Large-scale ferromagnetic enhanced ICP in Ar/Cl_2 mixture

M.V. Isupov, A.Yu. Litvinsev, V.A. Pinaev, A.V. Fedoseev, G.I. Sukhinin

Kutateladze institute of thermophysics SB RAS, Novosibirsk, Russia

Ferromagnetic enhanced inductively coupled plasma sources (FMICP) are considered to be a promising solution to produce large volumes of dense (10^{10}–10^{12} cm^{-3}) uniform plasma for large-area plasma processing systems, due to a high power transfer efficiency, reduced driving frequency (<0.4 MHz), the absence of capacitive coupling between the ICP coil and plasma, and a low plasma potential [1]. Although the electrophysical properties of large-scale (chamber diameter up to 560 mm) FMICP sources have been comprehensively investigated for the case of inert plasma-forming gases (Ar, Xe, Ar/He) [1–5], even a small addition of electronegative molecular gases typical for plasma processing dramatically changes the discharge properties [6], therefore, the effects of electronegative gases addition into the FMICP are of interest for research. To investigate the plasma parameters of a large-scale FMICP in Cl_2/Ar mixture, an experimental setup has been developed (Fig.1). The scheme of the setup is similar to that of [2], except of the ferrite antennas construction (which are optimized for higher voltage operation), enlarged gas discharge chamber size and the construction of U-shaped gas discharge tubes (which are adapted for high heat loads).

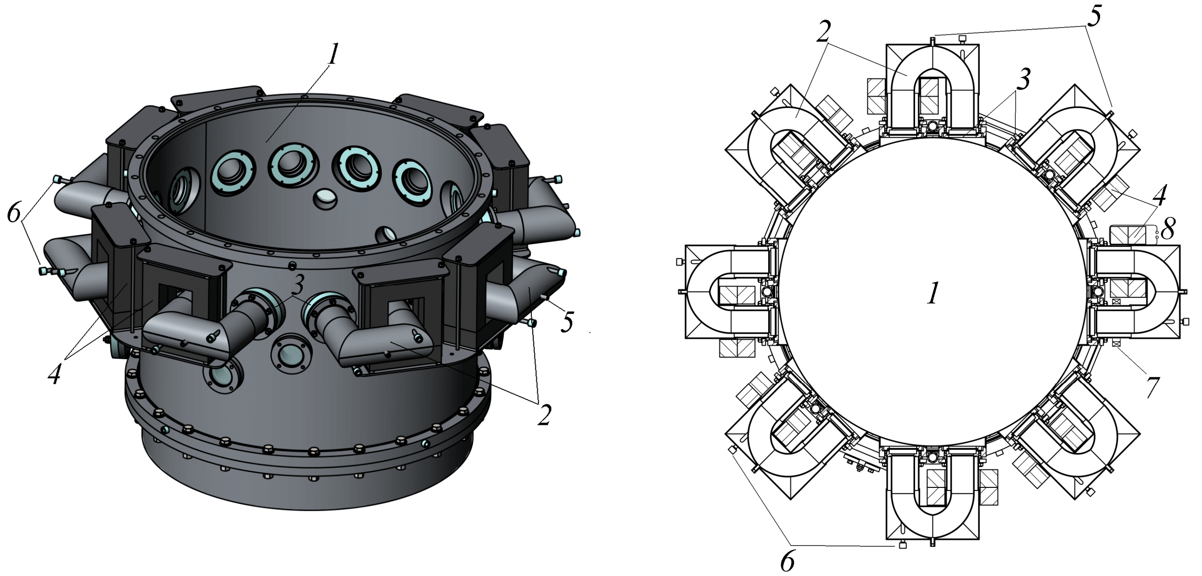

Figure 1a,b. 3D model (without the top flange) and a scheme of the experimental setup.
1 – gas discharge chamber, 2 – U-shaped gas discharge tubes, 3 – vacuum sealings, 4 – ferrite cores with ICP coils (not shown), 5 – gas inlets, 6 – water cooling inlets, 7 – Rogowski coil, 8 – voltage loop.

