Generation and characterization of spatially distributed laser produced plasma extreme ultraviolet source

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ABSTRACT

Two and three dot laser produced plasma extreme ultraviolet sources have been generated using a Fourier diffractive optical element (DOE). The DOE featured a >90% diffraction efficiency and a power handling capability of >100 MW. The plasmas were formed on a planar bulk tin target by pulses from a Nd:YAG laser delivering up to 360 mJ per pulse in a time of 15 ns (full-width half-maximum intensity) at the fundamental wavelength of 1064 nm. After passing through the DOE, the laser beam was focused onto the target by a pair of lens. The resulting spot radius was estimated to be 8.2±0.2 μm $1/e^2$ on the target. The extreme ultraviolet radiation emitted by the plasma was imaged using a 122 μm imaging slit in conjunction with the 38 μm slit of the spectrometer. The one dimensional image of the laser produced plasma extreme ultraviolet source, together with its spectrum, was recorded by an absolutely calibrated Jenoptic 0.25 m EUV spectrograph. The spectrograph was located at an observation angle of 45 degrees with respect to the target. The vacuum chamber and spectrograph were both maintained at a base pressure of 10^{-6} Torr. The recorded 1D spatial distribution and EUV spectra demonstrate the feasibility of EUV patterning by the novel optical method. The characteristics and potential applications of this method are investigated in this paper.

Keywords: LPP, EUV, lithography, DOE, patterning

1. INTRODUCTION

Extreme ultraviolet lithography (EUVL) emerges as one of the most promising techniques for next generation lithography (NGL)[1,2] beyond its 193-nm-based optical predecessors. It has a lower cost of ownership for high volume manufacturing (HVM) compared with other methods[3] and is believed to be the choice for practical mass fabrication. However, this technology could still be improved in some aspects to be more competitive. For example the trade-offs between in-band (the 2% band centered at 13.5 nm) extreme ultraviolet (EUV) power and the étendue.[4] The cost, complexity and life span of the sophisticated EUV reflective masks may be another concern.

Due to the reflectance (approximately 65%) of a Mo/Si multilayer mirrors, the typical overall transmittance of an EUV lithography tool is approximately 1%, as the EUV radiation must undergo 10 reflections in a HVM tool.[5] Consequently, the in-band EUV source power must be scaled up to meet HVM requirements.[6] Current EUV lithography sources are either the discharge produced plasma or the laser produced plasma (LPP).[7,8] Due to the strong absorption around the EUV wavelengths, a fraction of the in-band emission might be quickly re-absorbed by the plasma itself.[9–11] This self absorption limits the power from a point EUV source.[12] For a nominal pulse repetition rate of the excitation laser, higher power EUV emission would rely on the production of even larger plasmas. The étendue then increases quickly and eventually exceeds the acceptable range of the EUV lithography tool.[4] This limits the useful in-band power and hence the overall throughput. If it is not possible to increase the EUV power generation, then reducing the loss of the system may be an alternative. Compared with EUV optics, conventional optics are much more efficient, possessing a reflectance or transmittance up to 99.8%. If part of the EUVL system was replaced by conventional optics, the overall throughput should could improved and with a lower cost. Moreover, the mature technology of refractive and diffractive optics could

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grant more flexibility. Base on this concept, we propose to pattern a LPP EUV source directly onto the target surface by optical means and then project the EUV wavelengths for lithography. In this geometry, the setup from the laser to the EUV pattern generation uses only conventional optics, EUV optics appear only after the EUV target. Since the laser energy is spread out on the target to form the pattern, the problems associated with a single point high power EUV source are removed. The absence of an EUV reflective mask, whose use imposes painstaking handling requirements, may be another advantage, since the laser beam has been transformed to give the desired pattern by an optical element before arriving at the target. This paper aims to evaluate the feasibility of generating patterned plasmas as well as investigating the spectral and spatial distribution of the resulting in-band EUV by means of a simple experiment.

