Investigation on the interaction of long duration Nd:YAG laser pulse with Sn plasma for an EUV metrology source

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ABSTRACT

The effect of pulse duration of Nd:YAG laser with wavelength of 1.064 μm on the generation of 13.5 nm extreme ultraviolet (EUV) emission and ions was investigated. It was found that almost constant in-band (2 % bandwidth) conversion efficiency (CE) is obtained from Sn plasmas irradiated with Nd:YAG laser pulse with durations from 0.13 to 30 ns. It was also noted that Sn ions kinetic energy generated with a 30 ns laser pulse is much less than those with 0.13 and 7 ns laser pulses. The measurement on the narrow-band EUV imaging showed that EUV source size strongly depends on laser intensity instead of pulse duration and small EUV size is still possible with laser pulse duration as long as 30 ns. The key reason for the constant CE and the still small EUV source size obtained with long laser pulse duration comes from the small laser focal spot employed in the present experiment, i.e., 40 μm (FWHM). This research shows that an efficient and bright EUV source is feasible with a long pulse duration Nd:YAG laser. The lower peak intensity of EUV emission due to the long pulse duration makes the EUV source more suitable for EUV metrology.

Keywords: EUV lithography, metrology source, laser plasma, pulse duration

1. INTRODUCTION

High-resolution extreme ultraviolet lithography (EUV) actinic metrology is necessary to develop and inspect defect-free mask and resist for EUV lithography (EUVL) [1]. A high-brightness in-band (2% bandwidth) 13.5 nm EUV source is required for the EUV metrology. Recently, 13.5 nm (EUV) source attracts extensive efforts mostly motivated by EUVL, which is the most promising candidate for the next generation lithography tools used in semiconductor industry to produce microchips with electrode size down to 22 nm or smaller [2]. The requirements of the wavelength and bandwidth of the EUV source come from the limitation of the optics used in EUV lithography tool. Up to date, the only commercially available EUV optics with high reflectivity at normal incidence is multilayer Mo/Si interference mirror, which has normal-incident reflectivity of 70 % with bandwidth of 2% centered at 13.5 nm. There are two main candidates for the EUV source used in high volume manufacturing (HVM) EUVL tool, i.e., hot plasmas produced by electric discharge and high power pulsed laser. Laser-produced plasma is more suitable to be used as EUV metrology source due to intrinsic smaller EUV source size. For the EUV source based on laser-produced plasma, Nd:YAG laser with wavelength of 1.064 μm and CO_2 laser with wavelength of 10.6 μm are the two main laser drivers used in EUVL source. Nd:YAG laser is a better choice to drive a small EUV source since its shorter wavelength, which makes it easier to get a small focal spot size.

Compared with Nd:YAG laser, CO_2 laser has shown more potential to scale the EUV source to high power because of high in-band conversion efficiency (CE) from laser to 13.5 nm in-band EUV emission, better laser beam quality due to its gas laser medium, and high reliability [3][4]. The most critical limitations of high power solid-state laser to apply to

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HVM EUV lithography tool are its poor laser beam quality and not-so-good reliability induced by nonlinear effects, for example, thermal lensing and birefringence, induced by the thermal load inside its solid-state laser medium. The nonlinear effects strongly depends on laser intensity inside laser medium [5], characterized by B integral, defined as, $B = \frac{2\pi}{\lambda}\int n_2 I dl$, where λ is laser wavelength, n_2 is the nonlinear coefficient, I is laser intensity, and l is the length of laser medium. The use of long laser pulse could reduce laser intensity inside laser medium and relax the limitations.

For Nd:YAG laser produced Sn plasma, there have been a couple of works to investigate the effect of laser pulse duration to the in-band CE [6][7]. Ando et al. showed that, with a large laser focal spot, i.e., 500 µm, the optimum laser pulse duration is ~ 2 ns [6]. However, Sequoia et al. showed that with laser focal spot sizes from 60 to 270 µm the in-band CE is almost constant with pulse durations from 0.5 to 15 ns [7]. The discrepancy comes from the difference between the laser focal spot sizes. One possible idea from the comparison is that if the focal spot is reduced further the constant high CE may be obtained with longer pulse duration.

