Spatial variation behaviors of argon inductively coupled plasma during discharge mode transition*

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A Langmuir probe and an ICCD are employed to study the discharge mode transition in Ar inductively coupled plasma. Electron density and plasma emission intensity are measured during the E (capacitive discharge) to H (inductive discharge) mode transitions at different pressures. It is found that plasma exists with a low electron density and a weak emission intensity in the E mode, while it has a high electron density and a strong emission intensity in the H mode. Meanwhile, the plasma emission intensity spatial (2D image) profile is symmetrical in the H mode, but the 2D image is an asymmetric profile in the E mode. Moreover, the electron density and emission intensity jump up discontinuously at high pressure, but increase almost continuously at the E to H mode transition under low pressure.

Keywords: mode transition, inductively coupled plasma, Langmuir probe, ICCD

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1. Introduction

Plasma processing technology is widely used in the semiconductor industry, such as the plasma etch process and the plasma sputter deposition process.[1,2] However, the nonlinear dynamics phenomena in plasma can significantly affect the plasma assisted deposition and etching processes, such as chaos in direct current (DC) glow discharge,[3,4] E (capacitive discharge) to H (inductive discharge) mode transition, and hysteresis in radio-frequency (RF) inductively coupled plasma (ICP).[5−7] It is well known that E mode and H mode are two kinds of mode to maintain discharge in the ICP. In particular, the plasma density jumps suddenly during the E to H mode transition. Moreover, the variation of the plasma density with the applied power or coil current always depends on the discharge history, and the hysteresis of plasma parameters (such as the electron density, electron temperature, and light intensity) with power or current is found when the E to H mode transition occurs.[5−7]

Till now, the characteristics of the E to H mode transition have been experimentally investigated by tools such as the Langmuir probe, optical emission spectroscopy (OES), retarding field analyzer, and intensified charge coupled device (ICCD) etc. The Langmuir probe is one of the most commonly used diagnostic tools to measure the electron density, temperature and electron energy distribution function (EEDF), and a lot of experimental research using the Langmuir probe have been reported. EEDF evolutions with pressure and power have been observed by several groups using the Langmuir probe for the E mode[5−17] or for the H mode,[5−7,9−17] and even near the mode transition regions[13] in ICP. The electron density[8−10,18−21] and the electron temperature[19,20] have also been investigated by the Langmuir probe during the E to H mode transitions.

Compared with the Langmuir probe, OES is a noninvasive diagnostic that is increasingly used for quantitative plasma analyses. Consequently, many experimental groups[22−33] studied the evolution of the optical emission intensity during the E to H mode transitions using OES measurements. It is shown that the optical emission intensity in the E mode is weak, while the emission in the H mode is strong. In addi-

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tion to the Langmuir probe and OES measurements, Kang *et al.*[34] used the retarding field analyzer to observe the evolution of ion energy distribution during the E to H mode transition.

As the above mentioned literatures have indicated, most of the experimental studies involving the mode transition and hysteresis are focused on measuring the electron density, temperature, EEDF, and emission intensity at a fixed point. In order to control the essential plasma parameters, it is crucial to study details of the E to H mode transition, particularly of the spatial contribution of various plasma formation mechanisms. Therefore, the purpose of this paper is to study the spatial variation behaviors of the plasma parameters in the ICP during the E to H mode transition, with two-dimensional (2D) emission images obtained by ICCD and the electron density measured by Langmuir probe.

This paper is organized as follows. In Section 2, the schematic of the ICP reactor, Langmuir probe and ICCD setup are described. In Section 3, the evolution of electron density and emission intensity with applied power, as well as its dependence on the gas pressure is presented. Finally, a short summary is given in Section 4.

2. Experimental setup

The experimental setup is schematically shown in Fig. 1, which has been described in detail elsewhere.[21,35] Briefly, a 13.56 MHz RF power is connected to a two-turn planar coupling coil via a Γ-type matching network (see Fig. 2) which is composed of a series variable capacitor C_1 and a parallel variable capacitor C_2. In all the experiments, the impedance matching capacitances are kept constant ($C_1 = 117.4$ pF, $C_2 = 1022$ pF).

