Vol 16 No 12, December 2007
1009-1963/2007/16(12)/3732-06
Chinese Physics
© 2007 Chin. Phys. Soc.
and IOP Publishing Ltd

Large area planar plasma sustained by surface microwave*

Liang Bo(梁 波)[a], Ou Qiong-Rong(欧琼荣)[b], Liang Yi-Zi(梁以资)[a], and Liang Rong-Qing(梁荣庆)[a]†

[a] *The Key Laboratory of Applied Ion Beam Physics, the Ministry of Education, Shanghai* 200433, *China*

[b] *Institute of Plasma Physics, Chinese Academy of Sciences, Hefei* 230031, *China*

(Received 25 December 2006; revised manuscript received 26 April 2007)

In this paper, we show theoretically and experimentally that the large-area planar plasma with high density and good uniformity can be sustained by a surface microwave when the electron density is over-dense. From the experimental results we find that the nonuniformities in azimuthal plasma density and electron temperature have been greatly improved and in particular the nonuniformity is less than 10% when the gas pressure is 30 Pa. By improving the antenna shape, enhancing the microwave power and choosing the appropriate gas pressure, the large area planar plasma with high density can be produced.

Keywords: microwave, skin depth, surface wave, surface wave plasma
PACC: 5240D, 5250D

1. Introduction

The research on plasma source has aroused great interest in recent years due to its wide applications in modern industry, such as film deposition, preparation of nanometre powder materials, materials surface modification, etc. In the past decade the study of plasma source has concentrated mostly on the long plasma columns, of which the plasma diameter is much less than the column length.[1−4] Such a kind of plasma column is clean, quiescent and reproducible, but does not meet the recent needs of large-diameter plasma processing, such as the next generation of ultra large scale integration and the production of solar cells. Therefore a better plasma source to produce and sustain large-area planar plasma attracts our attention to the method of surface wave.[5−8] In this paper, we describe some important factors such as antenna structure, microwave power and gas pressure to improve the plasma performances in the surface wave plasma.

2. Theoretical model and surface wave modes

In order to identify the mechanism of sustaining a plasma by microwave, we use a simple interface model. In this model, the upper region of the interface is a thick dielectric plate of thickness d and relative permittivity $\varepsilon_{\rm d}$. The plasma produced in the bottom region is assumed to be cold and homogeneous with electron density $n_{\rm e}$, electron-neutral collision frequency ν and plasma relative permittivity

$$\varepsilon_{\rm p} = 1 - \frac{\omega_{\rm p}^2}{\omega(\omega + {\rm i}\nu)}, \tag{1}$$

where $\omega_{\rm p} = e(n_{\rm e}/\varepsilon_0 m_{\rm e})^{1/2}$ is the plasma oscillation frequency, $m_{\rm e}$ and (–e) are the electron mass and charge, respectively. The plasma permittivity $\varepsilon_{\rm p}$ can be simplified as follows when ν is neglected:

$$\varepsilon_{\rm p} = 1 - \omega_{\rm p}^2/\omega^2. \tag{2}$$

For a fixed wave frequency ω, the cut-off plasma density $n_{\rm c}$ is defined as

$$n_{\rm c} = \varepsilon_0 m_{\rm e}\omega^2/e^2. \tag{3}$$

In the case of infinite plasma, electromagnetic (EM) waves can propagate over longer distances with a relatively low attenuation ($|{\rm Re}\,\kappa \gg {\rm Im}\,\kappa|$) only under under-dense conditions ($n_{\rm e} \ll n_{\rm c}$ and $0 < \varepsilon_{\rm p} < 1$). In an over-dense ($n_{\rm e} > n_{\rm c}$, and $\varepsilon_{\rm p} < 0$) plasma, EM waves are evanescent ($|{\rm Re}\,\kappa| \ll |{\rm Im}\,\kappa|$) and decay exponentially along the axial direction. The skin depth is

$$\delta = c/\sqrt{\omega_{\rm p}^2 - \omega^2}\,, \tag{4}$$

*Project supported by Prof. Liu Wang-Dong's research project (Grant No 5131502).
†Corresponding author. E-mail: rqliang@fudan.edu.cn

which in a high density plasma is $\delta = c/\omega_{\rm p}$ resulting in a skin depth shorter than 1–2 cm. A real bounded plasma is shown in Fig.1, where a train of electromagnetic waves from point L in the dielectric with permittivity $\varepsilon_{\rm d}$, is incident into plasma region of permittivity $\varepsilon_{\rm p}$.

