Mass-limited Sn target irradiated by dual laser pulses for an extreme ultraviolet lithography source

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A thin Sn film was investigated as a mass-limited target for an extreme ultraviolet (EUV) lithography source. It was found that those energetic ions that are intrinsic with the mass-limited Sn target could be efficiently mitigated by introducing a low-energy prepulse. High in-band conversion efficiency from a laser to 13.5 nm EUV light could be obtained using an Sn film with a thickness down to 30 nm when irradiated by dual laser pulses. It was shown that the combination of dual pulse and inert Ar gas could fully mitigate ions with a low ambient pressure nearly without the penalty of the absorption of the EUV light. © 2007 Optical Society of America

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As the next generation lithography tool in the semiconductor industry, extreme ultraviolet (EUV) lithography is the most promising candidate for producing microchips with feathers of 32 nm or smaller by 2010.[1] However, EUV lithography faces several critical challenges and has been delayed in being applied to high volume manufacture (HVM).[2] The main challenge is to develop a powerful, efficient, clean, and reliable EUV light source. Laser-produced plasma is one of the most hopeful candidates due to its high conversion efficiency (CE) from a laser to in-band (2.2% bandwidth) 13.5 nm EUV light, high collection efficiency, manageable debris, and scalability to the increasing high power, 115–250 W, required by HVM. However, at present, because of the high cost of the driving laser, the output power of the EUV light generated from laser-produced plasma is limited to 10 W at intermediate focus.[2] An efficient, clean, and stable target supply is the key factor for lowering the critical requirements of the driving laser and for increasing EUV power. Sn is an attractive material as the fuel for the EUV lithography light source due to its high in-band CE.[3] However, debris becomes a critical issue for Sn.

Because dense Sn plasma is optically thick for in-band 13.5 nm EUV light, the final output of the EUV light is the trade-off between its generation and its reabsorption by the EUV plasma itself.[4] Suitable reduction in number density of Sn could reduce the Sn particles while keeping almost the same in-band CE as compared with that of full density Sn. For example, low-density SnO_2, Sn-doped foam, Sn-doped liquid droplet, and Sn-doped glass with a low concentration of Sn show high in-band CE.[5–9] However, these targets introduce extra O, H, and C ions with very high velocities, which are also critical to collector optics due to a high duty cycle.

High in-band CE has been obtained by using a pure liquid Sn jet and droplet,[10] but heavy debris requires additional innovations for application to the practical EUV light source for HVM. A thin Sn film has been investigated as a mass-limited target; it was shown that Sn as thin as 40 nm could provide almost the same in-band CE and much less neutral particle debris as compared with those of the massive Sn target.[11] Unfortunately when the mass-limited pure Sn target was used, Sn ions with kinetic energy up to several tens of kiloelectron volts were produced.[11] The possible reason for the energetic ions from the mass-limited target is that less Sn atoms are involved in the EUV plasma as compared with the massive target, and most of the atoms are ionized to a high charge state. Eventually, ions with a higher charge state gain more energy from the electric field built by the charge separation occurring in plasma expansion.[12] In this sense, energetic ions should always accompany the mass-limited target based on pure Sn. However, the damage to the optics induced by the ion strongly depends on its kinetic energy.[13] Reduction of the ion kinetic energy is very necessary to extend the optics lifetime and apply this kind of mass-limited target to the EUV light source. At the same time, the reduction in ion energy also reduces the gas needed to stop debris from the EUV plasma. Gas has been considered as the standard method for mitigating debris in the EUV lithography system.

In previous works,[14,15] we showed that a low-energy prepulse is effective for controlling the energy of the ions from the EUV plasma with a massive Sn target. In this Letter, we demonstrated that the high ion energy accompanied with the mass-limited target could also be controlled under 100 eV with the dual-pulse irradiation technique.

The present experimental arrangement has been described in a previous work.[15] The energy and pulse duration of the prepulse are constant at 2 mJ and 130 ps, respectively. A high-purity Sn slab, with a thickness of 1 mm, Sn foils with thicknesses of 10 and 1 μm, and Sn films with thicknesses of 100, 50, 30, and 20 nm overcoated on a silicon wafer are employed as targets. The Sn films are fabricated with an electron-beam vacuum evaporator (Temescal BJD 1800). The target is moved to maintain a fresh surface for each shot.

