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A low debris laser plasma soft X-ray source

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Abstract

Low debris laser plasma soft X-ray source is of great importance to micro-lithography and microscopy. In this paper, a 1.06 μm YAG laser with 2 J energy, 10 ns duration is employed to irradiate a CO_2 cryogenic target. Soft X-ray spectra from the CO_2 cryogenic target are obtained. Experimental results of debris measurement from both CO_2 cryogenic and Cu targets demonstrate that the light source based on the CO_2 cryogenic target shows great improvement over conventional metal targets in debris reduction.

Keywords: Cryogenic target; Laser plasma; Low debris

1. Introduction

Laser produced plasma (LPP) is an attractive table-top soft X-ray source for applications in both microscopy and lithography due to its small size, high peak power and spatial stability. However, the conventional LPP source with metal target has the disadvantage of ejecting high temperature and high speed debris [1], which may seriously damage the sensitive soft X-ray optics that are positioned close to the plasma source. LPP source is believed to be the most suitable light source for microscopy and lithography if debris could be eliminated. Under motivation of practical applications, several methods have been tried to reduce the production or relieve the side effect of the debris from plasma source in the past few years, such as using mass-limited tape target to minimize the production of debris, fast shutter or some noble backing gas to obstruct debris from reaching the optics, however, none of the above methods has successfully eliminated debris from plasma [2,3].

In this paper, we present experimental results of laser plasma produced by using a CO_2 cryogenic target. Some considerations on target material choice of the novel source are given in the first part. The cryogenic target chamber is described in the following section. Finally, we present the results of the measured soft X-ray emission and debris deposition from the CO_2 cryogenic target. Experimental results have proven that the CO_2 cryogenic target LPP is low debris.

2. Target material choice

Low debris and spectral characteristic are the two aspects of concern for a candidate source for soft X-ray projection lithography applications, and they are strongly determined by the target material used in a laser plasma source. In the light of low debris requirements of the target material by practical application, liquid compounds consisting of low Z elements or inert gas are ideal. On the other hand, spectral characteristic of a laser plasma is basically controlled by atomic number Z of target material. Atomic number Z determines the involved ionization stages, emission

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wavelength and spectral intensity distribution of the formed plasma. Thirteen nanometers is the most suitable operating wavelength to meet the requirement of the optical system in a prospective projection stepper [4], accordingly, the candidate target material should emit strongly at 13 nm. The transition probability of 2p–4 d for Li-like oxygen ions reaches $2.4 \times 10^{10}(S^{-1})$ by our calculation [5] using MCDF package [6], which is one of only a few strong transitions for Li-like oxygen ions. Based on the above-mentioned two aspects necessary for our plasma source, we chose CO_2 as the target material.

CO_2 target material has several characteristics favorable for the light source's operation. The target material is capable of being continuously fed into the laser interaction volume, which ensures that the light source works successively, and avoids system shutdown due to the replacement of the target which is necessary in the case of a conventional metal target. Tiny solid state CO_2 ejecting from laser interaction is able to vaporize easily in the vacuum chamber at room temperature, this avoids them depositing on the surface of the optics. In the case of the CO_2 cryogenic target, the service term of sensitive X-ray optics (e.g. expensive multilayers and zone plates) positioned near the plasma source can be prolonged, and X-ray emission can be utilized more efficiently by decreasing the distance between condenser optics and plasma point source. Besides, a higher laser-x ray conversion efficiency is expected because of more lasing ions within the focus volume in the cryogenic target than that of the gas jet target.

3. Cryogenic target chamber

Low temperature gas deposition technique is employed to capture CO_2 molecules in our experiment. We use cold finger as low temperature surface to catch CO_2 in the vacuum chamber. If temperature of the cold finger surface went down to critical value of phase transition of CO_2, then the gas flowing to the cold finger would be frozen.

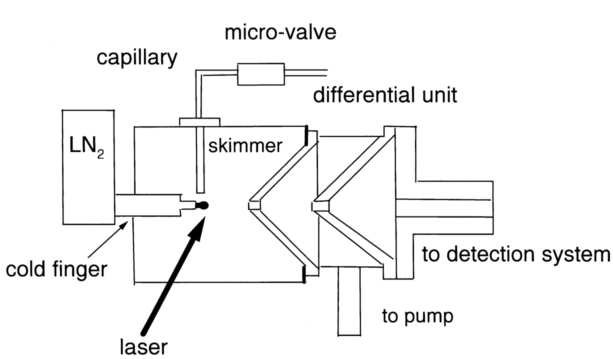

Fig. 1. Schematic of the cryogenic target chamber.

Fig. 1 shows the schematic of our target chamber. In practical use, a cold finger made of Cu with gas deposition surface is inserted into the chamber, temperature of the Cu finger is kept low enough by a liquid nitrogen Dewar bottle. CO_2 gas is continuously fed into the chamber and the flow rate of CO_2 is controlled by a micro-valve. A tiny CO_2 cryogenic target can be formed on the tip of the cold finger, and its formation process is monitored by a visible CCD camera. Successive gas input can be realized by optimizing gas flowing rate vs pressure in the chamber. It is important to keep CO_2 pressure favorable for both soft X-ray transmission and a faster target formation in the chamber, to fulfil this task, a differential unit is used to separate the target chamber and the soft X-ray detection system. By using the differential unit, the pressure in the chamber and detection system are 10^{-3} Torr and 10^{-5} Torr, respectively.

