Power Flow in Counter-facing Plasma Guns for Extreme Ultra-Violet Plasma Light Source

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ABSTRACT

The total energy consumed in the load of a laser-triggered discharge produced plasma light source was measured as functions of the applied voltage, the electrode polarity and the laser energy. When the device operated with negative polarity, the energy consumed in the load was low in comparison with positive mode. In addition, when the laser energy increased, the consumption energy decreased a little.

Keywords

Keywords : EUV light source, Plasma focus, High energy density plasma, Electrode erosion

1. Introduction

Extreme Ultra-Violet (EUV) light sources are attracting our attention as the next generation photolithography. We have developed a counter-facing plasma focus system for the EUV light source, and have been challenging for the practical use of the device. Highly repetitive and long-life operation are required for the practical use. Hence efficiency improvement with the reduction of the electrode heat load is necessary. Therefore the final goal of this research is to develop a high efficiency EUV plasma source with decreasing the electrode erosion.

Although it is said that the degree of integration of an integrated circuit increases 4 times every three years [1], this has been supported with the lithography technology especially the development of a practical light source. The minimum processing size of a photolithography depends on the wavelength of the light source, and Extreme Ultra-Violet (EUV) plasma light sources are attracting our attention as a short wavelength light source for the next generation micro fabrication.

The EUV light is contained in a radiation from a high energy density plasma (T_e=10~30 eV, n_e=10^{18}~10^{19} cm^{-3}) [2]. Practical schemes of the light source are classified as Laser Produced Plasma (LPP) [3] and Discharge Produced Plasma (DPP) [4]. In order to realize a practical EUV light source, high average power is of crucial importance. However, when the input power is increased simply for higher output power, life time of the device, such as electrodes and the optical component, are degraded by the huge thermal load accompanied by the electrode erosion and undesirable byproducts; debris. Therefore, coexistence of high average power and reduction of the heat load to the device component becomes indispensable for practical light source.

We have developed a counter-facing plasma focus system for the EUV light source [5], which may be classified into Laser triggered DPP. The pulse output of EUV light was typically 100mJ per shot [6]. The final goal of this research is to develop a practical EUV plasma source using the counter-facing configuration. Thus, as the following step towards the practical use, we are aiming at repetitive operations with 1 kHz - 10 kHz. However, because the conversion efficiency from the plasma to the output EUV energy is a few percent at most, increase of the heat load to electrode is expected in performing the highly repetitive operation.

At first, the consumption energy of the whole load per one shot was measured, and it is investigated how much energy was consumed in the plasma, at the electrodes, and transformed to the device components. If it is possible to evaluate the details of power flow in the EUV device, we can optimize the discharge condition, in which the heat load is smaller and the conversion efficiency is larger.

In this paper, the energy consumed in the whole load per one shot is measured as a function of the electrode polarity, applied voltages and the laser energy. The influence of those factors is discussed based on the results.

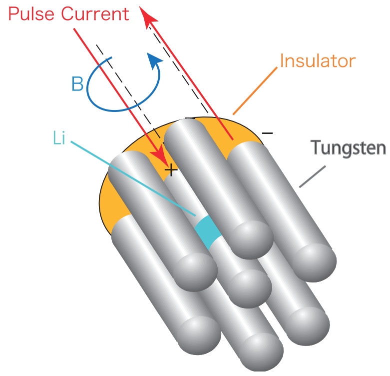


Fig.1 Electrode geometry of counter-facing plasma focus system.

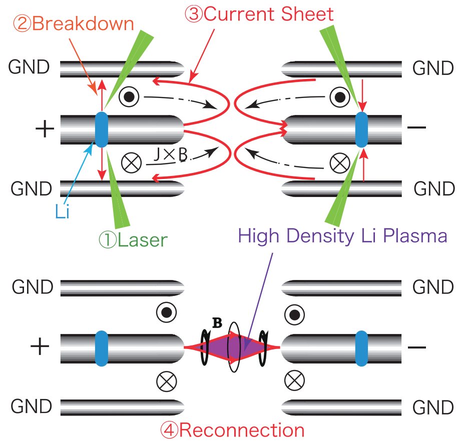


Fig. 2 Operation of counter-facing plasma focus system.

2. Experimental Setup and Method

2.1 Couter-facing Plasma Guns for EUV light source [5]

Figure 1 shows a schematic of the electrodes which has a plasma focus configuration. The operation procedure is shown in Fig. 2.

At first, voltages are applied between six independent outer electrodes and one center electrode. A pulse discharge is induced between the electrodes by irradiating a YAG laser on a Li source attached to the center electrode. Then, the plasma is accelerated to the top of center electrodes by the Lorentz force, which is generated by interaction of the current flowing in the plasma sheet and the self-magnetic field. The counter moving plasmas collide and thermalize in the center of electrode gap. As shown in Fig.2, the current sheets can reconnect when the electrodes are charged with reverse-polarity mutually. Then a high energy density plasma can be confined and make a bright EUV radiation for a long time.

