Development of Laser-produced plasma EUV light source for lithography

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INTRODUCTION

Extreme ultraviolet (EUV) lithography is a promising technology for large scale production of future microprocessors and memories whose node size is less than 45 nm. Requirements of the light source for lithography are following; EUV power at wavelength of 13.5 nm within 2% bandwidth should be at least 115 W at the intermediate focus point with a repetition rate of 10 - 100 kHz and an etendue of $\leq$ 3mm^2 sr. Higher power of 180W may be required for realistic sensitivity of EUV resists. If we assume efficiency of a focusing system of EUV light from the plasma source to the intermediate focus point to be 30%, EUV power should be about 600 W/2π sr at the source. To reduce driver laser power, heat load of a system and thus capital cost, a key issue in the source development is therefore obtaining high conversion efficiency (CE) from driver laser energy to 13.5 nm EUV emission energy.

In 2003, we have started the Leading Project promoted by MEXT for developing the EUV light source by laser-produced plasma, with the collaboration of METI project (EUVA). Our project aims at understanding physics of EUV emission from laser-produced plasma, and providing scientific database and technical guidelines for the practical EUV light source to the METI project. The project also aims at developing new targets and high power laser.

The target materials under considerations for EUV emitter are tin, xenon, and lithium. By the theoretical and the experimental studies, we have constructed the database on these materials, such as EUV emission spectra from plasmas, conversion efficiency from laser to EUV radiation within 2 % bandwidth, under the various conditions of laser parameters (wavelength, pulse duration, and intensity) and target parameters (size, shape, and initial mass density). In this year, our research efforts were concentrated into the tin target because of the highest conversion efficiency among them.

Tin is a very attractive target material for efficient EUV emitter. However, the tin plasma generates a lot of debris (neutral particles and ions), which will condense on the first EUV collection mirror and degrade the mirror reflectivity. In order to suppress the neutral debris the use of so-called “minimum-mass target” is highly desirable, where a target contains minimum mass of tin necessary for EUV emission at high conversion while minimizing the generation of neutral debris. We have evaluated the minimum mass of tin required for sufficient EUV emission [1], and proposed two kinds of minimum-mass targets [2], a tin droplet target with double pulse irradiation and “punch-out target” [3]. Even if the minimum-mass target is realized, the fast ions are still dangerous. For protecting the collection mirror from the fast ions, the mitigation by magnetic field is investigated.

We here briefly review the recent progresses.

LASER DEVELOPMENT

We have developed a high repetition (5 – 100 kHz) and high power (5.24 kW) Nd: YAG rod laser system for LPP [4]. The system consists of oscillator, pre-amplifier (front-end system) and main amplifier chain. The front-end system is constructed by fiber laser systems, so that those have stability and controllability. Main amplifier chain is constructed from the Quasi-CW and CW laser diode (LD) pumped Nd:YAG rod amplifiers. A laser light from the fiber front-end is amplified to 7 W by a large mode area fiber amplifier.

The thermal effects, such as thermal lens and birefringence and the luminescence shift of the central wavelength, are important problem for high averaged power laser system. The luminescence shift causes the wavelength mismatching among the front-end, pre-amplifier and the main amplifier. We adapted the wavelength of the oscillator and the pre-amplifiers to the one of the main amplifier module, at 1064.5 nm. It is important to achieve a uniform pumping for extracting the stored energy and compensating the thermal effects. We inserted a composite rod which has non-active layer of 13mm diameter around active layer of 10mm diameter. The composite rod has a few advantages compared with a normal rod. In a case of the side pumping, the pumping power distributes into two layer, the boundary layer and main body. The boundary layer is given by following, $r = (n_1/n_2)R$, where n_1 and n_2 are the refractive index of the coolant and the laser rod, respectively, and R is the radius of the laser rod. Therefore, the uniform pumping is realized by the composite structure which is constructed from two layers, with and without the dopant. In addition, the density of stored energy increases, and the volume matching is improved. But the thermal broken limit of the composite rod is lower than the one of the normal rod.

As a result, the output power of 5.24 kW has been achieved, when the pumping power is 30.4 kW (5Hz, on/off 40ms/160ms, Duty 20%). The pulse width is 10 ns, and the repetition rate is 100 kHz. The optical-optical transfer efficiency is about 17.2 %. The far field pattern is focused until 2.7 times of the diffraction limit.