An ion energy spectrum is deduced from the time of flight (TOF) measured by a Faraday cup (FC) from

Kimball Physics.[14] The FC is placed inside the vacuum chamber with an angle of 10° with respect to the target normal and at a distance of 15 cm from the plasma. The FC is biased with a −30 V voltage. The CE is integrated over a 2π solid angle.

The time of flight of the ions generated from laser-produced Sn plasmas was observed employing various Sn targets with thicknesses from 1 mm down to 20 nm. Typical results from the Sn film with a thickness of 30 nm are shown in Fig. 1. The black solid and the blue dashed curves represent the results driven by a single pulse in vacuum and in ambient Ar gas with a pressure of 40 mTorr, respectively; the green dashed and the red solid curves are from dual laser pulses in vacuum and in 14 mTorr Ar, respectively. The laser intensity of the pumping pulse is 2×10^{11} W/cm^2. The delay time between the pre- and the pumping pulses is 840 ns.

In Fig. 1, it is seen that, in the case of a single laser pulse in vacuum, most ions are focused at an early time and the flux peak is located at ~ 1 μs. The corresponding kinetic energy of Sn ions located at the flux peak deduced from Fig. 1 is above 10 keV. This energy is higher than that of a massive Sn target driven by a single pulse, 5 keV.[14] This higher ion energy obtained with a mass-limited target coincides with Fujioka and co-workers's measurement.[11] It was noted that this higher ion energy is always observed when the target thickness is less than 100 nm. The possible reason for the higher ion energy of the mass-limited target comes from the fact that less Sn atoms are involved in this plasma. Higher averaged charge states of Sn ions are obtained; and more kinetic energy can be gained during the plasma expansion.

However, it was noted that when dual laser pulses are used, most ions are shifted to a later time. As shown in Fig. 1, when a prepulse 840 ns prior to the pumping pulse is introduced, the flux peak is located later than 10 μs. Its corresponding kinetic energy is below 100 eV, which is comparable with that of a massive Sn target irradiated with dual laser pulses.[15] The reason for the reduction in ion energy in the case of dual laser pulses comes from the interaction of the pumping laser pulse with the gentle density profile formed by the prepulse instead of the infinitely sharp boundary.[15] This shows that the dual-pulse irradiation technique could also be applicable to mass-limited targets.

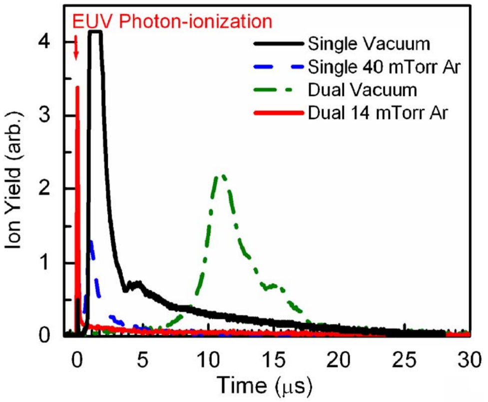

Fig. 1. (Color online) TOF of Sn ions from a 30 nm Sn film irradiated by a single laser pulse in vacuum (black solid curve) and in ambient Ar gas with a pressure of 40 mTorr (blue dashed curve), respectively; and irradiated by dual laser pulses in vacuum (green dashed–dotted curve) and in 14 mTorr Ar gas (red solid curve), respectively.

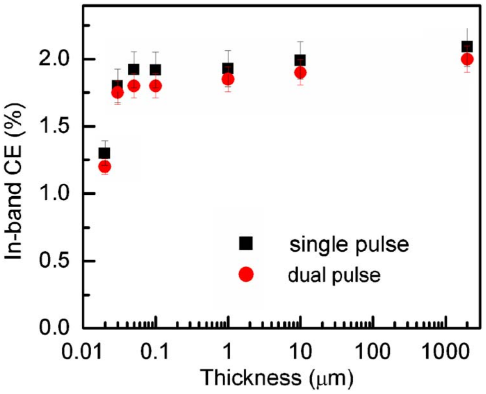

Fig. 2. (Color online) In-band conversion efficiency of laser-produced Sn plasmas driven by a single (black square) or dual pulse (red dot) versus the target thickness.

