Development of Counter-facing Discharge Device for Extreme Ultraviolet Source

～Control of Current Waveform and Its Effects on the Plasma Dynamics～

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ABSTRACT

We studied the effect of rise time of discharge current on the EUV output from the Li plasma in counter-facing discharge device and investigated the plasma dynamics in the device. Results indicated the waveform can control the plasma dynamics and improve the conversion efficiency. The EUV output depended on the shot number in a successive operation mode. The results indicated that changes of Li surface condition during the successive operation affect the plasma dynamics.

Keywords

Key Words : EUV light source, Plasma focus, High energy density plasma, Pulsed current waveform

1. Introduction

The miniaturization of integrated circuits (ICs) has contributed to the technological progress of modern societies because the smaller the IC is, the more efficient electronic devices become. Photolithography in the microfabrication processes uses a light source to transfer a circuit pattern from a mask to a light-sensitive chemical photoresist on a semiconductor wafer [1]. Therefore, it is important to develop a shorter wavelength light source for the miniaturization of ICs.

Recently, plasma-based extreme ultraviolet (EUV) light sources have been developed for the next generation lithography. EUV is a wavelength region corresponding to a range of 0.2 – 100 nm [2] in which the photons are easily absorbed by various substances. A multilayer mirror using Mo/Si, which has reflectivity of about 70% at the wavelength of 13.5 nm [3,4], was developed to accommodate the optical system of lithography.

The EUV light is contained in a radiation from a high energy density plasma (T_e=10~30eV, n_e=10^{18}~10^{19} cm^{-3}) [5]. There are mainly three ways to produce the EUV photons at the wavelength of 13.5 nm. They are a synchrotron radiation, radiation from a Laser Produced Plasma (LPP), and a Discharge Produced Plasma (DPP). As the synchrotron radiation source is extremely expensive, it is not appropriate for the industrial use. The plasma-based radiation sources are more practical compared to the synchrotron radiation. In the case of LPP, the EUV plasma is produced by focusing a pulsed laser on a target, while DPP utilizes a hot and dense plasma produced by a pulsed discharge [6,7]. Although LPP is a simple scheme to produce the EUV emission, the laser efficiency is a bottleneck of the application because it extremely degrades the plug-in efficiency and increases the operating costs. In contrast to the LPP sources, DPP is much more practical scheme because the electrical energy is directly converted to EUV plasma [7].

In order to realize an efficient EUV light source, we have developed a counter-facing plasma focus system [7]. From the proof-of-principle study so far, we assured that the pulse output of EUV light was typically 100mJ per shot. The next step is to demonstrate an average power exceeding 200W or more at 13.5nm (2% bandwidth) [8]. Therefore, the final goal of our research is to operate the device continuously with repetition of 1kHz – 10kHz.

However, there are some problems. One is electrodes damage when the device operates repetitively. One of the causes of the damage is considered to be joule heating by the pulsed current. Although the problem may be solved by reducing the drive current, the output of EUV tends to decrease. We need to optimize the waveform of pulsed current in order to prevent the decline of output of EUV. In addition, the optimization can lead to the improvement of the plug-in efficiency.

It is expected that it takes time until the discharge plasma starts to move by the Lorentz force because the rising time of the pulsed current is limited by the circuit parameter. The Li vapor proceeds to evaporate and expand while the current is still low level. If the rising rate of current is low at the initial phase of operation, the quantity of plasma which moves to the place of EUV radiation may be too much and the acceleration of plasma is not enough to come up to a hot-dense plasma which emits the EUV light.

In this paper, we discuss the effect of current rise rate on the plasma dynamics, in which we tried to increase the output of EUV with a fast rising current made by additional capacitors.

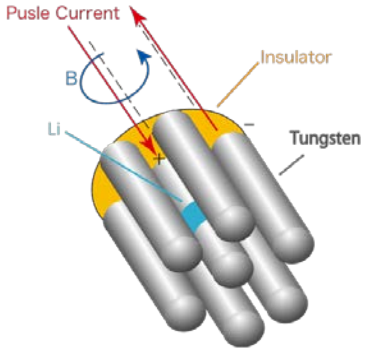


Fig.1. Electrode geometry of counter-facing plasma focus device.

