LARGE VOLUME ICP SOURCES FOR PLASMA-BASED ACCELERATORS

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Abstract

A series of large volume inductively coupled plasma (ICP) sources with immersed antenna has been developed. The electrical and plasma characteristics of the sources have been investigated. The source chamber, equipped with line magnetic multicusps, has volume from 18 to 1000 liters. Spatially uniform plasma is produced at the working gas pressure of ~(0.1–2.0) mTorr with the density of up to 10^{11} cm^{-3} even in the largest 1-m^3 chamber.

INTRODUCTION

Radio frequency (RF) discharge in both, so called 'E' and 'H' modes (i.e. capacitive and inductive coupling) has been used for a long time in variety of plasma and ion sources for particle accelerators and plasma facilities [1]. Compact (a few cm^3 in plasma volume) helical ICP source has been one of the key ion sources for Van de Graaf accelerators [2]. Last decade ICP sources with a plasma volume of up to some tens of liters are extensively used in semiconductor industry. Ability to produce high density plasma at low pressure, low contamination level, and remarkable scalability are some of the attractive features of ICP source. External helical or planar spiral antennas, often equipped with a Faraday shield to suppress capacitive coupling, are commonly used in ICP sources. However, further scaling up of ICPs for large area plasma processing tools and large volume plasma-based accelerators implies use of the internal (or immersed) antenna [3, 4]. In deposition environment, like that in plasma immersion ion implantation and deposition (PI^3D) facilities [5], the immersed antenna seems to be the only option. ICP with immersed antenna is well adapted for being used as an auxiliary plasma source in large area electron accelerators, and it ensures much lower plasma potential and higher plasma density than, say electrostatically confined source.

Spatial plasma uniformity and small contamination level are the two major factors in the ICP design. Antenna geometry is not that critical due to non-local electron kinetics in low-pressure ICP [6]. The capacitive coupling issue in the antenna design is more complicated comparing with external antennas due to absence of Faraday shield.

In this paper, we discuss characteristics of the developed large volume ICP sources with immersed antenna. Designed for PI^3D facilities, they can also be used in other plasma-based accelerators, and plasma processing tools as well.

All the sources have stainless steel cylindrical chamber equipped with linear magnetic multicusps based on Nd-Fe-B permanent magnets. A low-inductance immersed antenna has geometry optimized for particular application, and comprises a central copper conductor surrounded with fused quartz tubing. Water or air-cooling of the antenna interior is used.

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ELECTRICAL CHARACTERISTICS OF THE ICP SOURCES

Capacitive Coupling

The equivalent circuit of the ICP source is shown in Fig. 1. The antenna with inductance L_{ant} is connected to a (1 – 3) kW, 13.56 (12.56) MHz RF source through the matching network. The blocking capacitor C_{block} ensures twice less amplitude of the RF voltage at the antenna terminals, V_{rf}, due to symmetrical antenna excitation and, thus, reduces effect of capacitive coupling between the antenna and plasma [4]. Plasma is represented by inductance L_{pl} and resistance R_{pl} of the skin layer, and the wall sheath resistance $R_{w\ sh}$ and capacitance $C_{w\ sh}$. To damp the capacitive coupling, the antenna capacitance C_{ant} should be much smaller than the capacitance of the RF plasma sheath C_{sh}.

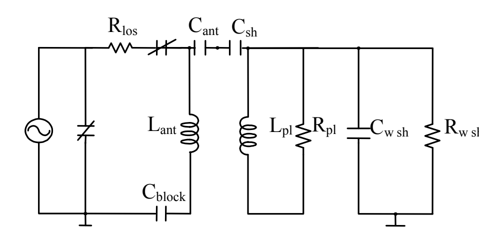

Fig. 1. Equivalent circuit of RF matching and antenna – plasma coupling in ICP source.

