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Theoretical RCI Simulation for Spectra Emitted from Sn and Xe Ions as an EUV Light Source

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Abstract

Using the relativistic configuration-interaction (RCI) atomic structure code developed by Kagawa, we have carried out simulations for spectra emitted from Sn^{9+} up to Sn^{14+} ions and Xe^{8+} up to Xe^{13+} ions in the extreme ultra-violet (EUV) wavelength range including 13.5 nm. In the present simulation, large intensity around the 13.5 nm wavelength region in the spectra from Sn^{10+}, Sn^{11+} and Sn^{12+} is observed. However simulated spectra from Xe ions do not necessarily predict large intensity at wavelengths near 13.5 nm.

Keywords:

atomic spectrum, relativistic effect, atomic structure, EUV spectrum, highly-charged ion

1. Introduction

The EUV emission from Sn and Xe in the wavelength region near 13.5 nm have attracted considerable attention in developing extreme ultra-violet (EUV) light sources for next-generation lithography machines. Nishihara *et al*. [1] have observed EUV spectra from laser-pumped (LP) Sn plasmas. Their experimental spectra consist of a broad peak spread over a wide range of wavelengths including 13.5 nm in which 4d-4f transitions in Sn ions play a major role in the emission processes. Recently Sasaki *et al*. [2] have made a theoretical analysis for the experimental EUV spectra emitted from Xe plasmas produced by a discharge or irradiation with a high power laser using the HULLAC code. As the spectral shape in Xe spectra observed in a discharge experiment [3,4] is quite different from that observed in a LP experiment [5], further detailed analysis of the spectra is needed with an appropriate plasma model. In particular, accurate atomic structure data for the ions are needed to obtain reliable theoretical analysis of the spectra observed.

In this work we focus on theoretical simulations for spectra from Sn and Xe ions with different charge states. Here we use the RCI atomic structure code developed by Kagawa [6-9]. We perform simulation for the spectra from Sn ions with charge states from 9+ through 14+ and Xe ions from 8+ through 13+ in the EUV wavelength range including 13.5 nm. Comparison between these simulated spectra and experiment is made to obtain the optimum experimental plasma conditions for EUV source development for lithography.

2. Method of calculation

Based on the RCI theory with finite-basis-function expansion method, Kagawa has implemented a general computer code to calculate various physical quantities in atomic systems such as energy levels, optical transition probabilities, electron scattering cross sections and so on. In the RCI calculation, Slater-type functions (STF's) are used to construct Dirac-Fock (DF) orbitals which form a set of one-electron basis functions. These DF orbitals are used to construct configuration state functions (CSF's) in the CI calculation. Energy corrections due to the Breit interaction and QED effects are calculated using first-order perturbation theory. In the simulation for spectra from ions it is assumed that each ion is embedded in a LTE plasma. In this case, the population in each excited level is calculated by assuming the Boltzmann distribution for excited levels in a system. So the intensity of an individual line is obtained as a product of a weighted transition probability gA and the population of an upper level for the transition under consideration.

3. Results and discussion

RCI calculations for transition energies and line in-

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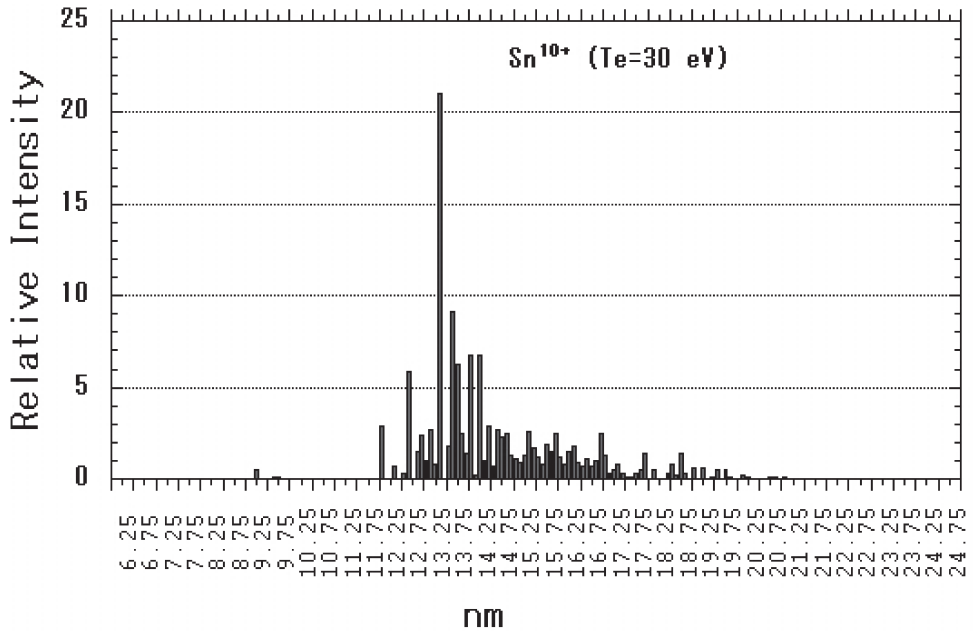

Fig. 1 RCI simulated EUV spectra from Sn^{10+} with $T_e = 30$ eV.

