Sn droplet target development for laser produced plasma EUV light source

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ABSTRACT

We are developing a Sn droplet generator for a LPP HVM EUV light source. Droplet trains with frequencies up to 500kHz and droplet diameters below 20um are generated via the continuous jet method. Charging single droplets and using deflector electrodes these charged droplets are selected from the droplet train and irradiated by the drive laser. Due to the small droplet diameter, the drive laser otherwise irradiates several droplets inside the droplet train thus increasing the Sn debris as is experimentally shown. In addition, the paper outlines that a 30um droplet size is the mass limit for up to 180W EUV generation based on the assumption that each Sn atom emits on average a single in-band photon.

Keywords: EUV light source, laser-produced plasma, droplet

1. INTRODUCTION

Extreme ultraviolet lithography (EUVL) is the candidate for next generation lithography (NGL). But the HVM light source requirements are very high with a EUV output power (13.5nm 2% bandwidth) of more than 115 – 180W at the intermediate focus (IF). We started the development of a Laser Produced Plasma (LPP) EUV light source system with Sn target in 2006.

A very attractive target due to its high EUV conversion efficiency is a mass limited Sn droplet. We generated Sn droplet trains with large droplets (ϕ 130μm), high frequency (340kHz) and high velocity (70m/s) using the continuous jet method [1]. But a ϕ130um Sn droplet is too large to generate 115-180W EUV output power at the intermediate focus. Table.1 summarizes that a EUV power of 180W requires a source energy of about 10mJ/4pi: 4sr collector mirror solid angle, 60% mirror reflectivity, 90% transmittance from source to IF and 100kHz repetition rate. Fig.1 shows the relationship between the EUV power at the IF and the required Sn atoms and Sn droplet diameters. The required photon number is calculated according to equation 1), where N_{photon} is the photon number, E_{euv} is the in-band EUV energy emitted per plasma and E_{pe} is the photon energy at 13.5nm.

$$N_{photon} = \frac{E_{euv}}{E_{pe}} \qquad 1)$$

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It is also assumed that on average every Sn atom emits a single 13.5nm photon. As can be seen, 4—8 x10^{14} Sn atoms are necessary for 115—180W EUV which results in a droplet diameter of about 30μm. Hence, the first issue of the target development is the droplet size minimization. The liquid droplet has a density of 1x10^{22}/cm^3 which is of the same order as solid Sn. On the other hand, the plasma cut off density for the CO_2 laser is about 1x10^{19}/cm^3. Assuming Sn^{10+} valence, the ion density is estimated as 1x10^{18}/cm^3. Therefore, pre-plasma formation, e.g double pulse laser irradiation, is needed for efficient interaction between the CO_2 laser and the Sn atoms. The pre-pulse irradiation onto the Sn droplet decreases the Sn ion density to 1x10^{18}/cm^3, i.e. the electron density is near the cut-off density, which guarantees efficient CO_2 laser absorption. The pre plasma size has in this case a diameter of more than 300um for an initial 30um droplet.

Table1. Required EUV power of a source system

Intermediate Focus	Source (4π)	
Power (W)	Power (W)	Energy(mJ)
115	670	6.7
180	1050	10.5

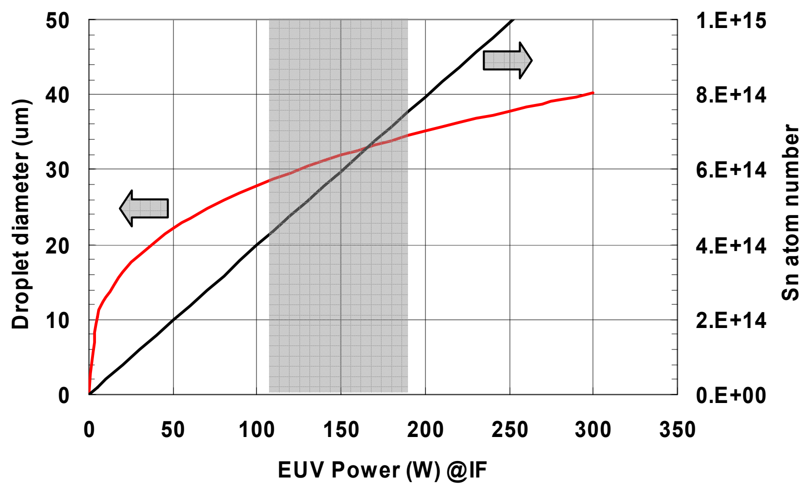


Fig.1 Relationship between EUV power and Sn atoms, Sn droplet diameter

The continuous jet method [2], which generates uniform droplet trains, generates a droplet spacing (center to center) of 2—3 times the droplet diameter. For example, for 30μm droplets the droplet spacing is 60 – 90 μm. Therefore, several droplets of 30um diameter are within the pre plasma region, which is estimated to be larger than ϕ300um. These additional droplets will increase the amount of debris. Hence, the second key technology of the target development is the droplet selection. Fig.2 illustrates the mismatch between the pre-plasma size and the droplet spacing. Fig.3 shows isolated droplets that were selected in order to enable laser interaction with a single droplet. In this paper we report the current status of our Sn droplet target development.

