Numerical Analysis of Electromagnetic Wave Propagation in Surface Wave Plasma Apparatus

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Abstract — A three-dimensional (3D) simulation algorithm has been developed to analyze the microwave propagation bounded by plasma with combining the momentum conservation equation of electron to the finite-difference time-domain (FDTD) method. Using this simulation algorithm, the characteristics of electromagnetic wave’s propagation in ring dielectric line typed surface wave plasma (RDL-SWP) apparatus have been simulated under the several conditions of gas pressures and electron densities. And the limitation for generating high electron density has been evaluated with this simulation tool.

Keywords — Surface wave plasma, Microwave, FDTD methods, Plasma devices.

I. INTRODUCTION

The surface wave driven plasma (SWP) is one of the most important techniques for generating uniform and dense plasma in large area configuration. Surface wave in plasma propagates along the interface of plasma and dielectric and the electromagnetic field intensity is strongest near the plasma boundary and attenuated exponentially off from the boundary. In SWP generation mode, the electromagnetic wave energy is efficiently absorbed at the boundary by plasma and that makes dense and stable bulk plasma generated and sustained in a large volume. Thus, many apparatuses with various structures of slot antenna and dielectric media have been developed and applied for various large area processes [1]. On the contrary to these high applicable possibilities for various processes, the design of microwave-excited SWP plasma apparatus is not facile, because the plasma parameters and the microwave propagation characteristics are coupled very strongly. On designing plasma apparatus, estimating the plasma parameters is necessary but very difficult. In order to overcome these problems, simulation method is one of very useful techniques. The simulation method developed by Young et al. is very useful [2]. In this simulation method, plasma is treated as a dispersive media by combing Largervin equation to Maxwell equations. And the plasma has uniform parameters in the plasma region to analyze the microwave propagation modes in plasma. This method is very useful to evaluate the dependences of microwave propagation modes on plasma parameters and the structural characteristics of transmission lines. The simulation tool for SWP has especially important significance to microwave excited plasma, because the propagating direction of the incident microwave is different from the direction of microwave for heating plasma in discharging chamber. This means that microwave excited plasma needs to be analyzed in a 3-dimensional (3D) simulation model.

Toba et al. has developed self-consistent simulation code in two-dimensional (2D) model and simulated in planar-type dielectric SWP apparatus [3]. And applying this simulation code, a 3D simulation has been performed by Nakagawa in Ring Dielectric Line typed Surface Wave Plasma (RDL-SWP) apparatus [4]. However, it is reported that this simulation’s stability has not been achieved over the gas pressure of 30 mTorr and the reason of instability have not been cleared.

To simulate the microwave-excited plasma, it needs to calculate the microwave propagation mode and the plasma parameters simultaneously in a self-consistent method. However, it is possible to evaluate the limitation of SWP apparatus with assumption of uniform plasma that is not updated with the incident microwave power absorbing distribution.

In this study, we have improved the JE convolution (JEC) method both conceptually and in terms of implementation. And it is well known that very wide ranges of problems can be handled and studied by FDTD method. In order to solve the microwave propagation problems bounded by plasma, some calculation methods have been developed with applying the momentum conservation equation of plasma to the basic FDTD method. Among them, JE convolution (JEC) method has been reported that not only the calculation cost is very low but also the accuracy is very high [3]. In this study, we have improved the JEC method and applied to 3D analysis. In this chapter, the government equations are indicated and the full 3D model for calculation is presented and explained.

II. SIMULATION METHOD

The FDTD method is an arguably simple simulation method both conceptually and in terms of implementation. And it is well known that very wide ranges of problems can be handled and studied by FDTD method. In order to solve the microwave propagation problems bounded by plasma, some calculation methods have been developed with applying the momentum conservation equation of plasma to the basic FDTD method. Among them, JE convolution (JEC) method has been reported that not only the calculation cost is very low but also the accuracy is very high [3]. In this study, we have improved the JEC method and applied to 3D analysis. In this chapter, the government equations are indicated and the full 3D model for calculation is presented and explained.
A. Goverment Equation

Maxwell’s equation, which govern the propagation of electromagnetic wave, are given as

\[
\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} (\nabla \times \vec{E}) \tag{1}
\]

\[
\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon} (\nabla \times \vec{H} - \vec{J}) \tag{2}
\]

where \(\vec{E}\) and \(\vec{H}\) are the electric and magnetic fields intensities with permittivity \(\mu\) and permeability \(\varepsilon\), respectively.

