Efficient 13.5 nm extreme ultraviolet emission from Sn plasma irradiated by a long CO_2 laser pulse

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The effect of pulse duration on in-band (2% bandwidth) conversion efficiency (CE) from a CO_2 laser to 13.5 nm extreme ultraviolet (EUV) light was investigated for Sn plasma. It was found that high in-band CE, 2.6%, is consistently obtained using a CO_2 laser with pulse durations from 25 to 110 ns. Employing a long pulse, for example, 110 ns, in a CO_2 laser system used in an EUV lithography source could make the system significantly more efficient, simpler, and cheaper as compared to that using a short pulse of 25 ns or shorter. [DOI: 10.1063/1.2951595]

The semiconductor industry is developing extreme ultraviolet lithography (EUVL) as the leading candidate for the next generation lithography tools used to produce microchips with features of 32 nm or less. Great progress in the development of EUVL has been achieved through the intensive efforts in recent years. However, several challenges are still standing on the road to apply EUVL in high volume manufacturing and cost of ownership (CoO) is at the heart of these challenges.[1] In an EUVL system, a powerful and long-lifetime in-band (2% bandwidth) EUV light source is one of the major CoO. The in-band requirement comes from the limited bandwidth of the optics used in EUVL system, i.e., multilayer Mo/Si mirrors. However, high CoO of high power laser is a critical obstacle to scale to high power. CO_2 lasers provide a more hopeful choice due to their relatively low cost, high efficiency, and commercially available high power as compared with solid-state lasers.[2–4]

High in-band CE from laser to 13.5 nm EUV light has been obtained from CO_2 laser-produced Sn plasma due to its lower opacity.[5] It has been widely believed that a short laser pulse with pulse duration of 25 ns or less is necessary to achieve high efficiency for CO_2 laser.[3,4,6] However, a high power short pulse CO_2 laser is complicated and expensive. For Xe plasma, it has been shown that a CO_2 laser with pulse duration of 25 ns is more efficient to generate the EUV light as compared to shorter pulse.[7] To date, there is still no systematic experimental effort to investigate the effect of CO_2 laser pulse duration for Sn plasma.

In this report, we present our efforts to clarify the effect of CO_2 laser pulse duration for Sn plasma. Experiments are carried out using a homemade short pulse master oscillator and power amplifier (MOPA) CO_2 laser system, consisting of a master oscillator and two stages of power amplifiers. Both the oscillator and the amplifiers are transversely excited atmosphere (TEA) CO_2 lasers. The laser works at a wavelength of 10.6 μm. The gas mixture ratio of the oscillator is optimized to remove the microsecond tail that usually accompanies TEA CO_2 laser and to obtain the maximum peak power. A plane-parallel ZnSe output coupler with a reflectivity of 80% is used in the oscillator. The pulse duration of the laser from the oscillator is shortened by an air-breakdown plasma shutter. The plasma shutter is triggered by the free electrons from an air-breakdown plasma induced by a Q-switched Nd:YAG laser and pumped by the oscillator itself. The four lasers are synchronized with a digital delay/pulse generator (SRS DG535). Various pulse durations can be achieved by varying the delay time between the oscillator and the Nd:YAG laser.

Typical shapes of the CO_2 laser pulse with pulse durations (full width at half maximum) of 25, 50, and 110 ns are shown in Figs. 1(a)–1(c) (red lines), respectively. For comparison, a laser pulse obtained without the plasma shutter is also shown in Fig. 1(d) (red line). It is seen in Fig. 1 that the peak power is almost constant for all pulse durations.

A Sn plate with high purity is always used as the target in the present experiments. The CO_2 laser is focused onto the target surface at normal incidence by a $F/10$ meniscus lens placed inside a vacuum chamber. The focal spot size is evaluated to be 200 μm. The laser intensity on the target can

