Characterization of the Tin-doped droplet laser plasma EUVL sources for HVM

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ABSTRACT

Tin-doped droplet target has been integrated with several lasers including high power high repetition rate lasers and demonstrated high conversion efficiencies for all the lasers. This implies the EUV source power is linearly increasing as the laser frequency goes higher. The target exhibit very low out-of-band radiation and debris emission. The drawback of increasing the repetition rate of the target and the laser will be limited. The total amount of tin consumed for a EUVL source system is also small enough to be operated for a long term without large effort for recycling of the target materials. We address and demonstrate in this paper the primary issues associated with long-term high power EUV sources for high volume manufacturing (HVM) using tin-doped droplet target.

Keywords: EUV sources, Droplet plasma, High power EUV source, Out-of-band radiation, debris mitigation

1. INTRODUCTION

EUVL sources are required to satisfy the stepper manufacturers' agreement where the source power, source lifetime, source etendue, power stability and source spectral purity are specified. We have previously reported many characteristics of tin-doped droplet target for EUVL source, such as the high conversion efficiency (CE),[1] the small out-of-band radiation,[2] and the limited ion emission.[3] We address and demonstrate in this paper the primary issues associated with long-term high power EUV sources for high volume manufacturing (HVM) using tin-doped droplet target.

The target configuration provides the highest CE with 1 μm laser irradiation where we can apply commercial laser systems that output the wavelength. High power EUV generation is demonstrated using high repetition rate (HRR) laser system synchronized with target delivery which is stabilized with advanced feedback schemes. We have currently two options for the HRR laser, diode pumped solid state laser (DPSSL) and diode pumped fiber laser (DPFL). High CE (1.8%) in the initial experiment was reported for DPSSL.[4] The HRR laser can be temporally and spatially multiplexed so that even higher EUV power can be generated. The tin-doped droplet target is capable of being operated at the same or higher frequency of the lasers, where the EUV power stability, therefore the dose stability is higher than that of the minimum frequency specified in the requirement.

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We can tolerate the penalty for operating at high frequencies which is the increased amount of ion emission. The tin-doped droplet target is a mass-limited target,[5] so that all the tin atoms are ionized and contributing to useful EUV radiation. If any ions are generated, they are captured by the effective ion mitigation schemes[6] before they reach the first collector mirror. We have conducted mirror lifetime estimation scaling with the ion kinetic energy distributions at the mirror distance and have calculated surface sputtering yield of Si and Mo. The estimated mirror lifetime is within the requirement at increased operation frequencies, with the use of prescribed ion mitigation schemes.

The radiation characteristics of the tin-doped droplet plasmas in terms of the spectral purity is studied. This ensures that limited number of photons of the out-of-band radiation (OOB) from the tin-doped droplet EUVL source propagates through the stepper optics. The source size is about 100 microns in diameter[7] which is well below the source etendue limit. Therefore, the tin-doped droplet target system satisfies all the source requirements.[8]

Detailed descriptions for producing a source that fulfills all the requirements stipulated are presented in the next section. The experimental setups for investigating relevant research areas are described in section 3. The latest results and discussions on those challenging issues are presented in section 4.

2. CLEAR PATH FOR THE TIN-DOPED DROPLET SOURCE TOWARDS HVM

2.1. High power high repetition rate EUVL laser plasmas

To achieve EUV power requirement for HVM (115 W), 1) an efficient target, 2) high power laser, and 3) efficient collection of EUV are the essential components. High CEs have been reported previously based on tin-doped droplet target scheme.[1] Therefore, the first essential component is already available. The second essential component, high power lasers have been recently provided so that generating high EUV power is the next objective. The last component, efficient collection will be described shortly.

Tin-doped droplet target scheme has also demonstrated high repetition rate delivery.[1] Stable droplet generation can be obtained at frequencies higher than 100 kHz. To generate efficient emission from plasma as demonstrated, the coupling of the laser to the target should remain the same. To generate higher power, generating the plasma at higher frequencies is the most practical choice. The laser intensity for the optimum laser energy coupling to the target is found to be $\sim 1.4 \times 10^{11}$ W/cm^2.[1] To provide such intensities, laser system candidates are limited.

