Development of a Capacitively-Coupled Plasma Device with Inhomogeneous Magnetic Field

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1. Introduction

Capacitively-coupled plasma (CCP) is widely used in industries such as semiconductor manufacturing for material processing due to its ease of discharge and the ability to accelerate ions to high energy within the sheath, facilitating chemical reactions at room temperature. However, this increase in ion energy also raises ion flux, rising the risk of material damage. To improve energy efficiency and mitigate these issues, magnetically enhanced reactive ion etching (MERIE) has been developed, applying a magnetic field parallel to the electrode surface to boost plasma density and improve process outcomes. Despite these efforts, MERIE has struggled with limited increases in plasma density and challenges related to uniformity. [1]

To address these limitations, recent research has focused on aligning coil-shaped electromagnets along the chamber axis to preserve azimuthal symmetry. However, most studies have relied on simulations and have not fully explained the plasma density changes induced by magnetic fields. This study, therefore, presents the design and diagnostic results of equipment developed to investigate magnetized CCP and its plasma characteristics.

2. Experimental setup

This section describes the CCP chamber design and magnetic field generated by concentric coils.

2.1 CCP chamber design

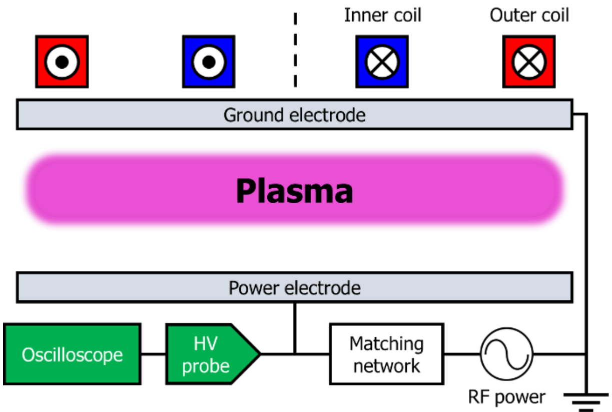

Fig. 1. The schematic diagram of the CCP chamber with magnetic field-generating coils is shown. A high-voltage probe measures the power electrode's RF voltage and DC self-bias. The coils are arranged concentrically to maintain azimuthal symmetry in the design.

The equipment used in this study closely resembles conventional CCP systems, and its structure is illustrated in Fig. 1. The chamber has an aluminum ground electrode at the top, which also functions as a showerhead to ensure uniform dispersion of the discharge gas within the chamber. The RF-powered electrode is made of stainless steel at the bottom of the chamber. A wafer is placed above this electrode, preventing direct contact between the plasma and the electrode. A 12.56 MHz single-frequency RF power source was used for plasma generation. The chamber walls, excluding the electrodes, are constructed from anodized aluminum, providing electrical insulation.

The chamber has eight ISO 100 ports on the sides and four NW 40 ports at the bottom. The eight ISO 100 ports on the chamber's sides allow for simultaneous plasma diagnostics from various angles. The greater the number of ports, the more precise the application of computerized tomography optical emission spectroscopy (CT OES) techniques, enabling the analysis of 2D plasma uniformity when a magnetic field is applied. Argon gas was used as the discharge gas, with a base pressure of 1.2×10^{-5} Torr.

2.2 Magnetic field

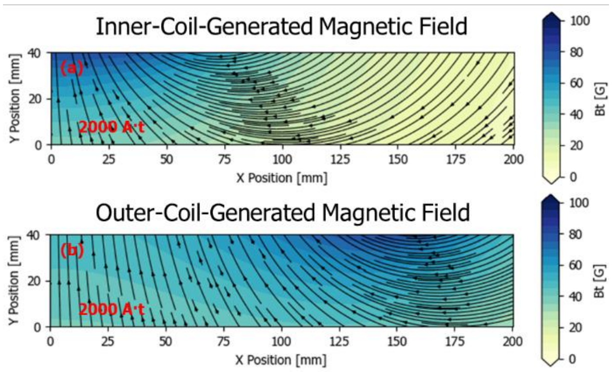

Fig. 2. (a) Magnetic field structure generated by the inner coil and (b) magnetic field structure generated by the outer coil. The magnetic field is plotted for a 2000 A-turn current and the maximum magnetic flux density is 80 G in both cases

Two electromagnets with different radii, positioned concentrically around the central axis of a CCP chamber and located 48 mm above the ground electrode, generate a magnetic field. The outer coil has 200 turns and an outer diameter of 297.5 mm, while the inner coil has 100 turns and an outer diameter of 87.5 mm, both wound with

2.5 mm diameter copper wire. The magnetic field strength, with a maximum flux density of 80 G at 2000 A-turns, is inhomogeneous due to the differing coil turns, with the axial component dominant near the chamber center and the radial component dominant near the coils.

