Time-resolved Density Measurement of Pulse Discharge Plasma by Curling Probe

カーリングプローブによるパルス放電プラズマの時分解密度測定

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Curling probe (CP) enables measurement of electron density even in depositions plasmas, measuring a shift of resonance frequency by network analyzer (NWA). In a pulsed discharge, the resonance frequency varies in time, and the frequency spectrum becomes complex and unstable. In order to obtain a stable frequency spectrum during the discharge, the frequency sweep of NWA is triggered by the discharge pulse, in on-sweep mode or on-point mode. The electron density was successfully measured in time-resolved manner for pulsed discharge frequency of 0.4 to 10 kHz.

1. Introduction

A Langmuir probe has been used as a simple plasma diagnostic tool, however it cannot be used in most reactive plasmas since the probe surface is stained with electrically nonconductive layer, thus interrupting the dc current measurement. Recently, a new type of microwave resonator probe, the curling probe (CP), has been developed [1] which enables direct measurement of electron density even in depositions plasma. Electron density \( n_e \) (cm\(^{-3}\)) is obtained from the measured frequency shift of 1/4-wavelength resonance at the frequency \( f_0 \) (GHz) in vacuum to \( f_r \) (GHz) in plasma from the following simple equation:

\[
n_e = \gamma \frac{f_r^2 - f_0^2}{0.806} \times 10^{10} \text{ [cm}^{-3}\text{]} \tag{1}
\]

Here the coefficient \( \gamma \) is determined by the probe structure and dimensions: \( \gamma = 5.1 \) for antenna length of 100 mm and a quartz cover thickness of 0.2 mm.

The CP is compact (minimum diameter ~6 mm) and free from metal impurities owing to alumina or yttria coating. A wide range of electron density (10⁹–10¹³ cm\(^{-3}\)) can be measured with high sensitivity. Moreover, an opto-curling probe (OCP) was recently developed [2]. Both CP and OCP are commercially available [3].

To date, the CP has been applied to a constant density stationary plasma where the resonance frequency is easily measured by network analyzer (NWA). However, when the CP is inserted into a pulse-modulated plasma, the resonance frequency oscillates at the modulation frequency due to temporal change in electron density. As a result, the frequency spectrum becomes complex and varies sweep by sweep of NWA. We have previously reported [4] that a stable frequency spectrum can be obtained with synchronization between the pulse period and the NWA sweep period. In this paper, we represent a time-resolved electron density measurement by externally triggering the NWA sweep with on-sweep mode or on-point mode.

2. Experimental

The CP measurement was performed in an apparatus shown in Fig. 1, where a pulsed glow plasma is produced in nitrogen at 10 Pa at the pulse frequency 0.4–10 kHz with duty ratio of 10–50 %, applying a negative high-voltage (~ -1.7 kV) to a 12-cm-diam. cathode K in a cylindrical discharge chamber of 60 cm in diameter and 50 cm in length. The CP of 1.6 cm in diameter is set at the center \((x = y = z = 0)\) of the chamber, 5 cm above the cathode \((y = -5 \text{ cm})\). Five sets of the grounded anode A (30 cm × 30 cm) are installed at the location \( x = \pm 15 \text{ cm}, y = 15 \text{ cm}, y = -17 \text{ cm} and z = -15 \text{ cm}\).

Fig. 1. Experimental apparatus.
The CP is connected to the NWA (Agilent, model E5071C) which enables time-resolved measurement of reflectance ($\delta(t)$), externally triggered by a signal delayed from a synchronous output of the high-voltage pulse generator.

3. On-Sweep Mode Measurement

First of all, the following synchronization condition [4] should be fulfilled to obtain a stable spectrum:

$$n - 1 \frac{T_{\text{pls}}}{T_{\text{swp}}} = m \text{(integer)}$$

(1)

where $n$ is the number of data points, $T_{\text{pls}}$ and $T_{\text{swp}}$ are periods of discharge pulse and frequency sweep, respectively. For example, a pulsed plasma at 0.4 kHz ($T_{\text{swp}}$=2.5 ms) and 13% duty ratio was measured as shown in Fig. 2(a) for $m$=10, $n$=1601, and a delay time of 20 µs. This spectrum simultaneously displays 10 spectra at an interval of $T_{\text{pls}}$/m=0.25 ms. Analyzing this spectrum, one can obtain a time-resolved reflectance spectrum as shown in Fig. 2(b) where $\tau$ denotes the time after discharge ignition.

![Fig. 2](image)

Fig. 2. (a) Raw data by on-sweep mode and (b) time-resolved data by post data analysis.

The resonance frequency observed in Fig. 2(b) gives the electron density at the discharge time $\tau$. In this way, the electron density of 0.4 kHz pulsed discharge (duty ratio 13%) was measured changing the delay time, as shown in Fig. 3.

![Fig. 3](image)

Fig. 3. Electron density measured by on-sweep mode.

4. On-Point Mode Measurement

For high-frequency discharge pulse (short $T_{\text{pls}}$), Eq. (1) requires a short $T_{\text{swp}}$ to get the same time-resolution (same $m$ and $n$). Then, the frequency sweep is often interrupted during the sweep, which makes post data analysis impossible. In this case, on-point mode is very useful where the NWA digitally sweeps the frequency and measures one data point per each external trigger. Thus, a full spectrum is obtained after $n$ triggers, and one can find the time-resolved spectrum (electron density) by changing the delay time. The measured example is shown in Fig. 4 for 1 kHz and 30% duty ratio discharge. The external trigger was delayed by 10µs each, and the resultant time-resolved frequency spectrum gives electron density as a function of discharge time $\tau$, as shown in Fig. 5.

![Fig. 4](image)

Fig. 4. Time-resolved spectrum by on-point mode.

![Fig. 5](image)

Fig. 5. On-point mode measurement of electron density.

The result of much higher frequency such as 10 kHz will be also reported in the conference.

References