Vacuum 132 (2016) 16–21

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

The study of influence of working pressure on mode conversion of argon radio-frequency inductively coupled plasma

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ARTICLE INFO

Article history:
Received 9 May 2016
Received in revised form
16 July 2016
Accepted 19 July 2016
Available online 20 July 2016

Keywords:
Inductively coupled plasma
Inverse hysteresis
Optical emission spectrum
Langmuir probe
Mode conversion

ABSTRACT

Electron temperature and plasma density was measured with change of working air pressure by Langmuir probe at a given power. Radio-frequency (rf) inductively coupled plasma (ICP) discharge mode conversion is determined by optical emission spectrum (OES) with the increase of gas pressure at different power. The results indicate that plasma discharge mode can change from E mode to H mode and spectral intensity appears inverse hysteresis phenomenon with the change of air pressure. The hysteresis width decreases with the increase of power and the hysteresis is no longer present when the power is 420 W and 435 W. Moreover, the jump pressure of E-H transition is gradually reduced with the corresponding increase of discharge power. ICP discharge mode appears E-H-E phenomenon with the increase of air pressure.

1. Introduction

From the first discovery of the inductive discharge in 1884, after more than 100 years of development, the related mechanism of the mode transformation and the nature of the plasma have been gradually understood by the people. But so far there is still not a systematic theory to explain the reasons for the change of mode. In recent years, during the research of the process of the ICP discharge mode conversion, people found that the plasma density would appear hysteresis phenomenon [1–3] when adjusting the rf power back and forth. The reason may be the metastable multi-step ionization [4,5] or the nonlinear behavior of energy dissipation [6]. However, in addition to the normal hysteresis, we can also observe inverse hysteresis phenomenon under very low pressure [7]. ICP discharge mode changes between the E mode and H mode and plasma parameters also change with the change of the experimental conditions. ICP discharge mode conversion and plasma parameters mutation behavior would bring huge impact on the plasma membrane preparation, plasma etching and plasma stripping process. Therefore, it's meaningful to study the effects of different parameters on the plasma discharge way.

Low temperature plasma is an important tool of material processing. The final material structure and performance are subjected to the plasma temperature, plasma density and electron energy distribution function and so on, which are determined by the experimental conditions such as air pressure, power and flow rate. At present, people focus on rf power, impedance matching network [8] and other conditions on the effect of plasma mode transformation, but no one has a systematic research on the relationship between working pressure and plasma mode conversion. The change of working pressure can cause the change of the plasma density and electron temperature, which makes change of gas load impedance in the chamber and thus affect the current and the electric field intensity in the coil. Therefore, we proposed a conjecture which the working pressure can also cause the ICP discharge mode transformation and it was further proved by experiment in this paper.

2. Experimental setup

Fig. 1 shows that the schematic construction of the cylindrical ICP experimental setup. The height and dimension of reacting cavity are 300 mm and 200 mm, respectively. The height and diameter of the reaction chamber 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.

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http://dx.doi.org/10.1016/j.vacuum.2016.07.022
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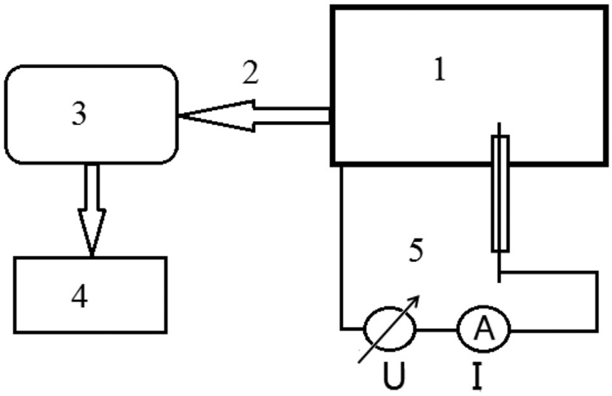

Fig. 1. The schematic construction of experiment. 1-chamber; 2-optical fiber; 3-Optical Spectrum Analyzer; 4-computer; 5-Langmuir probe system.

The optical emission spectrum of Ar was measured with a WDS8A-type multifunctional grating spectrometer that is composed of two parts as shown in Fig. 1. The inspection window in 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 and a blaze wavelength of 350 nm. Its spectrum measuring range is between 200 nm and 800 nm [9].

