§11. Emission Spectroscopy of Multiply Charged Heavy Ions for a Research of Atomic Processes and Light Source Applications

Ohashi, H., Oyama, K., Okajima, K., Ito, H. (Univ. Toyama),
O'Sullivan, G. (Univ. Coll. Dublin (UCD)),
Sakaue, H.A., Suzuki, C., Kato, D., Murakami, I.

The plasma light sources have been developed rapidly, especially for semiconductor lithography in the extreme ultraviolet (EUV) region where proposed Mo/Si multilayer mirror has a maximum reflectivity at the wavelength of 13.5 nm.[1)] The high-Z plasma have attracted attention as powerful plasma light source candidates because of their favorable emission properties, i.e. unresolved transition array (UTA), and Sn ($Z = 50$) plasma was suitable for the 13.5-nm light source. The tremendous effort of the research works for Sn plasmas suggests a possibility to apply higher-Z plasmas to UTA light sources for shorter wavelengths. For example, Tb (Z = 63) and Gd (Z = 64) were regarded as candidates for beyond EUV lithography using shorter wavelengths than 13.5 nm. In the water and carbon window regions, i.e. 2.3–4.4 nm and slightly longer wavelengths, soft x-ray emissions can be used for biological imaging and Bi (Z = 83), Pt (Z = 78) and Au (Z = 79) plasmas are some of the candidates. Emission spectroscopy of laser-produced plasmas (LPPs) with such high-Z elements was performed to demonstrate the dependence of UTA peak wavelengths on atomic number Z, i.e. a quasi-Moseley's low.[2)] As the results, the lighter-Z LPPs have shorter wavelengths of UTA peak while contributed charge states to the UTA peak were estimated by theoretical calculations due to the lack of experimental atomic data. In addition, although these UTAs correspond to $n = 4$–$n = 4$ transitions, $n = 3$–$n = 4$ transitions of lighter-Z ions, such as Ga (Z = 31) and Ge (Z = 32), are regarded as other candidates of the UTA light source in soft x-ray and EUV region.

The Compact electron beam ion trap (EBIT)[3)] at the National Institute for Fusion Science (NIFS) was employed to produce highly charged Ga, Ge and Pt ions for charged-defined emission spectroscopy of these plasmas with quasi-monoenergetic electron temperature. The EBIT is a unique source that can control the highest charge state through having a quasi-monoenergetic electron beam forms a plasma in ionization equilibrium. The highest charge states can be altered by changing the electron beam energy. The main components of the EBIT are an electron gun, drift tubes, an electron beam collector, and a superconducting Helmholtz coil. Compact EBIT is applied high-T_c coils and thus can operate with a liquid nitrogen as a coolant. Ions produced in the drift tubes are trapped by a well potential applied at trapping electrodes and a space charge potential of a compressed electron beam passing through the drift tubes. Trapped ions then collide with electrons and are ionized sequentially up to a maximum charge state determined by the ionization energy. Ga, Ge and Pt vapors were introduced into the trap region from an effusion cell operated at 745°C, 925°C and 1650°C, respectively, with each metallic element. Emission from trapped ions was observed at 90° with a flat-field grazing incidence spectrometer equipped with a laminar-type replica diffraction 1200 lines/mm grating (30-002, Shimadzu Corporation) and an x-ray charge-coupled device camera (PIXIS-XO:400B, Princeton Instruments). A 150-nm thin Zr-filter was placed in front of the grating to block stray lights from the Compact EBIT.

Electron beam energy was surveyed in 200–500 eV to observe emission spectra of different highest charge state plasmas in the wavelength of 4–16 nm. Theoretical calculations of gA values with the Flexible Atomic Code were performed to identify the transitions of observed emission lines. The $3d$-$4f$, $3d$-$4p$ and $3p$-$3d$ transitions were observed for Ge and Ga ions. Comparing reported ionization energies[4)] and operated electron beam energies, actual collision energy seems to be different about several tens of eV from applied voltage. This fact is not critical for previous results of Compact EBIT experiments because applied elements and produced charge states do not have close ionization energies and electron beam energies were not surveyed finely like this experiment. However, this revealed characteristic is important for future experiments especially in this electron beam energy region. As for Pt, any emissions were not observed while the vapor pressure at 1650°C was estimated to be enough to introduce atomic Pt into the trapped region of the Compact EBIT. It might be a large amount of outgas from the chamber since it was the first time to operate the effusion cell at such high temperature. Some improvement of the injection port, e.g. another differential pumping system, is necessary for high temperature operation. From another point of view, the laser ablation system[5)] is planned to be installed as another injection port resulting in capability of introduction of the elements with low vapor pressure into the Compact EBIT.

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