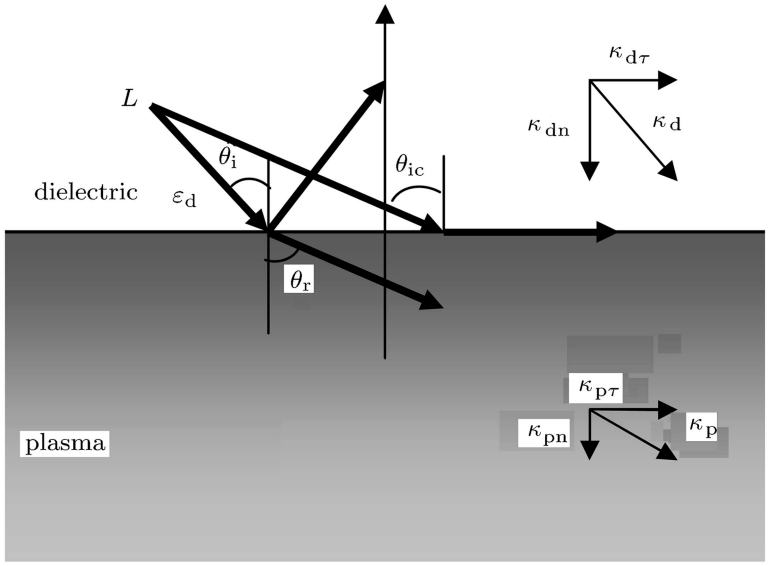


Fig.1. Geometry of electromagnetic wave propagation along plasma-dielectric interface.

Then let us make use of the boundary conditions along the plasma-dielectric interface are expressed as

$$\kappa_{\rm d\tau} = \kappa_{\rm p\tau} = \kappa_\tau, \tag{5}$$

where $\kappa_{\rm d\tau}$ and $\kappa_{\rm p\tau}$ are the wave vector components tangential to the interface of the dielectric and the plasma respectively. The wave vector components parallel to the surface of the plasma and the dielectric, respectively, are

$$\kappa_{\rm pn} = \sqrt{\varepsilon_{\rm p}\omega^2/c^2 - \kappa_{\rm p\tau}^2}\,, \tag{6}$$

$$\kappa_{\rm dn} = \sqrt{\varepsilon_{\rm d}\omega^2/c^2 - \kappa_{\rm d\tau}^2}. \tag{7}$$

As is well known in geometrical optics there exists

$$\frac{\kappa_\tau/\sqrt{\kappa_\tau^2 + \kappa_{\rm dn}^2}}{\kappa_\tau/\sqrt{\kappa_\tau^2 + \kappa_{\rm pn}^2}} = \sin\theta_{\rm i}/\sin\theta_{\rm r}\,. \tag{8}$$

From expressions (5)–(8), we can obtain the critical incident angle for total reflection

$$\theta_{\rm ic} = \sin^{-1}[(\varepsilon_{\rm p}/\varepsilon_{\rm d})^{1/2}]. \tag{9}$$

In this situation, there exist three kinds of wave modes: volume waves, hybrid surface waves and pure surface waves.[7−9] (i) Volume waves penetrate into the plasma bulk when $\theta_{\rm i} < \theta_{\rm ic}$; (ii) Hybrid surface waves are totally reflected at the interface when $\theta_{\rm i} > \theta_{\rm c}$. In the case, the amplitudes of electromagnetic waves decay exponentially from the interface to the plasma region; (iii) Pure surface waves occur with the amplitudes decaying exponentially from the interfaces both in the dielectric slab and the plasma bulk, when $\theta_{\rm i} < \theta_{\rm ic}$, if the plasma is over-dense, $\varepsilon_{\rm p}$ becomes negative, thus the volume waves cannot penetrate into the plasma.