To estimate the capacitive coupling in cylindrical geometry we apply the analytical expression for DC cylindrical sheath [7]:

$$\frac{r_{sh}^{dc}}{r_2} \cong \left(1+\varsigma^{0.455}\right)^{0.84} \quad , \quad \varsigma \equiv \frac{\left(\frac{V_{=sh}}{T_e}\right)^{3/2}}{\left(\frac{r_2}{\lambda_D}\right)^2} , \qquad (1)$$

where r^{dc}_{sh} is the DC sheath radius, r_2 is the radius of the antenna insulator, $V_{=sh}$ is the DC sheath voltage, T_e is the electron temperature, and λ_D is the Debye length. Neglecting the difference in the thickness of RF and DC sheaths, which is within 40% [8], and assuming $V_{=sh}$ ≈

$V_{rf\,sh}$, we derive the expression for the ratio of antenna insulator – to conductor radius, r_2/r_1, which is required to obtain desired value of $V_{=sh}/V_{rf}$, as a function of dielectric constant of the insulating material, ε, and plasma parameters:

$$\ln\left(\frac{r_2}{r_1}\right) \approx 0.84\varepsilon \cdot \frac{V_{rf}}{V_{=sh}}\left(1-\frac{V_{=sh}}{V_{rf}}\right)\cdot \ln\left(1+\varsigma^{0.455}\right) \qquad (2)$$

Figure 2 shows the r_2/r_1 ratio, calculated using (2), which is required to get $V_{rf}/V_{=sh} = V_{=sh}/T_e = 10$, vs. plasma density for air (ε=1) and quartz (ε=3.75) insulation.

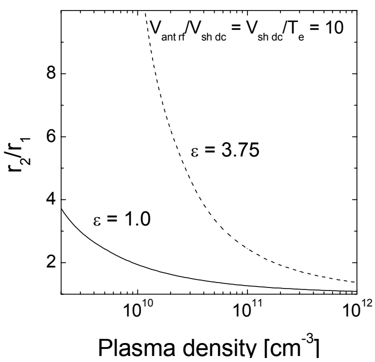

Fig. 2. Ratio of insulator – to conductor radius of the immersed RF antenna in ICP source, r_2/r_1, to obtain $V_{=sh}/V_{rf} = 1/10$ as a function of plasma density, for air (ε=1) and quartz (ε=3.75).

It is seen, that for practical value of $r_2/r_1 < (2–3)$, the use of air gap between the antenna conductor and thin quartz tubing is more effective than thick SiO_2 covering, especially for medium and low plasma density. We used dry air antenna cooling when contamination due to antenna self-bias could deteriorate the system performance.

RF Power Transfer Efficiency

The power transfer efficiency, η, of the ICP sources has been measured as follows:

$$\eta = \frac{P_{in} - I_{ant}^{2} R_{los}}{P_{in}} \qquad (3)$$

where the input RF power $P_{in} = P_{for} - P_{ref}$, P_{for} and P_{ref} are the forward and reflected RF power, respectively, R_{los} is the losses resistance (see Fig. 1), and I_{ant} is the RF antenna current (RMS). The Pearson current probe was used to measure I_{ant}.

The results for a 100-liter (MM) and 1000-liter (BB) ICP source, when argon and nitrogen plasma was produced, are shown in Fig. 3. The one-turn air cooled antenna was used in the MM source, and the water cooled Boswell-like configured antenna in the BB source. It is known that the capacitive coupling increases η. Difference in the curves behavior for MM and BB source in the low power region reflects higher level of capacitive coupling in the latter. The both sources have η > 80% for RF power more than ~ 400 W.

