

## Theoretical EUV Spectrum of Near Pd-like Xe

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The EUV spectrum of multiple charged Xe ion is theoretically investigated. The strong emission in the 11 nm band is attributed to 4d-4f transitions of  $Xe^{7+}$  to  $Xe^{18+}$ . The 4d-5p transition of  $Xe^{10+}$  contributes to the emission in the 13.5 nm band from low density plasma.

### Keywords:

EUV, spectroscopy, atomic process, laser produced plasma, Xe

The extreme ultraviolet light source (EUVL) is being studied intensively toward its application in semiconductor technology [1]. Use of Mo/Si multilayer optics requires that the EUVL should produce emission at the 13.5 nm band with high efficiency (> 1%).

Xe plasma has been considered as promising candidate, however, strong emission is usually obtained in the 11 nm band. The property of the spectrum should be understood to increase emission in the 13.5 nm band.

The atomic structure of Xe ions is investigated using the HULLAC code [2]. Figure 1 shows the schematic level diagram of  $Xe^{9+}$ , as representative of ions from  $Xe^{8+}$  to  $Xe^{15+}$ , which have a similar level structure, with a ground configuration of  $4d^n$ . Each box in the figure indicates the configuration's averaged state with its location and height corresponding to the averaged energy and width over the fine structure levels which belong to each configuration.

The first group of excited states consists of configurations for which one electron is excited out of 4d subshell to form  $4d^{n-1}nl$ . The second group consists of those out of inner subshell, 4p, to form  $4p^5 4d^n nl$ . In the case of Xe ions, the excitation energy between  $n = 4$  and 5 shell is comparable to  $l$ -changing excitation energy within  $n = 4$  shell. Therefore, emission lines in the transition array  $4d^{n-1}4f - 4d^n$ ,  $4p^5 4d^{n+1} - 4p^6 4d^n$ , and  $4d^{n-1}5p - 4d^n$  overlap each other in the wavelength region from 10 to 18 nm.

Figure 2 shows the calculated EUV emission

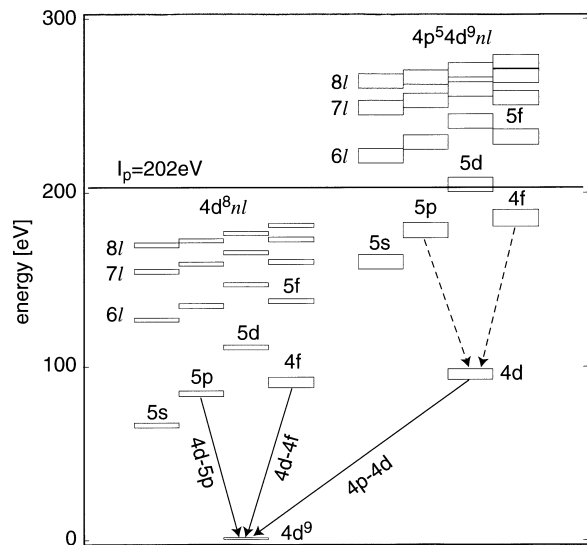


Fig. 1 Schematic level diagram of  $Xe^{9+}$ .

spectrum using the whiam code [3]. Firstly, the ion abundance for the ionization equilibrium is calculated including  $4d^{10}5snl$ ,  $4d^{10}5pnl$ ,  $4d^{10}4fnl$  of  $Xe^{6+}$ ,  $4d^{10}nl$ ,  $4d^9 5snl$ ,  $4d^9 5pnl$ , and  $4d^9 4fnl$  of  $Xe^{7+}$ , and the ground state  $4d^n$  and the excited configurations of  $4d^{n-1}nl$  and  $4p^5 4d^n nl$  of  $Xe^{i+}$  ( $8 \leq i \leq 12$ ), for  $n \leq 8$  and  $l \leq 3$ , into the collisional radiative (CR) model, based on averaged energy and rates. In particular, for  $n \geq 7$ , configurations with the same principal quantum number of excited

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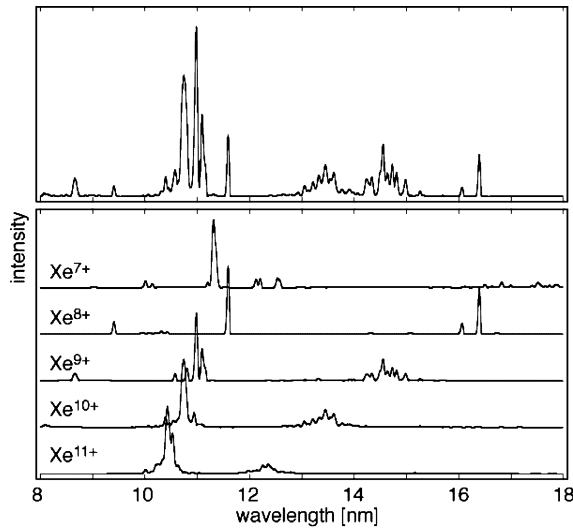


Fig. 2 Calculated spectrum of Xe<sup>7+</sup> to Xe<sup>11+</sup>, and synthetic spectrum of Xe plasma at  $T_e = 22$  eV, and  $n_i = 3 \times 10^{17}/\text{cm}^3$ .

