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Experimental Test of Absorption Saturation of Forbidden Line by Diode Laser for Number Density Measurement

数密度測定のための半導体レーザーを用いた禁制線の吸収飽和の実験的検証

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Combined laser absorption spectroscopy with absorption saturation using two transition lines was proposed to measure the ground state number density of atomic oxygen. In this method, a forbidden transition line of OI 636 nm is fully saturated by laser beam to increase the upper state number density. The number density of ground state is estimated by the upper state number density measured by laser absorption spectroscopy using allowed transition line of OI 558 nm. In this study, the saturation intensity for the forbidden line of OI 636 nm were numerically estimated. Then, the saturation intensity for ECR microwave plasma was experimentally examined by the ground state number density measurement using vacuum ultraviolet absorption spectroscopy of OI 130 nm.

1. Introduction

The atomic number density in plasma is important in several fields such as plasma etching, plasma processing, space propulsion and thermal protection system (TPS) for entry vehicle from the space. However, its measurement method has not been established yet. Recently, two-photon absorption laser-induced fluorescence (TALIF) is used as the effective measurement method for accessing the ground state. However, it has the problems that it is difficult to calibrate absolute intensity of fluorescence and results in inaccurate number density measurement under high pressure region due to quenching and reabsorption. [1]

Therefore, our group has proposed two-stage absorption spectroscopy (TSAS). Figure. 1 shows the schematic diagram of TSAS. In this method, the ground state is saturated with the upper state using a forbidden line of OI 636 nm. Then, laser absorption spectroscopy (LAS) is applied to the upper state using an allowed line of OI 558 nm. The number density of the ground state can be deduced from the number density of the upper state and the condition of the absorption saturation. The advantage of this method is that it can measure the number density of the ground state, applied to optically thick plasmas and conduct In-situ measurement. In this study, the saturation beam intensity for the forbidden line of OI 636 nm is numerically estimated. Then, the saturation intensity was experimentally examined by measuring the fractional absorption using vacuum ultraviolet absorption spectroscopy (VUVAS).

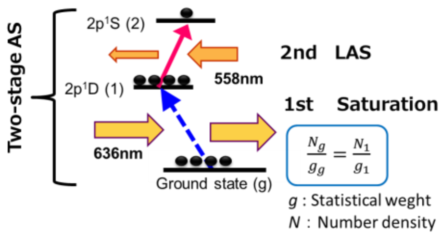

Fig. 1 Schematic diagram of TSAS

2. Measurement Principle

2.1 Absorption saturation

When the laser intensity gets high, the decrease of the number density of the lower state is not negligible and decrease of fractional absorption occurs. It is called as the absorption saturation.

The saturation beam intensity I_{sat} is expressed by the following equation:

$$I_{sat} = \frac{g_2}{g_1 + g_2} \frac{\pi c \Delta \nu_c}{2} \frac{A_{21} + Q}{B_{21}}, \tag{1}$$

where, A, B, g, Q and $\Delta\nu_c$ are the Einstein coefficients, the statistical weight, the quenching rate and the pressure broadening. Then, when the absorption saturation occurs, the rate of the number density between the upper and lower state is expressed as

$$\frac{n_2}{n_1} = \frac{g_2}{g_1}. \tag{2}$$

In this method, the absorption saturation is caused by diode laser. Then, the number density of the ground state can be obtained by Eq. (2).

2.2 Principle of absorption spectroscopy

The relationship between the incident beam intensity I_0 and the transmitted beam intensity I_t can be expressed by the Beer-Lambert law as [2]

$$I_t = I_0 \exp\{-k(\nu)l\}, \tag{3}$$

where $k(\nu)$ and l are the absorption coefficient at frequency ν and the absorption length, respectively. The vacuum ultraviolet beam is detected by using a VUV spectrometer. However, the wavelength resolution of it is two orders magnitude worse than the spectral line width. Therefore, the actual measured beam intensity is the frequency integrated value as [3]

$$\frac{I_t}{I_0} = \frac{\int f_1(\nu)\exp\{Kf_2(\nu)l\}d\nu}{\int f_1(\nu)d\nu}, \tag{4}$$

where $f_1(\nu)$ and $f_2(\nu)$ are the probe beam profile and the absorption profile of the target.

