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Investigation of ions emitted from a tin fuelled laser produced plasma source

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Abstract. In this work ions emitted from a laser produced plasma created from a solid tin target have been analyzed using a spherical sector energy analyzer (ESA). Employing time of flight analysis, the ESA allows determination of ion energy and charge stage as a function of ion emission angle. Ions of charge Sn$^{+1}$ - Sn$^{+9}$ with energy to charge ratios of 0.22 - 3.2 keV have been investigated over a range of emission angles from 20 - 80 degrees, relative to the target normal, for three distinct laser pulse energies.

1. Introduction
With the commercial drive to create ever smaller microprocessor features, in accordance with Moore’s law, the physical limits of current photolithographic methods are fast approaching. Extreme Ultra-Violet (EUV) lithography at 13.5 nm is favoured as the successor to current techniques for printing circuits at the 32 nm node and beyond [1]. As EUV radiation is absorbed strongly by all materials, Bragg reflectors must be employed as collector optics. Mo/Si multilayered Bragg reflectors are the driving factor in the choice of EUV wavelength, as they possess a high reflectivity at 13.5 nm within a 2% bandpass. Tin and xenon are candidate targets for laser produced plasma based EUV sources as they emit strongly in the 13.5 nm region [2, 3]. Laser produced plasmas (LPP’s) that are favourable for EUV emission emit energetic ions [4, 5, 6]. Such energetic ions would sputter EUV collector optics, greatly reducing their reflectivity [7]. For laser produced EUV sources to be viable for high volume manufacture a source cleanliness of $\geq$30,000 hours is required [1, 7]. In order to preserve collector optic lifetime, a number of debris mitigation techniques have been proposed [8]. To inform the optimization of such debris mitigation techniques, the energy and charge of ions ejected from LPP’s that emit strongly at 13.5 nm has been characterized using a spherical sector energy analyzer for ion emission angles spanning 20 – 80 degrees to the target normal. Previous studies on solid tin targets have demonstrated a strong dependence of the conversion efficiency, into the 13.5 nm band, on laser power density [3], thus the ion characterization measurements were performed over a range of laser power densities.

2. Experiment
The experimental arrangement is similar to one described previously [9]. A Comstock Model AC-902B Electrostatic Spherical sector energy Analyzer (ESA) was employed to characterize ions ejected from tin fueled laser produced plasmas according to their energy and charge state.
The ESA consists of two concentric hemi-spherical plates between which a potential difference is applied, so that only ions of a particular energy to charge ratio ($\frac{E}{q}$) reach the detector. The detector is a pair of micro-channel plates (Comstock Model CP-602B) and the resulting signals are recorded on a digital oscilloscope. Time of flight analysis is used to differentiate between ions of different charge states with the same value of $\frac{E}{q}$.

The plasmas were produced using a Nd:YAG laser that delivered 60 - 325 mJ per pulse, in a pulse duration of 7 ns (full-width at half-maximum intensity) at 1064 nm and over a spot size with a diameter of approximately 200 $\mu$m. As previously described, a rotating stage is used to mount a solid planar tin target [9]. The axis of rotation of the stage is centered along the optical axis to ensure that, after three reflections, the incoming laser beam strikes normal to the target face irrespective of any rotation undergone by the stage. This arrangement allows the fixed in space ESA to be exposed to ions emitted at a range of angles to the target normal.

For each spectrum recorded the tin target was shot twice with the laser. The initial shot cleared the oxidation and surface defects from the target face and the second was used to record the ion spectrum. Five individual ion spectra were recorded for each ($\frac{E}{q}$) and emission angle setting. The ions were banded according to their charge and these signals integrated. Over the five shots the signal area for each charge state remained relatively consistent, the average being used as a measure of the ion signal for that ($\frac{E}{q}$) and angle. Ion signals were recorded for emission angles from 20 to 80 degree angles, relative to the target normal, over a energy/charge range of 0.22 - 3.2 keV. These measurements were recorded for three laser pulse energies (60, 105 and 325 mJ). Each laser energy corresponded to a distinct power density, of the order of 2.5, 4.5, and $14 \times 10^{10}$ W cm$^{-2}$ respectively, the spot size and pulse duration being kept constant throughout.

3. Results

3.1. 60mJ Laser Pulse Results

In Fig.1 energy distributions for ions emitted from a tin plasma created using a 60mJ laser pulse are plotted for angles of emission from 20 to 80 degrees, with respect to the target normal. With increasing angle, the number of ions ejected decreases. However, the ion energy distribution remains similar from 20 - 50 degrees. Beyond 50 degrees the mean ion kinetic energy shifts to lower energies but the energy distribution profile is essentially the same shape for all emission angles. These results would indicate that ions are preferentially ejected close to target normal, parallel to the incoming laser, with the more energetic ions tending to be emitted in this direction.

![Figure 1](image-url)
3.2. 105mJ Laser Pulse Results
Increasing the laser energy from 60mJ to 105mJ, Fig.2, gives rise to an increase in the number of ions ejected as well as the mean kinetic energy of the ions. As with the results obtained for a 60mJ pulse energy, the ion energy distribution remains relatively similar in shape over all angles, but again the data show preferential ion emission close to target normal. The average ion kinetic energy is once again shifted to lower energies with increasing angle, although this effect is apparent over all angles and not just above 50 degrees as observed for 60mJ pulses (Fig.1).

![Figure 2. Energy distributions for ions emitted from plasmas created with a 105mJ laser pulse energy, data are shown for angles of emission from 20 to 85 degrees.](image)

3.3. 325mJ Laser Pulse Results
The highest pulse energy used was 325mJ, Fig.3 shows that further increasing the laser energy does not result in an increased mean ion kinetic energy at 20 degrees. However, some of the additional energy appears to be distributed over ions ejected in the 30 to 50 degree range, shifting their mean kinetic energy to larger values in comparison with the data shown in Fig.2. The number of ions ejected has once again increased and the preferential ejection of energetic ions close to the target normal continues. At this increased pulse energy, the peak number of ions ejected at 20 and 30 degrees is increased relative to those emitted at larger angles.

![Figure 3. Ion energy distributions for ions emitted from tin plasmas created using 325mJ laser pulses.](image)
Increasing the pulse energy from 105mJ to 325mJ resulted in no significant difference in the maximum ion kinetic energy, which was found to be somewhat short of 10keV. The maximum energy recorded for the 60mJ pulse energy being lower at approximately 5keV. This is in agreement with previous work, performed on tin plasmas with a Nd:YAG laser power density of $7 \times 10^{10} \text{W/cm}^2$, which indicated a maximum kinetic energy of 7keV [4].

4. Conclusion
The energy and angular distributions of ions emitted from tin plasmas created using Nd:YAG laser pulses have been recorded. The number of ions as well as their mean kinetic energy was found to increase with increased laser power density. The energy distribution profiles for each angle studied were all relatively similar in shape, although the mean ion kinetic energy showed dependence on both laser pulse energy and emission angle. In all cases studied, there was evidence for preferential ion emission close to target normal (parallel to the incoming laser beam), along with a decrease in ion energy with increased angle from target normal. The maximum kinetic energy of the ejected ions appears to plateau at laser pulse energies between 105mJ and 325mJ. These measurements provide information on ejected ion energies and angular distributions that should inform debris mitigation strategies for efficient, next generation EUV lithography sources.

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