Development of a distributed ferromagnetic enhanced inductively coupled plasma source for plasma processing

G I Sukhinin¹, M V Isupov¹, A V Fedoseev¹, and I B Yudin¹

¹ Kutateladze Institute of Thermophysics SB RAS, Lavrentyev Ave, 1, Novosibirsk, 630090, Russia

E-mail: Sukhinin@itp.nsc.ru

Abstract. A low frequency (~100 kHz) distributed ferromagnetic enhanced inductively coupled plasma (FMICP) source with a separate supply of argon and chlorine into the main discharge chamber is proposed in order to obtain a large volume of dense ($10^{10}$–$10^{12}$ cm$^{-3}$) uniform plasma at low pressures (1–100 mTorr). Argon is activated by FMICP sources in U-shaped tubes and diffuses into the main chamber, mixing with chlorine. The Ar/Cl$_2$ mixture is also activated in the main discharge chamber by vortex alternating electric fields circulating in U-tubes and in the chamber. A separate supply of Ar into the side FMICP sources and Cl$_2$ directly into the main chamber can significantly enhance the power transfer efficiency into the main discharge chamber to be used for plasma etching of 450 mm wafers.

1. Introduction.

Radio-frequency induction discharges are one of the most important types of gas discharges for many scientific and practical applications [1]. This electrodeless method of generating a low-temperature plasma with a high concentration of ions and radicals over a wide range of pressures (0.1-10$^3$ Pa) creates unique possibilities for carrying out a wide range of plasma-chemical reactions and processes and made it possible to create a whole range of new technologies in lighting engineering (electrodeless lamps), plasma chemistry (RF induction plasma torches), and microelectronics (plasma-chemical etching and deposition). The high frequency of generation of inductive discharges (of the order of 1-10 MHz) and low power factor of ICP coil resulting in a low power transfer efficiency stimulates the search for new ways of efficient generation of an inductively coupled plasma in the low-frequency radio range. The simplest way to achieve this is to use ferromagnetic materials to improve the magnetic coupling between plasma and ICP coil. At present, this type of ICP sources is termed as ferromagnetic enhanced inductively coupled plasma source or FMICP (the term was proposed by Valery Godyak). This approach was used in the 1960s to create an electrodeless argon laser [2] and a prototype of an electrodeless fluorescent lamp [3], the power of 40 W, with the frequency of 200–400 kHz. In the early 1970s, Eckert made theoretical and experimental studies of the possibility of generating an inductively coupled plasma in a very low frequency range (60–10000 Hz) using ferromagnetic cores [4, 5]. Interest in these studies was motivated by the prospects of creating powerful electrodeless gas heaters for aerodynamic research in the space industry. Eckert received a low-frequency induction discharge in argon at a pressure of up to 0.8 atm, a current frequency of 9600 Hz and a discharge current of up to 150 A. He also succeeded in initiating and generating a low-frequency induction discharge in argon at a current frequency of 60 Hz, argon pressure of up to 3 Torr, and a discharge current of up to 100 A. Similar studies were performed in [6]. The authors generated a
low-frequency inductive discharge in argon at a current frequency of 8000 Hz, argon pressure of up to 0.3 atm, discharge current of up to 245 A and discharge power of up to 25 kW.

The appearance of high-quality power ferrites and efficient compact semiconductor RF generators in the 1990s allowed OSRAM to create commercial samples of a highly efficient electrodeless fluorescent lamp ENDURA [7], with the efficiency of power transfer from the power supply to the induction discharge of up to 98%. A distinctive feature of these lamps is significantly higher discharge current densities than in conventional fluorescent lamps, which leads to the fact that the standard models of the positive column of the Hg-Ar discharge do not satisfactorily describe the characteristics of the FMICP sources [8]. This circumstance underscores the need to develop original FMICP models that take into account their specific features. In addition, a number of studies on FMICP have been performed to develop plasmatrons for carrying out plasma-chemical reactions [9–11].

It should be emphasized that despite a substantial difference in the volume of the discharge chambers, pressure and the composition of the plasma forming gas, the current frequency and discharge power, all the above-mentioned works have in common is that FMICP represents a single toroidal plasma loop magnetically coupled with an inductor via the ferromagnetic core.