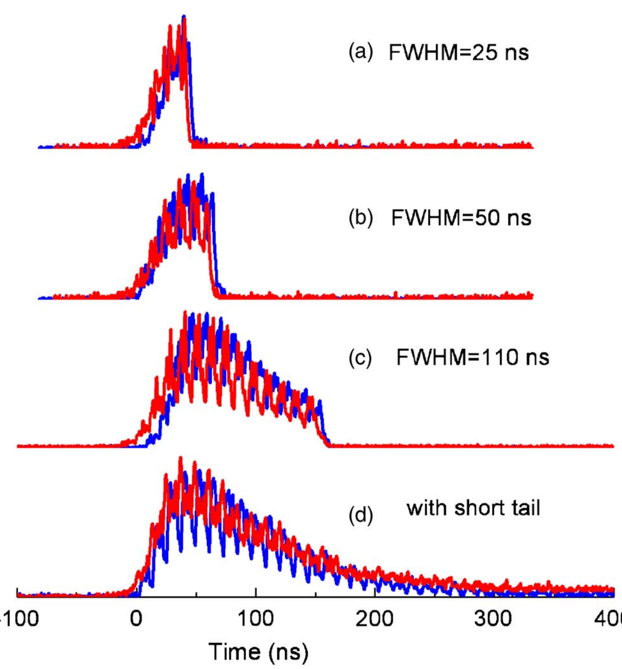

FIG. 1. (Color online) Temporal shape of laser pulse (red lines) and in-band EUV light (blue lines) from Sn plasma irradiated by CO_2 laser with pulse durations of (a) 25, (b) 50, (c) 110, and (d) 110 ns with a short tail.

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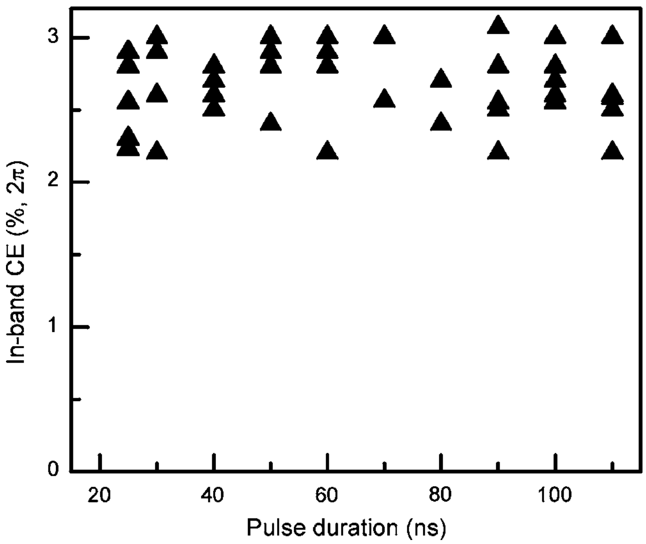

FIG. 2. In-band CE from CO_2 laser-produced Sn plasma as a function of laser pulse duration.

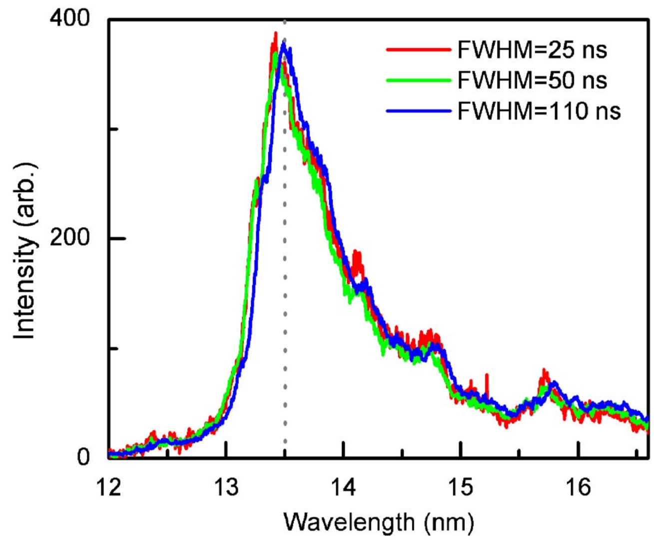

FIG. 3. (Color online) Soft x-ray spectra obtained with various laser pulse durations of 25 (red), 50 (green), and 110 ns (blue).

be up to 2×10^{10} W/cm^2. The temporal shape and energy of the laser pulse are monitored for each shot.

The in-band CE from laser to 13.5 nm EUV light is measured with an absolutely calibrated EUV energy monitor (E-Mon) from Jenoptik. The E-Mon is installed in the plane of laser incidence at an angle of 39° with respect to the target normal. The CE is integrated over a 2π solid angle. The soft x-ray spectrum is measured by a transmission grating spectrometer (TGS) with a spectral resolution better than 0.1 nm. The ion energy spectrum is measured with a Faraday cup (FC) from Kimball Physics. The FC is biased with a −30 V voltage and is placed 15 cm away from the plasma at an angle of 10° with respect to the target normal.

