Flat cutoff probe for real-time electron density measurement in industrial plasma processing

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Abstract
The microwave cutoff probe (CP) is an accurate diagnostic technique to measure absolute electron density even in processing gas plasmas. Because this technique needs the installation of two probe tips and a probe body in the plasma chamber, it may cause plasma perturbation in semiconductor plasma processing; this may increase the uncertainty of the measured value. In this work, a flat CP, which is embedded in the substrate chuck or chamber wall, is proposed to measure electron density without plasma perturbation and to monitor processing plasma in real-time. We first evaluated the performance of various types of flat CPs, such as the point CP, ring CP, and bar cutoff probe (BCP), through electromagnetic (EM) field simulation. The BCP showed better performance with clearer cut-off signal characteristics and minimization of noise signals compared with the other probe types. Therefore, we focused on the characteristics of the BCP through experiments and/or EM simulations and concluded the followings: (i) the measured electron densities of the BCP agree well with those of the conventional CP; (ii) the BCP measures the plasma density near the plasma-sheath boundary layer, which is very closely adjacent to the chamber wall or wafer; (iii) it was demonstrated for the first time that the plasma density can be measured, even though the processing wafers such as undoped silicon, P type silicon, amorphous carbon, or amorphous carbon/SiO₂ patterned wafers were placed on the flat CP; and (iv) we performed real-time measurements of the electron density using the BCP covered with the wafers in plasmas with various process gases, such as Ar, NF₃, and O₂. These results indicate that the chuck-embed-type or wall-type flat CP can be used as a real-time electron density measurement (monitoring) tool during industrial plasma processing, such as during etching, deposition, sputtering or implantation, and the chuck-embed-type flat CP can measure the plasma density impinging on the wafer in real-time without stopping the processing.

Keywords: plasma diagnostic, plasma metrology, microwave probe, industrial plasma, plasma physics, processing plasma monitoring

1. Introduction

Plasma diagnostics or monitoring has become important in industrial semiconductor and display processing, such as etching and deposition, because fine and feedback controls of the plasma based on plasma parameter measurement are strongly needed as the line width of devices continue to shrink. There are various plasma parameters, such as electron temperature (Tₑ), electron density (nₑ), electron energy probability...
function (EEPF), plasma potential, and so on. Among them, the electron density is a primary parameter to be measured or monitored in plasma processing because it can significantly alter the discharge property, and the processing result is predominantly governed by \( n_e \) [1–10].

Thus, various diagnostic techniques for measuring \( n_e \) have been studied. Typical measurement methods of \( n_e \) include the use of electrostatic probes [11], optical diagnostics [12], and microwave probes [13–17]. Electrostatic probes, such as the Langmuir probe, provide various plasma parameters (plasma potential, floating potential, \( T_e \), \( n_e \), ion density, etc) [18, 19]. When the Langmuir probe is applied to the processing gas plasmas, however, it has a limitation because of the etching and deposition of the probe tip. Optical diagnostics, such as the optical emission spectrometer [20], also have limitations because of the associated difficulty in measuring the absolute value of the electron density under complex gas-mixture conditions.

Microwave probe methods have been considered as a promising diagnostic technique in plasma processing because they can measure electron density even under the circumstance of probe tip deposition by a polymer or other dielectric materials [21–24]. There are several types of diagnostic tools based on the microwave method, such as the hairpin [17], multipole resonance [16, 25], cutoff [13], and absorption probes [15]. The hairpin probe obtains \( n_e \) by measuring the difference between the vacuum frequency \( f_0 \) (Hz) and plasma frequency \( f_p \) (Hz), as given by

\[
\Delta f = f_0 - f_p
\]

[26]. The absorption probe consists of a coaxial cable, an antenna, and a dielectric tube and \( n_e \) is obtained by using the resonant absorption frequency \( f_{\text{abs}} \) (GHz), as given by

\[
\omega = \sqrt{\varepsilon_0 \mu_0 \mu_r k^2 - \omega_p^2}
\]

[31]. Among the solutions to avoid plasma perturbation is embedding the microwave probes in the wall or chuck using a non-invasive method. To realize this, wall-type curling [32–35], planar multipole resonance [36], impedance probe [37, 38], and planer CPs [39] have been studied to measure \( n_e \) without intrusive probe structures in the plasma volume. Regarding these flat microwave probe studies, there currently are some open issues such as which plasma region is measured from the wall-type probe because the microwave can penetrate into the plasma at a scale of the skin depth, and if the microwave probe can measure plasma density even under the wafer. These are critically important during recent and next-generation plasma processing because, as the line width of the device shrinks and complex device structures with three-dimensional architectures are developed, the fine control techniques of the plasma from precise plasma monitoring are highly needed during plasma processing. Real-time plasma monitoring on the wafer plane is essential because information regarding the plasma parameters impinging on the wafer surface directly affects the processing result, yield, and device quality. However, a conventional diagnostic tool is limited to an ’on-wafer type sensor’ that should be placed on the chuck instead of the wafer after stopping the plasma processing, when the processing fails, or when an abnormality is found after wafer infection. This is a very time-consuming method and it is not a real-time plasma diagnostic tool in the true sense. This is basically because most of the plasma diagnostic tools cannot measure plasma parameters under the wafer (in the embedded chuck). Microwave probes can solve this problem because a microwave signal can be transmitted into the plasma across the wafer.

