EXPERIMENTAL RESEARCH OF ICP REACTOR FOR PLASMA-CHEMICAL ETCHING

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The results of systematic experimental researches of plasma-chemical etching reactor in the inductive mode are presented in this paper. Measurements of the integral discharge parameters (inductor voltage, gas pressure, input power) have been carried out as well as probe measurements of spatial distribution of local plasma parameters (plasma density, temperature and electron energy distribution function) and radial profiles of ion current to processed surface. The measured dependences differ essentially for atomic (Ar) and molecular (O_2,N_2,CF_4) gases. As the range of working pressure covers diffusive and collisionless modes of charged particles movement, radial distribution of ion current density and its absolute value change significantly. Comparison of the obtained results with the calculations executed using "Global" spatially averaged model and 2D-fluid model is carried out.

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1. INTRODUCTION

Last years ICP became the conventional basis for creation of various plasma technological devices, in particular for plasma-chemical etching in microelectronics [1]. By the present moment great progress have been achieved both in the field of basic research of ICP physics and in the field of practical reactor design, and focus of ICP application is shifted to development of the technological devices optimized for specific micro- and nanotechnologies with high requirements to the device parameters. It is impossible to satisfy these requirements without detailed experimental researches and improvement of ICP mathematical models.

This paper reports the results of systematic experimental researches of the universal module of plasma-chemical and ion-plasma etching based on ICP reactor with additional RF electrode biasing developed in the Kharkiv National University.

2. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup used in our investigation is shown in Fig. 1. The discharge vessel has a radius R = 7 cm and height L = 6 cm. The sidewall of the vessel is made of metal. The glass top cover and the inductive coil is cooled by air flow created by a fan. The vessel is evacuated by a turbomolecular pump down to a base pressure of about 10^{-6} Torr. The experiments were performed using argon in the pressure range 0.3…300 mTorr.

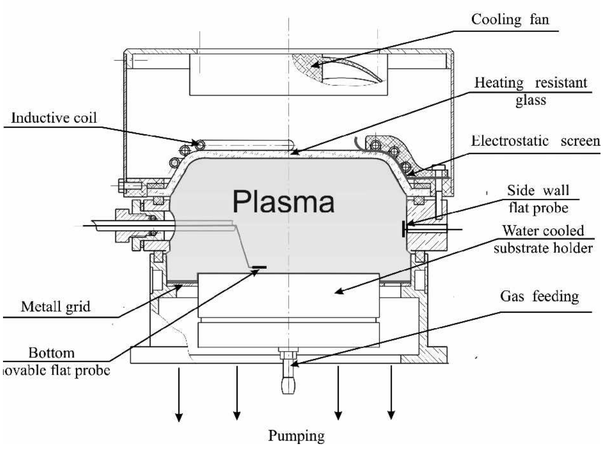

Fig. 1. Schematic diagram of the ICP reactor

The RF field is induced by a three-turn spiral copper coil cooled by air. The capacitive coupling is damped by a grounded electrostatic shield. RF power in the range 50…500 W at 13.56 MHz is coupled to the coil via a matchbox.

Measurement of the ion current density j was carried out adjacent to the grounded work surface, here a substrate holder, using a flat probe of 1×1 cm with 5mm mica guard ring around added to avoid edge effects. We assume here that the probe current in mA represents the ion current density in mA/cm^2. The probe could be moved in the radial direction by a coordinate drive. Second probe of the same design was mounted stationary on the chamber side wall (see Fig.1) allowing j measurement during etching process. The ion saturation regime was used. In the power range of interest the thickness of the near-probe layer is negligible in comparison with the probe dimensions, and is justified by excellent probe current saturation at probe potentials lower than -15 V. On the other hand, much more negative potentials may cause ionization current gain under high pressures. Thus, in all experiments a negative probe bias of -25 V in respect to the chamber was used.

3. EXPERIMENTAL RESULTS

3.1. ARGON

Typical radial profiles of the ion current density j at the substrate holder are presented in Fig. 2 at various argon pressures. Measurements were carried out at RF power of 200 W. It has been found, that in the power range 50-500W j is proportional to the power, and shape of radial profile $j(r)$ practically does not change.

As shown in Fig. 2, for pressure $p < 20$ mTorr the radial profile of j is convex, maximizing at the discharge axis. For $p < 5$ mTorr, the profile remains practically unchanged with further pressure decrease, only its magnitude changes. For $p > 20$ mTorr, the j profile becomes concave, with off-axis maximums. In this range the ratio of the peak density to the axis density increases with the pressure. There is relatively high uniformity of j in the region $r < 0.8R$ for $p \approx 200$ mTorr.

