ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 20(4), 360-365 (2015) http://dx.doi.org/10.4283/JMAG.2015.20.4.360

Magnetic Flux Density Distributions and Discharge Characteristics of a Newly Designed Magnetized Inductively Coupled Plasma

Hee-Woon Cheong*

Department of Electrical and Computer Engineering, Seoul National University, Seoul 08826, Korea

(Received 9 November 2015, Received in final form 17 December 2015, Accepted 17 December 2015)

Spatial distributions of magnetic flux density in a newly designed magnetized inductively coupled plasma (M-ICP) etcher were investigated. Radial and axial magnetic flux densities as well as the magnetic flux density on the center of the substrate holder were controllable by placing multiple circular coils around the etcher properly. The plasma density non-uniformity in M-ICP (25 Gauss) can be reduced (1.4%) compared to that in ICP (16.7%) when the neutral gas pressure was 0.67 Pa and a right-hand circularly polarized wave (R-wave) can be propagated in to the etcher by making magnetic flux density increases both radially and axially from the center of the substrate holder.

Keywords : M-ICP, plasma density, plasma density non-uniformity, R-wave

1. Introduction

The increase in density of semiconductor device integration and the design rule shrinkage make the requirements of dry etchers more stringent. In this regard, a magnetized inductively coupled plasma (M-ICP) etcher [1] which generates high density plasma by applying a weak and controllable magnetic field to the conventional inductively coupled plasma (ICP) etcher [2-5] had been developed. Furthermore, it was confirmed that the performance of M-ICP etcher can be enhanced not only by improving the uniformity of plasma density [6] but also by inducing a right-hand circularly polarized wave (R-wave) [7].

In this paper, two-dimensional magnetic flux density distributions inside the M-ICP etcher were investigated when the magnetic flux density on the substrate holder varies from 4 to 25 Gauss. Plasma density and plasma density non-uniformity characteristics of ICP/M-ICP etcher were also studied according to the magnetic flux density on the center of the substrate holder and the neutral gas pressure. Furthermore, the time-varying magnetic field (B_z) inside the ICP/M-ICP etcher was measured in order to demonstrate that R-wave propagation depends critically on the axial magnetic flux density distribution from the center of the substrate holder.

2. Experimental Setup

Figure 1 shows the schematic of the ICP/M-ICP etcher. The etcher is powered by two rf generators. One is the source power generator which supplies 27.12 MHz rf

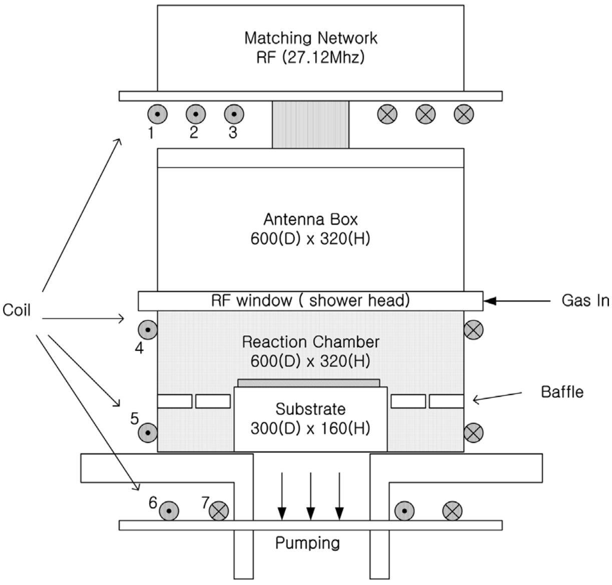


Fig. 1. Schematic of M-ICP etcher with seven circular coils (coil 1, 2, 3, 6, 7 : 1400 turns, coil 4, 5 : 1000 turns).

