Changes of the electron dynamics in hydrogen inductively coupled plasma*

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Changes of the electron dynamics in hydrogen (H_2) radio-frequency (RF) inductively coupled plasmas are investigated using a hairpin probe and an intensified charged coupled device (ICCD). The electron density, plasma emission intensity, and input current (voltage) are measured during the E to H mode transitions at different pressures. It is found that the electron density, plasma emission intensity, and input current jump up discontinuously, and the input voltage jumps down at the E to H mode transition points. And the threshold power of the E to H mode transition decreases with the increase of the pressure. Moreover, space and phase resolved optical emission spectroscopic measurements reveal that, in the E mode, the RF dynamics is characterized by one dominant excitation per RF cycle, while in the H mode, there are two excitation maxima within one cycle.

Keywords: mode transition, inductively coupled plasma, hairpin probe, hydrogen

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1. Introduction

Hydrogen (H_2) plasmas are widely applied in microelectronics for surface cleaning and etching, reduction of oxides on surfaces, and film deposition.[1–8] For example, H_2 and SiH_4 mixture discharges are used to produce microcrystalline silicon thin films and synthetic diamond.[6–8] In particular, high density inductively coupled plasma (ICP) is commonly used in the semiconductor industry.[9,10] It is well known that ICP exhibits two operational modes, E mode (capacitive discharge) and H mode (inductive discharge). In the E mode, at low radio-frequency (RF) powers, the discharges are sustained by an electrostatic field between the powered antenna coil and the ground, and the characteristics of the plasma are faint light emission, relatively low plasma density, and high plasma potential. On the other hand, at high powers, the discharges are maintained by the electric field induced from the RF antenna coil currents, and high plasma density, bright light emission, and low plasma potential are observed in the H mode. Moreover, when the input power increases (or decreases), the plasma density jumps up (or down) suddenly, meanwhile the E–H mode transition appears.[11–14]

Till now, the characteristics of the E to H mode transition have been discussed in a number of experimental and theoretical studies.[11–44] Most of those studies have been conducted with the rare gases, i.e., argon (Ar).[11–38] However, the chemically active gases (such as CF_4, O_2, N_2, H_2) are commonly used in real plasma processing. Miyoshi *et al.*[39] obtained the radial and azimuthal computerized tomography images of the E and H modes in pure Ar and CF_4(5%)/Ar mixture discharges. Besides, the E–H mode transitions in O_2 plasma were studied by a space and phase resolved optical emission spectroscopy.[40,41] In N_2 plasma, the electron energy distribution function was measured both in the E mode and the H mode.[42] In H_2 plasma, the transition was investigated using a space and phase resolved optical emission spectroscopy at high pressures (15 Pa, 25 Pa, and 60 Pa).[43,44]

Although the H_2 plasma is widely used in microelectronics, the research of the E–H mode transition in the H_2 plasma is rare at low pressures. Thus, a study of the E–H mode transition in H_2 ICP will be performed. In this paper, the electron density, plasma emission intensity, input current, and input voltage will be measured by a hairpin probe and an intensified charged coupled device (ICCD) during the E to H mode transitions in H_2 ICPs. In particular, the space and phase resolved optical emission will be studied for both modes. These results will make it possible to quantitatively control the H_2 plasma for various applications.

This paper is organized as follows. In Section 2, the schematic diagram of the ICP reactor, the hairpin probe, and the ICCD setup are described. In Section 3, the evolutions of electron density, plasma emission intensity, input current, and input voltage with applied power P_a, as well as their dependences on the gas pressure are presented. In addition, the space and phase resolved optical emission intensities at different pressures are shown. Finally, a short summary is given.

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2. Experimental setup

The experimental setup is shown in Fig. 1, it is a planar-type ICP driven by an RF power source of 13.56 MHz. The ICP reactor and the matching network have been described in our previous papers.[14,45,46] A *Z*-scan (advanced energy RF measurement system) is installed between the RF power source and the matching network to measure the applied power, input current, and input voltage. And a hairpin probe is fixed at about the center of the discharge chamber (4.5 cm away from the power coupling quartz window) to measure the electron density. The hairpin probe used in our experiment is based principally on the work of Piejak *et al.*[47,48] A fast gated ICCD camera (Andor's iStar) is used as the detector. The space and phase resolved optical emission intensity profiles are observed through a quartz viewport (20 cm in width and 12 cm height), which is welded to the front of the chamber with a 2.7 cm distance off the coupling quartz window.

