Investigation of emission spectrum profile of hydrogen atom in micro-hollow cathode discharge

K. Takeda[1], S. Shimizu[1], S. Takashima[2], M. Hiramatsu[1] and M. Hori[3]

[1]*Department of Electrical and Electronic Engineering, Meijo University, Nagoya, Japan*
[2]*Nagoya Industries Promotion Corporation, Nagoya, Japan*
[3]*Institutes of Innovation for Future Society, Nagoya University, Nagoya, Japna*

Abstract: Emission spectrum profile of hydrogen (H) atom (Lyman α line) emitted in an atmospheric pressure micro-hollow cathode discharge was estimated on the basis of the analysis of measurement results on absorption spectroscopy with the discharge plasma as a light source. From results, the emission spectrum profile of H atom emitted in the micro-hollow discharge was found to be a Voigt profile taken into account Lorentz and Gaussian broadenings and the ratio of Doppler to Lorentz broadenings was about 1.5.

Keywords: Spectrum profile, Lyman α, Absorption spectroscopy, Atomic radical.

1. Introduction

Processing plasmas are very important tools to achieve various nano and micro fabrication processes such as plasma etching, plasma enhanced chemical vapor deposition, surface modification, and so on. For developing the plasma processes, trial and error methods have been frequently used in the industry because it is difficult to understand the inside states of processing plasmas. Therefore, it is necessary to consume huge resource and energy to develop the more high precise plasma processes. In order to accelerate the developments of plasma processes for next generation technologies of nano and micro fabrications, it is strongly required to clarify the process reactions in the plasmas and control important parameters to determine the features of plasma processes [1]. As one of the parameters determining the process features, atomic radicals have been attracted much attention because the species have high reactive properties in the processing plasmas. Therefore, the quantitative behaviors of atomic radicals in the plasma processes must be measured and understood.

In our group, a measurement system for the absolute densities of atomic radicals in process plasmas has been developed by employing vacuum ultraviolet absorption spectroscopy (VUVAS) with an atmospheric micro-discharge hollow cathode lamp (MHCL) [2]. Since the micro-hollow cathode discharge in atmospheric pressure is used as a VUV light source, the VUVAS system using MHCL is very compact and convenient for measuring the absolute density of atomic radical. Therefore, the VUVAS system with MHCL could be applied to evaluate the behaviors of various atomic radicals such as H, O N, and C atoms in processing plasmas [2-5]. However, on the VUVAS with a plasma as a light source, the spectrum profile of light emitted from the plasma light source is very important to estimate the absolute density from the light absorption intensity due to atomic species in the processing plasma. In this study, from the measurement results of VUVAS with VUV laser and MHCL as light sources, the emission spectrum profile of atomic radical emitted in the micro-hollow cathode discharge was estimated for realizing more precise quantitative measurements of atomic species.

2. Experimental setup

Firstly, absolute densities and translational temperatures of H atom emitted from a hydrogen (H) atom source with an inductively-coupled plasma (ICP) were measured by VUVAS with the tunable VUV laser. And then, the absorption intensity of H atom in same condition was measured by VUVAS with the MHCL based on micro-hollow cathode discharge as light source. From the results, the emission spectrum profile of H atom emitted in the micro-hollow cathode discharge was estimated experimentally.

Figure 1 (a) and (b) show the experimental setups for VUVAS using the MHCL and the tunable VUV laser, respectively. These measurements were carried out at the position of 150 mm away from the H atom source. The transition line of H atom used for measuring the H atom was a Lyman α (L_α) line at 121.6 nm. The MHCL shown in Fig. 1 (a) has cathode and anode electrodes consisting of cupper plates with a through-hole hollow of 0.1 mm in diameter. Helium (He) gas containing small amounts of H_2 gas was used as a discharge gas. The MHCL was operated at a total pressure of 0.1 MPa. In the micro-hollow of cathode electrode, an atmospheric pressure micro-plasma was generated and an atomic line spectrum at L_α line of H atom were emitted from the plasma.