In this study, we assumed that the drift velocity of ions is too much slow against the electron drift velocity and it can be assumed that the background ions are fixed. Thus, the current density \(\vec{J}\) can be denoted in plasma as

\[
\vec{J} = -e n_e \vec{u}_e \tag{3}
\]

where \(e\) is the unsigned charge of an electron and \(n_e\) is the electron density, and \(\vec{u}_e\) is the electron-drift velocity, respectively. And there is no need of external magnetic field to generate dense plasma in RDL-SWP apparatus. Thus, we can denote the momentum conservation equation of electrons in plasma as follows:

\[
\frac{\partial n_e \vec{u}_e}{\partial t} = -\frac{e \vec{E}}{m_e} - n_e \nu_{\text{en}} \vec{u}_e \tag{4}
\]

where \(m_e\) is the mass of electron, \(\nu_{\text{en}}\) is the electron-neutral elastic collision frequency, respectively.

In the simulation tool, these government equations are discretized with the central-difference approximation and the components such as electric field, magnetic field and plasma current density are disposed based on Yee’s cell.

B. RLD-SWP apparatus and Calculation Model

The cross sectional illustration of RDL-SWP apparatus is shown in Fig. 1. The incident microwave that is traveled along waveguides with the frequency of 2.45 GHz propagates through the ring dielectric line, and forms a standing wave in that. The electric power introduced by electromagnetic waves transmits into the discharging chamber through the metal slots and the quartz disk window placed under the ring dielectric line. The discharges are excited at the metal ring at first and expanded to the center of the discharging chamber. And the plasma sustained by SWs, which propagate along the interface between plasma and quartz disk window, is generated. The full scale calculation modeling of RDL-SWP apparatus is shown in Fig. 2. The cell sizes of \(\Delta x\), \(\Delta y\), and \(\Delta z\) are 2.5 mm \(\times\) 2.5 mm \(\times\) 2.5 mm. And the number of cells is \(161 \times 161 \times 105\) in the \(x\)-, \(y\)-, and \(z\)-direction, respectively. The conductor which is surrounding the ring dielectric line, the quartz window, and plasma was assumed as a complete conductor. This means that the electric field components which are perpendicular to the surface of conductor are to zero in calculation. The relative permittivity \(\varepsilon_r\) of each material in RDL-SWP apparatus was set as shown in Fig. 2. And the relative permittivity of plasma was set to 1. In this simulation algorithm, there is no need to set the plasma permittivity in plasma region on calculation, because the plasma is assumed as a dispersive media that the direct current flows locally by the electron drift. And this assumption makes the plasma treated as a dispersive media on calculation.

C. Calculation Condition

The calculation conditions are shown in Table 1. The electron temperature were used the spatially averaged values that had been measured by single probe method in reference [1] at 30 mTorr of gas pressure. Moreover, we assumed the followings: (1) the discharging chamber is fulfilled with argon gas and the neutral gas pressure is uniform; (2) the background ion temperature and the neutral gas temperature is the same to 300°C.

<table>
<thead>
<tr>
<th>Neutral Gas</th>
<th>Argon</th>
</tr>
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<tbody>
<tr>
<td>Gas pressure (mTorr)</td>
<td>30 mTorr</td>
</tr>
<tr>
<td>Electron temperature (eV)</td>
<td>2</td>
</tr>
<tr>
<td>Electron-neutral Collision Cross section</td>
<td>Ref. [6]</td>
</tr>
</tbody>
</table>

And the incident power of microwave is excited in TE\(_{10}\) mode at microwave waveguide line, and the excited microwave travels toward ring dielectric line. The opposite side of the excited plane wave traveling was set by Mur’s 1st order absorbing boundary condition [7]. This
boundary condition makes the reflected wave penetrate the boundary. In order to satisfy the stability condition of the FDTD algorithm, time step $\Delta t$ was calculated as satisfying the following equation [3]:

$$\omega_{pe}^2 + c^2 \left\{ \left( \frac{2}{\Delta x} \right)^2 + \left( \frac{2}{\Delta y} \right)^2 + \left( \frac{2}{\Delta z} \right)^2 \right\} \leq \left( \frac{2}{\Delta t} \right)^2 \tag{9}$$

