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UC San Diego EUV Lithography Group

– Progress Report –

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Abstract

During 2010, our research remained focused on studies of light and particle emission from plasmas formed by short-pulse CO_2 and Nd:YAG lasers impinging on very small spherical targets. The overarching goal of our research is to understanding the plasma evolution and processes involved in production of light and acceleration and transport of particles. The applications of this research include both volume manufacturing of semiconductors and actinic metrology. Progress has been made in furthering our understanding of the differences between 1-µm and 10-µm irradiation on charge state evolution, the effects of laser pulse length, multi-pulse "pulse trains", and the sensitivities involved when using very small targets and laser spot size. Two doctoral students supported by this activity are expected to graduate this year.

Target development

Several advances were made in our laboratory to enable experiments with very small spherical targets. This is essential in order to remain relevant to commercial EUV systems, and especially actinic metrology systems that require a smaller étendue as compared with volume manufacturing sources.

1. Liquid tin targets. A system was deployed to produce pure liquid Sn droplet targets "on demand" within the chamber without breaking vacuum. Initially, the droplet dispenser was able to provide 150-µm targets through a nozzle. Improvements to the design were implemented such that currently we are able to produce and irradiate 50-µm pure Sn droplets.

2. Aqueous droplet dispenser. We acquired a room-temperature piezo-actuated aqueous droplet dispenser from Microdrop Technologies GmbH. Water droplets down to 30 µm have been produced and irradiated with a Nd:YAG laser. An aqueous dispersion of nano-sized SnO_2 particles was introduced into the droplet dispenser, but we have been unable to dispense it adequately into vacuum. At present we are planning to acquire and test a high-temperature dispenser from Microfab Technologies Inc. Alternative liquids, such as $SnCl_2$ solutions will also be tested.

3. Solid sphere targets. Sn-coated glass microspheres continue to be our most reliable platform for experimental research. We are able to mount and irradiate spheres of the order of

30 μm (or less) with high precision. Important questions remain regarding the relevance of solid targets, since we have observed different plasma dynamics from solids and liquids of the same diameter. However, the higher level of control of the target positioning allows us to explore some aspects of the physics more carefully.

Pulse length effects

Pulse length effects have been studied in our group with both 1-μm and 10-μm lasers. Our recent emphasis has been on 1-μm lasers due to the relevance to actinic metrology. Pulse lengths from 7 ns to 150 ns have been obtained by modifying our commercial (QuantaRay) Nd:YAG lasers. In addition, a Pockels cell has been used to manipulate the rising edge of the pulse, which we believe is as important as the pulse length in determining the plasma evolution.

Typical results are shown in the Table below. With pulse durations from 7 to 30 ns an almost constant CE is obtained, *i.e.,* 2 % (integrated over 2 π solid angle). With laser pulse length beyond 40 ns, lower CE results. EUV temporal pulse shapes show that the rising and falling slopes of the longer pulses don't contribute efficiently to the generation of 13.5 nm EUV emission due to their low intensity. This suggests that better control over the temporal pulse shape is needed to extract maximum emissions.

In-band conversion efficiency as a function of pulse duration

Pulse duration (ns)	Conversion efficiency (%, 2% BW, 2π)	Intensity (W/cm^2)
7	2-2.2	2×10^{11}
15	2-2.2	2×10^{11}
30	1.8-2	2×10^{11}
40	1.4-1.5	1×10^{11}
70	1.3-1.4	4×10^{10}
100	1-1.1	2×10^{10}
150	No reliable data yet	$<1\times10^{10}$

A surprising finding is the much lower kinetic energy of the ions from Sn plasma irradiated with a long laser pulse. The time of flight measured with a Faraday cup showed that with a 30-ns laser pulse duration the kinetic energy of the ions located at the energy spectral peak is less than 500 eV, which is at least 10 times less than that obtained with a 7 ns laser pulse, *i.e.,* 5 keV.

