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Comparative study on EUV and debris emission from CO$_2$ and Nd: YAG laser-produced tin plasmas

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Abstract. The emission characteristics of debris from laser-produced tin plasma were investigated for an extreme ultraviolet lithography (EUV) light source. The ions and droplets emitted from tin plasma produced by a CO$_2$ laser or an Nd: YAG laser were detected with Faraday cups and quartz crystal micro-balance (QCM) detectors, respectively. A higher ion kinetic energy and a lower droplet emission were observed in the case of CO$_2$ laser in compared with Nd: YAG laser in the same laser energy (50 mJ). The reason comes from the interaction of the laser pulse with the plasma. CO$_2$ laser is absorbed in superficial region of the plasma due to the long wavelength, in contrast, Nd: YAG laser penetrates deeply into the plasma. Therefore, the absorbed energy density of CO$_2$ laser will be much larger than that of Nd: YAG laser for the same laser energy. This causes the higher ion energy and complete vaporizing the target material.

1. Introduction

The extreme ultraviolet (EUV) light source has been developed for the next generation lithography tool to produce a micro-device with nano-scale electronic nodes [1]. In a practical EUV lithography light source, a EUV power of as high as 180 W in 2 %-bandwidth around 13.5 nm is required. One of the promising approaches is the laser-produced plasma (LPP) source. The most promising emission material is tin (Sn) because of the high conversion efficiency (CE) to 13.5 nm-light. However, tin target emits debris (high energy ions, atoms, and droplets), which damage the expensive and delicate optics; therefore the shield from debris is one of the most critical issues. The emission characteristics of debris should be fully understood to develop efficient shield.

In the previous work, we presented the CO$_2$ LPP for the EUV light source, and showed that the CE of CO$_2$ laser-produced tin plasma is comparable with that of Nd: YAG laser [2]. In this report, we investigate the emission characteristics of debris from laser-produced tin plasma for both of CO$_2$ and Nd: YAG laser.

2. Experimental Setup

Figure 1 shows the experimental arrangement. The CO$_2$ and Nd: YAG laser beam was focused on a rotating tin plate by a lens with focal length of 150 mm. The Nd: YAG laser (SPECTRA PHISICS
Quanta-Ray PRO) is Q-switched, and the pulse width is 8 nsec FWHM (full width half maximum). The CO\(_2\) laser (LAMBDA PHISIK EMG201MSC) has an unstable resonator, and the pulse has a spike pulse with 50 nsec FWHM and a long tail, as shown by dashed line in figure 2. The focal spot size was about 0.2 mm for Nd: YAG laser, and 0.3 mm for CO\(_2\) laser.

![Figure 1. Schematic of the experimental arrangement.](image1)

![Figure 2. Pulse shape of CO\(_2\) laser without PS (dashed line) and with PS (solid line).](image2)

The energy spectrum of ions from tin plasma is measured with four Faraday cups (FC) around the tin target to take the angle distribution for single shot. The distance between FC and tin target is 110 mm. The amount of debris and droplets are measured with four quartz crystal micro-balance (QCM) detectors and Si plates mounted at the same position of FC.

3. Experimental Results

3.1. Characteristics of ion kinetic energy

Figure 3 show the ion signals detected by the Faraday cups from Nd: YAG laser- and CO\(_2\) laser-produced tin plasma. The laser energy was 50 mJ for Nd: YAG laser, and 160 mJ for CO\(_2\) laser. The peak intensity is 6 x 10\(^{10}\) W/cm\(^2\) for Nd: YAG laser, and 9 x 10\(^9\) W/cm\(^2\) for CO\(_2\) laser. Although Nd: YAG laser intensity is larger than that of CO\(_2\) laser by several factors, these signals suggest that the ion kinetic energy of CO\(_2\) LPP is higher than that of Nd: YAG LPP. The ion signal of CO\(_2\) LPP has complex structure, and the time axis does not entirely correspond to the time-of-flight of ions because

![Figure 3. Ion signals from (a) Nd: YAG and (b) CO\(_2\) laser-produced tin plasma without PS.](image3)
of the long tail.

In order to avoid the complexity of analysis and investigate the effect of laser pulse shape, we arranged a plasma shutter (PS) to cut off the tail. The PS is composed of two lenses. The laser beam produces plasma in the focal point, and then the plasma blocks the beam tail. The compressed pulse shape is described in solid line in figure 2, and the ion signal with the compressed pulse is shown in figure 4. The laser energy was 50 mJ (4 x 10^9 W/cm²). The effect is obvious: the initial signal around 1 µsec and the later signal after 3 µsec disappeared. This result suggests that the tail part of CO₂ laser pulse generates not only low-energy ions but also high-energy ions. Figure 5 shows the ion kinetic energy distributions at 29 degree from target normal, which are derived from the signals in figure 3 (a) and 4. It is obvious that the ion kinetic energy of CO₂ LPP is higher than that of Nd: YAG LPP.

![Figure 4](image1.png)  
**Figure 4.** Ion signals from CO₂ laser-produced tin plasma with PS.

![Figure 5](image2.png)  
**Figure 5.** Ion energy spectra of Nd: YAG laser- and CO₂ laser-produced tin plasma.

### 3.2 Characteristics of debris accumulation

Figure 6 shows the amount of accumulation of debris measured by QCM as a function of shot number. It should be noted that the debris emission of CO₂ LPP is smaller than that of Nd: YAG LPP for same laser energy. The electron microscope image of surface of Si plate in figure 7 supports this result. The sizes of debris from Nd: YAG LPP are much larger than those from CO₂ LPP.

![Figure 6](image3.png)  
**Figure 6.** Debris accumulation from (a) Nd: YAG laser- and (b) CO₂ laser-produced tin plasma. The pulse energy is 240 mJ.
4. Discussion
The dominant absorption process of long-wavelength lasers is the inverse bremsstrahlung (IB), where electrons accelerated by laser field inelastically collide with ions or neutral atoms. The IB absorption coefficient is proportional to $\omega^{-2}$, where $\omega$ is the angular frequency of the laser [3, 4]. As the result, CO$_2$ laser is absorbed in superficial low-density region of the plasma due to the long wavelength, in contrast, Nd: YAG laser penetrates into the high-density region on the target surface. Therefore, the superficial temperature of CO$_2$ LPP will be much larger than that of Nd: YAG laser for the same laser energy. The ions emitted from Nd: YAG LPP will loss the energy due to the collisions with other particles in the plasma. On the other hand, the ions in CO$_2$ LPP will not loss so much energy because the almost all of ions generate the superficial low-density region. This also explains the effect of pulse shape on the ion signals shown in figure 3 (b) and 4. The tail of CO$_2$ laser pulse is efficiently absorbed in the expanded low-density plume, and generates high-energy ions.

The characteristics of debris emission shown in figure 6 and 7 are also attributed to the absorption mechanism of laser energy. In the case of Nd: YAG LPP, the laser penetrates to the target surface, and the target surface is superheated into liquid phase, and then droplets are formed. In contrast, in the case of CO$_2$ LPP, once plasma is produced, the energy is absorbed in the plasma surface; therefore the target surface is not heated so much as the Nd: YAG LPP.

5. Summary
In summary, the comparative study on the emission characteristics of debris from laser-produced tin plasma were carried out using two different lasers; Nd: YAG laser and CO$_2$ laser. A higher ion kinetic energy and a lower droplet emission were observed in the case of CO$_2$ laser as compared with Nd: YAG laser with the same laser energy. This characteristic is attributed to the interaction of the laser pulse with the plasma.

References

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