One of the most promising candidates as a suitable HRR laser to be coupled with the DPSSL, where the laser pulse parameters are very close to that of the precision solid state laser used with the experimental results obtained previously.[1] To balance the pumping photons from the diodes and extracting photons from the gain media, Q-switching operation frequency is around a few kHz. The average power currently available by a commercial DPSSL can be up to $\sim$ 1 kW. Even with the high power DPSSL and the high CE of 3 % assumed, the EUV source power at source is 30 W from a single laser module. Multiple of DPSSLs are needed to provide required EUV power. For the target delivery there is no difficulty in operating at higher frequencies more than 10 kHz.

Suppose 10 identical modules, with each module outputting 1 kW at 3 kHz, are temporally multiplexed and coupled to tin-doped droplet target that is operated at 30 kHz, the total laser input power is 10 kW and the total EUV power will be 300 W with CE of 3 % assumed. This is a reasonable projection for the future source development for HVM, since the laser pulse energy of 333 mJ is within the range to obtain the optimum intensity.

The other promising candidates for the suitable HRR laser is DPFL where the laser pulse energy is more than an order of magnitude lower than that of DPSSL. However, the repetition rate of the laser can be easily exceeding 10 kHz or even approaching 100 kHz. The average laser power from a single DPFL is more than 100 W or higher. For the target delivery it is possible to synchronize the droplet generation to the high repetition rate of the DPFL. To obtain the optimum laser intensity for the efficient plasma, the laser beam must be focused tighter than the case of DPSSL. However, since DPFL is operating higher frequencies than DPSSL's, multiple of DPFLs can be spatially multiplexed so that a single tin-doped droplet target is irradiated at the intensity preferred.

Suppose 10 identical modules, each module outputting 1 kW at 100 kHz, are spatially multiplexed and coupled to the target, which is operated at the same frequency of 100 kHz, the total laser input power is 10 kW and the total EUV power will be 300 W with the same CE assumed as the case of DPSSL. The laser pulse energy from one laser module is 10 mJ which is only a few times higher than the DPFLs currently available in the market. This is also a reasonable projection for EUVL source development for HVM.

There are some encouraging reports of increased CE values by using CO_2 lasers.[9,10] We are currently examining the consequences of using CO_2 lasers for tin-doped droplet target system for CE, as well as in terms of the scalability of repetition rate, foot print, lifetime, and the cost of the laser systems. There are some tradeoffs in using longer wavelength laser irradiation. For instance, larger source sizes, which will reduce the focusing solid angle of etendue, as described next, due to the lower critical density of the plasma for 10.6 μm laser wavelength. A disadvantage could be generating more debris since the CO_2 laser light heats only outside of the target, and therefore, a large fraction of the target will be left unheated. This unheated target material become debris, generating large numbers of tin aerosols, eventually degrade the collector mirror reflectivity. Also the plasmas heated by CO_2 lasers will have high temperature with lower density as predicted by hydrocode simulations[1] and the ions generated tend to remain in the high charge states due to reduced recombination rates, which have been observed.[11] The ions with higher charge states could destroy the surface of components[12] such as multilayer mirror (MLM) coatings on the collector mirror, nozzles of target delivery schemes and debris mitigation schemes.

2.2. High EUV transport to IF with large collector mirrors

Another factor essential for providing the required EUV power at the intermediate focus (IF) is efficient collection of the EUV generated at the source plasma. The overall transport of the EUV energy to the IF is the product of the efficiency of the light collection with regard to 2 π solid angle and the reflectivity of the mirror, or overall reflectivity if there are multiple reflections in the path from the plasma source to IF. The reflectivities of both grazing incident mirrors and the normal incident multilayer mirrors are theoretically limited. To increase the total efficiency of the EUV collection, collection angle must be increased.

Increasing the collection angle is achievable by many methods.[13,14] However, the collected EUV has to be focused at IF within a specified etendue.[8] The etendue is a product of the aperture and the solid angle of the focus therefore the smaller the focus to pass a smaller aperture can relax the strain of the solid angle of collected EUV. Small source sizes can provide lager the focus solid angle thus the larger the solid angle of EUV collection is also possible. EUV radiating plasma size of tin-doped droplet is measured to be about 100 μm in diameter[7] which is much smaller than the discharge plasmas where the collection angle is limited. The larger collection angle is possible for this small droplet plasma.

