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Improving the uniformity of RF-plasma density by a humped variable-gap spiral antenna*

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This paper develops a humped spiral antenna of top inductively coupled plasma with variable gap. Comparing with planar spiral antennae, it investigates the performance of humped spiral antennae in the calculated electromagnetic configurations and experimental results. It finds that the humped antenna has the improved uniformity of plasma density in the radial direction and the decreased electron temperature in the top inductively coupled plasma. By experimental and theoretical analyses, the plasma performance in the case of humped antennae is considered to be the combined results of the uniform electromagnetic configurations and the depressed capacitively coupling effect.

Keywords: inductively coupled plasma, Langmuir probe, planar antenna, density uniformity
PACC: 5240F, 5250

1. Introduction

Radio frequency (RF) wave through an inductively coupled mechanism can excite a high density uniform plasma ($10^{11} - 10^{12}\,\mathrm{cm}^{-3}$) under low gas pressure (0.1–5 Pa), which satisfies the requirements of the plasma sources for ultra-large scale integrated (ULSI) processing such as etching, deposition and ion implantation.[1−6] With the further development of large area substrates, many efforts have aimed at the excitation coil of top inductively coupled plasma (TICP) for the improvement of the plasma uniformity and the scaling-up capability. The enhanced coupled efficiency is achieved by the optimized five-turn antenna in Singh's group.[7] The improved uniformity of plasma density is reported in Srinivasan's group by the current reversal antenna.[8] Gans and his coworkers employ three coaxial coils to operate plasma at comparatively low pressures, down to 10^{-2} Pa.[9]

With the increase of the discharge chamber diameter, a spiral planar coil with an increased diameter gives rise to inherent non-uniformity of plasma configuration, due to the non-uniform magnetic inductive field and the standing wave effect.[10−12] To circumvent the plasma non-uniformity owing to single antenna, several antennae are arranged on the dielectric plate, so the plasma generated by each antenna can overlap with others to acquire large-area uniform plasma.[13−15]

Comparing with the planar spiral antennae, this paper investigates the performance of TICP excited by the variable-gap humped spiral antenna.

2. Experimental arrangement

The experimental setup is shown schematically in Fig.1(a). It consists of vacuum system, RF system and Langmuir double probe system. The vacuum stainless steel chamber ($\Phi 400 \times 500$ mm) is pumped by a 620 L/s turbomolecular pump to 5×10^{-4} Pa base pressure. The gas flow (Ar, N_2, O_2, 99.999%) is controlled by mass flow controller and the pressure is controlled by a gate valve. The RF system is comprised of three components: RF power supply, RF matching network and excitation antennae. 13.56 MHz RF power is coupled into the plasma through a 30 cm diameter 18 mm thick quartz dielectric. Based on the planar spiral antenna, our group develops the humped spiral antenna. The two turn planar spiral antenna (denoted as A1 in what follows) is 1 mm thick by 8 mm width with 25 cm outer diameter and 15 cm inner diameter.

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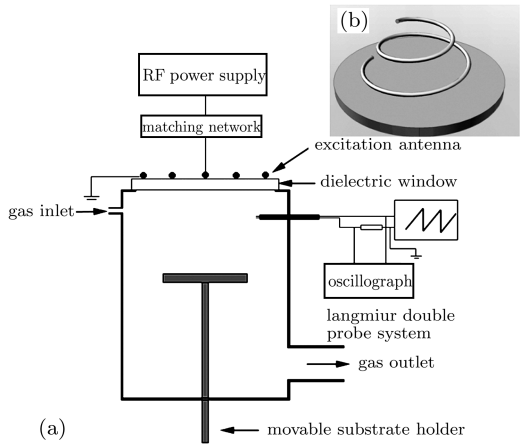


Fig.1. Schematic diagram of (a) the TCIP experimental apparatus, (b) the humped spiral antenna with two turns.

The humped spiral antenna has the same characteristic dimension with the planar spiral antenna mentioned above, except for the decreasing air gap between the antenna and the quartz window from the inner circle to the outer circle, shown in Fig.1(b). The air gaps of the inner ends of the antennae (denoted as A2 and A3 in what follows) adopted in our experiment are 50 mm and 100 mm, respectively. A Langmuir double probe was employed to measure the radial distribution of the electron density and the electron temperature in a plane 40 mm below the quartz window. The tips of Langmuir probe are made of the tungsten wire with 0.3 mm diameter and 10 mm length. The sweeping saw tooth voltage applied to probe diagnosis is 160 V peak to peak at a frequency of 45 Hz.

