# §23. 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. Development of EUV and soft x-ray sources with emission at wavelengths less than 10 nm is a subject of prime interest for next generation semiconductor lithography. 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, since the printing of smaller feature sizes requires moving to successively shorter wavelengths. After two decades of research, the semiconductor industry is about to introduce lithography sources operating at an EUV wavelength of $\lambda$ = 13.5 nm that have sufficient in-band power for high-volume manufacturing (HVM). In 2009 ASML announced that sources would be needed at 6.*x* nm, where La/$B_4C$ mirrors have a reflectivity of ~ 40% in a 0.06 nm bandwidth near 6.7 nm.[1,2] From a literature study of potential emitters at 6.*x* nm, we have identified gallium (Ga) as a potential target, since it possesses strong resonance peaks due to $3d$–$4p$ and $3d$–$4f$ transitions in this wavelength region at 6.55, 6.75, 6.97 and 7.10 nm. Since Ga is a liquid at room temperature it is potentially a more suitable candidate for development of a droplet target. The optimum electron temperature of a Ga plasma is expected to be around 50 eV, which corresponds to the conditions prevailing in a 13.5-nm Sn plasma source indicating that the required laser focusing conditions are similar to those used with Sn. The spectrum of Ge has similar atomic transitions to Ga in this spectral region. It is important to make a database for efficient 6.*x*-nm Ga and Ge plasmas.

An electron beam ion trap (EBIT) was employed to measure charge-defined emission spectra of Ge ions. The EBIT is a unique source that can control the highest charge state with a quasi-monoenergetic electron beam forming a simple plasma in ionization equilibrium. The emission from the highest charge states is identified by changing the electron beam energy. The main components of the EBIT are an electron gun, drift tubes, an electron collector and a Helmholtz coil as permanent magnets. The ions produced in the drift tubes were 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 collided with electrons and ionized sequentially up to a maximum charge state determined by the ionization energy. Ge vapor was introduced into the trap region from an effusion cell operated at 925°C with metallic Ge. Emission from trapped ions was observed at 90° with a flat-field GIS equipped with a laminar-type diffraction 1200 grooves/mm grating and an x-ray CCD camera.

Figure 1 shows the charge-defined Ge spectra obtained from the EBIT with a theoretical atomic code calculation of HULLAC. The electron beam energy was varied to produce $Ge^{q+}$ ($q$ = 8–21) ions as the highest charge state in the EBIT. It is possible to identify the strongest lines giving rise to 6.*x* nm and 13.5 nm emission as $3d$–$4f$ transitions of $Ge^{12+}$ and $3p$–$3d$ transitions of $Ge^{17+}$. These ions have open $3p$ or $3d$ subshells and lines arising from $3p^N$–$3p^{N-1}nd$, $3d^N$–$3d^{N-1}np$ and $3d^N$–$3d^{N-1}nf$ transitions should provide the dominant emission in the EUV range. Further experiments are necessary to elucidate the origin of this disagreement and identify some possible reasons, e.g. indirect ionization of lower charge states.[3)]

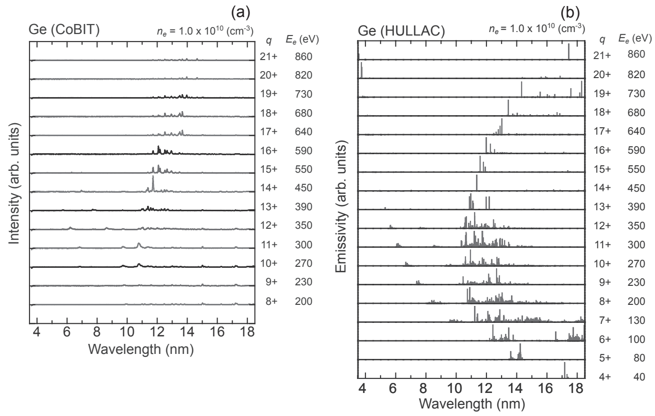


Fig. 1. (a) EUV emission spectra of Ge ions with electron beam energies of 200–860 eV by use of a compact EBIT (CoBIT). (b) Theoretical evaluation of the charge-separated spectra by an atomic code HULLAC.

In summary, we have observed the charge-defined spectra of Ge ions were also observed by use of the CoBIT system. It is possible to identify the strongest lines giving rise to 6.*x* nm and 13.5 nm emission as $3d$–$4f$ transitions of $Ge^{12+}$ and $3p$–$3d$ transitions of $Ge^{17+}$. 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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1) Banine, V. Y. et al.: J. Phys. D **44** (2011) 253001.
2) Otsuka, T. et al.: Appl. Phys. Lett. **97** (2010) 231503.
3) Li, B. et al.: J. Appl. Phys. **118** (2015) 073302.