Electron temperature and plasma density were measured with Langmuir probe diagnostic technique. The probe, ampere meter and adjustable DC voltage source 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 [10]. Electron temperature can be achieved by calculating the slope of lnI-V curve, and then combined with a saturated ion current density of the plasma is calculated [11].

3. Spectral diagnosis principle

The plasma spectrum is related to particle radiation transition process. Atoms will produce the excited group A^*, when it impacted with electrons, such as the Formula (1) below:

$$A + e \rightarrow A^* + e \tag{1}$$

Unstable group A^* will jumps into the low energy ground state or excitation state of A^{**}, the release of the excess energy in the form of photons forming a light emission line at the same time, such as the Formula (2) below:

$$A^* \rightarrow A^{**} + h\nu \tag{2}$$

where $h\nu$ is emitted photon energy. Assume the wavelength of the emission spectrum is λ, the relationship between energy and wavelength is represented by Formula (3) below:

$$\Delta E = E_2 - E_1 = \frac{hc}{\lambda} = h\nu \tag{3}$$

where E_2 is higher level of energy, E_1 is Lower level of energy, h is Planck constant, c is speed of light. Each emission line corresponds to a specific wavelength because each particle has a precise energy level. The strongest spectral lines from the first excited state to the ground state of the intrinsic emission lines and the intrinsic spectrum is a group-specific in plasma, therefore, we can infer the group consisting of plasma by the intrinsic spectrum and the intensity of the emission spectrum can reflect the relative concentration of the group of emitting this spectral line.

OES [12,13] is a non-intrusive measurement method which is used to analyze the spectrum of the plasma by spectroscopic instruments. It can be get the excitation state and ionization state of particles in the plasma, as well as the plasma chemical components and other important information. In this paper, OES for qualitative analysis, in which the plasma discharge mode is determined by scanning plasma emission spectrum, the experiment measured spectral image as shown in Fig. 2.

When the discharge power is 326 W, the relative intensity of Ar characteristic spectrum at 419.5 nm is 57 at pressure of 0.32 Pa and the luminous intensity is lower, which indicates that the plasma is in E mode as shown by black line in Fig. 2. The relative intensity of Ar characteristic peak at 419.5 nm is 530 at 0.34 Pa and the luminous intensity is higher, which indicates that the plasma is in H mode as shown by red line in Fig. 2.

4. Results and discussion

4.1. Probe diagnosis

When ICP discharge power is 357 W, the trends of electron temperature and the plasma density with pressure is shown in Fig. 3 where the black line represents the plasma density and red line indicates the electron temperature. From the graph we can see that the electron temperature and the plasma density increases first and then decreases with the increase of pressure. The maximum value is found in the vicinity of 0.38 Pa and 0.4 Pa, respectively.

The reason is that free electrons are accelerated in an electromagnetic field and collide with neutral particles stimulate new free electrons to form a plasma. When the power is constant, with the increasement of pressure, the number of particles increased, which leads to the chance's of collisions between electrons and neutral particles increasing and then the degree of ionization increase, therefore the plasma density increase [14,15]. The load impedance reduces due to the increase of electron density. This further enhances the current in the coil which makes the field intensity increases that finally raises the electron temperature and the electron energy.

However, as the pressure continues to rise, the increasement of

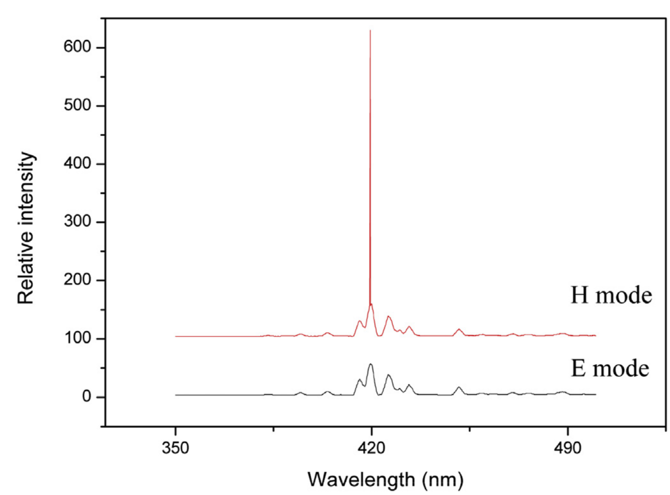

Fig. 2. The argon spectrum of plasma capacitive coupling discharge mode (E mode) for black line, inductive coupling discharge mode (H mode) for red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)