Distributed ferromagnetic enhanced inductive plasma source for plasma processing

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Abstract. New experimental data on the plasma density profiles have been obtained for a low-frequency (100 kHz) distributed ferromagnetic enhanced inductive plasma source at different locations of inductive discharges. An ability to control the plasma density profiles in a large gas discharge chamber in order to achieve a uniform treatment of a substrate is demonstrated. The differences between the obtained results and literature data for a distributed ferromagnetic enhanced inductive plasma source combined with a radio-frequency inductive discharge are discussed.

1. Introduction
Nowadays, inductively coupled plasma (ICP) is used to conduct a wide range of plasma-chemical processes in various industrial applications (e.g. sputtering, reactive ion etching, plasma enhanced chemical vapour deposition, ion implantation). However, the standard radio-frequency (RF) ICP sources have physical limitations: a weak magnetic coupling and at the same time a significant capacitive coupling between RF coil and plasma load [1]. The weak magnetic coupling results in a significant leakage inductance of the coil and hence the problem of reactive power compensation arises to match RF power supply and plasma load, while the presence of capacitive coupling leads to an intense ion bombardment of plasma chamber walls and plasma contamination. To overcome the above mentioned limitations of RF ICP sources, an alternative approach with the use of ferromagnetic enhanced inductively coupled plasma (FM ICP) was proposed [1–3]. This method is based on the enhancement of the magnetic flux coupling the coil and the load through the use of a closed ferrite core. It allows maximizing the magnetic coupling coefficient ($k \approx 1$), minimizing the coil reactance and significantly decreasing the ICP driving frequency (from about 10 MHz down to 100 kHz) [1]. The driving frequency decrease, in turn, eliminates capacitive coupling between the coil and the plasma as well as simplifies the power supply design. Thus, new simple and effective plasma processing systems could be developed based on the low-frequency ferromagnetic enhanced inductive discharges. To obtain a large volume of plasma, a distributed principle of plasma generation was used with a number of FM ICP sources placed inside [2] or outside [3] the gas discharge chamber. The key issue arising with the distributed FM ICP is that plasma density profile inside the discharge chamber should be controlled in order to achieve a uniform plasma treatment of a substrate. To control the plasma density distribution, an auxiliary RF ICP source placed over the discharge chamber was used in [4]. It was demonstrated that a small amount of the auxiliary RF power could adjust the uniformity of the distributed FM ICP. However, adding an RF ICP source may result in the issues discussed.
above; therefore the aim of the present work is to investigate the possibility to control the distributed FM ICP density using auxiliary low-frequency ferromagnetic enhanced inductive discharges.

2. Experimental setup
A principal scheme of experimental setup is shown in figure 1. The setup consists of a large (internal diameter of 70 cm, height of 50 cm) stainless steel water cooled gas discharge chamber 1 with eight U-shaped gas discharge tubes 2 placed on the side of the chamber, and two auxiliary U-shaped tubes placed on the top of the chamber. U-shaped gas discharge tubes 2 are dielectrically isolated from the chamber 1 with PTFE and rubber gaskets. On each U-shaped tube, a closed ferrite core 3 with a primary coil 4 is mounted. Plasma forming gas (argon) is fed through gas inlets 5 made in the U-shaped tubes. The gas is pumped out through a port in the center of the bottom flange.

The core 3 enhances magnetic coupling between the primary coil 4 and an inductive plasma loop $L$ that passes through the U-shaped tube 2 and the chamber 1. Improvement of magnetic coupling leads to an increase of the power transfer efficiency from a power supply (not shown in figure 1) into the inductive discharge. High magnetic flux $\Phi$ achievable in the core allows a significant reduction of the driving frequency $\omega$ required to maintain the discharge voltage $U = -d\Phi/dt = \omega\Phi$. As a result, capacitive coupling between the coil and plasma is eliminated. The coils of the eight side FM ICP sources are connected in series to a 100 kHz, 500 V power supply through a tuning network (variable LC circuit, not shown in figure 1), while the coils of the two top FM ICP sources are connected in series to a 100 kHz, 250 V power supply through another tuning network. This scheme of a distributed FM ICP generation makes it possible to independently control the power of the top and the side plasma sources. In figure 2, a photograph of the gas discharge chamber is shown with both the side and the top FM ICP sources activated. A similar experimental setup design was realized in [3–5], but with a smaller discharge chamber (ID of 56 cm, height of 32 cm) [3, 4], without the top FM ICP sources [3, 5] or with an RF ICP source placed on the chamber top [4].

To determine a plasma density profile inside the gas discharge chamber 1, an array of flat ion collecting probes 6 is used. The probes are placed approximately in the center of the gas discharge chamber below the top and the side U-shaped tubes at the distances of about 28 cm and 13 cm respectively. The probes are biased to -50 V with respect to the grounded gas discharge chamber 1, the ion currents are collected and measured.

