Global model of a low-frequency inductively coupled plasma in U-shaped discharge tube

A. Fedoseev[1], G. Sukhinin[1], M. Isupov[1], N. Demin[1], M. Salnikov[1], S. Sakhapov[1] and V. Pinaev[1]

[1]*Institute of Thermophysics SB RAS, Novosibirsk, Russia*

Abstract: The parameters of low-frequency inductively coupled plasma generated in a U-shaped discharge tube are studied both experimentally and numerically. The model is based on the solution of the balance equations for neutral and excited active argon/chlorine plasma species together with the energy balance equation and the quasi-neutrality condition. New data on plasma parameters of U-shaped discharge tube of FMICP are obtained for various values of chlorine molecules addition to argon and total gas pressure.

Keywords: Ferromagnetic enhanced inductively coupled plasma, argon/chlorine plasmas, plasma etching.

1. Introduction

Radio frequency inductively coupled plasma (RF ICP) devices are widely used for ion-plasma etching to obtain pure plasma of halogen-containing gases with a high concentration of active species at low (~1-10 Pa) pressures of the plasma forming gas [1]. To overcome physical limitations of the RF ICPs in modern technological processes for the future 450 mm standard of the semiconductor industry [2] one should use the ferromagnetic enhanced low-frequency (~100 kHz) inductively coupled plasma (FMICP) with the magnetic coupling between the inductor and plasma enhanced with ferromagnetic materials [2-5].

To produce large volume of dense uniform plasma for plasma treatment, it was proposed to use a distributed principle of the FMICP generation [2-5]. A substrate to be treated is placed in a main discharge chamber with a number of U-shaped discharge tubes installed on the main chamber (see Fig. 1). Every U-shaped discharge tube has its own ferromagnetic core with primary winding (inductor) connected to a power supply, which is used to induce a vortex electric field driving the FMICP. Every U-shaped tube, together with the main discharge chamber, forms a closed discharge current path of the FMICP. Having a cross-section of a few orders less, the plasma resistance in the U-shaped tube is much larger than that in the main chamber. Therefore, practically all power delivered to the ferromagnetic inductor generates plasma in the U-shaped tube. Since plasma density in the U-shaped tube is considerably larger than that in the main chamber, the predominant source of plasma in the main chamber is the diffusion of charged and excited particles from the U-shaped tube into the main chamber. Therefore, in order to obtain the plasma parameters in the main chamber it is very important to know the plasma parameters in the U-shaped discharge tube.

The aim of the paper is to perform the experimental measurements of the plasma parameters of low-frequency inductively coupled plasma generated in a U-shaped discharge tube and to develop a model of U-shaped tube of the distributed FMICP under conditions of interest for plasma processing (plasma forming gas pressure of about 1-10 Pa and high electron densities). New data on plasma parameters of U-shaped discharge tube is obtained.

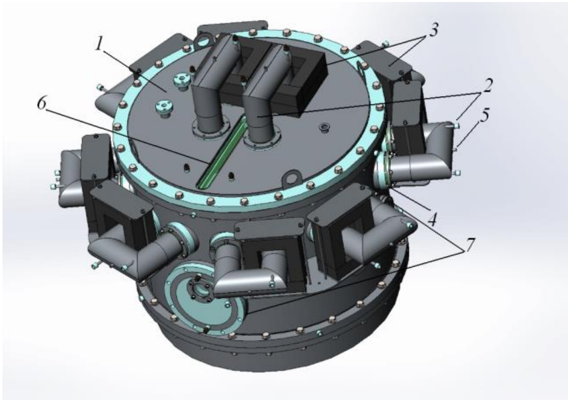

Fig. 1. Experimental setup. 1 – Gas discharge chamber with an inner diameter of 700 mm and a height of 500 mm, 2 – U-shaped discharge tubes, 3 – Ferrite cores with primary windings, 4 – Seals, 5 – Plasma forming gas inlets, 6 – Diagnostic windows, 7 – Side flanges.

