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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 depositive 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 depositive 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:

$$n_e = \gamma \frac{f_r^{\,2} - f_0^{\,2}}{0.806} \times 10^{10} \quad [\mathrm{cm^{-3}}] \qquad (1)$$

Here the coefficient γ is determined by the probe structure and dimensions: γ=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 (10^9–$10^{13}$$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 cm). Five sets of the grounded anode A (30 cm × 30 cm) are installed at the location x =±15 cm, y =15 cm, y = -17 cm and z = -15 cm.

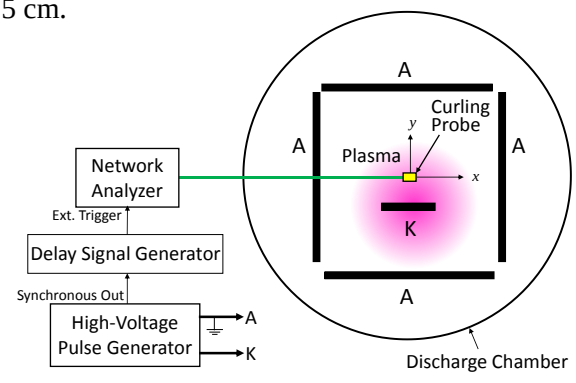

Fig. 1. Experimental apparatus.

The CP is connected to the NWA (Agilent, model E5071C) which enables time-resolved measurement of reflectance (S_{11}), 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:

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

where n is the number of data points, T_{pls} and T_{swp} are periods of discharge pulse and frequency sweep, respectively. For example, a pulsed plasma at 0.4 kHz (T_{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 a interval of T_{pls}/m=0.25 ms. Analyzing this spectrum, one can obtain a time-resolved reflectance spectrum as shown in Fig. 2(b) where τ denotes the time after discharge ignition.

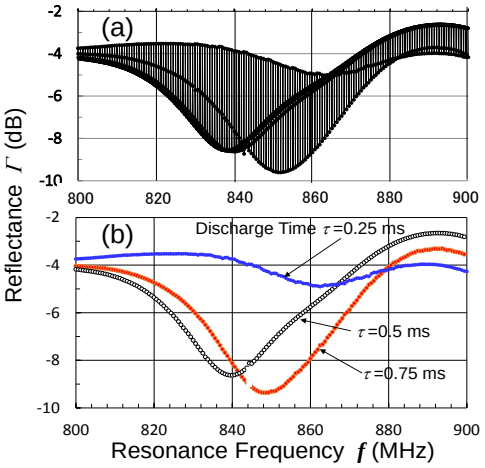

Fig. 2. (a) Raw data by on-sweep mode and (b) time-resolved data by post data analysis.

The resonance frequency observed in Fig. 2(b) gives the electron density at the discharge time τ. 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.

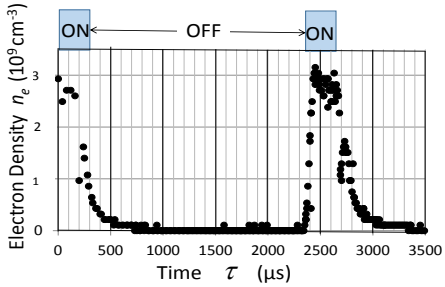

Fig. 3. Electron density measured by on-sweep mode.

4. On-Point Mode Measurement

For high-frequency discharge pulse (short T_{pls}), Eq. (1) requires a short T_{swp} to get the same time-resolution (same m and n). Then, the frequency sweep is often intermitted 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 τ, as shown in Fig. 5.

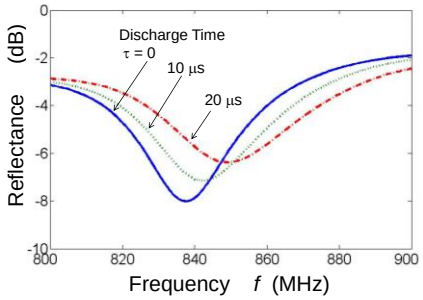

Fig. 4. Time-resolved spectrum by on-point mode.

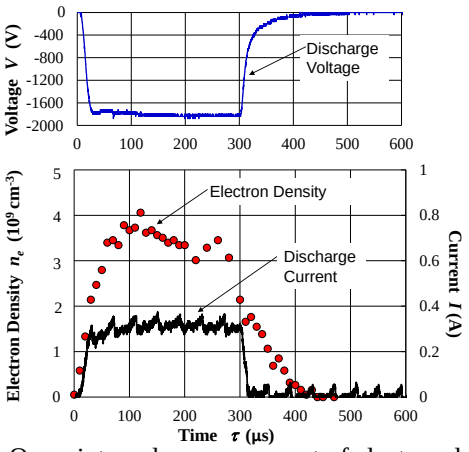

Fig. 5. On-point mode measurement of electron density.

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

References

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