In this study, we developed a bar flat cutoff probe (BCP) embedded in the surface of the chamber wall and substrate chuck to measure \( n_e \). Characteristics of the BCP were evaluated through both EM field simulations and experiments. These show that the flat CP measures plasma density near the plasma-sheath boundary layer, which is very closely adjacent to the chamber wall or wafer. It was demonstrated that the plasma density can be measured, even though various types of wafers are placed on the BCP under processing plasma conditions. To the best of our knowledge, this paper is the first to
study on the possibility of plasma diagnostics under a wafer using microwave probes or other plasma diagnostic methods.

2. Probe characteristics

2.1. EM simulation

The simulation is performed using a commercially available EM wave simulation tool that is a direct numerical solver for the full Maxwell equations at the given boundary conditions (CST Microwave Studio). This simulation is known to provide a very accurate result regardless of the frequency limitation, as there are few assumptions when solving the Maxwell equations \([40-44]\). In EM simulations, the boundary condition was designed as open boundary both to exclude other effects, such as reflected wave or cavity resonance by conductor walls, and to see only the characteristics of the probe itself. We performed calculations assuming a uniformly or non-uniformly distributed dielectric plasma medium, in which bulk plasma was treated as an immobile dispersive dielectric material using the Drude model \([45]\). The electron temperature is fixed at 2 eV (confirmed by Langmuir probe measurement) and the electron-neutral collision frequency \((\nu_{\text{en}})\) is calculated based on Ar plasma. The sheath between the probe and the plasma is modeled as a vacuum layer of the unity dielectric constant and the sheath width is calculated from the Child law sheath \(s = \frac{\sqrt{2}}{3} \lambda_{De} \left(\frac{2V_s}{e}\right)^{1/2} \approx 0.21 \text{ mm} \) at \(T_e = 2 \text{ eV}\), where \(\lambda_{De}\) is the electron Debye length \([1]\). During the simulations, all conductors (the chamber wall and antenna) are considered perfect electrical conductors and the insulator is teflon \((\varepsilon = 2.1)\).

2.2. Results and discussion

To compare the \(S_{21}\) spectra characteristics between the BCP and CP, we conduct the EM field simulations under the same plasma conditions. Figures 1(a) and (b) show the structures of the conventional CP and BCP, and (c) and (d) show the \(S_{21}\) spectrum at the fixed input plasma frequencies \(f_{\text{p,input}} = 0.5 \text{ GHz}\) and 1 GHz, respectively. The gas pressure is fixed at 20 mTorr. The CP is modeled with a tip height of 5 mm, a tip radius of 0.26 mm, and a gap distance of 5 mm, and 50 \(\Omega\) coaxial cable condition. In the BCP model, the distance between the antennas is 8 mm, the thickness of the antenna conductor is 3 mm, the antenna is 20 mm in length, and the internal injector is 1 mm in thickness (see also figure 2). As can be seen in the \(S_{21}\) spectrum shown in figure 1, the CP and BCP show a similar spectral shape termed an N-shape, and the minimum peak of the \(S_{21}\) frequency corresponding to the cut-off frequency matches well with the input plasma frequency calculated from the input \(n_e\). A good agreement between the input plasma frequency and the

Figure 1. Comparison of modeled transmission spectra from the CP and BCP at two conditions with a plasma frequency of (a) 0.5 GHz and (b) 1 GHz at a pressure of 20 mTorr in EM simulation.
obtained electron plasma frequency means that the BCP can measure $n_e$ in the same manner as that of the CP.

