Liquid Metal Micro-Droplet Generator for Laser Produced Plasma Target Delivery used in an Extreme Ultra-Violet Source

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ABSTRACT

The implementation of a Laser Produced Plasma Extreme Ultra-Violet (LPP EUV) source requires a high-power laser focused onto a target. In order to minimize the required laser input power the target material must have a high conversion efficiency to 13.5 nanometer radiation. Ideally, a pulsed laser is used and the target should be delivered in small uniform volumes to a point in space at high repetition rates. The small volumes minimize the amount of debris, the high repetition rates enable higher power systems and the free space delivery alleviates thermal issues and allows large collection angles. It has been demonstrated that lithium and tin have very high conversion efficiencies and system solutions exist to use these materials. In this paper we describe the requirements and performance of a liquid metal micro-droplet target generator capable of dispensing both lithium and tin. Finally it is shown that the current generator performance is sufficient to support stable source operation.

Keywords: LPP, EUV, Target, Droplet, Jet, Liquid Metal

1. INTRODUCTION

Mooreís law has guided the evolution of integrated circuit geometries for over thirty years. To enable the prophecy each generation of lithography technology must have the capability to image to a smaller resolution. Optical imaging technology is closely coupled to the wavelength of light used to expose the photoresist so light-sources have evolved from 365nm, to 248nm, to 193nm to allow critical dimension patterning for each new generation of semiconductors. Excimer laser technology has provided the necessary capability to fuel to transition to shorter wavelengths so far. Next generation lithography (NGL) technology is currently expected to utilize a source with a wavelength of 13.5nm. Cymer has pioneered source development since the late ninetyís to produce this Extreme Ultraviolet (EUV) wavelength with the required power and quality to meet industry needs.

The top contenders for plasma 13.5 nanometer sources are Discharge Produced Plasma (DPP) and Laser Produced Plasma (LPP). There are several versions of the DPP concept, all generate a plasma by an electrical discharge with an injected material (gas, liquid or solid). The LPP systems use a high powered laser focused on a target material with enough energy to create a plasma from the target.

Two of the promising materials used for targets in the LPP systems are tin and lithium. Both are metals with relatively low melting points (232 °C and 179 °C, respectively). To maximize the collection of the EUV radiation, it is desired to deliver the target material in small amounts to the focus of the drive laser. Delivering the target material in the form of droplets to the focal point of the drive laser is very appealing because it allows large collection angles of the EUV radiation. Both of these materials lend themselves to being delivered by some form of droplet generator.

Such a droplet generator should be capable of meeting a number of criteria. It should produce droplets from 20 to 120 micrometers in diameter. The delivery should meet or exceed, by some integer multiple, the repetition rate of the drive laser. The generator must be capable of melting the target material, and must do so without contaminating the material, as the susceptibility of the rest of the EUV source (the EUV collector mirror, specifically) to contamination is very high. In addition, the droplet generator must be capable of running 24 hours per day, 7 days a week and last for at least a year.

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With such small droplets, stability and uniformity become very important. Drop to drop mass uniformity should be less than 10%. The positional stability of the droplets, at the plasma point, should be +/- 5 micrometers in all three axes. The working distance should be far enough not to shadow the collector. And of course, the generator must be easy to operate and highly automated. Table 1 summarizes the key target generator requirements for a LPP source.

Table 1. General target generator requirements for an LPP system

- Droplet size
  - ∅20-120 µm
- Delivery rate
  - Match to laser firing rate
- Sustainable temperature
  - 250º C for use with tin
- Droplet position stability
  - +/- 5 um position
- Droplet mass uniformity
  - 10%
- Droplet spacing
  - > plasma affected region
- Operation
  - 24/7
  - Low maintenance
  - Fully automated
- Lifetime
  - 12 months
- Working distance
  - No collector obscuration
- Material compatibility
  - No target material contamination