2. EXPERIMENTAL CONFIGURATION

Based on theory of diffraction, DOE can be designed computational to transform light beam into virtually any pattern.[13] Depending on its constituent materials, a DOE may possess a diffraction efficiency >90% and a power handling capability >100 MW.[14,15] In this experiment a DOE was used to shape the intense Nd:YAG laser pulse before forming the LPP. For simplicity, in this study only two and three point foci were employed to simulate the patterning and were generated by custom made uncoated silica DOEs with clear apertures of 6 mm in diameter. These DOEs can be considered as diffractive beam splitters as they equally split the incident laser beam into two or three beams. The fan out angles between the output beams were 6.0 and 3.0±0.1 degrees respectively and the diffraction efficiencies for both were 80±3%. The schematic of the experiment is shown in the Fig. 1. A Nd:YAG laser delivering up to 360 mJ per pulse in a time of 15 ns (full-width half-maximum (FWHM) intensity) at the fundamental wavelength of 1064 nm was used to excite the plasma. The beam profile was Gaussian both before and after the DOE. After passing through the DOE, the laser beams were focused onto the target by a pair of lens. The focal length of lens 1 and 2 were 75 and 25 mm, respectively. The distance between them was approximately 300 mm. The resulting spot radii were estimated as 8.2±0.2 μm $1/e^2$ on the target for both DOEs assuming that they have diffraction limited performance.[16] The EUV generated from the plasma was imaged by the 122 μm imaging slit of the Jenoptic tool wheel in conjunction with the 38 μm slit of the spectrograph. The one dimensional image of the LPP EUV together with its spectrum was recorded by an absolutely calibrated Jenoptic 0.25 m EUV spectrograph. The spectrograph was located at an observation angle of 45 degrees with respect to the target.[11] The CCD was thermoelectrically cooled down to -70°C to minimize thermal noise. The planar bulk tin target was moved after each plasma formation to ensure a fresh and cleaned surface for each measurement. The vacuum chamber and spectrograph maintained a base pressure of 10^{-6} Torr. The laser system, beam delivery optics and the DOE were located outside the vacuum chamber. The system was initially aligned at atmospheric pressure, using alignment lasers, to ensure that the optic axis of the spectrograph was incident on the central position between the two point plasmas and incident on the central plasma formed by the three point plasmas. Fine adjustments were then made to the spectrometer to optimize the signal, after the systems were at the required pressure.

3. RESULTS AND DISCUSSION

The recorded images from the two and three point tin plasmas are shown in Fig. 2 and 3. Plasmas a and c were located closer to the spectrograph. The vertical axis represents the dimensions of the tin target and the horizontal axis gives the spectral wavelength. As the imagining slit limited the signal strength, the images shown represent the accumulation of ten measurements to improve the signal. Their in-band profile are shown in Fig. 4 and 5. The distance between the peaks of the two point plasma was 760±10 μm and between the three point was 380 ±10 μm. The spatial width of the in-band emission inferred from these figures was 260 ±5 μm FWHM. As this value was degraded by the imaging slit size, deconvolution was used to reconstruct the actual peak emission characteristics.[17] A top hat function was used to represent the instrument function of the slit. The resulting spatial width is 180±5 μm which is still an order of magnitude larger than the laser spot size. Due to plasma expansion,[9] the plume travels ∼10 μm in a nanosecond. Absorption of the incoming laser beam occurs primarily in the critical density layer which is within 100 μm of the target surface and the EUV emitting region is larger because of reheating of the plume by the relatively long duration laser pulse. This results in a significantly larger in-band emission width than the laser spot size. Thus to reduce the spatial extent of the in-band emitting region

