ECR heating of laser produced Sn plasma for drift control in B field

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A laser produced Sn plasma driven with a pulsed CO_2 laser and emitting EUV radiation has been generated in a magnetic field of 0.5T. The multiple-ionized plasma ions are efficiently guided along the B field lines of the double coil magnet. The neutral Sn atoms and Sn clusters, however, expand freely inside the vacuum chamber and contaminate e.g. EUV optics. We therefore evaluated ECR heating of the laser produced Sn plasma with 14GHz microwave frequency to ionize the remaining plasma neutrals. Sn ion signals were measured with micro-channel plates and Faraday cups placed inside the vacuum chamber across and along the B field lines. An increase of the Sn ion signal with ECR heating was observed along the B-field lines. The increase was maximal for the resonant microwave frequency outside the plasma position. Results demonstrate the principle of ECR heating for the cleanliness of a EUV light source.

Keywords: ECR heating, EUV light source, Laser produced plasma, neutral particles, ionization

1. Introduction

Extreme ultraviolet lithography (EUVL) at 13.5 nm is a major candidate of next generation lithography (NGL) planned to manufacture IC devices below the 32 nm node. The required EUV output power of 115W for a high volume manufacturing EUV lithography tool is very high to meet industry's required throughput of more than 100 wafer / hour. In addition, the lifetime of the collector mirror placed close to the plasma has to be sufficiently long in order to minimize the operation costs of the EUV lithography system. Improvement of the conversion efficiency (CE) of laser power into EUV in-band power and debris mitigation to extend collector mirror lifetime are major technical challenges for EUV light source development.

According to obtain the high CE the target material for EUVL plasma light source is Sn. Its main drawback, however, is the generated debris that severely limits the lifetime of the EUV collector mirror (and other optical) components. In general, the Sn debris from the laser-produced plasma consists of energetic plasma ions and neutrals, evaporated material, and liquid droplets, which solidify when they deposit on a surface. The latter, i.e. the ejected droplets, are typical debris particulates of a Sn target because tin is not a gas like Xe. In general, the generated Sn debris greatly reduces the EUV collector mirror lifetime via deposition (evaporated material, molten droplets, slow ions /neutrals), erosion (fast ions/neutrals), and implantation (ultra fast ions/neutrals). A plasma consists of neutrals, electrons and ions. The charged particles can be mitigated by electric and / or magnetic fields. This was experimentally confirmed, especially the effect of magnetic field mitigation [1,2]. Neutral particles can evidently not be controlled by electric or magnetic fields.

According to control the neutral particles in order to avoid deposition on the surface of EUV optics, neutrals have to be ionized. Ionization methods are electron collision (e.g. heating by electron cyclotron resonance) and photon absorption (e.g. laser resonant ionization) [3-5]. We developed the ion control technology using a magnetic field [1,2]. Charged particles (e.g. electrons, ions) bend due to the Lorentz force of the magnetic field. In a magnetic field the Electron Cyclotron Resonance (ECR) is expected to have an advantage in ionizing neutral particles. The resonance of ECR is given by

$$\omega_e = \frac{e \cdot B}{2 \cdot \pi \cdot m}$$

where ω_e is the cyclotron frequency, e is the electronic charge, B is the magnetic flux density, m is the electronic mass. The relationship between the magnetic flux density and the cyclotron frequency shows Fig 1.

In this paper, we investigated the characteristics of neutral particles under ECR ionization for a laser produced Sn plasma. The increase of the ion signal along the magnetic field lines was maximal at the resonant microwave frequency. The principle of ECR heating for the cleanliness of a EUV light source has been

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demonstrated.

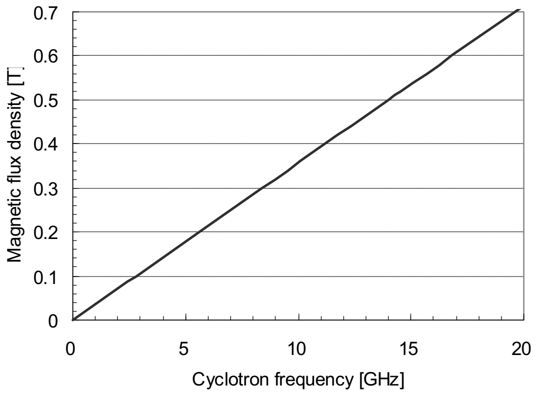

Fig.1 Relationship between Magnetic flux density [T] and Cyclotron frequency [GHz]

2. Experimental Setup

A schematic of the experimental set-up is shown in Fig. 2. A Sn plate target with a thickness of 0.5 mm was placed at the center of the magnetic field at an angle close to 0 deg related to the incident laser beam. A EUV energy meter was placed at 30 deg with respect to the target normal. All experiments were performed at a vacuum pressure below 10^{-4} Pa to avoid EUV absorption. Micro-channel plates (MCP) for ion and neutral detection were placed at 30 deg and 60 deg with respect to the incident laser beam. Faraday cups for charged particles were placed along and across the magnetic flux line.

