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Efficient laser-produced plasma extreme ultraviolet sources using grooved Sn targets

S. S. Harilal,[a)] T. Sizyuk, V. Sizyuk, and A. Hassanein
School of Nuclear Engineering and Center for Materials Under Extreme Environment, Purdue University, 400 Central Drive, West Lafayette, Indiana 47907, USA

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An efficient extreme ultraviolet (EUV) generation method has been developed with the use of a CO_2 laser-produced plasma from a grooved target. A ~5% conversion efficiency from laser to 13.5 nm photons was obtained with the use of grooves in a tin target or by repeated laser pulse shots at the same target position. Modeling studies proved that the groove target controls the hydrodynamic expansion of the plasma leading to confinement which prevents the plasma escaping from the EUV production zone. © *2010 American Institute of Physics*. [doi:10.1063/1.3364141]

Extreme ultraviolet lithography (EUVL) is a promising technology for developing smaller and faster microchips with feature sizes of 32 nm or less in the coming years. The essential requirement for EUVL is to have a reliable, clean, and powerful light source at a wavelength near 13.5 nm. A laser-produced plasma (LPP) radiation source from Sn target is one of the most promising options for the EUVL light source.[1] A suitable LPP source will require a high conversion efficiency (CE) of the incident laser pulse energy to EUV radiation in a 2% bandwidth centered at 13.5 nm (commonly called "in-band"), as well as nearly complete control of debris transport to collection mirror surfaces.[1]

Developing an EUVL source with high in-band CE is imperative, as this reduces the costs of production and ownership for EUVL light source systems. The CE of Sn LPPs depend on several laser and target parameters, including laser wavelength,[2] pulse duration,[3,4] intensity,[4] target geometry,[5] and target mass density.[6,7] Previously several methods were employed for improving the CE of a Sn plasma which includes prepulsing,[8] forced recombination,[9] low-density Sn targets.[6] It has been shown previously that[10,11] structured targets provide higher EUV and x-ray yield. In this letter, we report considerable enhancement of EUV emission from a CO_2 laser-produced grooved Sn plasma compared to a plasma generated from planar targets. Our results also suggest that grooved targets can be used for maintaining high EUV CE values for repeated pulse operation. EUV pinhole images as well as modeling studies employing the high energy interaction with general heterogeneous target systems (HEIGHTS) simulation package showed enhancement in CE is due to better plasma confinement by the grooved target.

The schematic of the experimental set up is given elsewhere.[4] Pulses from a CO_2 laser emitting at 10.6 μm are used for producing the plasma on either a planar or grooved Sn target. The CO_2 laser pulse width is varied in the range 25–55 ns full width half maximum (FWHM) employing a plasma shutter device.[12] The laser pulse is focused on to the target of interest using a f/10 meniscus ZnSe lens. The target is placed at the center of a vacuum chamber that is evacuated to pressures $\sim 10^{-4}$ Pa. We used an absolutely calibrated instrument (Power Tool) for measuring in-band energy[4] which consists of two Zr filters, one Mo–Si multilayer mirror, and an EUV photodiode. For estimating CE, we assumed a hemispherical symmetry of the plasma geometry, and that the output from the power tool is integrated over a 2π solid angle. An EUV transmission grating spectrograph is used for recording the spectral features of the Sn plasma. Both the spectrograph and power tool are attached to the chamber at 45° with respect to the laser beam. EUV images of the plasma were obtained using a home-built pinhole camera with a magnification ~10. The pinhole camera employs a Zr filter which filters radiation in the wavelength range 7–15 nm.

A CO_2 laser with an intensity of a few $\mathrm{GW/cm^2}$ is capable of ionizing materials to create plasmas with high temperature and densities. Typically, Sn plasmas emit very strongly in the EUV region when the temperature of the plasma is in the 20–40 eV range.[5] The radiation emitted can be controlled by fine tuning the plasma temperature which is inherently dependent on laser and target properties. Apart from that the opacity of the plasma can drastically reduce the EUV emission due to self-absorption. So it is essential to have a plasma with proper electron density and temperature along with maximum size (should be within the entendue limits of the condenser mirror) for the longest EUV lifetime for optimal EUV CE. The in-band energy of a Sn plasma consists of a very large number of closely spaced Sn spectral lines and has the appearance of a band commonly called an unresolved transition array (UTA).[13] Our recent studies showed that the CE of a laser-plasma depended strongly on laser focal spot.[4] The best CE values are obtained at either sides of the best focal position. Density analysis of the CO_2 LPP showed steep-density gradients at the best focal position, and a reduction of CE at the best focal position, which is explained by the lack of efficient coupling between the laser and the plasma.