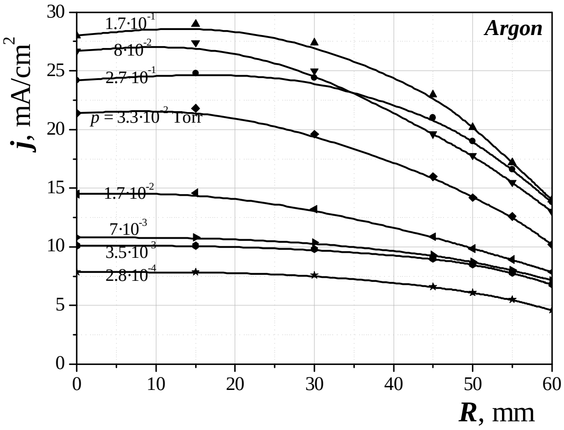

Fig. 2. Radial distributions of the ion current density to the chamber bottom (P = 200W)

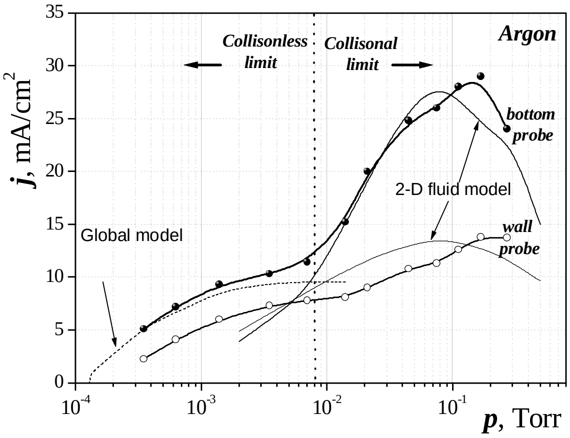

Fig. 3. Ion current to the bottom and the side wall probes on argon pressure in comparison with theoretical data

The dependence of j at $r = 0$ on the neutral gas pressure is shown in Fig. 3, in comparison with theoretical results. In the figure two regions are clearly seen: 1) low pressure region where mean free path of the charged particles is comparable or higher then the plasma dimensions, so the particle motion is mostly collisionless; 2) high pressure region where the mean free path is lower, particle motion is collisional, and diffusive approach is more appropriate.

It is also found that the magnitude of j is proportional to the RF power absorbed by plasma and the shape of the j radial profile has weak dependence on the power value.

3.2. MOLECULAR GASES

On Fig. 4, 5 dependences of the ion saturation current of the wall probe j, amplitude of the inductor RF voltage U_{ind} on pressure of working gas at RF power P = 200W for different gases are presented. Apparently from the graphs the dependences are essentially different for argon and for the molecular gases. We have monotonic j increase and U_{ind} decrease with pressure growth for argon, whereas for molecular gases both at high and at low pressures the ion saturation current I_{probe} monotonously decreases. For argon ion current is always higher, U_{ind} is always lower, and the range of effective ionization is more then order higher at pressure scale.

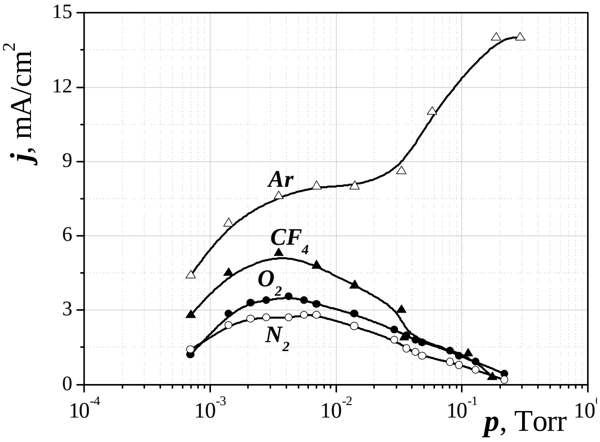

Fig. 4. Ion current to the wall probe vs. pressure for different gases (P = 200W)

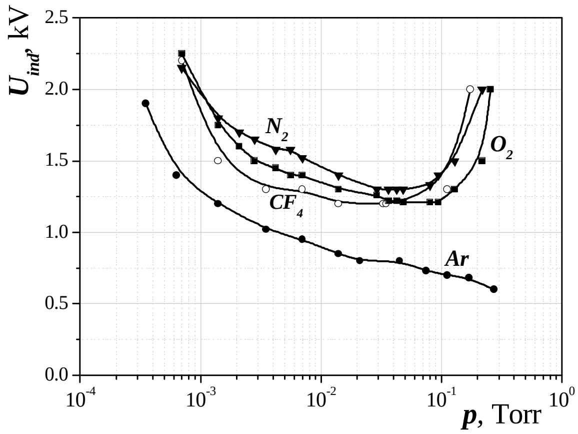

Fig. 5. Inductive coil voltage vs. pressure for different gases (P = 200W)

3.3. LANGMUIR PROBE MEASUREMENTS

For measurement of local plasma parameters a Langmuir probe was used. The probe was placed on the chamber axis approximately 2 cm higher the substrate holder. Measuring of the probe traces and the probe data processing was done using the “PLASMAMETER” device. All the presented here results are measured with pure argon feeding at RF power 200W.