In the dielectric-plasma interface boundary, if the following condition is satisfied:[9−12]

$$\kappa_{\rm pn}/\varepsilon_{\rm p} = \kappa_{\rm dn}/\varepsilon_{\rm d}, \tag{10}$$

from expressions (5)–(10) we obtain

$$\kappa_\tau^2 c^2/\omega^2 = \varepsilon_{\rm d}[1 + \omega_{\rm p}^2/(\omega^2 - 1 - \varepsilon_{\rm d})] \tag{11}$$

and from the above equation, for a given wave frequency, when

$$\omega_{\rm p}/\omega = \sqrt{1 + \varepsilon_{\rm d}}\,, \tag{12}$$

we find that $\kappa_\tau \to \infty$, and $\kappa_{\rm pn} < 0$, $\kappa_{\rm dn} > 0$, which means that the amplitudes of electromagnetic waves decay exponentially both from the interface to the

plasma and from the interface to dielectric region and the microwaves in the form of pure surface wave[7] propagate tangentially along the interface.

3. Experimental setup and results

The experimental setup is shown in Fig.2. It is assembled with three parts including a microwave power supply with transmitting lines, a microwave launcher and a plasma chamber. The microwave frequency is at 2.45 GHz, and its power can be adjusted from 0 to 900 W. Argon plasma is maintained at pressures ranging from 1.0 to 140 Pa in a Pyrex chamber. There is a highly pure Terracotta plate (99%Al_2 O_3) on top of the chamber with a coupling window and two slots in the broad wall of the feeding rectangular waveguide as shown in Fig.3. The Terracotta plate is 13 mm thick and the Pyrex vacuum chamber are 500 mm high and 300 mm in diameter.

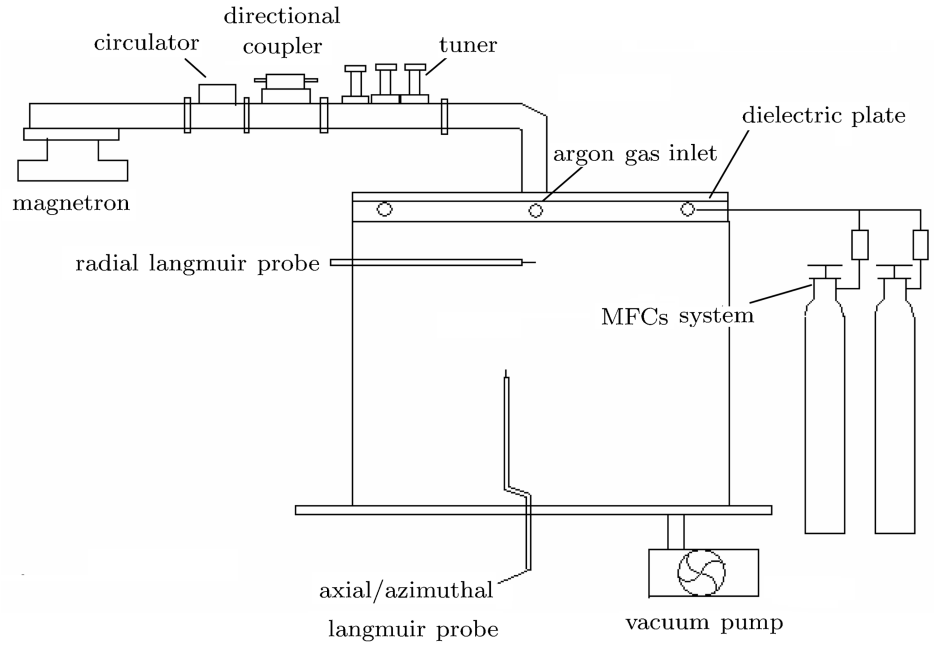


Fig.2. Schematic diagram of the experimental setup of surface wave plasma.

