Low-pressure low-frequency inductive discharge with ferrite cores for large-scale plasma processing

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Abstract. Electrophysical characteristics of a low–frequency (100 kHz) low–pressure (10–100 Pa) argon inductive discharge with ferrite cores have been investigated for discharge currents of 1–50 A, discharge chamber diameter of 230 mm. The dependencies of electric field strength on the argon pressure and discharge current were measured. Radial profiles of electron density and temperature were determined with double electric probes. Experimental results were compared with numerical results obtained by a self-consistent kinetic model of the low-frequency ICP, based on the simultaneous solution of a non-local Boltzmann equation for electron energy distribution function and balance equations for the metastable argon atoms density and gas temperature. Comparison of numerical and experimental results is presented.

1. Introduction

Low-pressure, high-density radio-frequency inductively coupled plasma (RF ICP) is widely used in many areas of semiconductor industry for plasma etching, plasma enhanced chemical vapour deposition, and plasma-immersion ion implantation. However, the principle of ICP generation has a few limitations that significantly complicate the scaling up of ICP sources for large-scale plasma processing systems (for example, for the future 450 mm wafers technology) [1]. ICP has a weak magnetic coupling between the ICP coil and plasma (k=0.2–0.7), a low power factor of the coil (cosφ<1) respectively, therefore the use of a resonant-matching network is necessary to improve the ICP power transfer efficiency, leading to high current and high voltage in the coil. The high coil current leads to high power losses in the coil and matching network, while the high coil voltage affects plasma through a capacitive coupling between the coil and plasma, leading to an intense ion bombardment of the discharge chamber. As the coil voltage is increasing with the coil size, this undesirable effect becomes a growing problem for large-scale plasma systems. Another limitation of ICP is a high driving frequency of its generation (typically, 13.56 MHz). As a result, a standing wave effect may arise with the increase in the ICP coil length, disturbing plasma uniformity (which is very important for plasma processing).

These limitations of RF ICP can be overcome with the enhancement of the magnetic coupling between the ICP coil and plasma by a closed ferromagnetic core [1]. In this case, the magnetic flux is concentrated almost in the ferromagnetic core, therefore magnetic coupling and power factor of the coil are high, leading to the increase in the ICP power transfer efficiency. It also allows to separate the ICP coil and discharge chamber in space, thereby the capacitive coupling between the ICP coil and plasma is eliminated. As the magnetic permeability of the core is high, the driving frequency can be
significantly decreased, to a few kilohertz, thereby the standing wave effect is also eliminated. As a result, new devices for large-scale plasma processing can be developed on the basis of the low-pressure low-frequency inductively coupled plasma sources enhanced with ferromagnetic cores [1].

It is necessary to underline that existing models of RF ICP cannot be used for the low-frequency ICP with a ferromagnetic core due to a principal difference in discharge configuration: in the low-frequency ICP with a ferromagnetic core, the discharge current is directed axially to the discharge chamber while in RF ICP – azimuthally. That is why the development of a model of the low-pressure low-frequency ICP enhanced with ferromagnetic cores and its experimental verification is an important task.

2. Experimental setup

A principal scheme of the experimental setup is shown in Figure 1. The discharge chamber of the setup consists of a wide (230 mm internal diameter, 1 meter length) part 1 and a narrow (40 mm internal diameter) U-shaped part 2 forming together with the part 1 a closed path for discharge current. The gas discharge chamber is made of stainless steel water cooled sections insulated and sealed with silicon rubber gaskets. On the U-shaped part 2, eight ferrite cores 3 with six turns of primary winding 4 are mounted. All primary windings are connected in parallel to a power supply 6 (50–100 kHz, 500 V) through a matching network 5 (variable LC circuit). To pump out the chamber a fore-vacuum pump 7 is used. Gas pressure is controlled with a leak valve (not shown) and measured with a MKS baratron 626A PR4000B 8. Discharge current is measured with a Rogowski coil 9. To determine an average electric field strength $E$, inter-section voltage $U$ is measured with a voltmeter $10 \ (E=U/L, \ where \ L \ is \ the \ discharge \ path)$. To determine electron density and temperature, a double Langmuir probe 11 made of tungsten wire with a diameter of 200 µm is used. The probe can be moved both along the discharge chamber axis and radius to determine a spatial distribution of plasma parameters in the discharge chamber.

