CONTROL AND STABILIZATION OF TIN-DOPED DROPLET FOR EXTREME ULTRAVIOLET LITHOGRAPHY

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Extreme Ultraviolet (EUV) sources rely on droplet laser plasmas for EUV generation. These sources consist of a small (30 µm diameter) droplet which is excited into plasma emitting EUV around 13.5 nm, the industry's chosen wavelength for EUV lithography (EUVL). These sources are the best candidates for the commercialization of EUVL allowing mass production of computer chips at 32 nm nodes and below. However, the biggest challenges which EUV source developers encounter today are the issues of conversion efficiency (CE) and debris. In order to satisfy the technology requirements, the source will need to meet high levels of stability, performance, and lifetime. Our tin-doped droplet plasma has demonstrated high CE and low debris resulting in long lifetime. Long term stability is obtained through the use of novel tracking techniques and active feedback.

The laser plasma targeting system combines optical illumination and imaging, cutting-edge droplet technology, dedicated electronics, and custom software which act in synchronization to provide complete stabilization of the droplets. Thus, a stable, debris-free light source combined with suitable collection optics can provide useful EUV radiation power.

Keywords: EUVL, conversion efficiency, debris, laser plasma

I. INTRODUCTION

One of the technologies for the production of the next generation computer microprocessor is extreme ultraviolet lithography (EUVL). The most important aspects of this new technology are the illumination source development, the optics lifetime, and the imaging characteristics on the wafer. EUVL is designed for circuitry printing where the minimum feature size is 32 nm or even smaller. To achieve such a small feature size, EUVL operates with a short wavelength of radiation (13.5 nm). The goal of this research is to control and stabilize laser plasma sources through the design and prototyping of the Laser Plasma Targeting System. The following will be demonstrated: an increase in the conversion efficiency (CE), a decrease in debris generation, and an enhancement in optics lifetime. This will place laser plasma source as the best candidate for commercialization of EUVL allowing computer microprocessors at 19 GHz with feature size smaller than 32 nm in 2009 [1].

II. SOURCE REQUIREMENTS

Laser plasma sources require high level of stability, lifetime, and cost effectiveness to become a practical technology for EUVL. High power laser technology generates KHz repetition rates forming stable laser plasmas. However, the main obstacle of laser plasma sources is the cost to increase the CE between the laser beam energy and the in-band emission. High-repetition rate lasers bring a bright future to laser plasma sources needing in-band power of 115 W which needs to be specified in terms of EUV power at the intermediate focus (IF) of the system considering the 2% bandwidth of 13.5 nm [2]. In addition, an important challenge is maintaining the EUV power for the required lifetime, 30,000 hours [2] since the EUV power can be reduced by the debris from the source plasma degrading the optical components. The reflectivity of the EUV optics needs to be able to last for this lifetime. In order to eliminate or reduce the debris, debris mitigation techniques such as foil trap mitigation can be applied [3].

III. SYSTEM OVERVIEW

The laser plasma targeting system is formed by three main elements. First of all, optical illumination and imaging in order to monitor and ensure optimal plasma formation. Secondly, software to achieve complete stabilization of the droplets positioning the droplet stream at the focus of the laser. Finally, a complete electronic system is in charge of controlling and adjusting the frequency of the droplet generator for good droplet

quality and the timing and frequency of the laser to ionize the whole droplet minimizing the debris.

In the system, a small droplet is targeted by a short-pulse high energy laser. Droplets are formed of water doped with ~30 weight % of tin for higher radiation emission in the 13 nm region. These droplets are an average of 30 μm in diameter produced by a system like-inkjet technology (fig. 1). The droplet driver generates a stream of about 30,000 droplets per second if a 30 KHz signal is applied. The droplet formation is a result of an applied voltage to a piezo-crystal that exerts surface tension instability on the jet formation. This process produces the breakdown of the liquid stream with the consecutive generation of droplets.

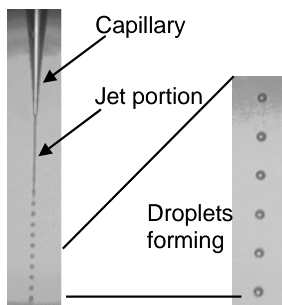

Figure 1: Droplet formation from capillary

If the laser irradiates the tin-doped target right in the center, the whole droplet is ionized producing plasma in the 13 nm EUV region which is the desired wavelength for EUVL. This wavelength radiation is easily absorbed in air. Thus, experiments are done in a vacuum chamber to guarantee maximum transmission.