2. Model

In order to understand which physical processes play an important role in the U-shaped discharge tube of the distributed FMICP (see Fig. 2), a simple 0-D model was developed. The gas discharge plasma is assumed to be in a steady state. It is homogeneous in the longitudinal direction and cylindrically symmetric, i.e. the U-shaped tube is replaced with a cylindrical tube with equivalent length L = 40 cm and radius R = 2.5 cm.

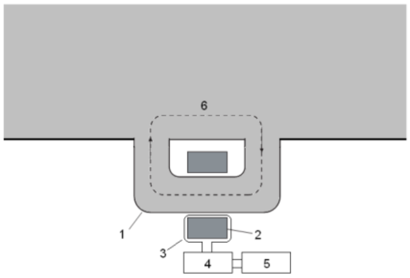

Fig. 2. Scheme of the U-shaped part of FMICP. 1 - U-shaped tube, 2 – Ferrite core, 3 – Inductor, 4 – Matching unit, 5 – Power supply, 6 – Half space of large FMICP. Dashed line denotes the electric current path.

The developed model for plasma parameters in the U-shaped tube is based in general on the model [5,6] for the main FMICP cylindrical chamber with some modifications. The balance equations for particles of type X were calculated in the same manner. Various processes of loss and generation of particles in a discharge are considered, which includes reactions between electrons and gas particles, between two (or more) gas particles, recombination of neutral particles on the discharge tube wall and neutralization of positively charged ions (for all neutrals and positive ions).

Besides the electrons, chlorine molecules in the ground state Cl_2, chlorine atoms in the ground state Cl ($3p^5\ ^2P$), negatively charged chlorine ions Cl^- (ε_{aff} = 3,6 eV), positively charged chlorine ions Cl^+ (ε_i = 13,0 eV) and Cl_2^+ (ε_{i2} = 11.5 eV), argon atoms in the ground state Ar ($3s^2\ 3p^6$), metastable states of argon atoms Ar_m ($1s^5$ and $1s^3$) (ε_m = 11.6 eV), radiation-related levels of Ar_r ($1s^4$ and $1s^2$) (ε_r = 11.7 eV), highly excited argon atoms Ar (4p) (ε_{ex} = 13.2 eV) and positive Ar^+ ($\varepsilon_{Ar,I}$ = 15,8 eV) are considered. Vibrationally excited chlorine molecules Cl_2 (v = 1–3) with excitation threshold ε_{ex} = 0,07-0,21 eV were taken into account only as the channel of electron energy losses .

Through an inlet, a constant flow Q_X of neutral particles (Cl_2 and Ar) is diluted into the discharge tube. The gas pressure p at the outlet of the tube is equal to the gas pressure in the working chamber and is defined as the sum of the partial pressures of all the components of the plasma gas. The supply of molecular chlorine Q_{Cl2} and argon atoms Q_{Ar} to the tube and the diffusive losses of gas particles on the open ends of the discharge tube are taken into account.

The discharge plasma is assumed to be electrically quasi-neutral. Sets of cross-sections for Cl_2, Cl and Ar are taken from the work [6]. It is assumed that electrons have a Maxwell energy distribution function, and the electron collision velocity coefficients are calculated using analytical equations for the electron temperature range of $0,01 < T_e < 10$ eV.

On the walls of the discharge tube, the loss and birth of particles occurs due to the recombination of chlorine radicals and argon atoms and the neutralization of positive ions (Ar^+, Cl^+, Cl_2^+). Diffusion losses of Cl atoms in the tube are assumed to be only on the discharge tube wall. V and A are volume and surface area of the discharge tube.

For the U-shaped discharge tube the power balance equation was modified:

$$\frac{d}{dt}\left(\frac{3n_e kT_e}{2}\right) = \frac{d}{dt}\left(\frac{3p_e}{2}\right) = \frac{1}{V}(P_{in} - P_{loss}). \qquad (1)$$

In the experiments, the discharge current I_d is maintained and controlled by the power supply. The Joule heat, i.e. $P_{in} = I_d U_d$, where U_d is the potential fall on the discharge tube length L, is spent to elastic and inelastic collisions of electrons and the energy carried by the flow of charged particles to the wall as in [5,6].

