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RAPID COMMUNICATION

Auto-cleaning of deposited tin debris in a laser-produced plasma extreme ultraviolet source by using a liquid jet target containing tin chloride

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Abstract We have demonstrated auto-cleaning of deposited tin debris produced in a laser-plasma extreme ultraviolet (EUV) source by using a liquid jet target containing tin chloride solution. The use of double laser pulse irradiation improved the EUV conversion efficiency of 1.1%, which was 3.3 times as large as that obtained with single laser pulse irradiation. At an appropriate concentration of tin chloride, the amount of deposited debris was balanced out with that of sputtered and/or etched debris, resulting in a thickness of deposited debris less than 1 nm after 40 000 laser pulse irradiations.

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1 Introduction

Extreme ultraviolet lithography (EUVL) has been under vital investigation for the next generation semiconductor manufacturing with a half-pitch line-width less than 32 nm. In the EUVL, the wavelength of EUV sources should be strictly determined to be 13.5 nm with a bandwidth (BW) of 2% because of requirements of presently available Mo/Si multilayer mirrors [1]. In addition to the wavelength requirements, EUV sources should be debris-free, have high conversion efficiency from primary energy sources, and have a high average output power larger than 180 W at a repetition rate on the order of kHz [2].

Laser-produced plasma (LPP) EUVL should have several advantages over discharge-produced plasma (DPP) EUVL. One of the most significant advantages may be the reduction of debris, since LPP can utilize mass-limited targets with various target materials. The use of low-peak power CO_2 laser oscillated at 10 μm [3], together with a metal tin as a fuel, has become one of the most promising combinations among numerous possibilities of driving laser wavelengths and fuels to produce efficient EUV emissions at 13.5 nm. Recently, a theoretical model predicts a LPP EUV source with conversion efficiency over 8% with the use of double pulse irradiations of a YAG (yttrium aluminum garnet) and a CO_2 laser with a tin target [4]. The use of mass-limited target of a tin layer could be an ideal target to produce completely ionized plasmas that should be expelled from EUV optics by electro-magnetic fields [5]. Mitigation of debris emissions, including ions and neutrals from any kinds of targets, nevertheless, should be one of the most challenging technical subjects in the next generation EUVL.

We have been developing a low-concentration colloidal target that contains tin dioxide nanoparticles as one of the low-debris emission targets [6]. The low concentration substantially provides the low debris emissions. The low EUV emission yield attributed to the low concentration could, however, be improved by the LPP regulation by using double pulse laser irradiations [6]. In addition, the colloidal target can be operated at room temperature, which relaxes the target design and maybe reduces the ionic debris emissions. We have, however, found out that the amounts of debris deposited on a witness plate placed adjacent to the target was totally independent on the double pulse or single laser pulse irradiations [7]. They were simply proportional to the laser

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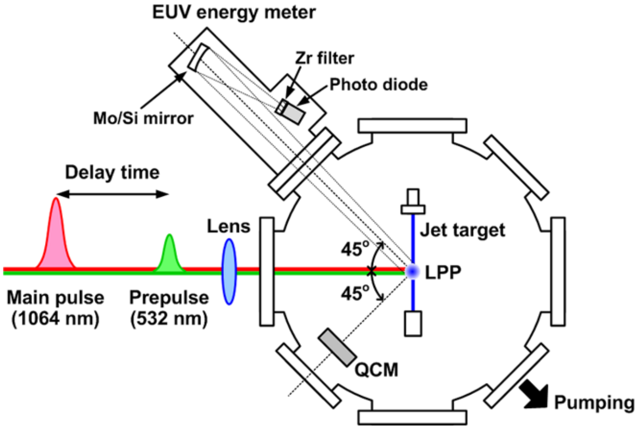

Fig. 1 A schematic diagram of the experimental setup

energy deposited onto the target. The active debris mitigation of such deposited debris has been demonstrated by heating a witness plate at a low temperature at around 100°C [7]. This type of active debris mitigation was proved to be useful for our colloidal target that contained water. Passive debris mitigation should also become useful, since it requires no additional techniques to mitigate debris emissions. Active debris cleaning of EUVL optics by using halogens has been demonstrated in the DPP EUVL [8]. The use of a halogen as an initial chemical substance of a target should thus become equivalent to the active halogen cleaning method, and may become an effective passive method to reduce deposited debris even in the LPP EUVL.

