§26. Measurement of Charge-defined Spectra for Laboratory Scale Light Source Applications

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The efficient generation of extreme ultraviolet (EUV) and soft x-ray (SXR) emission spectra is a topic of major interest for a number of areas of fundamental and applied science such as astrophysics, fusion science, high resolution imaging, and nanolithography. For the former, gallium and germanium gained considerable attention ever since their identification in the spectra of HgMn stars.[1)] Later, high-resolution UV spectral measurements of the abundances of iron-group elements in hot sub-dwarf B (sdB) stars revealed the presence of other heavy elements, especially gallium and germanium,[2)] which spurred a number of studies on the spectroscopy of laser-produced gallium and germanium plasmas. In fusion studies, liquid gallium was also proposed as a plasma-facing component in tokamaks.[3)] For lithography, laser-produced plasma (LPP) EUV source technology is gaining importance in the semiconductor industry due to the shorter wavelength requirements of future manufacturing nodes, as the printing of smaller feature sizes requires moving to successively shorter wavelengths. In addition, the water window soft x-ray emission from 2.3 to 4.4 nm is also useful in order to take a photograph of the biological cell. We have identified gallium (Ga) and germanium (Ge) as potential targets. The Ga, Ge, and in particular, galinstan plasmas might provide promising sources for two different wavelengths.

The compact electron beam ion traps (CoBIT) at the National Institute for Fusion Science (NIFS) was employed to generate charge-defined emission spectra of Ge and Ga ions. The CoBIT is a unique source that can control the highest charge state through having a quasi-monoenergetic electron beam form a plasma in ionization equilibrium. The highest charge states can be altered by changing the electron beam energy. The main components of the CoBIT are an electron gun, drift tubes, an electron collector, and a superconducting Helmholtz coil. Ions produced in the drift tubes are trapped by a well potential applied at trapping electrodes and a space charge potential from 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. Ge and Ga vapors were introduced into the trap region from an effusion cell operated at 925.8°C and 745.8°C, respectively, with metallic Ge and Ga. Emission from trapped ions was observed at 90° with a flat-field GIS equipped with a laminar-type diffraction 1200 lines/mm grating (Shimadzu Corporation) and an x-ray CCD camera (Princeton Instruments, PIXIS-XO:400B). A 150-nm thin zirconium filter was placed in front of the grating to block the stray light from the CoBIT.

The charge state defined spectra of Ge observed at the NIFS CoBIT are shown in Fig. 1. With the aid of theoretical calculations performed with the Cowan and HULLAC codes, it was possible to identify the contribution of emission lines giving rise to 6.*x* and 13.5 nm emission as $3d - 4f$ transition of Ge^{11+}, and $3p - 3d$ transitions of $Ge^{9+} - Ge^{12+}$. Further experiments are necessary to elucidate the origin of this disagreement and identify some possible reasons, e.g. indirect ionization of lower charge states.[4)]

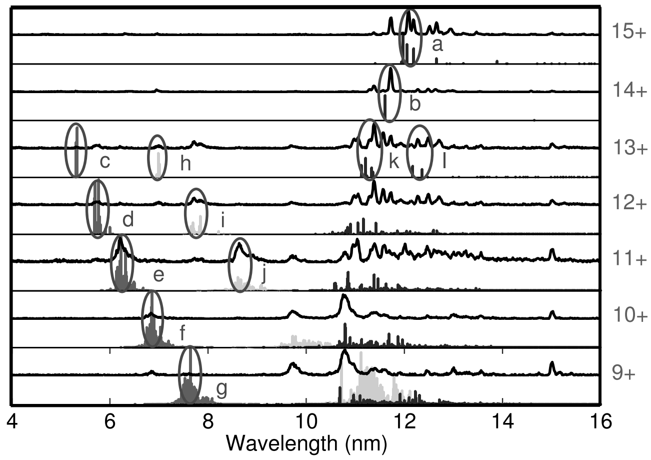

Fig. 1. EUV emission spectra of Ge ions. The calculated lines from transitions of the type $3d - 4f$ (red), $3d - 4p$ (green), and $3p - 3d$ (blue) with the Cowan code, with intensities proportional to their *gA* values are also presented. Calculated charge states and estimated highest charge state in the CoBIT are shown on the right-hand side of each spectrum.

In summary, we have studied the EUV emission of Ge using LPPs and the NIFS CoBIT. Comparison with atomic structure calculations performed with the Cowan and HULLAC codes aided identification of the strongest peaks. The strong lines from 4 to 16 nm spectral regions are from $3d - 4f$ transition of Ge^{10+}, and $3p - 3d$ transitions of $Ge^{9+} - Ge^{12+}$ ions. The experimental results provide a guideline for development of laser-induced EUV and soft x-ray sources for short wavelength applications, such as EUV lithography and *in vivo* biological imaging.

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