Computational study on reliability of sheath width measurement by the cutoff probe in low pressure plasmas

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ABSTRACT: Recently, the technique for measurement of the sheath width by using the cutoff probe and its equivalent circuit model was proposed and conducted experimentally. In this study, we investigate the reliability of this technique based on the computational simulation. The simulation of three-dimensional Finite-Difference Time-Domain reproduces the transmission spectrum of the cutoff probe with an input parameter of sheath width. We measure the sheath width by using the circuit model and calculate the discrepancy between them under various input plasma densities and sheath widths. The results show the acceptable discrepancy under all of the conditions we studied (the largest discrepancy is about 45%). This indicates that the technique for measurement of sheath width around the floating tip of cutoff probe is robust and reliable.

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1 Introduction

Plasma density is a key internal parameter closely related with the efficiency and throughput of plasma processing [1]. Therefore, the measurement of the plasma density is of concern and a reliable diagnostics method is demanded. The Langmuir probe measuring DC plasma current has been most widely used in the plasma diagnostics. However, it has a weak point for the diagnostics method in the reactive processing plasma, because it is sensitive to a non-conducting film layer on the tip [2].

On the other hand, the cutoff probe using microwave is useful for measuring the plasma density in the processing environment, because of its less sensitivity of microwave to the non-conducting film layer on the cutoff probe tips. Furthermore, it has the good reliability and accessibility as well as the above benefit for measuring the plasma density. It has been widely used for plasma diagnostics and actively investigated [2–7]. As a result, various types of cutoff probe has been invented during the last decade [8]. The cutoff probe consist of two small tips of radiation and detection. These are connected with the network analyzer for feeding microwave signals to the radiation tip and analyzing the transmitted microwave signal to the detection tip. The transmission spectrum is obtained by this operation. The frequency of cutoff resonance peak ($f_{cr}$) in the spectrum is used for measuring the plasma density based on the relation of $n_e = (f_{cr}/8980)^2 \text{cm}^{-3}$. The details of cutoff probe is described in ref. [7].

Recently, for improving the cutoff probe, the effect of sheath width on the measured plasma density from cutoff probe has been investigated [9, 10]. Kim et al. [10] presented the technique for measurement of the sheath width by using the cutoff probe and its equivalent circuit model. This experimental study shows good agreement between the measured sheath width by the proposed technique and the Child-Langmuir Law sheath width calculated based on the Langmuir probe data. Although there is a good agreement between the two results, it is unclear how accurate this method, because there is no reliable test for the method itself. Therefore, the reliability investigation of this sheath width measurement method should be performed for further applications of this method. However, experimentally investigations of reliability are awkward because of difficulties to know the exact sheath width, make complicate setup, and control the plasma parameters.
In this paper, the reliability of the sheath width measurement using circuit modeling of the cutoff probe is investigated based on the computational simulation of Finite-Difference Time-Domain (FDTD). In the FDTD simulation, the sheath width can be treated as a controllable input parameter, a reliability test of the proposed sheath width measurement can readily performed by comparison between the input sheath width and the calculated sheath width based on the circuit method. The calculated sheath width based on the circuit modeling method is compared with the input sheath width of the FDTD simulation ($S_{\text{input}}$) under various plasma densities ($n_e = 1 \times 10^{10} - 1.5 \times 10^{11} \text{cm}^{-3}$) and sheath widths ($S_{\text{input}} = 0.118 - 0.744 \text{mm}$). The result shows that the proposed method is a quite reliable technique for measuring the sheath width formed around the floating tips of the cutoff probe. It has an acceptable discrepancy under all of the conditions we studied (the largest discrepancy is about 45%). This indicates that this technique for measurement of sheath width by using the cutoff probe and its circuit model is robust and reliable.

2 Method

The transmission spectrum of cutoff probe is reproduced by the three dimensional FDTD simulation as shown in figure 1. The FDTD simulation is known to be accurate solver of Maxwell’s equations with realistic assumptions. It reproduces the experimentally obtained spectra of various microwave probes as well as the cutoff probe [7, 11–16]. The input parameters in the FDTD simulation are the material characteristic of the plasma density and collision frequency in the Drude model. The Drude model represents the bulk plasma assumed as an immobile dispersive dielectric material of which dielectric constant is $\epsilon_p = \epsilon_0 \left[ 1 - \frac{\omega_p^2}{\omega(\omega - i\nu_m)} \right]$ (Drude model [17]) having the input parameters (collision frequency ($\nu_m$) and a plasma oscillation frequency ($\omega_p$) related to the electron density). We fill the chamber with this uniformly distributed Drude model except the chamber and probe boundaries of the sheath. The sheath is represented by the vacuum layer and the width of this vacuum is assumed to be the width of sheath (see figure 1).

As shown in the previous report [7, 10], the main influence of variation of the sheath width on the transmission spectrum of cutoff probe is the change of the plasma sheath resonance (PSR) frequency. The PSR is mainly caused by the plasma electrons acting as inductor ($L_p$) and the sheath acting as capacitor ($C_s$). The sheath width is expressed by the gap distance of the capacitor. Therefore, we can extract the information of the sheath width by finding the PSR frequency closely related with the sheath width [10]. This PSR frequency is readily found in the phase of transmission spectrum as the first zero crossing frequency [7, 10].

The reliability test based on the FDTD simulation and circuit model is made in the following steps: (1) Design the cutoff probe having a certain sheath width in the FDTD simulation (see figure 1). (2) Run the FDTD simulation and get the phase of transmission spectrum (see black line in figure 2). (3) Run the circuit model calculation and find the sheath width of circuit model satisfying the condition that the PSR frequency calculated from the circuit model is in accord with the PSR frequency obtained from the FDTD simulation (see figure 2). (4) Compare between the input sheath width in the FDTD simulation and obtained sheath width by the circuit model based on the discrepancy between them.
Figure 1. Schematic representation of simplified electrical boundary and structure of chamber and cutoff probe used in FDTD simulation.

