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To cite this article: H Ohashi *et al* 2009 *J. Phys.: Conf. Ser.* **163** 012071

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Complementary spectroscopy of tin ions using ion and electron beams

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Abstract. Extreme ultra-violet (EUV) emission spectra of multiply charged tin ions were measured in the wavelength range of 10–22 nm following charge exchange collisions of Sn^{q+} ($q = 15\text{--}21$) ions with rare gas targets at 20 keV/ q or the electron impact excitation of tin ions with electron energy of 312–613 eV. In charge exchange collisions, we observed both the resonance lines and the emission lines corresponding to the transitions between the excited states. On the other hand, we observed mainly the resonance lines in the electron impact experiments. We can distinguish the resonance lines from other emission lines in the charge exchange spectrum by comparison with the emission lines in the electron impact spectrum. The comparison of the complementary experimental results can be regarded as a new method of spectroscopy of multiply charged ions.

1. Introduction

Tin plasmas have been studied not only by experimental investigations but also theoretical calculations as a candidate for a powerful light source for next generation semiconductor lithography [1, 2]. This technology requires light with a wavelength around 13.5 nm in the EUV region because a Mo/Si multi-layer coated mirror has a maximum reflectivity at this wavelength. Various kinds of plasma, e.g. capillary discharge and vacuum spark, were studied for the experimental spectroscopy of multiply charged tin ions because tin plasmas have a favorable emission around 13.5 nm [3, 4]. These plasmas, however, usually contain various charge states of tin ions [5]. Although there are some reported emission spectra of several ions for individual charge states around 13.5 nm [6, 7], more spectroscopic data of tin ions are necessary to diagnose and to understand tin plasmas.

An EBIT (electron beam ion trap) is a powerful device to produce highly-ionized atoms by electron impact [8]. We can estimate the highest charge state in the EBIT from the electron beam energy and the ionization potentials of the ions for each charge state in the EBIT. Most emission from the EBIT can be considered as the resonance lines. In charge exchange collisions, the excited states of the ion are determined by the charge state of the ion, the ionization energy

of the target atom and the collision energy [9]. In general, emission from excited states produced via charge exchange collisions is considered as due to both resonance lines and emission lines corresponding to transitions between excited states in charge exchange collisions.

In this study, we measured EUV emission from excited tin ions via both charge exchange collisions and electron impact to provide fundamental spectroscopic data and some information about the charge transfer processes of tin ions.

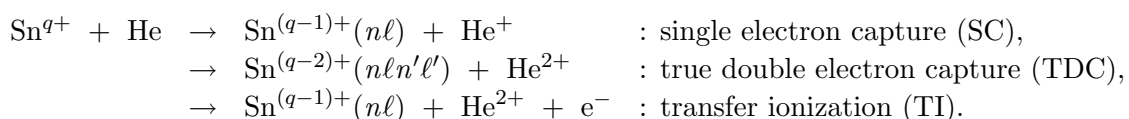
2. Experiment

In the charge exchange spectroscopy (CXS), multiply charged tin ions were produced in a 14.25 GHz ECR (electron cyclotron resonance) ion source at Tokyo Metropolitan University [10]. We inserted a rod of sintered tin oxide (SnO_2) in a plasma chamber and introduced O_2 gas to a pressure of about 1×10^{-5} Pa as a support gas for the plasma. The Sn^{q+} ($q = 15\text{--}21$) ions were extracted with an electric potential of 20 kV and selected by a 110° double-focusing dipole magnet according to their mass-to-charge ratios. The ion-beam was directed into a collision chamber, where it intersected an effusive beam of target gas ejected from a multi-capillary plate. The background pressure in the collision chamber was 6×10^{-6} Pa and the target gas pressure in the chamber was held at about 1×10^{-3} Pa during the measurements. In this setup, we could not directly measure the target gas density in the collision volume. The target gas pressure, however, was low enough to maintain single-collision conditions. The primary ion-beam, which had about 6 mm diameter, had a typical electrical current of $0.03\text{--}0.15$ μA as measured by a Faraday cup located behind the collision region. Optical radiation in the EUV region from the collision volume was observed at 90° to the ion-beam direction with a compact flat-field grazing-incidence spectrometer (SSK-260, Shin Seiki Co.) equipped with a toroidal-type converging mirror and a variable line space (ca. 1200 lines/mm) grating blazed at 100 nm. A liquid nitrogen cooled CCD (charge coupled device) camera (C4880, Hamamatsu) was installed in the EUV spectrometer. Emissions in a 18 nm range of wavelengths were observed and accumulated simultaneously. A slit width of 200 μm between the converging mirror and the grating gave the wavelength resolution of about 0.03 nm. The calibration of the wavelength was performed by observing more than 20 lines of O VI and O VII in collisions of O^{6+} and O^{7+} with Xe gas. The uncertainty of the observed wavelength was estimated at 0.02 nm.

