EUV Light Source by High Power Laser

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Abstract. In the development of a high power EUV source used in the EUV lithography system, it is important to understand basic physics of EUV plasma and to optimize laser and target conditions. We have been constructed EUV database of laser-produced tin plasma by the theoretical and experimental studies. On the basis of our understanding, the optimum conditions of lasers and plasmas were clarified, and we proposed the guidelines of laser plasma to obtain clean, efficient and high power EUV source for the practical EUV lithography system. In parallel to such studies, novel targets and high power laser system to generate the optimized EUV source plasma have been developed. Recent progresses of our program are presented.

1. Introduction

Extreme ultraviolet (EUV) lithography is a leading technology for fabricating the next generation semiconductor devices whose technology node is 32 nm and below. One of the key issues to realize the EUV lithography system is to develop an efficient, clean, and high power EUV light source. 300 – 500 W of EUV power at 13.5 nm of wavelength within 2 % of bandwidth is required at plasma. A laser-produced plasma is a powerful candidate of EUV light source. We have been developing EUV light source under the Leading Project promoted by MEXT (Ministry of Education, Sports, Culture, Science and Technology) with the collaboration of METI (Ministry of Economy, Trade and Industry) project (EUVA). Our program aims at understanding basic physics on EUV source plasma and providing database and technical guidelines for the practical EUV source of high volume production to METI project. The project also aims at developing new targets and high power laser.

The target materials to be considered 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 and target. Recently, 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 number of tin atoms 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 also investigated.

2. EUV data base for high efficiency

EUV spectra of highly ionized tin ions with different charge states [4] and the opacity of tin plasma [5] were measured. These spectroscopic data were used to improve the atomic models [6]. Both 1D and 2D radiation-hydrodynamic simulation codes have been developed and improved by the use of new atomic model data. In the experimental studies, the spatially and temporally resolved plasma parameters (temperature and density) [7], EUV emission spectra and conversion efficiencies [8,9] were precisely measured under the various conditions of laser parameters (wavelength, pulse duration, and intensity) and target parameters (size, shape, and initial mass density).

Figure 1 shows the calculated and measured EUV spectra from tin target [10] at three different laser intensities of (a) $9 \times 10^{10}$, (b) $3 \times 10^{11}$, and (c) $9 \times 10^{11}$ W/cm². The overall agreement is very good, particularly at 13 nm emission. Emission peaks at shorter wavelength increase with increasing laser intensity.

Figure 2 shows the conversion efficiency (CE) from laser to EUV emission as a function of laser intensity. By introducing photo-excitation process (PE) in the simulation, a good agreement with the experiments is obtained. In the experiments, tin-coated spherical targets were uniformly irradiated by 1 μm, 2 ns laser [8]. Maximum CE is 3% at 0.5 – 1.0 x 10¹³ W/cm².

Figure 3 shows the dependence of maximum CE in (a) and optimum laser pulse duration in (b) on electron temperature and ion density of tin plasma with the laser intensity required to sustain expanding plasma [7]. Very high CE of 4–6 % can be expected in the relatively low ion density region of $10^{17}$ – $10^{18}$ cm⁻³ and electron temperature of 30 – 50 eV. Opacity of tin plasma in the EUV region is large and low density plasma is desirable for high CE.

3. Minimum-mass target

Minimum number of tin atoms required for high conversion was evaluated by the experiments, where tin coated targets with different coating thickness were used. With the decrease of coating thickness...
until ~40 nm, the fluorescence from the neutral tin atom [12, 13] decreased linearly, while keeping EUV emission intensity constant. This suggests the importance of minimum-mass target to suppress the neutral debris. The number of tin atoms required in the target is suggested to be the same number of EUV photons required for the EUV light source. We have proposed two kinds of minimum-mass targets, tin droplet target with double pulse irradiation and so-called “punch-out target”.

In the double pulse irradiation scheme, a tiny droplet containing minimum number of tin atoms is irradiated by a pre-pulse laser to generate a pre-formed plasma. After the expansion of pre-plasma to the optimum density range a main laser pulse is irradiated to heat the plasma and to generate EUV emission. Figure 4 shows the CE by the simulation, where a tin droplet of 20 µm in diameter is irradiated by 0.5 µm (pre-pulse) and 10 µm (main pulse) lasers. The CE increases up to 6-7 % at low laser intensity.

In the punch-out target, a thin tin layer is coated on a transparent substrate, as shown in Fig. 5. A weak puncher laser illuminates the tin layer from the substrate side. A low temperature plasma is produced at the boundary between the substrate and tin. The plasma pressure pushes out the tin layer with a flying velocity of ~1 km/s or more. The shape, the velocity, and the density distribution of punched-out target have been measured precisely by a laser light scattering and an EUV backlighting, under the different conditions of puncher laser intensity, pulse duration, and tin layer thickness [15]. The flying target shows a jet like shape, and an angular spread of jet along the flying axis is very small. The flying target is heated by irradiating a heating laser to generate EUV emission. In the feasibility experiments [16], strong EUV emission was observed only when the heating laser irradiates the punched-out target at a proper temporal delay after the puncher laser. It should be noted that the fast ion energy reduced drastically in the punch-out target. The maximum ion energy was sub-keV, which is approximately one order of magnitude less than those in the solid targets, and the mitigation of ion debris by the magnetic field will be effective [11]. The EUV generation experiments by using a disc type punch-out target and the repetitive laser irradiation started.

![Figure 3](image_url)

**Figure 3.** Dependence of conversion efficiency (CE) (white line: %) in (a), required laser intensity (dotted line: W/cm²), and optimum pulse duration (white line: ns) in (b), on electron temperature and ion density of tin planar target. Red and blue circles indicate the optimum region for 1 µm and 10 µm lasers, respectively. Star shows the experimental result shown in Fig. 2.

![Figure 4](image_url)

**Figure 4.** Comparison of CE by double pulse with that by single pulse.

![Figure 5](image_url)

**Figure 5.** Concept of punch-out target.
4. Laser development
We have been developing a high repetition (5 ~ 100 kHz) and high power (5 kW) Nd: YAG rod laser system to generate EUV source plasma. Key subjects are (1) reliable front end, (2) uniform and high density pumping of main amplifier rods, and (3) compensation for thermal effects in the Nd: YAG rods. Layout of 5 kW laser is shown in Fig. 6. The system consists of a fiber front end, a fiber amplifier, pre-amplifiers and a main amplifier chain. At present, 4.6 kW output has been obtained. An additional fiber amplifier with 50 W output is under construction. Pre-amplifiers in the present laser system will be replaced by this fiber amplifiers, and a phase conjugate mirror will be introduced to compensate for the thermal lens effects in the main amplifier stage, which enables us to reach the designed performances.

![Figure 6. Layout of 5 kW Nd:YAG rod laser system.](image)

5. Summary
Systematic studies on EUV emission from the laser-produced tin plasma have been performed. Optimum laser conditions for obtaining high conversion efficiency have been predicted. The maximum conversion efficiency of 4-6 % will be available by the use of long wavelength laser and low laser intensity for relatively low density tin plasma. The minimum-mass target is important to suppress the neutral debris and to realize the clean EUV source.

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