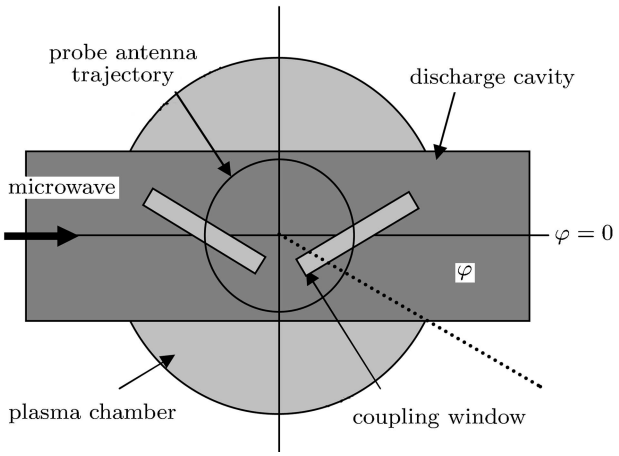


Fig.3. Slot geometry with the probe antenna trajectory.

Two moveable Langmuir probes are inserted into the chamber. One probe serves for the diagnostics of radial plasma parameters, the other for the diagnostics of axial and azimuthal plasma parameters and also for the measurement of the azimuthal electric field through the probe picking up the signal of the electrical field strength in plasma.

By fixing the microwave power at 600W and argon gas pressure at 30 Pa, we measure the azimuthal distribution of electron densities and electron temperatures in argon plasma with the movable probe in the direction. And as shown in Fig.4, the plasma density and electron temperature both have good uniformities in the azimuthal direction, in particular, the nonuniformity is less than 10% within the error range. The electron density has a variation fluctuating at 1.1×10^{12} cm^{-3} while the electron temperature

at about 2 eV. The good uniformity described above can be explained as follows: the free path of electrons in argon gas at a pressure of 30 Pa is long, so electrons can diffuse easily from the electrical field site of maximum power to that of minimum, and thus the effect of the electrical field distribution on plasma can be neglected.

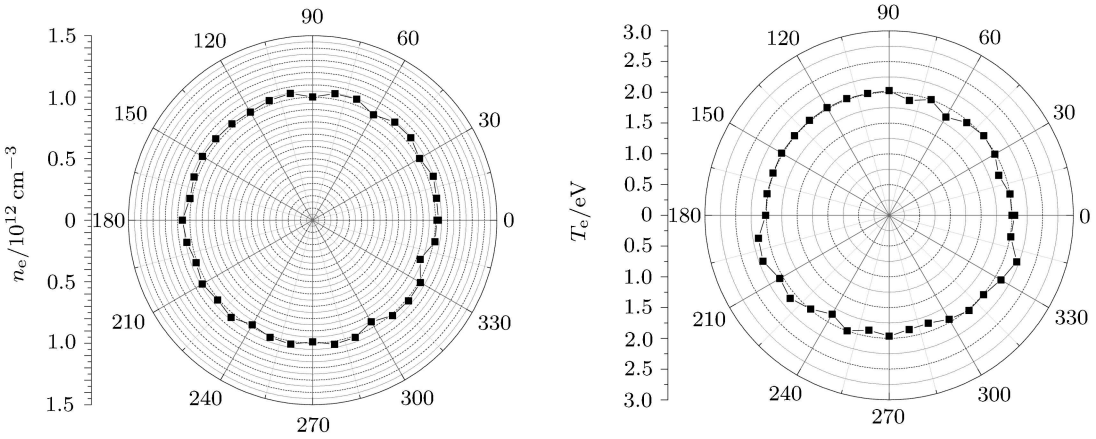


Fig.4. Spatial distributions of the electron densities and the electron temperatures of argon plasma in the azimuthal direction at 30 Pa, $P = 0.6$ kW, $R = 15$mm, and $z = 75$ mm.