In the paper [12], a new approach to the generation of FMICP, a so called distributed FMICP, was proposed. This plasma source has one main chamber with side-injected plasma produced with multiple ferromagnetic core antennas. The plasma radial profile in the main chamber is governed by plasma and metastable atom diffusion from side discharges as well as ionization caused by fast electrons generated there that are able to penetrate deeply into the main chamber. This approach was proposed to produce large volumes of homogeneous plasma and to solve the problem of scaling RF induction discharge devices for the future 450 mm standard of semiconductor industry. Experimental studies of distributed FMICP in argon, in the pressure range of 2–20 mTorr, were carried out. Probe measurements showed that plasma inhomogeneity in the central region of 300 mm under certain conditions does not exceed 3%. Experimental measurements confirmed the high efficiency of power transfer to plasma (> 95%) at a relatively low current frequency (400 kHz). Due to strong antenna coupling and utilization of relatively low driving frequency, this plasma source is free of capacitive coupling, free of the transmission line effect and has a low plasma potential. A conclusion was made that the side-type ferrite ICP source could be a viable alternative for large-area plasma processing. In [13], a method for controlling the spatial distribution of plasma density by imposing an auxiliary RF induction discharge on the central region of the distributed low-pressure (5 mTorr) argon FMICP was proposed. An auxiliary RF induction discharge was also used to control the spatial uniformity of the distributed FMICP discharge at elevated argon pressures of 600 mTorr [14].

Thus, the possibility to generate large volumes of "dense" plasma efficiently with the use of distributed FMICP, and the ability to control radial distributions of plasma parameters by means of an auxiliary discharge were clearly demonstrated. A conclusion was made about the prospects of using FMICP for large-scale plasma processing [15]. However, for plasma treatment of semiconductor materials it is necessary to introduce halogen-containing gases into the plasma. It is obvious that the addition of an electronegative plasma-forming gas will radically change the plasma parameters of the distributed FMICP, which creates new challenges for researchers. The purpose of this paper is to reveal the main problems and analyze the particularity of generating distributed FMICP in the atmosphere of electronegative plasma-forming gas.

2. Experimental setup.
In Figure 1, a scheme of experimental setup for the study of a distributed FMICP is shown. The discharge chamber is made of stainless steel. The internal diameter of the main gas discharge chamber (1) is 700 mm. On the sides of the main gas discharge chamber there are eight U-shaped gas discharge tubes (2) with an internal diameter of 50 mm. The U-shaped tubes and the main chamber are dielectrically insulated. Each U-tube has a ferrite core (3) with a primary winding (ICP coil) connected to a power source with a frequency of 100 kHz. Each U-shaped tube has an inlet (4) to supply a plasma-forming gas, which can flow through the open ends of the U-shaped tubes into the main
chamber. An additional inlet for the plasma-forming gas is located in the center of the top flange of the setup (not shown in the figure). In this paper, to control the uniformity of the plasma density profile inside the gas discharge chamber, two auxiliary FMICP sources with a frequency of 100 kHz (located on the top flange of the main discharge chamber) are proposed to be used instead of a 13.56 MHz RF ICP source [13]. This permits us to increase the power factor of the ICP coil and eliminate the capacitive coupling between plasma and the coil [15]. All these FMICP sources form a common spatial distribution of the plasma inside the main gas discharge chamber. In the setup there are ports for optical and probe methods of plasma diagnostics. The device is designed to study the processes that determine the formation of spatial distribution of plasma parameters in order to obtain large volumes of homogeneous plasma. A substrate (450 mm in diameter) will be placed inside the main chamber to investigate the processes of ion-plasma etching of various materials.

**Figure 1.** Experimental setup. 1 – Main discharge chamber (internal diameter of 70 cm), 2 – U-shaped discharge tubes (internal diameter of 5 cm), 3 – Ferrite cores with primary winding, 4 – Gas inlet.

**Figure 2.** A model representation of a single U-shaped tube. 1 – Discharge tube (dielectric breaks and gas inlet are not shown), 2 – Ferrite core, 3 – Primary winding; 4 – Matching unit; 5 – Power supply; 6 – Main chamber.

**3. The features of a distributed electronegative FMICP.**

The principal scheme of physical processes in distributed argon FMICP is considered in [12, 13]. Since the electric field strength and the FMICP current density are maximal within the narrow U-shaped tubes, the main energy release occurs there, followed by charged and excited particles diffusion into the main gas-discharge chamber, where plasma processing occurs. At low argon pressures, when the energy relaxation length of high-energy electrons is comparable to the radius of the main chamber, ionization processes in the main chamber are caused by fast electrons produced in the U-shaped tubes. These processes can be controlled by changing the plasma potential in the central region of the main chamber with the help of an auxiliary plasma source [13].