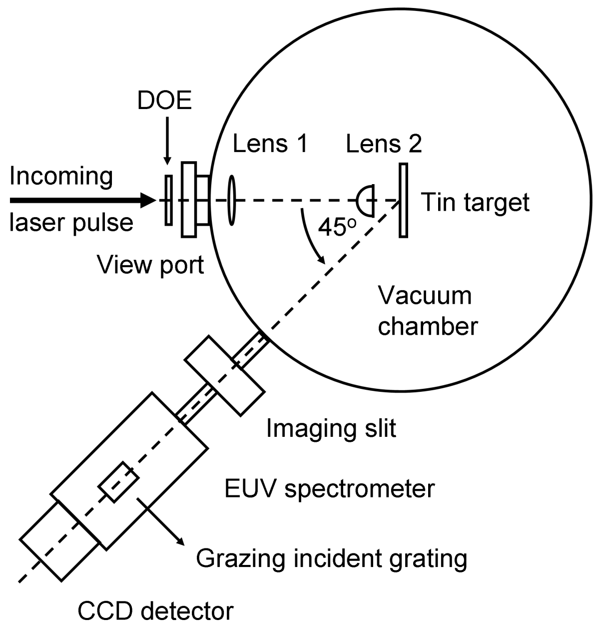

Figure 1. Schematic of the spatial LPP EUV generation and its characterization. The laser beam delivery optics and DOE are outside the vacuum chamber.

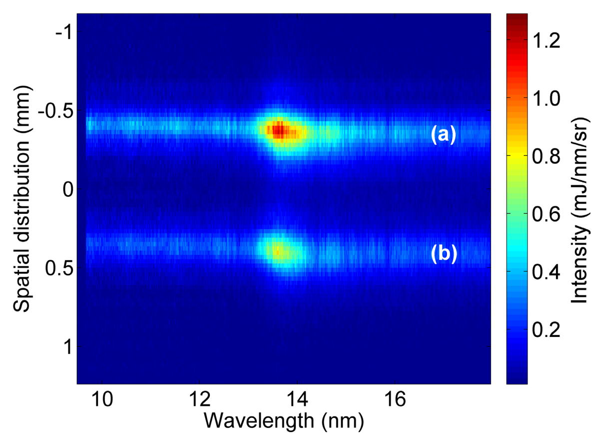

Figure 2. CCD image of the two point tin plasma spectra.

it is necessary to reduce the laser pulse duration and limit the energy so that the emitting stages are abundant only in the region of the plasma focus. For 1 μm resolution of the in-band pattern, the pulse duration would be expected significantly less than 100 ps.[9] However, this would lead to trade-offs between the optimum emission width/volume and the conversion efficiency (CE).[18] Fig. 6 shows the absolutely calibrated spectra from the two point plasma. The spectrum from plasma (b), located further from the spectrograph, has an in-band energy of approximately 75% of that of plasma (a). As the power density and spot size was the same for both plasma (a) and (b), this decrease in intensity can be attributed to plasma (b) being occluded by plasma (a), leading to a reduction in the in-band intensity. The absolutely calibrated spectra from the three point plasma is shown in Fig. 7. Again, the plasma formed closer to the spectrograph, plasma (c) has the greatest in-band intensity. This is also due to the more distant plasmas being occluded by those closer. For both results, the overall in-band CE is less than 1%.

Fig. 8 shows the normalized spectra from the two point plasma. The spectral regions where absorption by a

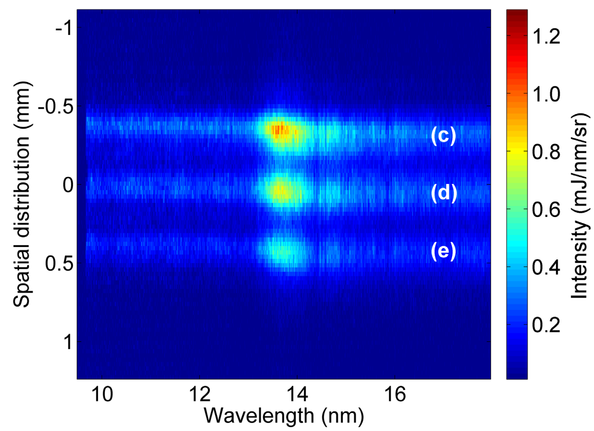

Figure 3. CCD image of the three point tin plasma spectra.