Typically 1.06 μm LPPs provided a CE (Refs. 5–7) around 2%. We estimated a CE ~2.7% with a CO_2 LPP from planar Sn targets with FWHM of 30 ns. The laser intensity at the target was $6 \times 10^9\ \mathrm{W/cm^2}$. CO_2 LPPs provide higher CE due to their low opacity inherently caused by two orders of magnitude less plasma critical density. However, the measured CE values are found to increase by repeated laser shots incident at the same target position. The estimated CE from a Sn plasma by repeated laser shots at the same target location

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[a)] Electronic mail: sharilal@purdue.edu.

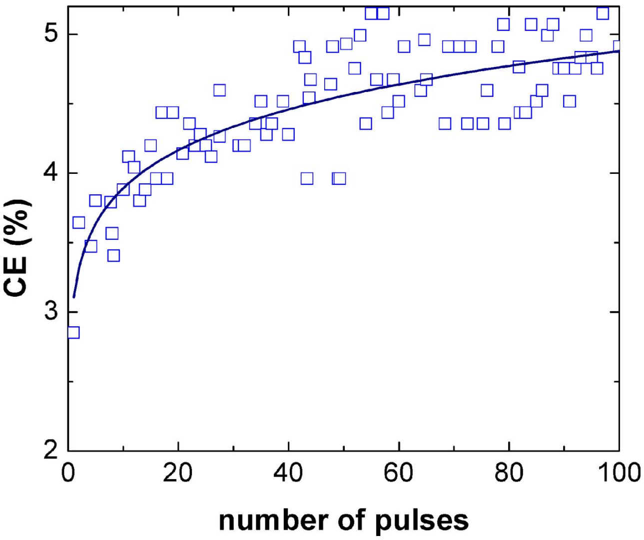

FIG. 1. (Color online) The estimated in-band CE from CO_2 laser-produced Sn plasma by repetitively hitting the laser at the same spot.

is shown in Fig. 1. The spot size and laser repetition rate used were 225 μm and 1 Hz. It can be seen from the figure that a CE value of 2.7% is obtained with a fresh Sn target, and the CE is increased to 4.5% by repeated shots at the crater location produced by previous pulses. The CE values increase gradually and reach a peak value after 35–40 shots. We repeated the experiments with longer durations CO_2 pulses (35–55 ns FWHM) under similar laser irradiance conditions. It has been noticed that plasmas emit efficiently only with shorter duration pulses, and maintain higher CE values for a large number of pulses compared to longer CO_2 pulses. With larger pulse durations, the lifetime for maintaining higher CE values for a large number of pulses is considerably reduced.

For an EUVL LPP source set up, the laser should be operated at a high repetition rate. Our studies indicated that a grooved target is a promising option if we move the target with appropriate velocity. We fabricated tin target grooves (Fig. 2 inset) with various widths. Figure 2 shows the estimated CE from a 400 μm wide, 200 μm deep grooved target moving at a fixed velocity of 15 μm/s with laser operating at 1 Hz frequency. For obtaining highest CE, the groove width should be maintained between one to two times the focal spot size. The obtained CE values behaved similar to a planar target when the groove width is much smaller than the spot size or greater than double the spot size. For example, the highest CE is obtained with groove width of 300 and 400 μm with a 225 μm laser spot size. Similar results are obtained with 500 μm groove width when the spot size is increased to 325 μm. However, the standard deviations in the estimated CE values are found to be higher in a target when the groove width approaches twice the spot size. The above results clearly showed that with a grooved target we can easily obtain and maintain a high CE consistently.