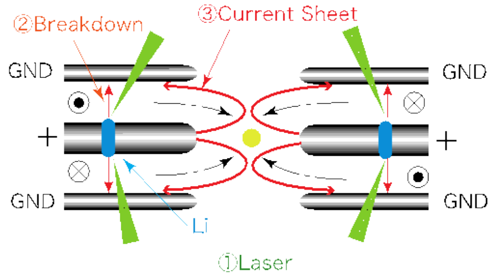


Fig.2.Schematic illustration of counter-facing plasma focus device.

2. Experimental Setup

2.1 Counter-facing Plasma Guns for EUV Light Sourse

Figure 1 shows a component of the plasma focus devices which consists of seven electrodes; a center electrode with a positive voltage and six outer ones with ground potential. For the plasma source, a target (Li) is set up in the middle of the center electrode.

A couple of the focus electrodes are facing each other and the operation procedure is shown schematically in Fig. 2. At first, capacitors connected between the center electrode and the outer electrodes are charged to ~ 7 kV and a Laser (Nd : YAG – 2 ω) irradiates the Li sources at the middle of two center electrodes. Then, the pulsed currents are induced through the plasma by the laser ablation. The plasma is accelerated to the center of the counter-facing electrodes by the Lorentz force. The plasmas which move from the counter-facing electrodes collide and thermalize at the center of electrodes. Then a high energy density plasma is generated through the thermalization of the plasma. We designed the time-constant of discharge current to be more than µsec. Therefore, we can expect that the plasma is confined at the place and emits an EUV light during an order of µsec.

2.2 Relation between rising time of the pulsed current and the EUV output

The plasma is accelerated by the Lorentz force as schematically shown in Fig. 2. However, the pulsed currents hardly flow through the plasma right after the laser ablation because the breakdown process depends on the particle distribution between the electrodes. The evaporation and the expansion of Li last during the operation time. Then, the mass of plasma is expected to depend on the breakdown time from the laser irradiation. As has been discussed in the introduction, if the mass is too much compared with an appropriate quantity, the output of EUV decreases because the energy to be distributed to the electrons decrease. That is, the electron temperature does not rise sufficiently when they collide and thermalize at the center of electrodes.

In this experiment, we added a peaking capacitor to drive an additional current in the conventional RC circuit and modified the current waveform as shown in Fig. 3. Then, we compared the output of EUV light with and without the additional current.

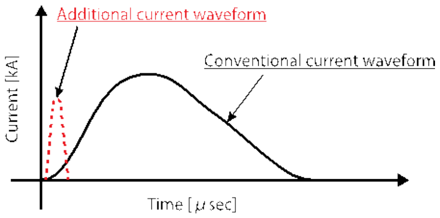


Fig. 3. Modification of current waveform.

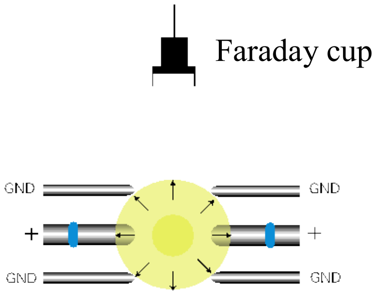


Fig. 4. Schematic of the ion flux measurements.

2.3 Observation of the ion flux after the formation of high energy density plasma

We set up a Faraday-cup 34cm above the center of counter-facing electrodes to investigate the plasma dynamics in the device. A schematic of the configuration is shown in Fig. 4. We can expect to observe the ion flux after time-of-flight of the EUV plasma, namely several µsec from the laser ablation, if the plasma is accelerated, thermalized, and confined in the place during the order of ~µsec.