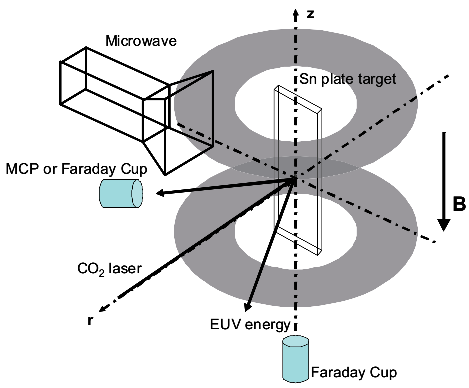

Fig.2 Schematic of the experimental set-up

A transversely excited atmospheric pressure (TEA) CO_2 laser has been used as a drive laser. This laser was based on a standard excimer microlithography laser from Gigaphoton Inc., wherein the shapes of the electrodes and the laser optics were specifically optimized for CO_2 laser operation. A pulse energy of 50 mJ per pulse was obtained. The laser beam was focused onto the target surface using a ZnSe meniscus lens with a focal length of 63.5 mm. The focal spot diameter was evaluated to be 300 um full width at half-maximum (FWHM). All experiments were operated at the laser intensity of 7 x 10^8 W/cm^2.

A double coil magnet is used to generate a maximum magnetic field of 0.6 Tesla. The coil pair spacing was 50 mm. The bore diameter was 60mm. The central magnetic flux density at the plasma position was set between 0.45 and 0.55 Tesla. The relationship between the coil current and the measured radial magnetic flux density distribution is shown in Fig.3. The magnetic flux density distribution is symmetrically to the Sn plasma position.

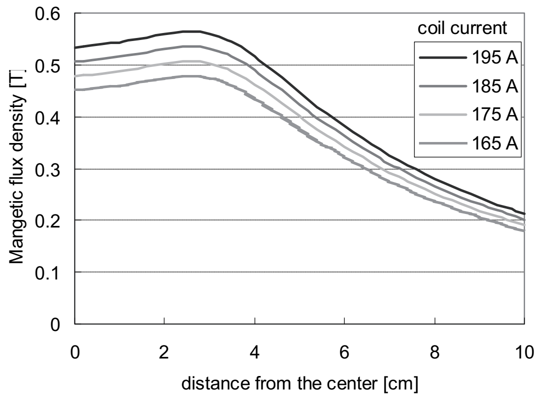

Fig. 3 Distribution of the radial magnetic flux density; parameter: coil current

The microwave beam was injected into the vacuum chamber at 90 deg with respect to the laser beam in pulsed mode operation and linearly polarized in the horizontal plane, i.e., vertically to the B-field. The microwave frequency was 14 GHz to optimize the ECR condition with the magnetic flux density of 0.5 Tesla. The pulse duration was 10 μsec the laser pulse and the power was 170 Watt.

3. Experimental results and discussion

The angular distribution of the neutral particles was measured by the MCP signal at different angles in the horizontal plane. The MCP detects ions and neutral particles. The detection efficiency of the MCP is the same for ions and neutral particles in the energy range above 1 keV [6,7]. The ion signal is removed due to the Lorentz force when the magnetic field is operated. Measured MCP signals with and without the magnetic field are shown in Fig. 4 and Fig. 5.

If fast neutral particles exist, we expect to detect them with magnetic field. But the MCP signal decreased to the detection limit at a magnetic field of 0.6 T. Therefore the present experimental result indicates that almost no fast neutral particles exist for the CO_2 laser produced Sn plasma.

Low energy neutral particles deposit on the surface of EUV optics, faster cause erosion. Therefore it is necessary to ionize and guide neutrals by the magnetic field in order to keep EUV optics clean. In this experiment we did not measure the amount of slow neutrals but roughly estimated the effect of ECR heating from the ion signal (see below).