The mechanism of plasma formation in the U-shaped tubes essentially depends on the plasma-forming gas composition. For the simplest case of low-pressure, low-frequency argon FMICP in a toroidal gas discharge tube, the processes have been considered in a number of papers [16–18]. In a rough approximation, FMICP properties inside a U-shaped tube are similar to the properties of a toroidal FMICP with the same discharge current, plasma forming gas pressure and tube diameter. Some difference is expected in the regions near the open ends of the U-shaped tube, where plasma is disturbed by diffusion fluxes into the main chamber. The typical current densities of the toroidal FMICP are quite high (~0.1–1 A/cm², [8, 16, 17]), the ionization balance is maintained predominantly
by a stepwise ionization from the argon metastable states. Vortex alternating electric field \(E(t)\) that drives the FMICP obeys the Faraday law
\[
\frac{1}{L} \int E \, dt = -\frac{\partial \Phi}{\partial t},
\]
where \(\Phi(t)\) is an alternating magnetic flux in the ferromagnetic core, \(L\) is a total closed discharge path. The characteristic RMS value of the electric field \(E\) for the case of low-pressure argon FMICP is about \(0.5\) V/cm [16, 17]. The frequency \(f \sim 100\) kHz of the alternating electric field \(E(t)\) in the tube is much smaller than electron-atom collisional frequency \(v_{em}\) in argon at pressures of \(1-100\) mTorr. At the same time, this frequency is comparable or larger than ion-atom collision frequency \(v_{im}\). Thus
\[
v_{im} \leq \omega = 2\pi f \leq v_{em}.
\]
In pure argon, the current is transferred mainly by electrons, whose losses occur mainly on the walls of the tube together with positive ions. Due to Coulomb collisions, electrons with a good accuracy have a Maxwellian-like distribution function. This electric field causes a corresponding electric current. The drift component of the electron velocity can be represented in the form [1]
\[
V_{ed} = \left(\frac{v_{em}^2}{m(\omega^2 + v_{em}^2)}\right) E_0 \sin \omega t = -\mu_e E(t),
\]
where the brackets denote averaging over the electron velocity distribution function, and \(\mu_e\) is the coefficient of electron mobility. The drift velocity \(V_{ed}\) is almost independent of discharge frequency for \(f \sim 100\) kHz and argon pressures in the range \(1-100\) mTorr. Thus in the U-shaped tube with pure argon, the current density is proportional to the electron density \(n_e\) and the field strength in the tube \(E\):
\[
j \approx e\mu_e n_e E
\]
The contribution of the ion \(Ar^+\) component to the current in pure argon can be neglected.

If a molecular gas is added to the argon, then the energy losses of the electrons to excite vibrational levels exceed losses in elastic collisions. To compensate for these losses and losses in other inelastic electron-molecule collisions, the electric field of the discharge increases. A more dramatic situation occurs with the addition of even a small quantity of a strong electronegative gas, for example, chlorine [19–24]. The most important process in \(Ar/Cl_2\) plasma is the dissociative attachment, which has a near-zero threshold energy and determines the creation of the negative ion \(Cl^-\). Usually, in such plasma, there is a considerable depletion of the electron component due to the attachment of electrons to chlorine molecules. The chlorine discharge is highly electronegative, and the ratio \(\alpha = n/\alpha_e\gg 1\), where \(n\) is the concentration of negative ions. In order to provide the same current as in pure argon, the axial electric field in the tube should increase considerably, and negative ions \(Cl^-\) and positive ions \(Ar^+, Cl^+\) and \(Cl_2^+\) can already make a certain contribution to the total current:
\[
j \approx e\mu_e n_e E + q_1\mu_{e,n} E + q_2\mu_{e,n} E
\]
where \(q_1\) and \(q_2\) are the charges of negative and positive ions, \(\mu_1\) and \(\mu_2\) are the coefficients of negative and positive ion mobility, which are considerably smaller than \(\mu_e\). For example, an addition of only \(5\%\) \(Cl_2\) to argon increases discharge electric filed strength four times [19]. The higher the discharge electric field strength \(E\), the higher the value of magnetic flux \(\Phi\) is needed to maintain the FMICP (equation (1)), the higher the power losses in the ferromagnetic cores. The significant increase in the FMICP electric field strength with \(Cl_2\) addition is a serious challenge for the development of new devices for large-scale plasma processing.