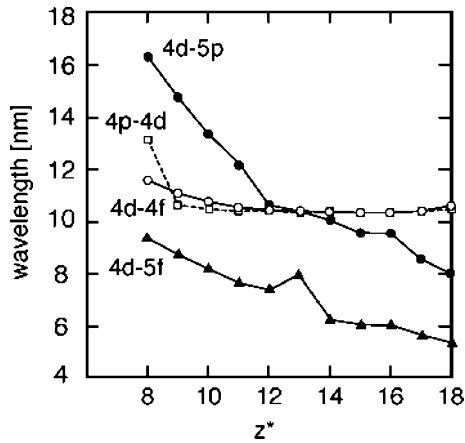


Fig. 3 Dependence of configuration averaged energy of 4d-4f, 4p-4d, 4d-5p, and 4d-5f transitions on charge state.

electrons are averaged. The abundance of Xe<sup>7+</sup> to Xe<sup>11+</sup> at  $T_e = 22$  eV and  $n_i = 3 \times 10^{17}/\text{cm}^3$  is calculated to be 0.003, 0.12, 0.45, 0.42, and 0.01, respectively.

Secondly, the population of detailed levels as well as the intensity of emission lines are calculated using the CR models for each charge state as shown in the lower plots of Fig. 2. The intensity is normalized for each charge state. The width of each emission line is assumed to be 0.02 nm. The total emission spectrum in the upper plot of Fig. 2 is calculated by taking summation of the emission multiplied by the abundance for each charge

state.

The emission from Xe<sup>8+</sup> consists of 3 predominant lines, from 4d<sup>9</sup>4f(5/2, 7/2)  $J = 1$ , and 4d<sup>9</sup>5p(2/3, 2/3)  $J = 1$ , 4d<sup>9</sup>5p(2/3, 1/2)  $J = 1$  to the ground state, at 11.6, 16.0, and 16.4 nm, respectively [4]. On the other hand, the emission of Xe<sup>7+</sup> and Xe<sup>9-11+</sup> consists of a large number of lines. In the 11 nm band, the peaks originating from the 4d-4f transition of Xe<sup>7+</sup> to Xe<sup>11+</sup> can be identified [5].

Dependence of wavelength on the charge state of each transition is shown in Fig. 3. The wavelengths of 4d-4f arrays are near 11 nm over Xe<sup>8+</sup> to Xe<sup>18+</sup>, which decrease slightly from Xe<sup>8+</sup> to Xe<sup>12+</sup>. In contrast, the wavelength of 4d-5p transition shifts toward the shorter wavelength from 16 nm for Xe<sup>8+</sup> to 8 nm for Xe<sup>18+</sup>. Peaks corresponding to 4d-5f and 4d-6p transitions also appear in the blue side of the 11 nm band. Peaks from the 4p-4d transition and 4d-5p of Xe<sup>12-14+</sup> cannot be identified.

From Figs. 2 and 3, one may see that only the 4d-5p transition of Xe<sup>10+</sup> contributes to the 13.5 nm band. This suggests that Xe<sup>10+</sup> should be selectively populated.

Furthermore, the plasma condition should be determined to produce stronger emission in the 4d-5p array rather than 4d-4f, even the latter has a greater radiative rate. For example, the intensity ratio between 4d-4f and 4d-5p transitions of Xe<sup>8+</sup> can be estimated based on the radiative rates of  $1.57 \times 10^{12}/\text{s}$  (4d<sup>9</sup>4f(5/2, 7/2)  $J = 1$ ) and  $8.17 \times 10^{10}/\text{s}$  (4d<sup>9</sup>5p(2/3, 1/2)  $J = 1$ ). Assuming a Boltzmann distribution of the population, the ratio is 4.5 at 22 eV. The calculated ratio is 1.5 in Fig. 2, which suggests the departure of the population of 4d<sup>9</sup>4f from LTE due to fast radiative decay. This implies that also in the case of Xe<sup>10+</sup>, the temperature and density of the plasma should be low to reduce population of the 4d<sup>7</sup>4f state in order to increase the intensity of the 4d-5p array in the 13.5 nm band.

The present analysis will apply the experimental spectrum from low density discharge pumped plasmas. On the other hand, further investigation may be needed regarding the spectrum from laser produced plasma in which the peak of 4d-4f transition is accompanied by broad red wing [1].

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