In this presentation we proved that using a 1.064 µm laser pulse with duration as long as 30 ns and with a 40 µm laser focal spot, high in-band CE is still available, the EUV source size is still comparable with that of the laser focal spot, and ions kinetic energy is much less than those of 0.13 and 7 ns laser pulses.

2. EXPERIMENTAL SETUP

A Q-switched Nd:YAG laser (Spectral-Physics, Qunta-Ray Pro 230) was modified to produce 1.064 µm laser with variable pulse durations 10 to 40 ns. The laser consists of a seeded Nd:YAG oscillator and two stages of Nd:YAG amplifiers. The voltage of the flash lamp of the oscillator, the high voltage of the Q-Switch driver, and delay time between the Q-Switch and flash lamp are adjusted to get laser pulse duration from 10 to 40 ns. Typical waveforms of laser pulse with various durations are shown in Fig.1. It is seen that longer pulse has a slower rising slope as compared with that of shorter pulse. The effect of the rising slope on ions kinetic energy will be discussed in section 4. With two stages of amplifiers, laser pulse energy can be up to 150 mJ at 40 ns. Laser focal spot size (FWHM) is measured to be 40 µm by an optical image relay system equipped with a CCD camera. A typical photo of 30 ns laser focal spot is shown in Fig.2. The central hot spot has a diameter of 40 µm. However, a part of laser energy is located outside of the hot spot. The narrow-band EUV images to be presented later showed that only the part of laser energy located within the hot spot can efficiently contribute to the generation of the EUV emission. No significant variation of the intensity distribution in the focal spot was noted with various laser pulse durations.

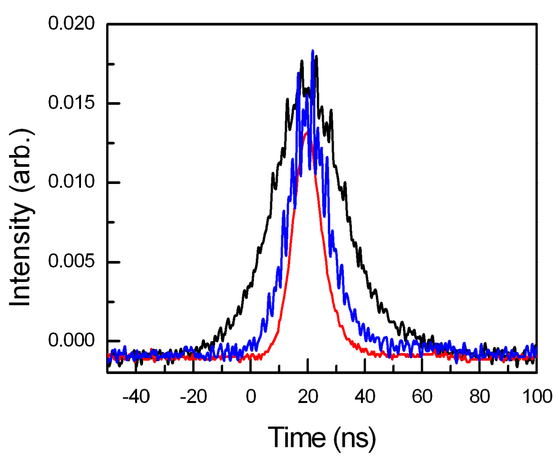

Figure 1. Waveforms of Nd:YAG laser with various pulse durations

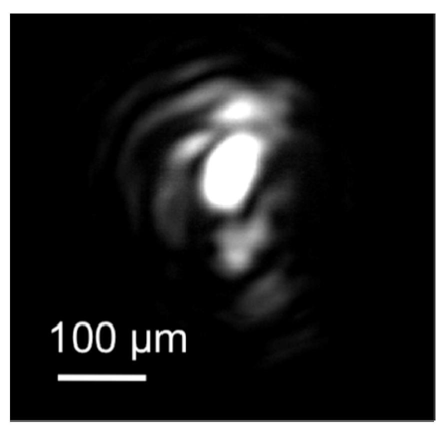

Figure 2. Image of 30 ns laser focal spot

A Q-Switched Nd:YAG laser (EKSPLA SSL-35) equipped with a stimulated Brillion scattering laser pulse compressor is used to produce laser pulse with duration of 0.13 ns. The short pulse laser has a little bigger focal spot, i.e., 60 μm, as compared with those of long pulse.

