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# Ultra-sensitive measurement of sheath electric field by laser-Stark spectroscopy of argon Rydberg states
# アルゴンリュドベリ状態のレーザーシュタルク分光による超高感度シース電界計測

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By applying laser-induced fluorescence-dip spectroscopy to Ar, we have developed a technique for sensitive measurements of electric fields in reactive plasmas. A detection limit of 3 V/cm has been achieved, which is the most sensitive detection limit in the world. We have measured electric fields in the sheath regions of Ar and Ar/$SF_6$ plasmas produced in an inductively coupled plasma source. In this paper, we show the distributions of sheath electric fields in electronegative Ar/$SF_6$ plasmas, together with the comparison with theoretical calculations based on a fluid model.

## 1. Introduction

The measurement of electric field is important for optimizing plasma processing of materials since the irradiation of positive ions accelerated in the sheath electric field plays essential roles. In addition, the detailed structure of the sheath electric field, especially in the case of electronegative plasmas, is of interest from the view points of basic plasma physics and basic discharge physics. We have developed a technique for sensitive measurements of electric fields in various processing plasmas [1-3]. The technique is based on laser-induced fluorescence-dip (LIF-dip) spectroscopy, which was demonstrated by Czarnetzki and coworkers in several years ago [4]. Czarnetzki and coworkers employed H atoms as the probe particle. We have applied LIF-dip to Ar, by which we can measure electric fields in various plasmas. In this paper, we demonstrate the measurements of sheath electric fields in electronegative Ar/$SF_6$ plasmas produced in an inductively-coupled plasma source. The experimental results are compared with theoretical calculations based on a fluid model.

## 2. Principles

The principles of LIF-dip of Ar have been reported previously. It is a sort of laser Stark spectroscopy. Since the energy level structure of high Rydberg states is a function of the electric field, we can determine the strength of electric field from the measurement of the energy level structure of high Rydberg states. In LIF-dip, the energy level structure is detected as a dip spectrum of LIF intensity by employing a two-step excitation scheme using two tunable lasers. We detected a high Rydberg state with a principal quantum number of $n = 58$, and we achieved a sensitive detection limit of 3 V/cm by measuring the magnitude of Stark shift of an Rydberg state with $n = 40$.

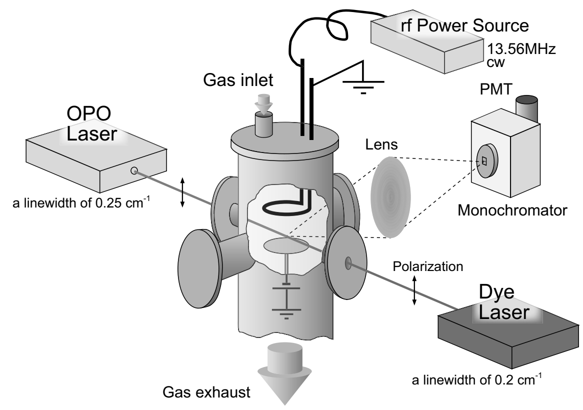


Fig. 1. Experimental apparatus.

## 3. Experimental setup

The experiment was carried out in an inductively-coupled plasma source shown in Fig. 1. A movable planar electrode was inserted in plasmas produced by an internal ICP antenna activated by an rf power supply at 13.56 MHz.

The electrode was connected to a dc power supply, and was biased at $-20$ V with respect to the grounded chamber wall. The plasma potential was estimated to be $+23$ V. The distribution of the electric field in the sheath in front of the planar electrode was measured by LIF-dip spectroscopy. We used a dye laser and an optical parametric oscillator (OPO) for measuring the structure of Ar high Rydberg state by the two-step excitation scheme. The LIF intensity was detected using a photomultiplier tube via a monochromator.

## 4. Distributions of electric field in electronegative plasmas

To demonstrate the sensitive measurement, we show the distributions of electric field in Fig. 2. The horizontal axis is the distance $z$ from the electrode surface. These distributions were observed in electronegative $Ar/SF_6$ plasmas. The degree of electronegativity is defined by the ratio of the negative ion density to the electron density ($\alpha = n_-/n_e$), which was controlled by changing the partial pressure of $SF_6$. The value of $\alpha$ was measured by probe-assisted laser photodetachment using a XeCl excimer laser as the light source. We measured the electron density using a surface-wave probe, since the measurement of electron density was difficult by a Langmuir probe in an electronegative plasmas. The degree of electronegativity and the electron density in each experimental condition are indicated in the figure.

A fluid model for calculating the distribution of electric field in an electronegative plasma has been reported by Kono [5]. We calculated the distribution of the sheath electric field in the experimental conditions by using the fluid model. The theoretical electric field is also shown in Fig. 2 by solid curves, together with the distributions of electric potential (dashed curves) which was obtained by integrating the theoretical electric field.

The most important feature of the electric field observed in the electronegative plasma is the distribution with the two-stage structure, typically shown in Fig. 2(c). The almost constant electric field at $z \geq 3$ mm may be due to the detection of quasi-random microfield, and in not included in the theoretical calculation. The jump in the electric field strength at $z \simeq 2.8$ mm is explained by the reflection of negative ions with low temperature. This jump was reproduced by the theoretical calculation. The slope of the electric field in the range of $0.6 \leq z \leq 2.8$ mm is consistent between the experimental and theoretical results. However, the jump in the electric field strength at $z \simeq 0.6$ mm, which may be due to the reflection of electrons, was not reproduced theoretically.

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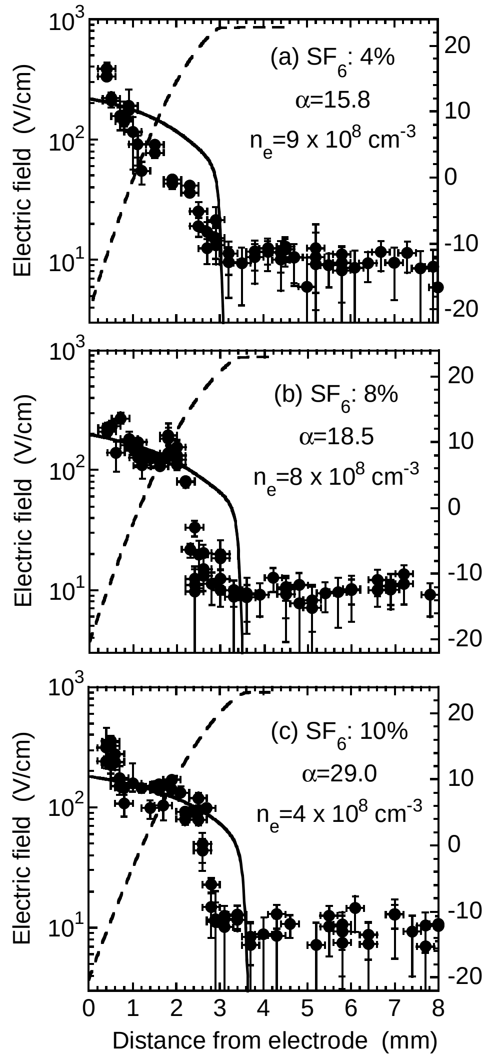


Fig. 2. Distributions of sheath electric field observed in $Ar/SF_6$ ICP plasmas at various percentages of $SF_6$. The voltage between the plasma and electrode potentials was 43 V. The degree of electronegativity defined by $\alpha = n_-/n_e$ was examined by laser photodetachment and the electron density $n_e$ was measured using a surface-wave probe. The solid and dashed curves represent theoretical electric field and potential calculated by a fluid model at each experimental condition.