Activities at the Tokyo-EBIT 2005

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Abstract. A report is given on recent activities at the Tokyo-EBIT (electron beam ion trap), which include mainly two subjects; (1) interaction of highly charged ions with surface, and (2) electron - highly charged ion collisions. For the former subject, highly charged ions extracted from the EBIT are used to impact samples, such as H-terminated Si. Incident charge dependence of sputtering ion yield is measured by means of time-of-flight secondary ion mass spectrometry (TOF-SIMS). For the latter subject, we have constructed the second beam line for extracted highly charged ions, where ions with several charge states are monitored at the same time with a position sensitive detector. From the electron beam energy dependence of the charge state distribution at the equilibrium, resonant processes, such as dielectronic recombination and resonant excitation double autoionization, are studied.

1. Introduction
The Tokyo-EBIT [1, 2] was constructed in 1997 at the Institute for Laser Science, University of Electro-Communications. Using this device, physics of highly charged ions (HCIs) has been studied intensively up to now. The main subject of the Tokyo-EBIT project in a period of 1997-2002 was atomic physics of trapped HCIs, including spectroscopy in the visible and X-ray range and the collision processes with electrons. After that, we built and arranged a beam line for the HCIs extracted from the EBIT. Using the extracted beam, HCI-surface collision experiments are currently ongoing as well as atomic physics experiments. In this report, we report the present status of the Tokyo-EBIT and the recent progress in the above experiments.

2. Present status of the Tokyo-EBIT
The maximum electron beam energy and current achieved so far is 200 keV and 330 mA, respectively. However, because the recent main subject is the study of HCI - surface collision processes, in which the required charge state is not so high, the typical parameters in recent operation are 10-70 keV in energy, 0-200 mA in current and 3-4 T in the central magnetic field. With these parameters, typical extracted ion number is ∼ 3 × 10⁵ cps for He-like Ar¹⁸⁺, ∼ 2 × 10⁵ cps for Ne-like Xe⁴⁴⁺ and ∼ 10² cps for bare I⁵³⁺ with a beam size of 1 mm².
Along the HCI beam line [3], there are two equipments for HCI-surface collisions: a scanning probe microscope (SPM) and time-of-flight secondary ion mass spectrometer (TOF-SIMS). In order to extend the experimental subject, recently we built a new HCI beam line. An electrostatic bender is used for switching the HCI beam into the first or the second beam line. The second beam line is currently used for the atomic physics experiments such as electron-HCI collisions, which are described in Sec. 4.

3. HCI-surface collisions

In the collisions of slow HCl ions, potential energy contributes to sputter processes as large as kinetic energy does. Such process is called “potential sputtering” and reveals interesting phenomena different from kinetic sputtering. For example, Fig. 1 shows the sputtering ion spectra from H-terminated Si for Xe\(^{50+}\) impacts. The peak of proton appears predominantly, accompanying that of H\(^{+}\) with the intensity of about one tenth. Other small peaks were assigned as shown in the figure, H\(^{3+}\), singly and multiply charged silicon, oxidized or hydroxidized silicon and silicon dimers were identified.

![Figure 1. TOF spectrum of secondary ions from Si(111) 1 × 1-H surface irradiated with Xe\(^{50+}\).](image)

Specific features in the present investigation as compared to those with the lower charged states \((q \leq 12)\) of HCl ions [4] are; (a): The ratio of H\(^+\) to Si\(^+\) becomes much larger, which indicates stronger \(q\) dependence for the proton sputtering yield. (b): Multiply charged Si ions are detected with non-negligible intensities. This seems to be caused partly by the kinetic sputtering with much higher kinetic energy of projectiles \((E_k = 175\) keV\) in this work compared to the previous one \((E_k = 2 \sim 5\) keV\) [4]. It was reported [5] that even singly charged nitrogen ions with 30 keV kinetic energy can sputter Si\(^n+\). (c): The carbon peak appears, although the carbon was not detected in the Auger electron spectroscopy measurement for the same sample. This suggests a possibility of application of HCI-SIMS with higher \(q\) to a highly sensitive analysis for the surface elements.