The experimental arrangement is shown in Fig.3. The combination of a half waveplate and a polarizer is used to adjust laser pulse energy onto the target. A quarter waveplate is inserted after the polarizer to avoid the reflected laser light from the plasma to go back to laser cavity. A fast photo diode (EOT ET-2000) and a calorimeter (Ophir PE50) are used to monitor laser pulse shape and energy for each shot.

In-band CE is measured by an absolutely calibrated EUV energy monitor (Jena Optiks E-Mon), which is installed in the laser incident plane with an angle of 39 degrees with respect to the target normal. The CE is obtained by integrating over 2π solid angle. Soft x-ray spectrum is observed with a transmission grating spectrometer (TGS) with a spectral resolution better than 0.1 nm. Energy spectrum of the ions from the plasma is obtained with a Faraday cup placed at an angle of 10 degrees with respect to the target normal. The distance between the Faraday cup and the plasma is 15 cm. The Faraday cup is biased with a –30 V voltage to avoid electrons. Temporal shape of EUV emission is observed with a narrow-band EUV detector, which consists of a Zr filter, a multilayer Mo/Si interference mirror, and a fast EUV photodiode (International Detector IRD AXUVHS4). The signal of the EUV detector is recorded with digital oscilloscope with a 500 MHz bandwidth (Tektronix TDS5054B-NV). The rising time of the system is ~ 1 ns. The bandwidth of the narrow-band EUV detector is 4 % center at 13.5 nm. The EUV image of the plasma is observed with a narrow-band EUV imaging system, which has a similar arrangement with that of the narrow-band EUV detector except for replacing the EUV photodiode with an x-ray CCD camera. The EUV imaging system has a spatial resolution better than 5 μm with a 10× magnification. The narrow-band EUV imaging system is installed in the laser incident plane with an angle of 90 degrees with respect to the target normal. So side-view of the plasma along the line of laser incidence is recorded.

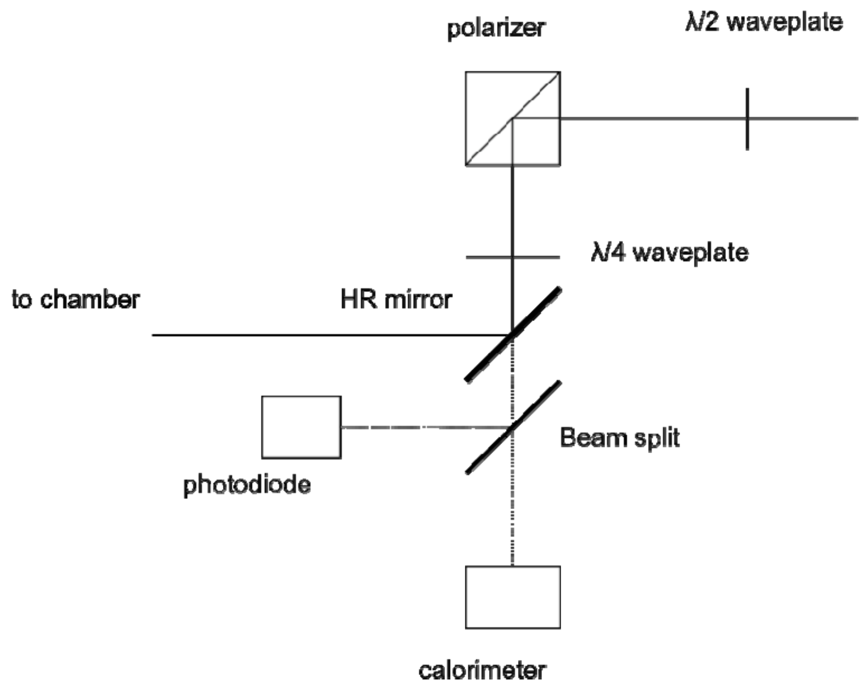

Figure 3. Experimental arrangement for the interaction of long duration laser pulse with Sn plasma

Target used in present experiments is always high-purity Sn plate with a thickness of 1 mm. The target is placed in a vacuum chamber with pressure lower than 10^{-6} Torr. The target is mounted on 3-dimention-translation stage and is moved after each shot to keep fresh. Laser is incident onto the target surface at the normal direction. A plano-convex F/10 lens is used as the focusing lens.