On the side of the gas discharge chamber 1 (internal diameter of 700 mm), eight U-shaped gas discharge tubes 2 with ID of 50 mm and perimeter of 420 mm are mounted through vacuum sealings 3. To prevent a shortcut, dielectric spacers are installed between the U-shaped tubes and the gas discharge chamber. Eight ferrite cores 4, each having a cross-section of 32 cm^2, are installed on the U-shaped tubes. ICP coils (not shown in the figure 1) are mounted on the ferrite cores and connected in series to a 100 kHz, 40 kVA power supply through a matching network (variable LC circuit). Plasma-forming gases (Ar and Cl_2) are fed through gas inlets 5 made in the U-shaped tubes and the top flange (not shown in the figure). We have tested both a joint gas supply (Ar/Cl_2 mixture is fed into the U-shaped tubes) and a separate supply (Ar is fed into the U-shaped tubes, Cl_2 is fed into the gas discharge chamber through the top flange). The gas is pumped out through a port in the centre of the bottom flange (not shown in the figure). To prevent the overheating of the U-shaped tubes and the discharge chamber, water cooling 6 is used. Induction discharge current *I* is measured with a Rogowski coil 7 mounted on the U-shaped gas discharge tube. Discharge voltage *U* is measured with a voltage loop 8 encircling a ferrite core and collecting the alternating magnetic flux Φ that drives the discharge ($U=-d\Phi/dt$). Thereby, plasma in the gas discharge chamber 1 is formed as a result of a joint action of eight FMICP sources.

In figure 2, typical volt-ampere characteristics of a single FMICP source are shown for the case of the joint Ar/Cl_2 supply (RMS values of discharge voltage and current are presented).

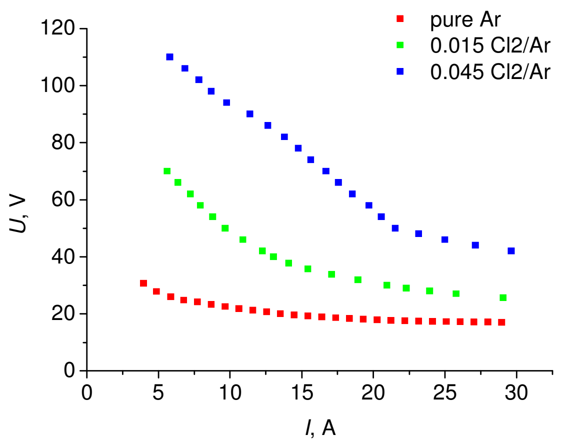

Figure 2. FMICP volt-ampere characteristics for various chlorine/argon flow rates ratios (joint gas supply). Gas pressure 10 Pa, argon flow rate 13 sccm, chlorine flow rates 0–0.6 sccm.

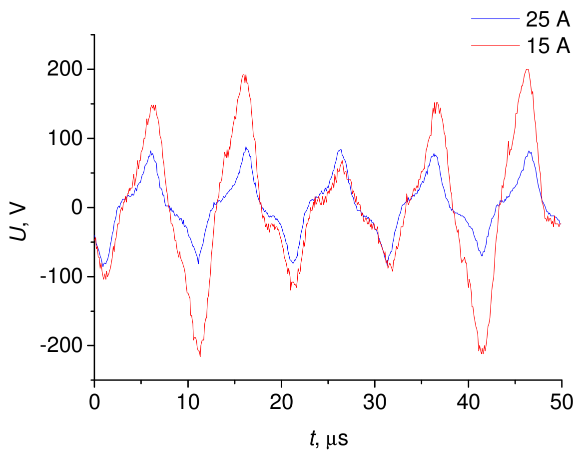

Figure 3. Typical FMICP voltage waveforms, for various FMICP currents. Argon flow rate 13 sccm, chlorine flow rate 0.48 sccm (joint gas supply).

It is seen that even a small addition of chlorine into the U-shaped tube significantly disturbs the voltage-current characteristics, leading to an increase of the discharge voltage after a decrease of the discharge current below a certain level. Simultaneously with the increase in discharge voltage, significant increase of the FMICP instabilities is observed (Fig. 3). In the case of argon FMICP, no instabilities were observed.

Since the U-shaped tube walls area is 16.8 times larger than the open ends area, the major part of the power consumed by plasma in the U-shaped tube is lost due to the wall recombination, and only a minor part is injected into the main gas discharge chamber with charged and excited particle fluxes. In this case, the increase in discharge voltage leads to the increase in the U-shaped tube heat losses and is highly undesirable. Also, higher discharge voltage leads to higher power losses in ferrite cores. To avoid the undesirable growth of discharge voltage, an effect of a separate gas supply on the electric field strength of the Ar/Cl_2 FMICP was analyzed [7]. DSMC gas-dynamic calculations indicate that the separate gas supply of argon into the U-shaped tubes and chlorine into the main discharge chamber allows to reduce the chlorine concentration in the U-shaped tubes and therefore to decrease the electric field strength and power losses inside the U-shaped tubes. In this case, the maximum chlorine concentration is expected to be in the main discharge chamber, therefore, the electric field strength and FMICP power consumption to be also maximal in the main chamber, where the plasma etching process takes place.