---

*Corresponding author: Tel: +82-2-880-9554
Fax: +82-2-872-3005, e-mail: cheong1982@empas.com

power to a two-turn planar antenna and the other is the bias power generator which supplies 2 MHz and/or 13.56 MHz rf power to the substrate holder whose diameter is 300 mm. A chiller using ethylene glycol as a refrigerant maintains the substrate holder temperature at 15°C during the experiments. The etcher is pumped by a 3500 l/s turbomolecular pump and the base pressure for the experiment was 0.004 Pa. Discharge gas, whose flow rate is regulated by the mass flow controller (MFC), flows into the etcher through a gas inlet and the resultant neutral gas pressure is measured by the hot-filament ionization gauge and baratron gauge (Granville-Phillips® 392 Micro-Ion® Plus). A 20 mm-thick rf window made of alumina-based ceramic is employed to allow the power transfer from antenna to plasma.

Meanwhile, the magnetic fields are generated using seven coils. Firstly, three coaxial coils are placed on top of antenna box. The number of turns of each copper coil is 1400. Secondly, two coaxial coils are located at the bottom of the frame shown in the figure and the number of turns of each coil is also 1400. Lastly, two coils are located at upper and lower sides of the chamber. The number of turns of each coil is 1000.

The two-dimensional magnetic flux density distributions inside the etcher were simulated with the finite element method magnetic (FEMM) field calculation software when the magnetic flux density on the substrate holder were varied from 4 to 25 Gauss. The experimental measurement of the radial and axial magnetic flux density distributions from the center of the substrate holder were also performed using tesla meter (KANETEC TM-601).

Meanwhile, the radial plasma density distributions inside the ICP/M-ICP etcher were measured using a dual Langmuir probe (DLP) [8]. The vertical height of DLP from the substrate holder was 10 mm. The radial distance of the probe tips from the center of the substrate holder was varied from 0 to 160 mm at 20 mm intervals. The plasma density non-uniformity was also calculated using:

$$\text{Non-uniformity (\%)} = \frac{(\text{maximum of plasma density} - \text{minimum of plasma density})/2}{\text{average of plasma density}}. \quad (1)$$

The spatial distributions of the B_z of R-wave inside the ICP/M-ICP etcher were also measured using differential magnetic probe (also known as B-dot probe), which is connected directly to a center-tapped transformer to compensate for its alternating current (ac) coupling to electrostatic potential fluctuations [9]. B_z is determined by the number of turns of coil (three turns in our experiment) and the coil area (the inner radius of the coil and the coil area are 1.5 mm and 2.25π mm^2, respectively, in our experiment). The vertical height of B-dot probe from the substrate holder was varied from 10 to 170 mm at around 10 mm internals.