4. Results

YAG laser pulses (1.06 μm) with 2 J energy and 10 ns duration enter the chamber through quartz windows, they are focused on the cryogenic target by an aspherical lens. A grazing incidence spectrometer is used to measure soft X-ray emission from the cryogenic target [7].

Fig. 2 shows a typical X-ray spectra obtained from the CO_2 cryogenic target at a laser intensity of 1×10^{12} W/cm^2. We obtain strong emissions at 11.6, 13.0, 15.0 and 17.3 nm, respectively. These lines are ident-

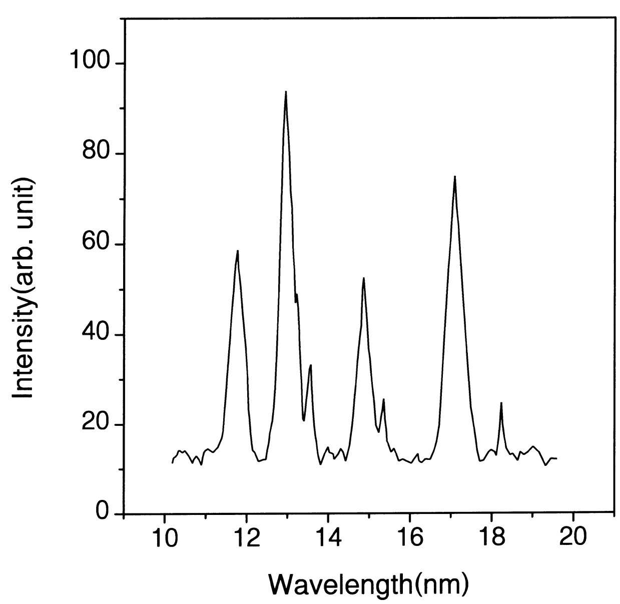

Fig. 2. Observed spectra from the CO_2 cryogenic target.

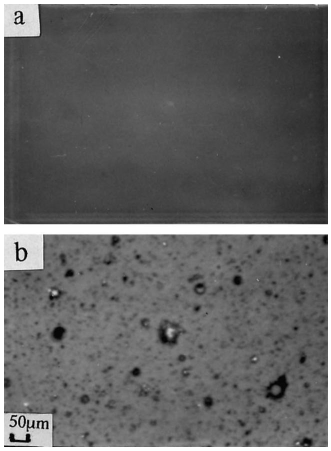

Fig. 3. Microscopic images that show debris adhered on the surface of witness plates. (a) CO_2 cryogenic target, (b) Cu target.

ified by the literature [8] as OVI 2 s-4p (11.6 nm), OVI 2p-4 d (13.0 nm), OVI 2 s-3p (15.0 nm) and OVI 2p-3 d (17.3 nm). The experimental results agree with our MCDF calculation [5]. The obtained spectra indicate that Li-like oxygen ions dominate in the created plasma under our experimental conditions. The emissions from carbon ions are expected to be located mainly at a wavelength of less than 5 nm, however, they are beyond the measurement range of our spectrometer.

In order to check debris deposition, pre-cleaned glass plates are arranged as witness plates to detect debris from both CO_2 cryogenic and metal target plasma sources. The witness plates are placed 100 mm away from target surface. After 10^3 laser pulses, an Olympus optical microscope is employed to check debris deposition on the surface of the plates.

Fig. 3 shows typical pictures obtained from both CO_2 cryogenic and Cu targets under the same experimental conditions. In the case of CO_2 as shown in Fig. 3(a), no obvious debris is observed, this indicates that the ejected small blocks from CO_2 cryogenic target evaporate in the vacuum chamber before they reach the witness plate. The result for Cu is shown in Fig. 3(b), it can be seen clearly that there are densely-populated Cu debris of different sizes that adhered to the surface of the witness plate, most of them are in the size range 1–5 μm, the diameter of some others are in the range of 10–20 μm, a few are even as big as 50 μm. The generation of debris is a result of the interaction between strong shock wave near the critical density and the metal surface. More experiments conducted at different laser energy and pulse duration show that the CO_2 cryogenic target has a great advantage over the metal target in debris reduction.

5. Conclusion

In summary, we have conducted experimental studies on a CO_2 cryogenic target LPP soft X-ray source. Some considerations on target material selection for low debris soft X-ray source are given and a cryogenic target chamber has been developed. A new target, CO_2 cryogenic target, is employed in our experiment. Strong emissions at 11.6, 13.0, 15.0 and 17.3 nm are obtained from the interaction between an ns laser and the CO_2 cryogenic target. Experimental results have proven that the CO_2 cryogenic target exhibits low debris characteristics. The light source based on the new target is a potential candidate for micro-lithography. Besides, carbon ions of the CO_2 cryogenic target are expected to emit strongly in water window range (2.3–4.4 nm) [8], the source can also play an important role in biological sample microscopic applications.

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