It was mentioned that the goal is to demonstrate control, stabilization, and timing synchronization to shoot the droplets at the right time, however, many parameters need to be corrected and adjusted through a feedback loop. Therefore, the system diagram shown in figure 2 must perform several tasks automatically: 1) Aligning and positioning the droplet stream at precisely the focus of the laser; 2) Adjusting the frequency of the droplet generator for good droplet quality; 3) Synchronizing the timing and frequency of the laser to hit the droplet target; 4) Monitoring the resulting plasma to ensure optimal performance.

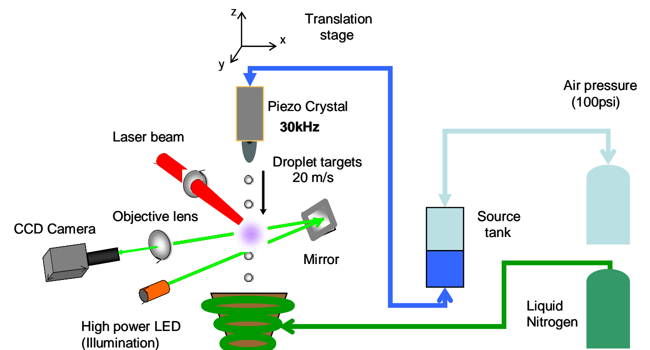

Figure 2: Scheme of Laser Plasma Targeting System.

A computer will interface the control software with the electronics to synchronize the droplets with the laser and the mechanized stages in order to control the position of the droplet nozzle. The droplets can be seen on real time through the computer monitor (fig.3). The targeting system can compensate both temporal displacement based on droplet velocity changes produced mainly by pressure alteration and spatial displacement due to trajectory changes. The advantages of this system are not only to track and feedback in three dimensions, but also to compensate for other uncertainties of the physical parameters of the target within the system loop. In order to bring this technology much closer to commercial systems, this system must run continuously with no interruption to produce maximum average EUV light.

IV. IMAGE PROCESSING

The Laser Plasma Targeting System uses optical imaging to stabilize droplet laser plasmas for EUV generation. The images are fed to a computer that performs advanced image processing techniques to determine the position of the droplet relative to a predefined position. If the software finds that the droplet has drifted, commands are issued to adjust the translation stages, and the droplet is physically moved back into position.

In order to image the droplets, which are being produced at a rate of about 30-40 kHz and traveling ~20 m/s, two high power LED diodes are functioning at the same rate as the droplet production, providing back-illumination of the droplet for imaging through two different angles. The electronics perform synchronization of illumination and droplet generation. This produces images that are collected using standard optical imaging techniques and imaged onto high-resolution CCD cameras (fig. 3). Images are taken from two angles, which are configured orthogonal to the droplet's path. Since they

are orthogonal, the two images provide *x*, *y*, and *z* coordinates position directly.

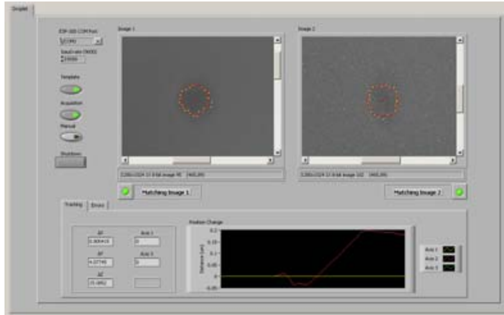

Figure 3: Droplet control software

Once the computer receives images of the droplets, it computes the center position of the droplet. During initial alignment of the system, an optimum position is found manually by observing the EUV emission from the source plasma. Then this optimum position is used to compare with real time positions. If the droplet's current position deviates from this position by more than a preset limit, the computer calculates the needed position correction and sends corresponding commands to a motorized translation stage. This process repeats continuously while the source is operating.

V. EXPERIMENTAL RESULTS

In order to maximize the EUV light emission, it is required to synchronize the laser pulse to the droplet target. Also plasma diagnostic is important for CE and debris characterization. All the experiments in this study are performed under vacuum of <1 mTorr to guarantee maximum transmission of the EUV radiation. The laser energy per pulse is 150 mJ and its pulse duration 21 ns (FWHM). This energy is able to ionize the droplet target at the focal region. Under these conditions, plasma is created to be analyzed by the spectrograph. A spectrum from a Sn-doped droplet (fig. 4) shows the EUV narrow emission with a peak in the 13.5 nm region. This spectrum is obtained using a laser intensity of 1.4 x 10^{11} W/cm^2 at 3.125 KHz. In figure 4, a comparison of the source spectra, (a) one with better laser-droplet synchronization and (b) one with poor synchronization, which emulate the impact of the targeting system installation on optimizing CE for a long term operation. This demonstrates an increase in the EUV intensity emission from the laser targeting system spectrum. The CE of the EUV emission from Sn-doped droplet is calculated as 2.4% into 2π str in the 2% bandwidth of 13.5 nm [4]. It is possible to optimize the CE through a better coupling of the target geometry and laser irradiation. In addition, optimizing the laser intensity will improve the CE [5].

