Experimental and numerical study of a low-frequency ferromagnetic enhanced inductively coupled plasma

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Abstract. Low-frequency ferromagnetic-enhanced inductively coupled plasma (FMICP) has been investigated under conditions typical for large-scale plasma processing. Radial profiles of ion density and plasma floating potential were determined with a Langmuir probe. A self-consistent radial kinetic model of argon FMICP was developed, based on the simultaneous solution of a non-local Boltzmann equation for the electron energy distribution function, balance equations for the ion and metastable argon atom densities, the thermal balance equation and the Poisson equation for a self-consistent radial electric field. A satisfactory agreement between the numerical and experimental results was found that confirms the validity of the presented approach to the description of the FMICP.

1. Introduction
Radio-frequency inductively coupled plasma sources (RF ICP) allow to produce high-purity plasma with high density of ions and radicals at low gas pressures, which is widely used in semiconductor industry (plasma etching, plasma enhanced chemical vapour deposition, plasma-immersion ion implantation, etc.). However, RF ICP has a weak magnetic coupling between the ICP coil and plasma ($k \approx 0.2–0.7$), therefore a low power factor of the ICP coil ($\cos\phi < 1$) respectively. In this case, a resonant-matching network is used to improve the power transfer efficiency between a power supply and a load. The resonance matching increases the coil voltage and current, leading to high ohmic losses in the coil. As the ICP coil and plasma are separated with a dielectric window, a substantial capacitive coupling exists between the coil and plasma. The high ICP coil voltage affects plasma through the capacitive coupling, leading to an intense ion bombardment of the dielectric window. As the coil inductance and voltage are increasing with the coil size, this undesirable effect becomes a growing problem for large-scale plasma systems (for example, for the future 450 mm silicon wafers [1]).

This situation can be improved with enhancement of the magnetic coupling between the ICP coil and plasma by a ferromagnetic core [1]. In this case, magnetic flux is concentrated almost in the core, therefore magnetic coupling and power factor of the ICP coil are high, leading to increase in the ICP power transfer efficiency. As the ICP coil and discharge chamber are placed on the opposite sides of the core, the undesirable effect of capacitive coupling between the coil and plasma is eliminated. Another important advantage of the ferromagnetic enhanced inductively coupled plasma sources is the possibility of generating electrodeless plasma at relatively low frequencies [2], due to high magnetic field in the ferromagnetic core. In this case, mass-produced induction heating power supplies with the frequency of ~10–100 kHz can be used instead of specialized 13.56 MHz RF ICP power supplies.
Hereby, the principle of the low-pressure low-frequency ferromagnetic enhanced inductively coupled plasma (FMICP) can be used for development of new plasma sources for large-scale plasma processing [1].

Despite of being an inductive discharge, the toroidal plasma loop of the FMICP acts similar to a positive column of a glow discharge [3], with induced electric field $E$ directed axially. The positive column is well studied for discharge tube radiuses of order of 1 cm and charged particle densities of about $10^8$–$10^{10}$ cm$^{-3}$, while large-scale plasma processing requires discharge chamber diameters of tens of cm and charged particle densities of about $10^{10}$–$10^{12}$ cm$^{-3}$. Therefore, the existing models of the positive column cannot be transferred onto the FMICP in a simple way. That is why the development of a numerical model of the low-pressure FMICP and its experimental verification is an actual task.

2. Experimental setup

A scheme of the experimental setup is shown in figure 1. Gas discharge chamber of the setup is made of a main part 1 and an additional $U$-shaped part 2 forming together with the part 1 a closed path for discharge current. The internal diameter of the main part is 23 cm that makes the conditions of plasma generation similar to those for large-scale processing systems. The internal diameter of the $U$-shaped part is 4 cm. The length of the main part is 100 cm. The main and the additional parts of the chamber are made of dielectrically insulated stainless steel sections. 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 is used. Gas pressure is controlled with a leak valve (not shown) and measured with a MKS baratron 626A 7. Discharge current is measured with a Rogowski coil 8. To determine an induced electric field strength $E_z$, inter-section voltage $U$ is measured with a voltmeter 9 ($E_z = U/L$, where $L$ is the discharge path between two neighbor sections). To determine ion density, a double Langmuir probe 10 made of tungsten wire with diameter of 200 $\mu$m is used. The probe can be moved along the discharge chamber radius, to determine a radial distribution of plasma parameters. Also, a radial distribution of plasma floating potential is measured, to estimate radial electric field strength $E_r$.