3. Results and Discussion

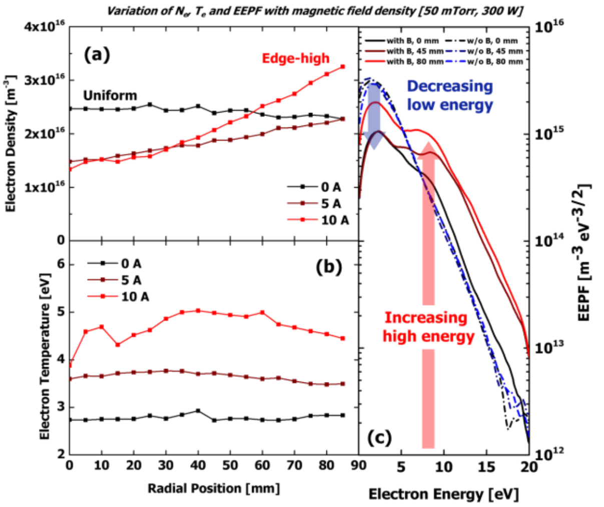

Fig. 3 (a) Electron density and (b) electron temperature measured at varying currents through the outer coil. To analyze the effect of the magnetic field on electron temperature, the electron energy probability function (EEPF) was measured at positions 0, 45, and 80 mm, both without a magnetic field and with 10 A applied to the outer coil, as shown in (c). Discharge condition is 50 mTorr, 300 W.

The characteristics of the chamber are evaluated by measuring the plasma properties, specifically electron density and electron temperature, using a Langmuir probe. An LC filter accompanies the Langmuir probe to remove the 13.56 MHz frequency and its second harmonic components. Additionally, the probe tip is oriented perpendicular to the magnetic field to prevent underestimating electron density due to reduced electron mobility caused by the magnetic field. In this experiment, only the outer coil is used to apply the magnetic field.

Fig. 3 presents the results of the plasma diagnostics with and without the magnetic field at 50 mTorr, 300 W. As shown in Fig. 3(a), when no magnetic field is applied, the plasma density remains uniform across the diagnostic range. However, when the magnetic field is applied, the density decreases at the center of the chamber while increasing at the periphery. Increasing the magnetic field strength further intensifies the density at the periphery, consistent with previous simulation results [2, 3].

Fig. 3(b) shows the results of the electron temperature measurements. In the absence of, or with a weak magnetic field, the electron temperature remains nearly uniform across the entire region. However, when a strong magnetic field is applied, significant variation in electron temperature is observed, with a difference of about 1 eV between the highest and lowest temperatures. Moreover, a general increase in electron temperature is noted as the magnetic field strength increases.

To investigate the cause of these phenomena, the electron energy probability function (EEPF) is presented in Fig. 3(c). The EEPF shown in Fig. 3(c) compares the cases without a magnetic field and with a 10 A current applied to the outer coil, measured at positions 0, 45, and 80 mm. Without the magnetic field, the EEPF at all three positions follows a Maxwellian distribution with no significant variation. However, when the magnetic field is applied, the central region exhibits a decrease in density across all energy levels. Moving toward the periphery, an increase in high-energy electrons (around 10 eV) is observed, and by the time the periphery is reached, an increase in low-energy electrons becomes evident. These observations suggest that the decrease in electron density at the center, the increase at the periphery, and the overall rise in electron temperature under the influence of the magnetic field can be attributed to the increased proportion of high-energy electrons.

4. Conclusion

This study demonstrates the effects of magnetic fields on the characteristics of capacitively coupled plasma (CCP) systems. The experimental results show that applying a magnetic field decreases plasma density at the chamber's center while increasing it at the periphery. This effect becomes more pronounced with stronger magnetic fields. Additionally, the electron temperature, which remains uniform without a magnetic field, shows significant variation when a strong magnetic field is applied, with up to 1 eV differences observed.

In this study, we successfully developed equipment capable of observing changes in plasma states under inhomogeneous magnetic fields. Future research will focus on elucidating the mechanisms by which magnetic fields influence local plasma density and electron temperature. This work is expected to enhance the performance of currently used capacitively-coupled plasma systems and contribute to a deeper physical understanding of magnetized plasma.

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