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Collective Thomson Scattering Diagnostics of EUV Plasmas

Kentaro TOMITA[1], Taisuke. KAGAWA[1], Kiichiro UCHINO[1],
Sunao KATSUKI[2], Hidenori AKIYAMA[2]

[1]*Interdisciplinaly Graduate School of Engineering and Sciences, Kyushu University, Fukuoka, Japan*
[2]*Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan*

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Collective laser Thomson scattering (LTS) has been successfully applied to Z-pinched plasmas produced for extreme ultraviolet (EUV) light sources. Results of measurements gave plasma parameters just after the pinch as the electron density n_e=1.5×10^{24} m^{-3}, the electron temperature T_e=15 eV, and the averaged ionic charge $\bar{Z}$=7. Furthermore, based on measurements of temporal evolutions of n_e and T_e spatial profiles, the pinched plasma behavior was discussed.

Keywords: Collective Thomson scattering, EUV lithography, EUV light sources, Z-pinch plasmas, Electron density, Electron temperature, Ionic charge.

1. Introduction

Extreme ultraviolet (EUV) lights are going to be used for semiconductor lithography after the 32 nm half-pitch technology node. Only a Mo/Si multilayer mirror has reasonable reflectance in the EUV region and it restricts the wavelength range to be at around 13.5 nm with a bandwidth of 2 %. For the practical use, the power necessary in this bandwidth should be more than 115 W at the intermediate focal point [1, 2]. There are two candidates as the EUV light source. One is the discharge produced plasma (DPP) and the other is the laser produced plasma (LPP) [3, 4]. However, these sources have not yet succeeded to radiate the EUV lights in the required band with the necessary power. For both methods, high density (electron density n_e=10^{24} - 10^{26} m^{-3}) and high temperature (electron temperature T_e= 10 - 30 eV) plasmas should be generated using Xe or Sn atoms [5, 6]. In order to produce required EUV lights efficiently, these plasma parameters should be optimized. A prerequisite for such optimization is the quantitative measurements of these parameters.

In the case of DPP, the high density and high temperature plasma is generated through the mechanism of magnetic implosion (pinch) of the pre-produced plasma by applying a high current with a short rise time. The pinched plasma is alive during a short time (< 50ns) and the plasma size is small (radius < 200 μm). Therefore, a high temporal resolution (<10 ns) and a high spatial resolution (< 100 μm) are required for measurements of DPP sources. A laser Thomson scattering (LTS) method can be expected to fulfill these requirements. The method can yield n_e and T_e values unambiguously.

Depending on the scattering parameter, the Thomson scattering spectrum can be either a coherent (collective) or incoherent [7, 8]. When we use the second harmonics of Nd:YAG laser (λ=532 nm) as the light source, the LTS spectra from the EUV plasmas having aforementioned plasma parameters are in the collective regime. The spectrum of the collective Thomson scattering consists of an ion term and an electron term. The ion term is present very close to the central wavelength of the probing laser, and its expected spectral spread for the EUV plasma is about 100 pm. On the other hand the spectral spread of the electron term is of the order of 10 nm. Taking account of the strong background radiation from the plasma, we determined to measure the ion term, for which we could expect enough SN ratios against the background radiation. One problem to measure the ion term is that the spectral resolution of 10 pm is needed, and the other problem is that the intense wall-scattered laser lights easily overwhelm the ion spectra. In order to overcome these problems, we constructed a newly designed LTS measurement system whose spectral resolution and stray light rejection were enough to resolve fine feature of the ion term. Using the system, we succeeded to evaluate n_e, T_e and $\bar{Z}$ of a Z-pinch type DPP. Furthermore, temporal variations of n_e and T_e spatial profiles were measured and the results were discussed in connection with the evolution of the EUV emission.

2. Experiment

LTS measurements were performed for the EUV source plasma produced in a compact Z pinch device. The device has a main capacitor bank of 42 nF. The

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author's e-mail: tomita@ence.kyushu-u.ac.jp

capacitor bank is rapidly charged up to 24 kV by a magnetic pulse compressor and then a current pulse with an amplitude of 15 kA and duration of 120 ns is delivered to the Z pinch discharge tube. The Z pinch is generated by magnetic pressure due to the current flowing through the tube. More detailed explanations about the Z pinch device used in this study are described in [3].