To check the effects of the separate gas supply experimentally, argon (13 sccm) was fed through eight gas inlets 5, and chlorine was fed through a gas inlet placed in the centre of the top flange. In figure 4, a dependence of discharge voltage on the chlorine/argon flow rates ratio is shown for the case of the separate gas supply (discharge current 20 A, gas pressure 10 Pa). Comparing the data presented in the figures 2 and 4, the separate gas supply leads to significantly lower values of the discharge voltage, giving a possibility to operate at higher flow rates of chlorine. DSMC gas-dynamic calculations [7] indicate that at low gas pressures chlorine distribution in the main gas discharge chamber is quite uniform, therefore, chlorine is activated in the FMICP zone (which is located near the open ends of the U-shaped tube) even in the case of the separate gas supply.

In figure 5, a photograph of the main discharge chamber with FMICP sources is shown. It is necessary to underline that plasma inside the main gas discharge chamber 1 is formed partly by the charged and excited particle fluxes from the open ends of the U-shaped tubes, and partly by the power consumed inside the main gas discharge chamber: $P=E\cdot j$, where E is the FMICP electric field strength, j is the FMICP current density. The idea of the separate chlorine supply is to enhance the electric field strength and the energy consumption inside the processing chamber while keeping it low in the U-shaped tubes. Otherwise, the high electric field strength inside the U-shaped tube gives the major contribution to the overall discharge voltage (Fig. 2) and the overall discharge power, leading to high heat losses on the U-shaped tube walls.

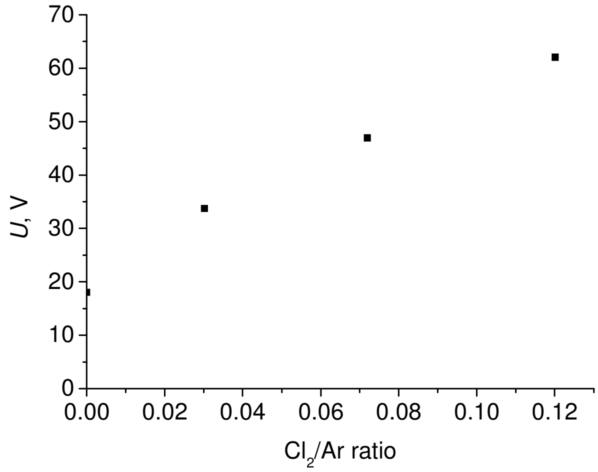

Figure 4. FMICP voltage vs. chlorine/argon flow rates ratio (separate gas supply). FMICP current 20 A, gas pressure 10 Pa, argon flow rate 13 sccm, chlorine flow rates 0–1.6 sccm.

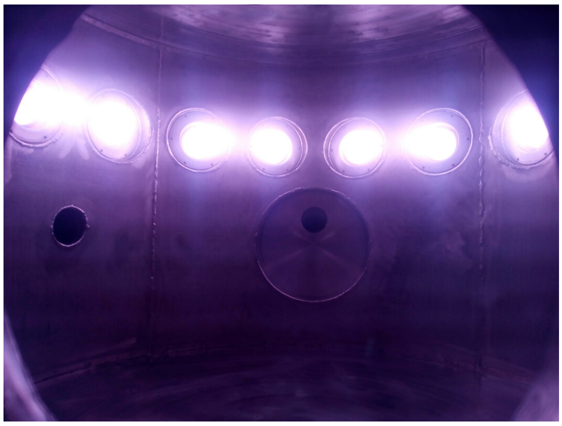

Figure 5. FMICPs in the gas discharge chamber. Gas pressure 10 Pa.

Conclusions

In contrast to a typical planar RF ICP generated in a processing chamber, a part of the toroidal FMICP is confined outside the processing chamber. In the case of argon FMICP, the electric field strength and power losses outside the processing chamber are quite low. Adding an electronegative gas significantly increases the FMICP electric field strength, leading to high power losses outside the processing chamber and in the ferrite cores. To solve the problem, a separate gas supply was tested with the electronegative gas (chlorine) injected into the processing chamber and argon injected into the FMICP U-shaped tubes. Experiments indicate a significant decrease in the overall discharge voltage in the case of the separate gas supply. Thereby, the plasma parameters inside the large scale FMICP can be regulated by changing the gas dynamics of the plasma forming gases.

Acknowledgments

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