In the case of the H atom measurement with the VUV laser, in order to generate the VUV laser radiation around 121.6 nm, two photon resonance four wave sum frequency mixing technique using two dye laser system and Krypton (Kr) gas was used [6]. The two dye lasers generated the laser radiations with wavelength of ω_1 and ω_2, respectively. The wavelength of ω_1 was 212.56 nm which was generated by frequency doubling the dye laser output in the BBO I and the wavelength of ω_2 was around

844.6 nm. These laser radiations were focused in the Kr gas phase (20 Torr) in the gas cell using a lens with a focusing length of 300 mm though a quartz window at the same time. In this case, for the adjustment of ω_1 to an exact two-photon resonance line, photo ionization current of Kr atom in the gas cell was monitored by using a probe. In the system, the wavelength of radiated VUV laser light could be tuned around 121.6 nm by changing the wavelength of ω_2. The generated VUV lights of MHCL and VUV laser passed though the MgF_2 window and introduced into the chamber. And then, these VUV light transmitted in the chamber were focused on the slit of a VUV monochromator by MgF_2 lens and detected by a solar-blind photomultiplier tube (PMT). The absorption path lengths of incident lights into the chamber were set at 170 and 190 mm in the experimental setups for the MHCL and the tunable VUV laser, respectively.

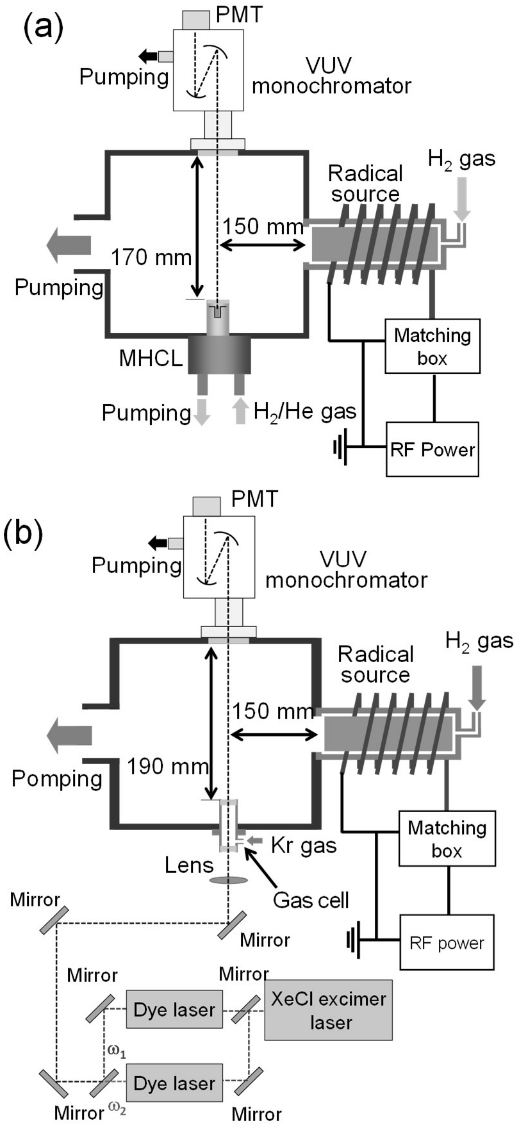

Fig. 1. Experimental setups for VUVAS using (a) a MHCL and (b) a tuneable VUV laser as light sources.

3. Results and discussion

Firstly, the absolute densities and the translational temperatures of H atom emitted from the atom source with H_2 gas ICP were measured using the setup of VUV laser absorption spectroscopy (VUVLAS) shown in Fig. 1 (b). Figure 2 shows an example for a profile of absorption intensity due to H atom at L_α line measured by VUVLAS. In the measurement, the ICP was generated at the condition of a pressure of 4 Pa and a H_2 gas flow rate of 8 sccm and an input RF (13.56 MHz) power was set at 200 W. From the result shown in Fig. 2, the absolute density and the translational temperature of H atom were estimated to be 3×10^{11} cm^{-3} and 400 K in the condition.