Figures 2(a)–(c) shows the shape of the point flat cutoff probe (PCP), which removes the protruding part of the CP; the shape of the ring flat cutoff probe (RCP); and the BCP, which is a structure that can increase coupling between antennas. Figures 2(d) and (e) shows the transmission spectra in a vacuum and plasma with a plasma frequency of 2 GHz at a pressure of Ar 20 mTorr against the flat CP designs. As shown in figure 2(d), the PCP shows the characteristics of a typical capacitor in $S_{21}$, which increases the level of the transmission signal with an increasing frequency under a vacuum condition. For the RCP, the vacuum $S_{21}$ spectrum shows minimum transmission peaks that are thought to be generated by the resonance of the probe structure, which is undesirable in plasma measurement. For the BCP, however, such minimum transmission peaks are not visible. Figure 2(e) shows the $S_{21}$ spectrum when the input plasma frequency is 2 GHz. The minimum frequency from the PCP corresponds to the input plasma frequency indicating good agreement for the electron density between them. For the RCP, two minimum peaks appear in the plasma condition: a first minimum peak corresponding to the input plasma frequency and a second minimum peak corresponding to 2.7 GHz derived from the vacuum $S_{21}$ spectrum. Because the cut-off probe measurement uses a minimum peak in the $S_{21}$ spectra to obtain the cut-off frequency (plasma frequency), it is likely that the minimum peak derived from the vacuum $S_{21}$ spectra can result in confusion during plasma measurement. From our results, the BCP showed better performance than that of the other CPs (PCP and RCP) because it has a higher signal intensity compared to that of the PCP and does not generate minimum peaks by the probe geometry resonance compared to those of the RCP.

Figures 3(a) and (b) shows the $S_{21}$ spectrum depending on the gas pressures for the BCP at a fixed input plasma frequency of 0.5 and 1 GHz, respectively. In low-pressure plasma between 50 and 500 mTorr, $S_{21}$ shows sharp minimum peak characteristics. However, as the pressure increases above 500 mTorr, the minimum peak broadens and the shape of the $S_{21}$ spectra appears to be similar to that of the vacuum $S_{21}$ of BCP as shown in figure 2(d). This result is because the
wave cut-off phenomenon does not properly occur when the electron-neutral collision frequency is near or higher than the driving frequency [1, 46]. Thus, the measurable pressure range of BCP is approximately up to a few Torr when we use $S_{21}$ spectra to obtain the cutoff frequency, but this pressure limitation can be solved if the phase-resolved cut-off method is used [42, 43].

Normally, the sheath is assumed as the dielectric material with unity dielectric constant in plasma circuit model and EM simulation [1, 28]. In some cases, however, the dielectric constant may have slightly different value compared to the unit value. For example, the gas dielectric constant is dependent on driving frequency and temperature [47, 48]. Thus, it is needed to identify the BCP measurement characteristics in situations in which the dielectric constant of the sheath changes. Also, in the condition of the thick sheath due to the high voltage biased system, such as RF biased inductively coupled plasma [49, 50] or capacitively coupled plasma, the BCP characteristics should be identified. To study these, the following simulations were performed: figure 4(a) shows the $S_{21}$ spectrum depending on sheath dielectric constant ($\varepsilon_s$) from 0.5 to 1.5, and (b) shows the transmittance spectrum depending sheath width ($d_s$) from 0.1 to 1 mm for the BCP at a fixed input plasma frequency 2 GHz and 20 mTorr of gas pressure, respectively. The changes in the sheath dielectric constant and sheath width do not affect the cutoff frequency and thus, the measured plasma density is not affected in these conditions. Thus, this probe can be also applied in plasma etching, deposition, and sputtering where the sheath voltage is high.

3. BCP experiment

3.1. Experimental setup

Figure 5 shows the chamber and measurement system setup for the experimental study. Two BCPs (wall-embed-type BCP...
1 and chuck-embed-type BCP 2) and a CP were used to measure $n_e$. The BCP 1 was inserted into the chamber sidewall port and placed on the same plane as the chamber wall, while the BCP 2 was embedded in the chuck. The BCPs had an 8 mm distance between the two antennas and an antenna length of 20 mm. The antenna material was copper, and the insulator was Teflon. The CP was placed 20 mm from the BCP 2 surface. An inductively coupled plasma (ICP) chamber was used in this experiment [51]. A 13.56 MHz power supply was delivered to the one-turn planar-type antenna through the L-type auto matcher. The input power during the experiment was 300–900 W. The gas used in the experiment was Ar; in addition, NF$_3$ and O$_2$ gas were used. A rotary vane pump and turbo molecular pump were used to maintain the base pressure below 3 × 10$^{-6}$ Torr. The experimental pressure ranged from 20 to 200 mTorr, as measured using a capacitive manometer gauge, which is calibrated with a standard pressure gauge at the Korea Research Institute of Standards and Science (KRISS). The probes were connected to a network analyzer (Agilent N5245A) via coaxial cables to obtain the $S_{21}$ spectrum from each probe. An RF switching module (NI PXI-2596) was used for simultaneous measurements of the BCP 2 and CP, and for real-time measurements, the RF switching module and network analyzer were programmed to record measurements every 5 s, using LabVIEW program.