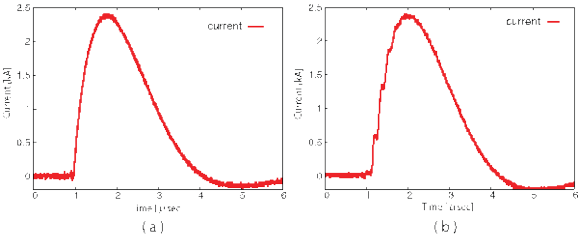
3. Results and Discussion

3.1 Evaluation of the effect of additional circuits

Figure 5 shows a comparison of current waveforms driven by (a) the conventional circuit and (b) the modified one. As shown in the figure, the first peak made by the additional circuit corresponded to roughly 30% of the maximum peak. The rise time to reach 30% of the maximum peak from the laser breakdown was 70 nsec in the case of (a), while it reduced to 60 nsec in the case of (b). Therefore, we know that the additional circuit slightly increased the rising rate of the current.

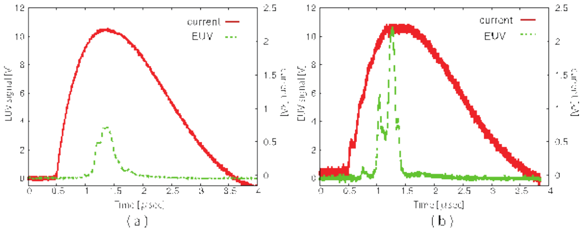
3.2 The output of EUV light

Figure 6 compares typical EUV signals obtained from the plasma driven by the currents (a) without and (b) with additional circuit. Although similar waveforms of EUV shown in (b) was observed in the case of the conventional current waveform too, the higher peak signal (≧ 6 V) tended to appear in the case of (b). We observed that the peak of the EUV output tended to increase by the waveform modification.



(a) (b)

Fig. 5. Comparision of current waveforms driven by (a) conventional circuit and (b) modified one.



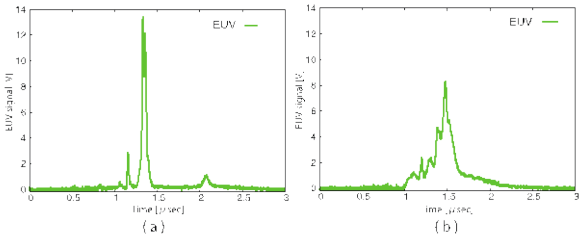
(a) (b)

Fig. 6. EUV waveforms (a) without and (b) with additional capacitors.

3.3 Two characteristic EUV waveforms in the case of the modified current waveform

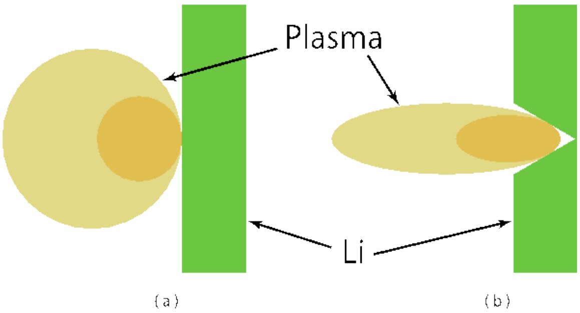
We observed that the EUV waveforms have two modes in the case of the modified current waveform. The EUV waveform shown in Fig. 7 (a) was observed frequently right after starting the experiment, while the one shown in Fig. 7 (b) was observed after successive operation of about 20 times. We think two modes of EUV waveforms are caused by the imprint of Li surface due to the laser ablation. A schematic of the ablation from smooth (a) and the imprinted surface (b) is shown in Fig. 8.

It is expected that the plasma made by the laser ablation expands spherically as shown in Fig.8 (a) if the Li surface is smooth, while it should expand with oval shape if the surface is imprinted by the successive laser irradiations as shown in Fig. 8 (b). The results indicate that the plasma formation process depends on the condition of Li surface. In other words, the value of the plasma quantity moving to the center depends on the Li surface condition in the case of solid plasma source.



(a) (b)

Fig. 7. Typical EUV waveforms;
(a) with narrow peak and (b) broad peak.



(a) (b)

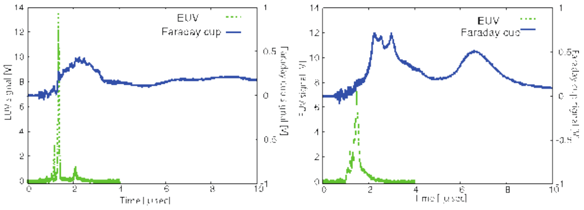
Fig. 8. Ablation of the plasma from (a) smooth and (b) imprinted surfaces.

