Fundamental Properties of the Counter-facing Plasma Focus Device for Extreme Ultra-Violet Light Source

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ABSTRACT

Fundamental properties of a counter-facing plasma focus device were characterized. The plasma dynamics in the device, the out-put energy, the spectra from plasma, images of the plasma radiation, and the recovery rate of electrical insulation, were investigated using a proof-of-principle experimental device. All of the results indicated that the device has potentiality as a high average power extreme ultraviolet light source for the next generation lithography system.

Keywords

Extreme ultraviolet (EUV), light source, high energy density plasma, plasma focus, counter-facing

1. Introduction

An intense radiation in extreme ultraviolet (EUV) region is expected for the next generation lithography system in semiconductor manufacturing. It is the light from a plasma with wavelength of 13.5nm±1% (so called "in-band") considered now for the realization of lithography process using the EUV light. However, the EUV light source device has various problems and is not yet applied for the mass-production process. A practical EUV light source would be essential for development of the future semiconductor industry.

The plasmas made by laser irradiation (LPP: Laser-produced plasma) and energized by electric discharge (DPP: Discharging-produced plasma) are the influential candidate as the EUV light source [1-4]. Important specifications required as the practical lithography light source include high average power of a kW level, smallness of the emission size, low scattering particles (low debris). The EUV output power provided from conventional light sources cannot yet reach for the requirement. Among the issues, increase of average power is the most serious [2]. That is, when we increase the input power to accommodate the high average power, it leads shortening of the life time of the electrodes and the optical components by the heat load and debris after the operation. Therefore, the increase of the output power and the improvement of the energy conversion efficiency are necessary at the same time to develop a practical EUV source. We have proposed to extend the EUV emission time per pulse, both to increase the output power and to improve the conversion efficiency [5].

In this paper, we show proof of concept experiments and recent results of our research and development for the practical EUV source.

2. Concept and Characteristic

It is well-known that the spectrum property of lithium ions is promising. However, output intensity is low compared with Sn plasma, because only few lines contribute the in-band EUV emission. In addition, an effective time duration of μ second order is necessary to get the in-band emission from doubly ionized (hydrogen like) lithium ions [6]. This means we can make use of spectrum property of lithium by maintaining the plasma for more than μ second. In other words it becomes a challenge of the EUV research and development to hold the lithium plasma at a high temperature and high density state for a long time in a minute area.

We have developed a new configuration for the EUV light source using "counter-facing plasma focus method" for the next generation lithography system. The device consists of two counter-facing plasma focus electrodes which is expected to produce a high energy density lithium plasma by the collision of the focus plasmas. Also it is expected to be able to confine the plasma by the counter-facing current sheets and can emit the EUV light during the discharge period.

By prolonging the plasma confinement, we can extract higher EUV energy per pulse with high spectrum efficiency. In addition, we can also expect to reduce the debris because, in the configuration, the lithium supply point is far from the location of high energy density plasma.

As the plasma impedance is usually much lower than that of the pulse power generator, we also developed a recyclable power generator for the plasma device. We could recover almost 80% of electric energy during a quasi-continuous operation by the recyclable pulse power driver.

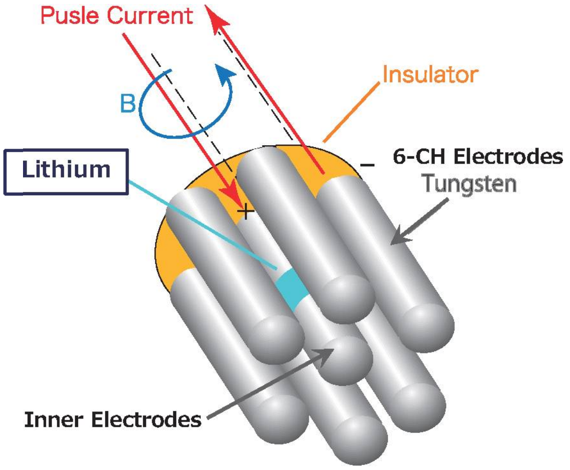

Fig. 1. Plasma focus device composed of 6-channel electrodes (one side).