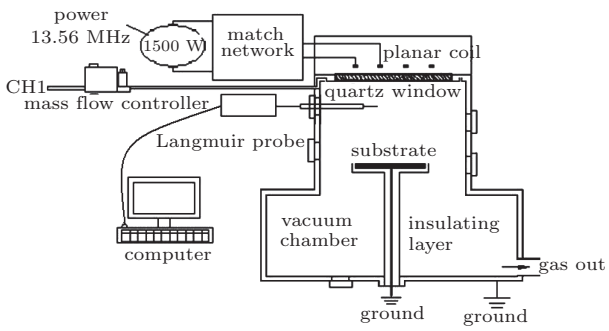


Fig. 1. Schematic diagram of the planar-type ICP reactor in the experiment.

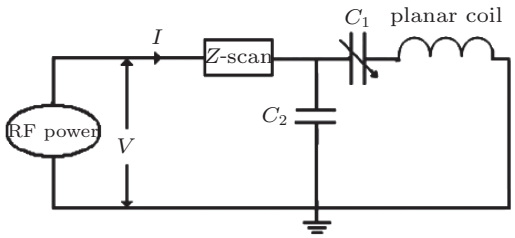


Fig. 2. The matching network circuit.

The applied power is measured by a Z-scan (advanced energy RF measurement system) which is installed between the power source and the matching network. A Langmuir probe (Hiden Anaytical Ltd) is fixed at about the center of the discharge chamber (6.0 cm from the power coupling quartz window) to measure the electron density. The probe tip (10 mm in length and 0.2 mm in diameter) is made of a tungsten wire. A commercial ICCD (Andor's iStar ICCD) camera is used to measure the plasma emission intensity. The 2D images of plasma emission are observed through a quartz viewport (20 cm in width and 12 cm in height), which is welded to the front of the chamber with a 2.7 cm distance off the coupling quartz window. The exposure time of the ICCD is set as 50 ms. An interference filter with a center wavelength of 750.4 nm and a bandwidth of 10 nm is set in front of the ICCD. By the ICCD and the interference filter, the Ar 750.4 nm signal line intensity originating from the $2p_1$ level is measured.

3. Results and discussion

3.1. 2D emission images in the E and H modes

In this section, the spatial changes of the plasma emission intensity profile with the applied power at different pressures are observed by the ICCD as shown in Figs. 3–6. We can see from Figs. 3(a) and 3(b) that the 2D images in the E mode are asymmetric profiles and the peaks of plasma emission intensity deviate from the center of the chamber because of the influence of the local abundance of the capacitive coupled field caused by the RF coil. With the increase of the applied power, the E to H mode transition is accompanied by a localized emission from asymmetrical to symmetrical in the observed 2D image. After the E to H mode transition, the H mode is established,

and the 2D images are shown as axisymmetric profiles in Figs. 3(c) and 3(d). Moreover, before the E to H mode transition, the plasma is localized in the region of the near discharge coil, and the emission is very weak. After the E to H mode transition, the plasma firstly expands from near the coil region to near the substrate region, then the discharge chamber is filled with plasma. The peak of emission intensity is near the center of the vacuum chamber. Meanwhile, the emission is stronger in the H mode than in the E mode.

Compared with the 2D images at low pressure ($\leq$ 5 mTorr in Figs. 3, 4), it is obvious that the emission intensity is stronger in the H mode at high pressure ($\geq$ 20 mTorr in Figs. 5, 6) than that at low pressure, while the emission intensity is weaker in the E mode at high pressure than that at low pressure. The 2D images have better symmetry in the E mode at low pressure. Moreover, at high pressure, a clear peak appears in the vicinity of the current terminal connected to the power source in the E mode.

