Optimum Laser-Produced Plasma for Extreme Ultraviolet Light Source

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Abstract. The optimum plasma conditions of extreme ultraviolet (EUV) light source for lithography were experimentally clarified that is optically thin and minimum mass Sn plasma generated from a limited size target. Sn plasma is quite opaque for EUV light of 13.5 nm in wavelength, therefore 13.5 nm light emitted from deep within a Sn plasma is strongly absorbed, thus optically thin plasma production is essential for efficient EUV generation. Contamination of EUV optics caused by debris emanated from laser irradiated Sn targets is a serious problem in the Sn based EUV source system. Target residue around the laser spot is the dominant source of neutral debris, which can be reduced with supplying the minimum mass target containing the minimum number of Sn atoms required for sufficient EUV generation. Spectral purity of generated EUV light is an important requirement to expose clear mask image on a photo-resist film without chromatism. Out-of-band radiation in the vacuum ultraviolet range is dominantly radiated from the laser spot peripheral. Target size must be equal to the laser spot size to suppress the out-of-band radiation.

1. Introduction

Extreme ultraviolet (EUV) lithography is a developing technology expected for mass production of the next generation semiconductor device [1]. Moore’s law, famous scaling law of feature size of semiconductor device, requires to implement the EUV lithography in manufacture stage until 2011 [2]. 13.5 nm within 2% bandwidth has been selected as EUV light for lithography because Mo/Si multilayer mirror has high reflectivity for this light. A laser produced plasma is an attractive light source in terms of its brightness and compactness. The laser produced tin (Sn) plasma has a highly intense emission peak at 13.5 nm, thus much effort is devoted to the development of the Sn-based EUV light source [3], [4], [5], [6], [7], [8], [9], [10]. There are some critical issues in the Sn-based EUV source development, i.e. high efficient energy conversion from incident laser to 13.5 nm light, reduction of debris generation from laser produced plasma, and suppression of out-of-band radiation beside 13.5 nm 2% bandwidth. Minimum mass target [11], [12], which contains the minimum number of Sn atoms required for sufficient EUV generation, is one of the solutions for these problems.
2. Conversion efficiency from minimum mass target

The opacity, as well as the emissivity, of laser-produced Sn plasma is so high for 13.5 nm light that the light emitted from deep within the Sn plasma is absorbed strongly by the surrounding plasma. Opacity of an uniform Sn plasma produced by thermal radiation confined in a laser-heated gold cavity was measured for evaluating quantitatively the opacity effects on EUV conversion efficiency (CE) [9]. The experimental results reveals that laser energy transported into target layers deeper than 10 nm thickness is not efficiently converted into 13.5 nm light, and therefore only a thin Sn layer below 10 nm thickness should be heated by a laser pulse, giving efficient EUV emission [9].

![Figure 1](https://example.com/figure1.png)

**Figure 1.** EUV-CEs obtained with changing target thickness and geometries.

The minimum number of Sn atoms for sufficient EUV emission was evaluated by measuring EUV-CEs with changing target thickness and geometries. Three kinds of target were used in this experiment, that is, 5 \( \mu \)m-thick Sn bulk target (called `bulk`), 100 and 10 nm-thick Sn layer coated on whole area of a plastic plate (called `all coat`), 43 and 10 nm-thick small Sn disk, whose diameter was 500 \( \mu \)m, coated on a glass plate (called `dot`). The diameter of 500 \( \mu \)m is equal to the Nd:YAG laser spot size. Figure 1 shows dependence of CEs on the shape and thickness of the targets. The square, triangle, and circular points, respectively, represent CEs for bulk, all coat, and dot targets. As shown in Fig. 1, 10 nm-thick dot target is enough to generate sufficient EUV-CEs, this results is consistent with the previous model [11].

