

Using Plasma Simulation as a Smart Controller of Microwave Discharge Devices for Material Processing

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ABSTRACT

Proposed is a novel microwave plasma device control system based on physics, in which a fluid simulation is used to obtain a device control parameter necessary to produce a target density profile. This means that the input and output is reversed in the simulation compared to the conventional ones. It is shown that by following the output of this hyper simulator, radial profiles of produced plasmas are in good agreement with the target density profile.

1. INTRODUCTION

Plasma uniformity in a device for plasma-aided manufacturing is one of the most important parameters in determining qualities of processing, especially for large wafers. At present, evaluation and control of the uniformity are performed empirically without the knowledge of plasma physics. On the other hand, plasma simulation on the basis of physical models is used to predict spatial profiles of plasma or radical densities as output for a given input condition, in order to make comparison with experiments [1,2].

We propose to use a plasma simulation as a controller of microwave discharge devices, in which an optimal condition of the device setting for a desired uniformity (flat, hollow, or hill like density profile as required by a process) is provided as an output from the plasma simulation. It is recognized that, in this case, the simulation has the input and output just opposite to conventional simulations.

The most important condition that determines the plasma uniformity is the radial distribution of the

power absorption of electrons from the microwave fields since it directly affects electron temperature and then ionization rate [3,4]. The simulation code, called a hyper simulator, is designed so as to calculate a power absorption profile necessary to produce a plasma density profile that is given by an device operator [5]. Consequently, the device to be controlled must have a mechanism to adjust the power absorption profile. By using such a device, it is shown in this paper that the proposed controller using the hyper simulator can produce microwave plasmas with a radial profile that is very similar to a given target profile in various parameters.

2. HYPER SIMULATOR

The diagram in Fig. 1 shows a system for profile control of the microwave plasma device. Our device has the multi-slotted planar (MSP) antenna, the slot plate of which is divided into inner and outer radial sections driven by two power sources at 2.45 GHz. Therefore, it is possible to control radial distribution of the microwave power to some extent by changing the power, P_{in} and P_{out} , of the two sources.

The hyper simulator with reversed input and output is incorporated in the control system. A target profile of radial density distribution in the device and, if necessary, the past measured density profile obtained by a probe or a visible emission monitor are input to the hyper simulator to obtain power absorption profile necessary to produce the target profile as output. The output represents the device control parameters, and is used, through a hardware interface, to set the microwave power setting. In the hyper simulator, we introduce a profile parameter that characterizes radial density profile and a power coupling parameter as an index of modifier of radial profile of the power deposition. We define

that the normalized electron density is $a_n(x)$ in the real space and $A_n(i)$ in the wavenumber space. Here,

$$a_n(x) = \sum_i A_n(i) P_i(x) \quad (1)$$

is used with $P_i(x)$ being the Legendre function, and the normalized radius $|x| = r/R$. In the expansion, we use only lowest three components; $i = 0, 2,$ and 4 (odd terms are 0 because of assumed axisymmetry), which were found to be mostly sufficient to represent observed density profiles.

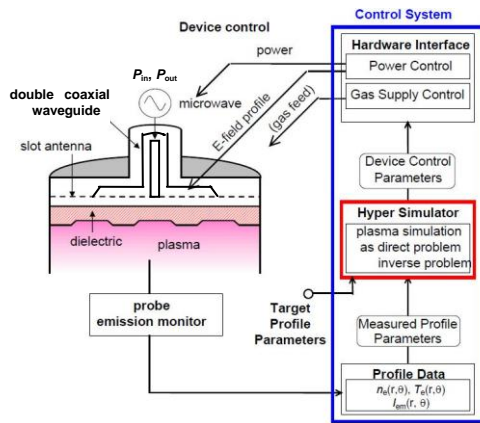


Fig. 1 Diagram of the total system including the microwave discharge device and the control system.

The hyper simulator consists mainly of a direct-problem fluid simulation part and a transfer function part as shown in Fig. 2. It calculates device control parameter that is necessary to obtain a target density profile by using binary search or quasi-inverse calculation. The fluid simulation part uses the code to solve basic equations as follows. Maxwell equations for the electric field \mathbf{E} and the magnetic field \mathbf{B} of the incident microwave are given by

$$\frac{\partial}{\partial t} \mathbf{B} = -\nabla \times \mathbf{E}, \quad (2)$$

$$\frac{\partial}{\partial t} \mathbf{E} = c^2 \nabla \times \mathbf{B} - \frac{1}{\epsilon_0} \mathbf{J},$$

and the equation of motion of electrons under microwave fields for the current density \mathbf{J} is

$$\frac{\partial}{\partial t} \mathbf{J} = \epsilon_0 \omega_{pe}^2 \mathbf{E} - \sum_j \nu_{mj} \mathbf{J}, \quad (3)$$

where ϵ_0 is the permittivity in vacuum, c is the velocity of light, and ν_m is the momentum transfer collision frequency of electrons with neutral species j . The power absorption of

electrons from the microwave fields is calculated using

$$P_{abs}(\mathbf{r}, t) = \frac{1}{T} \int_{t-T/2}^{t+T/2} \mathbf{J} \cdot \mathbf{E} dt, \quad (4)$$

where T is the period of the microwave and the integration is over one period. Note that the time variation of P_{abs} is much slower than microwave oscillation, with which \mathbf{J} , \mathbf{E} , and \mathbf{B} vary, and is of the order of the time variations of the electron density $n_e(r, t)$ and the electron temperature $T_e(r, t)$. The time variations of n_e and T_e are governed by the fluid equations represented by