2. JET AND DROPLET THEORY

There are numerous ways to generate liquid droplets[1] but controlled breakup of a liquid jet is the most stable method and has therefore been chose as an initial approach. It is important to remember that although most other applications of liquid droplets have similar placement accuracy demands as outlined for LPP target delivery their working distance is typically limited to a few millimeters whereas this application calls for working distances on the order of 10ís of centimeters. This of course translates into a significant increase in relative angular and speed stability as any instability has a longer time to develop. Liquid jet and droplet formation has been extensively studied elsewhere and will only be briefly described here. For a more extensive treatment of conventional liquid jet theory see e.g. Refs. 2-7. A liquid jet is formed when liquid is forced through a nozzle orifice. For certain parameters this will result in a stable, well collimated, jet that will eventually break up into droplets due to minimization of surface energy. This is called Rayleigh breakup and normally occurs if the pressure is above some lower limit where the liquid simply drips out of the orifice and below some upper limit where other breakup mechanisms dominate. Here it is assumed that we operate in this stable region. As mentioned the jet is energetically unstable and small initial disturbances grow exponentially until they are comparable to the jet radius and droplets form. For an idealized jet with diameter d the breakup distance l is proportional to the jet speed v and is given by[8]

$$l = Ln\left(\frac{d}{2\delta_0}\right)\cdot v\cdot\left(\sqrt{\frac{\rho d^3}{\sigma}}+\frac{3\eta d}{\sigma}\right), \tag{1}$$

where δ_0 is an initial disturbance, ρ is the density, σ the surface tension and η the viscosity. The initial disturbance must generally be experimentally verified but the entire logarithmic expression is typically ~10.[8] The average spontaneous drop formation frequency, f, is given by

$$f = \frac{v}{4.51\cdot d} \tag{2}$$

and results in an average drop diameter of $1.89\cdot d$.[9] The spontaneous drop formation can be controlled to create equally spaced and sized droplets. This is done by applying an external disturbance with a frequency close to that of the natural resonance but with an amplitude that dominates over any spontaneous initial disturbances. The speed of a liquid jet depends, as a first approximation, only on applied pressure, p, and the liquid density. Conservation of energy gives[10]

$$v = \sqrt{\frac{2p}{\rho}} \tag{3}$$

assuming a negligible pressure in the exit region as well as a static fluid reservoir. However, there are always losses in the nozzle due to, e.g., viscous friction and turbulence, that will generally depend on both nozzle geometry and fluid parameters. The loss fraction, i.e. the ratio of the actual jet exit speed and the theoretical exit speed, is called the nozzle discharge coefficient, *C*, and typically range from ~0.6 up to almost unity.[11]

Table 2. Approximate material properties for different target materials showing a broad range of fluid properties

Material	M.p. [∝C]	Density [kg/m^3]	Viscosity [10^{-6} Ns/m^2]	S. Tension [10^{-3} N/m]
Water	0	997	1040	73
Tin	232	7000	1700	540
Lithium	179	534	650	400

Looking at Table 1 it is evident that the fluid dynamic material properties of different proposed LPP target material liquids span a broad range. In general it can be said that an increase in density will require a higher pressure to achieve the same speed and will require more stimulation energy to maintain stable droplet formation. An increase in surface tension will translate into a decrease of the breakup distance and an increase in viscosity will increase the breakup length.

3. EXPERIMENTAL SETUP

A liquid metal droplet generator has been built that can operate with liquids that span a broad range of liquid properties and is only limited by material compatibility, extremely high viscosity or low surface tension. The droplet generator is built into a stainless steel tube that is welded to an 8î CF flange and virtually all materials exposed to the source chamber are stainless steel, making it UHV compatible. Figure 1 shows an image of the current generator with the interior of the tube comprised of a large upper liquid reservoir and a lower droplet generator. The assembly also contains integral heater elements and can be uniformly heated up to 250 °C to accommodate low melting point metals.

