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Ion and neutral temperatures in an electron cyclotron resonance plasma

Akira Yonesu[a,*], Shunjiro Shinohara[b], Yasumasa Yamashiro[a], Yoshinobu Kawai[b]

[a]*Faculty of Engineering, Ryukyu University, 1 Senbaru, Nishihara, Okinawa, Japan*
[b]*Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka, Japan*

Abstract

Transverse ion and neutral temperatures at the electron cyclotron resonance position were measured in an electron cyclotron resonance (ECR) plasma using a high-resolution optical emission spectroscopy of Doppler profiles of Ar and Ar^+ transition. The transverse ion temperature increase from approximately 0.4 to 1.0 eV as the operating gas pressure is lowered from 1.0 to 0.1 mTorr. On the other hand, the transverse neutral temperature is much lower than the transverse ion temperature. By means of Langmuir probe measurement, large-amplitude potential fluctuation was observed at the ECR position under the low gas pressure. These observations suggest that the large-amplitude potential fluctuation directly affects the transverse ion temperature. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: ECR plasma; Ion temperature; Neutral temperature; Optical emission spectroscopy; Potential fluctuation

1. Introduction

Electron cyclotron resonance (ECR) plasmas have been attracting considerable attention in the field of plasma etching and deposition processes for semiconductor manufacturing, because they can be generated at low gas pressure compared to other plasmas and have high plasma density [1,2]. In ECR devices, most of the studies on the ECR plasma process have been carried out in the downstream region far from the ECR position. Recently, it has been reported that the high process rate can be achieved at the ECR position in the ECR plasma, because the plasma density at the ECR position is higher than that of downstream region [3,4]. For better understanding of these processes, it is important to obtain information about characteristics of the plasma at the ECR position.

In this paper, therefore, we report preliminary measurements of the transverse ion and neutral temperatures at the resonance position of an ECR processing plasma using a high-resolution optical emission spectroscopy of Doppler profiles of Ar and Ar^+ transitions. Transverse ion and neutral temperatures are important factors that determine anisotropy of etching and deposition property. In addition, the relationship between the ion temperature and the plasma parameters measured with Langmuir probe are investigated.

2. Experimental apparatus and method

Fig. 1 shows the schematic diagram of the experimental apparatus. The experiments were performed using a stainless-steel vacuum chamber, 1200-mm long and 290-mm in diameter. The magnetic fields were applied using six magnetic coils, and the magnetic field configuration is shown in Fig. 1. Microwaves (2.45 GHz) oscillated by a magnetron were converted from the rectangular TE_{10} mode to the circular TE_{11} mode, and were introduced into the chamber through a tapered waveguide and a quartz window. The microwave

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* Corresponding author. Tel.: +81-98-895-8692; fax: +81-98-895-8708.

E-mail address: yonesa@eee.u-ryukyu.ac.jp (A. Yonesu).

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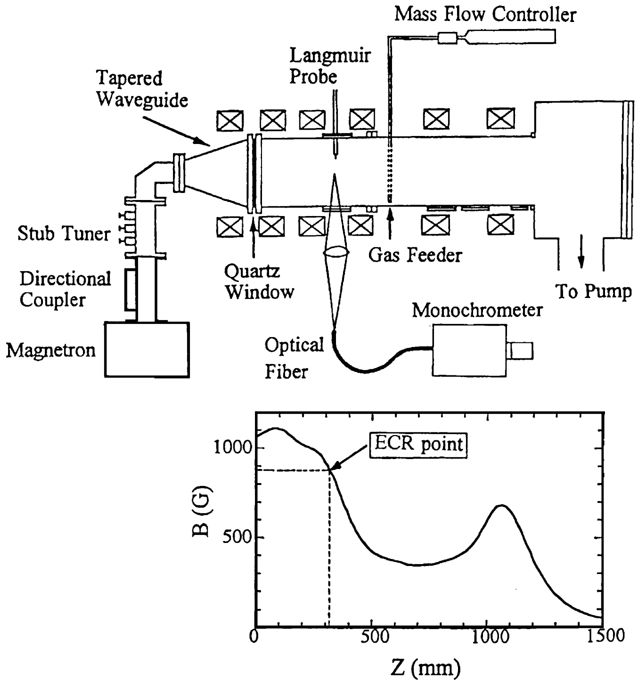

Fig. 1. Schematic diagram of the experimental apparatus and magnetic field configuration.

power is coupled very efficiently into the plasma near the ECR resonance magnetic field of 875 G ($z = 350$ mm).