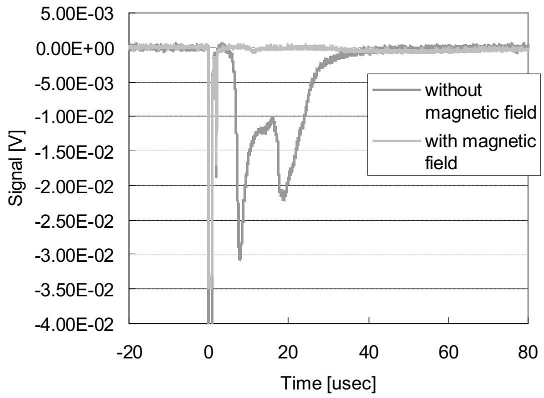

Fig.4 MCP signal with / without the magnetic field at 30 deg

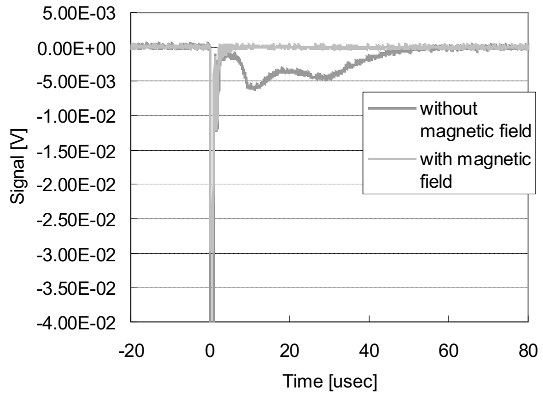

Fig.5 MCP signal with / without the magnetic field at 60 deg

To investigate the behavior of ions with the magnetic field, a Faraday cup is placed to measure the ions along the magnetic field line. This Faraday cup is placed 200 mm from the plasma and at 90 degree from the incident laser.

The Faraday cup signal increased with increasing magnetic field. Evidently the ions travel along the magnetic field lines. The relationship between the magnetic field and the integrated Faraday cup signal is shown Fig. 6.

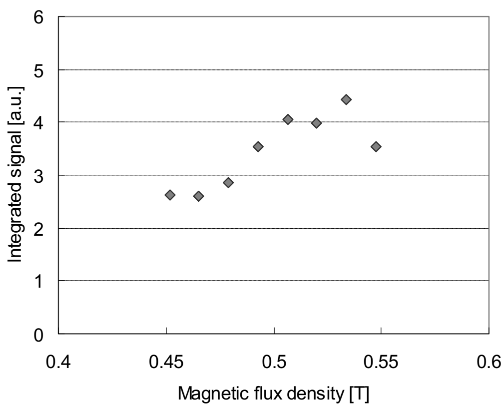

Fig.6 The relationship between the magnetic field and the integrated signal

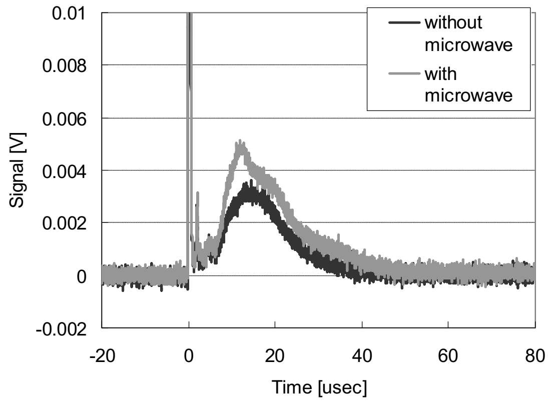

Fig.7 The typical faraday cup signal with / without the microwave

In addition we investigated the effect of ECR ionization via resonant microwave frequency. The typical Faraday cup signal with and without the microwave is shown in Fig. 7. With ECR heating the Faraday cup signal increases. This experimental result indicates that the ion number increases by the ECR ionization of the neutral particles.

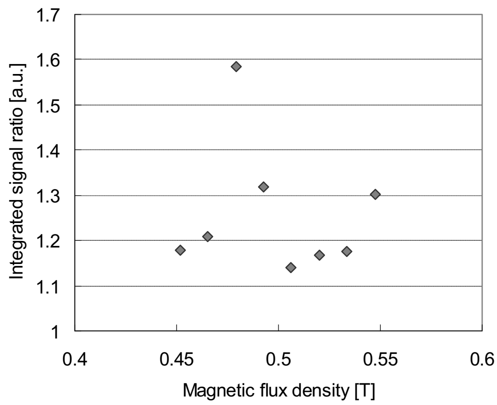

Fig.8 Signal ratio with / without microwave and magnetic flux density at Sn plasma position

Faraday cup signal ratio with and without microwave depends on the magnetic flux density at the Sn plasma position, which is shown in Fig. 8. The ion signal increase was maximal for a B-field of 0.48T at the plasma position, which means the ECR resonance at 0.5 T is about 3 cm for the plasma position. With ECR heating the Faraday cup signal peak increased 1.5 times. This compares to the deposition measured with and without magnetic field by the Quartz Crystal Microbalance in this experiment: The deposition decreased to 60 % with a magnetic field of 0.5 T. This result shows that 40 % of the total debris is ions. The lifetime increase of EUV optics due to ECR heating is therefore roughly estimated as 1.5 times.

4. Conclusion

The neutral particles from a CO_2 laser produced Sn plasma are investigated with a MCP. For this purpose the ions signal was removed by magnetic field that bends the ion trajectories due to the Lorentz force. The MCP signal for a magnetic field of 0.6 T decreased below the detection limit. The result indicates that no fast neutral particles exist.

The ECR ionization of the neutral particles is confirmed measuring the ion signal with a Faraday cup. The ion number increase was maximal for the resonant microwave frequency outside the plasma position. The principle of ECR heating for the cleanliness of a EUV light source has been demonstrated.

5. Acknowledgements

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