In the electron impact experiment, highly charged tin ions were produced by the Tokyo EBIT at the University of Electro-Communications [11]. A Knudsen cell with metallic tin was placed horizontally at the center level of the drift tube of the EBIT [12, 13]. Tin vapour was produced in the cell and was introduced to the drift tube. Electron energies between 312 and 693 eV were applied, an extremely low energy for this device as it was designed to operate at energies of up to 300 kV, and the electron beam currents were between 2.2 and 6.4 mA. The optical radiation from the ion trap region was observed at 90° to the electron beam direction with the same detection setup which was used in the CXS.

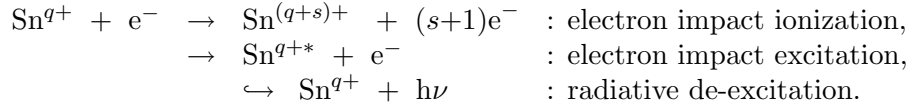
3. Results and Discussion

In low energy collisions of Sn^{q+} with He, the following processes take place:



Emission from $\text{Sn}^{(q-1)+}$ and $\text{Sn}^{(q-2)+}$, therefore, must be considered. In slow collisions of multiply charged ions with He, generally speaking, SC is the dominant process and TI has a significant contribution, while TDC has very small cross section, as observed in Xe^{q+} ($q = 10\text{--}43$), Ar^{q+} ($q = 8\text{--}16$) and other multiply charged ions [14, 15, 16, 17]. Therefore, we can assume that

the final charge states in the product Sn ions are $(q-1)+$ in collisions of Sn^{q+} ions with He. On the other hand, in the EBIT under our experimental conditions, the following processes take place dominantly:



The distributions of both the charge states and the excited states depend on the electron beam energy. The highest charge state can be estimated by the ionization energies of tin ions, which had been obtained with SCF (self-consistent field) calculations [18]. Most of the radiation from the ions can be assumed to be due to resonance lines, not to transitions between excited states.

Figure 1 shows the EUV emission spectra in which we consider that most emissions come from the same charge state. Figure 1(a) shows the observed emission spectra in collisions of Sn^{15+} with He and in the EBIT with an electron beam energy of 312 eV. Both of the spectra have a strong emission line at 13.3 nm, and we consider it to be a resonance line of Sn^{14+} . We also consider that the emissions between 13.5 to 14.3 nm are satellite lines corresponding to the 4d-4f transitions by comparison with the theoretical calculations [19]. Since the $4d^{k-1}n\ell$ configuration has quite a number of fine-structure levels, the 4d- $n\ell$ transitions make a band-like emission, which is called an UTA (unresolved transition array). In figure 1(b), some narrow