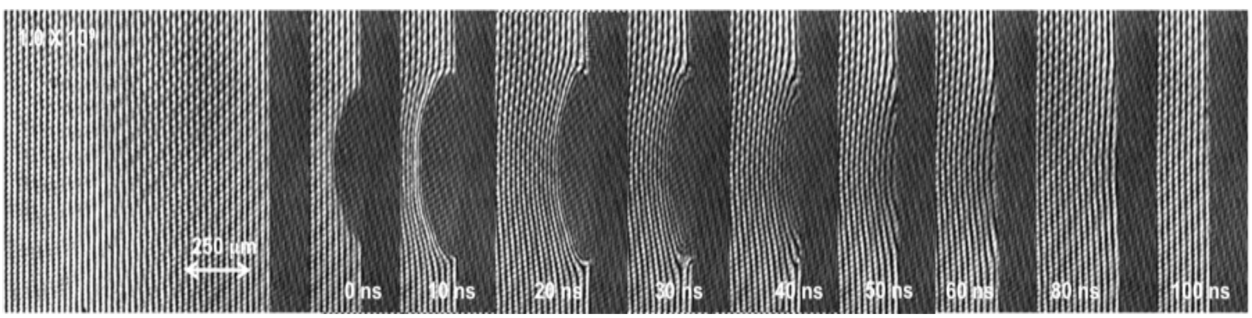
Images of in-band 13.5-nm EUV emission with various laser pulse durations were observed with an in-band EUV imaging system. It was found that the EUV source depends more strongly on laser intensity than laser pulse duration. With durations from 7 to 35 ns the size of the EUV source remains almost constant. With lower laser intensity, *i.e.,* less than 1×10^{11} W/cm^2 and long pulse, a very small EUV source appears feasible.

Pulse train results

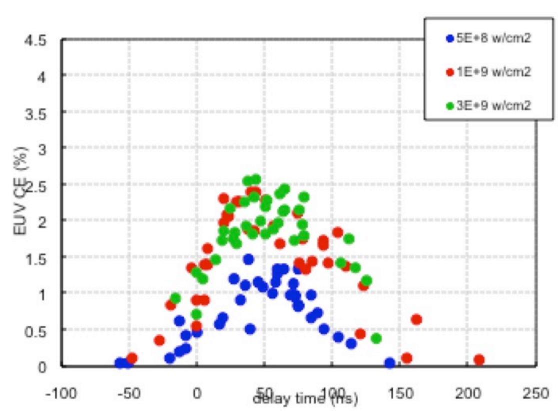
A train of CO_2 laser pulses from two TEA CO_2 lasers was applied to liquid Sn droplets with diameters from 50 to 250 μm. The interval between the two pulses was varied from 100 to 1000 ns. The laser focal spot size was around 90 μm (1/e of full magnitude). Laser intensities on the target were 5×10^{9} and 1×10^{10} W/cm^2 respectively. With droplet diameter larger than 90 μm, the in-band CE from laser to 13.5 nm EUV emission with a single laser pulse is comparable to that of a Sn plate target. The CE using two pulses with interval as long as 1000 ns is higher than that of a single laser pulse. It was found that when the droplet diameter is smaller than 90 μm a significantly lower CE results.

Effect of plasma density on in-band CE

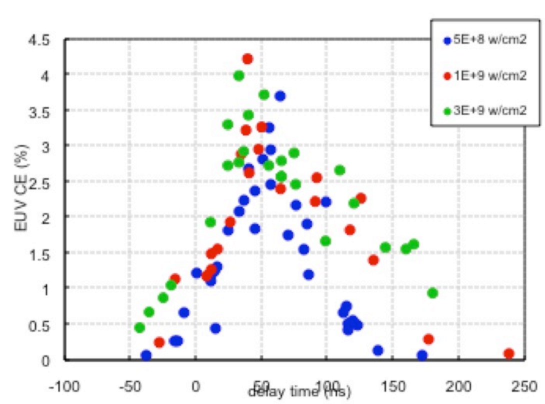
The purpose of this research is to clarify the optimum plasma density profile to generate efficient 13.5 nm EUV emission from CO_2 laser-produced Sn plasma. The basic idea is to use a separate Nd:YAG laser to generate an expanded plasma along the target normal, and then a CO_2 laser pulse is applied at an angle of 90 degrees with respect to the target normal. Interferograms of the plasmas generated with a Nd:YAG laser at intensity of 1.8×10^{9} W/cm^2 and various delay times are shown in the figure below. It is seen that by choosing different delay times between Nd:YAG and CO_2 lasers, various plasma densities can be chosen for interaction with the CO_2 laser.