3.4 Plasma dynamics after plasma thermalization

After the thermalization, the plasma is expected to be confined during the current pulse. After that, the plasma should expand isotropically when the EUV plasma is confined properly. To confirm the behavior, we placed a Faraday-cup 34 cm above the plasma. We can expect an ion flux waveform which has a peak after several μsec from the laser ablation if the plasma is properly confined during several μsec.

Figure 9 shows typical ion flux waveforms. There were two kinds of EUV waveforms as shown in the figure. The first peaks of about 2 μsec duration shown in both figures are considered to be the signal by a photoelectric effect. The peak at 6 ~ 8 μsec did not appeared in the case of (a), while the one appeared in the case of (b). This peak was expected to be the signal of the ion flux originated from the confined plasma.

Therefore, we know that the cause of the narrow EUV waveform in the case of (a). That is, in the case (a), the plasma temperature reaches the appropriate value for irradiating EUV light in a moment, it can not keep the state for several μsec, probably due to the non-uniformity of current sheet. Then, the current sheet can not keep the EUV plasma for the time duration. The arrival times of the current sheets seem to be different due to jitters of the discharge channels. Consequently, the plasma cannot keep a quasi-stable state in the case shown in Fig. 9 (a).



(a) (b)

Fig. 9. Correlation of ion flux and EUV waveforms (a) with narrow peaks and (b) broad peaks.

4. Conclusions

We investigated the effect of current waveform on EUV-signals by placing additional capacitors in the discharge circuit. A highly peaked signal (≧ 6 V) appeared in the operation driven by the modified circuit. In addition, there were two modes in the EUV waveforms with the additional circuit; the narrow peaked and the broad ones.

We set up a Faraday-cup (to observe the ion flux) above the center of the counter-facing electrodes to examine whether the plasma is confined in the right place for several μsec. The EUV waveform had a broad peak width when the plasma was observed after 6 ~ 8 μsec from the laser ablation. Therefore, we could interpret that the plasma was confined as expected, if the EUV waveform had the broad peak.

Results also showed that waveform can control the plasma dynamics. Decreasing the rising time of pulsed current is likely to lead the output increase of EUV light. That is, the waveform control has a possibility not only to prevent the electrode damage but improve the plug-in efficiently also.

References

[1] W. Christian and et al., "EUV LITHOGRAPHY Lithography gets extreme", *NATURE PHOTONICS*, **4**, 1, pp.24-26 (2010).

[2] D.Attwood, "SOFT X-RAYS AND EXTREME ULTRAVIOLET RADIATION : Principles and Applications", Cambridge University Press, pp.1-2(1999).

[3] N. Benoit et al., "Radiation stability of EUV Mo/Si multilayer mirrors", *PHYSICA B-CONDENSED MATTER*, **357**, 1-2, pp.222–226 (2005).

[4] S. Yulin et al., "EUV/soft x-ray multilayer optics", *SPIE*, **5645**, pp.289–298 (2005).

[5] Majid Masnavi et al., "Estimation of optimum density and temperature for maximum efficiency of tin ions in Z discharge extreme ultraviolet sources", *Journal of Applied Physics,* Vol.101, No.3, pp. 033 306 1-9 (2007).

[6] V. Banine et al., "Plasma sources for EUV lithography exposure tools", *JOURNAL OF PHYSICS D-APPLIED PHYSICS,* **37**, 23, pp.3207-3212 (2004).

[7] T. Sodekoda, et al., "Repetitive operation of counter-facing plasma focus device : toward a practical light source for EUV lithography", *Proc. SPIE*, **9048**, Extreme Ultraviolet Lithography Ⅴ, 904824 (2014).

[8] A. Hassanein et al., "Multidimensional simulation and optimization of hybrid laser and discharge plasma devices for EUV lithography - art. no. 692113", *SPIE*, **6921**, 1-2, 92113 (2008).