The experimental arrangement for LTS measurements is shown in Fig. 1. The second harmonics of a Nd:YAG laser (Continuum Powerlite 9010 with an injection seeder; spectral spread < 0.1 pm) was used as a light source of LTS measurements. The laser energy injected into the plasma was less than 10 mJ, and an achromatic lens (L1, *f*=170 mm) was used to focus the laser beam. The laser spot size at the focusing point was measured by detecting Rayleigh scattering signals from a nitrogen gas at a pressure of 300 Torr. For this experiment, the spatial resolution was set to be 20 μm. The evaluated laser spot diameter was 80 μm (FWHM). The timing between the laser pulse and the plasma generation was controlled by using a delay pulse generator (Stanford Research Systems Inc., DG535).

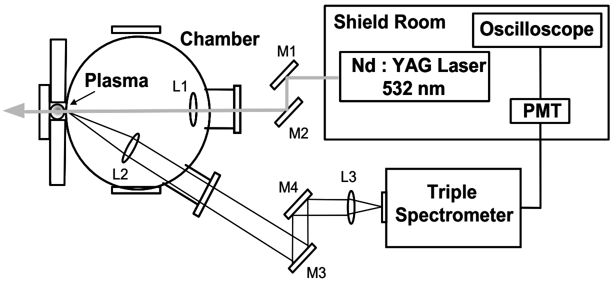

Fig.1 Experimental arrangement.

Scattered lights into the scattering angle of 150 degree from the plasma were focused onto the entrance slit of a triple grating spectrometer (TGS) that is described below, and then dispersed by it. The signal lights passed through an exit slit of the TGS were guided by an optical fiber into an electromagnetically shielded room which was very effective to avoid electromagnetic noise produced by the discharge circuit for the plasma generation. Finally, the signal lights were detected by a photomultiplier tube (Hamamatsu, R943-02).

Because the Z pinch plasmas were generated in a ceramics tube having a diameter of 5 mm, wall-scattered laser lights were very strong and overwhelmed the ion term if they were not eliminated carefully. To overcome this problem, we especially designed and fabricated the TGS to eliminate the wall-scattered laser lights. The schematic diagram of the TGS is shown in Fig. 2. The structure of the TGS was almost the same as before [9], but its design was different from the previous one to achieve a high spectral resolution. The TGS has three gratings (G1-G3) of identical specification (58 mm×58 mm holographic gratings with 1800 Grooves/mm, blazed at 500 nm), four slits (S1-S4) and six lenses (L1-L6, achromatic lenses of focal length *f*=250 mm). Widths of four slits S1, S2, S3 and S4 were 15 μm, 25 μm, 10 μm and 15 μm, respectively. Three gratings were arranged to give additive dispersion at each stage. The overall inverse dispersion of the TGS was 0.57 nm/mm. In order to change the measurement wavelength, the two intermediate slits (S2 and S3) and the lens L6 were finely translated with a step of 1 μm by using stepping motors.

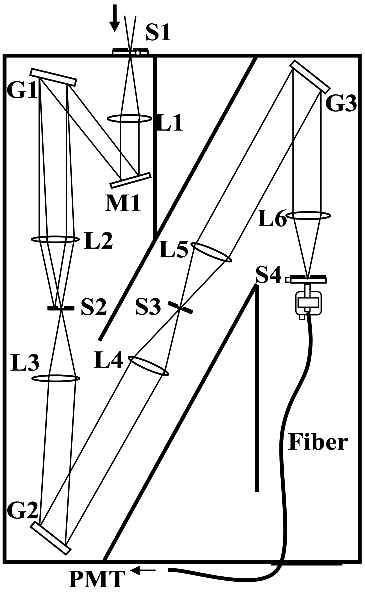

Fig.2 Schematic diagram of the triple grating

Figure 3 shows the instrumental function of the TGS. The spectral resolution of 16 pm (FWHM) was achieved. It can be seen from Fig. 3 that the stray light rejection at $\Delta\lambda$=40 pm was 10^{-5}. These performances of the TGS made us possible to measure the ion term spectra from EUV plasmas.