THEORETICAL MODELING

1. Further improvement of conversion efficiency by CO_2 laser double pulse irradiation

The conversion efficiency depends strongly on the electron temperature and the ion density. An electron temperature in the range of 30 - 70 eV is required for the high CE, because most of 13.5 nm emission from tin comes from ions with the charge state $Sn^{10\text{-}14+}$ and this rang of electron temperature is required for the ionization. The relatively high CE can be obtained in relatively low ion density region. This is mainly due to a large spectral efficiency, the ratio of 13.5 nm emission with 2% bandwidth to total radiation, and lower opacity in the low density region. The power balance model indicates that a longer wavelength laser, such as CO_2, may result in higher CE than a shorter wavelength laser, such as Nd : YAG glass laser.

We consider the use of CO_2 laser. High laser absorption efficiency requires relatively long density scale for CO_2 laser light. At the scale length of about 200 μm around the ion density of 4-5 x 10^{17} cm^{-3} and the electron temperature of 45 eV, we can expect high laser absorption efficiency and less opacity effect for 13.5 nm radiation, and thus a high CE. At this point the spectral efficiency becomes about 35%. Thus it is necessary to produce a plasma with relatively long density scale of about 200 μm for a high CE.

On the other hand, although a tin target gives higher CE than xenon and lithium, the debris is a serious problem. Therefore we have to use a minimum mass target. The experiment showed that if the thickness of a tin layer coated on a planar plastic was thinner than about 40 nm, amount of EUV emission flux decreased with the decrease of the thickness for the case of Nd glass laser with the pulse duration of 10 ns [1]. Recent experiments also showed that the neutral debris decreases very much in decreasing thickness of tin layer coated on a plastic shell [1]. These experiments indicate that the minimum thickness is about Δ = 40nm as a EUV source for a planar target. The size of the EUV light source should be about 1mm or less in diameter to satisfy the etendue limit. Therefore the equivalent minimum volume of a spherical target could be of the order of $2R_0$ = 40 μm or less in diameter, $4\pi R_0^3/3 = \pi R_0^2\Delta$. We consider a small droplet target of the order of 40 mm or less in diameter, as an example of the minimum mass target.

We here propose to use a double pulse laser irradiation scheme that consists of a prepulse laser with relatively weak power followed by a high power mainpulse laser [5]. We use the prepulse laser so that the minimum mass droplet target expands before the main pulse laser and the density scale becomes about 200 μm but the plasma size still satisfies the etendue limit. We have optimized the conditions of the double pulse irradiation scheme using our benchmarked radiation hydrodynamic code to get a higher CE. We show that the double pulse irradiation scheme can give the high CE up to 6-8%, roughly two times greater than that with the single pulse. Here the prepulse laser first arrives on a tin droplet target of 40 μm in diameter. The conditions of the pre-pulse laser are wavelength of 1 μm and intensity of $5X10^8$W/cm^2 with a pulse duration of 10 ns. The main CO_2 laser with a pulse duration of 10 ns irradiates with various laser intensities at a time of 180 ns after the prepulse peak. The prepulse laser irradiation makes a plasma expansion velocity with the order of 10^5 cm/s, and then the density scale length becomes of the order of 200 μm with the duration of 200 ns before the main laser pulse, which results in high laser absorption. In the single CO_2 laser case, the laser absorption fraction is roughly 50%. However, the double pulse case can give 90% absorption, and this can directly improve the CE. It should be noted that the conditions of the prepulse laser intensity and the duration of the interval between the two pulses does not affect the CE because of low intensity of the prepulse. However the CE strongly depends on the main pulse intensity and its pulse duration.

2. Mitigation of fast ions by magnetic field

Electrons in LPP first expand into vacuum, and generate an electric field, which accelerates ions outward. It was found that an isothermal plasma expansion model of a limited mass could explain experimental spectra of energetic ions [6]. A self-similar expansion theory self-consistently treating charge separation [7] shows that the maximum energy is approximately given as $E_{max} = 2\langle Z\rangle T_e \ln(\Lambda^2/2/\ln\Lambda^2/2)$, where $\Lambda = R_0/\lambda_D$ is the plasma size parameter, R_0 is a initial target radius, and λ_D is the electron Debye length. If we consider a droplet with a mass of $4\pi m_i R_0^3 n_0/3 = M$, the plasma size parameter becomes $\Lambda = M^{1/3} n_0^{1/6}/(T_e/m_i)^{1/2}$. Therefore we expect the reduction of the maximum ion energy by using the minimum mass target and low initial density.

