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Spatial-resolved laser absorption spectroscopy on a micro hollow-cathode helium plasma in the pressure range from 10 to 100 kPa

10~100 kPaのマイクロホローカソードヘリウムプラズマの
空間分解レーザー吸収分光

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For the 1s2p(^{1}P) → 1s3d(^{1}D) transition at 667.815 nm of helium atoms in a micro hollow-cathode plasma having the diameter of 300 μm, we measured the absorption line profiles with the spatial resolution of 30 μm using a vertical-cavity surface-emitting laser diode. For the gas pressure below 20 kPa, the observed profiles near the electrode were asymmetric. By fitting the observed profile with a Voigt function including the DC Stark effect, we determined the Doppler and Lorentz widths and the electric field strength. From the determined widths, we evaluated the gas temperature and electron density. For the gas pressures above 30 kPa, we evaluated the gas temperature and electron density only because the asymmetry was not detected. We made two-dimensional maps of the gas temperature and electron density from 10 to 100 kPa.

1. Introduction

Atmospheric-pressure plasmas have been attracting much interest because of their possibility for various applications, such as surface treatment, nano-particle formation and pollution gas processing [1]. One of the methods for reliable plasma generation under high-pressure at moderate voltage is a micro hollow-cathode discharge. The gas temperature and electron density of the micro hollow-cathode plasma have been measured with emission spectroscopy [2].

In comparison with the emission spectroscopy, laser absorption spectroscopy is nearly free from spectral resolution. Since the spectral line width at atmospheric pressure broadens over several tens of GHz in full width at half maximum mainly due to the pressure broadening, we used in this work a Vertical-Cavity Surface-Emitting Laser (VCSEL) diode, which can scan the light frequency over several hundreds of GHz in the single longitudinal mode operation [3,4]. We measured the absorption line profile of the helium atom 1s2p(^{1}P) → 1s3d(^{1}D) transition with 30 μm spatial resolution (in the Rayleigh criterion) and with 10.8 μm step in a 300 μm-diameter micro hollow-cathode plasma.

2. Experiment

Figure 1 shows a schematic illustration of the experimental set-up. The light source is a VCSEL diode (vixar, V670S-002-0001) set on a diode mount (THORLABS, TCLDM9). We set the light frequency around that of the helium 1s2p(^{1}P) → 1s3d(^{1}D) transition. We scan the injection current at the repetition rate of 10 Hz to tune the laser light frequency by a current driver (THORLABS, LDC202C).

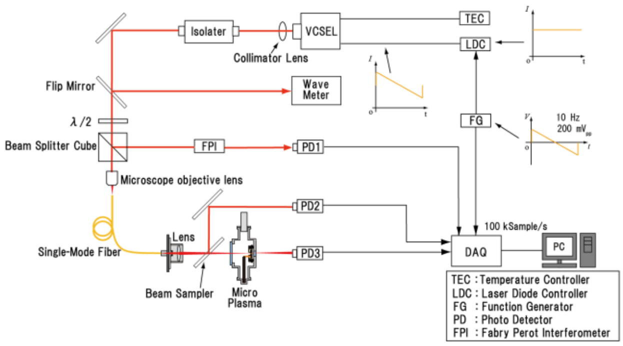

Fig. 1. Experimental set-up

A part of the laser light beam is used for the frequency scan measurement by a Fabry-Pérot interferometer (NEOARK, SA-40C; FSR=1.85 GHz) with a photo-detector (PD1). The main light beam is focused on an edge of a single-mode optical fiber, which is used as a spatial filter to select the TEM_{00} mode. The light transmitted through the optical fiber is focused on the plasma with a diameter of 30 μm. The focused position in the plasma can be tuned. A part of the light beam is separated by a beam sampler (SURUGA SEIKI, F56-30) and measured by a photo-detector (PD2) as the intensity reference. The light intensity transmitted through the plasma is measured by a photo-detector (PD3).