### 3.2. Results and discussion

Figure 6 shows the $S_{21}$ spectra from the BCP and CP at an input power of 400 W and gas pressure of 20 mTorr. The BCP measured $S_{21}$ spectra from the wall of the chamber (BCP 1), while the CP measured $S_{21}$ spectra at 1.5 mm distance from BCP 1. The experimental result shows that both probes measure the N-shaped signal and minimum peak (cut-off frequency). As power increases, both the CP and BCP confirm that the minimum peak moves to a high frequency (see figure 8). When we monitored the $S_{21}$ spectra at the BCP 1 as the CP moves from the radial chamber center to the edge region of 1.5 mm distance from the BCP 1, the measured $S_{21}$ spectra at the BCP 1 did not change indicating non-perturbing by the CP in this experimental condition.

![Figure 5. Schematics of the experimental setup and measurement system.](image)

We can also see that the cut-off frequency measured by the CP is approximately 1.6 times higher than that measured by the BCP. This implies that the BCP at the wall measures plasma density within 1.5 mm distance from the chamber wall.

To understand in-depth which plasma region is measured by the BCP, we investigated spatially resolved radial measurements of $n_e$, $T_e$, and EEPF and an EM simulation were also performed. Figure 7(a) shows the radial plasma density profile measured by the CP from 1.5 to 132 mm from the wall and (b) shows the radial EEPFs measured by a single Langmuir probe from 2 to 130 mm from the wall. Detailed information regarding the Langmuir probe structure and RF compensation can be found in [51, 52]. The radial plasma density profile has a maximum density at the center of the chamber and the density decreases as it nears the chamber wall. The $T_e$ obtained from the Langmuir probe measurement is 2.82 eV and the plasma potential is 13.62 V. Figure 7(b) shows that the measured EEPFs have an identical shape when the total electron energy (kinetic energy + potential energy) is considered. This identical EEPF is direct evidence that our experimental conditions are in a non-local electron kinetics regime where the Boltzmann relation is valid [52–54].

Figure 7(c) shows the estimated (using Boltzmann relation) and measured position-dependent electron densities using CP and Langmuir probe measurements at 20 mTorr of pressure and 400 W of input power. The solid black line represents the electron density calculated from the Boltzmann relation; the red square symbol represents the CP measurement measured between 1.5 and 8 mm from the wall; and the blue star symbol represents the BCP measurement. The Boltzmann relation is given as follows: $n_e = n_{e0} \exp \left( \frac{e\phi}{kT_e} \right)$, where $n_{e0}$, $k$, and $\phi$ are the electron density at the position with a maximum plasma potential of $\phi = 0$, Boltzmann constant, and plasma potential, respectively [55]; $n_{e0}$ is the maximum electron density measured by the CP, and $T_e$ and $\phi$ are obtained from the results of the Langmuir probe. From the spatial profile of the electron density obtained from the Boltzmann relation, EM simulations including the electron density gradient were possible. The EM
simulation was performed using an electron density gradient structure (figure 7(d)) from the Boltzmann relation and the measured \( n_e \). For this simulation, an electron density gradient structure with 60 layers was established for the simulation modeling. For the 60 layers, the entered density of the first layer directly above the sheath was the density measured by the BCP, and the \( n_e \) from the Boltzmann relation was entered from the 2nd to 48th layers. For the 49th to 60th layers, the measured \( n_e \) from the CP was entered. Figure 7(e) presents a comparison of the \( S_{21} \) spectra results between the measured \( S_{21} \) spectra from BCP1 and the EM simulation with the plasma layer model under a 400 W and 20 mTorr condition.

Figures 8(a) and (b) show the radial \( n_e \) measured using the CP at 20 mTorr of pressure and 200 and 800 W of input power and the \( n_e \) measured using the BCP and the estimated \( n_e \) using the Boltzmann relation. Figures 8(c) and (d) compare the experimental results with the EM simulations. The solid black line represents the \( S_{21} \) spectra of the BCP via the experiment (top figure) and EM simulation (bottom figure), and the red dashed line represents the \( S_{21} \) spectra of the CP measured at 1.5 mm from the wall. In the case of EM simulation, the plasma layer modeling was performed under 200 and 800 W conditions in the same manner as that shown in figures 8(c) and (d). The measured \( T_e \) values at 200 and 800 W were 2.85 and 2.74 eV, and the measured plasma potentials 13.62 and 13.87 V, respectively. The experimental results show that the \( S_{21} \) spectrum measured by the CP and BCP is \( N \)-shaped, and the minimum peak can...
move to a high frequency when the power ($P_{RF}$) is increased from 200 to 800 W. Similarly, with the 400 W results, the cut-off frequency measured by the CP is higher than that measured by the BCP. The experimental and simulation results show that the minimum peak frequencies match under 200 W and 800 W power conditions. As with the 400 W result, the calculated $S_{21}$ spectra of the plasma layer model show that the plasma layer corresponding to the minimum peak is immediately above the sheath surface, and it confirms that the $n_e$ measured by the BCP measures the plasma near the plasma-sheath boundary.