3. Results

The numerical calculation of plasma parameters of U-shaped discharge tube were performed for different values of the discharge current I_d, total gas pressure p, and argon Q_{Ar} and molecular chlorine Q_{Cl2} flow rates. These parameters can be maintained manually during the experiments. As a result of calculations, the plasma content, i.e. the densities of neutral, excited and charged particles, as well as the electron temperature T_e and the axial electric field strength E_z in the U-shaped discharge tube were calculated.

In Fig. 3, the numerical calculations of the electric field strength E_z dependencies on total gas pressure p are shown for different values of chlorine dilution Q_{Cl2}. Discharge current I_d = 20 A, total gas pressure p = 10 Pa, argon flow rate Q_{Ar} = 13 sccm were the constants. The same values of the electric field strength (E_z ~ 0.5 V/cm) were obtained experimentally in [7] in cylindrical ICP discharge tube with the same inner diameter (D = 5 cm) for pure argon. The electric field strength increases with the total gas. The calculated results also show an increase of the electric field strength with chlorine dilution.

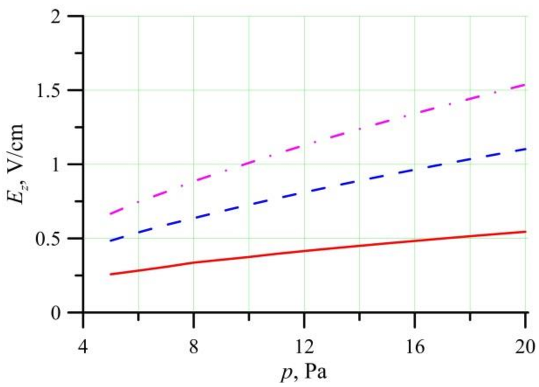

Fig. 3. The electric field strength E_z dependencies on total gas pressure p for different dilutions of Cl_2 to argon. Solid line for Q_{Cl2} = 0 sccm (pure argon), dashed line for Q_{Cl2} = 0.5 sccm, dash-dotted line for Q_{Cl2} = 1 sccm.

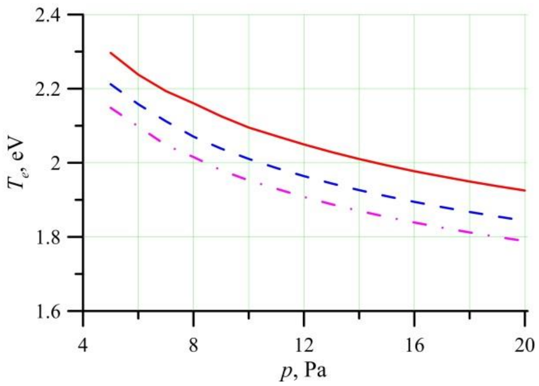

Fig. 4. The electron temperature T_e dependencies on total gas pressure p for different dilutions of Cl_2 to argon. Solid line for Q_{Cl2} = 0 sccm (pure argon), dashed line for Q_{Cl2} = 0.5 sccm, dash-dotted line for Q_{Cl2} = 1 sccm.

Fig. 4 presents the electron temperature T_e dependencies on total gas pressure p for different dilutions of Cl_2 to argon for the same discharge parameters as in Fig. 3. The electron temperature decreases with the gas pressure and the chlorine dilution that is the common feature for the discharges.