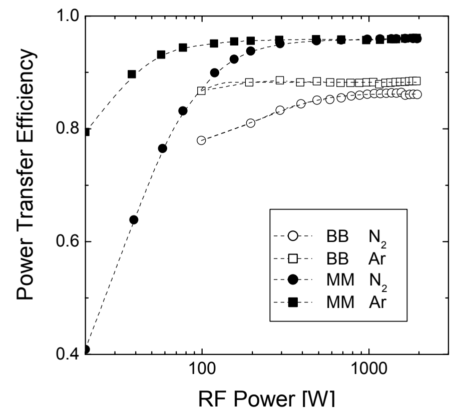

Fig. 3. Power transfer efficiency in a 100-liters and 1000-liters ICP source vs. input RF power for argon and nitrogen at pressure of 0.5 mTorr.

PLASMA DIAGNOSTICS

Ion Mass Composition

The ion mass analyzer described elsewhere [9] was used for measurement of the ion mass composition in nitrogen and ammonia plasma of the ICP sources. Within the pressure range of (0.2 – 2) mTorr, the ratio of atomic nitrogen in both gases was found rises from about 10% to 50% when RF power is increased from 0.2 kW to 2 kW, and it is higher for lower pressure. Further enhance of atomic ion contents require special measures like magnetic filtering [10]. In plasma ion implanters, when radiation effects due to hydrogen are of minor concern, the use of ammonia allows to get as high as (60 – 80)% of atomic nitrogen containing ions, i.e. N_1^+, NH_1^+, NH_2^+, and NH_3^+, at low RF power of just 0.1 kW, as it is seen from Fig. 4.

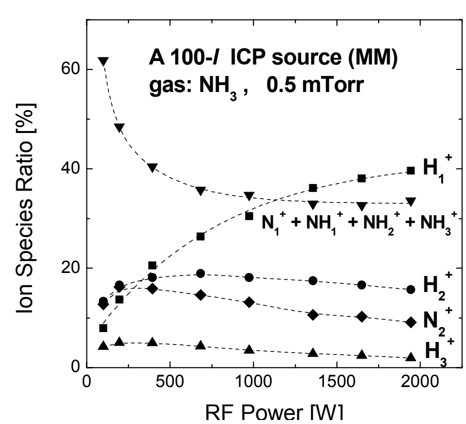

Fig. 4. Ion mass composition as a function of RF power in ammonia plasma of a 100-liters ICP source at pressure of 0.5 mTorr.

Langmuir Probe

Electron energy distribution function and ion plasma density in the sources were investigated with cylindrical (r_p = 0.25 mm, l_p = 10 mm), and spherical (r_p = 0.35 mm) RF-compensated Langmuir probes using the procedure described elsewhere [7]. Fig. 5 shows nearly linear dependence of plasma (ion) density on input RF power in a 100-liter and a 1000-liter ICP source. Spatial uniformity of plasma can be seen from Fig 6, where the radial distribution of the argon plasma (ion) density, plasma potential V_{pl}, and effective electron temperature T_{eff} in a 1000-liter source is shown.

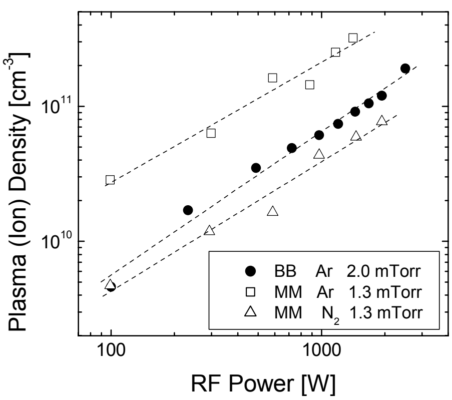

Fig. 5. Plasma (ion) density vs. input RF power in a 100-liters (MM) and 1000-liters (BB) ICP source.

