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Spectral control of emissions from tin doped targets for extreme ultraviolet lithography

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Abstract
We have investigated the unresolved transition array (UTA) emission around 13.5 nm from solid density tin and tin doped foam targets. Extreme ultraviolet (EUV) spectral measurements were made in the wavelength region 11–17 nm using a transmission grating spectrograph and the EUV in-band conversion efficiency was measured using an absolutely calibrated EUV calorimeter. The aim of this work was to optimize the UTA emission with the proper density of tin dopant in low-Z foam targets. The addition of tin as an impurity leads to a reduction in the plasma continuum and narrowing of the UTA compared with fully dense tin targets. Our studies indicate that the required percentage of tin for obtaining bright in-band spectral emission is less than 1%.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Extreme-ultraviolet lithography (EUVL) is considered an attractive candidate to succeed conventional optical lithography in the coming years. To enable this technology, a reliable source will be required that consistently provides sufficient and clean power at 13.5 nm to yield adequate wafer throughput in a manufacturing tool. Researchers are considering various kinds of 13.5 nm sources including synchrotron radiation, discharge produced plasma (DPP) and laser-produced plasma (LPP) [1]. The use of synchrotron radiation as the light source is not practical considering the cost as well as the size and is more complex technologically. Extreme-ultraviolet (EUV) sources based on LPPs have several advantages over discharge-based EUV sources that include power scalability through the tuning of laser parameters, good dose control, flexibility in dimensions, spatial stability, minimal heat load and a large solid angle of collection [2]. A suitable scheme will require at least 3% conversion efficiency (CE) of incident laser energy to soft x-rays in a 2% bandwidth centred at the 13.5 nm peak. The success of an EUVL target depends not only upon its emission characteristics at 13.5 nm but on the effective mitigation of its debris as well. Different targets were considered for generating 13.5 nm plasma emission including lithium, xenon and tin. Lithium plasma exhibits strong Lyman-α emission of Li^{2+} at 13.5 nm [3]. The CE obtained with different Xe target plasmas is ∼1% which is not enough for commercial lithography production purposes [4]. Laser-produced tin plasma is considered to be an ideal source for EUVL as it provides a CE better than 3% [5].

Tin plasmas characteristically emit broadband spectra around 13.5 nm that originate from many different ionization stages. These energy levels are so close that the radiation they generate in the EUV regime can be considered as a continuum (unresolved transition array, UTA). However, plasma from solid tin targets creates extreme debris problems. Apart from various particulates emitted from the plasma, the ions and neutrals which propagate with high expansion velocities ($\sim$(1–5) $\times 10^6$ cm s^{-1}) can damage the nearby optics in an EUVL system [6, 7]. Several methods can be employed for limiting debris from the tin targets including electrostatic repeller fields [8], the addition of ambient gas [9] and application of magnetic fields [7]. Another method of restricting debris is to use the minimum amount of Sn atoms

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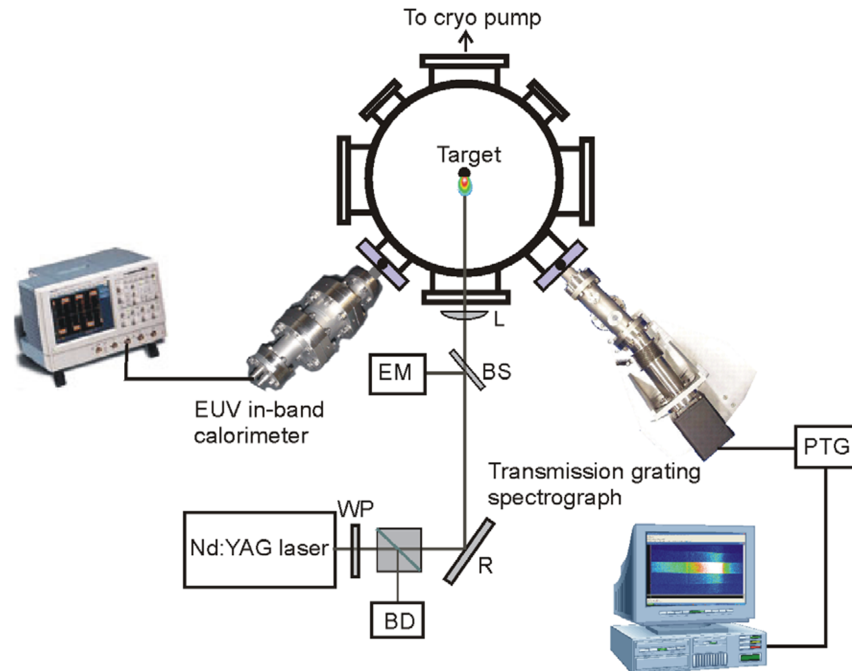

