Control of Plasma Profile in Microwave Discharges by Using Hyper-Simulation

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Abstract: Two novel techniques are introduced to control the uniformity of microwave discharges; one is a microwave slot antenna that can change distribution of the radiated power in real time during operation, and the other is a hyper simulator that can predict microwave power distribution necessary for a desired radial density profile using physical model equations. It is noted that the hyper simulator has the input and output just opposite to conventional simulations. By using a feedback control system consisting of a density profile monitor, the hyper simulator, and the adjustable antenna, it is possible to obtain a target density profile or to select a desired edge-to-center density ratio in online. A detailed description of the feedback system and initial results of experiments is given.

Keywords: Microwave discharge, plasma uniformity, hyper simulation.

1. Introduction

Plasma uniformity is one of the most important parameters in determining qualities of processing, especially for large wafers. In fabrication lines, a plasma device is given an operating condition from a recipe and generates plasmas or processes wafers with uniformities in variation in radial or azimuthal direction, which usually cannot be controlled precisely. In other word, at present, evaluation and control of the uniformity are performed empirically without the basis of plasma physics. On the other hand, plasma simulation is used to predict 2D or 3D profiles of plasma or radical densities as output for a given input condition, in order to make comparison with experiments, but not to control the device [1-3]. If input and output can be reversed, the simulation code would predict conditions for a desired profile of, for example, plasma density.

In this paper, we introduce two novel techniques to control the uniformity of microwave discharges; one is a microwave slot antenna that can change distribution of the radiated power in real time during operation, and the other is a hyper simulator that can predict microwave power distribution necessary for a desired radial density profile using physical model equations [4]. By using a feedback control system consisting of a density profile monitor, the hyper simulator, and the adjustable antenna, it is possible to obtain a target density profile or to select a desired edge-to-center density ratio in online. A detailed description of the feedback system and initial results of experiments is given.

2. Control of microwave plasma device

2.1 Slot-excited microwave plasma

We use a microwave plasma as shown in Fig. 1(a), where a slot antenna radiates microwave field at a frequency $\omega$ through a glass window to an axially non-uniform plasma. The density $n_e$ along the axis is schematically shown at the right. The electromagnetic field is cutoff at a location where $\omega$ equals to plasma frequency $\omega_{pe}$, but at the same time, axial electric field $E_z$, which is parallel to the density gradient, is strongly peaked there to heat electrons, which is called resonant absorption. The values of
$E_z$ along the axis is plotted in Fig. 1(b) with the origin at the interface of a glass plate and the plasma.

Since the electric field at the resonance location is very large as seen from Fig. 1(b) and the absorption is strong, the microwave propagates to the plasma almost uni-directionally with little reflection. This indicates that the radial and azimuthal profile of power absorption in the plasma can be changed by antenna radiation profile.

### 2.2 Slot antenna with double coaxial feed

We have constructed a microwave plasma device for 300 mm wafer where dynamic control of power absorption profile can be performed by changing power outputs of two microwave sources. The cavity space over the slot plate is divided into two radial sections as shown in Fig. 2, and driven by a double coaxial feeder to change the balance of powers of the inner and outer sections, $P_{\text{in}}$ and $P_{\text{out}}$. This can modify the radial distribution of the antenna radiation and control the radial profile of power absorption in the plasma.

### 3. Hyper simulator

The diagram in Fig. 3 shows a system for profile control of the microwave plasma device. The device has a mechanism to regulate radial profile of microwave radiated from the slot antenna as described in the previous section, and in future, to adjust wave polarization for the azimuthal profile control. Gas feed control will also be used.

![Figure 1](image1.png)

**Figure 1.** (a) Sketch of the microwave plasma device and the axial ($z$) density profile on the right. (b) Plot of $E_z$ along $z$ from the slot, through the air and glass, to the plasma.

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![Figure 2](image2.png)

**Figure 2.** Slot antenna with inner and outer coaxial feeders.

The simulator with reversed input and output, which we call a hyper simulator, is incorporated in a feedback control system. A target profile of radial density distribution in the device and the past measured density profile obtained by a probe or visible emission monitor, if necessary, 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 microwave power and gas feed.

![Figure 3](image3.png)

**Figure 3.** Diagram of the system for profile control of the microwave plasma device.
At present, the hyper simulator is similar to usual code, which solves iteratively basic equations consisting of Maxwell equations for wave propagation, power absorption of electrons, plasma transport equations, and neutral chemistry equation for radical production in gas phase. We introduce power absorption profile coefficient \(a_p(r)\) that represents the ratio of modified power absorption profile in the plasma to that obtained for a standard antenna radiation profile. The calculation is iterated adjusting \(a_p(r)\) until a target density profile is obtained. Actually, \(a_p(r)\) is represented by a few parameters of components of Legendre expansion to minimize data storage.

We show an example of the result of the hyper simulator used to control radial density profile. Figure 4(a) shows the 2D distribution of \(n_e\) in the case of a standard radiation profile of the slot antenna (different from that shown in Fig. 2), and (b) represents the 1D profile at the location near the stage indicated by dotted region in (a). Then we set a target profile shown by the red circles in Fig. 4(d) and input it to the hyper simulator. The simulator seeks \(a_p(r)\) that gives the best fit of calculated density profile to the target profile and finally outputs the profile parameter. The new radiation profile determined by the output gives the 2D distribution of \(n_e\) in Fig. 4(c) and the 1D profile given by the solid line in (d), which is very close to the target profile. This output is used to set the device control.

4. Experimental results

The hardware interface shown in Fig. 3 is given the device control parameter from the hyper simulator, which is three lowest components of Legendre expansion of \(a_p(r)\), and calculates parameters for antenna power control to realize the modified radiation profile.

For the case of the antenna shown in Fig. 2, the output from the hardware interface may be the ratio of the output power to the input power.
Here, we measure ion saturation current density $J_{is}$ in the device shown in Fig. 1(a) with the antenna in Fig. 2 in order to confirm the ability of controlling the density profile according to a command from the hardware interface. The radial profiles of $J_{is}$ are shown in Fig. 5 for (a) $P_{in}/P_{out} = 310/125$ W, (b) 220/125 W, and (c) 120/125 W, for Ar plasma with a gas pressure of 70 mTorr. The electron temperature was around 1.6 eV. As shown in Fig. 5, we can vary the radial profile of the plasma from hill type to hollow type through a very flat shape by changing the power ratio $P_{in}/P_{out}$. The profile in (b) is very uniform for a wafer of 300 mm size or even for 400 mm. It is therefore confirmed that the present device can fully respond to the command from the hyper simulator to realize desired antenna radiation profile producing the density profile close to any target profile.

5. Summary

We have introduced two novel techniques to control the uniformity of microwave discharges; one is the microwave slot antenna that can change distribution of the radiated power in real time during operation, and the other is the hyper simulator that can predict microwave power distribution necessary for a desired radial density profile using physical model equations. Detailed descriptions of the feedback system including the hyper simulator and the experimental results demonstrating profile control by the slot antenna with double coaxial feed have been presented. We are now in a position to readily use the total feedback control system consisting of a density profile monitor, the hyper simulator, and the slot antenna to obtain a target density profile or to select a desired edge-to-center density ratio in online.

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References