III. SIMULATION RESULT

The simulations were performed at the conditions of electron densities from $4.0 \times 10^{16}$ m$^{-3}$ to $3.4 \times 10^{17}$ m$^{-3}$ and the results of the electric field intensities were normalized with the maximum intensity at each calculation as shown in Fig. 4. These simulations are including the conditions of electron densities for cut-off density and SW cut-off density. The cut-off density against the incident microwave’s frequency of 2.45 GHz is 7.4 $\times 10^6$ m$^{-3}$. And the SW cut-off density for the quartz dielectric window is $3.4 \times 10^7$ m$^{-3}$.

As it is shown in Fig. 4 (a), the electromagnetic wave is transmitted deeply into the plasma and the propagation component for the direction along the interface is attenuated. Thus, the SW cannot reach the center of the apparatus at this condition. However, around the cut-off density, the propagation component along the interface is attenuated weakly and the SW propagates into the center of the apparatus. The electric field intensity of SW is synched with the same phase of the incident wave as shown in Fig. 4 (b). On the contrary of this condition, the electric field intensity of SW is lagged with the phase of incident wave in Fig. 4 (c). This indicates that the propagation component of phase lag strengthens and the propagation component of same phase weakens over the conditions of cut-off densities. And at the higher electron density than that, the propagation component of same phase to incident wave is attenuated very strongly and SW mode is not appeared in the plasma region at the source phase of 1/2$\pi$ and 2/3$\pi$ as shown in Fig. 4 (d). However, increasing the electron density more, SW mode is appeared again at the source phase of 1/2$\pi$ and 2/3$\pi$ as shown in Fig. 4 (e). At the condition of electron density over $2.0 \times 10^{17}$ m$^{-3}$, the propagation components of phase lag and same phase along the interface weaken together as shown in Fig. 4 (f) and SW mode does not appear as shown in Fig. 4 (g).

IV. DISCUSSION

The propagation mode of SW appeared at the boundary of plasma and dielectric at same phase with the incident wave under the cut-off density and at lagged phase with the incident wave over the cut-off density. However, at higher electron density than that, the electromagnetic wave propagating component along the interface with the same phase to the source’s phase was attenuated strongly. After that, the SW of same phase to the source wave appeared and was attenuated at higher electron density than that. In these simulations, one of the most important points is that there were no SW propagations around the SW cut-off density of $3.4 \times 10^{17}$ m$^{-3}$. This is related the SW cut-off density is derived under the assumption of limitless and uniform plasma in the direction of SW propagation. The theoretical SW propagation characteristics are shown in Fig 3. This indicates that the surface wave resonances appeared at the conditions of lower electron densities than the theoretical SW resonance density. And it is confirmed that the simulation tool of this study is very useful to evaluate the limitation of generating electron density. In the structures like this RDL-SWP apparatus, it is possible to generate plasma of electron density around $2.0 \times 10^{15}$ m$^{-3}$ at the interface of plasma and dielectric, because SW is attenuated strongly and the electric power cannot be absorbed efficiently at the conditions over that electron density. These results are also confirmed from the experimental results in reference [1]. The electron densities measured by single probe method are limited around $2.3 \times 10^{18}$ m$^{-3}$ at all gas pressures in that.

V. REFERENCE

<table>
<thead>
<tr>
<th>Electron density ($m^{-3}$)</th>
<th>Source Phase of Incident Microwave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0\pi$</td>
</tr>
<tr>
<td>(a) $4.0 \times 10^{16}$</td>
<td><img src="image" alt="" /></td>
</tr>
<tr>
<td>(b) $6.0 \times 10^{16}$</td>
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<tr>
<td>(c) $8.0 \times 10^{16}$</td>
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<td>(d) $1.2 \times 10^{17}$</td>
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<tr>
<td>(e) $1.6 \times 10^{17}$</td>
<td><img src="image" alt="" /></td>
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<tr>
<td>(f) $2.8 \times 10^{17}$</td>
<td><img src="image" alt="" /></td>
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<tr>
<td>(g) $3.6 \times 10^{17}$</td>
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Figure 4. The simulation results of the electric field intensity at the position of boundary between plasma and quartz window. The electric field intensities are normalized with the maximum intensity at each calculation condition.