Let us consider a hypothetical situation – there is pure argon in the U-shaped tubes and \(Ar/Cl_2\) mixture in the main chamber. Only a part of the integration path in Faraday’s law (1) passes inside the U-tube, the contour of integration is closed in the main chamber (figure 2). According to Kirchhoff’s law, the discharge current inside the U-shaped tube is equal to the discharge current in the main chamber that flows between the two open ends of the U-shaped tube. However, in the atmosphere of chlorine, plasma is electron depleted. In the case of DC discharges, heavy ions of argon and chlorine make a significant contribution to the current formation (equation (5)), but in the case of
ω > ν\text{im}, the ion mobility is decreased (see, equation (3), in which the mass of electron m and the electron collision frequency ν\text{em} are replaced by the corresponding ion mass M_i and ionic collision frequency ν\text{im}). Thus, the value of the electric field E_{ch} in the main chamber with Ar/Cl_2 mixture should be considerably higher than the electric field E in the U-shaped tube with pure argon. It leads to the redistribution of the FMICP energy consumption: the energy is consumed predominantly in the main chamber. This is radically different from the case of pure argon, when the energy consumption occurs mainly in the U-shaped tubes. As the area of the open ends of the U-shaped tube is much smaller than the surface area of the U-shaped tube walls, the major part of charged particles generated in the U-tube recombines there, and only a minor part diffuses into the main chamber. This leads to the fact that the energy efficiency per one ion injected into the main chamber turns out to be quite low for the pure argon case. If we change the location of the FMICP energy consumption from the U-shaped tubes to the main chamber, we significantly increase the efficiency of ions production. As the electric field strength in argon is much lower than in Ar-Cl_2 mixture, it significantly reduces the total value of the FMICP voltage and the magnetic flux in the ferrite core respectively (equation (1)), which leads to the increase in the power transfer efficiency.

Figure 3. The scheme of the computational domain and the spatial distribution of the numerical density of Ar (above) and Cl_2 (below). Gas pressure P = 0.1 Pa, argon flow rate Q = 10 sccm.

In this project, argon is fed into the side U-shaped tubes and chlorine is fed strictly into the main chamber. It should be noted that the supply of pure argon through the U-tube is not easy to carry out due to the diffusion of chlorine into the U-tube from the chamber. The penetration of chlorine into the side U-shaped tubes should lead to a sharp increase of the electric field strength in U-shaped tubes (in the FMICP), and, accordingly, to a significant increase of losses in ferrite cores and to a reduction in the efficiency of the device. In order to avoid or reduce chlorine penetration into the U-tube, the flow rate of argon should be chosen in such a way as to prevent chlorine from diffusing into the tube. Such conditions for argon flow rates were obtained by the Direct Simulation Monte Carlo Method [25, 26].

This method is successfully used to solve gas-dynamic problems of various degrees of non-equilibrium and rarefaction: from a free molecular regime to a continuous one. In this work, the axisymmetric algorithm of the DSMC method was adapted to the calculation of flows in cylindrical
channels and behind them. To describe the collisions of particles of argon and chlorine with each other, a model of soft spheres with a variable cross section (VCS) was used [26]. To describe the law of interaction with the surface, a mirror-diffuse reflection model [26], which is typical for a rarefied gas, with an accommodation coefficient on surfaces of 0.4 was used.

Figure 4. The ratio of the chlorine density to the argon density along the U-tube axis for different pressures \( P \) and argon flow rates \( Q \): 1 – \( P = 1 \) Pa, \( Q = 1 \) sccm; 2 – \( P = 1 \) Pa, \( Q = 5 \) sccm; 3 – \( P = 1 \) Pa, \( Q = 10 \) sccm; 4 – \( P = 0.1 \) Pa, \( Q = 10 \) sccm.

In this paper, the problem of chlorine penetration from a large volume with the given pressure of argon-chlorine mixture into the tube with some argon flow rate is considered. To simplify the calculations, the distributions of the densities of argon and molecular chlorine and their fluxes were determined for the case when the discharge in the chamber was not ignited. The U-shaped tube is replaced with a cylindrical tube of the same length and diameter. The computational domain has cylindrical symmetry; therefore, it considers only a half section of tube A and the adjacent region — chamber C (Figure 3). The length of the tube is 0.3 m, the diameter is 0.05 m. The dimensions of the chamber: 0.3 m in length, 0.5 m in diameter. Argon is fed into the tube through the left end A. Argon flow rate in the calculations was set to range from 1 to 10 sccm. The chlorine pressure varied from 0.1 to 1 Pa and was set at the gas-permeable boundaries C. The residual pressure of argon was set equal to the chlorine pressure. Temperatures of gases and surfaces (A, B) in all calculations were set equal to 300 K. It is seen (Figure 4) that chlorine molecules can be substantially removed from the U-tube by the argon flow of 10 sccm. Therefore, a separate supply of argon and electronegative gas can be useful for reducing the electric field strength necessary to maintain the distributed FMICP inside the U-shaped tubes and to enhance the power transfer efficiency into the main chamber.

