Spectroscopic measurements of ablation plasma generated with laser-driven intense extreme ultraviolet (EUV) light

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Abstract. Material ablation by a focused Extreme ultraviolet (EUV) light is studied by comparing expanding ion properties and plasma parameters with laser ablation. The kinetic energy distributions of expanding ions from EUV and laser ablation showed different spectra implying different geometries of plasma expansion. The calculation results of plasma parameters showed that EUV energy is mostly deposited in high electron density region close to the solid density, while laser energy is deposited in low energy density region. Plasma parameters experimentally obtained from visible spectra did not show noticeable difference between EUV and laser ablation due to the corresponding low cut off density.

1. Introduction

Extreme ultraviolet (EUV or XUV) is extremely short-wavelength radiation ranging from a few to a few tens of nm, and many types of radiation sources have been widely developed. Although one of the most well known applications of this radiation is EUV photolithography, recent progress on EUV sources can lead to many other possibilities in the industry, such as material processing and material analysis. One of the possible applications is micro- and nano-machining using material ablation by focused EUV [1,2].

Since there are significant differences between EUV and conventional laser in terms of the wavelength and photon energy, heating mechanism and ablation physics of EUV ablation are expected to be quite different from that of laser ablation. Dynamics of material ablation strongly depends on the wavelength of the incident radiation or laser, especially with a pulse length in nano-second order. Ablation plasma is formed in pico-second order after the front end of the laser reaches the sample surface. This means that the rest of laser enters the plasma. In the plasma, the laser light does not penetrate further at a certain electron density called the critical density \( n_c \) written as follows,

\[
 n_c = \frac{\omega^2 m_e \varepsilon_0}{e^2} = \frac{4\pi^2 c^2 m_e \varepsilon_0}{\lambda^2 e^2},
\]  

(1)
where $\omega$ is the angular frequency of the incident radiation or laser, $m_e$ is the electron mass, $\varepsilon_0$ is the vacuum permittivity, $c$ is the speed of light, and $\lambda$ is the wavelength of the incident radiation or laser. The critical density corresponding to the EUV wavelength range exceeds the solid density (e.g. $6.1 \times 10^{24}$ cm$^{-3}$ for 13.5 nm EUV), while that corresponds to conventional laser wavelength is 1-2 orders of magnitude smaller than the solid density (e.g. $1.1 \times 10^{23}$ cm$^{-3}$ for 1064 nm Nd:YAG laser). One hand, the dominant heating process of laser ablation is the collisional energy absorption by electrons in low-density plasma followed by thermal heating of the materials by electrons. On the other hand, EUV can penetrate through the plasma and reach the sample surface, and deposit its energy into the material directly. Furthermore, orbital electrons would be directly excited by EUV photons with energy about 100 eV, e.g., photo-ionization. These possible differences in plasma heating mechanisms between EUV and lasers could result in different plasma properties. Thus, an effective approach for understanding the EUV ablation physics is the study of the ablation plasmas and its comparison with conventional laser ablation. In this paper, plasma characteristics of EUV and laser ablations are shown.

2. Experimental setup
A laser produced plasma (LPP) EUV source was utilised in the experiments. A drive laser (Nd:YAG, 1064 nm) was focused onto a solid Xe target. The EUV light emitted from the Xe surface was collected by a toroidal elliptical total reflection mirror with a gold coated reflection surface. For the laser ablation experiments, a Nd:YAG laser (1064 nm) was directly focused onto the sample. The focused EUV or laser intensity was in the order of $10^9$ W/cm$^{-2}$, and the spot size was 150 µm. Silicon and aluminium were chosen as the ablation samples because they have L absorption edges in Xe EUV wavelength range.

Two different measurements were conducted. One was time-of-flight (TOF) measurement of expansion ions by using a charge collector and the other was spectroscopy of the ablation plasma. TOF is a popular and useful technique for studies of flowing particles with velocities, such as particle beams or particle emissions. It is also suitable for the study of ablation plasma, because particle expansion is a key for understanding the ablation dynamics [3]. Time evolution of the ion current flowing into the charge collector was measured at the sample surface normal. Photoemission spectra from the ablation plasma were measured using a spectrometer in the visible range (350-700 nm) located at the 90-degree side view of the sample surface.