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{u}) = \sum_{j,k} n_j \nu_{kj} n_e, \quad (5)$$

and

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{3}{2} n_e k_B T_e \right) + \nabla \cdot \left(\frac{5}{2} k_B T_e n_e \mathbf{u} + \mathbf{q} \right) \\ = P_{abs} - \sum_j \left(\frac{3m}{M_j} \nu_{mj} k_B T_e - \sum_k n_j \nu_{kj} V_{kj} \right) n_e, \end{aligned} \quad (6)$$

where \mathbf{u} is the fluid velocity, \mathbf{q} is the thermal flux, k_B is the Boltzmann constant, and ν_{kj} and V_{kj} are the cross section and threshold energy of the k -th-type inelastic collision of electrons to the j -th species.

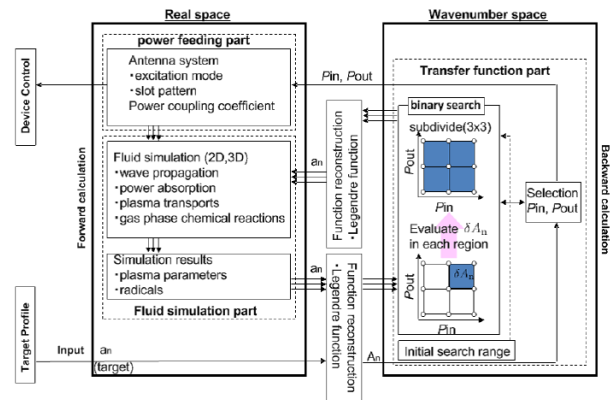


Fig. 2 Diagram of the hyper simulator consisting of the fluid simulation part and the transfer function part.

At the beginning, a target density profile is given by using $a_n(x)$. The transfer function part sets the initial search range on P_{in} - P_{out} plane, and the range is divided into the 3×3 grid. So, this range has 9 calculation points of different combinations of P_{in} and P_{out} , i.e., different radial power deposition profiles. The fluid simulation is conducted, and the error between the simulation results A_n and the target A_n is calculated and minimized by using the binary search method. Search for the minimum error is performed three

times, and the values of P_{in} and P_{out} with minimum error of A_n is obtained as the optimal solution. Then, the result is used to adjust the ratio of inner and outer power levels from the slot antenna.

3. CONTROL OF PLASMA PROFILES

We use the hyper simulator to control the microwave device as shown in the left part of Fig. 1, where the microwave fields from inner and outer sources propagate in the double coaxial waveguide and radiate from the segmented multi-slot plate through a quartz glass window toward the plasma chamber of 50-cm in diameter and 15-cm in depth. It is expected that the hyper simulator predicts the values of P_{in} and P_{out} that are necessary to produce the plasma with a radial profile very similar to a target profile that is given to the simulator as an input.

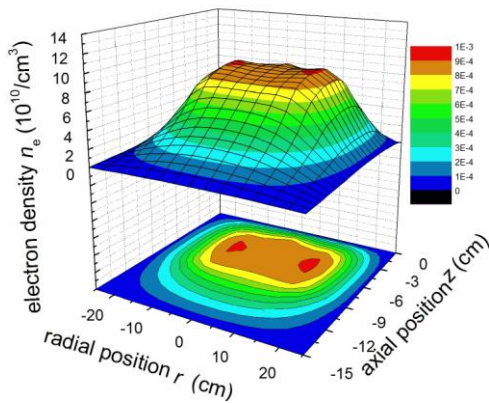


Fig. 3 Calculated 2D profile of the plasma density in the microwave plasma device for Ar gas pressure of 30 mTorr and $P_{in}+P_{out}=250$ W.

An example of calculation result of the fluid simulation is shown in Fig. 3, where $n_e(r, z)$ is plotted for Ar gas pressure of 30 mTorr, $P_{in} = 50$ W, $P_{out} = 200$ W, and calculation time of 0.5 ms.

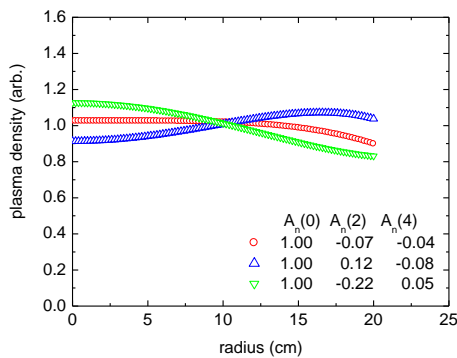


Fig. 4 Radial distribution of the plasma density for three cases of target profiles.

