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Counter-facing plasma guns for efficient extreme ultra-violet plasma light source

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Abstract. A plasma focus system composed of a pair of counter-facing coaxial guns was proposed as a long-pulse and/or repetitive high energy density plasma source. We applied Li as the source of plasma for improvement of the conversion efficiency, the spectral purity, and the repetition capability. For operation of the system with ideal counter-facing plasma focus mode, we changed the system from simple coaxial geometry to a multi-channel configuration. We applied a laser trigger to make synchronous multi-channel discharges with low jitter. The results indicated that the configuration is promising to make a high energy density plasma with high spectral efficiency.

1. INTRODUCTION

Recently radiation from high-energy-density plasma is attracting our attention as an Extreme Ultra-Violet (EUV) light source for the next generation semiconductor process. Schemes of the plasma light source are classified as Laser Produced Plasma (LPP) and Discharge Produced Plasma (DPP).

Both high average power and high conversion efficiency are needed for a practical EUV light source. However, the sources of light developed now have problems. That is, the average output power is extremely low compared with the requirement. When we increase the input power, life time of the device and the optical system are degraded by the huge quantity of thermal load. We should improve energy conversion efficiency; that is the ratio of output EUV energy to input electric energy. To improve the energy conversion efficiency, we would like to extend the radiative time of source plasma. Then we intend to prolong the life time of plasma.

In this study, we applied a counter-facing plasma focus system as the plasma generation device [1]. The plasma focus system has a possibility to prolong the life time of EUV plasma more than μ second. In addition, we adopted lithium as the plasma source which has a narrow and strong spectrum at 13.5 nm wavelength [2]. By using the counter-facing plasma focus system and lithium source, we aim to improve the energy conversion efficiency, spectral efficiency and repetition capability [3, 4].

2. OPERATIONAL PRINCIPLE OF COUNTER-FACING PLASMA GUNS

Figure 1 shows the operating principle of the counter-facing plasma guns. A pair of plasma focus electrodes are facing each other, and center electrodes are charged so as to have a reverse-polarity [5].

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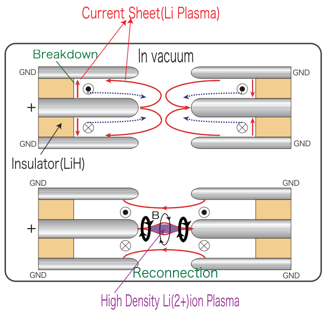

Figure 1. Schematic diagram of counter-facing coaxial plasma focus system.

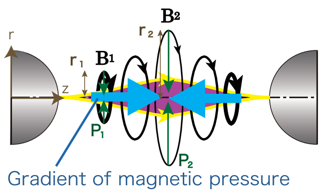

Figure 2. Image of magnetically confined plasma between the electrodes.

When electrode gaps are energized by a pulsed high voltage, breakdown occurs along the insulator surface between the coaxial electrodes and current sheets are driven [6]. In this experiment, LiH is used as the insulator and the plasma source. The radial current carried by the plasma sheet produces magnetic field inside the coaxial electrodes. The magnetic pressure (J $\times$ B) accelerates the plasma to the top of center electrodes. The plasma collides and is heated up in the center of electrode gaps. Figure 2 is an image of the plasma confinement. The magnetic pressures P near the electrode (subscript 1) and at the center (subscript 2) are shown as follows,

$$P_1 = \frac{{B_1}^2}{2\mu_0} = \frac{\mu_0 I^2}{8\pi^2 r_1^2} \tag{1}$$

$$P_2 = \frac{{B_2}^2}{2\mu_0} = \frac{\mu_0 I^2}{8\pi^2 r_2^2} \tag{2}$$

$$P_1 > P_2, (\because r_2 > r_1) \tag{3}$$

where μ_0 is permeability in vacuum, I is the plasma current, r is the radius of plasma, and B is the magnetic field. The geometry of plasma is expected to be ellipsoidal. Then, the plasma can be confined stably, if symmetry is maintained. When the current sheets can reconnect smoothly, the self magnetic field confines the plasma radially and the gradient of magnetic pressure suppresses the plasma escaping in the axial direction [7]. The stably confined, high temperature plasma is expected to be able to make bright EUV radiation for more than μ second [8, 9].

3. LASER-ASSISTED FLASHOVER FOR CURRENT SHEET FORMATION

In the plasma-focus system, smooth current reconnection is important. Smooth current reconnection needs uniform plasma formation at the insulator surface. We changed the electrode from coaxial to multi-channel configuration [10]. In the case of coaxial electrode, the discharge produced a few streamer-like plasma at random. On the other hand, the multi-channel structure is expected to trigger the discharge in place and that should produce uniform plasma sheet.

The old-configuration made the flashover plasma by self breakdown. For synchronization of the plasma-focus, we applied laser trigger to make the multi-channel discharge, in which laser assists the flashover formation at the insulator surface [11].

Figure 3 shows an image of laser-assisted flashover process. In the operation, the outer electrodes are charged and the laser ablation plasma induces successive breakdown along the insulator surface,

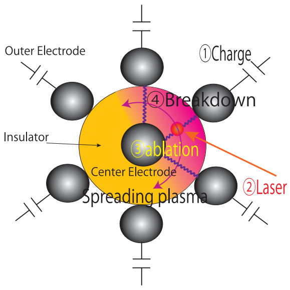

Figure 3. Schematic of 6-channel electrode and laser-assisted flashover.