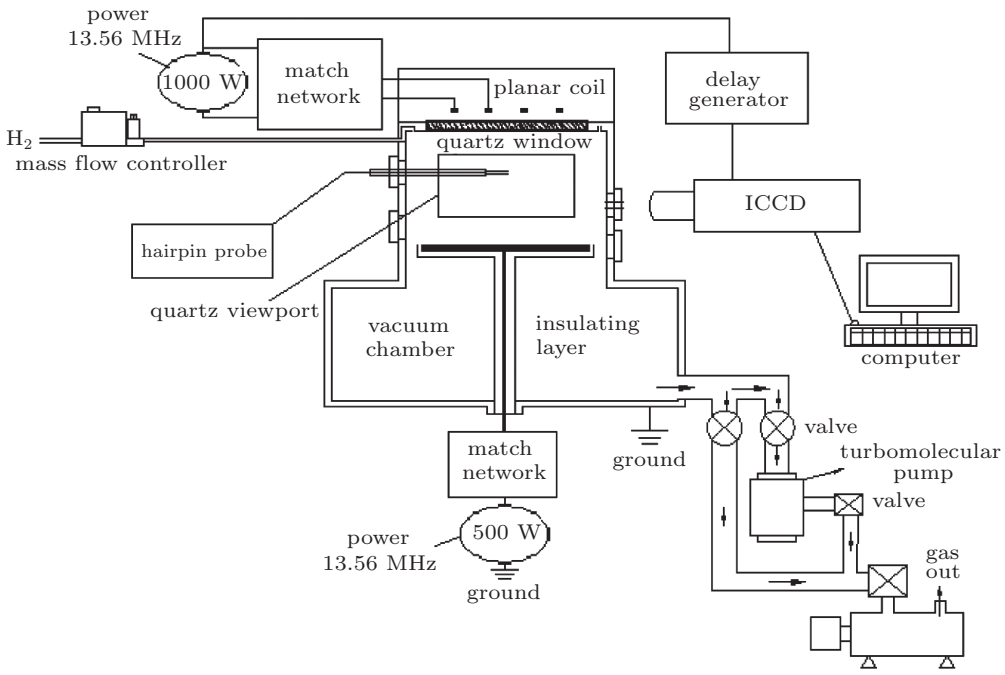


Fig. 1. Schematic diagram of planar-type ICP reactor in the experiment.

3. Results and discussion

3.1. The E to H mode transition

In this section, the dependences of the electron density and the plasma emission intensity on the applied power are investigated at various gas pressures in H_2 discharges. The electron density and emission versus the applied power under different pressures are shown in Figs. 2 and 3. It is found that the 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. It is also shown that the electron density and the 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. A similar behavior of the electron density has been previously reported in Ar plasma.[5,7]

From Figs. 2 and 3, it is clear that the threshold power of the E to H mode transition decreases with increasing pressure. The results illustrate that the E to H mode transition needs less power at high pressures. This may be caused by the increase of the plasma sheath thickness or the enhanced multistep ionization when the pressure is increased.[5,35]

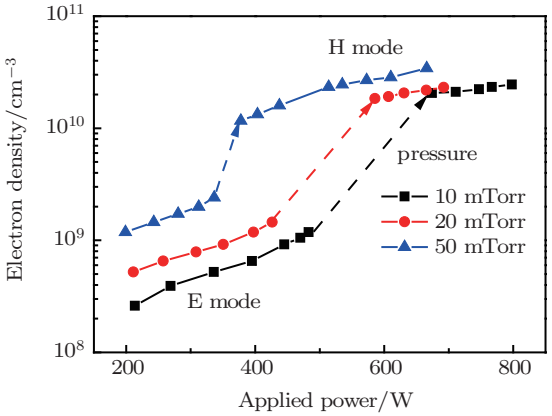


Fig. 2. (color online) Dependence of the electron density on the applied power under different pressures.

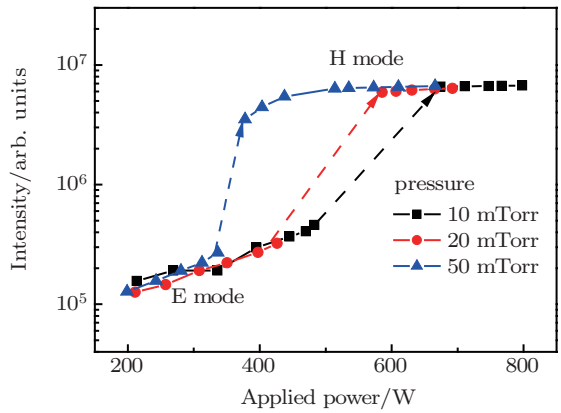


Fig. 3. (color online) Dependence of the plasma emission intensity on the applied power under different pressures.