3. RESULTS

In-band CEs from Sn plasma irradiated with Nd:YAG laser pulse with various durations of 11, 15, 20, 25, 30, and 40 ns are shown in Fig.4. Laser intensity is optimized to obtain the highest in-band CE for the individual laser pulse durations. Laser intensity for the data shown in Fig.4 is constant at 1×10^{11} W/cm^2. It is seen that the in-band CEs are almost constant from 11 to 30 ns, i.e., 1.6 %. For 40 ns laser pulse, the CE is lower, i.e., 1.2 %. This is consistent with the results with durations from 0.5 to 15 ns as mentioned in ref.7. For comparison, the in-band CE obtained with 0.13 ns laser pulse as a function of the focusing lens position respect to the best of focus is shown in Fig.5. Laser pulse energy is 12 mJ. It is seen that the optimum in-band CE is obtained with the focusing lens located at a distance of 1 mm off the best of focus. The similar in-band CE is seen from Fig.4 and 5 with laser pulse durations from 0.13 to 30 ns.

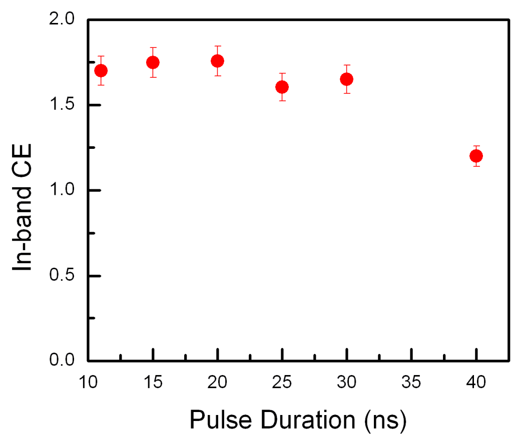

Figure 4. In-band CE as a function of laser pulse durations

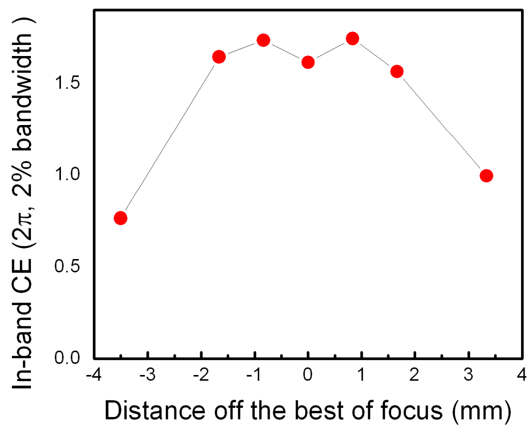

Figure 5. In-band CE from Sn plasma irradiated with 0.13 ns laser pulse as a function of lens position

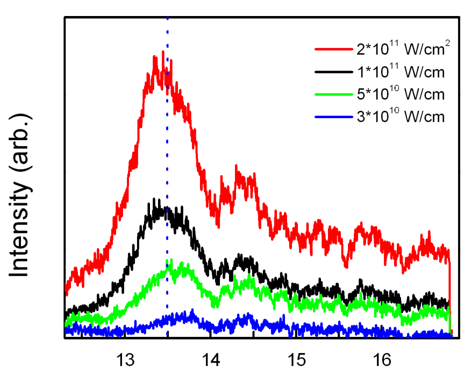

Figure 6. Soft x-ray spectra of Sn plasma irradiated with 30 ns laser pulse with various laser intensities