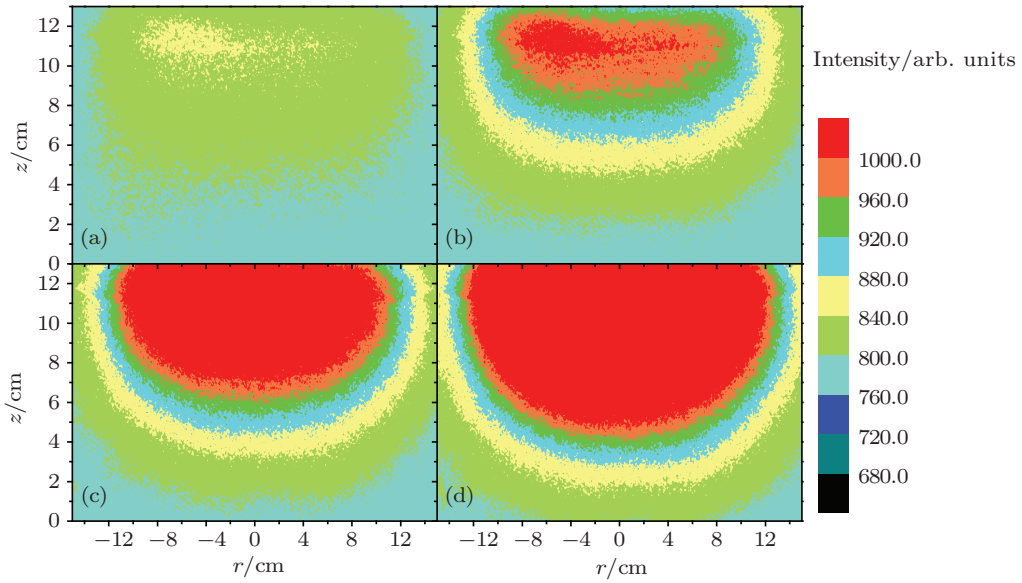


Fig. 3. (colour online) 2D profiles of Ar 750.4 nm intensity for different applied powers at 1 mTorr: (a) 25.4 W, (b) 35.5 W, before the E to H transition, (c) 41.4 W, after the E to H transition, (d) 52.5 W.

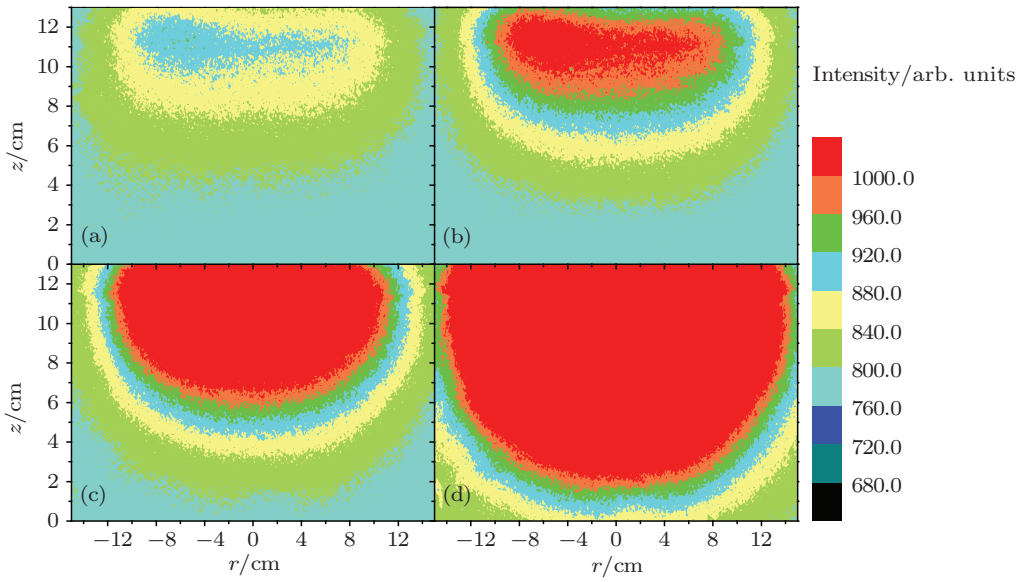


Fig. 4. (colour online) 2D profiles of Ar 750.4 nm intensity for different applied powers at 5 mTorr: (a) 30.5 W, (b) 36.0 W, before the E to H transition, (c) 42.6 W, after the E to H transition, (d) 70.0 W.