To overcome lifetime requirement,[8] which is another challenging issue listed in the EUVL source requirements, effective debris mitigations are needs to be inserted between the source plasma and the collector mirror surface. Physical objects block and absorb the EUV radiation decreasing EUV transmission to IF. Therefore, high transmission of debris mitigation schemes are important. Simultaneously, debris mitigation schemes are required to reduce the debris flux. We have already developed two effective mitigation schemes,[3,6] as well as the mass-limited target concept is implemented. The debris emission of tin-doped droplet plasma and the debris mitigation schemes developed are also described later in this section.

2.3. Low Out-of-Band radiation

The EUV source plasmas generated from tin-doped droplet target have exhibited low emission in the radiation outside of the MLM reflectivity band. We define the radiation outside the band in two regions, off-band radiation (1 nm - 30 nm) which will be absorbed at the first mirror surface, and out-of-band (OOB)radiation ($\geq$ 30 nm) which will be reflected and transported to the illumination and projection optics in the stepper. When the off-band radiation is absorbed, the collector mirror will be heated. High temperature causes reflectivity degradation due to inter diffusion of the Mo/Si layers. However, there is already a high temperature rated multilayer coating fabricated and tested at high temperature.[16] The OOB is more problematic than the off-band radiation. The transported OOB photons will also be used to expose the photoresist causing reduced contrast of the mask image. Typically, thin metallic films can absorb longer wavelength than EUV. There are several methods proposed such as a rigid thin film which will be placed between collector mirror and IF,[17] installing a mirror surface with a grating structure between collector mirror[18] and IF, and thin layers deposited on top of the multilayer mirror coatings in the optics in the stepper.[19] Regardless, large amount of OOB power will be absorbed if the source plasma radiates OOB.

Controlling the plasma temperature will prevent the amount of OOB generated. We have diagnostics for the entire wavelength regions as well as spectral modeling capabilities for virtually any wavelength emission from any target materials.[2] We have observed limited number of line emissions in visible and near IR (NIR) wavelength regions from oxygen and hydrogen which are the supporting materials for tin in the droplet targets. We have also observed scattering of irradiating laser light. Total energy in the visible and NIR regions are characterized.[2] The remaining threatening wavelength regions are XUV and UV. Intensive studies focusing an OOB in those regions are currently underway.

2.4. Low debris and low tin-consumption

The plasmas generated on tin-doped droplet target inherently create less debris than the target schemes with with larger geometries or solid density because the size of the target is comparable to the size of the laser focus and the number of tin atoms in the target is significantly small. Debris emission from the plasma is fully characterized.[3] Undesired tin aerosols are eliminated by optimizing the laser energy coupling to the target materials. The kinetic energies of ions generated in the plasma follow the distributions in thermal plasma, large fraction of ions have lower energies and the population decreases as the kinetic energy increases. This low ion energy reduces the erosion rates on the multilayer coatings on the collector mirror as well as the required ion flux suppression of debris mitigation schemes.

We have developed two effective and high EUV transmission mitigation schemes, Repeller field mitigation[15] and Magnetic Foil Trap mitigation.[6] Both schemes exhibit large factor for suppressing the ion flux reaching the collector mirror.[6] Moreover, they can be installed in different distances from the source plasma for the integration of the schemes.[6] The structures of these schemes are simple and can provide high EUV transmission so that EUV power at IF is not reduced significantly by these installations.

The mitigation schemes are basically trapping unwanted debris. Their effectiveness can last long when used for the tin-doped droplet target scheme since the tin consumption of the target scheme is limited. The target contains only tin atoms used in generating EUV radiation. Since there is no tin material wasted in the system, the amount of tin used and trapped in the mitigation schemes are also limited. We have investigated the impact on this issue and found that it consumes only less than 1 kg for one year operation.[20] The tin inventory required to operate the source system with tin-doped droplet target scheme for a year is about 6 kg without any tin material recycled.[20] The amount of tin necessary for the target scheme is significantly smaller than the other source architectures. For HVM source operation, consuming as little tin as possible is required not only for the cost of the material but also for the small impact on the mitigation schemes.