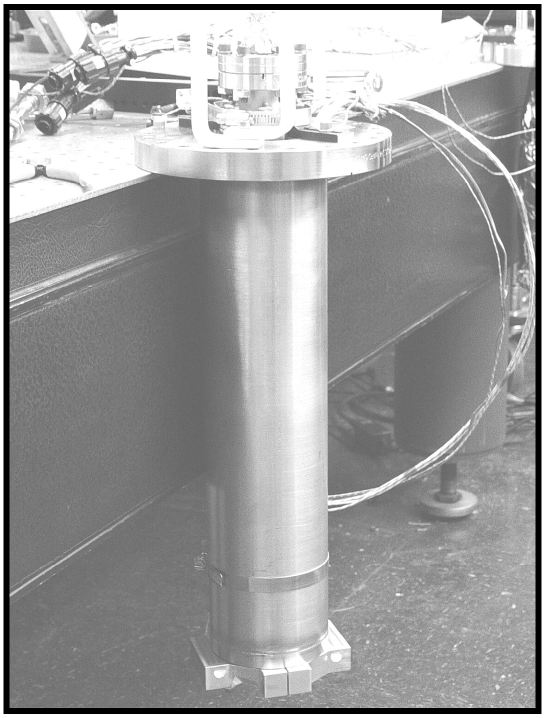

Figure 1. Image of assembled liquid metal droplet generator.

Prior to operation the upper reservoir is filled with the desired target material. After installation in the source chamber, the generator is heated to melt the target material. The generator is then energized and droplets produced. Windows are arranged to look at he plasma region from two directions, 60 degrees apart, on a horizontal plane, perpendicular to the droplet stream. Long working distance microscopes are attached to digital cameras for imaging the droplets. Figure 2a depicts the schematic system configuration showing the generator, interaction point vacuum vessel, imaging ports and cameras etc.

