Beyond Extreme Ultra Violet (BEUV) Radiation from Spherically symmetrical High-Z plasmas

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Abstract. Photo-lithography is a key technology for volume manufacture of high performance and compact semiconductor devices. Smaller and more complex structures can be fabricated by using shorter wavelength light in the photo-lithography. One of the most critical issues in development of the next generation photo-lithography is to increase energy conversion efficiency (CE) from laser to shorter wavelength light. Experimental database of beyond extreme ultraviolet (BEUV) radiation was obtained by using spherically symmetrical high-Z plasmas generated with spherically allocated laser beams. Absolute energy and spectra of BEUV light emitted from Tb, Gd, and Mo plasmas were measured with an absolutely calibrated BEUV calorimeter and a transmission grating spectrometer. $1.0 \times 10^{12}$ W/cm$^2$ is the optimal laser intensity to produce efficient BEUV light sources with Tb and Gd targets. Maximum CE is achieved at 0.8% that is two times higher than the published CEs obtained with planar targets.

1. Introduction

Continuous development of semiconductor device technologies gives large impacts on our society. Photo-lithography is a key technology for volume manufacture of high performance and compact semiconductor devices. Smaller and more complex structures can be fabricated by using shorter wavelength light in the photo-lithography. Current photo-lithography uses 193 nm-wavelength ArF laser as a light source. 13.5 nm-wavelength extreme ultraviolet (EUV) is a light of the next generation photo-lithography [1]. The transmittance of EUV light in a material is significantly low, thus EUV lithography (EUVL) system is composed of reflective optics. Mo/Si multilayer mirrors are used in the EUVL system because reflectivity of a Mo/Si multilayer mirror is relatively high (70%) at 13.5 nm. It is proposed to switch wavelength of a EUVL light source from 13.5 nm to a shorter one for enhancement of resolution of the EUVL. The next generation EUV light is called as “beyond EUV (BEUV)” in the...
EUVL community. Development of BEUV light source has been started to extend the capability of the EUVL [2]. As is shown in Fig. 1, reflectivity of a La/B₄C multilayer mirror is relatively high in the BEUV range, it is more than 50% at 6.7 nm, and bandwidth (BW) of its reflectivity is about 0.6% of the central wavelength, therefore 6.7 nm is a candidate wavelength for the BEUV lithography.

![Graph of reflectivity vs wavelength](image)

Fig.1 Measured reflectivity of La/B₄C in BEUV range

Optical system of the lithography is composed of, at least, eight mirrors to reduce image aberration, this means only 0.5% ≈ 0.4% of the source power is utilized in the BEUVL processes. The BW of BEUV light, which is transmitted through the BEUVL system, becomes narrower (0.3%) than the BW of a single multilayer mirror owing to multiple reflections. One of the most important issues in BEUVL development is to maximize the energy conversion efficiency (CE) from laser to BEUV light. In this study, the CE is defined as energy ratio between 6.7 nm ± 0.3% BW light and the laser.

2. Generation of spherically symmetrical plasmas

Laser-produced plasma (LPP) is one of intense EUV and BEUV radiation sources. A target material becomes a high temperature plasma by irradiation of intense laser pulse. Nd:glass laser system, GEKKO-XII at Institute of Laser Engineering, Osaka University, was used in this study. GEKKO-XII laser facility consists of twelve laser beams, whose wavelength, pulse shape, duration and energy are 1.053 µm, Gaussian, 1.3 ns of FWHM, and 12 J in total, respectively. The twelve laser beams are allocated at twelve faces of the regular dodecahedron to irradiate spherical targets uniformly. The twelve laser beams were focused onto spherical Tb, Gd, Mo targets and the laser focal point was displaced based on the target diameter such that the target was illuminated uniformly. Mean squared error of the non-uniformity was 1.8%, which was uniform enough for this research [3]. Laser intensity on the target surface was varied from 3 x 10¹¹ to 3 x 10¹³ W/cm² by adjusting diameters of the spherical targets from 100 µm to 1000 µm. 2 µm-thick metallic layer is coated on spherical polystyrene balls.

There are three advantage of generation of q spherically symmetric plasma. Kinetic energy loss caused by lateral plasma expansion along the target surface is suppressed, high CE can be obtained due to reduction of the additional kinetic energy losses. Spherical symmetry of the plasma makes it easy to compare the experimental results with theoretical model and simulation results. The plasma can be observed simultaneously from multiple directions with various diagnostics.