Figure 1. The schematic of the experimental set-up. (WP, wave plate; BD, beam dump; R, reflector; L, lens; PTG, CCD controller; EM, laser energy meter; BS, beam sampler.)

required for sufficient EUV emission [10, 11]. It has been shown numerically that the tin ion distribution was not significantly changed when the concentration of tin dropped from 100% to 1% [12]. Hayden *et al* [13] found that targets containing 15% tin emit more brightly in the in-band region than fully dense tin targets. The aim of this study is to maximize the efficiency of EUV emission from tin doped foam targets while minimizing the number of tin atoms. Our results indicate that the density of tin necessary to obtain bright UTA emission at 13.5 nm is around 0.5%.

2. Experimental details

The schematic of the experimental set-up is given in figure 1. The targets were irradiated with 1064 nm, 10 ns pulses from an Nd : YAG laser focused with an antireflection coated plano-convex lens. The 60 μm diameter focal spot was measured using an optical imaging technique and remained unchanged during the experiment. The target was mounted in a vacuum chamber with a base pressure $\sim 10^{-6}$ Torr. EUV emission from the plasma was measured using a transmission grating spectrograph (TGS) equipped with a 10 000 lines/mm grating. The TGS was positioned at 45° with respect to the laser beam and employed a 50 μm slit to collimate incident radiation onto the transmission grating. The dispersed spectra were recorded using a Princeton Instruments back illuminated x-ray CCD camera. An absolutely calibrated EUV calorimeter (Energy monitor, E-Mon, JenOptik Mikrotechnik, Jena) was used for measuring the CE of the in-band radiation at 13.5 nm with 2% bandwidth. The principle of operation of the energy monitor is filtering out the in-band range from the broadband incidence spectrum of the EUV source by using a Zr filter (it suppresses the radiation above 50 nm) and two Mo/Si multilayer mirrors (for filtering in-band radiation). A photodiode (IRD, SUXV-100) that is sensitive to EUV range is used for detection. The energy monitor is placed at 45° with respect to the laser beam.

For fabricating the foam bead targets, the required amount of tin oxide is dispersed in a resorcinol formaldehyde (RF, 100 mg cc^{-1}) solution and dried. The density of tin in the foam target is controlled by the concentration of tin in the solution. The target beads are $\sim$500 μm microns in diameter, and the uniformity of the tin concentration was verified using a scanning electron microscope.

3. Results and discussion

Four different targets were used in the present experiment which included a 10 μm solid density tin foil and tin doped foam targets of varying tin concentration (1%, 0.5% and 0.1%). A typical time integrated UTA recorded with our TGS for the 10 μm tin foil is given in figure 2. The spectral features of the 10 μm Sn foil were exactly like those of the solid Sn slab. That is not surprising because the reported ablation depth for Sn target with similar experimental conditions is less than 100 nm [14]. The UTA emission is concentrated around 13.5 nm with a narrow band gap of 5–10 eV arising from $4p^64d^n$–$4p^54d^{n+1} + 4p^64d^{n-1}4f$ transitions of various Sn ions ranging from Sn^{6+} to Sn^{14+} with occupancy in the range of $n = 2$ to $n = 8$ [12, 15]. The EUV in-band energy was measured using the energy monitor in a well-defined solid angle, which was determined by an aperture and its distance from the source along the beam path. Since the EUV plasma emission has an approximately hemispherical symmetry [16, 17], the output from the energy monitor was simply integrated over a 2π solid angle. The estimated CE for different laser intensity levels at the target surface is given in figure 3. The variation of the CE signal with laser power density shows that the maximum CE