Figure 9 shows the determination of the measurement uncertainty for the BCP. The uncertainty of the cutoff frequency, $\Delta f_c$, is a result of the broadening of signals in the frequency spectrum. For the determination of the frequency interval $\Delta f_c = f_1 - f_2$, 10% of the amplitude between the cut-off frequency and the baseline was considered [56]. For most of our measurements using the BCP, the relative standard uncertainty

Figure 8. Estimated electron density by Boltzmann relation under input power conditions of (a) 200 W and (b) 800 W and measured $S_{21}$ spectra from BCP 1 and calculated by EM simulation at (c) 200 W and (d) 800 W.

Figure 9. Calculation of the measurement uncertainty of the BCP under a 400 W and 20 mTorr condition.
The relative standard uncertainty was ±1.8% at 200 W, ±1.9% at 400 W, and ±1.4% at 800 W of input power.

We measured \( n_e \) with various types of wafers placed on the BCP to observe if the BCP is available during the process, which will be highly important in current and next generation plasma processing. Figure 10(a) shows the \( S_{21} \) spectra without a wafer on top of the BCP, while figures 10(b)–(e) shows the \( S_{21} \) spectra for cases where undoped Si, P-type Si, and amorphous carbon layer (ACL)/Si wafers and patterned wafers are placed on top of the BCP 2 at 300, 600, and 900 W input powers and a pressure of 200 mTorr. The detailed information regarding the wafers is shown in figure 10 and table 1. Figure 10(f) shows a graph of the \( n_e \) calculated from the \( S_{21} \) spectra shown in figures 10(a)–(e). In all wafer conditions, the experimental result shows that BCP 2 measures the \( N \)-shaped signal and minimum peak, and the frequency of the minimum peak increases as the input power increases from 300 to 900 W in the transmission spectrum. This means that the electron density measurements are possible even though the wafer is placed on the probe. Figure 10(b), in the case of undoped Si, the \( S_{21} \) spectra are not significantly

| Wafer                        | Resistivity                  | Thickness                  |
|------------------------------|------------------------------|----------------------------|
| Undoped Si                   | >100 \( \Omega \) cm \( (\varepsilon = 11.7) \) | 279 ± 20 \( \mu \)m        |
| P type Si                    | 1–10 \( \Omega \) cm (Boron dopant) | 275 ± 20 \( \mu \)m        |
| Amorphous carbon (bulk)      | 1.5–4.5 \( \times 10^{-3} \) \( \Omega \) cm | 2 \( \mu \)m (carbon)/wafer (Si) |
| Patterned wafer              | —                            | 1.5 \( \mu \)m (ACL)/2.5 \( \mu \)m (SiO\(_2\))/wafer (Si) |

Figure 10. Experimentally obtained transmission spectra when various wafers are placed on the BCP: (a) without wafer, (b) with undoped Si, (c) P-type Si, (d) ACL, and (e) patterned wafer. (f) Measured electron density in each situation depending on the input RF power.
different from those without the wafers and a shift in the minimum peak frequency to a high frequency occurred compared to the 'without wafer' condition. Figures 10(c)–(e), in the case of a conductive wafer, such as the P-type Si or ACL, and the patterned wafer, the minimum peak width widens. In addition, a shift in the minimum peak frequency to a low frequency is evident compared to the case of the P-type Si and shift to a high frequency for the ACL/Si or patterned wafers.

Figure 11(a) shows a normalized cutoff frequency from the measured $S_{21}$ spectra shown in figures 10(a) through (c). Figure 11(b) shows the normalized cutoff frequency results calculated by EM simulation. Both results were normalized based on the values as the cutoff frequency under the condition that the wafer was not raised. The input plasma frequency used in the simulations was the $n_e$ measured and shown in figure 10(a); the input resistivity of the P-type Si was 8 Ω cm and the input dielectric constant of the undoped, P-type Si was 11.9. Both the experimental and simulation results show that when a dielectric wafer is placed on a BCP, the cutoff frequency moves to a high frequency, and when a conductive wafer is placed on a BCP, the cutoff frequency moves to a low frequency. Based on the circuit analysis, in the case of the dielectric wafers, the serial capacitor is additionally connected to the conventional plasma and sheath circuit [28] for $S_{21}$ analysis. Therefore, if the wafer on top of the BCP is an insulator, the resonant frequency is slightly shifted to a higher frequency because of the decrease in total capacitance. In the case of conductive wafers, the inductor and resistor are connected in a series and the conductor wafer is shifted to a lower frequency because of the increased total inductance. In the case of an ACL/Si wafer or patterned wafer, cutoff frequency moves to a high frequency, the effects appear to have been a combination of the insulator and conductor effects. These results indicate that the plasma density can be measured, even though the wafers are placed on the flat CP and thus, this technique can be used as a real-time measurement (monitoring) tool of the plasma density on the wafer plane without stopping processing, which can overcome the drawback of the conventional on-wafer sensor.