2.2 Measurement of Consumption Energy in the Whole Load

Figure 3 shows a circuit diagram of the experiment that corresponds to one of the six channels. As shown, the current and the potential difference between the electrodes are measured by a Rogowski coil and a high-voltage differential probe respectively. The energy was calculated by time-integration of the current and the potential difference product.

Figure 4 shows an illustration of the potential distribution between electrodes. As shown, we measured the potential differences of not only the plasma but also sheaths and obtained consumption energy in the whole load.

In this experiment, we operated the plasma focus device with single-side mode. The current waveform

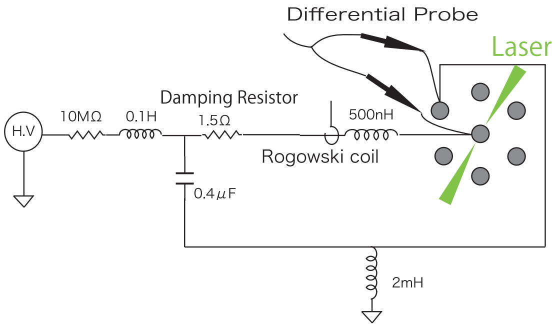


Fig. 3 Circuit diagram of the experiment.

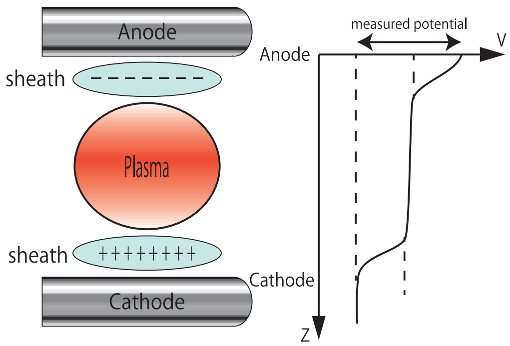
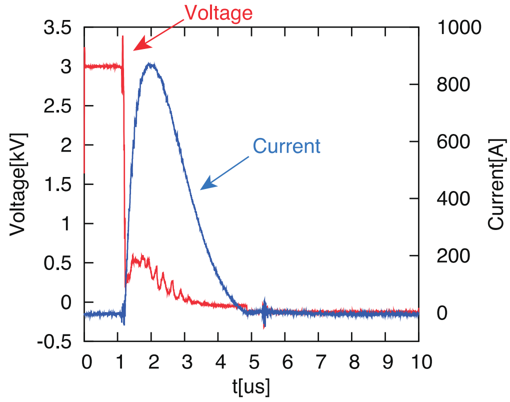
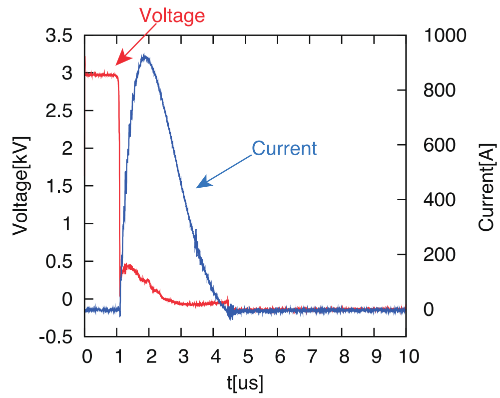


Fig. 4 Potential distribution between electrodes.

was regulated by putting a damping resistor to secure the stable EUV output. When we perform highly repetitive operation, we will use a power supply with an energy recover unit, which applies first half period of current to the load and the remainder is recovered for the next operation. We used a Nd:YAG laser for the formation of initial plasma with 2ω (532 nm) mode and 15 ns pulse width. In this experiment, we measured power input as a function of the applied voltages, the polarity, and the laser energy.



(a) Center electrode : positive



(b) Center electrode : negative

Fig. 5 Discharge voltage and current waveforms for operations with positive(a) and negative(b) polarities.

3. Results and Discussions

3.1 Discharge Voltage and Current Waveforms

Figure 5 shows typical waveforms of the discharge voltage and the current. When we compare the polarity effect on the waveforms, it is obvious that the spike of the discharge voltage waveform of negative is fewer than positive polarity. The results show that the current is slightly larger and the voltage during discharge is a little lower in case of negative polarity operation. That means, the plasma impedance is smaller when the device was operated with negative polarity.

3.2 Consumption Energy in the Whole Load

Figure 6 shows the dependence of consumed energy (i.e. the energy consumed in the electrode region) on the applied voltage. The vertical axis is the consumed energy in the load for one channel of the six channels and the horizontal axis is the charged voltage of the capacitor.