Optical emission from the ECR position in the ECR plasma is collected along the radial direction through a view port on the side of the camber ($z = 350$ mm) using a lens-optical fiber combination. The emission enters a 1500-mm focal length monochrometer equipped with a 2400-groove/mm grating brazed at 300 nm and is detected by a photomultitube. This measurement yields values, which are integrals along the line of sight. The line broadening due to the instrument was determined by measuring a spectral profile of Hg-lamp light at 313.18 nm. The instrument broadening was measured at various times during the collection of data, and was fairly stable at 0.0038 ± 0.0003 nm. The emission line profiles observed in plasmas may be broadened by many factors. Natural and collisional broadening are insignificant compared to the Doppler width. Typical charged particle densities in this device are on the order of 10^{11} cm^{-3}, which is roughly 2 orders of magnitude less than densities which produce significant Stark broadening [5]. The presence of the static magnetic field at the ECR position (~ 1 kG) can cause a broadening of emission lines due to the Zeeman effect, and it is estimated to contribute approximately 0.001 nm to the line broadening [5]. The expected Zeeman broadening at the ECR position was less than the instrument broadening, and is neglected. Hence, after the removal of instrumental broadening by applying the following equation:

$$(\Delta\lambda)^2 = (\Delta\lambda_{\mathrm{m}})^2 - (\Delta\lambda_{\mathrm{i}})^2$$

where $\Delta\lambda$ is the true width (FWHM) of the Doppler profile, $\Delta\lambda_{\mathrm{m}}$ is the width of the measured line shape, and $\Delta\lambda_{\mathrm{i}}$ is the width of the instrument shape, the temperature can be computed from the following equation:

$$kT_{\mathrm{i}} = \frac{mc^2}{8\ln 2}\left(\frac{\Delta\lambda}{\lambda}\right)^2$$

where m is the mass, c is the speed of light, and λ is the line center wavelength.

Langmuir probe measurements were made to obtain the plasma potential. The probe was set at the ECR position ($z = 350$ mm). In the experiments, Ar gas was introduced into the chamber through a mass flow controller.

3. Results and discussion

Typical emission line profiles of the HgI (313.18), ArI (420.06 nm) and ArII (487.99 nm) transitions and least square fitting of a Gaussian to the profiles are shown in Fig. 2. The microwave input power was 2.5 kW and gas pressure was 0.1 mTorr. The line profiles are well fitted by Gaussian. Similar agreement could be obtained for all observed Ar and Ar$^+$ transitions, indicating that the Doppler profiles of all emission lines are parameterized by single Boltzman distribution.

Fig. 3 shows the dependence of the transverse ion and neutral temperatures on the gas pressure at the input microwave power of 2.5 kW. Transverse ion and neutral temperatures were estimated from the Doppler profiles of ArII 487.98, ArII 434.81 and ArI 420.06 nm lines, respectively. It is seen in this figure that the transverse ion temperature increases with decreasing gas pressure. On the other hand, the transverse neutral temperature shows a weak dependence on gas pressure. The input microwave power is resonant to electron cyclotron frequency and thus, couples into the electron only. Also, the transfer of energy from electrons to the ions and neutrals with collision is extremely inefficient. Thus, these experimental results indicate that there is some ion heating mechanism other than the collision in this reactor at the low gas pressure. Several investigators have observed high transverse ion temperature at the downstream region in the ECR devices [6–8].