To assess if real-time measurement by using the BCP under the wafer is possible during the process, we measured the $n_e$ under various power conditions. To compare the BCP measurement result, the CP was also used. The BCP 2 and CP simultaneously measured through the RF switching module, and each probe measured the $n_e$ every 5 s. Here, the BCP 2 measured $n_e$ under the undoped Si wafers. Figure 12(a) shows a graph of the conditions under which power varies over time under a fixed pressure of 50 mTorr. In the areas shown region (1)—region (5) in figure 12(a), the forward power ($P_{FWD}$) is increased or decreased from 500 to 700 W without reflected power ($P_{REF}$), while region (6) shows the condition in which the $P_{FWD}$ is 700 W but the delivered power ($P_{DEL}$) is 510 W because the $P_{REF}$ is 190 W by changing the capacitance of the tune and load capacitor inside the L-type matcher. Figures 12(b)–(d) show the $n_e$ over time measured by the CP and BCP in the Ar, NF3, and O2 plasmas under the same power and pressure condition of figure 12(a). As can be seen in figure 12(b), both the CP and BCP show that $n_e$ is in an identical trend with $P_{DEL}$. The standard deviation of the measured $n_e$ with time under the same power condition is about 1.9% of the mean $n_e$. It can be seen that the $n_e$ with time is measured stably. The average value of the ratio of the measured $n_e$ by the CP to the measured $n_e$ by the BCP is approximately from 19.9 to 26.3 at the different power conditions. In addition, figures 12(c) and (d) shows changes of the $n_e$ in the processing gas type to NF3 and O2. The average value of the ratio of measured $n_e$ by the CP to measured $n_e$ by the BCP is approximately from 2.83 to 8.21 in the NF3 plasma and approximately from 6.95 to 9.50 in the O2 plasma, which seems to be related with the collision frequency and negative ion plasma property. The ratio of the measured $n_e$ by the CP to the measured $n_e$ by the BCP is shown in table 2. Through this, it can be seen that not only the argon plasma but also the process plasma is well measured over time.

Figure 13 shows the result of etching ACL using O2 plasma under conditions (1), (2), (3), and (6) of figure 12(a). As the power increases under the (1), (2), and (3) conditions, the ACL etch rate increases, and the forward power is constant; however, the delivered power decreases under condition
by changing the capacitances inside the L-type matcher to make non-impedance-matching, and the ACL etch rate decreases. It shows that the $n_e$ measured at the BCP under the wafer in O$_2$ plasma conditions is well matched to the ACL etching result.

4. Conclusion

We propose a BCP installed in a chamber wall or chuck and it enables real-time measurement of $n_e$ in plasma processing. The EM simulation confirmed that the BCP showed novel characteristics with clearer cut-off signal characteristics and minimization of noise signals compared with the other probe types. The comparison of the experiments and EM simulations showed that the BCP measures plasma density near the plasma-sheath boundary and the $n_e$ can be measured even if different types of wafers are placed on the BCP. The potential
for plasma diagnostics and monitoring during the actual plasma process using the BCP was demonstrated in this study.