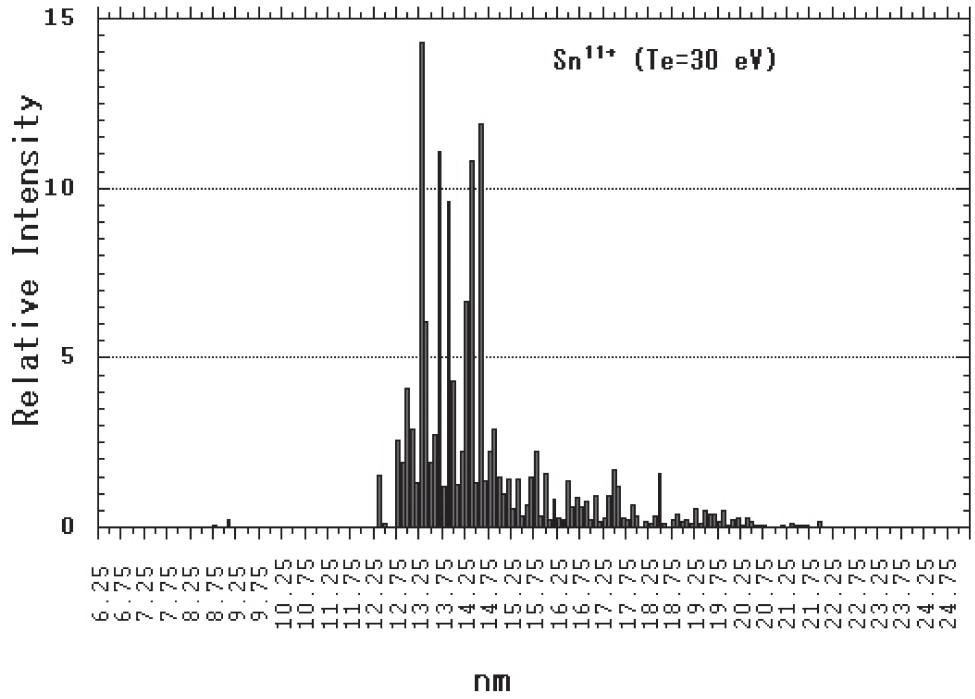

Fig. 2 RCI simulated EUV spectra from Sn^{11+}.

tensities for emission spectra from Sn^{8+} up to Sn^{13+} have been carried out by assuming a 30 eV electron temperature in Sn plasmas [1]. In Figs. 1, 2 and 3, RCI simulated spectra for Sn^{10+}, Sn^{11+} and Sn^{12+} are shown. In obtaining the simulated spectra for a particular ion, the wavelength range is divided into narrow intervals of 0.5 nm and the line intensity for each wavelength interval is then obtained as a sum of line intensities for the transitions whose wavelengths are included in this interval. It is found from the simulation that strong lines near 13.5 nm are mainly emitted from Sn^{10+}, Sn^{11+} and Sn^{12+} ions. The strong lines from Sn^{9+} are shifted to the long wavelength side of 13.5 nm, whereas those from Sn^{13+} are shifted to the shorter wavelength side. This suggests that the observed strong broad band around the 13.5 nm region in the Sn spectra by Nishihara et. al. is due primarily to emission from Sn^{10+}, Sn^{11+} and Sn^{12+} : More Sn^{10+}, Sn^{11+} and Sn^{12+} ions are contained in the LP plasma compared to ions with different charge states. We also compare the RCI simulated spectrum for Sn^{12+} with that obtained with the MR-RCI calculation by Koc [10]. It is found from the comparison between the two