In this paper, we report on auto-cleaning of deposited tin debris in a LPP EUV source by using a room-temperature liquid jet target containing chemical substances such as tin chloride. The amounts of deposited debris were well regulated by selecting concentrations of the tin chloride solution. At a tin chloride concentration of 17%, the deposition of tin debris was balanced out with the sputtering and/or etching by chlorine atoms or ions produced as debris. At this concentration, the maximum EUV CE of 1.1% has been simultaneously observed by using double pulse irradiations at a delay time of 180 ns with a thickness of deposited debris less than 1 nm after 40 000 laser pulse irradiations.

2 Experimental setup

Figure 1 shows a schematic diagram of the experimental setup. Room-temperature tin chloride dissolved in ethanol was provided as a continuous jet target inside a vacuum chamber through a nozzle with a diameter of 50 µm. The diameter of the jet target was measured to be 75 µm. Residual static pressure inside the chamber was kept at less than 5 Pa during the plasma production. A Q-switched Nd:YAG laser at 1064 nm was used as a main pulse, which produced the maximum output energy of 550 mJ with a pulse duration of 10 ns full width at half maximum at a repetition rate of 10 Hz. In the experiments using double laser pulse irradiations, a second-harmonic pulse of another Q-switched Nd:YAG laser was used as a prepulse. Two pulses with a variable time delay were combined collinearly using a dichroic mirror and were focused onto a jet target with the maximum laser intensities of main and prepulses of 2.3×10^{11} and 4.0×10^{10} $\mathrm{W/cm^2}$, respectively. The total energies of both irradiation modes were adjusted to become approximately same values. The absolute in-band (±1% BW at 13.5 nm) EUV emission energy was measured by use of an EUV energy meter consisting of a Mo/Si multilayer mirror, a Zr thin film filter, and a photodiode. All optical components and a detector inside an EUV energy meter were absolutely calibrated. The EUV conversion efficiency was thus evaluated based on the emission energy at 13.5 nm within 2% BW with an emission solid angle of 2π sr. An almost isotropic angular distribution of the EUV emission from a liquid jet target was verified elsewhere [9]. A quantitative thickness of deposited debris was evaluated by using a quartz crystal microbalance (QCM) placed at a distance of 15 cm with an angle of 45° from the jet target.

3 Results and discussions

3.1 EUV emission from laser-produced tin chloride plasma

The EUV CE at 13.5 nm as a function of the delay time between main and prepulses is shown in Fig. 2a. A positive delay represents the prepulse irradiations prior to those of the main pulses. The EUV CE was defined as a ratio between the EUV emission energy at 13.5 nm and the main pulse laser energy, since the prepulse was only used to initiate preplasma that did not produce EUV emissions [6]. The EUV CE of 0.33% was measured using a single pulse irradiation at a tin chloride concentration of 17%, which is represented as a horizontal line. By increasing a positive delay time, the EUV CE increased, and reached at its peak of 1.1% at a delay time of 180 ns. The low concentration of the tin chloride solution was well compensated by regulating plasma dynamics by using double pulse laser irradiations [6]. After the peak the EUV CE decreased until it resumed to 0.33% at a delay time of longer than 700 ns. The delay time dependence of the EUV CE could be explained based on a simple plasma expansion model, where preplasma was expanded to reduce its density to a critical density of a main laser pulse [10]. The EUV CE by using double laser pulse irradiations at the optimum delay time was thus enhanced 3.3 times as much as that with a single laser pulse irradiation. Figure 2b shows the EUV CE values with single and double laser pulse irradiations as a function of a tin chloride concentration. Squares and circles represent the EUV

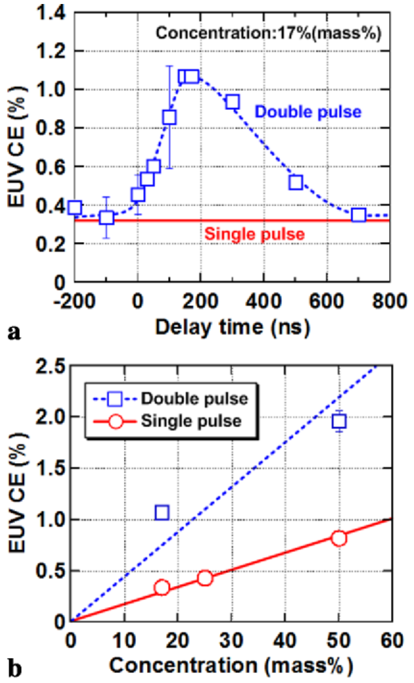

Fig. 2 **a** EUV CE as a function of a delay time between a prepulse and a main pulse. **b** EUV CE as a function of the tin chloride concentration