The temporal shape of 13.5 nm in-band EUV emission is observed with a narrow-band detector, consisting of a Zr filter, a normal incidence Mo/Si multilayer interference mirror, and a fast EUV photodiode (IRD AXUV HS). The narrow-band detector has a bandwidth of 4% centered at 13.5 nm. The EUV photodiode is biased with a voltage of −50 V. The output of the detector is recorded by a digital oscilloscope with a bandwidth of 500 MHz. The rise time of the narrow-band detector is less than 1 ns.

In-band CEs from Sn plasma irradiated by the CO_2 laser with pulse durations from 25 to 110 ns are shown in Fig. 2. Averaged laser intensity on the target varies from 2×10^{10} to 1.5×10^{10} W/cm^2 for pulse durations from 25 to 110 ns. It is seen in Fig. 2 that almost constant CE, 2.6%, is obtained with pulse durations from 25 to 110 ns. These CEs are consistent with that described in Ref. 6 obtained by a short pulse CO_2 laser with pulse duration of 10 ns with a planar target surface. For comparison, the in-band CE from Nd:YAG laser-produced Sn plasma measured with the same diagnostic arrangement is 2% with laser intensity of 2×10^{11} W/cm^2, as described in Ref. 8.

Soft x-ray spectra from Sn plasma irradiated by CO_2 laser with various pulse durations were observed using the TGS. Typical results with pulse durations of 25, 50, and 110 ns are shown in Fig. 3. The experimental conditions are identical with those used in the CE measurement. The spectra are normalized according to individual pulse energy of the CO_2 laser pulse. It is seen in Fig. 3 that the spectral peak for all pulse durations is always located near 13.5 nm. This reveals that the plasmas for all the cases should be close to the optimum condition for efficient 13.5 nm EUV emission generation. It is also clear in Fig. 3 that the spectra obtained with various pulse durations are very similar near 13.5 nm. These two features confirm the high and constant in-band CE obtained with a wide range of CO_2 laser pulse durations, respectively.

In order to clarify the dynamics of in-band 13.5 nm EUV emission generated with various laser pulse durations, the temporal shape of the in-band EUV light from CO_2 laser-produced Sn plasma was observed with the narrow-band detector. Typical results with pulse durations of 25, 50, and 110 ns are shown in Figs. 1(a)–1(c) (blue lines), respectively. For comparison, the result obtained with the unshortened laser pulse is also shown in Fig. 1(d) (blue line). Again, the conditions are identical to those used in the measurements of in-band CE.

It is seen in Fig. 1 that the temporal shape of the EUV light follows that of the laser pulse for pulse durations of 25, 50, and 110 ns, even when the pulse includes a short tail except for a delay in the rising slope. It is also worth noting in Figs. 1(a) and 1(b) that for short pulse, i.e., 25 and 50 ns, there is a 3–4 ns delay of the EUV light after the laser turns off. In these cases, the EUV light is a little longer than the laser pulse. This delay and expansion of the EUV light may come from the recombination and other energy transport processes in the plasma. It is seen in Figs. 1(c) and 1(d) that significant EUV emission is generated at the falling slope and even the short tail with low intensity. Since there is still notable EUV emission at 200 ns [as shown in Fig. 1(d)], it is clear that this EUV emission does not come from the recombination and other energy transport processes of the plasma. So in our cases, even low intensity slope can efficiently contribute to the generation of EUV light. Now, we can conclude that the efficient EUV light generated with laser pulse as long as 110 ns is reasonable.

The possible reason for the constant in-band CE obtained with a wide range of laser pulse durations may come from the long wavelength of the CO_2 laser, i.e., 10.6 μm. For a long laser pulse, the rising slope ablates and ionizes the target to form a plasma in front of the initial target surface. The main part of the pulse can only reach the plasma with a