3. Experimental Setup

Fig. 1 shows a schematic illustration of our plasma focus electrodes in EUV light source [7,8]. It is composed of an inner electrode and six outer electrodes which are placed on the circumference. Solid lithium was filled in grooves at the inner electrodes as the plasma source. Two sets of the focus electrodes were placed face to face in the counter facing plasma focus device.

Operational principle of the device is shown in Fig. 2. After the installation of the lithium filled electrodes, a high voltage is applied between the inner and the outer electrodes through 2x6-channel inductively isolated pulse power circuits. When a pulsed laser irradiates the lithium surface, the ablation lithium plasma triggers 2x6-channel discharges which produce two counter-facing initial plasmas around the inner electrodes. The two ring-shaped lithium plasmas are accelerated toward the tops of electrodes by the Lorentz force induced by the discharge current and the self-magnetic field.

The two ring plasmas are collided and heated at the center of inner electrodes. The converged plasma is radially compressed to a small sphere. Finally the plasma becomes a high temperature and high density state. When the discharge parameters are appropriate, an EUV light can be obtained from hydrogen like lithium ions in the high energy density plasma.

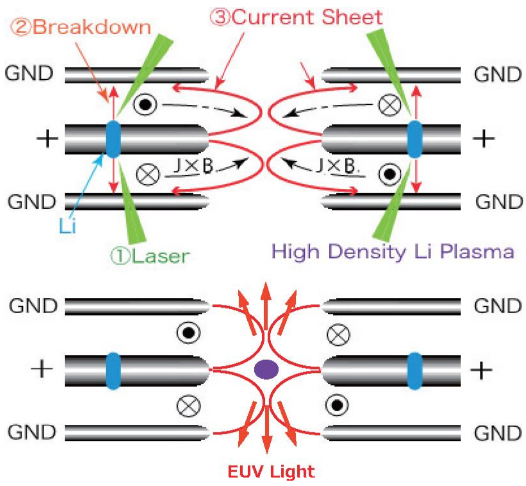

Fig. 2. Operational principle of counter-facing plasma focus device.

4. Results and Discussion

4.1 Characteristics of EUV Output

Fig. 3 shows typical waveforms of EUV emission and the discharge current. The EUV signal was obtained by a Zr-filtered EUV diode (AUXV 20HS1). As shown, the plasma discharge current had a quasi-sinusoidal waveform with its wavelength of about 2 μsec and peak value of 2kA/channel. Note that the EUV light emission is observed during more than 1 μsec.

The spectrum of the plasma radiation was measured with a glazing incidence spectrometer composed of a grating and a micro-channel plate (MCP). A typical (time-integrated) MCP image of the spectrum measurement is shown in the Fig. 4. As shown, a narrow peak was observed at 13.5nm. The spectrum line emission at 19.9nm is considered to be from He-like lithium ions and the lines at 15.5, 17.3 and 19.2nm were identified to be the light from contaminated oxygen ions [9].

The output energy was estimated by integrating the EUV waveform considering the transmission of the Zr-filter, the quantum efficiency and the effective solid angle of the diode. The results are shown in Fig.5, as a function of discharge voltage. As shown, the EUV energy per pulse increased almost proportionally to the voltage. As shown, the output energy reached more than 400 mJ/shot.

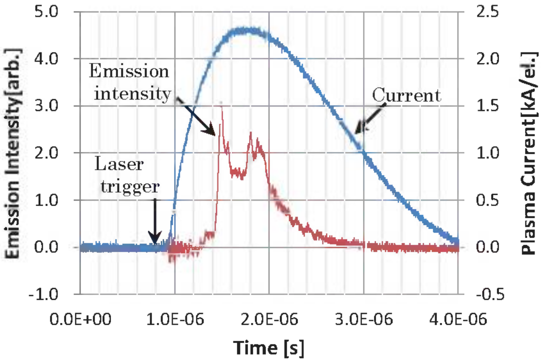

Fig. 3. Waveforms of EUV light emission by filtered photodiode and the discharge current.

