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Present Status of Extreme Ultraviolet Source Development by Laser Produced Plasma

レーザープラズマEUV光源開発研究

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Properties of laser-produced plasmas (LPP) are discussed to generate extreme ultra violet (EUV) light, particularly at 13.5 nm in 2% bandwidth (BW), for use in the next-generation lithography. We present some topics of the LLP-EUV source; dependence of conversion efficiency to the EUV light on laser conditions for tin target, present understanding of EUV emission, and relevant experimental results

1. Introduction

Intense radiation emanating from laser-produced-plasma has a wide range of applications including radiography [1], a short-pulse probe for condensed matter research [2], and lithography [3]. Among them, extreme ultraviolet (EUV) radiation has recently attracted particular attention for use in production of the next generation semiconductor devices. It is expected to generate over 115 W at 13.5 nm within 2% bandwidth at the repetition rate of 7-10 kHz [4]. In 2003 Leading Project (LP), of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan was started dedicated for the EUV source development. The main tasks of LP are

(1) Acquisition of databases:

For practical application of EUV source, it is of great importance to optimize plasma conditions. Thus comprehensive experimental databases must be provided for a wide range of parameters including laser intensity, wavelength, pulse waveform, target materials, structures, and so on. These experimental data will be utilized to benchmark a radiation hydrodynamic code including equation-of-state solvers and advanced atomic kinetic models suitable for EUV plasmas. Energy levels and transition probabilities of multi-ionized state of high-Z material such as xenon and tin will be solved by these codes.

(2) Target design and fabrication:

Target technology is another key issue for EUV lithography system. Various types of targets have been proposed including gas, liquid, solid or clusters. In addition, innovative targets are desired in order to attain acceptably high conversion efficiency and to mitigate debris from targets.

(3) Establishment of laser technology for commercial use in EUV lithography system:

In order to supply sufficient EUV output, laser system of several-ns in duration, a few Joule in energy, one- or sub-μm in wavelength at a high repetition rate over 10 kHz will be necessary. Thus, establishment of advance technologies needed for such a high average power laser system is another important task. A 5 kW laser system will be constructed to demonstrate feasibility of efficient EUV generation under optimized plasma conditions.

2. Optimum plasma and laser conditions

To satisfy the EUV power demanded, emission energy E_{EUV} of 30-40 mJ per pulse should be attained at repetition rate of 10 kHz. Suppose EUV pulse duration of τ_{EUV}=1-10 ns, EUV flux will be $I_{\mathrm{EUV}}=E_{\mathrm{EUV}}/S\tau_{\mathrm{EUV}}$, here S is the source area-size defined by the demanded etendue (product of source area-size and available solid-angle) This will be that of a circle of 600 μm in diameter assuming the etendue of 1 mm^2sr.. Using typical EUV conversion efficiency of 1%, optimum laser intensity will be 10^{11}-10^{12} W/cm^2.

Ion density can be estimated using EUV photon number flux : $\Gamma_{\mathrm{EUV}} = I_{EUV}/h\nu$ = 7x10^{25}~7x10^{26} photons/scm^2, and this should be balanced with $(n_{\mathrm{EUV}}\ l_{\mathrm{EUV}})_{\mathrm{OD}=1}A$. Here n_{EUV} is the fractional ion density contributing to the EUV emission. Since Einstein A coefficient for Sn or Xe plasma of concern is typically 10 ps, product of density and length $(n_{EUV}\ l_{EUV})_{OD=1}$ will be 10^{15}-10^{16} cm^{-3}. We can then obtain l_{EUV} as a product of plasma sound speed and laser pulse duration. Figure 1 shows the optimum ion density and plasma length for EUV emission, and relation with laser parameters. Laser conditions were obtained assuming $\square_L l_{EUV}$ = 1~2 where $\square_L$ is the laser absorption coefficient supposing plasma temperature of 30 eV and inverse Bremsstrahlung for laser absorption. For longer wavelength laser, optimum pulse duration tends to be longer. In fact, strong self-absorption is observed in Sn plasma generated even with 0.53 μm laser light [5].

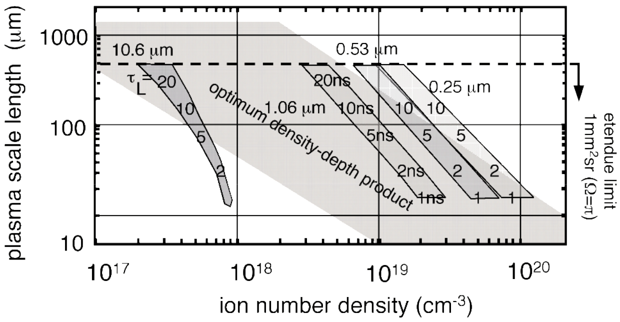

Fig. 1 Optimum plasma parameters and relation with laser conditions.

3. EUV emission from spherical Sn plasma

Spherical solid tin targets were illuminated uniformly with twelve beams from the Gekko XII laser system to create spherical plasmas, and the extreme ultraviolet (EUV) emission spectra from the plasmas were absolutely measured. As shown in Fig. 2, the highest conversion efficiency of 3% to 13.5 nm EUV light in 2% BW was attained for an irradiance of around $5x10^{10}$ W/cm^2 of 1.05 μm wavelength laser. The experimental results were reproduced fairly well using a theoretical model taking the power balance in the plasma into consideration [6].

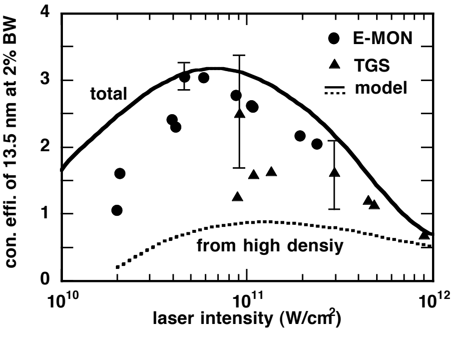

Fig. 2 EUV conversion efficiency measured with a Sn spherical plasma, and comparison with the power balance model

4. Electron density and EUV emission profiles of Sn planer plasma

We investigated electron density profile of laser-produced planar Sn plasmas with combination of green and UV interferometers. Good coincidence between the two sets data confirmed their reliability. Comparison with one-dimension radiation hydrodynamic simulation showed a reasonable agreement and the discrepancy could be attributed to multi-dimensional plasma expansion. Comparison with 13.5 nm extreme ultraviolet (EUV) emission profile denoted that the combined profile covers the dominant region of EUV emission. It is found that most of the EUV light comes from well under-dense plasma region, due to opacity effect [7]. This result validates the prediction described above.

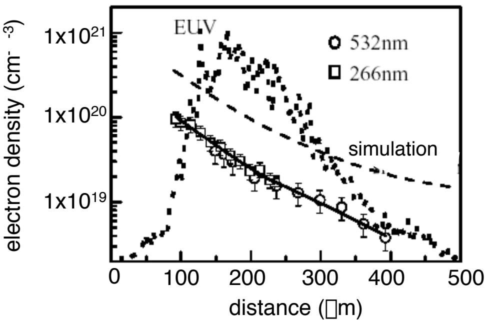

Fig. 3 Electron density profile measured with a laser interferometer. EUV emission profile measure with a monochromatic imager coupled with an EUV streak camera is also shown for comparison.

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