We have measured the \(q\)-dependence of the sputtering yield, and found that the absolute yield of H\(^+\) is grater than one for Xe\(^{50+}\) \((q \geq 44)\) irradiation. This suggests a single HCI impact produces one impact site on the naked Si surface by removing covered H atoms. Borsoni et al. [6] proposed the following HCI-based nanoprocessing on silicon surfaces. HCI-bombardment to a Si-H surface creates nanometer-sized active regions due to removing protons. Through reactions of oxygen gas with this region, nano-SiO\(_2\) layers can be produced. However, since the proton-sputtering yields by HCl ions with lower \(q\) such as Ar\(^{8+}\) are estimated to be \(10^{-3}\) /incident ion, there is very low probability of removing protons from the surface by such a HCI impact.
On the other hand, a HCI with very high q displays great ability to process a surface in nanoscale, as follows. One HCI impact on a substrate can be monitored by secondary electrons with the 100 % detection efficiency [7]. By using such a higher q-HCI, it would be possible to create one by one single nano-active naked region without hydrogens on the Si surface. Moreover, the impact position and the space might be controllable with the sequential detection of secondary electrons.

4. Resonant processes in electron-HCI collisions

An EBIT is suitable for studying collision processes of HCIs with electrons. In an EBIT, a monoenergetic and unidirectional electron beam is interacting with the trapped HCIs. By observing X-ray spectra or charge state distributions with controlling the electron beam energy, one can investigate various electron-HCI collision processes, such as excitation, ionization, radiative recombination (RR), dielectronic recombination (DR), and so on.

At the charge equilibrium, the number ratio between adjacent ions can be expressed in terms of cross sections for related e-HCI collision processes,

\[ \frac{n_{q-1}}{n_q} = \frac{\sigma_{\text{q}^\text{re}} + \langle \sigma_{\text{q}^\text{CX}} \rangle}{\sigma_{\text{q}^\text{ion}}}, \]

where \( \sigma_{\text{q}^\text{re}} \) is the recombination cross section for \( q \rightarrow q-1 \), \( \sigma_{\text{q}^\text{ion}} \) the EI cross section for \( q-1 \rightarrow q \), and \( \langle \sigma_{\text{q}^\text{CX}} \rangle \) the effective charge exchange cross section [8]. When there is no resonant process, ratio \( n_{q-1}/n_q \) varies slowly with electron energy. Since \( \langle \sigma_{\text{q}^\text{CX}} \rangle \) can be excluded by observing gas pressure dependence and by extrapolating it to 0, \( \sigma_{\text{q}^\text{ion}} \) can be obtained by normalizing \( \sigma_{\text{q}^\text{re}} \) to a reliable theoretical value for RR cross section. When certain resonant process exists, the ratio \( n_{q-1}/n_q \) shows strong and sharp electron energy dependence. For example, at the electron beam energy at which DR is available, \( \sigma_{\text{q}^\text{re}} \) can be represented as the sum of two components, \( \sigma_{\text{q}^\text{RR}} \) and \( \sigma_{\text{q}^\text{DR}} \), and the ratio \( n_{q-1}/n_q \) is thus enhanced. Since the amount enhanced corresponds to the ratio \( \sigma_{\text{q}^\text{DR}}/\sigma_{\text{q}^\text{ion}} \), \( \sigma_{\text{q}^\text{DR}} \) can be obtained by using the experimentally obtained ionization cross section \( \sigma_{\text{q}^\text{ion}} \). Figure 2 shows the electron energy dependence of the number ratio between adjacent charge states of highly charged iodine ions extracted from the Tokyo-EBIT. Lots of structures which correspond to KLL DR processes can be found.