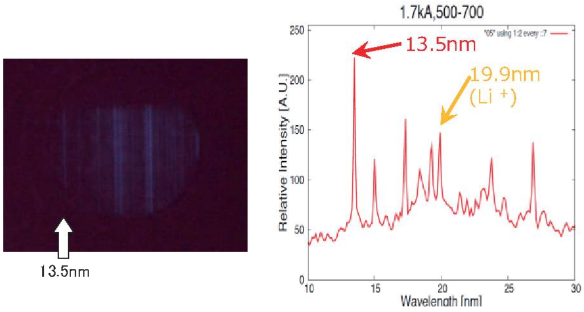

Fig. 4. MCP image (left) and its intensity profile during for 10-30nm in wavelength (right).

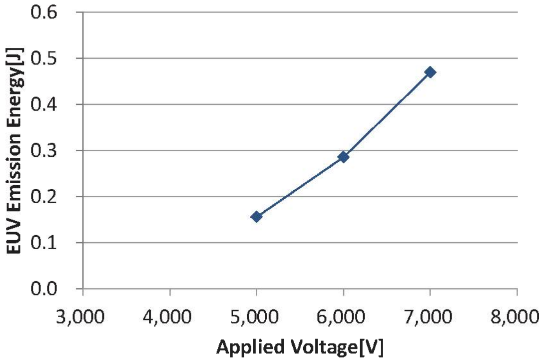

Fig. 5. EUV energy per shot as a function of applied voltage.

4.2 Characteristics of plasma dynamics

The size and the position of EUV light emitting area were observed by a pinhole camera, in which the radiation from the plasma was imaged on a CCD camera through a pinhole and reflections by two multi-layered Mo/Si mirrors. Then, only the region of in-band light emission was imaged on the CCD camera. The exposure time of CCD camera was about 1 msec, which is much longer than emission duration. Then the image was time-integrated during the discharge pulse.

Fig. 6 shows the photograph taken by the CCD camera around the gap between two inner electrodes. The estimated shapes of inner electrodes are shown in the dashed lines. The gap between the tips of inner electrodes was approximately 3 mm. As shown, the pinhole image revealed that the light emitting area located at the middle position of two inner electrodes.

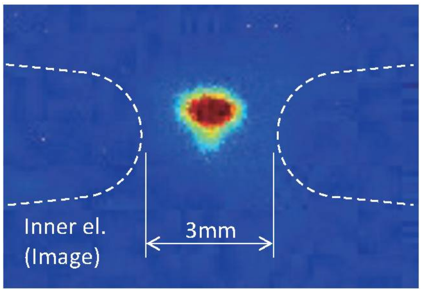

Fig. 6. Photograph taken by pinhole EUV-CCD camera around emission area between two inner electrodes.

By image analysis of this photograph, the half width of the EUV light emitting area was estimated to be about 1 mm.

In addition, plasma behavior was taken by high speed camera in the other experiments [10]. By this photography, laser irradiation to lithium, initial plasma generation, acceleration movement of the plasma, a collision between two plasma and plasma confinement are continually taken. Although the detail is left out, it is confirmed that the plasma behaves in the way as mentioned in the previous section.

5. Conclusions

An EUV light source using counter-facing plasma focus configuration was designed and tested.

Results of proof of principle experiments of the light source were as follows:

- The EUV emission duration prolonged more than μsec, which is, at least, ten times of conventional EUV sources.
- The energy output was more than 400 mJ/shot owing to the long emission time.
- Spectroscopic measurements revealed in-band line emissions from lithium ions and indicated also higher spectral purity than Sn-plasma based light sources.
- A time-integrated pinhole camera showed the size of EUV plasma is less than 1 mm.
- Images of plasma dynamics observed by the pinhole camera and a fast framing camera supported the operational principle discussed in Sec.2.

Although a lot of works still remain including an improvement of laser triggering geometry, all of the experimental results indicated that the EUV device has potentiality as an efficient and high average power light source for the next generation lithography [10].

Acknowledgements

The authors would like to express their sincere thanks to Drs. K. Uematsu, H. Nakai, and K. Shitara in IHI Corporation for their helpful advice and the encouragement on this study. They also thank M. Masuda, S. Liu, K. Kawaguchi, D. Nishii, K. Kanou, T. Kawasaki and S.Kittaka for their valuable supports during this study.

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