3. TIN-DOPED DROPLET LASER PLASMA SOURCE FACILITIES

3.1. Target chambers for tin-doped droplet laser plasma EUVL sources

We currently utilize three vacuum chambers with tin-doped droplet target systems for different objectives, which are generating high EUV power, studying fundamental characteristics of tin-doped droplet laser plasmas, OOB studies, debris characterization, and examining debris mitigation schemes. A cylindrical chamber with the inner diameter of $\sim$ 600 mm is used for the high power EUV generation purpose. There are two turbo molecular pumps are mounted in case of higher vacuum load at higher EUV generation. Target diagnostics and plasma diagnostics are also mounted which are described shortly. Fig. 1 shows the target chamber with equipments mounted. HRR lasers are coupled with the target chamber to generate high EUV power and more detailed descriptions will be found in a reference.[21]

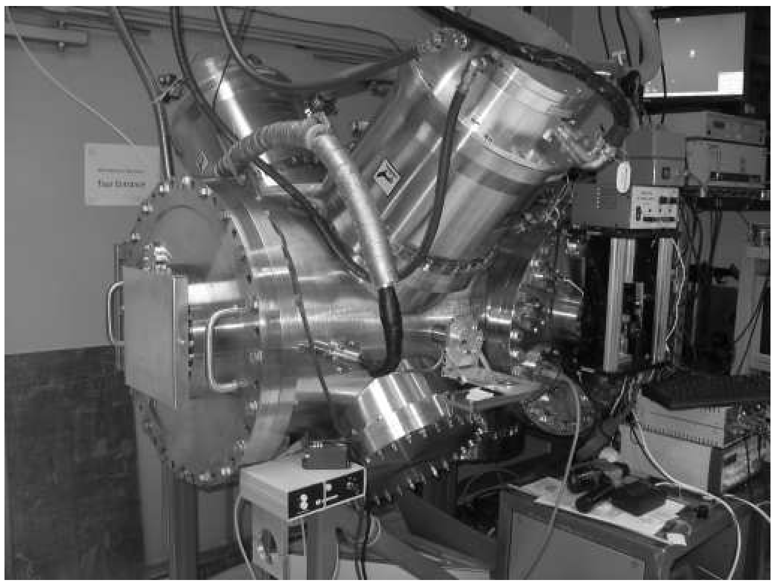

Figure 1. Vacuum chamber facility for high power EUV generation.

A separate vacuum chamber is utilized for the fundamental studies on the plasmas generated with tin-doped droplet target by different laser parameters.[1] The chamber provides several view-ports at different angles from the laser incident. It is advantages for the radiation studies such as high resolution spectroscopy and in-band metrology. A flat-field spectrograph (FFS) is mounted at 30 degrees from the laser incident. The detectable wavelength range is 5 nm to 20 nm with a high sensitivity multichannel plate (MCP) detector. The EUV energies are monitored at the same angle from the laser incident by Flying Circus (FC)[22] with mirrors and Zr filters that are calibrated at NIST. Mainly the precision solid state laser is coupled to the target chamber which can be used by other laser systems using the same beam path.

Another vacuum chamber is used for the OOB studies, debris characterization, and debris mitigation implementations. The laser coupled to this chamber operates at an intermediate frequency, 100 Hz, which is ideal for the OOB measurements and ion spectrometer measurements. The OOB radiation diagnostics and ion diagnostics are interchangeable. Also debris mitigation schemes are evaluated using the chamber by analyzing the date obtained from the ion diagnostics. More detailed descriptions of the diagnostics are presented later in this section.

3.2. High repetition rate stabilized target delivery system

Tin-doped droplets are generated by a capillary nozzle assembly with a specific driving frequency that is provided by a laser-target synchronizing system. The diameter of a single droplet is around 30 μm $\sim$ 45 μm depending on the driving frequencies. A continuous uniform droplet train is obtained and these droplets travel at a velocity of typically 20 m/s. The position of the droplet targets in the laser focus region is observed by microscopes and any displacement of the target position is fed back to the control system so that the new droplet targets generated will be placed at a desired position in the laser focus. The feedback system ensures the optimum laser-target coupling that provides highest CE and highest EUV source power all the time.

3.3. OOB radiation diagnostics

XUV-visible monochromator is used to study the out-of-band radiation from the tin-doped droplet plasmas. The OOB radiation study is pursued in a separate chamber described above where a commercial 100 Hz laser is coupled, shown in fig. 2. The plasmas are generated while the monochromator scans the wavelength region from $\sim$30 nm to $\sim$400 nm. The multilayer mirror reflectivity is high in the wavelength region[23] compared to the reflectivity at 13.5 nm. Therefore the OOB radiation study is very important for the implementation of the target scheme as EUVL source for HVM.

