EUV spectroscopy of mass-limited Sn-doped laser plasmas

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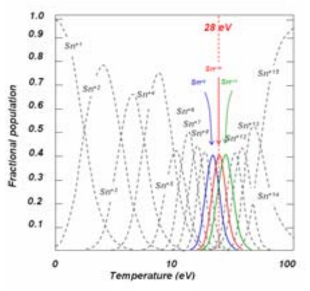
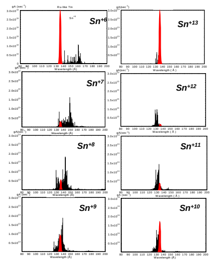
SEMATECH

Spectroscopy and Radiation Modeling

To optimize EUV source performance, and to control detrimental off-band radiation, we implement spectroscopy combined with modeling, as a powerful diagnostic tool

Tin has strong emission at the wavelength of 13.5nm based on Unresolved Transition Array (UTA). Spectroscopically, Sn has advantages over Xe, because its main UTA is centered at ~ 13.5 nm, whereas forXe it is at 11.6 nm . Many ion species contribute to the Sn UTA; Sn^{7+}, Sn^{8+}, Sn^{9+}, Sn^{10+}, Sn^{11+} and Sn^{12+}. The optimum plasma temperature for Sn^{10+} is ~ 28 eV





Plasma conditions are optimized by theoretical predictions based on hydrodynamic code calculations

Mass-limited Targets

Ideally the mass of the target is limited to the number of atoms that are sufficient to provide radiators to allow efficient and required conversion. The laser pulse duration should be sufficient to allow full ionization of the target. This will then minimize the particluate debris emanating from the target.

The EUV source development: 2 facilities

Vacuum target chamber 1: cylindrical, 45cm diameter, 12 ports, configured for FFS and TGS and equipped with a Precision EUV diagnostic instrument.

Vacuum target chamber 2: MCPIGS is configured to this chamber.

LASERS

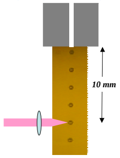
Custom built, precision Q-switched, Nd:YAG laser, 11.5ns pulse, 1064 nm, 1-2 Hz, 1.7J max energy, $M^2 = 1.5$, minimum focused spot size ~ 35 μm with f = 10 cm lens, Pulse-to-pulse stability ~ 5%

Spectra-Physics Quanta-Ray GCR-190 1064 nm, Q-switched, ~340 mJ, 100 Hz, 10ns pulse duration, minimum focused beam size is 20 μm

High Resolution Spectroscopy – Five instruments

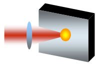
- Flat-field Grazing Incidence Spectrograph (FFS)
- Transmission Grating Spectrograph (TGS)
- Microchannel Plate Intensified Grazing Incidence Spectrograph (MCPIGS)
- Vacuum UV normal incidence Grating Spectrograph
- Visible/IR grating spectrograph (EG&G)

Spherical Targets
Tin-doped spherical droplet

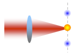


Two target architectures are used

100% Sn or Xe planar target



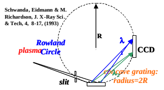
Sn doped droplet target



A Xe jet/droplet system will soon be installed.

Flat-Field Grazing Incidence Spectrograph

- 1200 lines/mm, gold-coated, variable spaced reflective grating
- 0.5 μm thick, freestanding Zr filter to select wavelengths from 6.5 – 16.8 nm (FWHM)
- selection of collimation slits (from 10μm to 80 μm), resolutions 0.006 nm to 0.01 nm.



Schwanda, Eidmann & M. Richardson, J. X-Ray Sci. & Tech, 4, 8-17, (1993)

Spectrograph Parameters:

Gold plated Hitachi grating

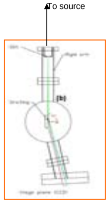
R_G = 5.649 m

Line spacing = 1200 lines/mm (nominal)

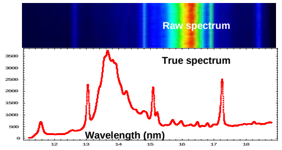
Angle of incidence: α = 87°

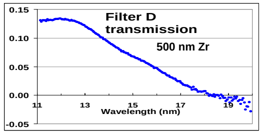
slit width = 70μm

at ~ 10nm Δλ ~ 0.04 nm R ~250



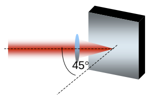
Raw data for FFS and TGS is collected using a 512 x 512, back illuminated CCD detector, without Antireflective coating

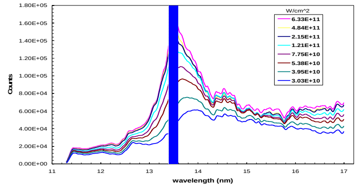




To extract the true spectral output from the plasma, the raw data must deconvolved for the filter transmission, as well as various other factors, and the CCD arrays must be calibrated to the wavelength range. A numerical code was developed for spectral deconvolution.

