Development of Tin Droplet Target for 13.5 nm Lithography

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A new flow control method for a tin droplet generator in a vacuum has been developed for Extreme Ultra-Violet Lithography. A vibration rod forced by a piezoelectric crystal varies the flow resistance, thus changing the flow rate at a high repetition rate. This droplet generator is advantageous for high temperature liquids such as molten metal. The formation of tin droplets using this generator was demonstrated at a frequency range of 10 kHz to 22 kHz by a 100 μm nozzle.

Keywords: tin droplet, droplet generator, EUV, lithography

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Extreme Ultra-Violet (EUV) Lithography at 13.5 nm is currently slated as the next light source after the present 193 nm ArF excimer laser source. The tin target has been the most promising for more efficient conversion from laser energy or discharge energy into EUV radiation energy than are other target materials composed of xenon or lithium. The droplet target requirements for EUV Lithography have not yet been fixed. But roughly, Laser Produced Plasma (LPP) requires a tin target diameter of less than 50 μm, and a droplet formation frequency of more than 100 kHz, while Discharge Produced Plasma (DPP) requires the same target diameter and a droplet formation frequency of about 10 kHz. These requirements have not yet been satisfied for the tin droplet.

The theory of continuous liquid jets and the drop formation of such jets requires further discussion. This theory is well known and summarized in Refs. [1, 2].

A cylindrical liquid jet is inherently unstable and tends to spontaneously break-up into drops. A small disturbance at the nozzle exit grows exponentially until drops are formed. This drop formation is due to the minimization of surface energy and occurs at a spontaneous break-up length L from the nozzle orifice [3],

$$L = 12vd\left(\sqrt{\frac{\rho d}{\sigma}} + \frac{3\mu}{\sigma}\right),$$

where d is the diameter of the jet, v the jet velocity at the nozzle exit, ρ the density of the jet liquid, μ the dynamic viscosity, and σ the surface tension. Due to growing jet instabilities far away from the nozzle's orifice, a short drop formation distance is necessary by some vibrating methods.

For well over 100 years, capillary stream break-up has been used to generate droplets [4]. Certain methods, such as nozzle vibration [1], have been used to break the capillary stream into streams of uniformly sized droplets. On the other side, ink jet technology, called drop-on-demand, has been used for printing [5]. However, this ink jet technology cannot satisfy EUV requirements because of its low droplet production rates and low droplet velocity.

We have developed a new flow control method [6]. The outline of this method is shown in Fig. 1. The pressured droplet liquid flows out through a narrow piston gap to the nozzle. The gap between the piston rod and the orifice in the droplet generator is as short as approximately 30 μm in order to increase flow resistance. The vibration piston rod forced by a piezoelectric crystal (PZT) varies the gap space to change the flow resistance, resulting in changing the flow rate at high frequency. This new-type droplet generator allows the generator to be separated from

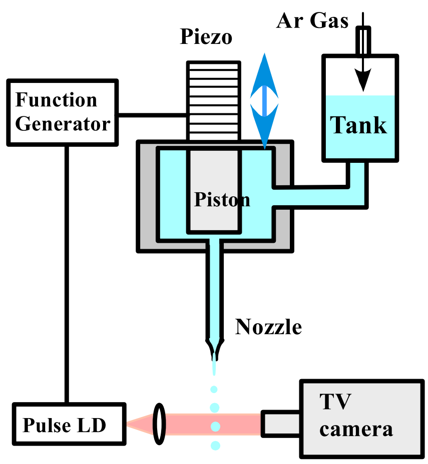

Fig. 1 Flow control droplet generator and experimental arrangement.

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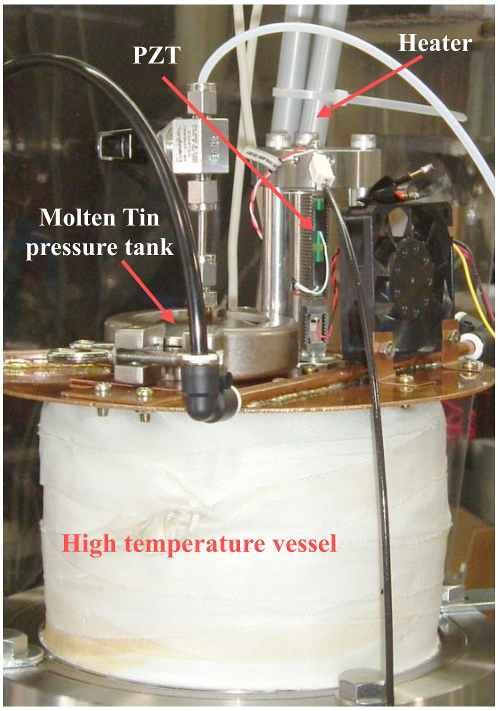

Fig. 2 The tin droplet generator prototype.