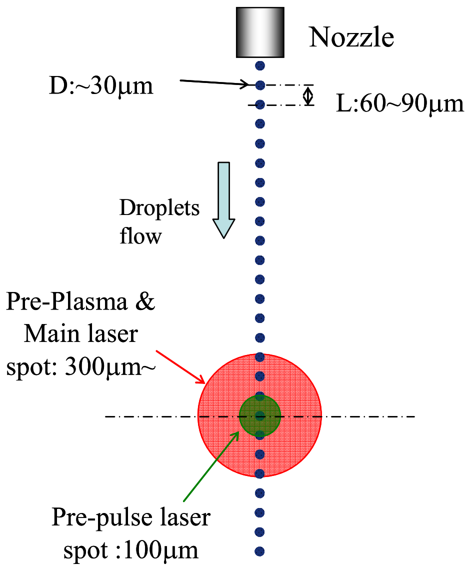


Fig.2 Droplet train and pre-plasma region

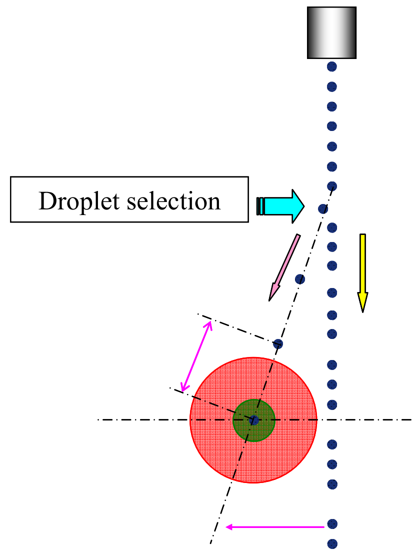


Fig.3 Isolated droplets and pre-plasma region

2. Sn DROPLET DEVELOPMENT

2.1 Experimental setup

Fig.4 shows a schematic of the droplet generator and the droplet selection system via electrostatic charging. The Sn supply tank is heated above the melting point of Sn, i.e. 232 ^{o}C. The liquid Sn jet is emitted from the nozzle pressurizing the supply tank and inducing periodic disturbances on the jet surface via PZT oscillations that generate a uniform droplet train. The droplet size and the droplet spacing change depending on the nozzle inner diameter and the PZT frequency. The electrodes for the droplet charging and deflection are placed below the nozzle. The liquid Sn jet first passes at breakup point the electrode area that selectively charges single droplets, which are then deflected, i.e. selected, by a second electrode pair. We measure the horizontal displacement of the selected droplet using a CCD camera and back light illumination. The droplet charge is calculated according to equation 2), where Q is the charge, m the droplet mass, v the droplet velocity, δ the horizontal displacement, E the electric field between the deflection electrodes, Lo the deflection electrode length and L is the length from the deflection electrode to the measurement point.

