24B03

Numerical Analysis of Discharging Characteristics in Microwave-excited Surface Wave Plasma Apparatus with Self-consistent Simulation Method

Self-consistentシミュレーションによる
マイクロ波励起表面波プラズマ装置の放電特性解析

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A self-consistent simulation tool for the microwave excited plasma was developed. In this simulation tool, microwave propagation in plasma is analyzed by combining the electron oscillation to the finite-difference time-domain (FDTD) method. And the plasma parameters such as electron temperature, electron density and space potential are simulated by the ambipolar diffusion model that is described by the fluid conservation equations. Using this simulation tool, we simulated microwave propagation characteristics and the distributions of plasma parameters in the surface wave driven plasma (SWP) apparatus.

1. Introduction

The microwave-excited SWP is one of the most important methods to generate uniform and dense plasma in a large area. However, the design of microwave-excited SWP apparatus is not facile, because the plasma parameters and the microwave propagation characteristics are coupled very strongly. In order to overcome this difficulty, many simulation techniques have been developed and performed. Toba et al. has developed self-consistent simulation code in two-dimensional (2D) model and simulated in planar-type dielectric SWP apparatus[1]. And applying this simulation code, a three-dimensional (3D) simulation has been performed by Nakagawa in Ring Dielectric Line typed Surface Wave Plasma (RDL-SWP) apparatus[2]. In this study, we have developed a feasible simulation tool for applying to design a microwave- excited plasma apparatus. In this paper, we will indicate the simulation method and result and discuss about the validity of this simulation tool with comparing the experimental result.

2. Simulation Method

The microwave propagation is governed by a very shorter time scale than the plasma evolution such as electron and ion's drift and diffusion in bulk plasma. This makes it possible to decompose the electromagnetic fields and the plasma parameters into separated calculations of microwave propagation and plasma evolution in simulation.

Maxwell's equation, which governs the propagation of electromagnetic wave in plasma, are given as

$$\frac{\partial \tilde{\mathbf{H}}}{\partial t} = -\frac{1}{\mu}\nabla \times \tilde{\mathbf{E}} \tag{1}$$

$$\frac{\partial \tilde{\mathbf{E}}}{\partial t} = \frac{1}{\varepsilon}\left(\nabla \times \tilde{\mathbf{H}} + \tilde{\mathbf{J}}\right) \tag{2}$$

$$\frac{\partial \tilde{\mathbf{J}}}{\partial t} = \frac{e^2 n_e}{m_e}\tilde{\mathbf{E}} + \nu_{en}\tilde{\mathbf{J}} \tag{3}$$

where $\tilde{\mathbf{E}}$ and $\tilde{\mathbf{H}}$ are the electric and magnetic field intensities with permittivity ε and permeability μ, respectively. And $\tilde{\mathbf{J}}$ is the local plasma current density by electron oscillation, e is the unsigned charge on an electron, n_e is the electron density, me is the electron mass and ν_{en} is the electron-neutral elastic collision frequency. The power absorbing distribution by incident microwave in plasma is calculated by Poynting vector. And it was averaged through several time periods of the microwave source as follows.

$$P_{abs} = \frac{1}{T}\int_t^{t+T}\oint_v -\left(\tilde{\mathbf{E}}\cdot\tilde{\mathbf{J}}\right)dv\,dt \tag{4}$$

where P_{abs} is the power absorption, and T is the time period taken into count.

In this simulation, we considered the chemical reactions as shown in table 1. And it is assumed that the velocity distribution is satisfied the Maxwellian distribution at everywhere. Thus, we can determine the rate coefficient k in j process with integration as shown in equation (5) from the known cross section as referred in table 1.

$$k_j = \overline{\sigma_j v} = \int_0^\infty f(\varepsilon)\sigma_j(\varepsilon)v(\varepsilon)d\varepsilon \tag{5}$$

At the plasma model, the governing equations for electron's ambipolar diffusion, metastable atoms, and neutral atoms are as follows.

$$\frac{\partial n_e}{\partial t}+\nabla\cdot\mathbf{\Gamma}_0=S_e \tag{6}$$

$$\frac{\partial n_{m,n}}{\partial t}+\nabla\cdot\mathbf{\Gamma}_{m,n}=S_{m,n} \tag{7}$$

$$S_e=k_i n_n n_e+k_{si}n_m n_e+k_{mp}n^2 \tag{8}$$

$$S_m=k_{ex}n_n n_e-k_{si}n_m n_e-k_{sc}n_m n_e \\ -k_r n_m n_e-2k_{mp}n_m^2 \tag{9}$$

$$S_n=-k_i n_n n_e-k_{ex}n_n n_e \tag{10}$$

$$\mathbf{\Gamma}_0=-\frac{\nabla k_b n_e T_e}{v_{in}m_i}=-\frac{\nabla P_e}{v_{in}m_i} \tag{11}$$

$$\mathbf{\Gamma}_{m,n}=-D_{m,n}\nabla n_{m,n} \tag{12}$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2}p_e\right)+\nabla\cdot\frac{5}{2}\left(k_b T_e\mathbf{\Gamma}_0\right)+\nabla\cdot\frac{5}{2}\frac{k_b T_e}{m_e v_{en}}\nabla p_e \\ =\alpha P_{abs}-e\mathbf{\Gamma}_e\cdot\mathbf{E}-P_{loss} \tag{13}$$