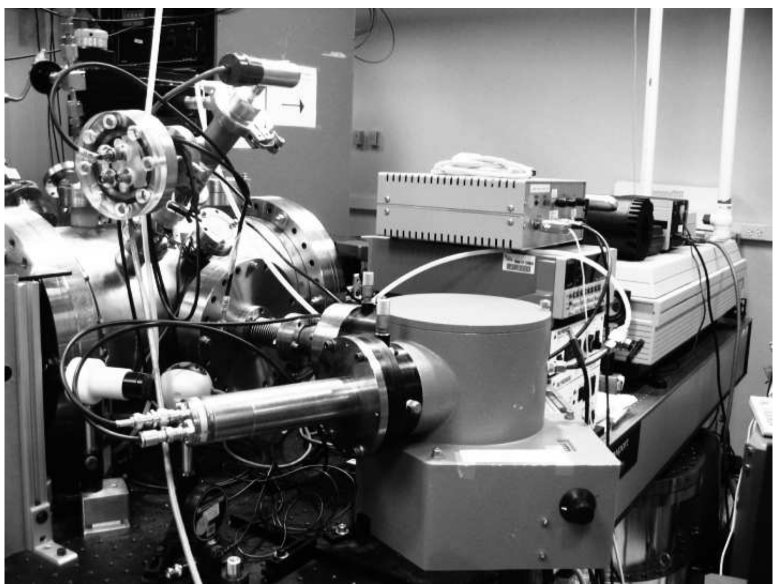

Figure 2. Facility for OOB study with the chamber, the monochromator and the laser.

3.4. Ion diagnostics and mitigation schemes

The source lifetime requirement is also a challenge for EUVL source development. The lifetime of EUVL source is determined by the lifetime of the collector mirror reflectivity The primary cause of the multilayer mirror reflectivity degradation is the erosion of the mirror coating by high energy ion flux. We have developed several ion diagnostics that provide sufficient information in order to estimate the mirror lifetime. The primary ion diagnostics utilized in this study are ion probes (IP) and ion spectrometer with electrostatic ion energy analyzer (ESIEA) which are described in the reference.[3, 24]

We examine the effectiveness of debris mitigation schemes by using IP with knowledge of the ion kinetic energy distributions obtained from ESIEA. Without knowing the distributions and the ion charge states, measurements of IP cannot be analyzed well especially for multi-component target such as tin-doped droplet target scheme. Measuring ion kinetic energy distributions by ESIEA under influence of debris mitigation schemes is also challenging because the ion trajectory at the entrance of the ion spectrometer must be coaxial in order to measure the correct ion energies. Small angle difference makes an error in the energy analyzer or ions simply will not reach the analyzer. Therefore combining two ion diagnostics in proper way is essential to study ion emission from the plasma and the debris mitigation schemes.

4. RESULTS AND DISCUSSIONS

High EUV source power is measured using HRR DPSSL.[4] The initial measurements were encouraging.[21] The initial demonstration was aimed to achieve $\sim$ 10 W of EUV generation at plasma source. The EUV power generated from the second laser is also providing high EUV power generated. By multiplexing the two lasers, the EUV power should be doubled. More detailed analysis on the CEs and EUV powers are underway.

Comprehensive OOB studies are in progress. We have already observed the radiation from the plasma in the ranges of 1 nm - 30 nm, and 400 nm to 1100 nm.[2] Recently radiation characteristics in the wavelength range of 30 nm - 400 nm are measured.[25] Also extensive studies are underway in the visible and NIR with high resolution spectrometries for better identification of the spectral signatures of the target materials.

The two mitigation schemes are improved in suppressing ion flux. The IP signals measured with the magnetic foil trap from the tin-doped droplet plasma show virtually no high energy tin ions detected by IP while small level of low energy oxygen ions are detected. Those oxygen ions pass through the trap can be captured by the Repeller field mitigation which works better for low density plasma and charged aerosols. The evaluation of the combined two mitigation schemes is underway.

5. CONCLUSION

We address and demonstrate in this paper the primary issues associated with long-term high power EUV sources for high volume manufacturing (HVM) using tin-doped droplet target scheme. The advantages of this target scheme are the HRR operation capability and low tin material content. As described, low OOB and debris emissions from the plasma reduce the impact on not only the source system but also the optical systems in the stepper. So far there is no major road block to reach EUV power level at source of some what like 300 W, which gives more than 150 W for the ideal case of the efficient EUV collection and high transmission of the mitigation schemes. Limited tin inventory is required for the target scheme and it consumes only radiating tin atoms which will be trapped by the mitigation schemes.

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