To examine the relationship between the electrical properties of the plasma and the transverse ion temperature at the ECR position, Langmuir probe studies

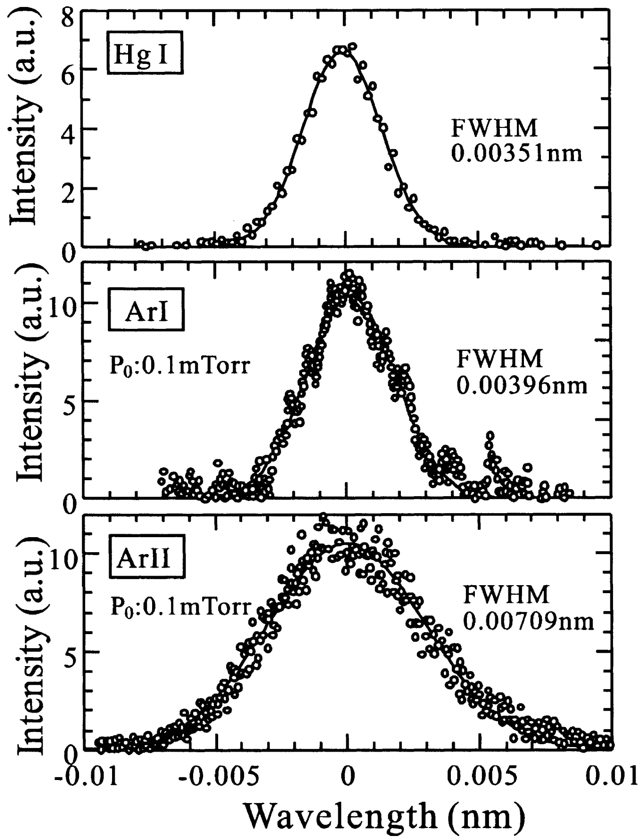

Fig. 2. Typical emission line profiles of the Hg (313.18 nm), ArI (487.99 nm) and ArII (420.06 nm) transition and Gaussian fitting curve for the pressure of 0.1 mTorr and microwave power of 2.5 kW.

of the plasma potential were carried out under the conditions at which the optical measurements of the temperature were conducted. Rossnagel et al. proposed that the radial component of the plasma potential is a possible mechanism for ion and neutral heating in an ECR reactor [9]. Then, to determine the influence of radial electric fields on the transverse ion temperature in this system, Langmuir probe measurement of the plasma potential were performed at various points along the radius of the chamber. A moveable Langmuir probe was inserted into the plasma at the ECR position, and plasma was operated at pressures of 1 and 0.1 mTorr. Fig. 4 shows the radial profiles of the plasma potential.

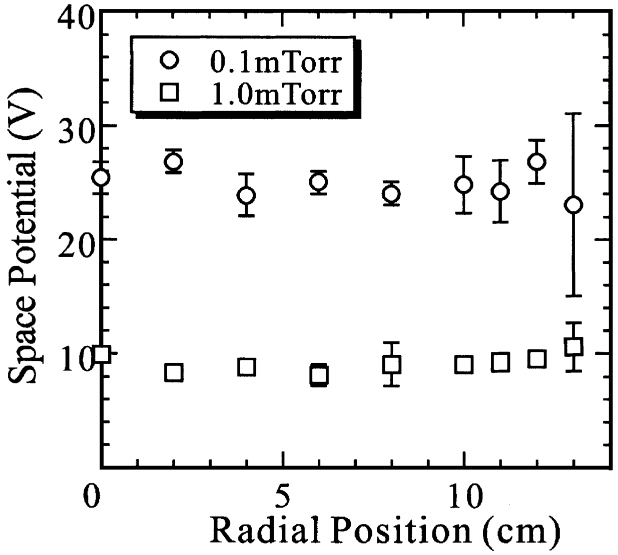

Fig. 4. Radial profiles of plasma potential at gas pressure of 0.1 and 1.0 mTorr, where the microwave power is 2.5 kW.

