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飽和吸収分光法によるアルゴン準安定状態の緩和周波数測定：電子密度計測への応用
Relaxation frequency measurement of metastable argon by saturation spectroscopy: application to electron density measurement

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Introduction We developed a system of saturation spectroscopy with the intention of applying it to the measurement of electron density in an argon-containing plasma.The principle of the electron density measurement is that the amplitude of the saturation spectrum in the $4s[3/2]_2^o - 4p[3/2]_2$ line of argon is a function of the electron density.The broadband spectrum which was originated from the velocity changing collision was separated from the observed saturation spectrum to obtain the true amplitude of the $4s[3/2]_2^o - 4p[3/2]_2$ line. The electron densities in argon-helium mixture plasmas were evaluated by the proposed method, and the results were in reasonable agreements with the measurements using a Langmuir probe.

Experiment We used an inductively-coupled plasma source with an internal antenna in this experiment.The antenna was connected to an rf power supply at 13.56 MHz via a matching network.The discharge gas was the mixture of argon and helium.The partial pressure of argon was 5 mTorr.The light source of absorption spectroscopy was a diode laser.The diode laser beam was divided into two beams, and the diode laser beams with higher and lower intensities were used as the pump and probe beams, respectively.The pump and probe laser beams were injected into the plasma from the contrary directions. The intensity of the probe laser beam passing through the plasma was detected using a photodiode.

Results and discussion Fig. 1 shows the difference between absorption spectra observed with and without pump laser beam by saturation spectroscopy. The shape of the saturation spectrum is Lorentzian in the simple theory of saturation spectroscopy. However,the saturation spectrum shown in Fig. 1 has Gaussian components which are attributed to “velocity changing collisions” of the argon metastable state at the bottom of the spectrum.The saturation spectrum with the components due to velocity changing collisions was analyzed on the basis of a theory[1].The sharp spectrum(b)(the red curve) at the line center in Fig. 1 corresponds to the Lorentzian component separated from the measured spectrum, from which we evaluated $\Delta\alpha/\alpha_0$ in $S_0 = 1/(1-\Delta\alpha/\alpha_0)^2 - 1$.This equation shows the relationship between the amplitude of saturation spectrum and the saturation parameter.The saturation parameter is given by $S_0 = B_{12}I_v/cR^*$,where B_{12} is the Einstein's B coefficient,I_v is the spectral intensity of the pump laser beam,c is the speed of light,and $R^*$is the effective relaxation frequency of the relevant energy system.

For $4s[3/2]_2^o - 4p[3/2]_2$ absorption which we employ in this work,the lower energy state of this absorption line is metastable. In the case of the absorption line originated from an argon metastable state, the relaxation frequency is dominantly determined by the relaxation frequency of the metastable state. The lifetime of the metastable state in a plasma is determined by collisional quenching.There are two kinds of quenchers, neutral species and electrons.The former has much smaller rate coefficients of collisional quenching than the later's which is known as a large value of 2×10^{-7} cm^3/s [2]. The relaxation frequency in saturation spectroscopy has an additional factor, which is the transit time of metastable argon through the diameter of the pump laser beam. Hence, the total relaxation frequency is given by $R^* = k_q^e n_e + a/v$,where k_q^e is the rate coefficient of electron impact quenching, n_e is the electron density, a is the diameter of the pump laser beam, and v is the mean velocity of metastable argon. Therefore, by measuring the amplitude of saturation spectrum $\Delta\alpha/\alpha_0$, we can evaluate the relaxation frequency R^*, and then the electron density n_e according to the theory mentioned above.

Fig.2shows the comparison between $1/S_0$ and the electron density.The electron density was measured using a Langmuir probe, and $1/S_0$ was evaluated from $\Delta\alpha/\alpha_0$ using $S_0 = 1/(1-\Delta\alpha/\alpha_0)^2 - 1$. As shown in Fig. 2, linear relationships were observed between $1/S_0$ and n_e. The linear relationships represent $R^* = k_q^e n_e + a/v$, and the intercepts correspond to a/v. Therefore, in conclusion, the experimental result shown in Fig. 2 indicates that the proposed method can work as a method for the electron density measurement in argon-containing plasmas.

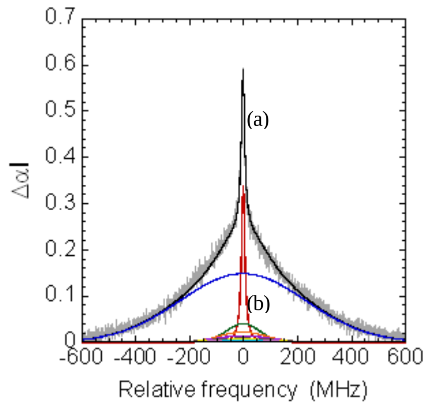

Fig.1. Spectrum (a) shows the difference in the two absorption spectra observed with and without pump beam.Sharp spectrum (b)shows the Lorentzian component separated from velocity chaning collision.

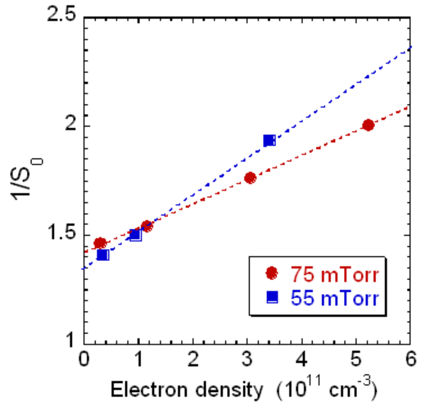

Fig.2. Comparison between the reciprocal of the saturation parameter and the electron density.

[1] C. Brechignac and R. Vetter, Phys. Rev. A **17**, 1609 (1978).
[2] K. Sasaki and R. Asaoka, Jpn. J. Appl. Phys. **50**, 08JB02 (2011).