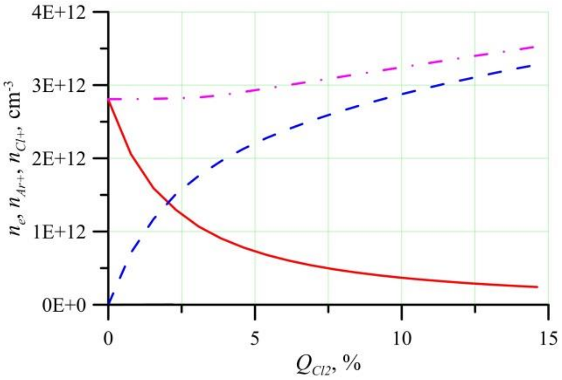

Fig. 5. The densities of charged particles versus volume fraction of Cl_2 in gas flow rate. Solid line for argon ion density n_{Ar+}, dashed line for chlorine ion density n_{Cl+}, dash-dotted line for electron density n_e.

In Fig. 5, the densities of electrons n_e, argon ions n_{Ar+}, and chlorine atom ions n_{Cl+} are presented. Discharge current I_d = 20 A, total gas pressure p = 10 Pa, argon flow rate Q_{Ar} = 13 sccm were the given parameters. The densities of other charged particles (positive chlorine molecular ions n_{Cl2+}, negative chlorine atom ions n_{Cl-}) are sufficiently lower for the present condition and are not shown in Fig. 5. In the model, the electrically quasi-neutrality of the discharge plasma is assumed that is seen in Fig. 5. The argon ions density gradually decreases with the chlorine dilution while the chlorine atom ions increases. The electronegativity, $\beta = n_{Cl-}/n_e$ increases with chlorine dilution but not exceed 10^{-2} value at 10% of chlorine fraction.

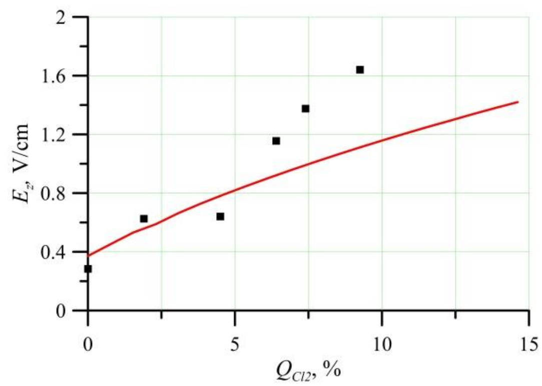

Fig. 6. The electric field strength E_z dependencies on the volume fraction of Cl_2 in gas flow rate. Square dotes denote the experimental data, solid line for calculated results.

Fig. 6 presents the experimental data on the electric field strength depending on the molecular chlorine dilution to the argon flow rate for the same discharge parameters as in Fig. 5. In the experiments, the argon flow rate was constant, Q_{Ar} = 13 sccm, as well as the discharge current I_d = 20 A and total gas pressure p = 10 Pa were maintained. The additional chlorine dilution was in the range Q_{Cl2} = 0-2 sccm that corresponds to the volume fraction of chlorine 0-20 %. It is seen that the electric filed strength strongly increases with the chlorine dilution. The experiments show the 6-time increase of the axial electric field with 10% of chlorine. The numerical results also show an increase of the axial electric field with chlorine dilution.

4. Conclusions

A simplified model of ferromagnetic enhanced low frequency inductively coupled argon plasma generated in a U-shaped discharge tube has been developed. The model is based on the solution of the balance equations for neutral and excited active argon/chlorine plasma species together with the energy balance equation and the quasi-neutrality condition. The Maxwellian electron distribution function is assumed.

The numerical calculation of plasma parameters of U-shaped discharge tube were performed for different values of the discharge current I_d, total gas pressure p, and argon Q_{Ar} and molecular chlorine Q_{Cl2} flow rates. As a result of calculations, the plasma content, i.e. the densities of neutral, excited and charged particles, as well as the electron temperature T_e and the axial electric field strength E_z in the U-shaped discharge tube were calculated. The results show that the electron temperature decreases with the gas pressure and the chlorine dilution that is the common feature for the discharges. The electric field strength increases with chlorine dilution that was shown both experimentally and numerically.

5. Acknowledgement

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6. References

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