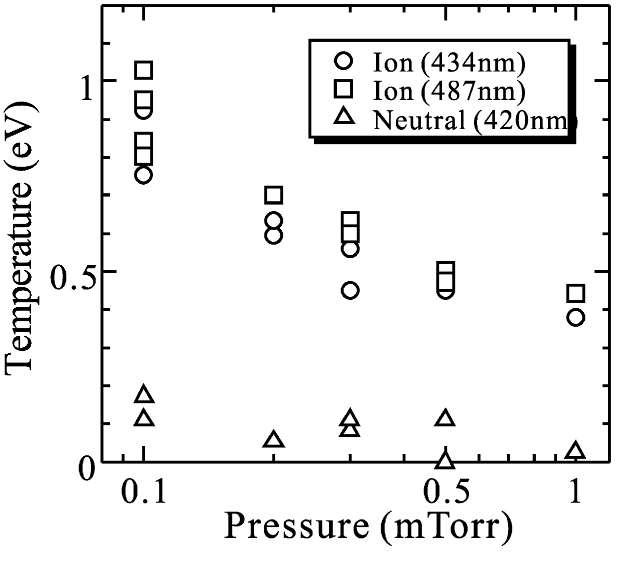

Fig. 3. Dependence of transverse ion and neutral temperatures on gas pressure at microwave power of 2.5 kW.

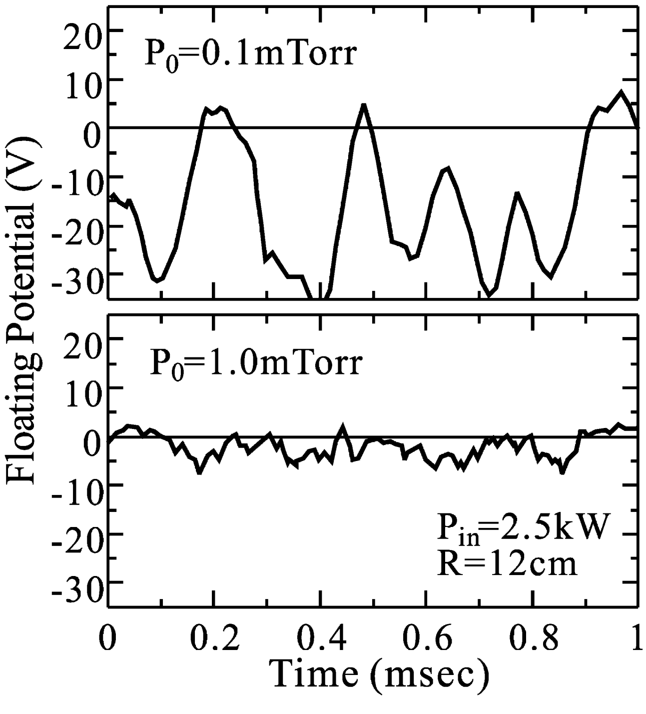

Fig. 5. Evolution of floating potential at gas pressures of 0.1 and 1.0 mTorr.

The error bars were determined by repeated measurements. The uncertainty in the plasma potential is dominated by the fluctuation in the plasma. It is found that radial profiles of the plasma potential are uniform. Thus, there is no radial electric field in this system at the ECR position. Next, we measured time evolution of floating potential by means of Langmuir probe under the gas pressures of 0.1 and 1.0 mTorr. From Fig. 5, it is found that large amplitude potential fluctuation is observed at the low gas pressure of 0.1 mTorr. And, the amplitude of the potential fluctuation decreased with increasing gas pressure. These results seem to indicate that this potential fluctuation affects the ion temperature. According to measurements of azimuthal mode number and propagating direction, this fluctuation is considered to be a flute mode instability. Additional research is needed to elucidate ion-heating mechanism.

4. Conclusion

We have measured transverse ion and neutral temperatures at the ECR position in the ECR plasma. The transverse ion temperature ranges from approximately 0.4 to 1.0 eV as the operating gas pressure varies from 1 to 0.1 mTorr, while the transverse neutral temperature is much lower than the transverse ion temperature. This high ion temperature attributed to the potential fluctuation at the ECR position in the ECR plasma. These results have important implications for the use of ECR devices for plasma etching, since transverse ion temperature may determine the ultimate limit to the anisotropy of the etching.

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