Figure 2. Calculated transmission phase spectrum from FDTD simulation (black line) and the circuit modeling (red line) at $p = 6.7$ Pa and $n_e = 2.5 \times 10^{10} \text{cm}^{-3}$. 
The simulations are performed at low pressure \( p = 6.7 \) Pa and low electron temperature condition \( T_e = 2 \) eV for the comprehensive ranges of sheath width and electron density, \( n_e : 1 \times 10^{10} - 1.5 \times 10^{11} \text{ cm}^{-3} \) and \( S_{\text{input}} : 0.118 - 0.744 \text{ mm} \), respectively.

3 Result and Discussion

The cutoff probe obtains the transmission spectrum composed of interactions between microwave signals and plasma-sheath around the probe antennas. The magnitude and phase of the transmission spectrum provide informative peaks and slopes characterizing the plasma-sheath. When we see the phase of transmission spectrum (strictly speaking phase difference spectrum between current and voltage), the sign of the phase changes with frequency in series, plus, minus and plus [7, 10]. This sign changes are originated from the fact that the property of the cutoff probe changes with frequency in series, capacitor, inductor, and capacitor as noted in the previous studies [7, 9, 10].

Figure 2 shows the phase of transmission spectrum obtained from the FDTD simulation at the condition of \( n_e = 2.5 \times 10^{10} \text{ cm}^{-3} \), \( p = 6.7 \) Pa, \( S = 0.33 \text{ mm} \), and \( T_e = 2 \) eV (see black line). The red line in figure 2 is the phase of transmission spectrum reproduced by the circuit model at the same condition as the FDTD simulation. The circuit model reproduces the zero crossing resonance frequencies of PSR and PR (Plasma Resonance) in accord with the FDTD simulation, even though, the phase offset below the PSR frequency and phase jump by cavity resonances observed in the FDTD simulation are not reproduced by the circuit model. The origin of this discrepancy below the PSR frequency is not well analyzed yet, but it is believed to be the effect of the propagation only a function of surface waves \( (f_{\text{surface}} < f_p/\sqrt{2}) \) [18].

The PSR frequency is the function of the sheath width if all other variables \( (n_e, T_e, \text{ etc.}) \) are substituted in the circuit model [10]. We can obtain the sheath width in the circuit model by finding the proper sheath width that the PSR frequency of the the circuit model \( (f_{\text{PSR–circuit}}) \) is in accord with the PSR frequency observed in the FDTD simulation \( (f_{\text{PSR–FDTD}}) \) as shown in figure 2.

The quantitative investigation of reliability of measurement of sheath width by the circuit model is possible based on the discrepancy between the input sheath width in the FDTD simulation and the estimated sheath width by the circuit model. Figure 3 shows the result of the reliability investigation for the proposed method, presenting the discrepancy under various conditions. The discrepancy \( (\delta) \) is calculated by the following relations: \( \delta = \frac{|S_{\text{output,Circuit}} - S_{\text{input,FDTD}}|}{S_{\text{input,FDTD}}} \times 100\% \), where \( S_{\text{input,FDTD}} \) and \( S_{\text{output,Circuit}} \) are the sheath width in the FDTD simulation and obtained from the circuit model. The result shows that this technique measuring sheath width have a small discrepancy under the most conditions we studied (less than 20%), apart from the condition for high density and thick sheath width (but even in worst case, the error is less than 45%). Fortunately, the conditions showing worst results for high density and thick sheath width, are not a physically meaningful region. Because the thick sheath is abnormal in the high density plasma. To see the physically meaningful regime in our simulation conditions, we plot the lines of sheath width as a function of plasma density based on the theoretical model of sheath as shown in figure 3. This result shows that we can measure the sheath width with a small discrepancy less than \( \sim 15\% \) in the meaningful region that the real experimental sheath widths are possible to locate. The cylindrical C-L sheath model and \( 5\lambda_D \) sheath model would seems to be adequate sheath model for the cutoff probe.
The reason for the large discrepancy up to 45% is not analyzed rigorously yet, but in this status we believe that the phase difference of microwave current between the two probe tips may be the origin for the large discrepancy. We assume that the phase difference of the current between the two probe tips is to be zero in the circuit model. However, the phase difference increases when the electron density and sheath width increase as shown in figure 4. Figure 4 presents the calculated phase difference of the microwave current between the two probe tips at the PSR frequency under the same conditions of figure 3. This may cause the large measurement discrepancy of our method at the regime of high density and thick sheath condition.

4 Conclusion

We investigate the reliability of measurement of the sheath width by using the cutoff probe and its equivalent circuit model based on the computational simulation. The simulation of three-dimensional Finite-Difference Time-Domain reproduces the transmission spectrum of the cutoff probe with an input parameter of sheath width. We measure the sheath width by using the circuit model and calculate the discrepancy between them under various input plasma densities and sheath widths. The results show the acceptable discrepancy under all of the conditions we studied (the largest discrepancy is about 45%). Especially, for physically meaningful condition estimated by...
Figure 4. Phase changes of microwave passing through gap between cutoff probe tips at the PSR frequency under the same input plasma density and sheath width conditions of figure 3.

theoretical sheath model, the discrepancy is less that 20%. This investigations confirm the possibility of robust sheath width measurement using the cutoff probe, which is important for further understanding and development of the cutoff probe diagnostics.

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