3. Reduction of debris generation with minimum mass target

Debris generated from laser produced plasmas contaminates EUV optics in the light source system. Laser-induced fluorescence (LIF) technique [13] was used to visualize and evaluate amount of neutral Sn debris. LIF is optical emission from atoms that are excited to higher energy levels due to absorption of a certain wavelength laser radiation. The fluorescence intensity is directly proportional to population of excited atoms through the Einstein probability coefficient \( A \) for spontaneous emission. The fluorescence of 317.5 nm in wavelength according to \( 5d^2D_{2}^0 \rightarrow 6s^3P_{2}^0 \) transition was used [14]. The dye laser of 286.33 nm in wavelength was used as a probe laser to excite Sn atoms from the ground state to \( 6s^3P_{2}^0 \) level. Pulse duration, spot size, and intensity of plasma generation laser (Nd: YAG) were 2 ns, 500 \( \mu \)m in diameter, and \( 1 \times 10^{11} \) W/cm\(^2\), respectively. To observe cross section of neutral Sn debris plume, the dye laser was focused to be a sheet beam with cylindrical lens. Incident axis of the dye laser is perpendicular to that of the Nd:YAG laser. The dye laser was synchronized with the Nd:YAG laser.

LIF emission was imaged on a gated CCD camera installed at 37.5 degree upside respect to the Nd:YAG laser axis. A 317.5 nm band-pass filter was set in front of the CCD camera to
select only the fluorescence from neutral Sn debris. Exposure time of the CCD camera was 20 ns, is longer than lifetime of the fluorescence.

Figure 2 shows spatial distribution of neutral debris generated from three kinds of targets. All the figures are drawn with the same color scale. Amounts and distributions of neutral debris drastically change with the shape of the targets. Bulk Sn targets are too thick to be wholly ionized, target residue is a source of the neutral debris. Sn atoms around the laser spot are heated due to thermal conduction and shock wave, and evaporate as lowly charged ions or neutral particles. In all coat targets, almost all Sn atoms in the laser spot are highly ionized and few neutral debris was observed along the laser incident axis, because Sn coat layer is thin enough to be thoroughly ionized. However, temperature of laser spot peripheral is not so high that lowly charge or neutral debris emitted from there. In dot targets, there are no Sn atoms around the laser spot so that few neutral debris was observed. Compared with bulk targets, the amount of neutral debris from 43 nm-thick dot targets is reduced 95% or more, while EUV-CEs for 43 nm-thick dot targets is almost same as that for bulk target.

4. Out-of-band radiation emitted from minimum mass targets
Mo/Si mirror has high reflectivity (∼70%) also for vacuum ultraviolet (VUV) light in wavelength range of 130 - 400 nm. The out-of-band (OOB) light degrades quality of lithography due to chromatism because resist material is sensitive to the OOB light. It is required that the OOB light energy in the range from 130 to 400 nm is less than 7% of 13.5 nm within 2% bandwidth. Transmission grating spectrometer and reflective grating spectrometer were used to measure spectra and energy of the OOB light emitted from laser produced Sn plasmas. Reflective grating spectrometer has high spectral resolution, but is difficult of absolute energy calibration, while transmission grating is easy of absolute energy calibration but has low spectral resolution. In this experiment, planar and spherical Sn targets were used to clarify energy of the OOB radiation emitted from the laser spot peripheral. Diameter of the spherical target was 500 µm that is equal to the laser spot size.

Figure 3 shows the measured OOB radiation spectra. Out-of-band (OOB) radiation spectra consist of continuum emission from relatively low temperature (several eV) and high dense
plasma. OOB radiation energy integrated from 130 to 400 nm wavelength from spherical targets were four times lower than that from planar targets. This result indicates laser spot peripheral is the dominant OOB radiation source. Furthermore, 50% of OOB radiation energy is reduced in decreasing Sn layer thickness with keeping sufficient EUV generation. Reduction of OOB radiation can be achieved with the use of the optically thin and minimum mass Sn plasma sources.

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6. References
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