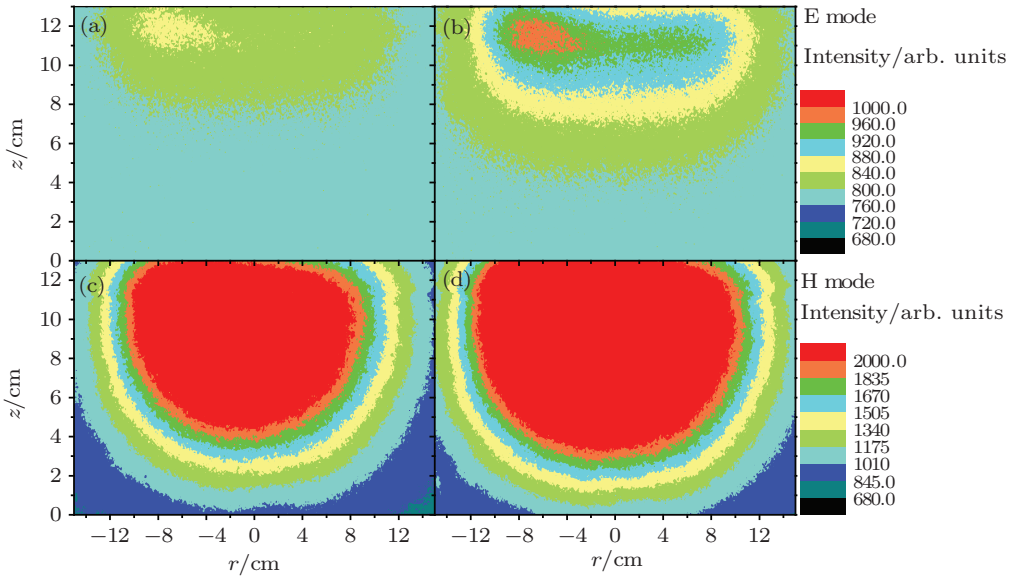


Fig. 5. (colour online) 2D profiles of Ar 750.4 nm intensity for different applied powers at 20 mTorr: (a) 25.4 W, (b) 30.8 W, before the E to H transition, (c) 97.1 W, after the E to H transition, (d) 121.2 W.