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References

[1] Lieberman M A and Lichtenberg A J 2005 Principles of Plasma Discharges and Materials Processing 2nd edn (New York: Wiley)
[2] Chen F F 2013 Introduction to Plasma Physics and Controlled Fusion (New York: Plenum Press)
[3] Chabert P and Braithwaite N 2011 Physics of Radio-Frequency Plasmas (Cambridge: Cambridge University Press)
[4] Lee H-C 2018 Review of inductively coupled plasmas: nanomaterials and bistable hysteresis physics Appl. Phys. Rev. 5 011108
[5] Schulze J, Donkó Z, Schingel E and Czarnetzki U 2011 Secondary electrons in dual-frequency capacitive radio frequency discharges Plasma Sources Sci. Technol. 20 045007
[6] Ahr P, Schingel E, Schulze J, Tsankov T V and Czarnetzki U 2015 Influence of a phase-locked RF substrate bias on the E-to H-mode transition in an inductively coupled plasma Plasma Sources Sci. Technol. 24 044006
[7] Lee H C and Chung C W 2014 Control of electron energy distribution by adding a pulse inductive field in capacitive discharge Plasma Sources Sci. Technol. 23 062002
[8] Lee H C and Chung C W 2015 Electron heating and control of electron energy distribution for the enhancement of the plasma ashing processing Plasma Sources Sci. Technol. 24 24001
[9] Berndt J, Kovačević E, Selenin V, Stefanović I and Winter J 2006 Anomalous behaviour of the electron density in a pulsed complex plasma Plasma Sources Sci. Technol. 15 18–22
[10] Keese A M and Scime E E 2007 Neutral density profiles in argon helicon plasmas Plasma Sources Sci. Technol. 16 742–9
[11] Braithwaite N S J and Franklin R N 2009 Reflections on electrical probes Plasma Sources Sci. Technol. 18 014008
[12] Reeverall R and Ritchie G A D 2019 Spectroscopy techniques and the measurement of molecular radical densities in atmospheric pressure plasmas Plasma Sources Sci. Technol. 28 073002
[13] Kim J H, Seong D J, Lim J Y and Chung K H 2003 Plasma frequency measurements for absolute plasma density by means of wave cutoff method Appl. Phys. Lett. 83 4725–7
[14] Blackwell D D, Walker D N and Amatucci W E 2005 Measurement of absolute electron density with a plasma impedance probe Rev. Sci. Instrum. 76 1–7
[15] Kokura H, Nakamura K, Ghanashe F P and Sugai H 1999 Plasma absorption probe for measuring electron density in an environment soiled with processing plasmas Japan. J. Appl. Phys. 1 38 5262–6
[16] Lapke M, Mussenbrock T and Brinkmann R P 2008 The multipole resonance probe: a concept for simultaneous determination of plasma density, electron temperature, and collision rate in low-pressure plasmas Appl. Phys. Lett. 93 051502
[17] Piejak R B, Godyak V A, Garner R, Alexandrovich B M and Sternberg N 2004 The hairpin resonator: a plasma density measuring technique revisited J. Appl. Phys. 95 3785–91
[18] Chen F F 2009 Langmuir probes in RF plasma: surprising validity of OML theory Plasma Sources Sci. Technol. 18 035012
[19] Godyak V A, P R B and Alexandrovich B M 1992 Measurements of electron energy distribution in low-pressure Plasma Sources Sci. Technol. 1 36–58
[20] Kaupe J, Riedl P, Coenen D and Mitic S 2019 Temporal evolution of electron density and temperature in low pressure transient Ar/N2 plasmas estimated by optical emission spectroscopy Plasma Sources Sci. Technol. 28 065012
[21] Blackwell D D, Walker D N, Messer S J and Amatucci W E 2005 Characteristics of the plasma impedance probe with constant bias Phys. Plasmas 12 1–7
[22] Nakamura K, Ohata M and Sugai H 2003 Highly sensitive plasma absorption probe for measuring low-density high-pressure plasmas J. Vac. Sci. Technol. A 21 325–31
[23] Boris D R, Fernsler R F and Walton S G 2015 Measuring the electron density, temperature, and electron-electron scattering in plasma beam-generated plasmas produced in argon/SF6 mixtures Plasma Sources Sci. Technol. 24 025032
[24] You K H, You S J, Kim D W, Na B K, Seo B H, Kim J H, Shin Y H, Seong D J and Chang H Y 2013 A cutoff probe for the measurement of high density plasma Thin Solid Films 547 250–5
[25] Lapke M et al 2011 The multipole resonance probe: characterization of a prototype Plasma Sources Sci. Technol. 20 042001
[26] Šamara V, Bowden M D and Braithwaite N S J 2012 Modulation of microwave resonance probes Plasma Sources Sci. Technol. 21 024011
[27] Kim J H, Choi S C, Shin Y H and Chung K H 2004 Wave cutoff method to measure absolute electron density in cold plasma Rev. Sci. Instrum. 75 2706–10
[28] Kim D W, You S J, Na B K, Kim J H and Chang H Y 2011 An analysis on transmission microwave frequency spectrum of cut-off probe Appl. Phys. Lett. 99 1–4
[29] You K H, You S J, Na B K, Kim D W, Kim J H, Seong D J and Chang H Y 2018 Cutoff probe measurement in a magnetized plasma Phys. Plasmas 25 013518
[30] Kim D W, You S J, Kim J H, Chang H Y and Oh W Y 2016 Computational comparative study of microwave probes for plasma density measurement Plasma Sources Sci. Technol. 25 035026
[31] Godyak V 2017 Comments on plasma diagnostics with microwave probes Phys. Plasmas 24 060702
[32] Liang I, Nakamura K and Sugai H 2011 Modeling microwave resonance of curling probe for density measurements in reactive plasmas Appl. Phys. Express 4 4–7
[33] Pandey A, Sakakibara W, Matsuoka H, Nakamura K and Sugai H 2016 Time-resolved curling-probe measurements of electron density in high frequency pulsed DC discharges Japan. J. Appl. Phys. 55 016101
[34] Pandey A, Tashiro H, Sakakibara W, Nakamura K and Sugai H 2016 Curling probe measurement of a large-volume pulsed plasma with surface magnetic confinement Plasma Sources Sci. Technol. 25 65013

