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Spatial distribution study of argon radio-frequency inductively coupled plasma in inverse hysteresis transition area

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A B S T R A C T

Parameters of radio-frequency (rf) inductively coupled plasma (ICP) have been investigated with Langmuir probe and optical emission spectrum (OES) in this paper. Through the observation results of OES, we can finally get that inverse hysteresis phenomenon would occur when the air pressure is 0.6 Pa. The mode of plasma is demonstrated based on OES while spatial distribution of electron temperature T_e, plasma density n_p and plasma potential V_p at the same power and pressure in inverse hysteresis transition area could be assured with Langmuir probe. The experiment results indicate that even though T_e, n_p and V_p distribute more homogeneously in both axial and radial direction at the stage of H mode than E mode, the result shows no great difference of the data in both H mode and E mode.

1. Introduction

Ever since Hittorf reported an electrodeless ring discharge in 1884, researchers have begun to investigate what drives this discharge phenomenon on earth, electrostatic field or induced electric field. In 1991, Amorim and his coworkers observed two distinct discharge modes which are electrostatic mode known as E mode and electromagnetic made known as H mode [1] in the argon cylindrical ICP with 11.4 MHz. By adjusting the experimental conditions, ICP discharge would jump between E mode and H mode and also accompany with sudden variations of the plasma parameters. In consideration of that, both mode transition of ICP and mutation behavior of plasma parameters have great influence on preparation of plasma thin film, plasma erosion and plasma removing processes, so it is of great significance to investigate plasma characteristics in mode transition region.

For the past few years, researchers found that hysteresis would occur in ICP discharge mode transition when adjusting the rf power back and forth, scientists declare maybe it is because of the multi-step ionization under metastable state [2,3] or the nonlinear power consumption [4]. Chung and his coworkers [5] find hysteresis would occur when air pressure is less than 4.5 mTorr, and the power is lower when plasma jumps from E mode to H mode than that when plasma jumps from H mode to E mode, resulting in inverse hysteresis. Most recently, researchers have studied the variation of n_p [4], T_e [6] and V_p [7] and optical emission intensity [8,9] in different mode. However, to the best of our knowledge, there is no relevant study on plasma parameters variations in mode transition region. This paper firstly investigates spatial distribution of T_e, n_p and V_p of cylindrical discharge chamber at the same power and pressure in inverse hysteresis transition region.

2. Experimental setup and details

2.1. Experimental setup

The schematic construction of the cylindrical ICP experimental setup is shown in Fig. 1. The height and dimension of reacting cavity are 300 mm and 200 mm, respectively. We adapt SY type radio frequency power source and SP-II radio frequency adapter which has a power range of 0–1 kW and output frequency of 13.56 MHz as our rf power source. It connects with the induction coils through the matching circuit. The tube is surrounded by an antenna coil made of water-cooled copper tubing which has 4 turns in total. The chamber is evacuated through a mechanical pump (2XZ-2) and a molecular pump (F-100/110), the pressure of which is measured by DL-90 type compound vacuum gauge.

The optical emission spectrum of Ar was measured with a WDS8A-type multifunctional grating spectrometer which is composed of two parts as shown in Fig. 1. The inspection window in

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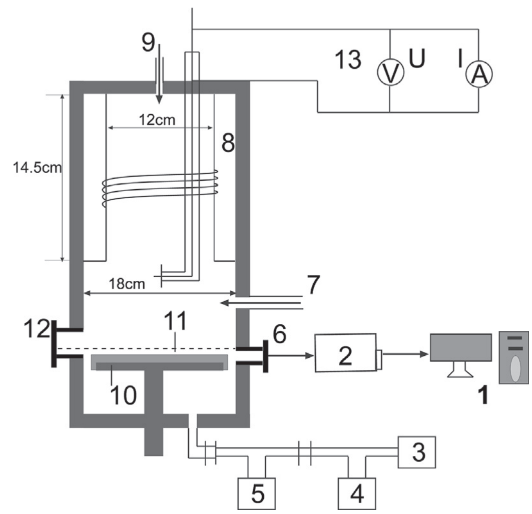