CEs by using double and single laser pulse irradiations, respectively. In both irradiation modes, the EUV CE linearly increased with the increase of the concentration. When the concentration of tin chloride was increased to 50%, the EUV CE of 0.8% was obtained even with single pulse irradiation. The EUV CE of 2.0% was observed by applying the double pulse laser irradiation at a high concentration. The double laser pulse irradiation to regulate the plasma dynamics was effective even for a liquid jet target at such a high concentration.

3.2 Passive auto-cleaning of deposited tin debris

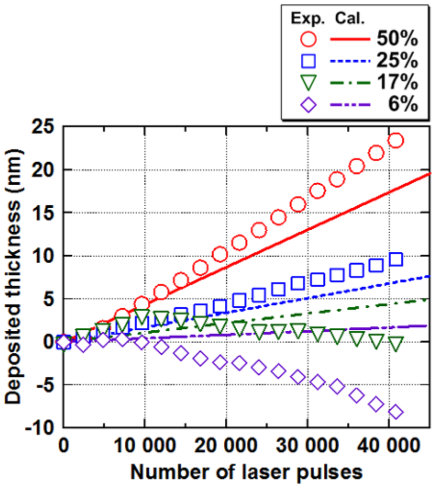

Fig. 3 The thickness of deposited debris as a function of the number of laser pulses. *Symbols* and *lines* represent measured and calculated values, respectively

Figure 3 shows the thickness of deposited debris measured by a QCM as a function of the number of laser pulses. Circles, squares, triangles, and lozenges represent the tin chloride concentrations of 50, 25, 17, and 6%, respectively. The single pulse irradiation was used in these experiments, since the double pulse irradiation showed similar debris deposition rates observed elsewhere [7]. Each straight line represents a calculated thickness evaluated from the number of tin atoms in a cylindrical interaction volume of the target determined by a focused laser pulse. Isotropic spatial debris emissions were assumed based on the measurements [11]. By analyzing deposited debris on a witness silicon plate with the X-ray photoelectron spectroscopy (XPS), tin and chlorine peaks appeared in addition to oxygen and carbon peaks. Judging from the XPS spectra, the majority of the deposited debris was determined to be tin. Since similar XPS spectra were observed by analyzing several points on the surface, certain uniformity of the deposition may be justified. The thicknesses of deposited debris at concentrations of 50 and 25% linearly increased with the increase of the number of the laser pulses. The experimental results of the deposited thickness were slightly larger than calculated values, since the continuously provided jet target would have been heated over the interaction volume determined by the focused laser pulse. When the tin chloride solution target at a concentration of 17% was used, the deposition rate of the deposited debris increased linearly with the number of laser pulses less than 10 000. When the number of the laser pulse increased more than 10 000 pulses, the deposited debris started to decrease and reached approximately zero after 40 000 laser pulses, which corresponded to the irradiated laser energy of 20 kJ. The deposition of debris was, therefore, balanced out with the sputtering and/or etching by chlorine atoms or ions produced as debris. More significant decrease of the deposited thickness was observed at a low concentration of 6%. Note that the head of the QCM was prepared with the presence of the deposited tin during these experiments. The thickness of the deposited tin on the QCM head was thick enough not to be affected by an original gold surface of the head. Details of the auto-cleaning mechanism may not be clarified presently. The angular dependence and surface morphology of the target may become key information on the cleaning mechanism. Nevertheless, there was a parameter window of the concentration to mitigate debris caused from a liquid jet target, in which deposited debris was effectively balanced with other effects caused by chlorine produced as debris.

4 Conclusions

We have demonstrated a passive auto-cleaning effect in a LPP EUV source by using a room-temperature target containing chemical substances, such as tin chloride. The amounts of deposited debris using a tin chloride solution as a continuous jet target were well regulated by selecting concentrations of the solution. By using a concentration of 17%, the deposition of tin debris was balanced out with sputtering and/or etching caused by chlorine atoms or ions produced as debris. At this concentration, the maximum EUV CE of 1.1% has been simultaneously observed by using double pulse irradiation at a delay time of 180 ns with a thickness of deposited debris less than 1 nm after 40 000 pulse irradiations.

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