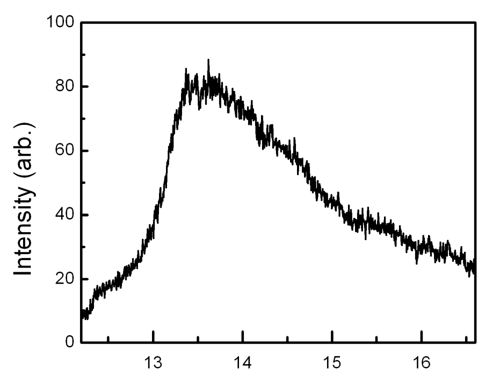

Figure 7. Soft x-ray spectrum of Sn plasma irradiated with a 0.13 ns laser pulse

In order to understand the constant in-band CE obtained over wide laser pulse durations, soft x-ray spectra from Sn plasma irradiated with Nd:YAG laser pulse with various pulse durations were observed. No significant difference was noted among the spectra obtained with laser pulse durations from 11 to 30 ns. The typical results of 30 ns and 0.13 ns are shown in Fig.6 and Fig.7 respectively. It is seen in Fig. 6 that for 30 ns laser pulse with laser intensity above 5×10^{10} W/cm^2 the spectral peak is always located at ~ 13.5 nm. The lower intensity, i.e., 3×10^{10} W/cm^2, produces a flat spectrum. It was also found that the in-band CE is constant with laser intensities from 5×10^{10} to 2×10^{11} W/cm^2. It is seen in Fig.7 that a little spectral dip is located ~ 13.5 nm, which due to re-absorption of 13.5 nm EUV emission in the Snplasma driven with 0.13 ns laser pulse even with a 60 μm focal spot.

Temporal shape of the in-band EUV emission from Sn plasma was observed with various laser pulse durations. The results for 0.13, 12, and 32 ns laser pulses are shown in Fig.8, 9, and 10 respectively. For comparison, the corresponding laser waveforms are also included in the figures. In Fig.8, two kinds of laser waveforms are plotted, one is measured with a fast photodiode (EOT ET-2000) and the same oscilloscope used to record the EUV waveform (solid red line), and the one measured with an optical correlator (dashed pink line). The correlator gives out the correct pulse duration, 0.13 ns. Since the rising times of the two photodiodes used for laser and EUV emission are similar, i.e., both < 200 ps, the broadened pulse duration measured by the photodiode equipped with the oscilloscope, i.e., 1.1 ns, gives the upper limit of the time resolution of the two systems used to measure laser and EUV.