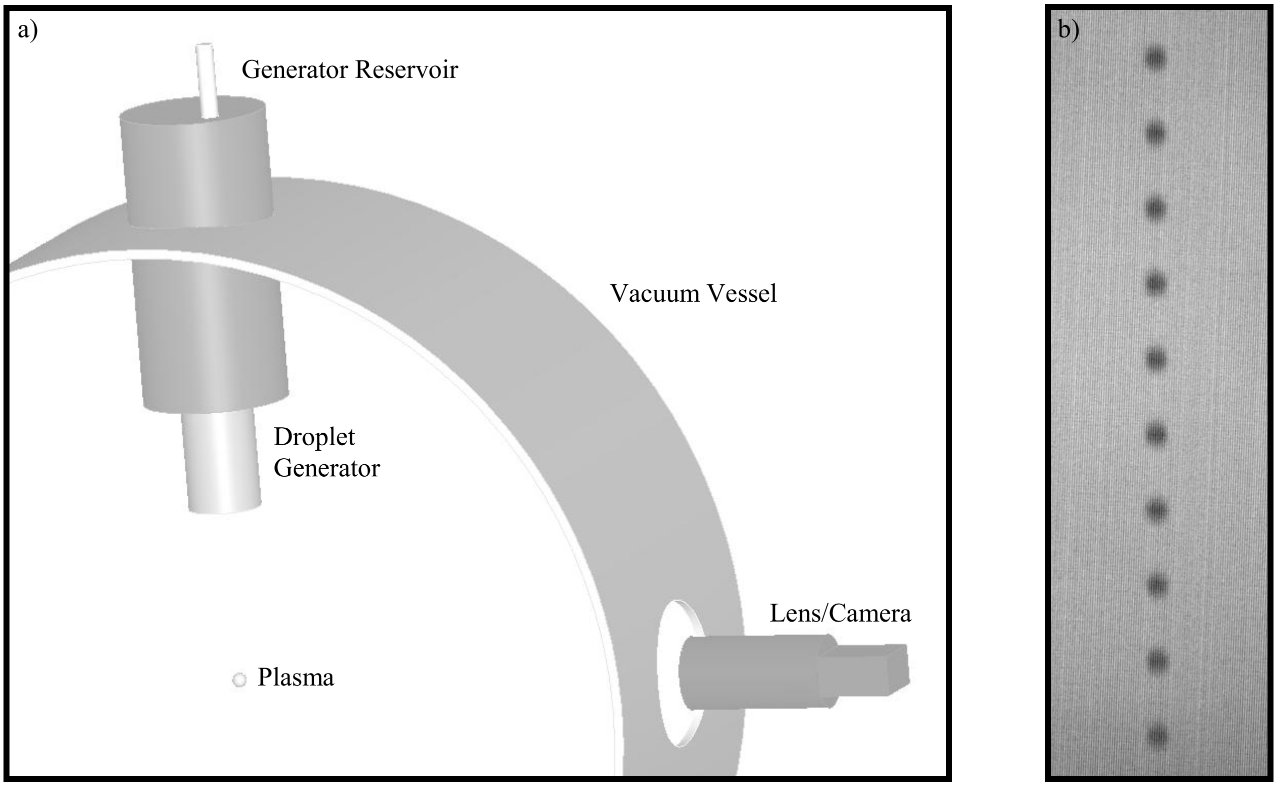

Figure 2. Schematic view (a) of the liquid metal droplet generator system configuration. (b) shows typical back illuminated single shot droplet image. This image was acquired 50 mm down stream of the nozzle orifice and shows tin droplets produced at 36 kHz from a 50 µm diameter orifice.

The 8 bit cameras are capable of 20 frames per second and image at .8x magnification. The droplets are back illuminated by synchronized LEDs, controlling the effective exposure time and adjusted to avoid motion blur. Figure 2b shows a typical droplet image obtained in the above described system. Video is streamed to a computer where the images are processed to calculate droplet center position, which is tracked from frame to frame. It should be noted that no exhaustive effort has yet been placed on magnification calibration, mechanical vibrations or algorithm robustness in the imaging system and both a systematic error and low amplitude noise could exist in the extracted position data.

Operating frequencies have been demonstrated from 12 to 48 kilohertz. Working distance is currently 50 mm and both tin and lithium droplets have successfully been produced. The run time is currently limited by the capacity of the liquid reservoir and, as expected, varies greatly with droplet diameter and jet velocity. Table 3 summarizes the current generator performance.

Table 3. Current generator data

Target materials
- Successful droplet delivery of tin and lithium
- Capable of sustaining 250º C

Working Distance
- ≥ 50 mm

Droplet sizes
- Demonstrated droplet sizes from ϕ 60 – 200 um

Droplet Spacing
- ~4.5 x jet diameter

Droplet rates
- Droplet frequencies range from 8 – 48 kHz

Run times
- Demonstrated runs in excess of 4 hours

4. RESULTS

As previously described the performance of the liquid droplet target delivery system is primarily measured through image analysis of droplet images. For a 50 µm liquid jet stimulated at 36 kHz and imaged 50 mm downstream of the orifice Figure 3 shows the stability measurement during stable operation. The droplet position standard deviation is 37 µm vertically and 4.5 µm horizontally.