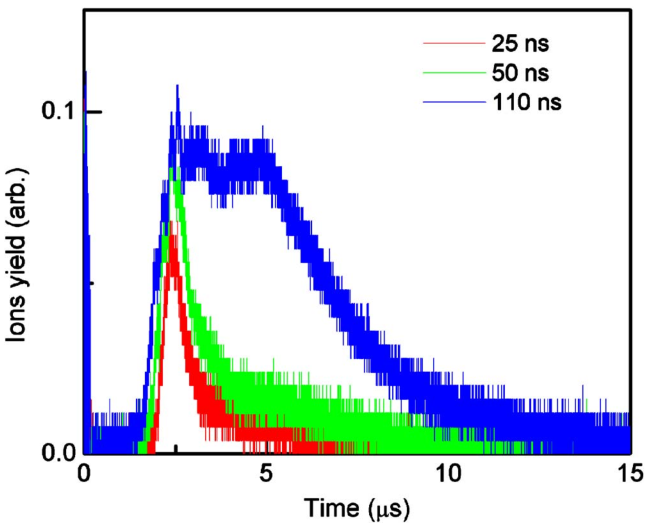

FIG. 4. (Color online) Time of flight of Sn ions from Sn plasma irradiated by CO_2 laser with various pulse durations of 25 (red), 50 (green), and 110 ns (blue).

density equal or less than the critical density rather than the initial solid target surface. A corona is formed in front of the critical density (n_c) due to the isothermal expansion of the plasma. It has been shown for an Nd:YAG laser with wavelength of 1.06 μm ($n_c = 1 \times 10^{21}$ cm^{-3}) that significant laser energy is absorbed in the corona by distributed absorption.[9,10] However, for a CO_2 laser, the critical density is 10^{19} cm^{-3} and the corona is well underdense. The absorption of the laser energy in the corona may be negligible.[11] In this case, during the whole pulse, laser energy is always deposited locally near the critical density, so efficient laser absorption via inverse bremsstrahlung can be expected for the whole laser pulse including the low intensity slopes.[12] Another physics process effecting in-band CE is the reabsorption of the EUV light induced by the EUV plasma itself. For an Nd:YAG laser, it has been shown that reabsorption of the in-band EUV light is a key effect on in-band CE.[13] A long laser pulse produces a longer scale corona in front of the critical density as compared to that of a short pulse. The long scale corona results in more reabsorption of the EUV light. However, for a CO_2 laser, the corona is so underdense that opacity may not be important at all. The combination of good laser absorption and lower opacity of CO_2 laser-produced Sn plasma may be the reason for the efficient generation of in-band EUV light with a long CO_2 laser pulse.

In addition to in-band CE, another key issue related to an EUV source is debris generated from the EUV plasma. Figure 4 shows the time of flight of Sn ions from Sn plasma irradiated by CO_2 laser with pulse durations of 25 (red), 50 (green), and 110 ns (blue). It is seen that the kinetic energy of the ions located at the peak is almost the same for all pulse durations. The kinetic energy is 2 keV at the peak. The number of ions located at the peak increases slightly with the length of the laser pulse, but doesn't linearly depend on pulse duration. It is worth noting in Fig. 4 that more slow ions are generated with a long pulse. Since laser intensities are fixed, the energy in a long pulse is higher than that of a short pulse. Such that, a small part of the extra energy in a long pulse contributes to fast ions similar with that of short pulse, but most of the extra energy goes to slow ions. Slow ions are easier to be mitigated using electric and magnetic fields, gas, etc. In this case, a long pulse is better than a short pulse.

Lengthening the pulse duration of the CO_2 laser used in an EUVL source system could significantly simplify and reduce the cost of the system. Generally, CO_2 lasers used in EUVL are based on a MOPA structure, consisting of a short seeding pulse and a series of amplifiers. A radio frequency (rf) excited continuous wave (cw) high power CO_2 laser is employed as amplifier. Since the gain of cw CO_2 lasers is low for a short pulse, several stages of preamplifiers are required to efficiently extract power from the final amplifier.[4] Lengthening the pulse duration, for example, from less than 25 to 110 ns, would increase the pulse energy by a factor of 4 without any extra cost. This could make the whole laser system much more efficient, simpler, and cheaper while keeping high in-band CE. Another impact of lengthening the laser pulse is to make it easier to realize mass-limited target operation for the commonly used droplet target with diameters from several 10 to 100 μm. Such solid Sn droplets are not really a mass-limited target since a thin Sn film with less than 1 μm thickness can provide enough ions for efficient EUV light generation.[14] Lengthening pulse duration could increase the laser energy per pulse. More laser energy permits more material involved in each droplet. And long pulse duration may make it easier to align the laser to tiny droplets as a result of the plasma expansion induced by the rising slope of the laser pulse.

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