$$\mathbf{E}=-\frac{\nabla P_e}{en_e} \tag{14}$$

$$P_{loss}=\left(k_{en}n_n\frac{3m_e}{m_i}p_e\right) \\ +en_n\left(\varepsilon_{ex}k_{ex}+\varepsilon_{gi}k_{gi}+\varepsilon_{si}k_{si}\right) \tag{15}$$

where n_m and n_n are metastable and neutral atoms density, $\mathbf{\Gamma}_0$ is the flux by ambipolar diffusion, $\mathbf{\Gamma}_m$ is the metastables flux and $\mathbf{\Gamma}_n$ is the neutrals flux. And S_e is the electron generation rate, S_m is the metastables generation rate and S_n is the generation rate of neutral atoms. P_e is the thermal energy density and **E** is the ambipolar electric field in bulk plasma, α is a normalization factor to fix the total absorbed power amount in plasma. ε_{gi} is the threshold energy for ionization from the ground state, ε_{si} is the threshold energy for ionization from the metastable state, and ε_{ex} is the excitation energy.

At the wall boundary in plasma, the electron flux is limited with Bohm sheath criterion and the thermal flux is assumed as lost as the average kinetic energy by electron.

Table. 1 Chemical reactions taken into count in simulation

No	Process	k_j	Ref.
1	$\mathrm{Ar}+e\rightarrow\mathrm{Ar}^*+e$	k_{ex}	[3]
2	$\mathrm{Ar}+e\rightarrow\mathrm{Ar}^++2e$	k_i	[4]
3	$\mathrm{Ar}^*+e\rightarrow\mathrm{Ar}^++2e$	k_{si}	[3]
4	$\mathrm{Ar}^*+e\rightarrow\mathrm{Ar}+e$	k_{sc}	[5]
5	$\mathrm{Ar}^*+e\rightarrow\mathrm{Ar}^r+e$	k_r	[6]
6	$\mathrm{Ar}^*+\mathrm{Ar}^*\rightarrow\mathrm{Ar}^++\mathrm{Ar}+e$	k_{mp}	[7]
7	$\mathrm{Ar}^*+\mathrm{Ar}\rightarrow 2\mathrm{Ar}$	k_{2q}	[7]
8	$\mathrm{Ar}^*+2\mathrm{Ar}\rightarrow\mathrm{Ar}_2+\mathrm{Ar}$	k_{3q}	[7]

3. Simulation Result

The microwave propagation mode is shown in figure 2. A standing wave formed in a wide area of plasma boundary and has synchronous phase with incident microwave. At this propagation mode, the power absorbing distribution by plasma is as shown in figure 2. This distribution is normalized with the maximum power value.

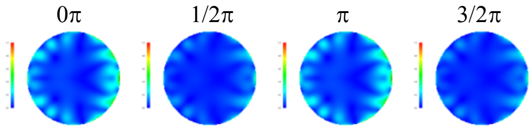


Figure. 1 Microwave propagation in plasma boundary

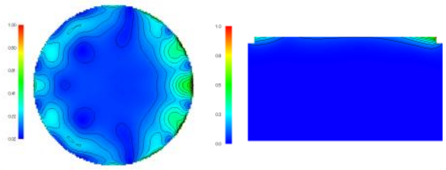
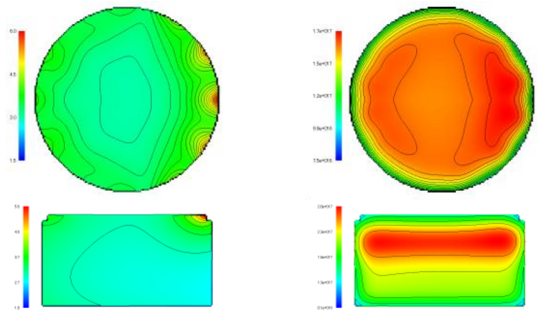


Figure. 2 Power absorbing distributions in plasma

The distributions of electron temperature and electron density are shown in figure 3. The electron temperature is distributed widely ~3 eV in the center of discharging box but ~6 eV at the power absorption concentrated area. And the electron density is highest as ~2.7×10^{17} m^{-3} at the place of 5 cm off from dielectric window.



(a) electron temperature (b) electron density

Figure. 3 Simulation result at 10 mTorr of argon gas pressure and 1.5 kW of incident microwave power

4. Summary

We have performed a self-consistent simulation in RDL-SWP apparatus. And the validity of this simulation tool was confirmed with comparing the experimental results in reference [2]. The plasma parameter distributions are well matched but the SW propagated more deeply into the center of plasma boundary in experimental result.

References

[1] T. Toba, et al., IEEE Trans. Plamsa Sci., vol. 30, No. 6, 2002
[2] T. Nakagawa, et al, IEEJ, Vol. 150 No. 4, 2005
[3] M. Hayashi,NIFS DATA 072, 2003.
[4] H. A. Hyman, Phys. Rev. A Vol. 20, No. 3, 1979
[5] G. R. Scheller, et al., J. Appl. Phys., Vol. 64, 1988
[6] K. Tachibana, Phys. Rev. A Vol. 34, No. 2, 1986
[7] D. P. Lymberopoulos, et al., J. Appl. Phys., Vol.73, 1993