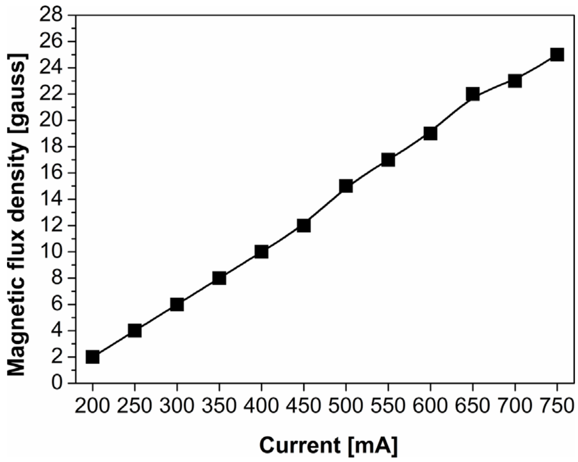
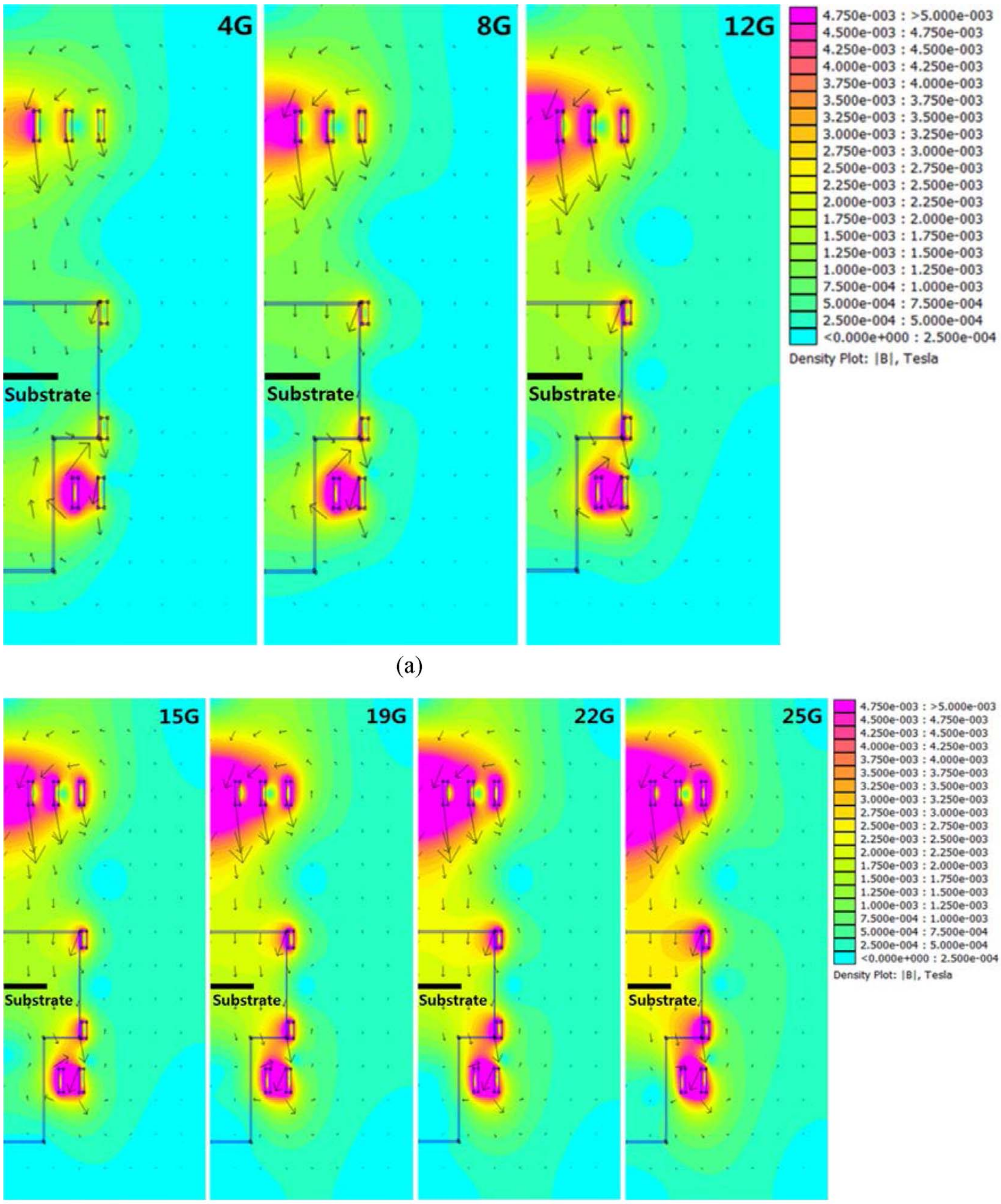


Fig. 2. Magnetic flux density on the center of the substrate holder according to the electric current supplied to coils 1-6 while the fixed electric current was supplied to coil 7.

3. Results and Discussion

Figure 2 shows the magnetic flux density on the center of the substrate holder according to the electric currents supplied to coils 1-6 while the fixed electric current value of −750 mA was supplied to coil 7. The magnetic flux density on the center of the substrate holder where the Si wafer is placed on is controllable from 0 to 25 Gauss when the electric current of coils 1-6 increases from 0 to 750 mA. Meanwhile, the radial magnetic flux density distributions inside the etcher should be considered carefully because they deeply affect the plasma density non-uniformity [6].