The following figures show in-band CE as a function of delay time. The left-hand figure is obtained with one Nd:YAG laser pulse on the same target spot. It is seen that in-band CE is comparable to that of a plate target, *i.e.,* 2.5 %. The right-hand figure shows an enhancement of in-band CE above 4% with accumulation of 50 shots of Nd:YAG laser on the same target spot.



In-band CE *vs.* delay times between Nd:YAG and CO_2 lasers with one Nd:YAG laser shot on the same spot

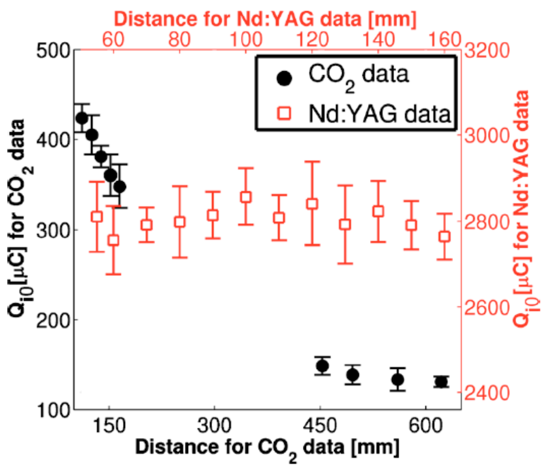


In-band CE vs delay times between Nd:YAG and CO_2 lasers with 50 Nd:YAG laser shots on the same spot

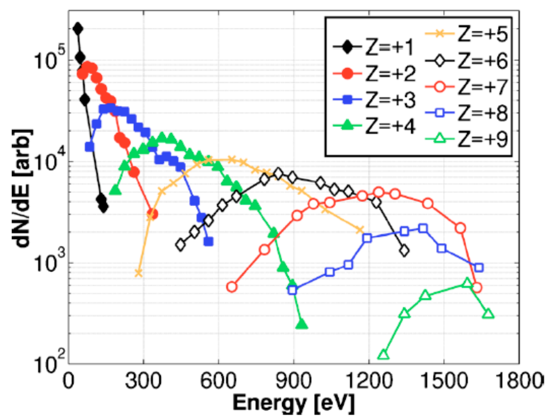
Recombination and charge state evolution in CO_2 and Nd:YAG laser-produced plasmas

Complete recombination of an expanding laser-produced plasma is prevented by rapid expansion to a sufficiently rarefied state such that recombination processes become negligible. The distance from the target surface over which the charge state distribution evolves before "freezing" for subsequent expansion is affected by the laser parameters determining the initial recombination rates, and particularly the laser wavelength.

The evolution of the charge state distribution during the expansion of laser produced Sn plasma was investigated experimentally and compared with analytic models. The two figures below show results from scanning a Faraday cup and from our electrostatic energy analyzer. The charge state "freezes in" over a distance less than 6 cm with a planar target irradiated by a 1-μm laser at 8.3×10^{11} W/cm^2 but greater than 60 cm when a 10.6-μm laser at 2.5×10^{10} W/cm^2 is used. The difference is attributed to the laser wavelength dependence of the coronal electron density and the subsequent recombination processes during expansion.



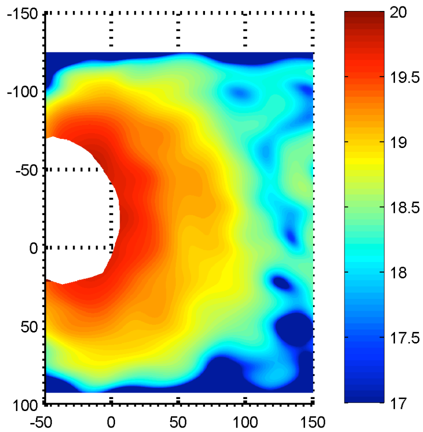
Normalized charge Qi0 as a function of distance from the Faraday cup to the target. Each data point is the average of least 15 shots. For the CO_2 data Qi0 decays over both spatial intervals investigated, implying the critical distance is greater than 622 mm.