3. Numerical model

In the positive column of low-pressure direct current gas discharges, plasma parameters are mainly determined by non-local electron kinetics in a radial space-charge field [4], responsible for the confinement of electrons in plasma. We assume the same mechanism for the low-pressure FMICP, with the plasma parameters to be axially inhomogeneous and depending only on the radial coordinate $r$. To describe the electron component of the FMICP, a non-local Boltzmann equation for the electron energy distribution function (EEDF) is solved [4, 5], with the EEDF taken in a well-known two-term
approximation by isotropic $f_0(\varepsilon,r)$, radial $f_r(\varepsilon,r)$ and axial $f_z(\varepsilon,r)$ anisotropic components ($\varepsilon$ is the electron kinetic energy).

Anisotropic parts of the EEDF are related to the isotropic part with equations (1) and (2) [5]:

$$f_r = -\frac{1}{H} \left( \frac{\partial f_0}{\partial r} - e_0 E_r \frac{\partial f_0}{\partial \varepsilon} \right)$$  \hspace{1cm} (1)

$$f_z = -\frac{1}{H} \left( -e_0 E_z \frac{\partial f_0}{\partial \varepsilon} \right)$$  \hspace{1cm} (2)

where $E_r(r)$ and $E_z$ are radial and axial components of electric field strength, $H(\varepsilon,r)$ is the total momentum loss of electrons in elastic and inelastic collisions with atoms. Inelastic collisions of electrons with argon atoms are summarised into one group with the energy threshold 11.5 eV and the ionization collisions with 15.8 eV threshold.

Solving the Boltzmann equation for the isotropic part of EEDF and equations (1), (2) 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 $j_z(r)$ [5].

Metastable density $N_m(r)$ is described by a balance equation (3):

$$\frac{\partial N_m}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left( r D_m \frac{\partial N_m}{\partial r} \right) = k_{me} n_e(r) N_g(r) + k_{rec} n_e(r) n_i(r) - k_{sw} n_e(r) N_m(r) - 2k_{mm} N_m^2(r)$$  \hspace{1cm} (3)

where $k_{me}$ is a rate constant of metastable atoms excitation, $k_{rec}$ is a rate constant of radiation recombination ($n_i(r)$ is an ion density), $k_{sw}$ is a rate constant of stepwise ionisation from metastable atoms, $D_m$ is the metastables diffusion coefficient, $k_{mm}$ is a coefficient of Penning ionization, $N_g$ is a density of argon atoms in the ground state.

Ion density $n_i(r)$ is described by a balance equation (4):

$$\frac{\partial n_i}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r j_i \right) = k_{di} n_e(r) N_g(r) + k_{sw} n_e(r) N_m(r) + k_{mm} N_m^2(r) - k_{rec} n_i(r) n_i(r)$$  \hspace{1cm} (4)

where $k_{di}$ is a rate constant of direct ionization, $j_i(r)$ is a radial ion flux. The rate constants $k_{di}$, $k_{me}$ and $k_{sw}$ are determined by the EEDF and the cross sections of the processes.

The radial ion flux is taken in a drift-diffusion approximation (5):

$$j_i(r) = \mu_i n_i(r) E_r(r) - D_i \frac{\partial n_i(r)}{\partial r}$$  \hspace{1cm} (5)

where $\mu_i$ and $D_i$ are the ion mobility and diffusion coefficients.

Also we take into account neutrals heating by elastic collisions of electrons and atoms. For this purpose we solve the following thermal balance equation (6):

$$\frac{\partial T_e}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \kappa_e(T_e) \frac{\partial T_e}{\partial r} \right) = P^{ei}(r)$$  \hspace{1cm} (6)

where $\kappa_e$ is a heat conductivity coefficient, $P^{ei}$ is the neutrals heating due to elastic collisions of electrons and argon atoms. Gas heating may change the gas density distribution $N_g(r) = p/kT_e(r)$ and thus affect the EEDF and balance equations for ions and metastables.