4. The features of gas dynamics in the main chamber.

In this paper, argon is fed through eight U-shaped tubes and two additional ones located on the chamber top flange and chlorine is fed into the main chamber through the inlet in the center of the top flange as in [22]. The flow rate of argon from each tube into the chamber has the order of 1–10 sccm. The flow rate of chlorine has the order of 100 sccm. The flow rates are comparable with those taken in [22, 24]. Argon and chlorine are mixed in the chamber due to diffusion. Pumping provides the total pressure of the mixture of argon and chlorine of the order of 0.1–1 Pa. To conduct plasma processing in the main chamber it is necessary that the density and composition of the working gas near the substrate should be uniformly distributed. Under what gas-dynamic conditions can such homogeneity be achieved?

To clarify this, 2D gas-dynamic calculations were carried out by the Direct Simulation Monte Carlo (DSMC) Method. As in the section 3, the distributions of the densities of argon and molecular
chlorine and their fluxes were determined for the case when the discharge in the chamber was not ignited. Due to cylindrical geometry of the chamber, we present only a half of the picture. In Figure 5, the argon density distribution $n_A$ and the argon flow $n_AV_A$ for argon flow rate 10 sccm and Ar/Cl$_2$ pressure 1 Pa are shown. In Figure 6, the molecular chlorine distribution of $n_{Cl}$ and the chlorine flow $n_{Cl}V_{Cl}$ at the flow rate of Cl$_2$ equal to 100 sccm, and Ar/Cl$_2$ pressure 1 Pa are presented. It is seen that the density of argon is rather homogeneous near the substrate; it is higher only near the open ends of U-tubes and lower in the vicinity of the central inlet for chlorine supply, where the intensive flow of chlorine blows out argon. The density of chlorine is also homogeneous near the substrate and considerably higher in the vicinity of the central inlet for chlorine supply. With the pressure increasing, the homogeneity of the mixture is further improved.

Figure 5. Argon density and flux distribution are calculated by Direct Simulation Monte Carlo Method. Argon flow rate 10 sccm, Ar/Cl$_2$ pressure 1 Pa. Substrate is placed in the bottom part of the chamber. The pumping port is under the substrate.

Figure 6. Chlorine density and flux distribution are calculated by Direct Simulation Monte Carlo Method. Cl$_2$ flow rate 100 sccm, Ar/Cl$_2$ pressure 1 Pa.
5. Conclusions

The features of the low frequency (100 kHz) low pressure distributed ferromagnetic enhanced inductively coupled plasma (FMICP) source for plasma processing (etching of 450 mm wafers in Ar/Cl₂ mixture) are discussed. To increase the power transfer efficiency into the main chamber a separate gas supply is proposed: Ar is fed into the U-shaped tubes of the distributed FMICP, and Cl₂ is fed directly into the main chamber.

For a separate gas supply, the maximal value of vortex electric field strength is expected to be achieved in the main discharge chamber between the ends of U-shaped tubes. The alternate vortex electric field heats the electron component of plasma and activates the Ar/Cl₂ mixture directly in the main discharge chamber.

The Direct Simulation Monte Carlo Method (DSMC) was used to evaluate the chlorine penetration from the main chamber into U-shaped tubes with argon, which is important for justifying the separate gas supply of FMICP for the typical partial pressures of Ar and Cl₂ of 0.1–1 Pa. It is shown that for Ar flow rate of about 10 sccm, the chlorine concentration in the U-shaped tube can be reduced 10–100 times. The DSMC method was also used to estimate the Ar and Cl₂ spatial distributions in the main chamber near the substrate. It is shown that though Ar and Cl₂ are fed separately, Cl₂ distribution near the substrate is quite uniform for the typical pressures of 0.1–1 Pa and gas flow rates of 100 sccm.

We consider the separate gas supply to be an effective way to enhance the power transfer efficiency in the distributed electronegative FMICP for large-scale plasma processing.

Acknowledgments

The work is supported by the Russian Science Foundation grant No. 18-19-00205.

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