We recorded the EUV spectra from a planar as well as grooved target and noticed negligible differences in their spectral features even though higher spectral intensity is observed from a grooved target. However, time integrated EUV images obtained using a EUV pinhole camera showed dramatic differences in the plasma volume. Typical EUV images recorded with planar and grooved targets are given in Fig. 3(a). It should be mentioned that the EUV images represent the photon emission coming from the entire Sn UTA rather than the in-band photons. EUV emission features clearly show the UTA emission from a planar target follows typical hemispherical emission geometry while the spatial extent of

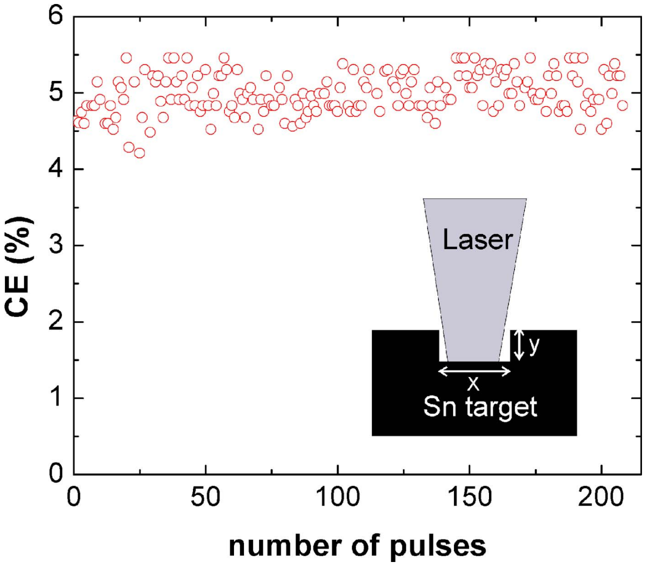

FIG. 2. (Color online) The CE obtained from a 400 μm wide, 200 μm deep grooved target. The spot size used in the measurement was 325 μm. Inset shows the schematic of the channel target (x and y are the width and depth of the channel target).

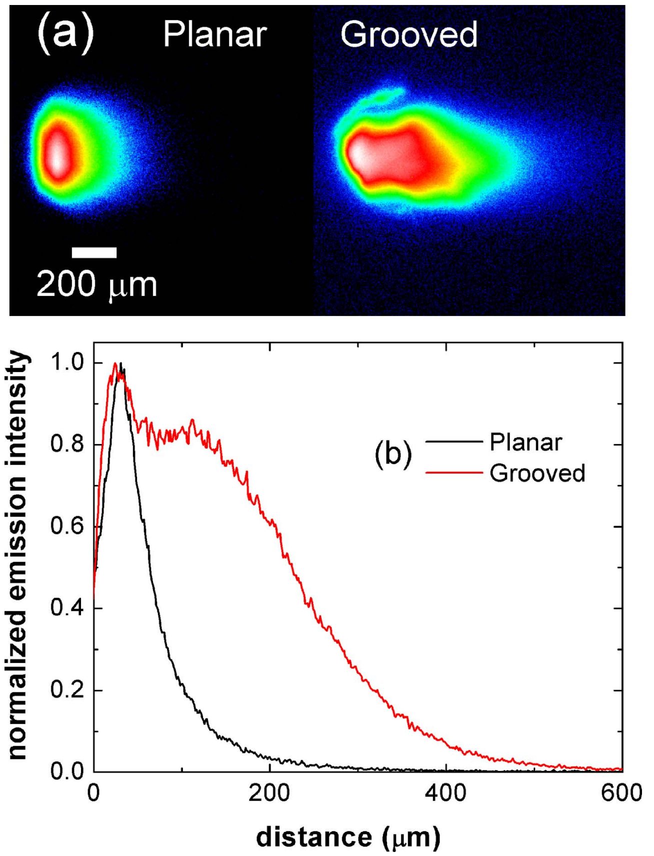

FIG. 3. (Color online) The EUV images obtained from planar and groove targets (a). The images are given in logarithmic scale for better clarity. Intensity counters obtained from EUV images are given in (b).

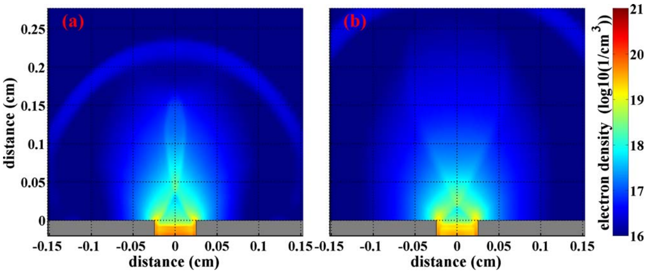

FIG. 4. (Color online) The estimated density distribution HEIGHTS 15 ns after the peak of the laser pulse (a) and at the end of the laser pulse (b) are given.