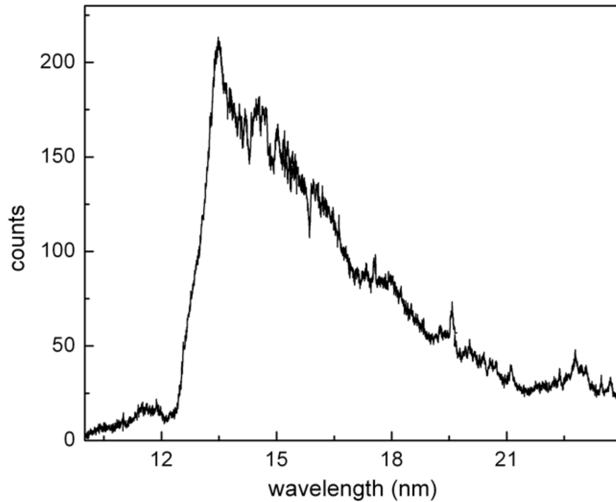

Figure 2. The UTA emission from 10 μm tin foil.

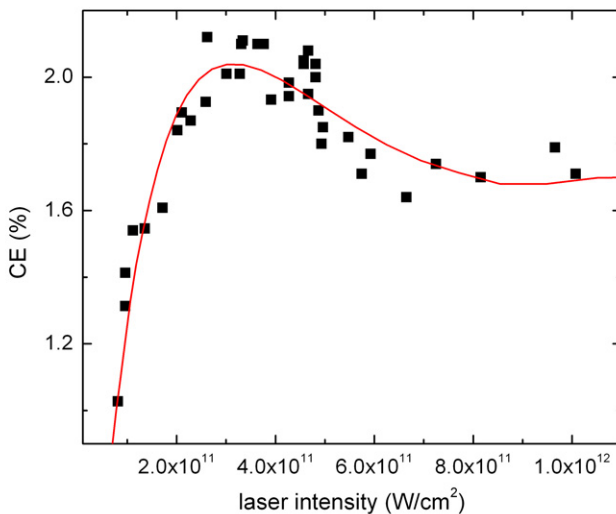

Figure 3. The CE measured using the EUV calorimeter for 100% Sn target at different laser intensity levels.

occurs near our experimental value of 4×10^{11} W cm^{-2}. Above the optimal laser irradiance, a greater portion of the radiated energy appears at shorter wavelengths, and at lower irradiance levels the plasma is insufficiently heated to emit at 13.5 nm. At the optimal laser irradiance level the ionization balance of the plasma shifts towards Sn^{9+} to Sn^{12+} which contributes primarily to in-band UTA radiation.

The EUV spectral energy from laser-produced tin plasma is significantly influenced by opacity effects. Tin plasma at 13.5 nm experiences attenuation of its strongest lines and is therefore optically thick [14, 18]. In order to improve CE it is important to facilitate the release of in-band plasma radiation. Fujioka *et al* [14] studied opacity effects and suggested that the optical thickness of the tin plasma should be controlled by changing the initial target density. One of the most effective ways in accomplishing this is to use Sn atoms as a measurable impurity in the EUVL target. Figure 4 shows the UTA emission spectra from the 100% tin along with spectra from Sn doped foam targets of varying tin concentrations. The laser intensity used was 4×10^{11} W cm^{-2} for all cases.

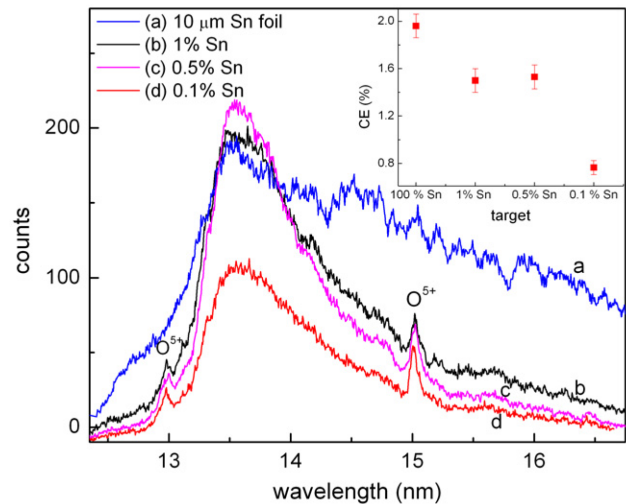

Figure 4. Typical UTA spectra from Sn foil target and Sn doped foam targets. The figure in the inset shows the estimated CE values for various targets used.