3. Energy conversion efficiencies from laser to 6.7 nm light.

![Graph of laser produced plasmas](image)

Fig.3 Schematics of laser produced plasmas
(Left) Multi-dimensional plasma expansion causes additional energy loss in the case of a plane target irradiated by a one-dimensional laser beam.
(Right) One-dimensional spherical plasma is generated with a spherical target irradiated by multiple laser beams.
Emission spectra from the plasmas depend on the atomic number. According to previous studies, laser-produced Gd, Tb and Mo plasma emits BEUV light near 6.7 nm [4]. Absolute radiant energy of BEUV radiation was measured with a BEUV calorimeter that consists of a Mo/B$_4$C multilayer mirror and a Zr filter, and a x-ray photodiode as shown in Fig. 4. Dependence of the CE on laser intensity is summarized in Fig. 5 (a). The maximum CEs of 0.8% was obtained with Tb and Gd plasmas generated with the laser intensity of $1 \times 10^{12}$ W/cm$^2$. The maximum CE (0.45%) obtained with Mo plasmas is much lower than those with Tb and Gd plasmas.

Fig. 4 Schematic of energymeter

Fig. 5 (a) Dependence of CEs on laser intensities and target material those obtained with spherically symmetry plasmas.

Fig. 5 (b) Comparison of CEs from spherical targets (closed square) and those from planar targets (open square). The CEs obtained with spherical plasmas is two times higher than those obtained with planar targets.

Fig. 5 (b) shows CEs obtained with spherical (this study) and planar (previous study [5] Gd target. The planar target experiment was conducted by using the same calorimeter and a 10 ns Nd:YAG with a maximum energy of 420 mJ at the wavelength of 1064 nm. This laser beam was injected normally onto solid planar Gd targets and after each laser shots the target surface was replenished. The CEs obtained with spherical plasmas is two times higher than those obtained with planar targets. This result approves that kinetic energy loss caused by multi-dimensional plasma expansion is suppressed in one-dimensional spherically symmetry plasmas.

4. Emission spectra of Tb, Gd and Mo plasmas

The BEUV emission was observed with time-integrated transmission grating spectrometer (TGS) coupled with an absolutely calibrated charge coupled device camera. Figure 6 shows BEUV spectra those are normalized with laser energy. The spectra were obtained with Gd, Tb, and Mo plasmas for $1 \times 10^{12}$ and $3 \times 10^{13}$ W/cm$^2$ of laser intensities. Emission peak of Gd, Tb spectra are located at 6.7 nm. A Mo plasma also emits 6.7 nm, however, the peak at 6.7 nm is relatively weak. BEUV emission from Gd and Tb plasmas decrease with increasing laser intensity, while shorter wavelength emission (< 2 nm) increases. Spectral shape of the Mo plasma becomes flat vaguely in 3-11 nm range with increasing laser intensity.
According to the experimental results, optimal laser intensity is $1 \times 10^{12}$ W/cm$^2$, electron temperature of laser-produced plasmas is too high to emits BEUV light for more than the optimal laser intensity. [6] Emission lines from highly charged (> 30) ions were observed in a wavelength range of 1 - 3 nm. [7] It shows that the laser energy is consumed for over-ionization, resulting in a degradation of BEUV-CEs.

5. Conclusion and future plans

1.0 $\times 10^{12}$ W/cm$^2$ is the optimal laser intensity to generate efficient BEUV light source. Maximum CE is achieved at 0.8% that is two times higher than the published CEs obtained with planar targets. Shorter wavelength emission increases due to higher plasma temperature in the case of the $3.0 \times 10^{13}$ W/cm$^2$ irradiation compared to the optimal intensity case. These data are expected to be of use in future plasma modeling for BEUV source development. It is necessary to clarify the parameters of BEUV source plasmas for further improvement of BEUV-CEs.

Fig.6 Comparison of BEUV spectra emitted from Tb, Gd, and Mo plasmas. Left and right spectra are obtained with $1.0 \times 10^{12}$ and $3.0 \times 10^{13}$ W/cm$^2$ of laser intensities, respectively.

Reference

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