Figure 5 shows the profiles of the electron density and temperature distributions along the axial direction. The plasma thickness is about 80 mm. At z from 16 mm to 30 mm, the electron density and electron temperature have a slight reduction fluctuating at 1.0×10^{12} cm^{-3} and 2 eV, respectively. And at z smaller than 16 mm, closer to the dielectric plate, the stronger the electrical field strength, the higher the electron temperature and the lower the electron density, because electromagnetic wave energy is strongly absorbed and transmitted[13] to the area at z larger than 16mm in the form of plasma wave including volume wave and hybrid wave. At z larger than 30 mm, the curves of electron density and the electron temperature sharply drop off and the plasma in this area is sustained mainly by the electrostatic oscillation.

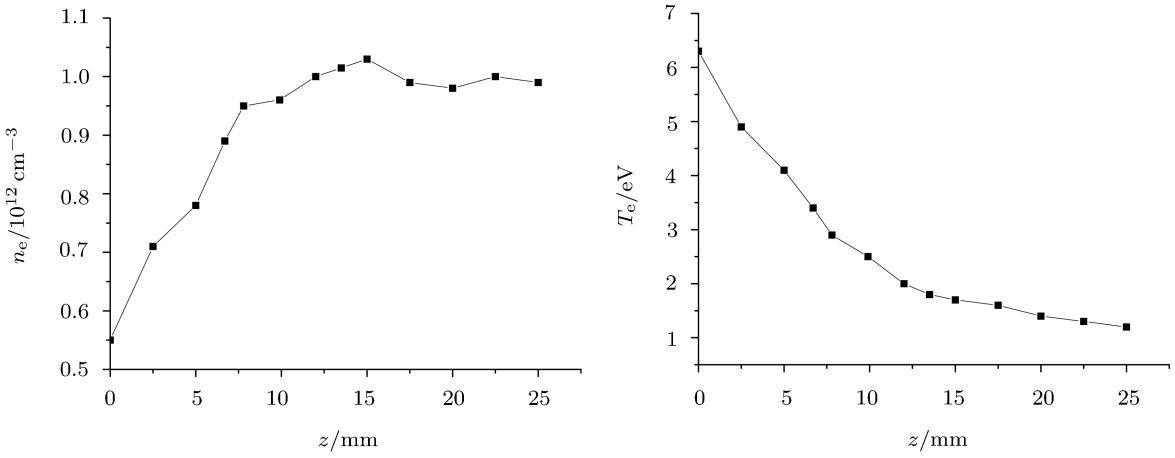


Fig.5. Spatial distributions of the electron densities and the electron temperatures of argon plasma in the axial direction at 30 Pa, $P = 0.6$ kW, $\theta = 4°$, and $R = 75$ mm.

We also measure the distributions of electron densities and electron temperatures in the radial direction using another movable probe. From Fig.6, we can see the maxima of electron density and the electron temperature and the strongest electrical field strength at a slot position ($r = 2$ cm). Away from the slot, as electromagnetic waves are strongly absorbed by the electrons and ions in the process of propagating around in the radial direction, the electron density and electron temperature decrease sharply. Specially, note that the curves of the electron distribution change smoothly at r closer to 15cm, which means that the electromagnetic waves propagating near the inner wall of the vacuum chamber are reflected by the wall and absorbed by plasma again.