3. Ion expansion from EUV and laser ablations
TOF measurement of expanding ions from aluminium sample was carried out. The charge and mass are estimated to be Al$^+$ for the analysis of the TOF signals. The kinetic energy distributions are shown in Fig. 1. The TOF spectra of ion current flowing into the charge collector are also shown in the figures. The two kinetic energy distributions show completely different spectra: laser ablation have a convex spectrum and EUV ablation have a slightly concave spectrum. The shapes of spectra can be explained by an analytical model that includes the dimension of plasma expansion [4].

$$ \frac{dN}{dE} = \frac{E/E_0^{(\alpha-2)/2}}{F(\alpha/2)} \exp(-E/E_0), $$

where $E_0$ is the plasma temperature in eV, and $E$ is the ion kinetic energy, $\alpha$ is the geometry of plasma expansion. $\alpha = 1$ to 3 corresponds to planar, cylinder, and spherical geometries, respectively. The plasma expansion is one dimensional in all coordinate systems. Plots of eq. 2 form convex ($\alpha = 1$), linear ($\alpha = 2$), and concave ($\alpha = 3$) spectra in semilogarithmic plot.
Figure 1. Kinetic energy spectra of the expanding ions measured by the charge collector. Small graphs show the TOF spectra. a) A convex ion energy spectrum was observed from laser ablation plasma, and b) a slightly concave spectrum was observed from EUV ablation plasma.

Figure 2. Spatial distributions of electron density, electron temperature, energy deposition and pressure along the sample surface normal simulated by the STAR-1D code. Both a) laser and b) EUV ablation of CH sample were calculated.

The concave ion spectrum of EUV ablation implies that the plasma expansion is likely more planar expansion, which is one-dimensional expansion along the sample surface normal.

4. Comparison of plasma parameters

Figure 2 shows spatial distributions of the electron density, electron temperature, and energy deposition along the sample normal calculated by a one-dimensional radiation hydrodynamic code, STAR-1D [5], for both laser and EUV ablations of CH sample. The input laser or EUV parameters are in the same order of magnitude as that in experiments. A 33 eV Planckian radiation spectrum with a dilution factor of 0.03 was used to simulate the incident EUV spectrum from Xe target. Corresponding EUV intensity on the sample was $5 \times 10^9$ W/cm$^2$. Plasma parameters at the peak of Gaussian pulse of the incident laser or radiation are shown. EUV energy deposition have a peak inside the original surface position at 0 $\mu$m, where the electron density is in the order of $10^{22}$ cm$^{-3}$, while laser energy is mostly deposited in lower density region. Electron temperature in EUV ablation plasma is about 3 times lower than that in laser ablation plasma. It implies that most of EUV photon energy is deposited into particles in high-density region and consequently energy deposition into individual particle is small.

Spectroscopic measurements in visible range (350-700 nm) were conducted for Si ablation plasmas. Most of peaks of the spectra correspond to photo-emissions from Si$^+$ or Si$^{2+}$ ions. Figure 3 shows the electron densities derived from the Stark broadening of the spectra, and the
Figure 3. Plasma parameters, a) electron densities and b) electron temperatures derived from the time-resolved visible spectra of laser ablation Si plasma (open square plots) and EUV ablation plasma (dotted open circle plots).

electron temperatures by using Boltzmann plot for both EUV and laser ablation plasmas. The plasma densities are almost $10^{19}$ cm$^{-3}$ during irradiation (0-10 ns), and they gradually decrease in both EUV and laser ablations. Slightly higher plasma temperature ($\sim 1$ eV) is observed in laser ablation compared to EUV ablation during irradiation (Fig. 3 b). The difference becomes larger as the time implying difference in cooling mechanism between two radiation sources. Noticeable difference between laser and EUV was not observed. One possible reason would be the wavelength range. Visible light from high density plasma is cut off due to the critical density and information of core plasma may not have been observed in this set of experiments. Time and specially resolved spectroscopy of shorter wavelength range such as VUV or soft X-ray would provide detailed information of plasma parameters.

5. Conclusion

Characteristics of EUV ablation of materials were studied by comparing expanding ion spectra and plasma parameters with that of laser ablation. Energy distributions of expanding ions from EUV and laser ablation show different ion spectra. An analytical model was applied for analysis. It has been found that the plasma expansion of EUV ablation is likely one dimensional along the sample surface normal. Simulation results of spatial distributions of plasma parameters showed clear differences between EUV and laser ablation plasma. EUV energy was mostly deposited into high-density region inside the original surface position resulting in lower electron temperature than that of laser ablation. The plasma parameters were also derived from experimental results of visible spectra. No significant difference was observed in visible wavelength range, and spectroscopy in shorter wavelength range would provide detailed plasma information.

Acknowledgments

This work was supported by JSPS Grant-in-Aid for Young Scientists (B) number 25800303, Grant-in-Aid for Scientific Research (B) number 22340172, and MEXT Project for Creation of Research Platforms and Sharing of Advanced Research Infrastructure "Opening up a new photonics industry through high-intensity lasers".

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