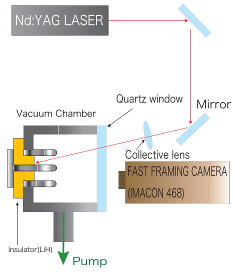

Figure 4. Optical set up for laser trigger.

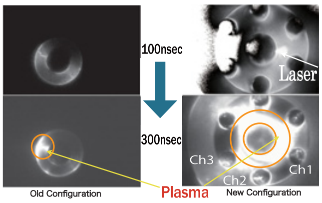

Figure 5. Fast frame pictures of flashover plasma for conventional (left) and multi-channel (right) configuration.

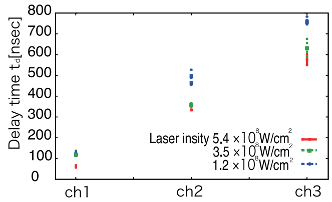

Figure 6. Trigger delay time versus channel number.

which makes uniform plasma. We investigated the dynamics of laser assisted flashover plasma using a fast framing camera (IMACON 468 DRS HADLAND).

4. EXPERIMENTAL SET UP

Figure 4 shows the optical system for laser triggered surface discharge. The outer electrode diameter is 2 mm. The center electrode diameter is 5 mm. Distance between the outer electrode and the center electrode is 2 mm. Chamber was evacuated to less than 10^{-5} Torr with turbo-molecular pump. A Nd:YAG laser was focused on the LiH surface in the electrode-gap to make the ablation using a convex lens. We observed time development of the plasma image by the high speed framing camera.

5. EXPERIMENTAL RESULT

Figure 5 shows pictures taken by the high speed framing camera for comparison of the behaviors with coaxial electrode (left column) and multi-electrodes (right column). Upper (lower) pictures are taken at 100nsec (300nsec) after the laser irradiation. As shown by the lower pictures taken at 300 nsec, although conventional flashover produced a few streamer-like plasma, laser assisted multi-electrode flashover produced uniform plasma. So, we confirmed that laser-assisted flashover can make the plasma sheet more uniform than that by coaxial electrode flashover.

Figure 6 shows delay time of the discharge channels. The horizontal axis shows the channel number of laser-assisted flashover shown in Fig. 5. Here the delay time is defined as a time duration between the laser irradiation and the start of breakdown. Figure 6 shows that the delay time is almost proportional to the distance from laser spot.

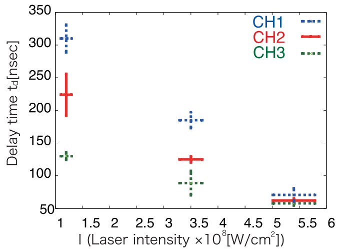

Figure 7. Delay time versus laser intensity.

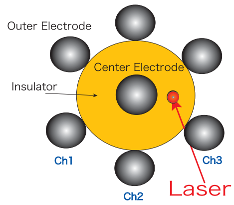

Figure 8. Laser trigger point for the delay time measurements (Fig. 7).

The results shown in Fig. 5 and Fig. 6 make us to expect that the plasma, triggered by the laser irradiation, evolves along the surface without large delay time. For uniform and synchronized formation of the focus plasma, the start delay of 6-channel discharge should be less than a criterion.

6. CRITERION FOR SYNCHRONOUS OPERATION OF COUNTER-FACING PLASMA GUNS

For applying multi-channel flashover to the counter-facing plasma focus system, delay time of the discharge is an important factor. That is to say, the jitter of delay time affects the plasma positioning at the center of electrodes and the delay time jitter should affect the structure of plasma sheet. As is known, EUV plasma size should be less than 1mm and typical current sheet velocity is about $2cm/\mu sec$. Then the acceptable jitter and delaytime difference are tens of nsec for the synchronization and current sheet reconnection.

Figure 7 shows relation between laser intensity and the delay time at $V_c = 5kV$. As shown in Fig. 7, the delay time was inversely proportional to the laser intensity. Also, the delay times among the channels were almost proportional to the distance from laser spot. As shown with these results, when laser intensity is over $5 \times 10^8\ W/cm^2$ and $V_c = 5kV$, the delay time and the jitter are acceptable. We can conclude that in this experimental condition, the laser-assisted flashover satisfies the criteria of jitter and delay time difference for 3 channel discharge. In other word, the flashover plasma driven by 2-point laser irradiation is expected to satisfy the criteria. That should be also the criteria for reproducible and efficient EUV-source.

7. CONCLUSION

We applied laser-assisted flashover to the counter-facing plasma focus system and evaluated the criterion for successful operation. We concluded that the laser-assisted multi-channel flashover is effective for making uniform plasma sheet. Results showed that 2-points laser irradiation with $5 \times 10^8 W/cm^2$ and $V_c = 5\,kV$, satisfies the criterion for 6-channel flashover. Results also indicated that the counter-facing plasma focus system based on the laser-assisted multi-channel flashover can produce long-life and high energy density plasma, namely efficient EUV light source.

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