Ambient gas or gas puff has been considered as a standard technique to stop debris from the plasma in the EUV lithography system.[16] The stopping power of neutral gas can be simplified as[17]

$$S = kZ_1Z_2^2L/\beta^2, \tag{1}$$

where $k = 0.3071/Z_2$ having units of keV/(mg/cm^2); Z_1 and Z_2 are atomic numbers of the target particle and the ambient gas, respectively; L is the stopping number; and $\beta = \nu/c$ is the relative velocity of the target particles. Equation (1) predicts that gas is more efficient for stopping slow particles. In Fig. 1, it is seen that for a single pulse, even with 40 mTorr Ar, significant fast ions are still observed. However, in the case of dual pulses, ions could nearly be stopped with 14 mTorr Ar. The calculated transmission of the Ar gas at 13.5 nm with pressures of 14 and 40 mTorr are 97% and 88%, respectively, with a distance of 70 cm.[18] This shows that the use of dual pulses enables the use of inert Ar as the gas to stop ions in the EUVL system.

The in-band CE from the laser to 13.5 nm EUV light from the Sn targets with various thicknesses was observed under the identical conditions used in the ion spectrum measurement. Typical results as a function of target thickness irradiated by a single (black square) and dual pulses (red dot) are shown in Fig. 2. In Fig. 2, it is seen that, in the case of the single pulse, 30 nm is thick enough to get almost the same in-band CE from the laser to the 13.5 nm EUV light as compared with that of the bulk slab. In Fig. 2, it is worth noting that, for the case of dual laser pulses, the measured in-band CEs are nearly the same as compared with those of a single pulse with various target thicknesses. In the case of the mass-limited target, less atoms are involved in the EUV plasma, and less EUV light should be generated. This reduction in generation could be compensated by less reabsorption of the in-band 13.5 nm EUV light induced by the EUV plasma. Thus almost the same in-band CE is obtained with a mass-limited target as compared with that of a massive target, such that high in-band CE and much lower ion energy could be obtained simultaneously by the combination of a mass-limited target and double pulses.

Soft x-ray spectra from the EUV plasmas using Sn targets with thicknesses from 1 mm to 20 nm were observed under the identical conditions used in the ion spectrum measurement. Typical results with the 1 mm slab (black dashed curve) and the 30 nm Sn film (red solid curve) are shown in Fig. 3. In Fig. 3, it is seen that the thin-film target shows a narrower spectrum as compared with that of the slab target. This spectral narrowing was always observed when the target thickness was below 100 nm. It is noted that 100 nm is the same threshold of the target thickness at which both a higher ion energy and a narrower spectrum are observed. This spectrum narrowing confirms the lower number density of Sn involved in the mass-limited plasma. Because the in-band EUV light centered at 13.5 nm comes mainly from the unresolved transitions array of Sn^{8+} to Sn^{13+}, the width of the spectrum depends on the distribution of the charge state of the Sn ions. The exchange of the charge state due to the collisions among ions is less in the case of the mass-limited target because of its lower number density, so a narrower spectrum is obtained. The purification of the spectrum is helpful for reducing the thermal load in the EUV light system.

The combination of a dual-pulse, mass-limited target and gas provides an efficient and clean target supply for an HVM EUV light source. A design for a high-speed target supply for HVM based on the combination of a free-standing thin Sn film and dual laser pulses, is being carried out at the University of California, San Diego. And the dual-pulse irradiation technique could hopefully be applied to Sn mass-limited targets in different forms, such as, tiny pure Sn droplets.

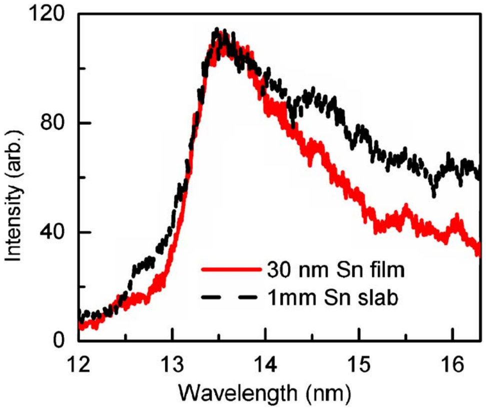

Fig. 3. (Color online) Soft x-ray spectra from laser-irradiated Sn targets of a 1 mm slab (black dashed curve) and a 30 nm Sn film overcoated on a silicon wafer (red solid curve).

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