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Quasi-steady Operation of Counter-facing Plasma-Focus Device for High-Average-Power Radiation Source in Extreme Ultraviolet Region
対向プラズマフォーカス型EUV光源装置の準定常動作

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In order to develop a practical extreme-ultraviolet (EUV) light source, the plasma dynamics in a counter-facing plasma-focus device was studied for power-flow analysis and/or steady operation. Visible light emissions from the triggered plasma, EUV emissions, and the ion flux from the EUV plasma were measured to diagnose the plasma dynamics. The emission from neutral particles indicated the time of discharge trigger. The EUV emission and ion-flux signals reflected the collision, thermalization, and confinement of the electro-magnetically accelerated plasma. The kinetic energy of ions, the thermalization process and the confinement of EUV plasma were discussed based on these measurements.

1. Introduction

Plasma-based EUV light sources are attracting our attention as the next generation semiconductor process. Available (in-band) 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}) [1]. Possible schemes of the light source are classified as Laser Produced Plasma (LPP) [2] and Discharge Produced Plasma (DPP) [3]. As the conversion efficiency from input energy to the in-band EUV energy is a few percent at most, mitigation of the heat load is of critical importance in performing a highly repetitive operation.

We have proposed a counter-facing plasma focus device for the EUV light source [4]. The output of EUV light was estimated to be around 100mJ per shot and the recovery time of the electric insulation was less than 100 μ sec, with single-shot operation [5]. Then the following step towards a practical device is a demonstration of quasi-steady operation with repetition of 1 kHz - 10 kHz, in which we are planning to increase the average power to a kW level. Also we have to reduce the heat load to the device component to a manageable level. Therefore, we need to clarify the power flow in the device and improve the conversion efficiency.

1.1 *Counter-facing plasma-focus device for EUV light source* [4,5]

Figure 1 shows a schematic of the plasma focus electrodes and the operational procedure. As shown, a pair of plasma focus electrodes are faced each other and a high voltage is applied to the center electrodes. A pulsed laser irradiates the plasma sources (Li) on the center electrodes, then multiple breakdowns between the electrodes are triggered by the ablation plasma. The discharge plasma is accelerated to the top of center electrode by the Lorentz force. The plasmas collide and thermalize to make EUV plasma at the center of counter-facing electrodes. As the plasma source and the high-temperature plasma are separated, this device has an advantage for mitigating the heat load.

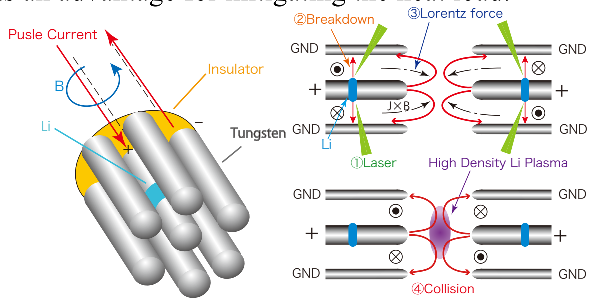

Fig. 1 Counter-facing plasma-focus device for EUV

1.2 *Power-flow in our EUV device*

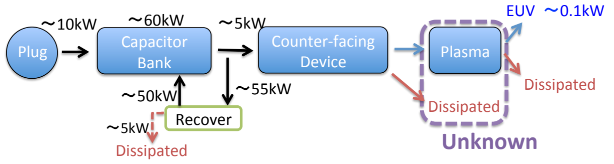

Fig. 2 Power-flow in our device under 1kHz operation

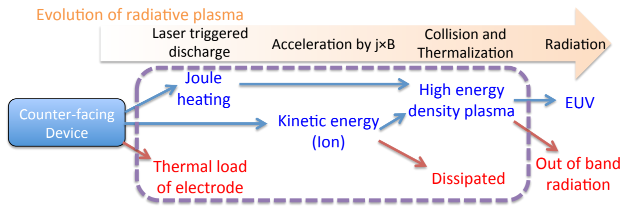

Fig. 3 Energy conversion process and plasma evolution in the counter-facing device

Figure 2 shows an approximate estimation of power-flow in the device under 1kHz operation. As indicated in the figure, the most indefinite part of the power flow is that in the counter-facing electrodes. The energy conversion process induced by the plasma dynamics and the evolution of EUV plasma in the counter-facing electrode region are shown in Fig. 3. The plasma dynamics in the electrode region is critically important not only for optimization of the EUV plasma formation but also understanding the power-flow; i.e., the mitigation of heat-load on the critical component.

The purpose of this research is to clarify the power-flow from electro-magnetic energy to the EUV plasma in the counter-facing device and improve the conversion efficiency.

2. Experimental method and Results

A spectrometer, a filtered EUV photodiode, and a Faraday cup were adopted as the diagnostics for study on the plasma dynamics. Signals from these diagnostics reflect the evolution of EUV plasma and the power flow in the region of counter-facing electrodes which is shown in Fig. 3. The light emission from laser ablated particles was measured by the spectrometer which showed the time of laser ablation and also the discharge trigger. Signals from the EUV photodiode reflected the status of EUV plasma. The signals of ion flux are expected to have the information of plasma collision and thermalization process of EUV plasma.

Figure 4 shows typical waveforms of the visible light emission, the EUV output and the ion flux. The first peak of the signal shows the laser ablation and the second peak corresponds to the discharge trigger. The plasma collided at the top of center electrode and thermalized at the time corresponding to the peak of the EUV waveform.

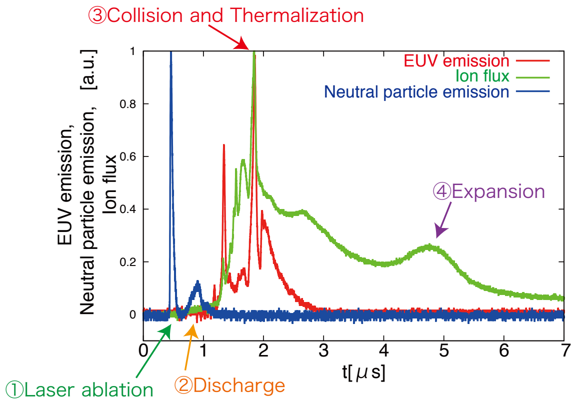

Fig. 4 Waveforms of spectrometer, EUV diode, and Faraday cup

After the collision and the EUV emission, the plasma expands radially.

We could estimate the plasma-run-time by the time difference between the discharge trigger and the EUV emission peak. The ion temperature at the stagnation can be estimated roughly from the plasma-run-time. The Faraday cup signal is expected to have important information of EUV plasma. That is, when the ion-flux signal has a drifted Maxwellian waveform, that means, the plasma was confined well at the electrode center.

3. Summary

The plasma dynamics in a counter-facing focus device was studied for the power-flow analysis. The kinetic energy of ions and the total energy of plasma were estimated. We are planning to optimize the electrode geometry and increase the energy conversion efficiency in the region based on these measurements.

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