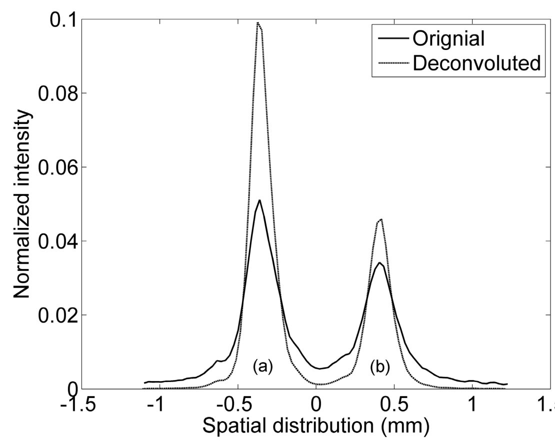

Figure 4. The in-band profile of the two point tin plasma.

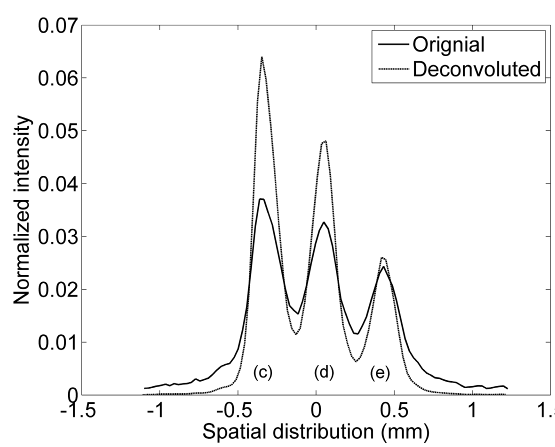

Figure 5. The in-band profile of the three point tin plasma.

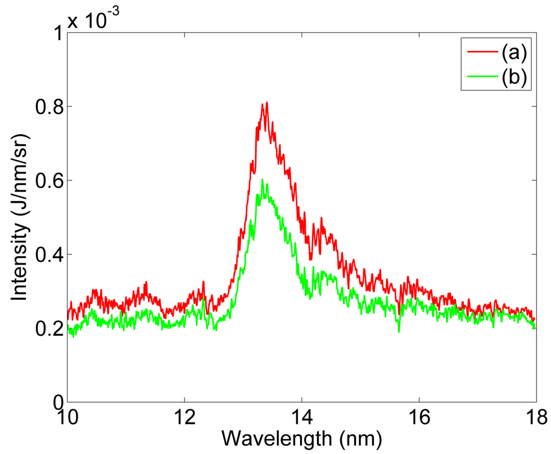

Figure 6. The absolutely calibrated spectra of the two point tin plasma.

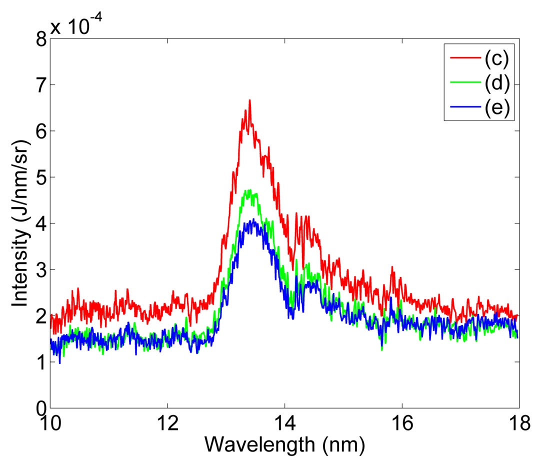

Figure 7. The absolutely calibrated spectra of the three point tin plasma.

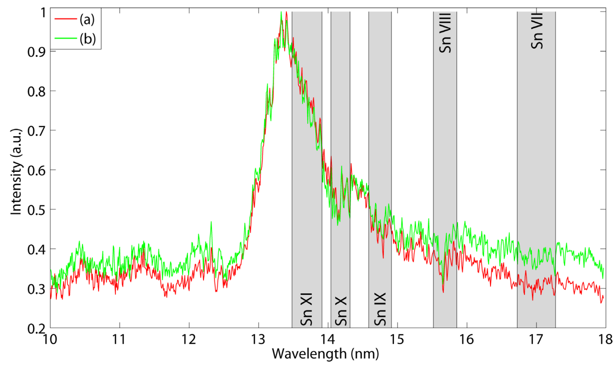

Figure 8. Normalized emission spectra of the two point tin plasma.