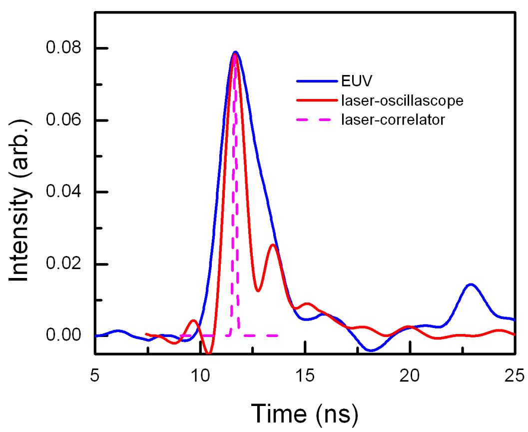

Figure 8. Waveforms of 0.13 ns laser pulse and its EUV emission

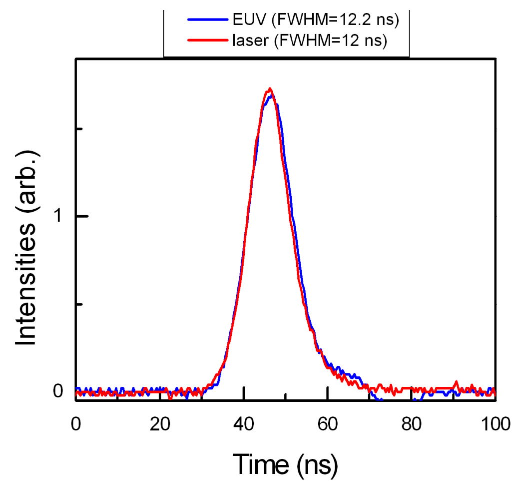

Figure 9. Waveforms of 12 ns laser pulse and its EUV emission

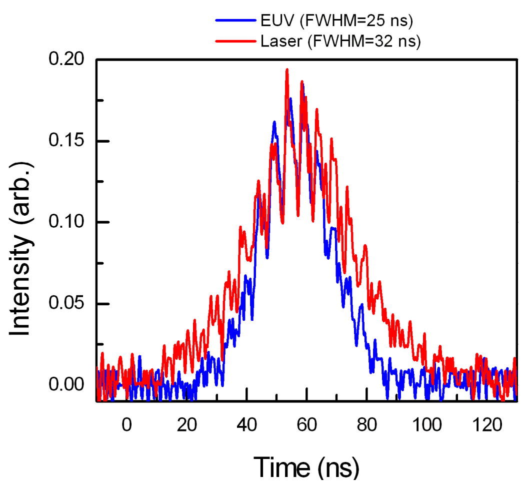

Figure 10. Waveforms of 32 ns laser pulse and its EUV emission

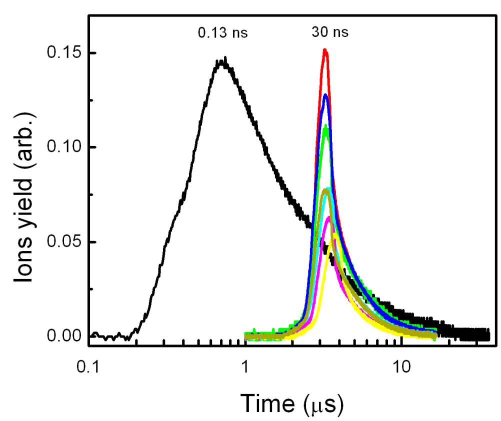

Figure 11. Time of flight of ions from Sn plasmas irradiated with 0.13 and 30 ns laser pulses

It is seen in Fig.8 that with 0.13 ns the EUV emission is much longer than that of laser, i.e., 2.3 ns. From Fig.9, it is seen that with 12 ns laser pulse the temporal shape of the EUV emission just follows with that of laser pulse. For longer laser pulse, like 32 ns, the EUV emission is shorter than that of laser pulse. The reason is that both the rising and falling slopes can't efficiently generate 13.5 nm EUV emission due to their low intensities. It is also shown that the longer laser pulse the long EUV emission pulse is result.

Fig.11 shows the time of flight of Sn ions from the plasma irradiated with 0.13 and 30 ns laser pulses. The different lines marked under 30 ns are obtained with various laser intensities from 1×10^{10} to 2×10^{11} W/cm^2. Laser intensity for 0.13 ns laser pulse is 1×10^{12} W/cm^2, which is necessary to obtain high in-band CE. It is seen in Fig.11 that for 30 ns laser pulse the peak of ions population is always located around 3 μs despite different laser intensities. However, for 0.13 ns, much faster ions with the peak located at ~ 0.7 ns are result.

In order to check the effect of laser pulse duration on the EUV source size, narrow-band EUV images of Sn plasmas irradiated with various laser pulse durations were observed. The results of 15 and 30 ns laser pulses with various laser pulse energy are shown in Fig.12. Laser is incident from right-hand in Fig.12. It is seen that with the same pulse duration the EUV source expand significantly with increasing of laser intensities. With the similar laser intensity, like the pictures of 15 ns with 35 mJ and that of 30 ns with 65 mJ, and so on, the EUV source sizes are similar despite of laser pulse duration. This shows that the EUV source size strongly depends on laser intensity instead of laser pulse duration. It was also noted that for the case of 30 ns laser pulse with pulse energy of 65 mJ and laser intensity of 1×10^{11} W/cm^2 the EUV size (FWHM) is comparable with that of laser focal spot, i.e., 40 μm.