Figure 3 shows two-dimensional magnetic flux density distributions inside the M-ICP etcher. The magnetic flux density vector is perpendicular to the substrate holder and the magnetic flux density increases when the distance from the center of the substrate holder increases radially. It is more clear from Fig. 4, which depicts the radial magnetic flux density distributions according to the electric currents supplied to coils 1-6 while the fixed electric current value of −750 mA was supplied to coil 7, that the magnetic flux density increases radially no matter what the magnetic flux density on the center of the substrate holder is. Based on the fact that the distributions shown in Fig. 4 suppress the flute instability and reduce the plasma density non-uniformity [6], it can be expected that the newly designed M-ICP etcher may exhibit low plasma density non-uniformity regardless of the value of



(a)

(b)

Fig. 3. (Color online) Two-dimensional magnetic flux density distributions when the magnetic flux density on the center of the substrate is (a) 4 (250 mA to coil 1-6), 8 (350 mA to coil 1-6), 12 Gauss (450 mA to coil 1-6) and (b) 15 (500 mA to coil 1-6), 19 (600 mA to coil 1-6), 22 (650 mA to coil 1-6), 25 Gauss (750 mA to coil 1-6).

the magnetic flux density on the center of the substrate.

Figure 5, Figure 6 and Figure 7 show plasma density, radial plasma density distributions and the calculated radial plasma density non-uniformity inside the ICP/M-ICP etcher, respectively, according to the magnetic flux density on the center of the substrate holder and the neutral gas pressure. In this experiment, the source power was fixed at 1000 W and Ar flow rate was fixed at 20 sccm, whereas the magnetic flux density at the center of the substrate holder was varied from 0 to 25 Gauss and the neutral gas pressure was varied from 0.13 to 2.67 Pa. The substrate holder was grounded. The plasma density increases when the magnetic flux density on the center of the substrate holder and/or the neutral gas pressure increases. It is notable that the radial plasma density non-uniformity of M-ICP, no matter what the magnetic flux

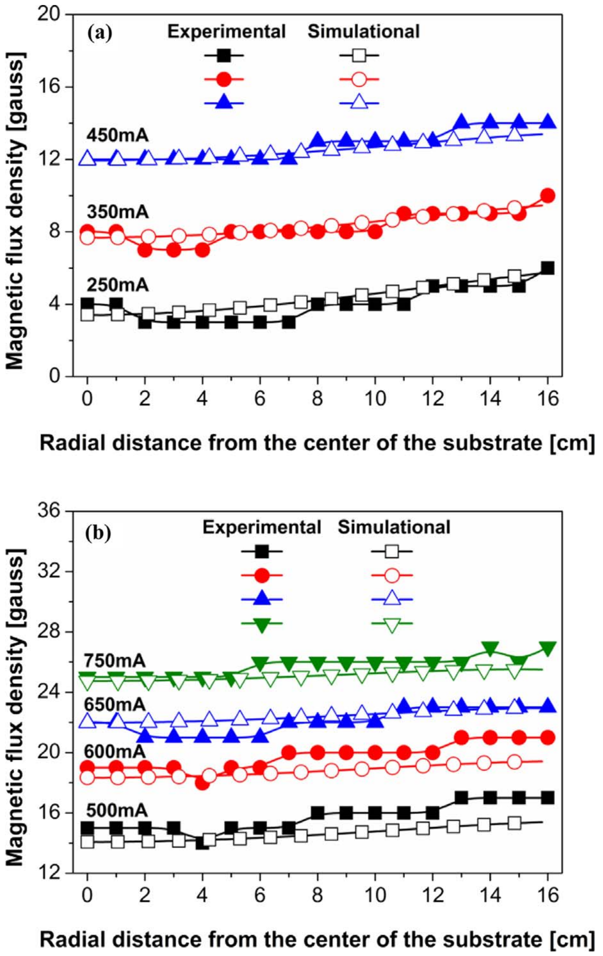


Fig. 4. (Color online) Radial magnetic flux density distributions when the magnetic flux density on the center of the substrate is (a) 4 (250 mA to coil 1-6), 8 (350 mA to coil 1-6), 12 Gauss (450 mA to coil 1-6) and (b) 15 (500 mA to coil 1-6), 19 (600 mA to coil 1-6), 22 (650 mA to coil 1-6), 25 Gauss (750 mA to coil 1-6).