3. Experiment results and discussion

The calculated electromagnetic configurations generated by the two-type antennae are shown in Figs.2 and 3. According to Faraday's Law, the axial component of time-varying magnetic field generates the azimuthal electric field, which accelerates electrons and maintains the plasma. However, the axial irrotational electric field dominates the ignition stage of

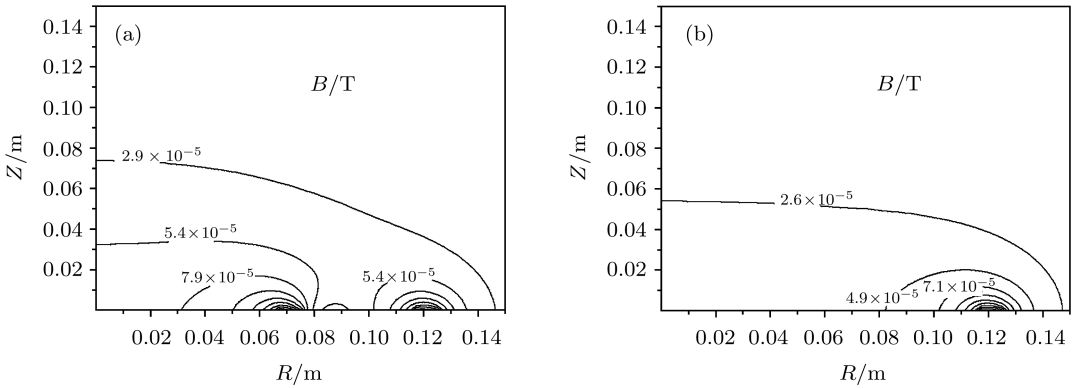


Fig.2. The configurations of magnetic fields excited by (a) the planar spiral antenna, (b) the humped spiral antenna with 5 cm gap.

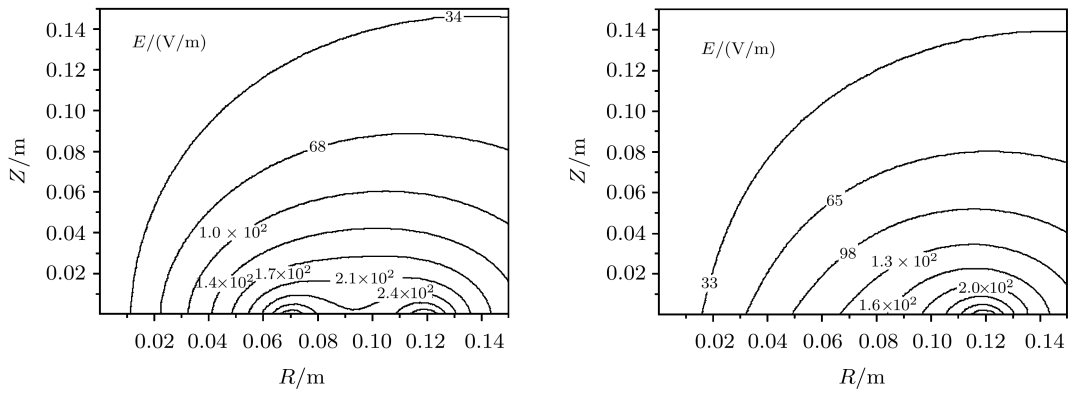


Fig.3. The configurations of azimuthal electric fields excited by (a) the planar spiral antenna, (b) the humped spiral antenna with 5 cm gap.

TICP when the capacitively coupling mechanism plays the key roles. It means that the plasma will be generated at the central area, where the irrotational field is intensive. Then the produced electrons will be accelerated by the azimuthal field and ionize the neutral particles through inductively coupling mechanism. In the case of humped spiral antenna, the intensive azimuthal electric field is produced at only one place in the radial direction of 120 mm, in contrary to the case of planar spiral antenna with the intensive azimuthal electric field at two places of 70 mm and 120 mm in the radial direction, as shown in Fig.3. Simultaneously the uniformity of magnetic field in the radial direction is improved by the variable-antenna, as seen in Fig.2. In the improved uniform electromagnetic configurations, the electrons and ions subject to a less radial acceleration due to the curvature of the magnetic field and static ambipolar electric fields established by radial electron acceleration, which results in the improved density uniformity in the radial direction in comparison with the case of planar spiral antenna.