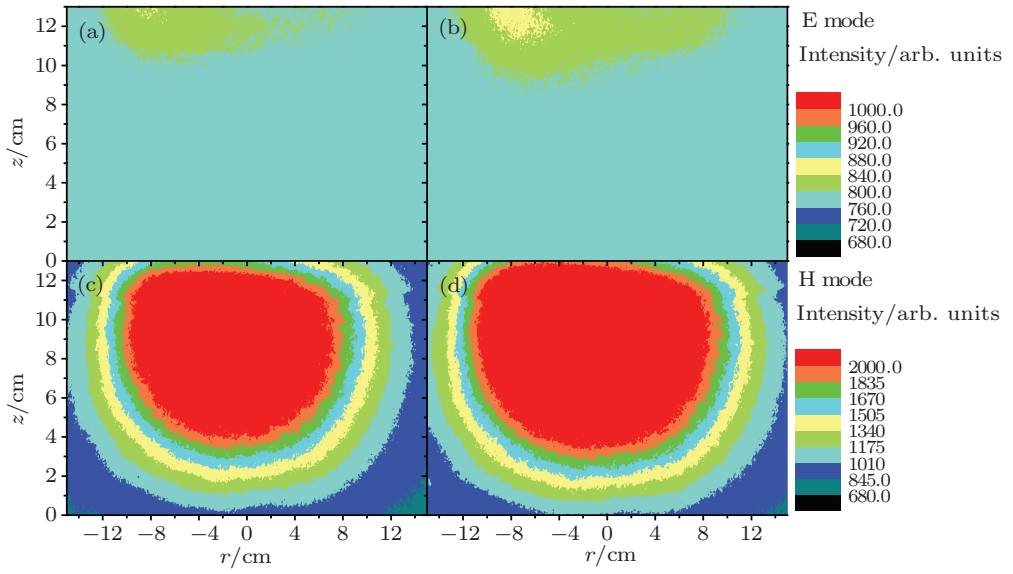


Fig. 6. (colour online) 2D profiles of Ar 750.4 nm intensity for different applied powers at 100 mTorr: (a) 20.1 W, (b) 24.4 W, before the E to H transition, (c) 85.0 W, after the E to H transition, (d) 100.3 W.

In Figs. 3–6, it is evident that the plasma emission intensity increases with the increasing applied power. In particular, at high pressure, the emission in the H mode is much higher than in the E mode, e.g., the peak of emission intensity is about 800 (arb. units) in the E mode in Fig. 6(b), while it is about 3000 (arb. units) in the H mode in Fig. 6(c) at 100 mTorr. This evolution of plasma emission intensity with applied power is consistent with previous works.[26,30]

3.2. Fixed-point measurement at different pressures

In this section, the dependences of the electron density and the plasma emission intensity on the applied power are investigated for various gas pressures (1–100 mTorr) in Ar discharge. The electron densities and emission versus the applied power under different pressures are shown in Figs. 7 and 8. It can be seen that at high pressures ($\geq$ 20 mTorr) the electron

density and plasma emission intensity jump up discontinuously at the E to H transition points. This may be caused by the shielding of the capacitive field and the high inelastic collisions which are enhanced by the high electron density in the H mode at high pressure. However, at low pressure ($\leq$ 5 mTorr) the electron density and plasma emission intensity change almost continuously during the E to H mode transitions. This continuous change may be caused by low shielding of the capacitive field due to the lower electron density at low pressure than that at high pressure in the H mode. Similar behavior of electron density has been previously reported in Refs. [5] and [7].

From Figs. 7(b) and 8(b), we can see that in the high pressure discharge the threshold power of the E to H mode transition decreases with the increase in pressure. The results illustrate that more power is required for the E to H mode transitions at low pressure. This may be caused by the increase of the plasma sheath thickness or the enhanced the multistep ionization when the pressure is increased.[5,36]

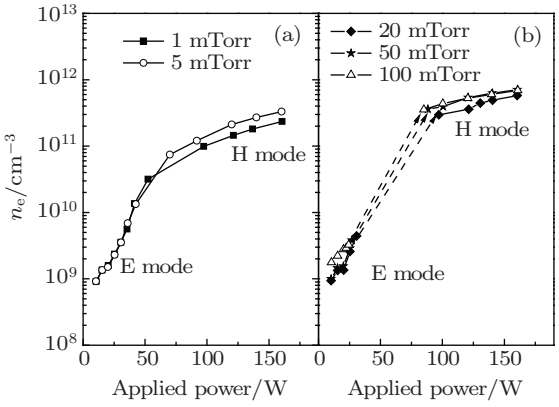


Fig. 7. The dependence of electron density n_e on the applied power at different pressures: (a) low pressure, (b) high pressure.