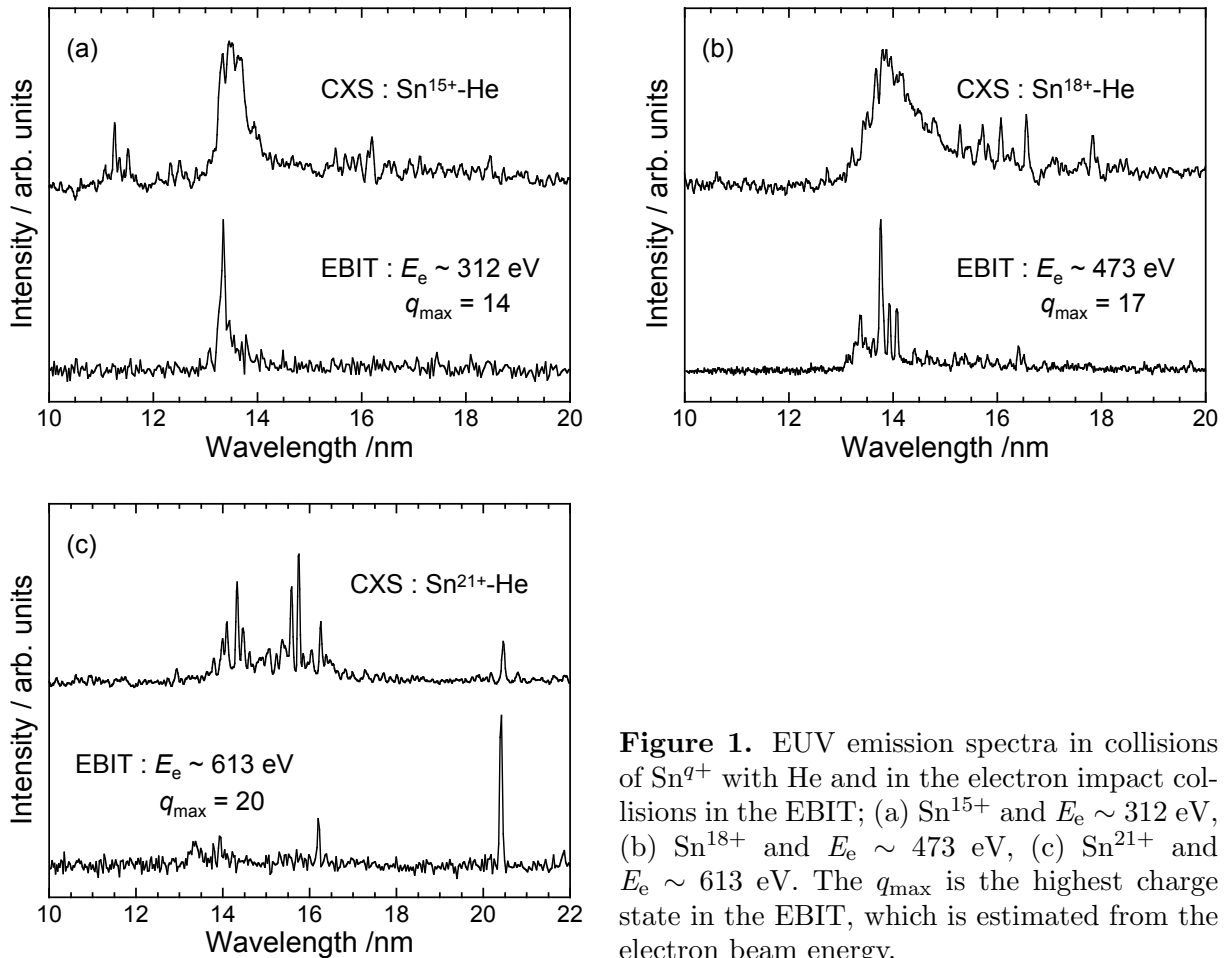


Figure 1. EUV emission spectra in collisions of Sn^{q+} with He and in the electron impact collisions in the EBIT; (a) Sn^{15+} and $E_e \sim 312$ eV, (b) Sn^{18+} and $E_e \sim 473$ eV, (c) Sn^{21+} and $E_e \sim 613$ eV. The q_{max} is the highest charge state in the EBIT, which is estimated from the electron beam energy.

emission lines were observed in the EBIT spectrum, and are regarded as the resonance lines of Sn^{17+} . These lines were also observed as a part of the UTA in the CXS spectrum. In figure 1(c), the EBIT spectrum has strong emission lines at 16.2 and 20.4 nm. Although the CXS spectrum also has those two lines, we considered only the line at 20.4 nm to be a resonance line of Sn^{20+} . Most ions in the EBIT are estimated as Sn^{20+} , but the EBIT also traps some ions with other charge states. The emission line at 16.2 nm is considered as the emission from Sn^{19+} by comparison with a calculation using the FAC (flexible atomic code). We can assume that double electron capture occurs in collisions of Sn^{21+} with He. More stronger emission lines between 13.8 and 15.8 nm were observed in the CXS spectrum. We consider that emission lines are correspond to cascade transitions which are considered as the 4d-4f transitions.

Although we cannot identify many emission lines in the CXS spectra, we can distinguish the resonance lines from other emission lines by comparison with the EBIT spectra. This complementary research using the different experimental methods is an effective way to study the spectroscopic properties of multiply charged ions.

Acknowledgments

This work was financially supported in part by MEXT (Ministry of Education, Culture, Sports, Science, and Technology, Japan) under construct subject "Leading Project for EUV lithography source development". Part of this work was performed under the collaboration program of the Institute of Laser Engineering, Osaka University.

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