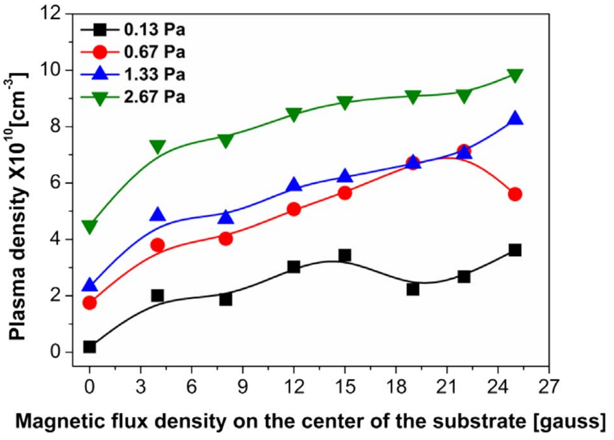


Fig. 5. (Color online) Plasma density according to the magnetic flux density on the center of the substrate holder and the neutral gas pressure.

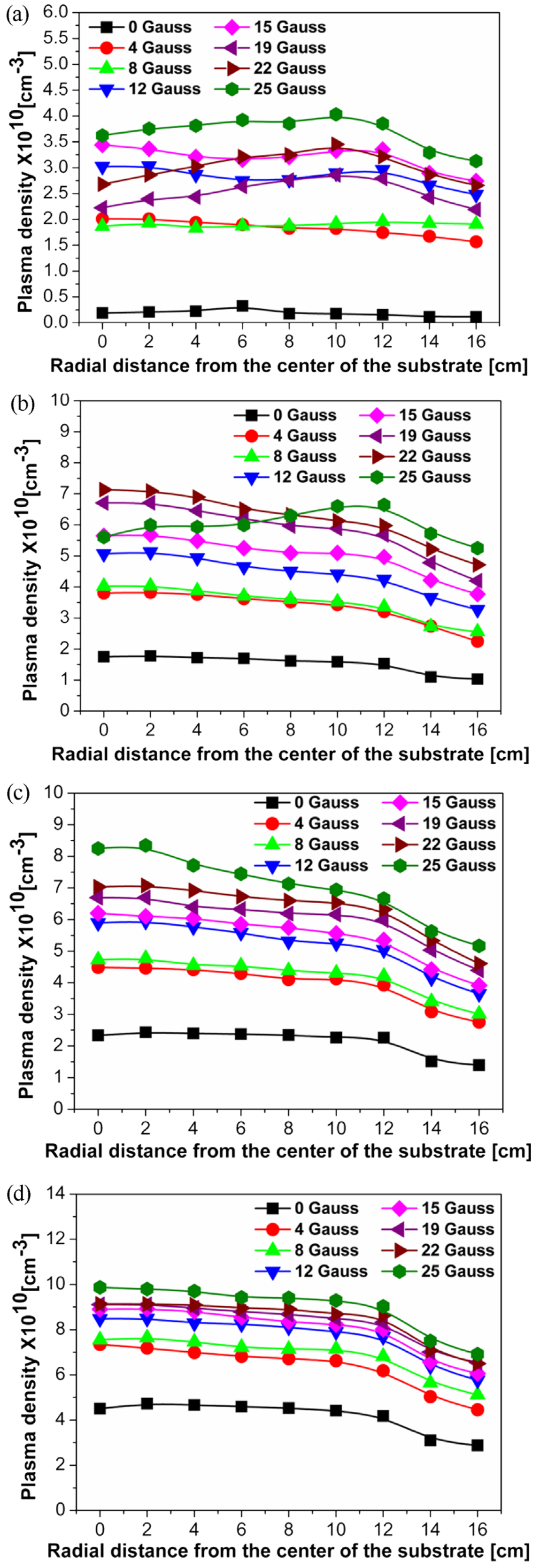


Fig. 6. (Color online) Radial plasma density distributions when the neutral gas pressure is (a) 0.13 Pa (b) 0.67 Pa (c) 1.33 Pa and (d) 2.67 Pa.