![Figure 1. Experimental setup: 1 – wide part of gas discharge chamber (ID of 230 mm), 2 – narrow U-shaped part of the chamber (40 mm ID), 3 – ferrite cores, 4 – primary winding, 5 – matching network (variable LC circuit), 6 – power supply 100 kHz, 500V, 7 – fore-vacuum pump, 8 – MKS baratron, 9 – Rogowski coil, 10 – voltmeter to measure inter-section voltage, 11 – Langmuir probe.](image)

3. Numerical model

A one-dimensional radial model of the low-frequency argon ICP has been developed based on the assumption of plasma stationarity and uniformity in axial direction. To calculate a radial distribution of the electron component of plasma, equation (1) for isotropic part of electron energy distribution function (EEDF) $f_0(\varepsilon, r)$ is used [2], where $\varepsilon=U-e_0W(r)$ is the total electron energy, $U$ is a kinetic electron energy, $W(r)$ is a radial distribution of plasma potential, $N_\parallel(r)$ is a radial distribution of gas density, $T_g(r)$ is a radial distribution of gas temperature, $Q_0(U)$ and $Q_{\parallel n}(U)$ are the scattering cross sections of electrons in elastic and inelastic collisions with gas atoms, with the total momentum losses $H(U)=N_\parallel Q_0(U)+\Sigma_iN_\parallel Q_{\parallel i}(U)$:

$$
1 \frac{\partial}{\partial r} \left[ \frac{r U}{3H(U)} \frac{\partial f_0(\varepsilon, r)}{\partial r} \right] + \frac{\partial}{\partial \varepsilon} \left[ \frac{m_e}{\mu} U^2 N_\parallel Q_0(U) \left( f_0(\varepsilon, r) + \frac{3}{2} \frac{\partial f_0(\varepsilon, r)}{\partial \varepsilon} T_g(r) \right) \right] = \frac{1}{\mu} \frac{\partial}{\partial \varepsilon} \left( \frac{m_e}{2} \frac{\partial f_0(\varepsilon, r)}{\partial \varepsilon} \right) 
$$

(1)
\[-\sum_{k}^{} UN_k \mathcal{Q}_k^\infty(U) f_0(\varepsilon,r) + \sum (U + U_k^\infty) N_k \mathcal{Q}_k^\infty(U + U_k^\infty) f_0(\varepsilon + U_k^\infty, r) + S = 0 \]

The last term \( S \) in equation (1) takes into account the processes of direct, stepwise and Penning ionisations. The inelastic collisions in argon are divided into four groups \((k = 1–4)\), namely, the allowed transitions are grouped and have a cross section with an 11.623 eV threshold, two forbidden transitions are with a 12.9 eV threshold, for 13 forbidden transitions the threshold is 11.273 eV, and the ionization potential is 15.6 eV. For simplicity, the radial distribution of plasma potential \( W(r) \) is taken as a parabolic function of radius, with a wall potential of 12 V, near the threshold for metastables excitation. This assumption is used to describe the radial distribution of plasma potential in DC glow discharges [3].

Anisotropic parts of the EEDF are related to the isotropic part with equations (2) and (3):

\[
\frac{\partial f_0}{\partial r} - e_0 E_r(r) \frac{\partial f_0}{\partial U} + H(U) f_r = 0
\]

\[
\frac{\partial f_0}{\partial r} - e_0 E_z(r) \frac{\partial f_0}{\partial U} + H(U) f_z = 0
\]

where \( E_r \) and \( E_z \) are radial and axial components of electric field strength.

Solving the Boltzmann equation (1) for isotropic part of EEDF and equations (2), (3) for anisotropic parts, macroscopic plasma parameters can be determined as the corresponding integrals of EEDF: a radial distribution of electron density \( n_e(r) \), a radial distribution of electron temperature \( T_e(r) \), radial and axial components of electron flux density \( j_r(r) \) and \( j_z(r) \).

Metastable density \( N_{m}(r) \) is described by a balance equation (4):

\[
\frac{\partial N_{m}}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r D_m \frac{\partial N_{m}}{\partial r} \right) = S_{m}(r) + k_{m1} n_i(r) n_{m}(r) - k_{m2} n_{m}(r) N_{m}(r) \]

\[
- 2 k_{m3} N_{m}^2(r)
\]

where \( S_{m} \) is a rate of metastable atoms excitation, \( k_{m1} \) is a rate constant of radiation recombination \( (n_i \) is an ion density), \( k_{m2} \) is a rate constant of stepwise ionisation from metastable atoms, \( D_m \) is the metastables diffusion coefficient, \( k_{m3} \) is a coefficient of Penning ionization. Here we assume the condition of electrical neutrality, \( n_e=n_i \).

Also we take into account gas heating by the electron current and heat conduction to the discharge tube wall. For this purpose we solve the following thermal balance equation:

\[
\frac{\partial T_g}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r k_g(T_g) \frac{\partial T_g}{\partial r} \right) = P_g(r)
\]

where \( k_g \) is the heat conductivity coefficient, \( P_g \) is the gas heating due to elastic collisions of electrons and argon atoms. Gas heating may result in changing of the radial profile of the gas density \( N_g(r) \) thus affecting the isotropic and anisotropic parts of the EEDF. Rate constants \( S_{m} \), \( k_{m2} \) and gas heating \( P_g \) are calculated by the integration of EEDF with the corresponding cross sections.