The density distribution of the plasma excited by two-type antennae in the radial direction in oxygen at 0.5 Pa is shown in Fig.4. Values of power monitored in our experiment are from the measurement of the incidence power to the matching network, from which the reflected power is subtracted. Thus, measured values include power dissipation in external components as well as in plasma. From Fig.4, it can be perceived that the plasma uniformity is improved by the variable-gap antenna at the cost of high coupling efficiency. The quantitative comparison of density uniformity of the plasma excited by three antennae is presented in Fig.5. Here, we define uniformity D, which indicates the density uniformity in the radial direction.

$$D = \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}}, \tag{1}$$

where $N_{\max}$ and $N_{\min}$ are the maximum value and the minimum value of the measured plasma density in the radial direction, respectively. Good uniformity is indicated by the small value of D, and vice versa. The experimental data show that the uniformity D has a tendency to decline with the increasing power and the increasing air gap. The antenna with variable gap reduces the power coupling efficiency, so the low density will be obtained by the antenna with large air-gap at the same power. Here, we compare the uniformity of TICP excited by two-type antennae in the same plasma density about $6 \times 10^{10}\,\mathrm{cm}^{-3}$ in argon, which corresponds to A1 at 50 W, A2 at 60 W and A3 at 110 W. The values of uniformity D in those cases are 0.21, 0.18 and 0.14, respectively. Using the humped antennae with variable gap, we can achieve the better radial density uniformity in comparison with the same plasma density in the case of planar spiral antennae.

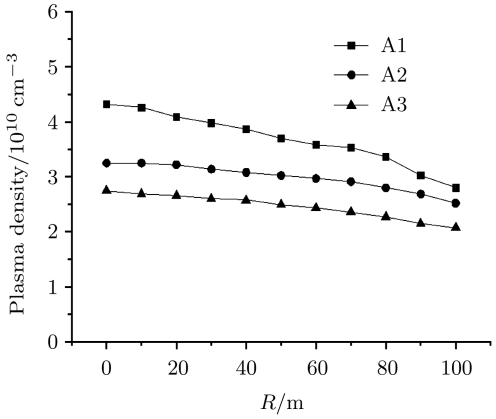


Fig.4. The density distribution of the plasma excited by three antennae in the radial direction in oxygen at 0.5 Pa.

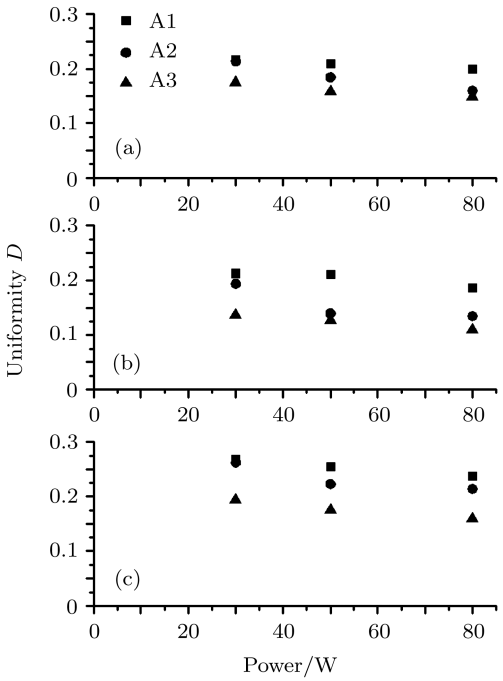


Fig.5. The radial density uniformity D of the plasma excited by three antennae at the gas pressure of 0.5 Pa: (a) argon, (b) oxygen, (c) nitrogen.

Figure 6 shows the power dependence of the plasma density produced by three antennae (A1, A2 and A3) in Argon gas at 0.5 Pa. It shows that the plasma density increases along with increasing RF power. At the same power, the highest density is

generated by the planar spiral antenna A1, followed by the humped spiral antenna A2 with the moderate density and then the A3 with the lowest density. The power coupling efficiency is very sensitive to the air gap and decreases with the increasing air gap,[16] which accounts for the lowest density generated by the antenna A3 with the largest equivalent gap at the same power.

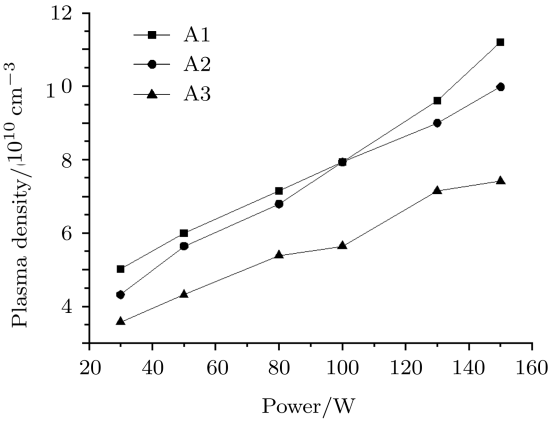


Fig.6. The power dependence of the plasma density produced in argon gas at 0.5 Pa by three antennae: A1 the planar spiral antenna; A2 the humped spiral antenna with 5 cm gap between the inner antenna end and the quartz window; A3 the humped spiral antenna with 10 cm gap between the inner antenna end and the quartz window.