$$Q = \frac{2mv^2\delta}{E(L_0^2 + 2L_0L)} \qquad 2)$$

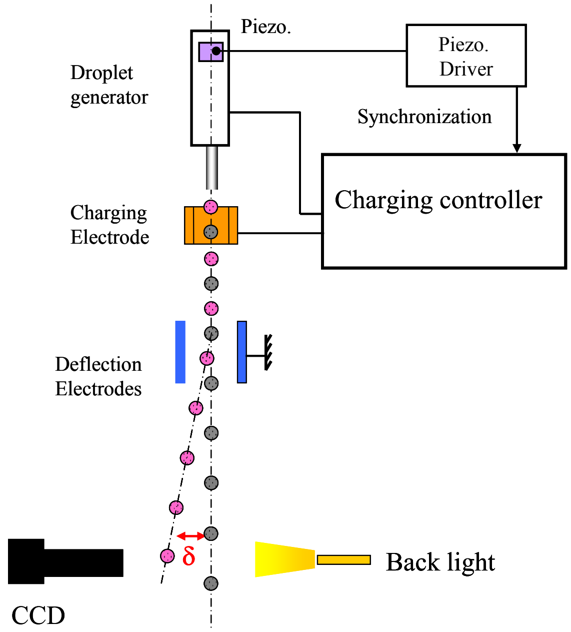
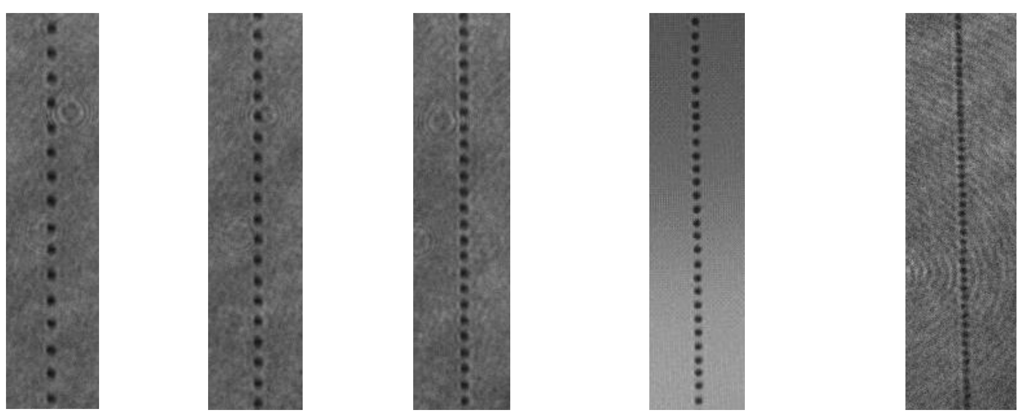


Fig.4 Schematic of droplet generator and selection system

2.2 Droplet Size

Changing the nozzle inner diameter, Sn droplets with various diameters and spacings are generated. Fig.5 shows photographs of Sn droplets observed at 50mm from the nozzle. We used nozzles having inner diameters of 20μm for (a) -- (c) 15μm for (d) and 10μm for (e). Therefore we obtained droplet diameters of less than 20μm with a frequency of 500 kHz and a velocity of about 20m/s by using a nozzle having an inner diameter of 10 μm; picture (e).



(a) (b) (c) (d) (e)

Fig.5 Sn droplets 50mm below the nozzle
(a) ϕ47μm 92kHz (b) ϕ44μm 112kHz (c) ϕ41μm 142kHz (d) ϕ28μm 320kHz (e) ϕ19μm 500kHz

2.3 Droplets charging and deflection

Electrostatic charging is a widely used technology to control droplet streams [3]. The theoretical maximum charge on a droplet is given by equation 3) called "Rayleigh limit", where Q is the droplet charge, ε_0 is permittivity, d is the droplet diameter and σ is the surface tension of the droplet material [2]. Fig.6 shows the relationship between the Sn droplet diameter and the maximum charge. For example, the Rayleigh limited charge on a Sn droplet having a diameter of 30μm is 3.5pC.

$$Q = \sqrt{8\pi^2 \varepsilon_0 d^3 \sigma} \tag{3)}$$

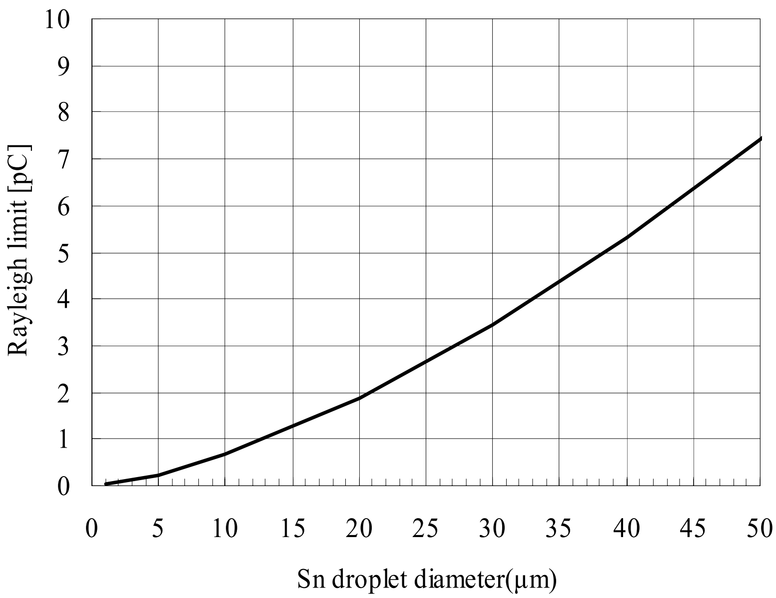


Fig.6 Relationship between the Sn droplet diameter and the Rayleigh limit.