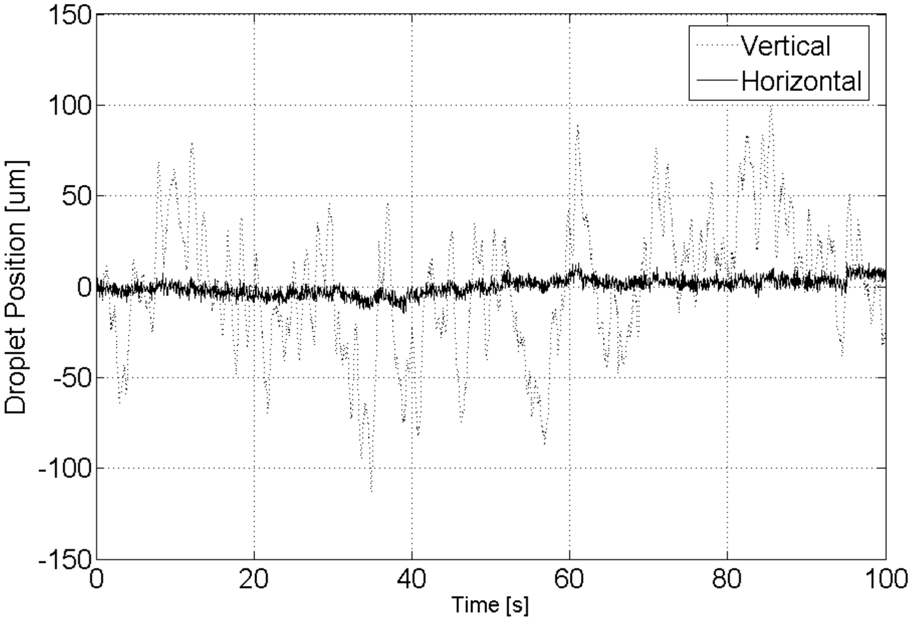

Figure 3. Target droplet position over time calculated from single shot video images taken at 20 Hz 50 mm downstream of the generator with liquid tin and a 50 µm orifice stimulated at 36 kHz.

Figure 4 shows the stability measured 75 min later during the same run and as can been seen the performance is essentially identical indicating the required long term stability of the system. The measured droplet position standard deviation is now stability is 37 µm vertically and 3.2 µm horizontally.

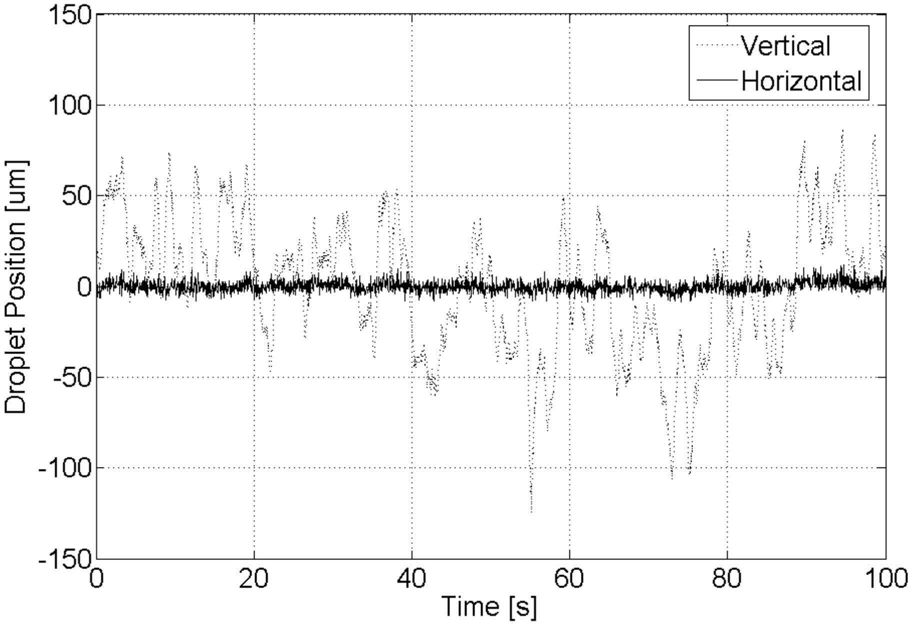

Figure 4. Target droplet position over time calculated from single shot video images taken at 20 Hz 50 mm downstream of the generator with liquid tin and a 50 µm orifice stimulated at 36 kHz. This data is taken during the same run as that presented in Figure 3 but 75 minutes later, indicating the long term stability of the system.

