Development of Combinatorial Plasma-Process Analyzer for Advanced R&D of Plasma Nano Processes

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Abstract: A plasma process analyzer has been developed on the basis of "combinatorial method", in which process examinations with a continuous variation of process parameters can be carried out in one execution of experiment via placing substrates on a substrate holder with an inclined distribution of plasma conditions (ion flux and radical flux). Plasma-fluid simulations have been performed to show the feasibility of the combinatorial plasma process analyzer.

Key words: Plasma nano science, combinatorial method, density-inclination plasma, process analysis

1. Introduction

Development of future nano devices including next-generation ULSIs [1], MEMS [2,3], NEMS [4,5] and bio-chips [6] requires device-fabrication process science and technologies, with which device structures can be controlled with a precision of nanometer size either via top-down or bottom-up process. In future development of these processes, it is greatly anticipated that optimal process conditions can be attained at a pinpoint window of the process conditions. Therefore methodologies widely employed in the conventional process developments with try-and-error manners should be hindered.

For the breakthroughs to overcome these constraints, it is of great significance to establish "Plasma Nano Science", in which the process results are characterized by the essential elements governing the plasma processes (fluxes and energy distributions of ions, radicals and photons, which are irradiated onto the substrate) rather than the conventional process parameters (gas pressure, plasma sustaining power, and so on), which are dependent on apparatuses and are generally different from each other.

On the basis of this guiding principle to establish scientific basis of plasma nano processes, a plasma process analyzer has been developed via the combinatorial methods, in which process examinations with a continuous variation of plasma-process conditions (ion flux, radical flux and/or radical-to-ion flux ratio) can be carried out on a substrate holder with an inclined distribution of plasma conditions (ion flux and radical flux) and the distributions of particle fluxes are finely controlled and characterized via particle diagnostics.

In this study density-inclination plasmas have been developed for the plasma process analyzer, in which the feasibility of the density-inclination plasmas are shown on the basis of principle to sustain discharge by localized profile of power deposition via inductive coupling of RF power with low-inductance antenna (LIA) modules [7]. The LIA module consisted of a U-shaped internal antenna with dielectric isolation, which allowed low-voltage and high-density plasma production. Furthermore it has been demonstrated that desired power-deposition profiles can be attained with multiple operations of LIA modules [8].

In this paper, design issues involved in production and control of density-inclination plasmas are elucidated for the plasma process analyzer via localized profile of power deposition to sustain discharge with inductive coupling of RF power using low-inductance antenna (LIA) modules.

2. Generation of density inclination plasmas

Figure 1 shows the plasma reactor for sustaining the density-inclination plasmas via localized power deposition of RF power through inductive coupling with a low-inductance antenna (LIA) module. The LIA module consisted of a U-shaped internal antenna with dielectric isolation, which allowed low-voltage and high-density plasma production. Furthermore multiple operations of LIA modules make it possible to attain desired power-deposition profiles. U-shaped low-inductance antenna consisted of a...
Fig. 1. Schematic illustrations of plasma chamber for generation of density-inclination plasma with a LIA module.

copper tube covered with a quartz tube with a dimension of 70 mm in width and 100 mm or 160 mm in length, and was mounted on a top flange of the chamber with a horizontal length (in the direction of density inclination) of 500 mm and a width of 150 mm. The LIA was coupled to an RF power generator at 13.56 MHz via a matching network. Plasma density profiles along the substrate were measured with a cylindrical Langmuir probe. In this study Ar plasmas were generated for feasibility test of the density inclination plasmas.

3. Numerical modeling

The numerical model for prediction of the density profiles is based on a three-dimensional (3D) plasma-fluid simulation code. In the present model, the density profiles of electrons, ions and excited radicals were predicted via numerically solving continuity and energy equations for neutral and charged species under the drift-diffusion approximation, in which the motions of electrons and ions were assumed to be governed by ambipolar diffusion, and the plasma was assumed to be quasi-neutral. Argon (Ar) plasmas sustained at an RF power (13.56 MHz) of 800 W are simulated in the present study.

Before describing the details of the simulation model, the validity of the simulation model is discussed concisely on the basis of the fluid dynamics. In the present investigation, simulations have been carried out for argon plasmas sustained in a rectangular chamber (500 mm in length, 150 mm in width and 300 mm in height) as shown in Fig. 1 at pressures of 0.67 – 2.6 Pa. These conditions refer to the Knudsen number (defined as the ratio of the collision mean free path length to a representative physical length scale of the system) of the order of $10^{-2} << 1$, indicating that the collision mean free path is much less than a length scale of the problem. Therefore, the continuum assumption of fluid mechanics is regarded as a good approximation in the present investigation.