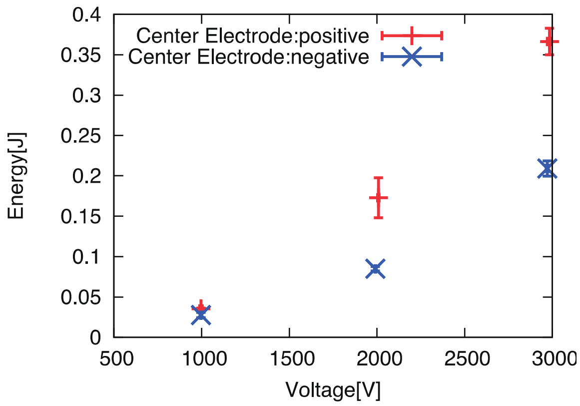
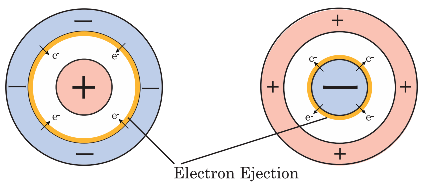


Fig. 6 Polarity dependence of consumption energy.



$$E \propto \frac{1}{r}$$

Fig. 7 Difference of initial plasma behavior between positive and negative polarity operations.

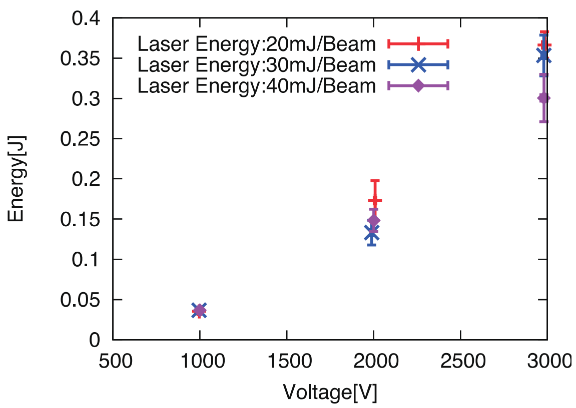


Fig. 8 Laser energy dependence of consumption energy.

According to Fig. 6, we know that the consumed energy in the discharge region is less than 10% of stored energy in the capacitor, and when the device is operated with negative polarity, the consumed energy is low in comparison with that of positive operation. The cause of this result is attributed to the voltage shown in Fig. 5, in which voltage during discharge is a little smaller in case of negative operation.

Figure 7 shows the difference in the strength of the electric field from which an electron receives energy for the discharge plasma. As illustrated in Fig. 7, in the coaxial geometry, electric field around the cathode is stronger and electrons are easily supplied when the center electrode is negative. As a result, the potential of the ion sheath is considered to become small and the load impedance decreases; i.e. the voltage during discharge decreases.

Figure 8 shows the laser energy dependence. In Fig. 8, although the difference is small, the consumption energy in the load tends to be small when the laser energy increased. As the amount of initial plasma increases by raising the laser energy, the number of careers increases. Consequently, the impedance of breakdown plasma is considered to decrease, and thereby energy consumption decreases.

4. Conclusions

In a counter-facing plasma focus device for EUV light source, the consumption energy of the whole load per one shot is measured as functions of the applied voltages, polarity and laser energy.

Results showed that, when the device was operated with negative polarity, the whole consumption energy was low in comparison with positive mode. This is likely to be attributed to the difference of the electric field strength from which electrons receive energy during the breakdown process. Moreover, the consumption energy tends to be a little smaller as the laser energy becomes large. This is likely to be due to enhancement of the number of careers by raising the laser energy.

The results discussed in this report was just only the whole consumption energy in the discharge region. In order to optimize the operation and the electrode geometry, we have to evaluate hereafter where the energy is consumed and how the amount of energy depends on the operating parameter.

References

[1] G.E. Moore, Tech. Digest of IDEM 1975, pp.11-13 (1975).

[2] 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).

[3] BRANDT David C. et al., “LPP Source System Development for HVM”, *Proc. Of SPIE,* **Vol.7**, 636, pp. 76 361 1-6 (2010).

[4] Y. Teramoto et al., “Dependence of Laser Parameter on Conversion Efficiency in High-Repetition Laser-Ablation-Discharge EUV Source”, *Proc. Of SPIE,* **Vol.7**, 271, pp. 727 139 1-8 (2009).

[5] Yusuke Kuroda et al., “Counter-facing Plasma Guns for Efficient Extreme Ultra-Violet Plasma Light Source”, *Seventh International Conference on Inertial Fusion Sciences and Applications **(IFSA2011)**,* p. 5 (2013).

[6] Tatsuya Sodekoda et al., “Repetitive operation of counter-facing plasma focus device: toward a practical light source for EUV lithography”, *Proc. of SPIE,* **Vol. 9048**, pp. 904824 1-8 (2014).