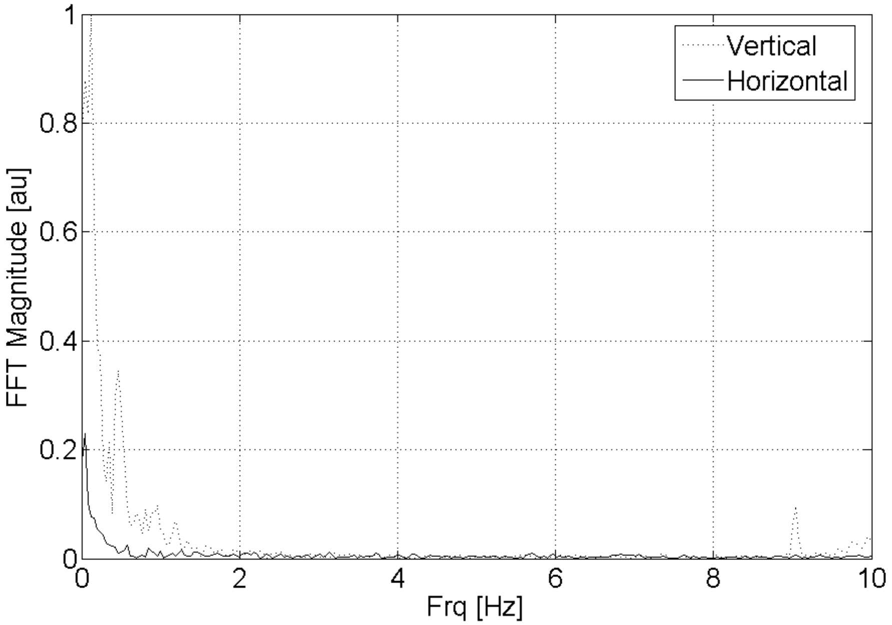

Figure 5. Frequency spectra of droplet typical droplet motion during stable operation calculated by a Fourier transform of data similar to than presented in Figure 3 and Figure 4. Notice that most of the motion is confined to the low frequency region.

As is evident from Figure 3 and Figure 4 most of the large motion in the direction of the jet is low frequency. Figure 5 shows the frequency spectra of the droplet position during a stable operation and shows that the bulk of the motion is limited to below 2 Hz. This is important as this is slow enough to be compensated for without resorting to shot to shot corrections. Also it should be mentioned that the crucial parameter to some extent is the transversal stability, as this has to be corrected for mechanically as the plasma position will otherwise move. For longitudinal drift the phase of the laser can be changed, which is acceptable given that the speed of the phase change is not too high to interfere with the stable operation of the laser. The current performance does suggest that an active trigger, on a shot to shot basis, might not be required.

5. DISCUSSION AND CONCLUSIONS

It has been shown here that a droplet generator can be built to meet the minimum requirements of a EUV LPP source. The positional stability of the droplets is sufficient to allow low speed control systems to account for or control the variations with enough accuracy to produce a consistent plasma source. Still a number of challenges and refinements need to be addressed to make this generator perform in a production worthy installation.

Run times are currently limited by the on-board reservoir size and result in 4 to 8 hours of operation. A continuous feed system will need to be developed to allow for extended production runs. It must be capable of being refilled while the generator is operating without adversely affecting the droplet performance. With the extended run times, long term stability and reliability requirements will be more important. A significant effort will be required to make the generators perform consistently on such a time scale.

Target materials must be developed that meet the stringent purity requirements of the EUV source. Several systems in the source chamber are highly sensitive to any contaminates that would be introduced in the plasma at even PPM levels. In addition to the requirement for ultra pure target materials, the droplet generator itself must not contaminate the target material.

To maximize the collection of the EUV radiation, the working distance will need to be improved and the physical package size of the generator will need to be minimized. The currently described system, at 4 inches in diameter, will cast too much of a shadow on the collector

With a number of improvements still required, this paper has shown that a liquid metal droplet generator has demonstrated stability levels that are sufficient for use in a LPP EUV light source.

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