As a mitigation scheme of the energetic ion debris, we consider a magnetic field shield generated by a single coil. For example, for tin ions with the charge state of Z^* = 1 , and the energy of a few keV , and the magnetic field of B = 3T , the Larmor radius R_{Li} becomes a few cm. Its diameter therefore is smaller than typical distance between plasma sources and a collecting mirror (10 cm). Since initial plasma pressure is much larger than magnetic pressure, $p_0/p_{B0} >>1$, the plasma expands at least until when the plasma pressure becomes comparable to the magnetic pressure. Since the electron gyroradius is typically much larger than the electron Debye length, electrons first expand and generate an electric field, which accelerates ions. However since the electrons are magnetized, they can not freely expand. On the other hand since the ion gyroradius is much larger than any spatial scales, the ions expands ahead and generates an inward radial electric field. Ions are not accelerated in the direction perpendicular to the magnetic field as the case of the free expansion. Based on PIC simulations, we showed sufficient reduction of the perpendicular energy for realistic parameters. The interchange instability may be induced during the plasma expansion. The suppression of the instability in the outer region ($R > R_{Li;max}$) can be attributed to large ion gyroradius [8]. The result indicates that the B-field mitigation scheme may work, if the ion energy is suppressed lower than a few keV by using the double pulse laser irradiation scheme.

PLASMA EXPERIMENTS

1. Neutral debris emanated from minimum mass Sn target

Sn is a condensable EUV fuel, thus Sn debris emanated from the source plasma deposits on the first EUV collection mirror. Laser-induced-fluorecence (LIF) technique was used to measure selectively neutral Sn debris emanated from laser-produced Sn plasmas. Dependence of the LIF intensity on the number of Sn atoms was calibrated by comparing the LIF intensity with neutral Sn atom density that is measured with EUV backlight technique. The minimum thickness required for sufficient EUV generation is 40 nm. Amount of the neutral debris generated from a 40 nm-thick Sn dot target, whose diameter is equal to the laser spot size (500 μm), was evaluated to be 4.8 x 10^{13} atoms that corresponds to 10% of the number of the supplied fuel. See the report written by M. Shimomura [9].

2. **Absolute evaluation of out-of-band radiation**

Out-of-band (OOB) radiation, > 130 nm of wavelength, from an EUV light source is one of deteriorative factors of lithography performance. Absolute radiant energy of the OOB light was measured with an absolutely calibrated transmission grating spectrometer. The dominant source of the OOB radiation is found to be the laser spot periphery heated via electron thermal conduction and radiation from the EUV source plasma. See the report written by H. Sakaguchi [10].

2. **EUV light generation from pure Sn droplet target**

Pure tin droplet target is a practical candidate of the minimum mass target. The diameter of a solid Sn drop, containing the minimum number of Sn atoms, is about 30 μm, but this diameter is much smaller than the required laser spot size of about 500 μm. The drop target must be expanded prior to the main drive laser irradiation. The expanded drop target was irradiated with Nd:YAG or CO_2 laser pulses, then sufficient EUV light is emitted from the produced plasma. A new droplet target generator has been developed in University of Hyogo. Continuous EUV light generation is now in progress. See the report written by T. Aota and Y. Nakai. [11]

4. Punch-out target irradiated with CO_2 laser pulses

EUV light generation from a punch-out target has been demonstrated, but conversion efficiencies from the punch-out targets were considerably lower than those from bulk targets. Density of the punch-out target is not high enough to absorb Nd:YAG laser light, CO_2 laser is more feasible for the punch-out target. CO_2 laser was introduced in our experimental laboratory. The CO_2 laser system consists of an oscillator and an one-pass amplifier, 150 mJ of the laser energy is obtained. A plasma shutter is inserted between the oscillator and the amplifier to shorten the CO_2 pulse duration below 50 ns. EUV conversion efficiency from the punch-out target was improved by the use of CO_2 laser. See the report written by S. Maeda [12].

MINIMUM MASS TIN TARGET COATED ON 500 μM SIZED BUBBLES

According to the previous research in leading project, minimum mass target has been proposed where 10^{14} ~ 10^{15} number of tin atom within a laser spot size of ~500 μm. The present bubble target is one of the low density target to supply minimum mass target without prepulse irradiation. Monodispersed size bubbles of 100 μm to 2mm were prepared using a microfluid apparatus and were reinforced with polyelectrolyte coatings with 10 ~ 20 nm thickness, then tin ion or tinoxide nanoparticle layer was coated. Polyelectrolytes were chosen to be negatively charged polystyrene sulfonate, PSS and positively charged polyallyl ammonium, PAA. The tin sources were fastened through electrostatic force which was characterized using ζ-potential measurements, In the case of Sn^{2+}, ~10^{14} tin atom was coated on the outer surface of 500 μm diameter bubble, while for tinoxide particle with 20 nm size coating, ~ 10^{15} tin atom was. The following picture is an example of fabricated bubbles lined in a grass capillary whose inner diameter was 500 μm.

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