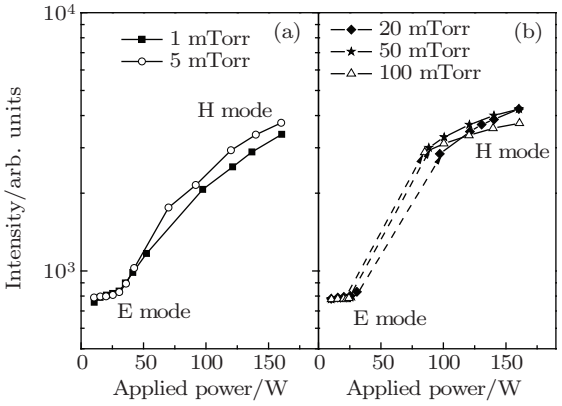


Fig. 8. The dependence of the Ar 750.4 nm signal intensity on the applied power at different pressures: (a) low pressure, (b) high pressure.

The evolution of the input voltage and current with the applied power are shown in Figs. 9 and 10, respectively. It is obvious that the input current and voltage increase continuously with the increase of applied power when the E to H mode transition occurs at low pressure. In the voltage curve, there is a clear inflection point at the E to H mode transition point in Fig. 9(a). At high pressure, the input current and the input voltage increase with the increase of applied power in the E mode and H mode respectively, as shown in Figs. 9(b) and 10(b). However, the input current jumps up while the input voltage jumps down during the E to H mode transitions. Therefore, there are two clear inflection points in the voltage curve, while only one inflection point appears in the current curve.

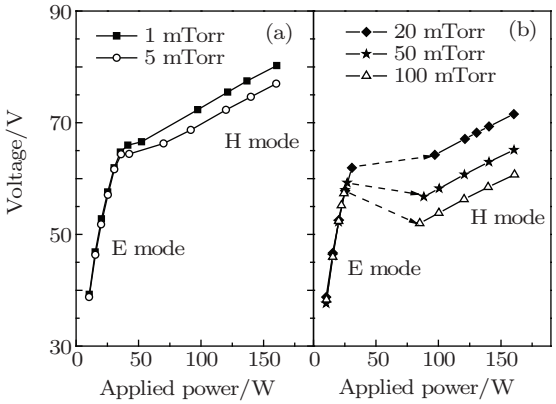


Fig. 9. The dependence of the input voltage on the applied power at different pressures: (a) low pressure, (b) high pressure.

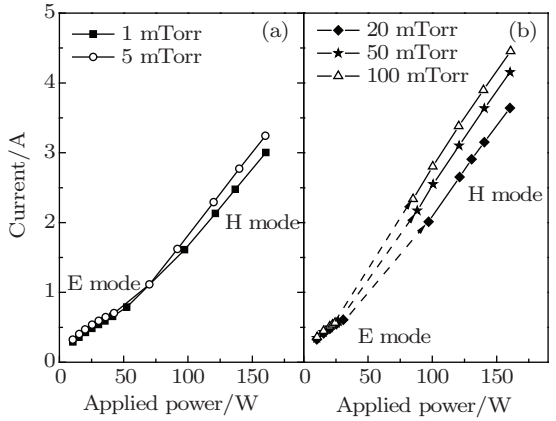


Fig. 10. The dependence of the input current on the applied power at different pressures: (a) low pressure, (b) high pressure.

4. Conclusions

We have investigated the characteristics of electron density and plasma emission intensity during the

E to H mode transitions at different gas pressures in Ar ICP by a Langmuir probe and an ICCD. The E to H mode transition is accompanied by the localized emission intensity from asymmetrical to symmetrical in the observed 2D image (plasma emission intensity spatial profile). Moreover, the 2D image is an axisymmetric profile in the H mode, while it is an asymmetric profile in the E mode at all pressures. In the E mode, a peak of emission appears in the vicinity of the current terminal connected to the power source. At low pressure ($\leq$ 5mTorr), the electron density and emission intensity increase almost continuously, while they jump up discontinuously at high pressure ($\geq$ 20 mTorr) during the E to H mode transitions. Meanwhile, the input voltage increases with the increase of applied power at low pressure, while it jumps down at the E to H mode transition point at high pressure. In future work, we will measure the plasma parameters during the E to H mode transitions in mixture gas discharge, such as Ar/N_2 and Ar/O_2.

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