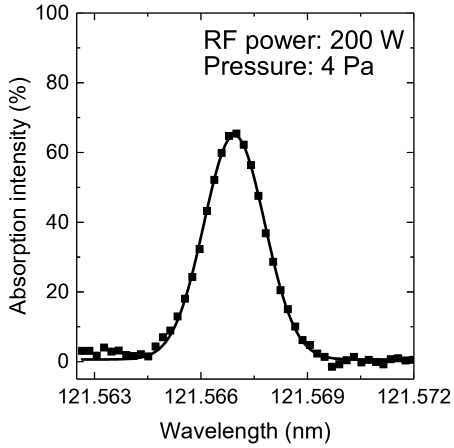

Fig. 2. Profile of absorption intensity due to H atom at L_α line measured by VUVLAS.

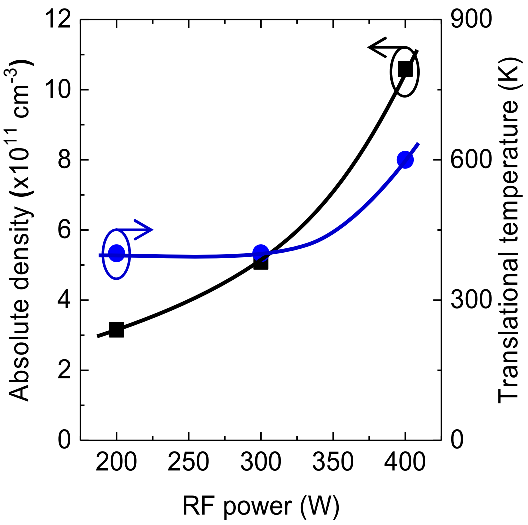

Fig. 3 Absolute density and translational temperature of H atom measured by VUVLAS as a function of RF power for ICP discharege.

Next, the absolute density and translational temperature of H atom were measured as a function of input RF power supplied to the ICP coil antenna. The RF power was changed from 200 to 400 W. The results are shown in Fig. 3. The absolute density increased from 3×10^{11} to 1×10^{12} cm^{-3}. And the translational temperature of H atom was almost constant around 400 K at the RF power from 200 to 300 W, although the temperature increased up to 600 K at the condition of 400 W.

In this study, the profile of VUV light emitted from the MHCL was estimated by using following equation (1) about the absorption intensity $G(k_0L)$.

$$G(k_0L) = 1 - \frac{I_{out}}{I_{in}} = 1 - \frac{\int f_1(v)exp[-k_0 f_2(v)L]dv}{\int f_1(v)dv} \qquad (1)$$

where ν is a frequency, $f_0(v)$ is an emission profile at L_α line of H atom emitted from the MHCL, $f_a(v)$ and k_0 are an absorption line profile of H atom and an absorption coefficient at the center frequency of absorption line profile of H atom measured by VUVLAS, and L is an absorption path length of incident light into the chamber emitted from the MHCL. In the MHCL, the effect of Lorentz broadening becomes large because the working pressure of MHCL is 1 atm. Therefore, the emission line profile $f_0(v)$ was assumed to be a Voigt profile taken into account Lorentz and Gaussian broadenings. From the measurement results using the VUVAS setup with MHCL as shown in Fig. 1 (a), the absorption intensities due to H atom were measured to be 25.3 (at RF power of 200 W), 47.2 (300 W), 56.6% (400 W) at the same conditions of ICP discharge with VUVLAS measurement, respectively. From the results, it was found that the ratio of Doppler broadening Δv_D to Lorentz broadening Δv_L was estimated to be about 1.5 by using Eq. (1).

4. Summary

The emission spectrum profile of H atom at L_α line emitted from the MHCL was estimated on the basis of analysis of measurement results on the VUVAS employing MHCL and tunable VUV laser as light sources. In this study, the H atom source with H_2 gas ICP was used for estimating the emission spectrum profile. From the measurement results of H atom emitted from the atom source by using the VUVLAS, it was found that the absolute density of H atom increased from 3×10^{11} to 1×10^{12} cm^{-3} with increasing the input RF power, and the translational temperature also increased from 400 to 600 K. On the other hand, the absorption intensities due to H atom measured by the VUVAS with MHCL were 25.3 (RF power: 200 W), 47.2 (300 W), 56.6% (400 W) at the same conditions of ICP discharge with the VUVLAS measurement. From the results, the ratio ($\Delta v_L/\Delta v_D$) of Doppler to Lorentz broadenings of emission spectrum profile of H atom at $L\alpha$ line emitted in MHCL was estimated to be 1.5.

5. References

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