Finally, the Poisson equation (7) is used to find out the radial electric field, determining the radial fluxes of ions and electrons $j_i(r) = j_{el}(r)$:

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r E_r(r) \right) = 4\pi e_0 \left( n_i(r) - n_e(r) \right)$$  \hspace{1cm} (7)
4. Results and discussion

In figure 2, typical calculated EEDFs are shown, for argon pressure of 50 Pa and FMICP currents of 1–5 A. It is seen that the number of electrons with energies higher than argon ionization threshold (15.8 eV) is negligible, therefore the main ionization mechanism is multistep or Penning ionization. The calculated and experimentally measured values of reduced electric field strength $E_z/p$ are about 1 V/cm·Torr, that is a few times smaller than those in the positive column of glow discharges. However, it is enough to produce metastable atoms of argon that play a key role in the ionization balance of the low-pressure FMICP. The typical values of ionization balance terms (equation (4)) on the discharge axis are: step-wise ionization $k_{sw}n_eN_m \approx 4 \cdot 10^{14}$ cm$^{-3}$s$^{-1}$, Penning ionization $k_{mm}N_m^2 \approx 3.4 \cdot 10^{12}$ cm$^{-3}$s$^{-1}$, and bulk recombination $k_{rec}n_eN_i$ is only $3.3 \cdot 10^{11}$ cm$^{-3}$s$^{-1}$ (FMICP current of 3 A, argon pressure of 50 Pa). Therefore, the main FMICP ionization mechanism is multistep ionization, while the charged particle fluxes in the radial electric field $E_r$ are responsible for ion and electron losses in the bulk plasma.

In figure 3, calculated and experimentally measured radial distributions of ion density are shown, for argon pressure of 50 Pa and discharge currents of 1–5 A (except of the experimental data for discharge current of 1 A, which are given for argon pressure of 30 Pa). The values of the FMICP ion density of about $10^{11}$ cm$^{-3}$ are typical for large-scale processing systems, and can be enhanced by increasing the discharge current.

In the bulk plasma, the calculated values of electron density are almost the same as the values of ion density $(n_i-n_e)/n_e \approx 10^{-6}$, i.e. plasma is quasi-neutral, but in the near-wall region the condition of quasi-neutrality is disrupted $(n_i-n_e)/n_e \sim 10^{-3}$. It follows from equation (7) that the radial electric field strength $E_r$ should be weak in the bulk plasma, but strong in the near-wall region. In figure 4, calculated and experimentally estimated radial distributions of radial electric field strength are shown, for argon pressure of 50 Pa and discharge currents of 1–5 A. The radial electric field strength $E_r$ is estimated as a derivative of the experimentally measured radial distribution of plasma floating potential. Experiment confirms the results of numerical calculations: in the bulk plasma ($r/R<0.9$) the radial electric field $E_r$ is comparable with the axial electric field $E_z$ (0.45 V/cm), while in the near-wall region the radial electric field is much larger than the axial electric field. Such a sharp increase of the radial electric field strength in the near-wall region is not typical for low-pressure glow discharges [4], with a parabolic-type distribution of the radial space-charge potential (and a linear-type electric field strength distribution $E_i(r)-r$, respectively).
In figure 5, the calculated radial distributions of electron and neutrals temperatures are shown. The electrons are confined in plasma by the radial space-charge potential, therefore the electron kinetic energy, metastables excitation and stepwise ionization rates are maximal on the axis of the discharge chamber. It is seen from figure 5, that in the case of a large chamber diameter neutrals heating creates a non-uniform radial distribution of gas density $N_g(r)$; even at low FMICP current of 3 A and specific discharge power of $P=E_z\cdot I\approx 1.3$ W/cm, gas density $N_g$ at the discharge chamber ($r = 0$) axis is two times smaller than in the near wall region. The reason of the significant neutrals heating is the large chamber radius that provides a good heat insulation of the central region with high electron density (and high frequency of electron-atom elastic collisions) from the cooled walls. Since gas density is included in the Boltzmann equation and equations (1)–(6) in explicit and implicit forms (e.g. $H(N_g)$, $\mu_i(N_g)$, $D_i(N_g)$, $P_{el}(N_g)$, etc.), the effect of gas heating should be taken into account carefully for the low-pressure FMICP with large diameter of discharge chamber.

5. Conclusion
A radial (1D) model of the low-pressure FMICP has been developed, to analyze the FMICP features under conditions similar to those for large-scale plasma processing (discharge chamber radius of order of 10 cm, electron density of about $10^{10}-10^{12}$ cm$^{-3}$). The model is based on the simultaneous solution of a non-local Boltzmann equation for EEDF, balance equations for ions and metastable atoms, the thermal balance equation for a plasma-forming gas and the Poisson equation for a self-consistent radial electric field. Numerical results were compared with the results of electric probe measurements, a satisfactory agreement was found. In particular, the probe measurements confirmed the numerically predicted peculiar radial electric field distribution with a sharp increase of radial electric field strength in the near-wall region.

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