In the figure, X-ray counts for the K-line are also plotted. Because it is practically difficult to resolve the charge state by the K X-ray energy with an ordinary Ge detector, contributions from the DR of several charge state are superimposed. On the other hand, the charge state has been clearly resolved for the extracted ions, so that DR for each charge state can be deduced. In order to determine the cross section, contribution from the escape and the double charge exchange can be treated carefully, and the analysis is on going.

Not only DR but also resonant ionization, e.g. resonant excitation double autoionization (REDA), can also make sharp electron energy dependence of the ion number ratio. Figure 3 shows the intensity ratio of extracted He-like I\(^{51+} \) and Li-like I\(^{50+} \) as a function of electron energy for the KMM resonance region. As seen in the figure, both positive and negative peaks exist on the slowly varying background. By extending equation (1) to include REDA, DR and ion loss processes, the ion number ratio can be expressed by the following formula in general,

\[ \frac{n_{\text{He}}}{n_{\text{Li}}} = \frac{\sigma_{\text{Li}}^{\text{ion}} + \sigma_{\text{Li}}^{\text{REDA}}}{e/j + \sigma_{\text{He}}^{\text{RR}} + \sigma_{\text{He}}^{\text{DR}}}, \]

where \( \sigma_{\text{Li}}^{\text{ion}} \) is the (non-resonant) ionization cross section of the Li-like ion including direct and indirect (EA) processes, \( \sigma_{\text{Li}}^{\text{REDA}} \) the REDA cross section, and \( \sigma_{\text{He}}^{\text{RR}} \) and \( \sigma_{\text{He}}^{\text{DR}} \) are the RR and DR
cross section for the He-like ion, respectively. The $\tau^{-1}$ term includes all other loss contributions, such as escape and charge exchange. As is clear from the equation (2), the negative peaks in the Fig. 3 correspond to the KMM DR contribution. In contrast, the positive peak is due to the REDA contribution. Another possible mechanism which can make a positive “peak” is the Fano line profile arising from the interference between RR and DR [9, 10]. However, since the natural width of the KMM resonance is estimated to be less than 1 eV, it is practically impossible to observe because the present electron energy resolution is about 50 eV. Therefore the positive peak in the present measurement is unambiguous evidence of REDA, which has never been observed previously for such a heavy HCI. The detailed analysis is ongoing, and will be published elsewhere.

5. Near future plans
The following subjects will be studied in the near future.
(1) DR and REDA experiments with higher $Z$ and higher resolution.
Although we have successfully observed REDA in Li-like I$^{50+}$, further details about the resonant fine structure can be expected in higher resolution measurements which will be achieved by decreasing the electron beam current. The measurements will be extended also for HCIs with higher $Z$, for which the separation between the resonant states becomes larger so that they will be clearly resolved even with high electron beam current.
(2) Periodical implantation of rare earth ions, such as Er, on Si.
Er ions doped in semiconductor shows luminescence at 1.54 $\mu$m, which is in the region of optimum transmission of silica based glass fiber. Thus, periodical implantation of Er ions is an important technology for the generation of a new photonic device such as ultra-low threshold laser. It is planned to use highly charged Er ions for such purpose by utilizing the one-by-one implantation technique [7].
(3) Development of a helium-free table-top EBIS for HCI-surface studies.
It is essential to have more intense and convenient electron beam ion source (EBIS) to extend our research subjects, such as the creation of ordered array of nanostructures. For this purpose, we are constructing a new EBIS with much smaller size and a helium-free superconducting magnet.

Figure 2. Number ratio between adjacent charge states of I$^{q+}$ as a function of electron energy for the KLL resonance region together with observed X-ray spectra. The horizontal axis is temporarily calibrated electron energy.

Figure 3. Intensity ratio between He-like I$^{51+}$ and Li-like I$^{50+}$ extracted from the Tokyo-EBIT as a function of electron energy for the KMM resonance region. The electron energy was calibrated with the DR resonant energy calculated by using the HULLAC code.
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