3. Results and discussion

In figure 2, the dependencies of electric field strength on argon pressure are shown, for various discharge currents. Also, literature data [4] for a low-frequency ICP enhanced with ferrite cores are shown for comparison. It is seen that \( E(p) \) dependence has a minimum at the pressure of about 100 Pa (except for the lowest discharge current of 1 A). The same pressure dependence was observed for the low-frequency ICP in a 50 mm discharge tube [4]. For argon pressure of 100 Pa, calculations give nearly the same values of the electric field strength of about 0.5 V/cm.

In figure 3, calculated EEDFs are shown on the discharge chamber axis, for argon pressure of 100 Pa and discharge currents of 1 and 10 A. It is seen that calculated EEDFs are non-Maxwellian: the tails of EEDFs are depleted for electron energies higher than the threshold of argon excited states (11.3 eV). The number of electrons with energies higher than argon ionization potential is negligible, the main ionization mechanisms are multistep and Penning ionizations (that is why the wall potential is chosen near the threshold for argon metastables excitation).

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Figure 2. Electric field strength vs. argon pressure. Black symbols – experimental results, hollow symbols – literature data [4].

In figure 4, calculated and experimentally measured radial distributions of electron density are shown, for argon pressures of 100 and 30 Pa, discharge currents of 1 and 10 A. The asymmetry of experimentally measured radial profiles of electron density is caused by a branch pipe placed on the front side of the gas discharge chamber (not shown in figure 1). The branch pipe was used to insert a double Langmuir probe into the discharge chamber radially, thus plasma was spread into the branch pipe resulting in a higher value of electron density in the near wall region. Calculated radial profile of the electron density is more contracted than experimentally measured due to a higher gas pressure, which leads to the decrease in the electron flux to the tube walls and increase in the gas temperature and current density on the discharge chamber axis.

Figure 4. Radial distributions of electron density. Symbols – experimental results (Ar pressure of 30 Pa). Lines – numerical results (Ar pressure of 100 Pa).

Figure 5. Radial distribution of electron temperature. Symbols – experimental results (Ar pressure of 30 Pa). Line – numerical results (Ar pressure of 100 Pa).

In figure 5, calculated and experimentally measured radial distributions of the electron temperature are shown, for argon pressures of 100 and 30 Pa, and the discharge current of 10 A. It is seen that experimentally measured values of the electron temperature are almost constant along the radius of the discharge chamber, while calculated radial profile has a parabolic-like distribution, due to the
The abovementioned assumption of plasma potential as a parabolic function of radius. Parabolic profile of electron temperature also leads to the contraction of gas discharge, while “flat” electron temperature means that ionization occurs even in the near wall region (figure 4). The observed discrepancy between experimental and numerical radial profiles of electron temperature indicates that the assumption of parabolic distribution of plasma potential may be incorrect for the case of the low-pressure low-frequency ICP with a ferrite core. It is necessary to underline that the assumption was made for DC glow discharges with a tube diameter of a few centimeters [3], while the low-frequency ICP discharge chamber diameter is 23 centimeters.

In figures 6, 7 the calculated radial distributions of gas temperature and density are shown, for argon pressure of 100 Pa, discharge currents of 1 and 10 A. It is seen that gas heating does strongly affect the radial profile of gas density at the pressure of 100 Pa, which in turn affects all equations (1)–(5). For example, decreasing the gas density \( N_g \) leads to an increase in the current density on the discharge chamber axis due to increasing the electron drift velocity \( v_e (E/N_g) \), which gives a contribution to the calculated effect of contraction of the electron density profile.

![Figure 6. Calculated radial distribution of gas temperature, argon pressure of 100 Pa.](image)

![Figure 7. Calculated radial distribution of gas density, argon pressure of 100 Pa.](image)

4. Conclusion
A radial model of the low-pressure low-frequency ICP in argon, based on the simultaneous solution of a non-local Boltzmann equation for EEDF and balance equations for metastable argon atoms density and gas temperature has been developed. EEDF is found to be non-Maxwellian, with a depletion of EEDF for energies higher than a threshold for metastable excitation. Numerical results are compared with the results of electric probe measurements. A model assumption of parabolic plasma potential taken from the case of DC glow discharges seem to be incorrect for our case, the radial distribution of plasma potential in the low-pressure low-frequency ICP enhanced with ferrite cores should be investigated more carefully.

References
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