In this study, the fractional absorption $1-I_t/I_0$ of OI 130 nm is measured for confirmation of the absorption saturation. When the absorption saturation occurs, decrease of the fractional absorption of OI 130 nm is deduced because the number density of the ground state is decreased.

3. Experimental Apparatus

Figure. 2 shows the schematic diagram of the absorption saturation system. The target plasma is generated by ECR heating. The input power is 50 W and the operation pressure ranges 10^{-1}-10^{2} Pa. The flow rate of the oxygen is 2-10 sccm. A single longitudinal mode diode laser (HL6312G; Opnext Ltd., LDC205C; Thorlabs Inc.) was used for the absorption saturation. The VUV beam of ICP is led to the VUV spectrometer (234/302, McPherson Inc.) through the test chamber. The wavelength resolution is 0.1nm.

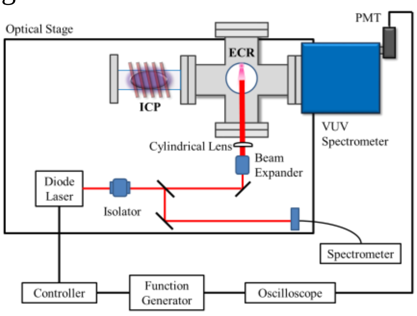

Fig. 2. Absorption saturation system

4. Results and Conclusions

The saturation beam intensity is numerically estimated by Eq. (3). The target forbidden line is OI 636 nm, whose spectroscopic parameters are g_1=3, g_2=5, A_{21}=5.63×10^{-3}, respectively. Figure. 3 shows the relationship between the pressure and the saturation beam intensity assuming the temperature T as a parameter. In Fig. 3, with increasing pressure, the saturation beam intensity also increases.

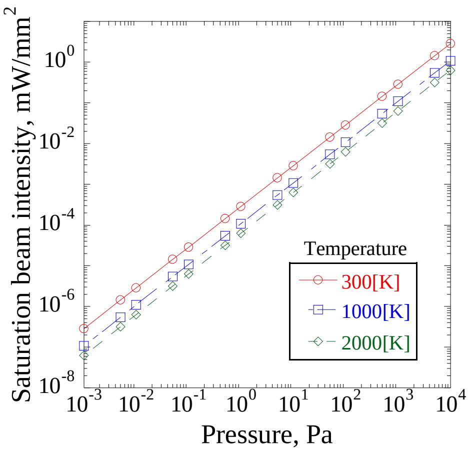

Fig. 3. Relationship between pressure and saturation beam intensity. OI 636 nm.

Figure. 4 shows the signal of oscilloscope using VUVAS without 636 nm diode laser. The fractional absorption is obtained from the relationship among the signal intensity of ECR, ECR+ICP and ICP regions. When the absorption saturation occurs, the increase of the signal intensity of the region of ECR+ICP is deduced.

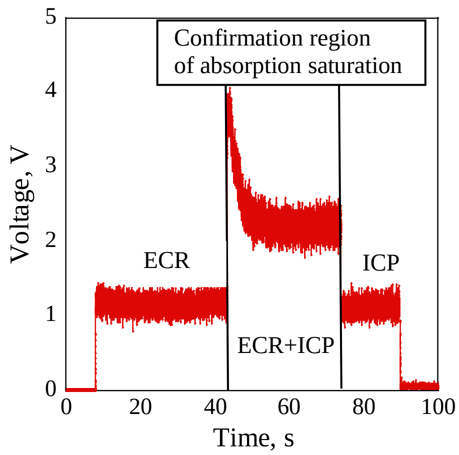

Fig. 4. Monitoring using VUVAS

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