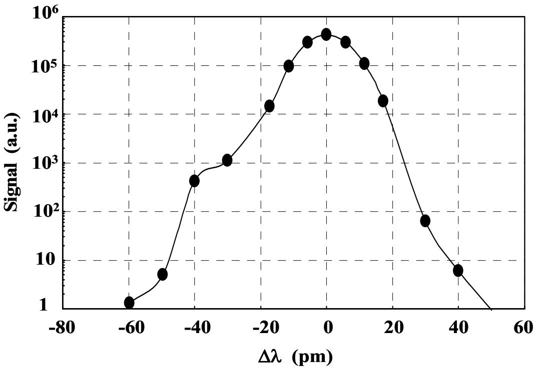

Fig.3 Instrumental function of the triple grating spectrometer.

3. Experimental results and discussions

We used the new LTS system to observe the ion term spectra from the Z-pinch plasmas. Normally, Xe gas is used for the EUV source as a working gas. Therefore, at first we tried to observe ion term spectra from Xe plasmas. The detected spectra had two peaks at both shorter and longer wavelength sides apart from the laser wavelength. However, the widths of those peaks were much broader than those predicted by the Thomson scattering theory. We thought that this was possibly caused by the steep radial distributions of n_e and T_e of the pinched Xe plasma. Because the spatial resolution of the present LTS system would not be enough, the observed spectrum should be composed of contributions from different fractional scattering volumes with different n_e and T_e values. In order to observe clear ion term spectra using the present system, we changed the working gas of the discharge from Xe to Ar. Since the mass of Ar is 3 times smaller than that of Xe, we expected that the radius of the pinched plasma would become larger and the distributions of n_e and T_e should be less steep. At the same time, the measurement of the ion term spectrum of the Ar plasma would be much easier than that of the Xe plasma, because the width of the ion term spectrum is inversely proportional to the root of the atomic mass number [7, 8]. For the production of the pinched Ar plasma, Ar was fed into the discharge tube at the flow rate of 300 cm^3/min. The discharges were generated at a frequency of 10 Hz.

Figure 4 shows an example of the LTS signal and the background radiation signal observed at Δλ=60 pm collected from the Ar gas discharge. It is clear that the LTS signal is almost one order of magnitude larger than the background radiation signal. Figure 5 shows the ion term spectrum collected from the Ar gas discharge at 10 ns after the pinch. In order to measure this spectrum, the signals were averaged over a number of 50 laser shots, and these averaged measurements were repeated for 10 times at each wavelength. The error ranges shown in Fig. 5 is the standard deviation of these data by 10 times measurements.

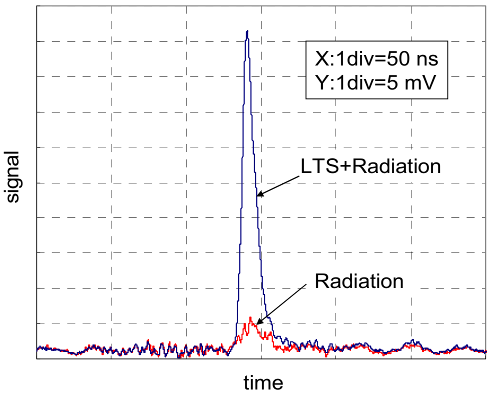

Fig.4 Examples of the LTS signal and the background radiation signal observed at Δλ=60 pm for an Ar plasma.

In this case, the plasma was flowing to the chamber side along the axis of the discharge (plus side of the z axis). Therefore, the ion term spectrum is Doppler shifted to the blue side by 20 pm. The measured position was z=500 μm. Here, we selected the origin of the Z axis (Z=0) to be the center of the pinched plasma. From the width of the spectral shift, the plasma velocity can be estimated, and the velocity was 1.2×10^4 m/s to the z direction. Because of the strong stray light signals, the ion term spectrum couldn't be measured at Δλ < 25 pm. However, it is easy to reconstruct the spectral shape of Δλ < 25 pm from the fittings of theoretical curves with the measured part of the ion term spectrum.

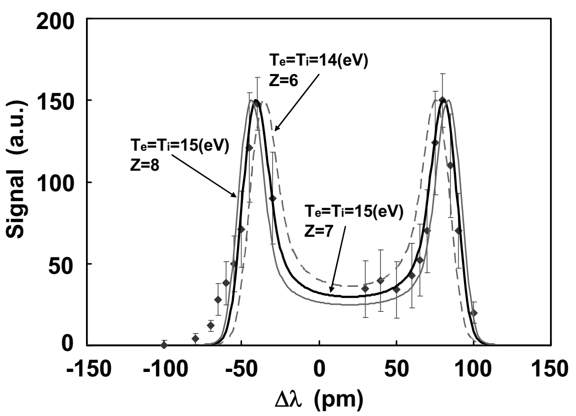

Fig.5 Observed ion term spectrum from an Ar gas discharge and fitted theoretical curves.