The evolutions of the input current and the input voltage with the applied power are shown in Figs. 4 and 5, respectively. The trends of the input current are parallel to those of the plasma emission intensity and the electron density. It is obvious that the input current jumps up when the E to H mode transition occurs at all the selected pressures. However in Fig. 5, the input voltage jumps down suddenly at the E to H mode transition point and then smoothly increases again with the increasing power.

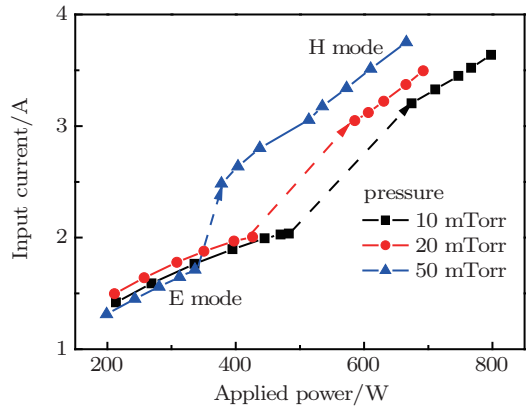


Fig. 4. (color online) Dependence of the input current on the applied power under different pressures.

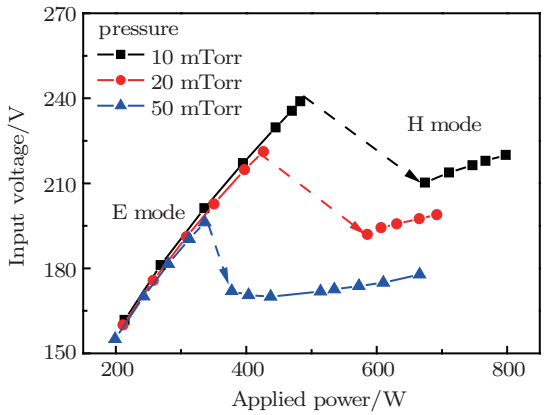


Fig. 5. (color online) Dependence of the input voltage on the applied power under different pressures.

3.2. Space and phase resolved optical emission

The space and phase resolved optical emission intensity profiles are obtained at different pressures by the ICCD, as shown in Figs. 6 and 7. The experimental results are obtained at high power (600 W, H mode) and low power (300 W, E mode), respectively. It is obvious that the temporal behavior of the emission in the E mode is different from that in the H mode. Figure 6 shows the space and phase resolved excitation in the E mode within two RF periods (148 ns). In our experiment, the two RF cycles of 148 ns are segmented into 37 time windows of 4 ns each. It is clearly that there is a dominant excitation within one RF cycle (74 ns). This is because that, in the E mode, the ICP antenna coils act as an electrode of capacitively coupled plasma, and the electron is accelerated vertically away from the electrode by the sheath voltage once during each RF cycle. In other words, this excitation structure is caused by the sheath expansion as the capacitively coupled discharge.[49,50]

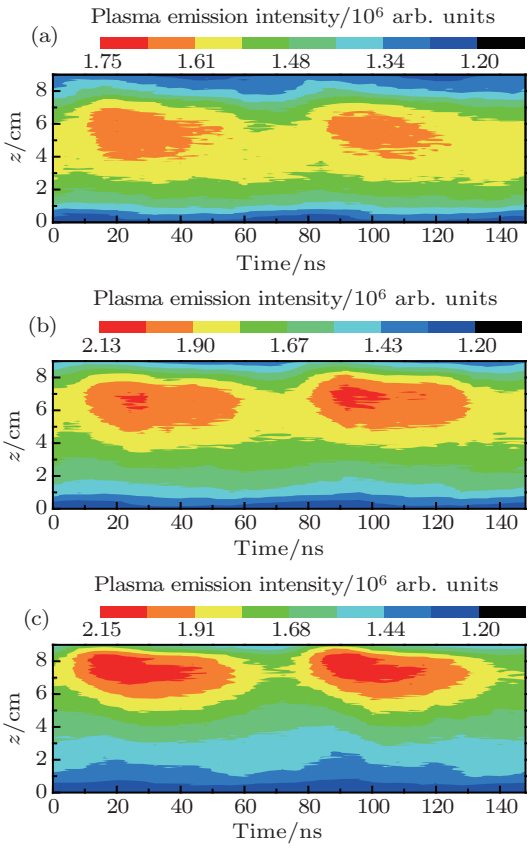


Fig. 6. (color online) Space and phase resolved optical emission intensity profiles in the E mode (300 W) at different pressures: (a) 5 mTorr, (b) 20 mTorr, and (c) 50 mTorr; z is the distance from the substrate.