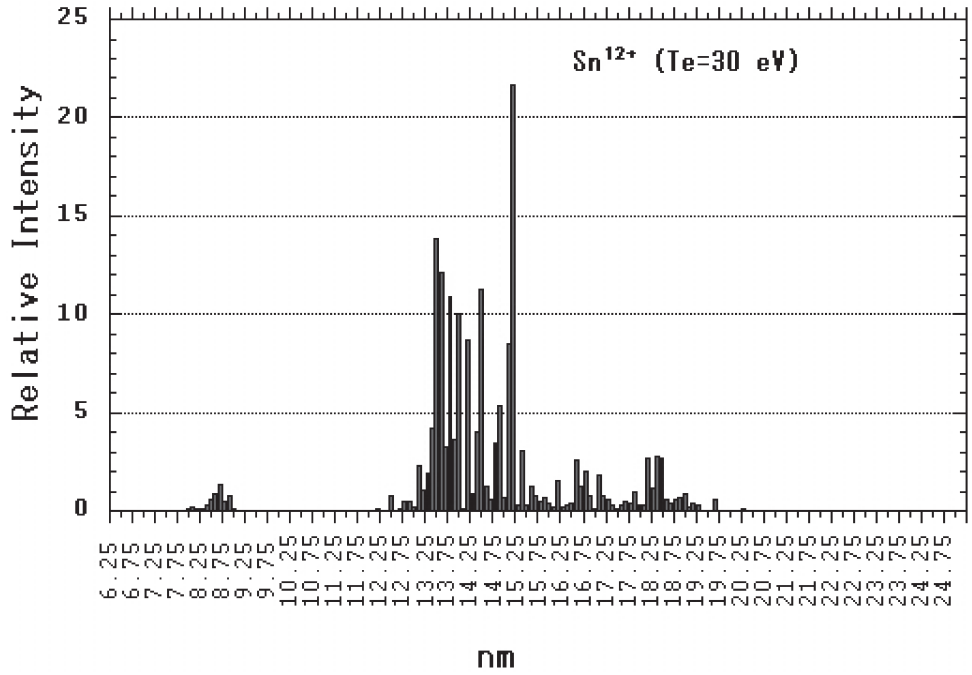

Fig. 3 RCI simulated EUV spectra from Sn^{12+}.

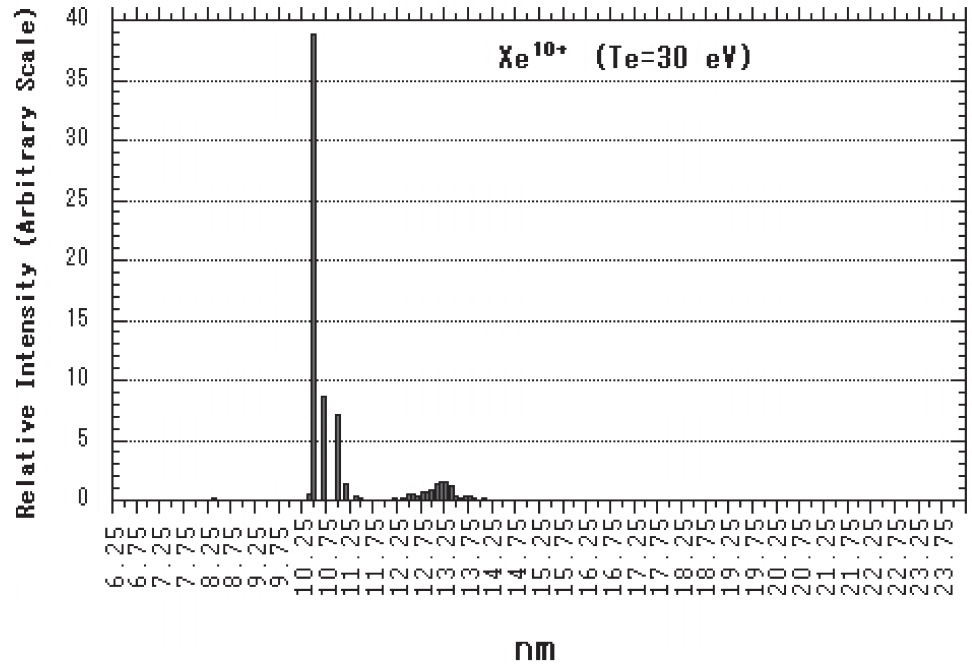

Fig. 4 RCI simulated EUV spectra from Xe^{10+}.

RCI calculations that the overall spectral pattern is almost the same between the two methods. However, the latter spectrum is shifted to the shorter wavelength side about 1 nm compared to the former one. This means that theoretical simulation of the spectra with the RCI method is strongly dependent on the CSF's used.

On the other hand, no strong lines near 13.5 nm were found in the simulation for all Xe ions considered here. Fig. 4 shows a simulated spectrum for Xe^{10+}. We have compared our simulated spectrum of Xe^{10+} near 13 nm wavelength region with corresponding spectra observed in the charge-exchange experiment by Tanuma *et al.* [11]. It is found that the spectral shape near the 13 nm region obtained with the simulation agrees well with experiment. However, the strong resonance lines around 10 nm seen in Fig. 4 have not been observed in their experiment. So more detailed analysis for the spectra from ions produced under different experimental conditions is needed to interpret the change of spectral shape of the spectra observed.

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