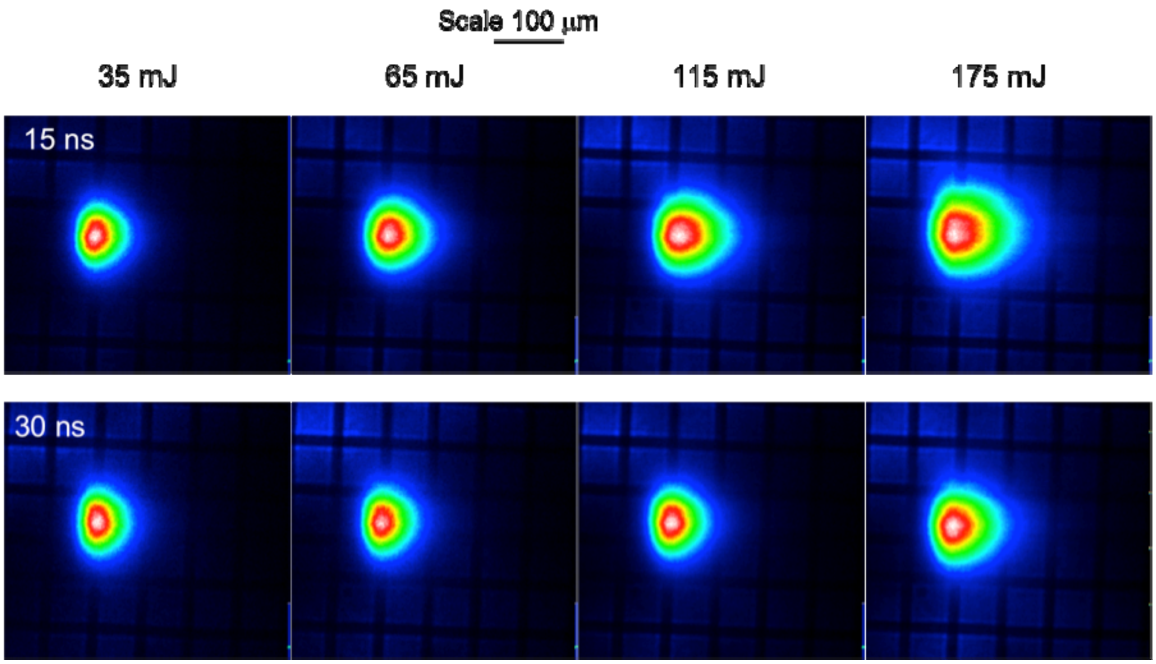

Figure 12. In-band EUV images of Sn plasma irradiated with laser with pulse durations of 15 and 30 ns with various pulse energy

4. DISCUSSIONS

It has been known that 1.064 μm laser-produced Sn plasma is optically thick to 13.5 nm EUV emission and plasma density profile play a key role in the generation and transport of EUV emission in the EUV plasma [8][9]. The in-band CE is a result of tradeoff between the emissivity and re-absorption of the EUV emission induced by the EUV plasma itself. One of the concern of the use of long duration Nd:YAG laser pulse is its long plasma scale length, which is described as [10], $l_s = C_s \tau$, where C_s is the sound speed and τ is the laser pulse duration. Longer plasma scale length attributes to more re-absorption of EUV emission, resulting in lower in-band CE. However, the scaling law is obtained under the assumption of 1-D plasma expansion. With a small laser focal spot, 3-D expansion is dominated and the lateral plasma expansion could reduce the plasma scale length significantly, resulting in a small corona [11][12]. The small corona reduces the opacity effect and results in high in-band CE even with a long laser pulse. The absence of re-absorption spectral dip in the soft x-ray spectrum of Sn plasma irradiated with 30 ns laser pulse as shown in Fig.6 provides an evidence of less opacity effect for the case of using long duration laser pulse with a small focal spot. This research reveals that the optimum laser pulse duration to efficiently generate in-band 13.5 nm EUV emission depends on laser focal spot size. The smaller laser focal spot the longer laser pulse can still be good to obtain high in-band CE of the EUV emission. Further reduction of laser focal spot can help extend Nd:YAG laser pulse to longer than 40 ns.