Here r is the radial position and z is the distance from the bottom surface of the quartz glass.

We ran the plasma simulation, giving several target density profiles (flat, hill, and hollow) as shown in Fig. 4 with $R = 20$ cm. The simulator calculates plasma production to seek a radial density profile with the optimum $A_n(i)$'s that are close to those values given in Fig. 4. The optimum profile of the simulator calculation for each target profile in Fig. 4 is plotted by the solid line in Fig. 5 together with the target profile with (a) flat, (b) hollow, and (c) hill shapes. The simulator output for each target profile is as a whole represents the trend of the target profile within the radius of 15 cm (12-inch wafer size), while the simulator curve includes some wavy form that may be due to a local change in intensity of microwave field caused by the edges of the quartz glass window (see Fig. 1).

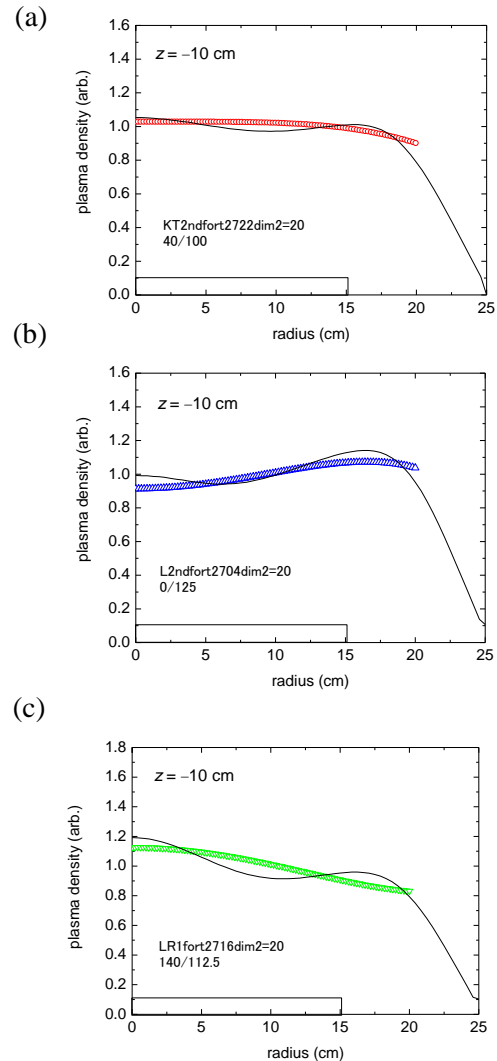


Fig. 5 Comparison of the prediction of the hyper simulator with the target profile of (a) flat, (b) hollow, and (c) hill shape.

The hyper simulator predicts the values of P_{in} and P_{out} together with the optimum profile given above. The predicted values of P_{in} and P_{out} for each target profile given in Fig. 4 are listed in Table 1.

Table 1 Device control parameters predicted by the hyper simulator and used in the experiment.

density profile		flat	hollow	hill
simulator prediction	P_{in}	40 W	0 W	160 W
	P_{out}	100 W	125 W	100 W
exp. result	P_{in}	45 W	0 W	70-160 W
	P_{out}	125 W	125 W	125 W

We produce plasmas in our microwave plasma device using the settings of P_{in} and P_{out} close to those predicted by the hyper simulator for each target profile with some adjustment to compensate a reflected microwave power.

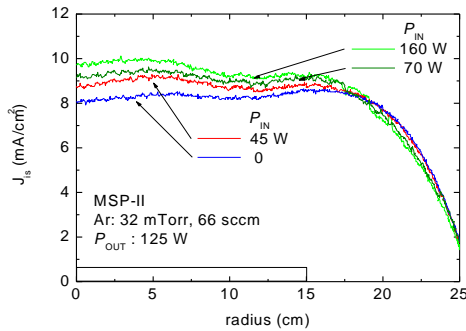


Fig. 6 Radial distribution of the ion saturation current obtained in the experiment for four cases of P_{in} with $P_{out} = 125$ W and Ar gas pressure of 32 mTorr.

Figure 6 shows the ion saturation current density as a function of radius for four cases of P_{in} with $P_{out} = 125$ W and Ar gas pressure of 32 mTorr. The curve for $P_{in} = 45$ W represents almost flat profile for an area of 15 cm in diameter, as well as hollow profile for $P_{in} = 0$, and hill profile for $P_{in} = 70$ and 160 W.

These values are tabulated in Table 1 and compared with the values predicted by the hyper simulator. We find good agreement between the simulator prediction and the experimental result for each target profile.

4. SUMMARY

We have proposed a novel device control system based on physics, in which a fluid simulation is used to obtain a power deposition profile necessary to produce a target density distribution. A control system of a microwave slot antenna regulates power distribution dynamically according to the output of the hyper simulator that has inputs and outputs opposite to conventional one.

We have shown configuration of the control system, operating procedure, and examples of operation on a slot-excited microwave plasma device. Plasmas close to the target density profiles can be obtained (in offline) by following the hyper simulator output.

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