The wavelength at which peak UTA intensity occurs is hardly affected by the percentage of the Sn dopant. Compared with the solid Sn slab and Sn foil targets, the UTA emission from Sn doped foam targets showed reduced continuum emission and a narrowed spectrum peaked at 13.5 nm. It is reported that the presence of low-Z elements with tin atoms will effectively reduce the average ionization state $\langle Z \rangle$ of the plasma, and hence the recombination continuum [13]. Fujioka *et al* [14] also observed similar narrowing of the UTA using low density targets and attributed it to a reduction of satellite emission from multiply excited Sn ions and opacity broadening during the radiation transport. Theoretical calculations showed [19, 20] that the core tin ions contributing to the UTA at 13.5 nm range from Sn^{9+}–Sn^{12+}, while lower charged species (Sn^{6+}–Sn^{8+}) emit at the longer wavelength side of the UTA (>15 nm). Our results show that decreasing the tin density leads to the quenching of lower ionization states and may be due to a reduction in the amount of cold plasma.

It should be noted that the peak intensity around 13.5 nm did not change when the tin concentration dropped to 0.5%. The estimated CE values for various targets used are also given in figure 4 (inset). The estimated CE values are 1.5 ± 0.1, 1.53 ± 0.08 and 0.76 ± 0.06 for 1%, 0.5% and 0.1% Sn doped foam targets, respectively. Even though EUV spectral measurements showed more or less the same UTA brightness for 100% Sn and 1% and 0.5% Sn doped targets, the estimated CE from the tin doped foam targets are slightly lower and the reason for this phenomenon is presently unknown. The brightness at 13.5 nm of the 0.1% Sn target is considerably lower than that of the other targets and most likely due to the limited number of tin emitters ultimately resulting in poor efficiency.

The spectral features of Sn doped foam targets also contained oxygen emission lines. They are identified as O^{5+} lines at 12.99 nm (2p–4d) and 15.00 nm (2s–3p). Electron temperature is one of the most important parameters in determining the efficiency of the EUV emitting plasma since it determines the ion populations and ionization levels contributing to the UTA. Temperature of the tin doped foam

targets was obtained using the intensity ratio of the O^{5+} lines by assuming local thermodynamic equilibrium (LTE) [21]. The estimated temperatures of the foam targets were 28.5 ± 2.0 eV, 27.6 ± 1.5 eV and 18.0 ± 2 eV for 1%, 0.5% and 0.1% tin doped foam, respectively. These represent the average temperature values of the EUV emitting plasma rather than defining the conditions at a particular stage of its evolution. Nevertheless, the reported optimum temperature required for better in-band CE was ~20–35 eV which agrees well with estimated values [12].

4. Summary

We have investigated the properties of EUV emission from laser created solid density Sn plasma and Sn doped foam plasmas. The spectral features and CE measurements showed that the EUV in-band efficiency was not much lowered when the tin concentration was reduced from 100% to 0.5%. This implies that the optimal tin concentration required for EUV plasma emission is less than 1%. The EUV emission from tin doped targets also showed better contrast between in-band and out of band radiation with narrower UTA spectral profiles. This indicates that the reduction of Sn density leads to a quenching of the population of lower ionization states that contribute the UTA. The spectral narrowing will definitely reduce the thermal loading to EUV collection optics since a reduced bandwidth spectrum would fall onto the multi-layer mirrors in the lithographic system. Moreover, tin doped foam targets are more promising for ion debris mitigation using a magnetic field since it is much easier to block low-Z ions than tin ions [22]. Our preliminary results on the controlling of ions using a magnetic field agrees with this statement [23].

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