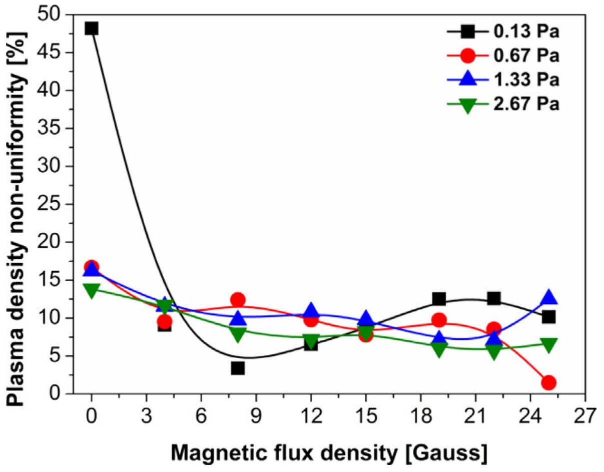


Fig. 7. (Color online) Plasma density non-uniformity according to the magnetic flux density on the center of the substrate holder and the neutral gas pressure.

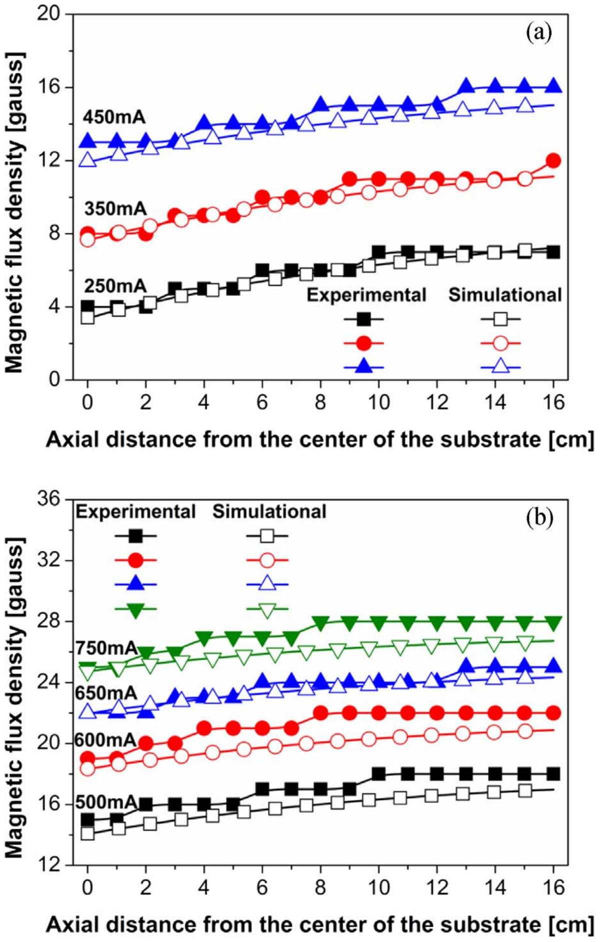


Fig. 8. (Color online) Axial magnetic flux density distributions when the magnetic flux density on the center of the substrate is (a) 4 (250 mA to coil 1-6), 8 (350 mA to coil 1-6), 12 Gauss (450 mA to coil 1-6) and (b) 15 (500 mA to coil 1-6), 19 (600 mA to coil 1-6), 22 (650 mA to coil 1-6), 25 Gauss (750 mA to coil 1-6).

density on the center of the substrate holder is, is lower than that of ICP. More importantly, the lower the neutral gas pressure is, the more remarkable the uniformity improvement effect becomes. Especially, the plasma density non-uniformity was less than 2% (1.4%) when the magnetic flux density on the center of the substrate holder and the neutral gas pressure are 25 Gauss and 0.67 Pa, respectively.

Figure 8 shows the axial magnetic flux density distributions according to the electric currents supplied to coils 1-6 while the fixed electric current value of –750 mA was supplied to coil 7. The axial magnetic flux density also increases no matter what the magnetic flux density on the center of the substrate holder is, which is very important for R-wave propagation in M-ICP etcher. R-wave is generated and propagated along the magnetic field if the dispersion relation is satisfied ($\omega < \omega_{ce}$) [10]. Figure 9 shows the axial distributions of B_z inside the ICP/M-ICP etcher. In this experiment, two types of magnetic flux density distributions were chosen. One is M-ICP-A, whose magnetic flux density decreases both radially and axially from the center of the substrate holder. The electric current supplied to all coils 1-7 was 200 mA. The other is M-ICP-V, whose magnetic flux density increases both radially and axially from the center of the substrate holder. The electric current supplied to coils 1-6 was 350 mA while the one supplied to coil 7 was –750 mA. The magnetic flux density on the substrate for both cases was 8 Gauss. The Ar gas flow was 60 sccm and the neutral gas pressure was 0.67 Pa. The source power and the bias power were 1000 W and 0 W, respectively. The B_z is limited to areas near the rf window and decays rapidly as it penetrates into the plasma within the skin depth in ICP or even in M-ICP-A because the