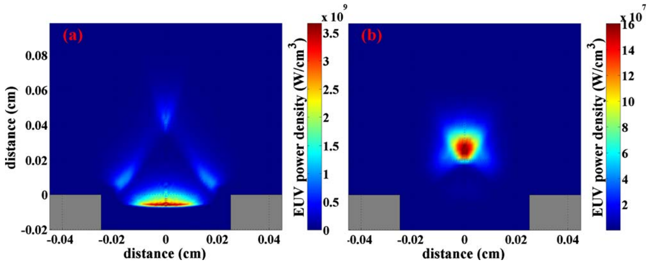

FIG. 5. (Color online) The estimated in-band EUV photon distribution using HEIGHTS 15 ns after the peak of the laser pulse (a) and at the end of the laser pulse (b) are given.

the EUV emission is largely enhanced with a grooved target. EUV emission from the plasma could be enhanced either by increasing the plasma scale-length and/or volume. Figure 3(b) shows the emission intensity as a function of distance along the direction of plume expansion for Sn planar and groove targets. These plots are obtained from the EUV images and for easier comparison, where each profile has been normalized to its maximum intensity. The EUV emission from a grooved target showed a double hump structure. It indicates that a plasma from a grooved target creates a secondary hot region in front of the target. Previous studies showed that presence of cavities modify the plasma temperature and density profiles considerably.[14]

In order to get more insight on EUV emission enhancement from the grooved target, we performed modeling studies using the HEIGHTS computer package. Details of the HEIGHTS code can be found elsewhere.[5,15] We used experimentally recorded laser temporal profiles and intensities two-dimensional cylindrical modeling calculation. One of the main goals for the modeling studies is to understand spatial hydrodynamic evolution and confinement process with a grooved target. Previous modeling studies using HEIGHTS showed planar targets provide greater geometrical confinement in comparison to the spherical target case leading to higher CE.[5]

Figure 4 shows the density distributions at various times after the peak of the laser pulse with a groove width of 500 μm and depth of 200 μm. The spot size used for modeling studies was 325 μm. The electron density inside the groove reaches a maximum of $10^{19}/\mathrm{cm}^3$ at the earliest time. Compared with a planar target, where the plasma expands freely and the density drops rapidly,[4] a grooved target is found to control the hydrodynamic expansion by confining the plasma leading to a denser region appearing in front of the target at a later time. Hence the geometrical hydrodynamic confinement prevents the energy loss from the EUV production zone. We utilized the HEIGHTS Monte Carlo model for radiation transport simulation which calculates the location and intensity of the photon source for EUV output in 2π sr. Figure 5 gives the source of EUV photons estimated using HEIGHTS at various times after the peak of the laser pulse. In the planar target, the most significant EUV production zone is located around the laser focal point as seen in the EUV pinhole images. In contrast, for a grooved target, in addition to the EUV emitting zone at focal spot, a secondary emitting zone appears. This is consistent with time-integrated images obtained from a grooved target where we noticed an EUV secondary production zone formed apart from EUV emission from the target surface.

Modeling studies show the plasma expansion from a groove is restricted by the groove walls, which leads to efficient confinement and heating. For optimal CE, high electron density with stable temperatures should be created. The temperature control in the plasma confinement region is dictated by energy loss. Our calculation showed that the denser region caused by plasma confinement is heated to 30–50 eV which is the ideal condition for 13.5 nm photon production. The hydrodynamic effect caused by confinement within the grooved target and laser absorption by the denser region prolongs the EUV emission time. It should be mentioned that it is essential to create a plasma with appropriate electron density and temperature along with maximum size for the longest EUV lifetime to get the optimal CE.

In summary, an efficient method for EUV generation has been described with the use of a CO_2 LPP and a grooved tin target. A CE $\sim$5% from laser to 13.5 nm was obtained with the use of a grooved Sn target. We demonstrate that higher conversion efficiency values can easily be maintained by moving a grooved target with appropriate velocity. Modeling studies showed high CE with a groove target is due to hydrodynamic confinement of the plasma cause by the groove, leading to an efficient EUV production zone slightly outside the target.

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