In the following we report droplet isolation with Sn droplets having a diameter of 40μm. The original droplet train has a generation frequency of 177 kHz and a velocity of 17m/s. The selection frequency is 17.7 kHz, i.e. the selection ratio is 1/10. Fig.7 shows the relationship between the charging electrode voltage and the droplet charge. The deflection length is the horizontal distance between the selected droplet and the initial droplet train. The deflection length was measured about 60mm from the nozzle. We obtain 1.1pC and 4.5mm deflection length at 2.0kV charge electrode potential. Fig.8 shows isolated Sn droplets with uniform spacing of about 1mm.

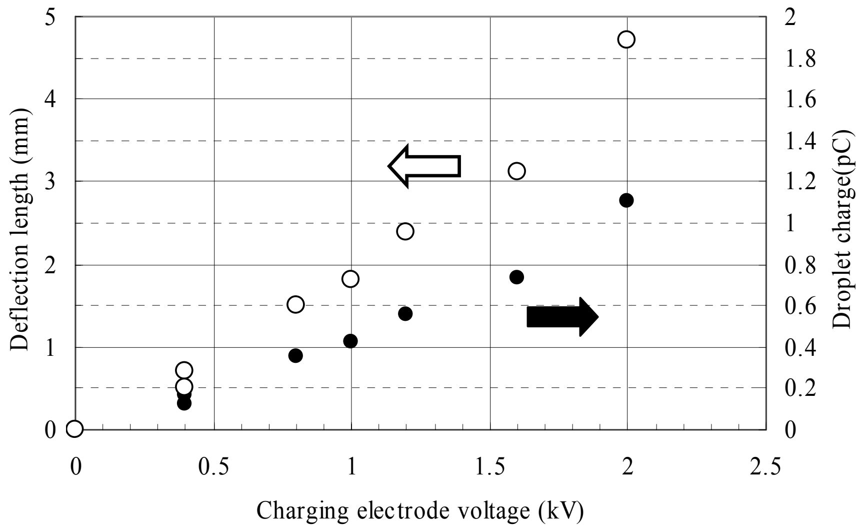


Fig.7 Relationship between charging electrode voltage and droplet charge; 40um droplet, 60mm below nozzle.

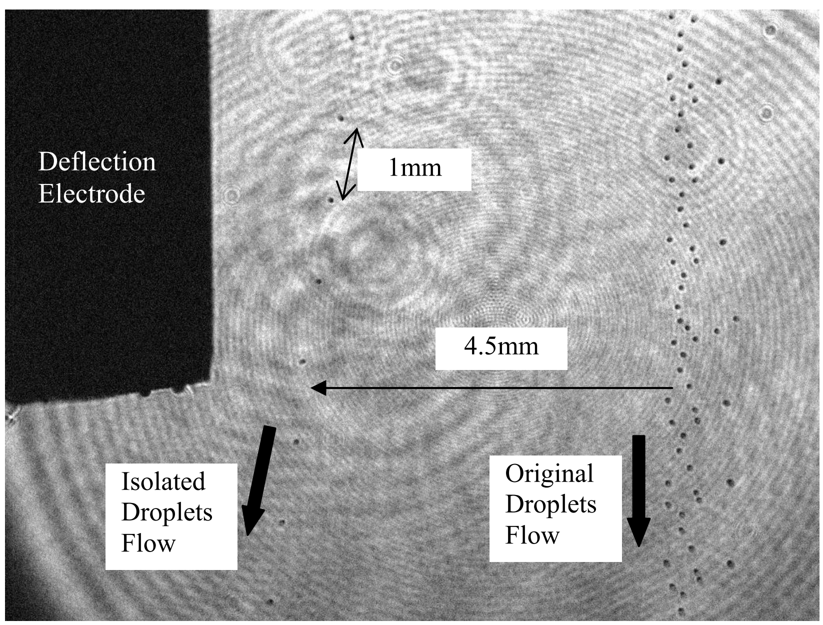


Fig.8 Isolated droplets

2.4 Laser irradiation

We demonstrated laser irradiation onto isolated Sn droplets. Fig.9 shows a schematic of the experimental setup. Droplets having 28μm diameter and 70μm spacing were generated with 300 kHz frequency. The selection frequency was 30 kHz. Hence one out of ten droplets was taken from the original droplet train and the selected droplets spacing is about 0.7mm. The deflection length at the laser irradiation point was more than 1mm. A Nd:YAG drive laser (1064nm) having a spot size ($1/e^2$) of 300μm and 10mJ pulse energy was used. The time synchronization between the droplet selection and the laser oscillation was controlled by a delay generator. The Droplet behavior after laser irradiation was observed with a CCD camera focused on isolated droplets and illuminated with a synchronized flash lamp.