The absolute value of LTS signal is also needed to evaluate plasma parameters. The calibration of the LTS signal was done by using the Rayleigh scattering signals from a nitrogen gas at a pressure of 300 Torr. Since the shape, the spectral peak wavelength, and the absolute value of the ion term could be measured, n_e, T_e, and $\bar{Z}$ could be evaluated. It can be seen from Fig. 5 that the solid line is most close to the measured spectrum. So the plasma parameters deduced from the spectrum were n_e=1.5×10^{24} m^{-3}, $\bar{Z}$=7, T_e=T_i=15 eV. The error ranges for these values were less than ±10 %.

Temporal variations of n_e and T_e spatial profiles of the plasma were measured after the pinch time. Again, the argon gas was used as a working gas. Figure 6 shows spatial distributions of n_e along the z axis at different times after the pinch. T_e profiles are shown in Fig. 7 similarly. The pinched plasma was first formed in the extent of about 1 mm along the z axis at 80 ns from the start of the discharge current. Then, the plasma particles were pushed away from the center of the originally formed position (z=0) along the z axis. n_e peaks moved both sides of the z axis and extended to the positions z=±3 mm. As described before, the pinched plasma was formed in the ceramics tube of the diameter of 5 mm. The gas was introduced from left hand side (minus side of the z axis) of Fig. 1 into the tube. The other end of the tube was connected to the large chamber. As the n_e peak moved to the gas-upstream side (z<0), n_e increased and T_e decreased. This can be due to the occurrence of frequent ionization because of the high neutral gas density on the upstream side. On the other hand, as the n_e peak moved to the large chamber (z>0) where the neutral density was low, T_e kept high while n_e decreased. We contrasted these plasma evolutions with the EUV emission behavior. Then, we found that the EUV lights were radiated on the way that the high temperature plasma moved to the downstream side.

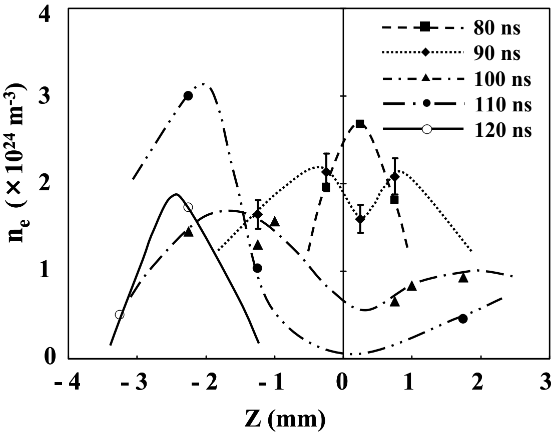

Fig.6 Temporal evolution of axial n_e profile of the pinched plasma.

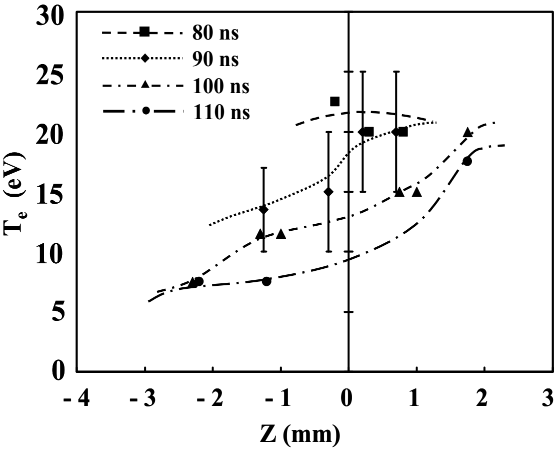

Fig.7 Temporal evolution of axial T_e profile of the pinched plasma.

4. Conclusion

We have developed a collective LTS system for measurements of n_e, T_e, and $\bar{Z}$ of Z pinch plasmas produced for EUV lithography. The system was successfully applied to the diagnostics of pinched plasmas produced in the argon gas. However, in order to apply the LTS system to the Xe plasmas, spatial and spectral resolutions of the system must be improved. Such improvements are now in progress.

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