The broadening or narrowing of the EUV emission temporal waveform at different pulse duration provides a way to understand the physics processes dominating the generation and transport of in-band 13.5 nm EUV emission inside small Sn plasma. For a short pulse, since there is not much plasma expansion during the laser pulse, deposition of laser pulse energy is localized near the n_c, which is too dense to let the EUV emission escape from the plasma. An extra plasma expansion process is necessary to get the EUV emission out of the plasma. The broadening of the EUV temporal shape is the time of the extra expansion. There should also be a delay between the laser and the EUV emission, but the time-resolution of the photodiode system may overlap the delay [12]. This research reveals that ~ 2 ns may be the shortest EUV emission pulse duration we can get despite whatever laser pulse duration is used.

The slower ions generated from Sn plasma irradiated with a long laser pulse may come from the longer rising slope related with longer pulse. It is seen in Fig.1 that longer laser pulse has a slower rising slope as compared with that of a shorter pulse. For example, for 11 and 30 ns laser pulse the rising time (10 to 90 % of the maximum magnitude) are 5 and 15 ns respectively. Even the low-intensity rising slope can't heat the plasma up to the optimum temperature (30-60 eV) to efficiently emit in-band 13.5 nm EUV emission [13]; it can act as a pre-pulse to reduce plasma density gradient to form a more gentle density profile and to form a cold plume in front of hot plasma, both contribute to reduce the kinetic energy of ions [14]. The narrower energy distribution reveals more uniform temperature distribution inside the plasma with a longer laser pulse. More detailed study is necessary to clarify the mechanism.

The energetic ions could damage or degrade the expensive collector via penetration into and overcoating onto the Mo/Si layers. Ambient gas and electromagnetic fields are the most widely used techniques to mitigate debris from the EUV plasma. Since 13.5 nm EUV light is heavily absorbed in all of the materials, the gas pressure applied to EUV source chamber has to be kept below a certain level to avoid absorption of the EUV emission. Both gas and electromagnetic fields are more effective for slower ions [15], so the slower ions are helpful to reduce the pressure of the gas and the strength of the electromagnetic fields.

EUV source size is not equal to the whole plasma size, rather than only the part of plasma with correct temperature to efficient emits 13.5 nm EUV emission, which is 30 to 60 eV. With a small laser focal spot, small corona is result due to the lateral expansion. In this case, laser absorption mainly happens near the n_c instead of widely distribution over a wide density range in the corona. This makes the situation of Sn plasma irradiated using long duration Nd:YAG laser pulse with a small focal spot similar to the case of CO_2 laser [16]. The size of the EUV source mainly comes from the moving of the n_c, and the material burn-through process could cancel the moving of the n_c toward vacuum at late time of laser pulse. So small EUV source is result even for a long laser pulse.

5. SUMMARY

To summarize, this research showed that long duration 1.064 μm laser is a good choice to drive an in-band 13.5 nm EUV source for metrology due to its high in-band CE, slower ions, and still small EUV source size. Furthermore, there are extra advantages with long laser pulse duration as compared with short laser pulse: (1) lower peak EUV intensity allows to increase brightness of the source applied to inspected mask or resist; (2) better laser beam quality means better focusing ability, which is required to reduce the source size to enhance brightness, and the better focusing ability the more laser energy is inside the focal spot resulting high efficiency; (3) better reliability is important for high duty application; (4) simple laser structure lowers the cost of the owner ship; and (5) higher pulse energy uses the target more efficient.

6. ACKNOWLEDGEMENTS

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