3. Results and discussion

Figure 2 shows examples of the observed absorption spectra. All the spectra is normalized at their peaks for easy comparison of the profiles. Around the center of the micro hollow-cathode plasma shown in Fig.2 (a), the profile is symmetric and the pressure broadening is clearly seen in the measured pressure range from 10 to 100 kPa. Around the edge of the micro hollow-cathode plasma, the pressure broadening is also clearly observed but the profiles at lower pressures shows asymmetry as seen in Fig.2 (b); a low frequency tail is observed.

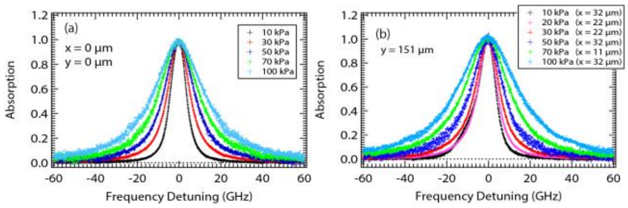

Fig. 2. Examples of the observed absorption spectra around the center (a) and around the edge (b) of the micro hollow-cathode plasma from 10 to 100 kPa.

It is known that there is a sheath electric field near the cathode [5]. It is also known that an electric field leads Stark effect, which causes an asymmetric line profile or splitting [6]. For the observed transition line, the second order Stark effect of the upper 3^1D level is dominant [6,7,8], and we calculate it for the magnetic sublevels.

By fitting the observed profile with a Voigt function including the DC Stark effect for 10 and 20 kPa, we determined the Doppler and Lorentz widths and the electric field strength. From the determined widths, we evaluated the gas temperature and electron density. Since the asymmetric profile was not clearly observed for the gas pressures from 30 to 100 kPa, we evaluated the gas temperature and electron density only.

Figures 3 and 4 are two-dimensional maps of the gas temperature and electron density, respectively. It is noted the black and white spots in the plasma show the positions where the evaluated parameters are below and beyond the color scales, respectively. The change of the observed plasma shape in the maps is thought to be due to imperfection of the position scan.

At 10 kPa, the spatial distribution of the gas temperature has a peak around the plasma center, while they are rather flat at the pressures above 20 kPa. Fig. 5(a) shows the spatially averaged gas temperature together with the plasma input power as a function of the gas pressure. Correlation can be seen between them. Fig. 5(b) shows the spatially averaged electron density. Change of the discharge condition around 20 kPa is suggested.

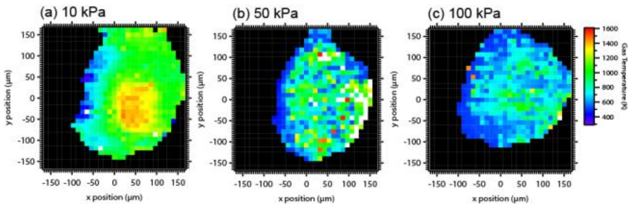

Fig. 3. Two-dimensional maps of the gas temperature

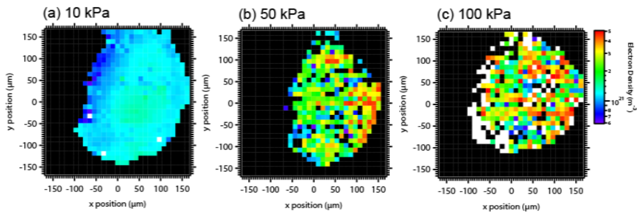

Fig. 4. Two-dimensional maps of the electron density

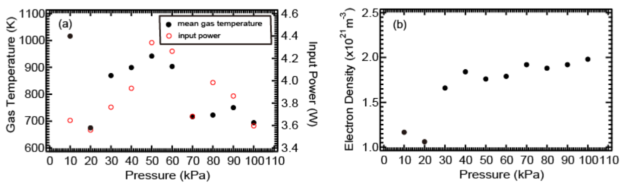

Fig. 5. Spatially averaged gas temperature (a) and electron density (b) as a function of the gas pressure. The input power to the plasma is also shown in (a).

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