Investigations on frequency shift probes for monitoring of electron conditions in nano-materials processing plasmas†

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1. Introduction

In advanced materials processing for manufacturing LSI devices, improvement of accuracy and repeatability has been required to achieve high performance process. In general, temporal variation of plasma components is believed to be one of reasons for the problems, so it is important to understand the phenomena in the plasma and to develop technologies for accurate plasma control. As one of solutions, we have developed a frequency shift probe as a novel in-situ plasma monitoring technology. The probe enables us to measure an electron density from variation of the resonance frequency of the probe head caused by the plasma, and the density measurement is possible under minimum disturbance to the plasma. Furthermore, the probe is applicable to reactive plasmas such as fluorocarbon plasmas since the deposited polymer has little effect on the resonance frequency.

Recently, the frequency shift probe has been studied from a viewpoint of fundamental measuring characteristics and miniaturization of the probe size[1, 2]. When the resonance frequency of the probe varies from f_0 (GHz) to f_r (GHz) by producing the plasma with the electron density of n_e, (10^{10} cm^{-3}), the value of n_e is given by

$$n_e = (f_r^2 - f_0^2)/0.81$$

However influences of the sheath formed around the probe have not been considered in the studies. In this work, sheath effects on the frequency shift probe are investigated based on finite difference time domain (FDTD) simulation, and it is examined how much influences on the measured density the sheath have[2]. Furthermore, the frequency shift probe is tried for measurements of electron temperature using the sheath effects.

2. Model of Frequency Shift Probe

The frequency shift probe was modeled as shown in **Fig. 1**: a 3 cm x 4 cm rectangular probe head with a thickness of 0.2 mm is immersed into a 10 cm x 10 cm x 10 cm cubic plasma, and has a semi-circular slit. Frequency-swept microwave voltage is applied to the end of the slit, and a resonance frequency of the probe head was calculated for the slit width of 1 mm, 5 mm or 8 mm in the present FDTD simulation.

Since the sheath is formed around the probe head homogeneously, a vacuum thin layer was considered as the sheath in the whole surface of the probe in the model. The resonance frequency was examined as a function of a thickness of the vacuum layer.

3. Results and Discussions

Figure 2 shows dependence of a resonance frequency of the probe head on the sheath width as a parameter of the slit width for the electron density of $3x10^{10}$ cm^{-3}. The resonance frequency shown in Fig. 2 was normalized by

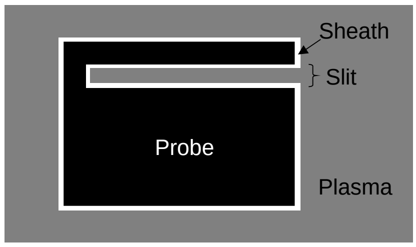

Fig. 1 Model of frequency shift probe

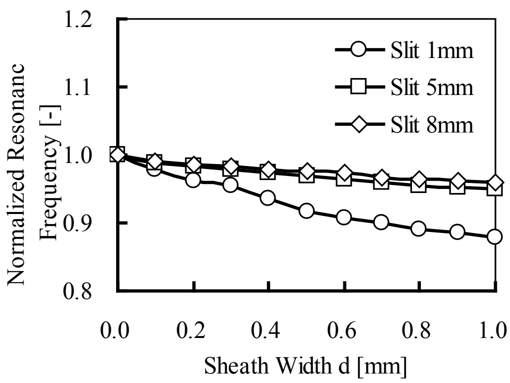

Fig. 2 Variation of resonance frequency with sheath width as a parameter of slit width

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that for the sheath width of 0 mm. The resonance frequency decreased as the sheath width increased since effective permittivity of the media around the probe head decreased. Such a decrease of the resonance frequency was observed regardless of the slit width, however its dependence on the sheath width was affected by the slit width, and it became significant as the slit width decreased. Actually, when the 1-mm-thick sheath was formed around the probe, the resonance frequency varied by ~3 % at most for the slit width as large as 8 mm, but by ~13 % for the slit width of 1 mm. The sheath width is proportional to Debye length, so the resonance frequency shown in Fig. 2 is given as a function of electron density and electron temperature.