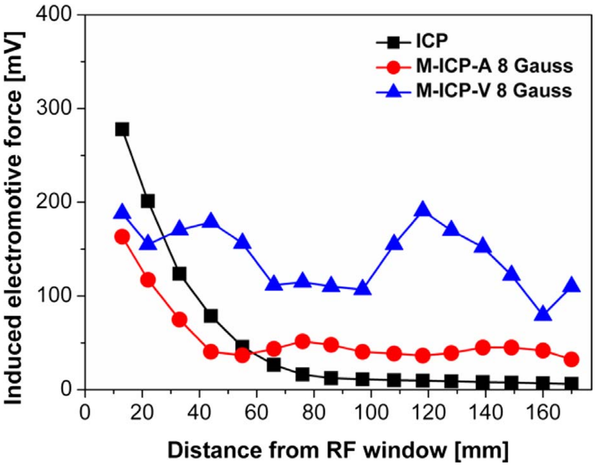


Fig. 9. (Color online) R-wave propagation in ICP, M-ICP-A (8 Gauss) and M-ICP-V (8 Gauss).

dispersion relation is not satisfied in M-ICP-A, whereas the one is not limited within a skin depth and the energy can be transferred deeper into the plasma in M-ICP-V because the dispersion relation is satisfied and R-wave can be propagated into the etcher in M-ICP-V case.

4. Conclusions

Magnetic flux density distributions inside the newly designed M-ICP etcher were investigated. It was confirmed that the magnetic flux density increased radially from the center of the substrate holder, no matter what the magnetic flux density on the center of the substrate holder was. As a result, the flute instability could be effectively suppressed and plasma density non-uniformity in M-ICP (25 Gauss) was significantly reduced (1.4%) compared to that in ICP (16.7%) when the neutral gas pressure was 0.67 Pa. The magnetic flux density also increased axially from the center of the substrate holder no matter what the magnetic flux density on the center of the substrate holder was under the developed system. In doing so, R-wave can be propagated into the M-ICP etcher, which results in the electron heating and the increase in plasma density. After all, controlling the magnetic flux density on the center of the substrate, radial and axial magnetic flux density distributions simultaneously with the proper placement of multiple coils is great advantage of the newly designed M-ICP etcher.

References

[1] H. J. Lee, J. H. Kim, K. W. Whang, and J. H. Joo, J. Vac. Sci. Technol. A **14**, 1007 (1996).
[2] S. Imai, J. Vac. Sci. Technol. B **26**, 2008 (2008).
[3] B. Wu, A. Kumar, and S. Pamarthy, J. Appl. Phys. **108**, 051101 (2010).
[4] F. Karouta, J. Phys. D: Appl. Phys. **47**, 233501 (2014).
[5] A. C. Westerheim, A. H. Labun, J. H. Dubash, J. C. Arnold, and H. H. Sawin, J. Vac. Sci. Technol. A **13**, 853 (1995).
[6] W. H. Lee, H. W. Cheong, J. W. Kim, and K. W. Whang, Plasma Sources Sci. Technol. **24**, 065012 (2015).
[7] H. J. Lee, I. D. Yang, and K. W. Whang, Plasma Sources Sci. Technol. **5**, 383 (1996).
[8] Y. Sung, H. B. Lim, and R. S. Houk, J. Anal. At. Spectrom **17**, 565 (2002).
[9] C. M. Franck, O. Grulke, and T. Klinger, Rev. Sci. Instrum. **73**, 3768 (2002).
[10] M. A. Lieberman and A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, John Wiley & Sons, New Jersey (2005).