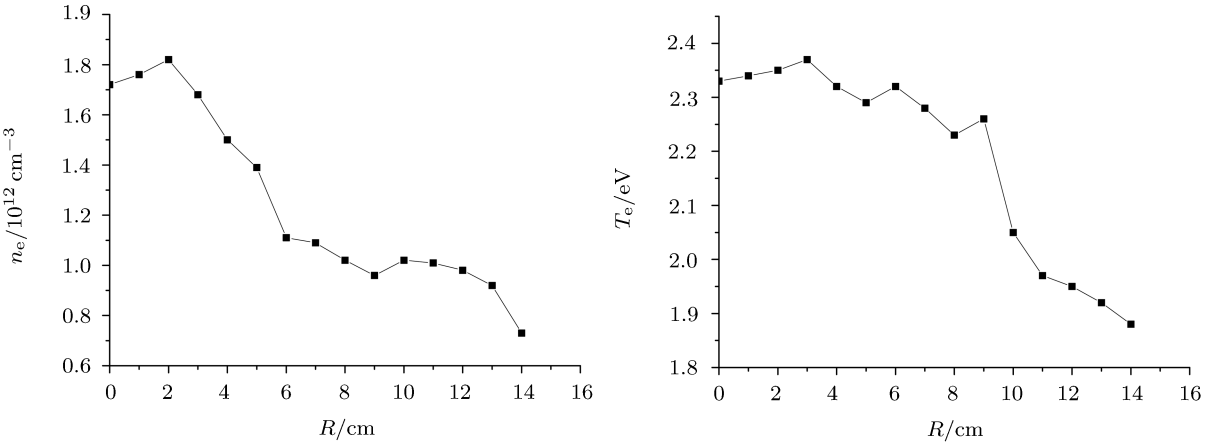


Fig.6. Spatial distributions of the electron densities and the electron temperatures of argon plasma in radial direction at 30 Pa, $P = 0.6$ kW, $\theta = 240°$, and $Z = 15$ mm.

4. Discussion and conclusions

The data given above are measured under the condition of running the experiment equipment quite well and under such a condition the critical matter is a balanced combination of the density and the uniformity of the plasma. In our experiment, when the gas pressure is higher (> 80 Pa), it is found that when the gas pressure is raised, the electron density initially increases and then decreases, while the temperature nonmonotonically decreases. At the same time, the uniformities of the electron density and temperature in azimuthal and radial directions turn worse with the rising of the gas pressure, and the plasma thickness along the axis direction decreases. Inversely, when the gas pressure is lower (< 20 Pa), the uniformities of the electron density and temperature in the azimuthal and radial directions become better, but the electron density drops off and the electron temperature increases.

From the above discussion, we can conclude that the large area, uniform and high density planar plasma can be obtained by increasing the incident microwave power, and choosing the appropriate gas pressure and shape of the coupling antenna. Surface wave can easily produce a large area and high density plasma without any external magnetic field applied, unlike an ECR plasma source. And it has some favourable advantages including no contamination from electrodes, a broad range of gas pressure for discharging and low temperature of electron, etc. All these advantages make surface wave plasma have future applications in industries especially in the high-technology field. But it has some disadvantages in the industry application, such as the nonuniformity in the radial direction.

On the basis of the present study, we will continue our work on how to optimize the coupling antenna, how to improve the uniformity in the azimuthal and radial directions, and how to extend the area and increase the plasma density.

References

[1] Komachi K and Kobayashi S 1989 *J. Microwave Power Electromagn. Energy* **24** 140

[2] Fang F, Liang R Q and Ou Q R 2001 *Thin Solid Films* **390** 197

[3] Korzec D, Werner F, Winter R and Engemann J 1996 *Plasma Sources Sci. Technol.* **5** 216

[4] Ghanashev I, Nagatsu M, Mortia S and sugai H 1998 *J. Vac. Sci. Technol.* A **16** 3

[5] Ghanashev I and Sugai H 2000 *Phys. Plasmas* **7** 3051
[6] Nagatsu M, Morita S, Ghanashev I, Ito A, Toyado N and Sugai H 2000 *J. Phys. D: Appl. Phys.* **33** 1143
[7] Sugai H, Ghanashev I and Nagatsu M 1998 *Plasma Sources Sci. Technol.* **7** 192
[8] Liu M H, Sugai H, Hu X W, Ishijima T, Jiang Z H, Li B and Dan M 2006 *Acta Phys. Sin.* **55** 5905 (in Chinese)
[9] Collin R E 1960 *Field Theory of Guided Waves* (New York: McGraw-Hill) Ch 11
[10] Ghanashev I, Nagatsu M and Sugai H 1997 *Japan. J. Appl. Phys.* **36** 337
[11] Raether H 1998 *Surface Plasmons* (New York: Springer)
[12] Zayats A V, Smolyaninov I I and Maraduin A A 2005 *Phys. Reports* **131** 408
[13] Sugai H, Chanashev I and Mizuna K 2000 *Appl. Phys. Lett.* **77** 3523