Since the resonance frequency of the frequency shift probe is a function of electron density n_e and electron temperature T_e, resonance frequencies obtained in two frequency shift probes with different sheath dependence give unique solutions of ne and T_e.

For example, assume that production of plasma induced shift of resonance frequency from 1.78 GHz to 2.8 GHz for the probe of 1 mm in a slit width and from 1.62 GHz to 2.9 GHz for that of 5 mm in a slit width. A relationship between n_e and Te to satisfy the measured resonance frequency can be calculated from the FDTD simulation, and it is shown in **Fig. 3** as a n_e -Te characteristic curve for each probe. A crossing of the two curves represents a solution of 7.5×10^{10} cm^{-3} in n_e and 4.8 eV in T_e.

According to the above procedure, the electron temperature of an inductively-coupled plasma (ICP) was measured and compared with a conventional Langmuire probe. The ICP was produced with 13.56 MHz RF power up to 400 W at an argon pressure of 3 mTorr. Two frequency shift probes whose slit widths were 1 mm and 5 mm gave measured electron temperatures as constant as 3.1 ~ 4.8 eV, which was comparable to 4 eV obtained by the Langmuir probe. These results suggest that measurements of electron temperature is available with the frequency shift probe.

4. Conclusions

Recently, the frequency shift probe has been studied from a viewpoint of fundamental measuring characteristics and miniaturization of the probe size. However influences of sheath formed around the probe have not been considered in these studies. In this work, sheath effects on the frequency shift probe are investigated based on finite difference time domain (FDTD) simulation, and it is examined how much influence on the measured density the sheath has. As a result, the resonance frequency decreased as the sheath width increased since effective permittivity of the media around the probe head decreased. Furthermore such a characteristic enabled us to measure electron density as well as electron temperature.

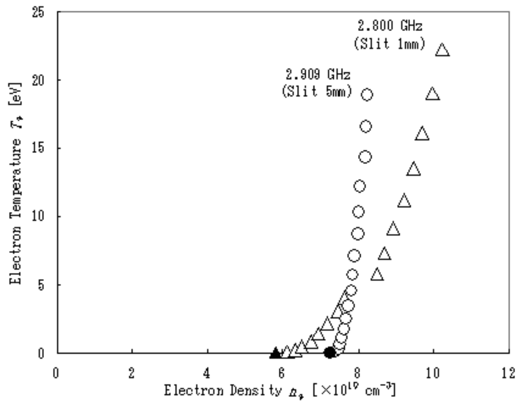

Fig. 3 n_e-T_e characteristic curves for different frequency shift probes

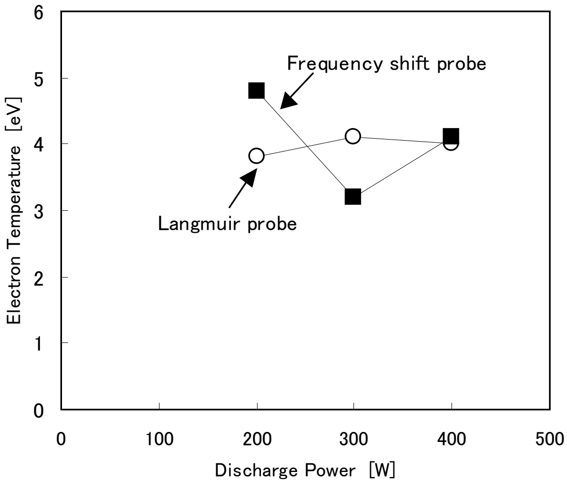

Fig. 4 Comparison of electron temperature between frequency shift probe and Langmuir probe

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