[35] Pandey A, Sakakibara W, Matsuoka H, Nakamura K and Sugai H 2014 Curling probe measurement of electron density in pulse-modulated plasma Appl. Phys. Lett. 104 1–5

[36] Schulz C, Styrnoll T, Awakowicz P and Rolfs I 2015 The planar multipole resonance probe: challenges and prospects of a planar plasma sensor IEEE Trans. Instrum. Meas. 64 857–64

[37] Gillman E D, Tejero E, Blackwell D and Amatucci W E 2018 Using a direct current (DC) glow discharge electrode as a non-invasive impedance probe for measuring electron density Rev. Sci. Instrum. 89 113505

[38] Gillman E D, Tejero E M, Blackwell D and A W E 2019 Non-invasive method for probing plasma impedance US Patent Specification 2019/0242838 A1

[39] Kim D W, You S J, Kim S J, Kim J H, Lee J Y, Kang W S and Hur M 2019 Planar cutoff probe for measuring the electron density of low-pressure plasmas Plasma Sources Sci. Technol. 28 015004

[40] Na B K, Kim D W, Kwon J H, Chang H Y, Kim J H and You S J 2012 Computational characterization of cutoff probe system for the measurement of electron density Phys. Plasmas 19 055304

[41] Jun H S, Na B K, Chang H Y and Kim J H 2007 Wave transmission characteristics of a wave-cutoff probe in weakly ionized plasmas Phys. Plasmas 14 095506

[42] Kwon J H, You S J, Kim D W, Na B K, Kim J H and Shin Y H 2011 Measurement of electron density with the phase-resolved cut-off probe method J. Appl. Phys. 110 023304

[43] Kwon J H, You S J, Kim J H and Shin Y H 2010 Plasma density measurements by phase resolved cutoff Appl. Phys. Lett. 96 1–4

[44] Kim S J, Lee J J, Kim D W, Kim J H and You S J 2019 A transmission line model of the cutoff probe Plasma Sources Sci. Technol. 28 055014

[45] Anon 2000 Time-domain simulation of dispersive media with the finite integration technique Int. J. Numer. Modelling, Electron. Netw. 13 329–48

[46] Kim D W, You S J, Kim J H, Chang H Y and Oh W Y 2012 Sheath width effect on the determination of plasma frequency in the cutoff probe Appl. Phys. Lett. 100 244107

[47] Fofanov Y A, Kuraptsev A S, Sokolov I M and Havey M D 2011 Dispersion of the dielectric permittivity of dense and cold atomic gases Phys. Rev. A 84 1–9

[48] Schmidt J W and Moldover M R 2003 Dielectric permittivity of eight gases measured with cross capacitors Int. J. Thermophys. 24 375–403

[49] Lee H C, Bang J Y and Chung C W 2011 Effects of RF bias power on electron energy distribution function and plasma uniformity in inductively coupled argon plasma Thin Solid Films 519 7009–13

[50] Lee H C, Chung C W, Kim J H and Seong D J 2019 Electron energy distribution modification by RF bias in Ar/SF6 inductively coupled plasmas Appl. Phys. Lett. 115 064102

[51] Lee H C, Seo B H, Kwon D C, Kim J H, Seong D J, Oh S J, Chung C W, You K H and Shin C 2017 Evolution of electron temperature in inductively coupled plasma Appl. Phys. Lett. 110 1–6

[52] Godyak V A and Piejak R B 1993 Paradoxical spatial distribution of the electron temperature in a low pressure rf discharge Appl. Phys. Lett. 63 3137–9

[53] Tsendin L D 2010 Nonlocal electron kinetics in gas discharge plasma Usp. Fiz. Nauk. 53 133

[54] Lee H C, Lee M H and Chung C W 2010 Experimental observation of the transition from nonlocal to local electron kinetics in inductively coupled plasmas Appl. Phys. Lett. 96 10–3

[55] Lee H C, Hwang H J, Kim Y C, Kim J Y, Kim D H and Chung C W 2013 Experimental verification of the Boltzmann relation in confined plasmas: comparison of noble and molecule gases Phys. Plasmas 20 033504

[56] Kim J-H, Chung K-H and Shin Y-H 2005 Analysis of the uncertainty in the measurement of electron densities in plasmas using the wave cutoff method Metrologia 42 110–4