![Figure 1](image1.jpg)  ![Figure 2](image2.jpg)

Figure 1. Experimental setup: 1 – Gas discharge chamber, 2 – U-shaped gas discharge tubes, 3 – Ferrite cores, 4 – Coils (primary winding), 5 – Gas inlets, 6 – Flat probes array. Figure 2. Photograph of the gas discharge chamber (argon pressure of 10 Pa).
3. Results and discussion

In figure 3 radial distributions of the ion flux density in the gas discharge chamber are shown measured for different configurations of the activated FM ICP sources at the argon pressure of 75 mTorr: 1 – only the side plasma sources, 2 – only the top plasma sources, 3 – both the side and the top FM ICP sources are activated. Also, a sum of ion flux densities measured in the modes 1 and 2 is shown for comparison.

Figure 3. Radial distributions of the ion flux density measured at the argon pressure of 75 mTorr:
1 – the side FM ICP sources are activated with the total discharge power \( P_{\text{side}} = 1330 \text{ W} \), 2 – the top FM ICP sources are activated with the total discharge power \( P_{\text{top}} = 640 \text{ W} \), 3 – both the side and the top FM ICP sources are activated with \( P_{\text{side}} = 1330 \text{ W} \) and \( P_{\text{top}} = 640 \text{ W} \), 4 – a sum of the radial distributions 1 and 2.

The plasma density profile 1 has a typical concave shape formed by ambipolar diffusion of charged particles from the side plasma sources to the center of the chamber [3–5]. In contrast to it, the plasma density profile 2 has a convex shape with a maximum density reached in the chamber center under the top FM ICP sources. In [4] an additional RF ICP source with the frequency of 13.56 MHz was used to improve the uniformity of a distributed FM ICP within a discharge chamber of 56 cm. It was shown that at argon pressure of 5 mTorr even a small addition of auxiliary RF power \( (P_{\text{side}}/P_{\text{top}} = 10) \) to the chamber center resulted in a drastic increase of the center density, which was much higher than the linear sum of plasma densities generated by the top and the side plasma sources separately. At the same time, the edge density near the side FM ICP sources was found to decrease despite of a fixed power \( P_{\text{side}} \) of 1000 W. The change of the plasma density profile was found to be a result of the change in plasma potential distribution caused by the auxiliary discharge in the chamber center. At \( P_{\text{top}} = 0 \text{ W} \), electrons were locked at the chamber edge near the side FM ICP sources by a high potential barrier in the chamber central region. As \( P_{\text{top}} \) was increased, the potential barrier was reduced; due to a relatively long energy relaxation length of the electrons comparable with chamber radius, high-energy electrons from the side FM ICP sources were able to penetrate into the discharge chamber and lost their energy in inelastic collisions with argon atoms. Thereby, it was shown in [4] that an auxiliary discharge could be used to control the energy flux from the side FM ICP sources into the discharge chamber.

In contrast to [4], adding of an FM ICP power to the discharge chamber center has not resulted in a non-linear increase of the plasma density. Figure 3 shows that the sum of plasma densities generated by the top and the side FM ICP sources separately is close to the values measured with all plasma sources being simultaneously activated. In addition, plasma density near the side FM ICP sources does not decrease nor increase with the auxiliary FM ICP power applied to the discharge chamber center. The difference between the obtained results and the work [4] is most likely due to a significantly higher gas pressure of 75 mTorr and hence an order of magnitude shorter the energy relaxation length.
of the electrons. In this case, all energy gained by electrons in the discharge electric field \( E = \frac{U}{L} \) is spent on inelastic processes locally in the discharge loop \( L \) that passes through the U-shaped tube and between the open ends of the U-shaped tube, while the bulk plasma is kept only by ambipolar fluxes from the FM ICP loops into the gas discharge chamber. At the same time, a constant plasma density value near the side FM ICP sources indicates that charged particles generated by the top plasma sources do not enter the chamber edge. As a result, the measured plasma density profile is a bit more uniform than the sum of plasma densities. Thereby, even without the non-local electron energy transport from the side FM ICP sources into the discharge chamber realized in [4], the auxiliary FM ICP sources allow to compensate the plasma density drop in the central region thus significantly improving the plasma uniformity inside the discharge chamber.

4. Conclusions
A conventional electric transformer principle based on the concentration and amplification of magnetic flux coupling a primary and a secondary coil by a ferromagnetic core could be used to improve the ICP sources performance in industrial applications. An increase of the magnetic coupling enhances the ICP power factor and hence simplifies the matching of a power source and plasma load. Amplification of the magnetic flux allows to generate an inductive discharge in the low-frequency radio range. In turn, a decrease of the driving frequency eliminates the undesirable capacitive coupling between the primary coil and plasma load, simplifies the power source design. While a single loop of ferromagnetic enhanced ICP is not suitable for uniform plasma treatment of a substrate, a number of such plasma sources could be placed on the sides of a discharge chamber to obtain a large plasma volume. Our experimental results show that plasma density profile inside the discharge chamber can be controlled by varying the position and power of the ferromagnetic enhanced ICP sources. In particular, by placing additional ferromagnetic enhanced ICP sources over the central region of the discharge chamber, it is possible to compensate the lack of charged particles in the discharge chamber center.

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