Fig. 6 shows evolution of electron energy distribution

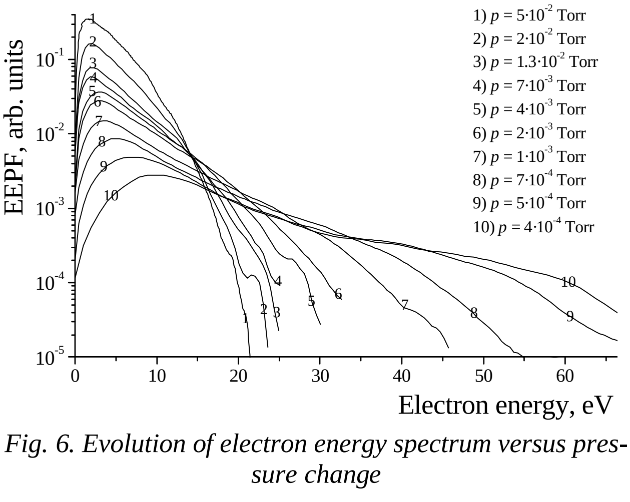

Fig. 6. Evolution of electron energy spectrum versus pressure change

with pressure change. On can see the monotonic decrease of mean electron energy with the pressure growth. At pressures below 2 mTorr the electron energy spectrum became clearly two-temperature, at higher pressures it is Maxwellian with damped tail, and at highest pressures it have Druevestain-like shape.

Electron density N_e and temperature T_e in the chamber center vs. argon pressure are shown in Fig. 7. Experimental results presented with bold lines. As one can expect from general gas discharge theory, we have monotonic decrease of the electron temperature and increase of the electron density with the pressure growth in the whole researched pressure range.

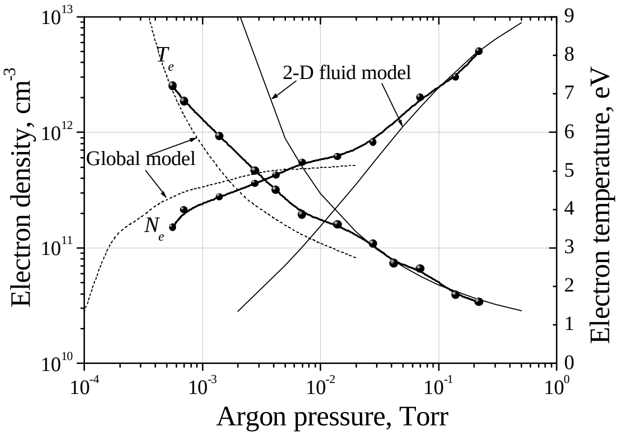

Fig. 7. Electron density N_e and temperature T_e in the chamber center vs. argon pressure. Bold lines – experimental results

4. COMPARISON TO THEORY

In Fig. 3 and 7 the described above experimental data are shown in comparison to theoretic results. The well known spatially averaged "Global" model [2] was used as well as 2-D fluid model described in detail in [3]. Obviously the Global model matches the experimental data at low pressures (excluding the lowest pressures near the discharge distinction where power loss grows in the inductive coil decreasing the power absorbed by plasma), whereas the fluid model is good for high pressures according to the validity condition of the diffusive approach.

ACKNOWLEDGEMENT

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ИНДУКЦИОННОГО РАЗРЯДА В РЕАКТОРЕ ПЛАЗМО-ХИМИЧЕСКОГО ТРАВЛЕНИЯ

С.В. Дудин, А.В. Зыков, А.Н. Дахов, В.И. Фареник

Представлены результаты систематических экспериментальных исследований реактора для плазмо-химического травления на базе ВЧ- индукционного разряда. Проведены измерения интегральных параметров разряда (давления, напряжения на индукторе, вводимой ВЧ-мощности), зондовые измерения пространственного распределения локальных параметров плазмы (плотность плазмы, температура и функция распределения электронов по энергии) и радиальных профилей плотности тока ионов на обрабатываемую поверхность. Измеренные зависимости существенно отличаются для инертного газа (Ar) и молекулярных (O_2,N_2,CF_4). Проведено сравнение полученных результатов с расчетами, выполненными с использованием глобальной пространственно усредненной и двухмерной гидродинамической моделью.

ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ІНДУКЦИЙНОГО РОЗРЯДУ У РЕАКТОРІ ПЛАЗМОВО-ХІМІЧНОГО ТРАВЛЕНИЯ

С.В. Дудін, О.В. Зиков, О.М. Дахов, В.І. Фареник

Надані результати систематичних експериментальних досліджень реактора для плазмово-хімічного травлення на базі ВЧ- індукційного розряду. Проведено вимірювання інтегральних параметрів розряду (напруги на індукторі, тиску, ВЧ-потужності), зондові вимірювання розподілу локальних параметрів плазми (густини, температури, функції розподілу електронів за енергією) та радіальних профілів густини течії іонів на оброблювану поверхню. Досліджені залежності суттєво відрізняються для інертного газу (Ar) та молекулярних (O_2,N_2,CF_4). Проведено порівняння отриманих результатів з розрахунками, виконаними за допомогою глобальної та двомірної гідродинамічної моделей.