Development of EUV light source by laser-produced plasma

Yasukazu Izawa

INTRODUCTION

Extreme ultraviolet (EUV) lithography is the most promising technology for fabricating the next generation semiconductor devices whose technology nodes are less than 45 nm. One of the key issues to realize the EUV lithography system is to develop an efficient, clean, and high power EUV light source. More than 115 W of EUV power at 13.5 nm wavelength is required at an intermediate focus. A laser-produced plasma is a powerful candidate for EUV light source.

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.

THEORETICAL MODELING

1. Optimization of conversion efficiency

A simple analytical model has been constructed to evaluate the EUV conversion efficiency [4]. The model reproduced the experimental results very well, which were obtained under different conditions of the laser wavelength, the pulse duration, and the laser intensity. The model also shows that with the increase of laser wavelength, the maximum conversion efficiency will increase by decreasing the laser intensity.

On the basis of power balance model, the optimum laser conditions to obtain high conversion efficiency have been predicted [5]. The model gave us that, for tin target, the maximum conversion efficiency of 4 – 6% will be available by the use of long wavelength laser and low laser intensity. The optimum ion density is relatively low due to opacity effect in tin plasma.

2. Code development and double pulse irradiation

Both 1D and 2D hydrodynamic codes were improved by introducing a new atomic model data, which were reconstructed by the use of experimentally obtained emission spectra from the highly ionized tin ions. The simulation results on EUV emission spectrum from tin plasma produced by the three different laser intensities show very good agreements with the experimental results [6].

The double laser pulse irradiation scheme can provide the low density plasma in the above mentioned optimum region for high conversion efficiency. We have started the analytical works on double pulse irradiation scheme by 1D and 2D codes. The simulation results show the increase of conversion efficiency at a proper temporal delay between the two laser pulses for pre-plasma generation and heating of plasma.

3. Mitigation of fast ions by magnetic field

Expansion of laser-produced tin plasma in the various magnetic field configurations was simulated by using PIC 3D code. It was found that the plasma is bounded in the direction perpendicular to the magnetic field, and the expansion strongly depends on the initial position of plasma. These results suggest us that the first collection mirror of EUV light will be protected from the fast ions efficiently by tuning the configuration and strength of the magnetic field and the position of plasma generation.

PLASMA EXPERIMENTS

1. Minimum-mass target

Minimum number of tin atoms required for high conversion was evaluated by using the tin-layer coated targets with different coating thickness. With the
decrease of coating thickness until ~40 nm, the fluorescence from the excited neutral tin atom [7, 8] and also the laser induced fluorescence from the non-excited tin atom 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 that required EUV photons for the EUV light source.

2. “Punch-out target” experiment

In the punch-out target, a thin tin layer is coated on a transparent substrate. 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 flying target is heated by irradiating a drive laser to generate EUV emission. In the feasibility experiments performed last year [8], 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, and the mitigation of ion debris by the magnetic field will be effective.

In this year, 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 and pulse duration, and tin layer thickness. The flying target shows a jet like shape, and an angular spread of jet along the flying axis is very small. The tip of the jet consists of rarefied tin gas, and the middle is dense gaseous tin or liquid tin. At the later part, tin small particles are observed.

By irradiating the heating laser, the EUV emission was observed at the tip and the middle of the jet like structure. The EUV intensity was around 2/3 of that from the bulk tin target. We also started the EUV generation experiments by using a disc type punch-out target at 10 Hz repetition.

3. Out-of-band radiation

A tin plasma emits a wide spectral range radiation beside 13.5 nm within 2 % bandwidth, which is called out-of-band (OOB) radiation. In the EUV lithography system, the OOB radiation power should be limited to < 1 % for UV region (130 ~ 400 nm) and < 10 ~ 100 % for visible and IR region (400 ~ 3000 nm), compared with that at 13.5 nm radiation. The OOB radiation was measured with temporally and spatially resolved visible and VUV spectrometers for the tin-coated planar and spherical target. The OOB radiation mainly comes from LTE plasma with low temperature and high density. For the planar target, the OOB radiation is emitted not only from the laser spot but also from its peripheral, and the radiation power was ~ 4 times larger than that from the spherical target.

NEW TARGETS

Several new targets, such as a rare gas droplet target on which a thin tin compound layer is adsorbed and a micro-capule target with bubble inside, were proposed and developed for fabrication. Adsorption rate of tin compound on the solid rare gas surface was measured, which is high enough to feed the target in the practical EUV light source system. Stability of the adsorbed layer is being studied now. Micro-capules with the diameter of sub μm to 10 μm have been fabricated by a layer-by-layer method. Overcoating of tin compound on the micro-capule was successful.

For the use of basic experiments on EUV emission and debris behaviors, and for the punch-out target experiments, so-called “dot target” has been fabricated by printing method. Tin compound solution was dropped slowly through an inkjet printing device on a glass plate or a transparent film. Typically several hundreds of dot with diameter of 200 ~ 500 μm and thickness of 20 ~ 30 nm were easily fabricated. The shape, diameter and thickness of dot are controllable by changing the concentration of tin compound solution.

LASER DEVELOPMENT

We have been developing a high repetition (5 ~ 10 kHz) and high power (5 kW) Nd: YAG rod laser system for laser-produced EUV 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. Basic system has been constructed and used for the EUV generation experiments at 10 kHz repetition.

In this year, a fiber amplifier with the average output of 10 W was newly developed and introduced into the front end system. An additional fiber amplifier with 50 W output is under construction. Pre-amplifiers in the present laser system will be replaced by the fiber amplifiers, and a phase conjugate mirror will be introduce for compensating for the thermal lens effects in the main amplifier stage, which enables us to reach the designed performances.

REFERENCES