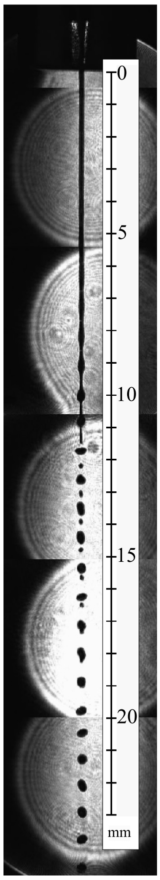

Fig. 3 Composite photograph of water droplet.

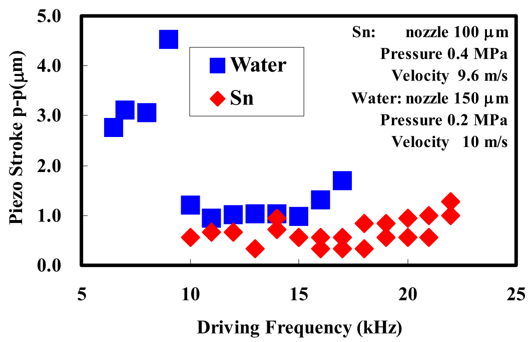

Fig. 4 Minimum piezo full stroke for stable droplet generation for water and tin droplets.

the nozzle. This characteristic is advantageous for high temperature liquids such as molten metal.

The liquid droplet system is shown in Fig. 2. The experimental setup consists of a droplet generator controlled by a PZT, a stainless steel particle filter, and a tin metal or water filled pressure tank which is placed inside a heated oil vessel and connected to argon gas up to 0.3 MPa as a backing pressure. A vacuum chamber under the high temperature vessel was evacuated by an oil-sealed rotary vacuum pump up to about 1 Pa. The nozzles are made from quartz for water and sapphire for tin, adopting a smooth cone-shape. The droplets are back-illuminated by a pulse laser diode having a pulse width of a few µs synchronized by the PZT controller and delay circuit. The nozzle diameters for the experiments were 150 µm for water and 100 µm for molten tin, respectively. The oil tank and nozzle were heated to a temperature of 540 K for the tin droplets.

The droplet interval λ was measured by video images. The droplet speed V is calculated by the droplet generation frequency f and λ, given by $V = \lambda f$. The droplet generation frequency was changed from 6 kHz to 22 kHz, and the initial jet speed was changed according to the argon backing pressure.

Figure 3 is a composite photograph of water droplet formation from capillary stream break-up in atmosphere illuminated by a pulse laser diode. The conditions were an initial water jet speed of 11 m/s, a practical nozzle diameter of 150 µm measured by the jet diameter, a droplet formation frequency of 12 kHz, and a backing pressure of 0.15 MPa. The PZT was controlled by sine wave voltage with offset. The Reynolds number was 2100, which corresponds to the transition flow from laminar flow to turbulent flow. The spontaneous break-up length L from the nozzle orifice is calculated as $L = 40$ mm. In contrast, the break-up length was reduced to 11 mm for a 2.1 µm PZT full stroke in Fig. 3, and 9 mm for a 4.4 µm stroke.

Figure 4 shows the minimum PZT full stroke for stable droplet generation as a function of the driving frequency for water and tin droplets. The tin droplets were generated at a frequency range of 10 kHz to 22 kHz, a droplet speed of 9 m/s, and a diameter of 190 to 240 μm. The lower PZT stroke for tin than that for water is due to tin's smaller droplet diameter. The stable droplet intervals were restricted to the range of λ/d = 3.8-9.8 for water and λ/d = 4.4-9.6 for tin droplets, in which λ is the droplet interval and d the diameter of the jet. The measured range λ/d obtained by the new method was almost as same as λ/d = 3.5-7 by the conventional nozzle vibration method [7].

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