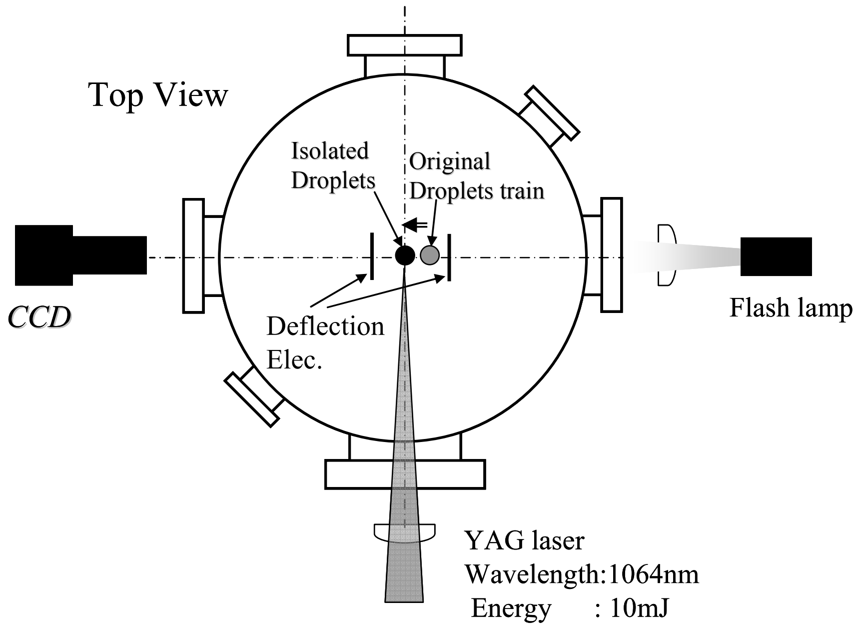


Fig.9 Schematic of laser irradiation experiment

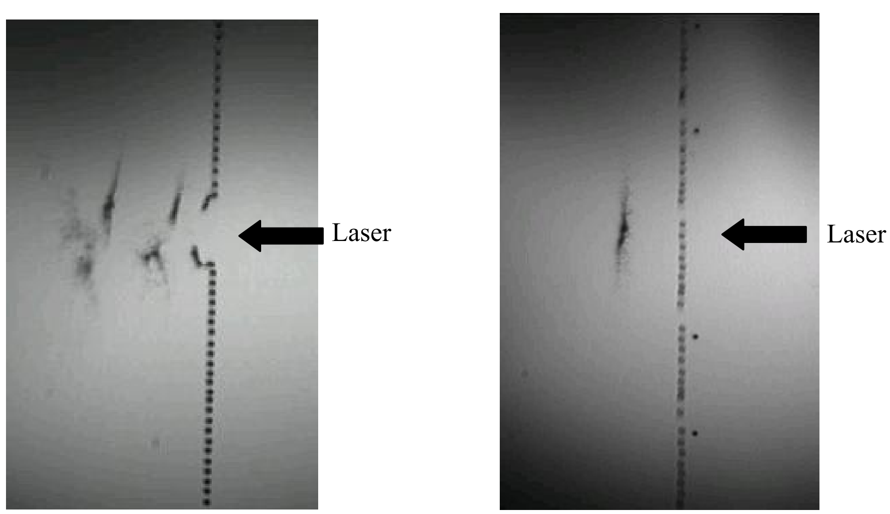


Fig.10 Images taken 4μs after laser irradiation onto a) continuous droplets b) isolated droplet

Fig.10 shows the droplet train 4μs after laser irradiation onto a) continuous droplets and b) isolated droplets. In case of the droplet train, several droplets within the laser spot area are hit and target material is sprayed into the laser direction. In case of an isolated droplet, it is clearly seen that only this droplet is hit by the laser. In both cases the velocity of the tin spray is more than 150 – 200 m/s.

3. CONCLUSION

We are developing Sn droplet target supply technology for a next generation lithography LPP-EUV light source. Main issues of the present development are droplet size minimization and droplet isolation. We obtained Sn droplets having a diameter of less than 20μm at a frequency of 500 kHz and with a velocity of about 20m/s. We also presented droplet selection technology that is based on droplet charging and deflection via electric fields. We generated isolated 40μm diameter Sn droplets at 1/10 of the main droplet train frequency and with a deflection length of 4.5mm. Finally, laser irradiation onto a small isolated Sn droplet (ϕ30μm) was demonstrated.

4. ACKNOWLEDGEMENTS

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