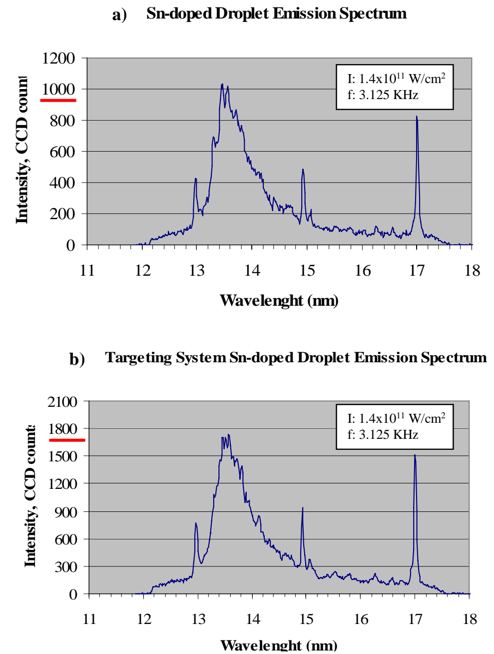

Figure 4: (a) Spectrum from tin-doped droplet and (b) spectrum from the laser plasma targeting system tin-doped droplet.

Although power requirements are reachable with tin-doped droplets, plasma particle and cluster emissions can damage the optical components of the system. Thus, EUVL developers try to eliminate the plasma debris in their sources. The tin-doped droplet size is matched to the laser spot size in the focal region. In this way, having a laser pulse with the right intensity, the whole droplet target will be ionized eliminating the formation of debris. If the entire droplet is not ionized, the optical components of the system will suffer a short lifetime due to the increase EUV absorption of deposited debris on the surface. Figure 5(a) shows negligible debris on a 10 cm focusing lens used under operation at optimal intensity of the targeting system for 3 hrs at 6.6 KHz and 7x10^7 shots. Figure 5(b) illustrates a photograph of a lens under low intensity of a fiber laser system operation after 10 min at 1.8 KHz and 1x10^6 shots, showing visible debris on the lens surface [6].

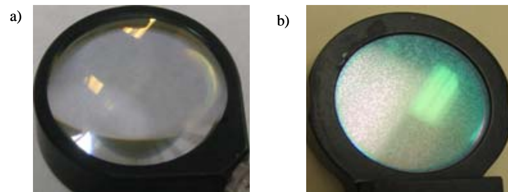

Figure 5: (a) laser focusing lens used in an experiment with the Laser Plasma Targeting System and (b) lens used in a low intensity fiber laser system.

Mass-limited targets are used in order to minimize the effects of target debris. Assuming that we have no particles emanating from the droplet target, another issue is to protect the collection mirrors from the ions emitted by the plasma. These ions can be controlled through mitigation techniques such as applying magnetic fields [3]. Even though debris has been observed in different forms, ions and small particles or clusters are the main source of debris. Ions are a consequence of plasma source production and small particles debris are a product of vaporized material under laser irradiation with lower intensity. A large amount of source material coming from the source plasma will be accumulated on the EUV optics having a laser at high repetition rate. The debris must be mitigated before EUV optical components are contaminated. Therefore, the main goal in our system prototype is to eliminate the debris and optimize the CE to reach the industry source requirements.

VI. SUMMARY

This research is an approach to the development of a EUVL high power source. The Laser Plasma Targeting System is being developed to control and stabilize droplet laser plasma. In order to satisfy the industry EUV Lithography wavelength of 13.5 nm, the droplet is irradiated with a high power laser which excites the droplet into plasma emitting such wavelength. However, stabilization is required due to the phase shift and instabilities in the droplet formation. Thus, the system needs to track the droplet source and apply adjustments through a feedback loop. The laser should target the droplet right in the center in order to ionize the whole droplet. In this way, the brightness of the light created is increased and debris is decreased providing longer lifetime of the optics. Therefore, this system combines inkjet-like droplet technology, electronics to synchronize the droplet with the laser, optical illumination and imaging, and custom software to provide active control and stabilization feedback to the system.

As a result, the Laser Plasma Targeting System has demonstrated accurate positioning with a high resolution imaging system and precise shooting at tin-doped droplets creating plasmas with useful EUV radiation power and minimum debris. The long term stability has been obtained through the use of tracking techniques and active feedback. High CE and low debris result in optical components with a long lifetime. Therefore, EUV light created from tin-doped droplet targets is a promising source for EUVL satisfying levels of performance, stability, and lifetime.

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