Figure 7 shows that the electron temperature I_e has a tendency to decline with the increasing air-gap, which verifies the depressed capacitively coupling effect by the humped spiral antenna. The high RF voltage applied to drive the excitation antenna creates a parasitic capacitive current pathway through the quartz window and RF sheath to the plasma, which increases the electron temperature by the stochastically heating mechanism. The air gap can be considered as an equivalent capacitance in series with the capacitance of the quartz window and the plasma. So there are amount of voltage applied to the air gap, which brings the significant decrease in the total voltage applied to the quartz window and the plasma. With the depressed capacitively coupling effect, the decreased electron temperature is observed in the TICP excited by the humped spiral antenna.

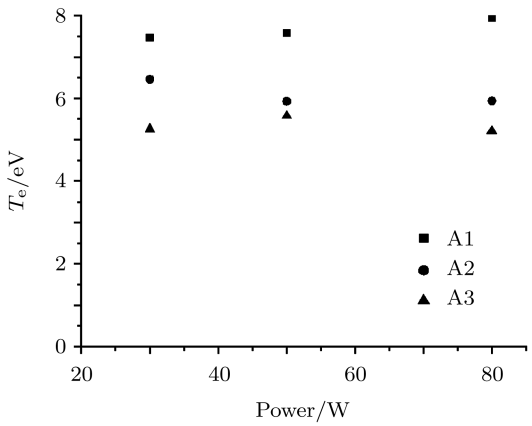


Fig.7. The power dependence of the electron temperature excited by three antennae in argon at the gas pressure of 0.5 Pa.

4. Conclusion

Using the humped spiral antenna with specifically chosen geometry, we will effectively achieve the plasma with the improved radial density uniformity and the reduced electron temperature. It considers the combined results of the uniform electromagnetic configuration in the radial direction and the depressed capacitively coupled effect in TICP excited by humped spiral antennae. The humped variable-gap design is not only applicable to the top inductively coupled plasma, but also to the side inductively coupled plasma. The variable-gap designation makes it possible to change the plasma parameters in the central region and outer region independently. The humped variable-gap antenna is a tradeoff between the power coupling efficiency and the improved plasma performance, but it differs from the planar antenna with fixed air gap in the modified electromagnetic configuration. The later just moves the excitation region to the downstream of RF electromagnetic field to acquire better plasma performances.

References

[1] Tynan G R, Bailey A D and Campbell G C 1997 *J. Vac. Sci. Technol.* A **15** 2885

[2] Godyak V A, Piejak R B and Alexandrovich B M 2002 *Plasma Sources Sci. Technol.* **11** 525

[3] Fu R K Y and Chu P K 2004 *Proceedings Chinese Materials Research Conference* (Beijing) Paper M.17 p385

[4] Liang B, Ou Q R, Liang Y Z and Liang R Q 2007 *Chin. Phys.* **16** 3732
[5] Huang S, Xin Y and Ning Z Y 2005 *Chin. Phys.* **14** 1608
[6] Gu G R, Wu B J, Jin Z and Ito Toshimichi 2008 *Chin. Phys.* B **17** 716
[7] Singh H and Graves D B 2000 *J. Appl. Phys.* **87** 4098
[8] Srinivasan1 S, Marquis J, Pratti L, Khater M H, Goeckner M J and Overzet L J 2003 *Plasma Sources Sci. Technol.* **12** 432
[9] Gans T, Crintea D L, Connell D O and Czarnetzki U 2007 *J. Phys.* D*: Appl. Phys.* **40** 4508
[10] Hopwood J, Guarnieri C R, Whitehair S J and Cuomo J J 1993 *J. Vac. Sci. Technol.* A **11** 147
[11] Forgotson N, Khemka V and Hopwood J 1996 *J. Vac. Sci. Technol.* B **14** 732
[12] Khate M H and Overzet L J 2000 *Plasma Sources Sci. Technol.* **9** 545
[13] Heinrich F, Bannziger U, Jentzsch A, Neumann G and Huth C 1996 *J. Vac. Sci. Technol.* B **14** 2000
[14] Park S G, Kim C and Beom-hoan O 1999 *Thin Solid Films* **355** 252
[15] Tian X B and Chu P K 2000 *Phys. Lett.* A **277** 42
[16] Watanabe M, Shaw D M and Collins G J 1999 *J. Appl. Phys.* **85** 3428