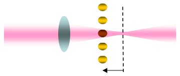
Target: 100% Solid Sn

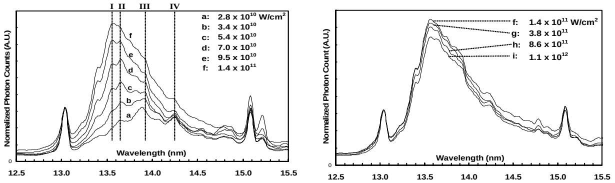




UTA emission in the 13.5 nm region increases streadily with increasing laser intensity. The highest conversion efficiency obtained to date at 13.5 nm, CE = 5% (2%bw, 2π sr) is at power density ~ 6 x 10^{11} W/cm²

Spectral features within 13.5nm UTA –Sn Droplet

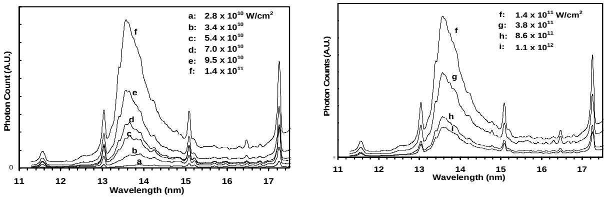




Spectra have been normalized to the peak of oxygen line (13.0nm) to observe the effects of intensity on spectral features.

(A) Below optimum intensity: Features I, II, III, and IV respond sensitively to intensity. Features I and II are most likely contribution from ions near Sn^{10+}.

(B) Above optimum intensity: The shape of UTA remains the same, implies that the relative ion population (of those emitting to the UTA) remains the same.

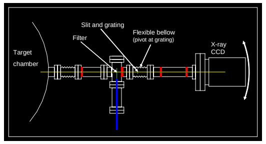


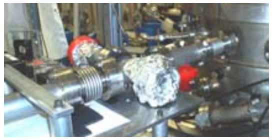
<u>The 13.5nm UTA from Sn ions (Sn^{6+} – Sn^{13+}) in the spectra</u>

Peak of UTA increases in height as intensity (A) until 1.4 x 10^{11} W/cm² (at spectrum f). Then, UTA peak decreased with increasing intensity (B). The intensity 1.4 x 10^{11} W/cm² corresponds to optimum intensity for max CE.

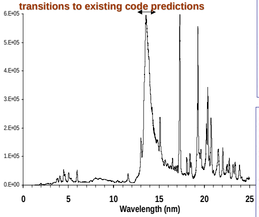
Transmission Grating Spectrograph

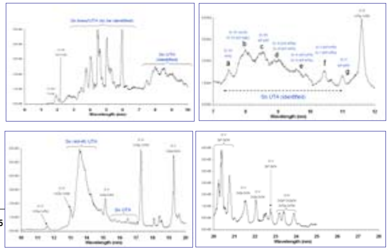
- 10,000 lines/mm SiN transmission grating, transmission 50%.
- filter selection allows choice of spectral region
- a back-thinned x-ray CCD camera to record spectrum
- slit selection (from 10μm to 100 μm), spectral resolutions 0.006 nm to 0.01 nm.





High resolution makes individual line identification possible, and comparison of transitions to existing code predictions

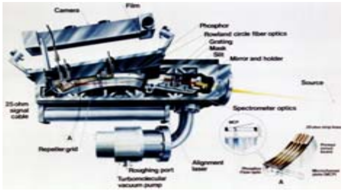




TGS Sn Droplet deconvolved Spectrum in the near band region from 0nm - 28nm, at intensity of 1 x 10^{11} W/cm² is shown. Lines originating from Sn and O transitions are identified

Microchannel Plate Intensified Grazing Incidence Spectrograph (Upcoming)

84.67mm long curved MCP is along the Rowland circle, with the length of the film plane at 228.6 mm. Electrons generated exit the back side of the MCP, and are accelerated by a potential, onto a phosphor fiber optic face-plate, which also serves as a vacuum barrier. The visible phosphorescence spectral image realyed by fiberoptic to CCD.



Rowland Circle Geometry, for first-order diffraction only, α = 88⁰

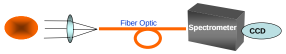
Microchannel plate: Channel pore size of 8 – 10μm

Survey Range: 1nm-60nm

Gratings available: 600, 1200, 2160, 2400 3600 lines/mm

Vacuum: > 1X 10^{-6} Torr

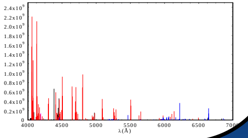
VUV/Vis/IR Spectrograph



EG&G Princeton Applied Research Model 1235 Digital Triple Grating Spectrograph

Three gratings that allow scanning in three wavelength regions are available for use with this spectrograph

Cowan code calculations for Oxygen visible lines



Summary

- *Plasma emission and opacity characteristics are quantified using spectroscopy as the key diagnostic*
- *Alternative methods for achieving better resolution spectral data in the different wavelength regions are being planned*
- *Using precision spectroscopy coupled with hydrodynamic, radiation and atomic physics code calculations, will lead to a better quantitative understanding of the radiation emission*
- *Inferences obtained from spectral data of tin-based targets have dramatically improved ourEUV source performance*
- *The conversion efficiency for Sn-doped droplets have reached 2%, while we see a CE of ~ 5% for Sn planar targets*

Acknowledgements

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