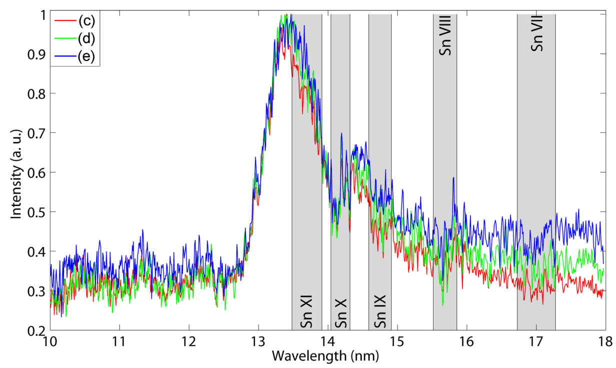

Figure 9. Normalized emission spectra of the three point tin plasma.

particular ion is dominant are highlighted with vertical bands. These bands were determined in a previous study by Morris *et al.* using atomic structure calculations performed using the Cowan suite of codes.[11,19,20] The two point plasmas have a very similar profile in the 12.5 to 14 nm region to the spectrum of Morris *et al.* recorded at an observation angle of 45 degrees, where the profile is very sensitive to absorption by Sn XI. Self absorption features from Sn VII to Sn X are also evident from 14 to 18 nm. For the normalized spectra for the three point plasma, shown in Fig. 9, the 12.5 to 14 nm region shows a slightly different profile to that of the two point plasma. Although the self absorption features from Sn VII to Sn X are evident, there is less self absorption by Sn XI which actually appears to decrease with increasing distance from the spectrometer. This is most like an increase in emission from this spectrum due to the three point plasma being formed at a lower power density than the two point plasma, resulting in the formation of a cooler plasma.

These result so far demonstrates that spatially distributed LPP EUV can be generated according to the laser beam shape. Now, returning to the starting point of this study, which was to attempt EUV patterning by introducing conventional optics. Ideally, if the optics before the EUV pattern generation of a EUV lithography tool can be replaced by conventional optics then the overall throughput should be improved by an order of magnitude. However, all of the parameters will be quite different and some may be challenging. The following is a calculation based on a thought experiment. Assuming first that, 1 μm LPP EUV in-band resolution on the target is achievable by conventional optics and a DOE with 1 ps pulse duration excitation laser. If one want to pattern a 1 mm^2 area on the wafer with 20 nm resolution, the pattern on the target will be 25 cm^2 in size and the lens will have to reduce the pattern by 50 times. If the power density needed on the target is 10^{11} watt/cm^2 for a 1 ps laser pulse, then the laser pulse energy will be 2.5 J. If the CE is 1%, then the EUV energy generated is 25 mJ. For a reduction lens consisting of five EUV mirrors of 65% reflectance, the overall transmittance is about 10%. Then the energy density on the wafer will be 250 mJ/cm^2 which is enough dosage for one exposure. Part of the EUVL system including the EUV reflective mask has been replaced by conventional optics but new problems will be introduced such as large target size and debris mitigation. As this is a concept, more investigation is needed for realization.

4. CONCLUSIONS

A patterned EUV source was proposed by using conventional optics. Two and three point LPP EUV sources have been generated by using DOEs. The in-band linewidth was 180±5 μm which could be limited by plasma expansion. The distance between the plasmas was 380 $\pm$10 μm for the three point plasma. The spectra show slight different compared with a previous study of single point LPP EUV source with the same 45 degree geometry, resulting from the absorption condition and laser intensity. The concept of LPP EUV patterning by using conventional optics is demonstrated. However, more work is needed for realization.

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