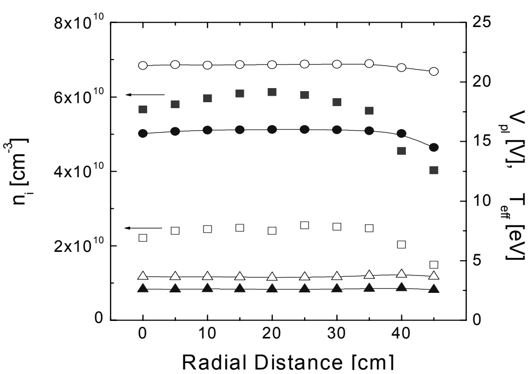

Fig. 6. Radial distribution of plasma (ion) density (squares), plasma potential V_{pl} (circles), and effective electron temperature T_{eff} (triangles) in a 1000-liters ICP source (BB) for argon at 0.2 and 1.0 mTorr (empty and filled symbols, respectively). Zero at the X-axis corresponds to the axis of a 1-m diameter cylindrical chamber.

CONCLUSIONS

A series of large-volume ICP sources with immersed insulated antenna were developed. Their use in (30 – 120) kV PI^3D facilities showed high overall performance even in deposition environment. The layout view of the 1000-liter source is shown in Fig. 7.

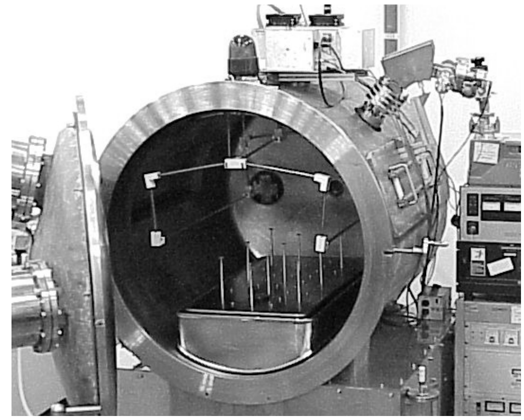

Fig. 7. Processing chamber of a 120-kV PI^3D system with a 1000-liters ICP source.

REFERENCES

[1] M. D. Gabovich, *Plasma Ion Sources*, US Air Force Trans. FTD-MT-65-229, AD623-822, 1964, Pub. Foreign Technology Division, US Air Force Systems Command.

[2] S. A. Nikiforov, V. P. Golubev, *et al.*, "Ion Sources for Use in Research and Applied High Voltage Accelerators", Proceed. of the PAC'95, vol. 2, pp. 1004-1006.

[3] Y. Wu and M. A. Lieberman, "The Influence of antenna Configuration and Standing Wave Effects on Density Profile in a Large-Area Inductive Plasma source", Plasma Sources Sci. Technol., vol. 9 (2000) pp. 210-218.

[4] K. Suzuki, K. Konishi, K. Nakamura and H. Sugai, "Effect of Capacitance Termination of the Internal Antenna in Inductively Coupled Plasma", Plasma Sources Sci. Technol. Vol.9 (2000) 199-204.

[5] S. A. Nikiforov, K. W. Urm, *et al.*, "Preparation and Characterization of TiN coatings produced by combination of PI^3D and ICP assisted magnetron PVD", Surf. Coatings Technol., 171 (2003) 106-111.

[6] V. A. Godyak, R. B. Piejak, and B. M. Alexandrovich, "Electron energy distribution function measurements and plasma parameters in inductively coupled argon plasma", Plasma Sources Sci. Technol. 11 (2002) 525-543.

[7] S. A. Nikiforov, G. H. Kim, G. H. Rim, "Dynamics of High-Voltage Pulsed Cylindrical Sheath", IEEE Trans. Plasma Sci., vol. 31, pp. 94 – 103, Feb. 2003

[8] V. A. Godyak, R. B. Piejak, and N. Sternberg, "A comparison of RF electrode sheath models", IEEE Trans. Plasma Sci., vol. 21, no. 4, 1993, pp. 378-382.

[9] G. H. Kim, G. H. Rim S. Nikiforov, "Monitoring of Ion Mass Composition in Plasma Immersion Ion Implantation", Surface Coat. Technol., vol. 136 (2001) 255-260.

[10] K. W. Ehlers and K. N. Leung, Rev. Sci. Instr., 52 (1981) 1452.