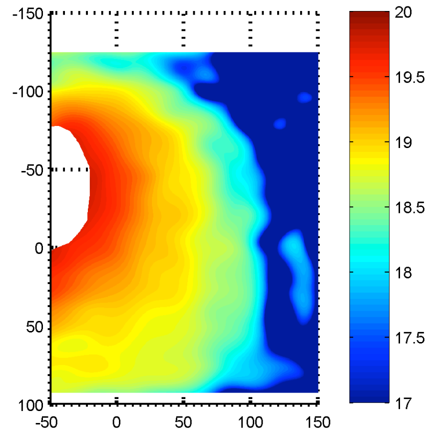
Charge-state resolved ion energy distribution measured at a distance of 100 cm from a Sn target irradiated by a CO_2 laser.

Sensitivity of laser-plasma interactions to alignment accuracy

The purpose of this research is to clarify the accuracy needed to generate efficient EUV emission with a tiny target. An Nd:YAG laser with focal spot diameter of 30 μm ($1/e^2$) is used to irradiate a Sn sphere with diameter of 40 μm. It was found that a 10 μm misalignment off the center of the sphere results in a 20% drop of in-band CE. Plasma density maps of the cases of well aligned and 10 μm mis-aligned laser are shown in the following figures. In the well aligned case, more plasma expansion is observed as compared with that of mis-aligned case. This means more laser energy is deposited into the target when alignment is good.



Plasma density map of Sn sphere with good alignment



Plasma density map of Sn sphere with 10 μm mis-alignment

Future plans

1. Operation of CO_2 laser at shorter wavelength and its application to EUV generation

- A diffraction grating is being investigated to tune the wavelength of TEA CO_2 laser from 10.6 to 9.6 or 9.3 μm.
- Frequency doubling of 9.6 and 10.6 CO_2 laser will be investigated to produce a wavelength of 5 μm.
- Properties of EUV emission and debris from the shorter wavelength CO_2 laser will be investigated.

2. Comparison of pure Sn and Sn-doped aqueous droplets with long duration Nd:YAG and CO_2 laser pulses

- Dependence of EUV source size on the concentration of Sn.
- In-band CE's with various concentration of Sn irradiated with long duration laser pulse.

3. Pre-pulse to Sn sphere or droplet for long duration Nd:YAG laser pulse

- EUV source size
- In-band CE

2010 Publications

Russell A. Burdt, Yoshifumi Ueno, Yezheng Tao, Sam Yuspeh, Mark S. Tillack and Farrokh Najmabadi, "Recombination effects during expansion into vacuum in laser produced Sn plasma," *Applied Physics Letters*, 97 041502 (2010).

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S. Yuspeh, K. L. Sequoia, Y. Tao, M. S. Tillack, R. Burdt and F. Najmabadi, "Heating dynamics and extreme ultraviolet radiation emission of laser-produced Sn plasmas," *Applied Physics Letters*, 96, 261501 (2010). (also appears in the Virtual Journal of Ultrafast Science, August 2010).

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Y. Tao, M. S. Tillack, S. Yuspeh, R. A. Burdt, N. Sheikh, N. Amin, and F. Najmabadi, "Interaction of a CO_2 laser pulse with tin-based plasmas for an extreme ultraviolet lithography source," *Transactions on Plasma Science* 38 Issue 4, Part 2 (2010) 714 - 718.

Nek. M. Shaikh, Y. Tao, R. A. Burdt, S. Yuspeh, N. Amin, and M. S. Tillack, "Spectroscopic analysis of temperature and density of Sn plasma produced by a CO_2 laser," *Journal of Applied Physics* to appear.

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