Figure 6 also shows the variation of the space and phase resolved excitation with pressures. It is obvious that the plasma emission intensity increases, and the peak of the excitation moves toward the ICP antenna coil more with the increasing pressure. This is because as the pressure rises, the

density of the neutral gas increases, and then more neutral particles are ionized. Thereby, the electron density increases and the sheath becomes thinner. Moreover, a beam of electrons, which is generated by the sheath expansion, penetrates into the plasma bulk, and then the beam is damped by collisions with the neutral gas, which is faster at high pressure than that at low pressure. Therefore, the peak of excitation is closer to the antenna coil at high pressures.

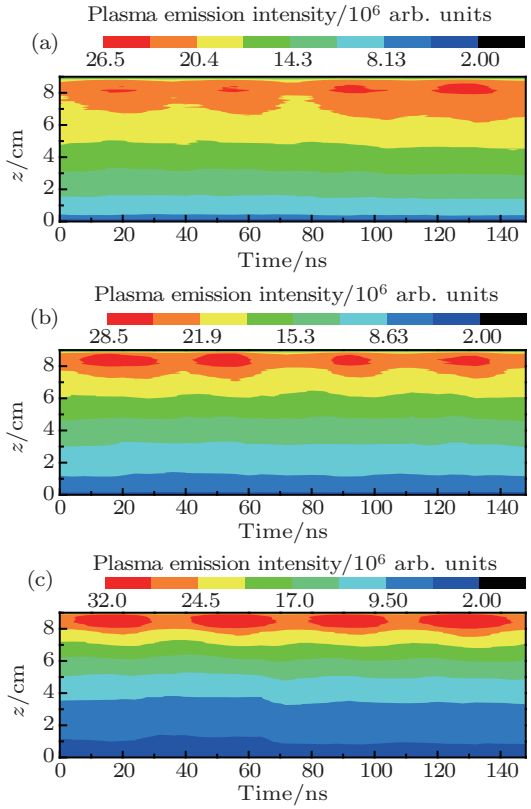


Fig. 7. (color online) Space and phase resolved optical emission intensity profiles in the E mode (600 W) at different pressures: (a) 5 mTorr, (b) 20 mTorr, and (c) 50 mTorr, z is the distance from the substrate.

Figure 7 shows the space and phase revolved excitation in the H mode at different pressures. We can see that the excitation clearly exhibits a two-peak structure within one RF cycle. This is because the plasma is maintained by the induced electric field from the antenna current in the H mode. The electrons obtain energy from the induced electric field, and cause the temporal modulation of the optical emission. As we all know, the RF antenna coil current moves clockwise in one half cycle and anti-clockwise in the other half cycle. Therefore, two excitation maxima within one cycle are observed in the H mode.

By comparing the space and phase revolved excitations in the E and H modes, it is found that the peak of excitation in the H mode is closer to the antenna coil than that in the E mode at all considered pressures. This may be caused by the fact that the energetic electrons are quickly consumed by the electron–electron collisions and the electron–neutral collisions due to the higher plasma density and higher collision frequency in the H mode.

4. Conclusion

In this paper, we investigate the characteristics of electron density, plasma emission intensity, input current, and input voltage at different pressures during the E to H mode transition in H_2 inductively coupled discharges by using a hairpin probe and an ICCD. And the space and phase revolved optical emission in the E and H modes are also observed with the ICCD. It is found that the electron density, plasma emission intensity, and input current jump up discontinuously, and the input voltage jumps down at the E to H mode transition points. The threshold power of the E to H mode transition decreases with the increasing pressure. Moreover, the space and phase resolved optical emission spectroscopic measurements reveal that, in the E mode, the RF dynamics is characterized by one dominant excitation per RF cycle due to the sheath expansion, while in the H mode, there exist two excitation maxima within one cycle. Besides, the peak of excitation is closer to the antenna coil at high pressure than that at low pressure. In the future work, the plasma parameters (electron density and plasma emission intensity) during the E to H mode transitions in mixture gas discharges, such as Ar/N_2, Ar/O_2, will be investigated.

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