1-computer; 2-monochromator; 3-vacuum pumps; 4-valve; 5-vacuum gauge; 6-the window for OES measurement; 7-gas supply 1; 8-rf electrode coil; 9-gas supply 2; 10-substrate holder; 11-the vicinity of plasma sheath; 12-observation window; 13-Langmuir probe

Fig. 1. The schematic construction of experiment.

the discharge cavity was connected with grating spectrometer through optical fiber to measure the intensity of plasma emission spectrum. The monochrometer has a raster of 2400 strips mm^{-1} and a blaze wavelength of 350 nm. Its spectrum measuring range is between 200 nm and 800 nm.

T_e, n_p and V_p were measured with Langmuir probe diagnostic technique. In our research, we choose tungsten filament with a diameter of 1 mm as the probe. The length inside the discharge cavity of the probe is 6.4 mm. By adapting insulation material to separate the probe from glass which was used as shell, the probe can be sealed. The probe, ampere meter and DC stabilized power supply were connected to each other to form a circuit as shown in Fig. 1. Current in the circuit varies with the change of voltage, so both *I–V* and *lnI-V* curves can be obtained. T_e can be achieved by calculating the slope of *lnI-V* curve [10]. The inflection point of *I–V* curve is difficult to be determined resulting in the non-availability of saturation electron current because of the fringe effect namely the limited surface area. In consideration of that, we can get electron density by using the method with which we achieved plasma density, according to the formula (1) below: [11].

$$I_0 = 0.61 n_i e \left({kT_e}/{m_i} \right)^{1/2} S \tag{1}$$

Where S is the surface area of probe, e is electron charge, k is Boltzmann constant, n_i is ion density, T_e is electron temperature and m_i is the mass of ion, respectively.

As to the plasma potential, it can be investigated following the formula (2) below: [10].

$$\Phi_f = \Phi_p - kT_e \Big/ 2e \ln\left(2M/_{\pi m} \right) \tag{2}$$

where Φ_p is the plasma potential and Φ_f is plasma floating potential, namely the intersection of the *I–V* curve and abscissa axis. M and m are ion mass and electron mass, respectively.

2.2. Experimental details

After the vacuum degree of the cavity is exhausted up to 4.5×10^{-3} Pa, then we aerate argon of which the purity is 99.99% into the cavity getting a pressure of 6×10^{-1} Pa inside. The discharge mode is diagnosed by a sudden change of plasma emission, and then we observe inverse hysteresis phenomenon with adjusting rf power repeatedly. Identify the discharge mode of plasma via optical emission spectrum device at rf power of 208 W (transition area of inverse hysteresis) and measure T_e, n_p and V_p to investigate their spatial distributions with single probe at the same time.

We can measure the plasma parameters at 0, 1, 2, 3, 4, 5 cm (which are calculated from the center of the cavity to the wall of vessel in radial direction) by rotating a eccentric electrostatic probe at a certain angle. By adjusting the height of probe, plasma parameters at 0, 3, 6, 9, 12, 15 cm which starts calculating from the top of chamber (2.5 cm in axial direction) can also be achieved.

3. Results and discussion

3.1. Variation of optical emission spectrum intensity with the change of rf power

The plasma emission variation of Ar characteristic spectrum at 419.5 nm against the rf power at pressure of 0.6 Pa is shown in Fig. 2. We can see from Fig. 2 that the inverse hysteresis would occur when rf power is adjusted repeatedly. It finds that the power point under which E mode jumps to H mode would ahead of that when H mode jumps to E mode. This phenomenon is in agreement with the argument reported previously [5]. Min-Hyong Lee and Chin-Wook Chung [5] get that electron energy distribution function (EEDF) is bi-Maxwellian distribution under E mode while Maxwellian distribution under H mode in lower air pressure. There are much more high-energy electrons under bi-Maxwellian distribution than under Maxwellian distribution. As the ionization energy of Ar atom is 15.76 eV, only part of the high-energy electrons could ionize it, so there is a higher ionization efficiency under bi-