strength spectra of the resonant lines at for each contributing ion stage are shown in (b) and (c).*

We have also observed the variation of spectral behavior in Gd plasmas in the 6.7 nm region when different laser wavelengths were used to change the critical electron densities. The corresponding EUV CEs were observed to be 1.1%, 0.7%, and 0.5% for laser wavelengths of 1064, 532, and 355 nm. The intensity ratio of the resonant lines around 6.7 nm to the satellite emission at wavelengths longer than 7 nm decreased for the 532 and 355 nm laser pulses compared to the 1064 nm pulse. Even allowing for the presence of an underlying recombination continuum, from Fig. 2 it is seen that satellite emission at wavelengths longer than 7 nm increases with decreasing wavelength. The decrease of 6.7 nm emission can be attributed to self-absorption in the denser, short-wavelength plasma [4]. As opacity effects on the resonance lines in Gd plasmas are large, it is important to produce a low-density plasma using a long wavelength laser and/or a low-initial target concentration of Gd.

As in Sn, the spectrum obtained with the low initial density target was narrower and more intense than that of the pure solid target. As a result, the maximum CE was observed to be about 1.8% in dual Nd:YAG laser-produced, low-density plasmas with a 30% initial target density of Gd[5].

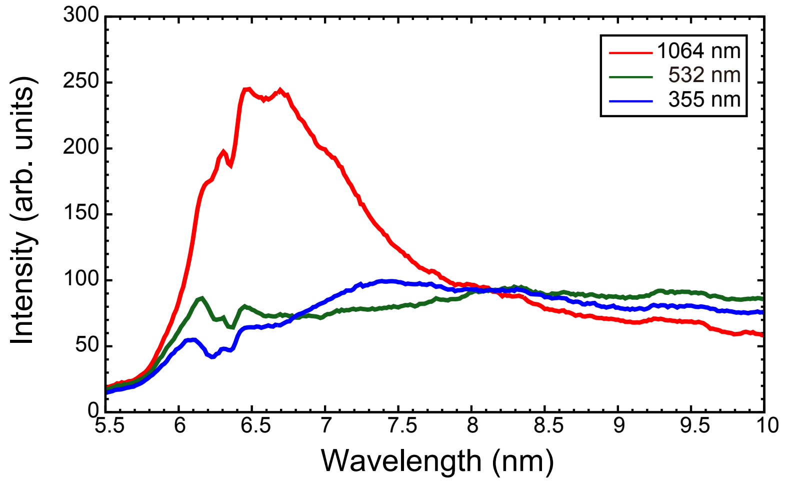

Figure 2.*EUV spectra at laser wavelengths of 1064 (red), 532 (green), and 355 nm (blue) for the same laser intensity of 1.6 x 10^{12} W/cm^2 (laser energy: 320 mJ/pulse; spot diameter: 50 micron (FWHM), respectively.*

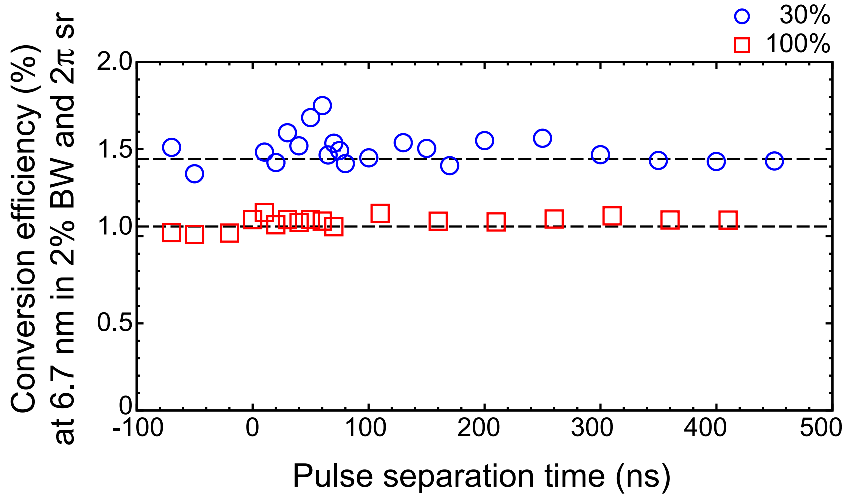

Figure 3. *Pulse separation time dependence on the EUV CE in dual laser pulse irradiation for a target containing 30% (blue, circles) or 100% Gd (red, rectangles). The dashed lines correspond the single pulse without a prepulse for 30% (blue) and 100% (red).*

Because it moves to shorter wavelength with increasing *Z*, the *n*=4–*n*=4 UTA can be used for other applications, such as transmission x-ray microscopy for biological imaging in the water window (Fig. 4). We have made preliminary studies of the potential of Bi as a BEUV source. Our calculations show that Bi plasmas, at an electron temperature in the range 570 to 600 eV, radiate strongly near 3.9 nm. We have initiated a number of experiments to explore how this emission may be optimized in practice.

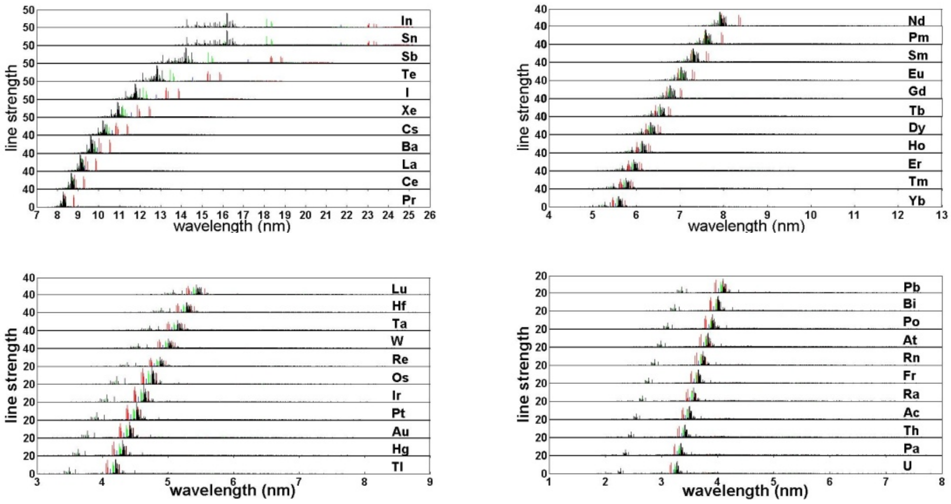

Figure 4. *Calculated position of n=4 – n = 4 transitions in key ions in elements from indium (Z= 49) to uranium (Z=92). The localization of emission near 6.7 nm in Gd and 3.9 nm in Bi is clearly evident.*

In summary, we have observed the spectral behavior and measured the EUV CE around 6.7 nm for shorter wavelength EUV emission. As the effects of self-absorption on the strongest resonance lines in the Gd UTA are large, it is important to produce a low-density plasma. The highest conversion efficiency in this spectral region was observed to be 1.8%. To increase the CE and the spectral purity, it is important to produce low-density plasmas such as CO_2laser-produced plasmas.

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