In the 3D model of this paper, Ar-plasma generation is simulated in the rectangular chamber (500 mm in length, 150 mm in width and 300 mm in height), in which x- and y-directions are taken to be parallel to the substrate holder with x-axis taken along the density-inclination direction of interest and z-direction is taken to be normal to the substrate holder, as schematically shown in Fig. 1. The simulation space in the rectangular chamber is divided into cubic numerical meshes in the x-, y- and z-directions.

In the simulation model, it has been assumed that the Ar plasmas are sustained using an LIA module indicated as "Antenna" (bold line) in Fig. 1. The LIA module is installed at the top flange of the discharge chamber and the shape of the LIA module is rectangular with dimensions of 70 mm in horizontal width (y direction) and 160 mm in height (z direction). Along the antenna conductor of the LIA module, RF current at 13.56 MHz is applied to sustain inductively coupled discharge and the RF power absorption to the plasma is assumed to be 800 W. For the purpose of sustaining Ar plasmas with the density inclination, the LIA module is located at a shifted horizontal position (x = 45 mm) of the top flange rather than at the center.

The RF power absorption (800 W in this study) is modeled as the power deposition in the electron energy equation, in which the amount of the absorbed power delivered to the numerical mesh is in proportion to the fraction of the antenna included in the mesh; i.e., the absorbed power in the mesh is calculated as (total power to the antenna) x (volume fraction of the mesh which includes the antenna) / (total volume of the meshes including the total length of the antenna).

For the cross sections of argon-electron collisions including excitation, ionization and elastic collisions, and the rates of electron-neutral momentum transfer as a
function of electron energy, we used the data reported by Bogaerts et al. [9] and Vahedi [10].

Plasma parameters (plasma density, 4s excited Ar (Ar\*) density and electron temperature) were evaluated at the center of the mesh above the substrate holder as those corresponding to the values at the neighbor mesh facing to the substrate.

4. Results and discussion

First, numerically simulated plasma density distributions were compared with Langmuir probe measurements as a bench-mark test. Figure 2 shows simulated and measured distribution of plasma density at an Ar pressure of 1.3 Pa. The simulated distribution showed excellent agreement with the measured profile, indicating justification of the numerical results with the present simulation code. Furthermore, the results demonstrate that the density inclination plasmas can be attained via localization of the power-deposition profile for sustaining the discharge.

Next, variation of plasma density profiles with Ar pressure was investigated using the plasma-fulid simulation code. Figure 3 shows simulated profiles of Ar plasma density with Ar pressure as a parameter. With increasing Ar pressure, the plasma density tends to localize at around the antenna position and to decay much more significantly along the substrate position x. These tendencies of the plasma density inclination with a variation of pressure imply that the charged particle distributions are significantly governed by the ambipolar diffusion together with the charged-particle loss at the walls. The charged particle distribution generally tends to peak at the center of the chamber due to the diffusion in the chamber and the loss at the walls. Therefore for obtaining the charged-particles distributions so as to enhance the inclination length much longer than the half size of the discharge chamber, it is considered to be effective to employ the discharge method with a localized power-deposition profile and to locate it near the non-central position as schematically illustrated in Fig.1.

The results described above indicate that a variety of process results can be efficiently analyzed via inclined distribution of process parameters along the substrate. One typical example is shown in Fig. 4 for analyses of plasma-polymer interactions using the combinatorial plasma-process analyzer. In this specific experiment, argon-oxygen mixture plasma with the inclined density distribution of the ion-saturation current along the substrate was exposed to polyethylene terephthalate (PET) films and the variation of the chemical bonding states at the surface of the films located along the substrate holder were analyzed with x-ray photoelectron spectroscopy (XPS). The XPS C1s spectra obtained from the samples located along the substrate holder clearly show systematic decrease of the...
C=O bond and increase of the C-O bonds with increasing ion-saturation current or the ion dose, which corresponds to the position along the substrate.

5. Summary

Plasma-fluid simulation has been carried out to show feasibility of density-inclination plasmas for combinatorial plasma-process analyzer. The simulated results showed that density-inclination plasmas can be obtained by localized power deposition for sustaining plasmas. The profiles of the charged particles are attributed to the diffusion characteristics together with the wall loss. The results indicate that a variety of process examinations can be efficiently analyzed via inclined distribution of process parameters along the substrate.

References