Monitoring of Condition of Deposited Film Causing Particles in Plasma Etching
by Using Practical Load Impedance Monitoring Method

Yuji KASASHIMA and Fumihiko UESUGI
Advanced Manufacturing Research Institute, National Institute of Advanced Industrial Science and Technology (AIST),
807-1 Shukumachi, Tosu-shi, Saga 841-0052, Japan
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We monitor the change in thickness of films deposited on the inner chamber wall of mass-production plasma etching equipment by using previously developed load impedance monitoring system. The film composed of etching reaction products causes generation of flaked particles and is a factor that decreases production yield and overall equipment effectiveness (OEE) in the mass production of LSI. The method that can monitor the change in film thickness and contribute to decreasing flaked particles is highly required. The results of this study indicate that mainly the imaginary part of load impedance changes when a film is deposited on the inner wall, and demonstrate that the system can detect changes in the film thickness without remodeling of the equipment. This real-time and noninvasive monitoring method is expected to improve the production yield and OEE, and it could be used to develop a predictive maintenance regime in future.

1. Introduction

In the mass production of LSI, particles generated in the plasma etching chamber short-circuit LSI and substantially decrease production yields\(^1\)\(^{–}\)\(^10\). Overall equipment efficiency (OEE) also decreases because equipment must be stopped periodically for maintenance and cleaning of the etching chambers. The particles are mainly generated by corrosion of inner wall and flaking of deposited film\(^1\), and generation of them depends on the number of processed wafers\(^2\). For a short while after periodic chamber cleaning using chemicals, particles are chiefly caused by corrosion of inner wall material of the process chamber due to residual moisture and process gases\(^3\). The number of particles gradually decreases with the decrease in the residual moisture. After that, the etching reaction products are attached and gradually deposited on the inner walls as more wafers are processed, and the products form films. Particles are generated from the films due to electric field stress, which acts at the boundary between the insulating inner wall and the film during plasma processing and causes the film to flake off\(^4\)\(^\text{–}\)\(^14\). The electric field is formed between the inner wall surface at a floating potential and the chamber at a ground potential. More the reaction products deposit and the thicker the films on the inner walls, the more particles are generated by the flaking of the film. The process chambers are cleaned again during periodic maintenance with not necessarily an optimized cycle. Optimizing the maintenance schedule can reduce maintenance and manufacturing costs greatly and improve the production yield and OEE. Hence, a method for continuous monitoring of the deposited film is urgently required. In addition, developing a practical monitoring method will allow a predictive maintenance regime to be used in mass-production lines.

In this study, we demonstrate a method for monitoring the inner wall condition with the load impedance monitoring system. Plasma impedance monitoring methods for plasma etching have been studied for end point detection\(^15\)\(^\text{–}\)\(^18\), real-time monitoring of electrode voltage and current\(^19\)\(^,\)\(^20\), and estimation of plasma parameters such as electron density. Load impedance monitoring can also be applied to monitoring inner wall because the load impedance in capacitively coupled plasma (CCP) discharge mainly depends on sheath capacitance\(^21\), which reflects not only the plasma discharge conditions but the inner wall conditions, including the film. However, conventional impedance measurement methods\(^15\)\(^\text{–}\)\(^19\) using high-voltage and high-current probes installed between the matching circuit and the powered electrode are impractical for mass-production equipment. This is because it is difficult to modify the existing equipment to install the probes and the modification can lead to the change in the impedance matching condition and the process conditions. We have previously developed an novel impedance monitoring method for detecting the end point and anomalies such as unusual wafer movement and micro-arc discharge during plasma processing without remodeling of mass-production equipment\(^22\)\(^\text{–}\)\(^24\). The developed system consists of a directional coupler, a cross domain analyzer (CDA; Advantest), and the software used for impedance monitoring. In this study, we use the system to detect changes in the inner wall condition and monitor changes in the film deposited on the inner wall during plasma etching under mass-production condition.

2. Experimental methods

Figure 1(a) shows the experimental apparatus and the impedance monitoring system. The mass-production reactive ion etching equipment has parallel plane electrodes and generates CCP discharge (13.56 MHz). A wafer with a diameter of 200 mm is chuck onto the powered electrode by an electrostatic chuck wafer stage. The etching process sequence and equipment parameters...
are measured. In the measurement of $R$, $C$ are the real and imaginary parts of the characteristic impedance, $Z_{\text{CIM}}$, which is calculated by high-speed vector processing of the measured forward and reflected rf powers, involves both the load impedance and the matching circuit impedance, including the capacitances of $C_1$ and $C_2$. Therefore, the system simultaneously monitors the capacitances to measure the load impedance\(^{22}\). The forward and reflected rf powers are recorded, and the values of $R_1$ and $X_1$ are calculated at a rate of 10 mega samples per second (MS/s) for 100 $\mu$s. The time intervals for the data acquisition are approximately 200 ms. The capacitances of $C_1$ and $C_2$ are simultaneously monitored at a rate of 10 MS/s.

Optical emission spectroscopy (OES) (C6670, Hamamatsu Photonics K.K.) with the wavelength range of 300–800 nm is used to monitor the change in plasma discharge in the experiment of detecting the change in inner wall condition. To investigate the relationship between the change in load impedance and plasma parameter, a Langmuir probe is used. The probe electrode (tungsten wire) has a radius of 0.6 mm and a length of 3.5 mm, and is set at a position of approximately 40 mm above the wafer and approximately 10 mm distant from the center of the wafer. The ion saturation current $J_s$ and floating potential $V_f$ are measured. In the measurement of the $J_s$, the voltage of $-80$ V is applied to the probe electrode. To monitor the floating potential on the inner surface of the chamber wall, a viewing port style plasma probe (VP-Probe)\(^{27}\) is used. The probe, attached to the outer surface of the viewing port of the process chamber, can indirectly measure the change in floating potential on the inner surface of the viewing port. A film deposited on the inner wall is also at the floating potential; hence, the probe can also monitor the change in the potential formed on the film indirectly. The signal of the VP-Probe is monitored by a digital oscilloscope with a sampling frequency of 100 MS/s.

3. Results and discussion

3.1 Monitoring of inner wall condition\(^{26}\)

Before the experiment, several hundred wafers are etched to deposit substantial amounts of the etching reaction product on the inner walls of the chamber. The deposited film composed of TiF$_4$ is deliquescent\(^{29}\), hence the thickness and the dielectric constant of the deposited film change when the chamber is opened to the atmosphere and the film absorbs moisture.

Figure 2(a)–(c) show the time variation of the load impedances $R_1$, $X_1$, and $|Z_L|$ during etching of 21 wafers. In Figs. 2(a) and 2(b), the averaged values of $R_1$ and $X_1$ measured during each etching process are plotted, and in Fig. 2(c), the $|Z_L|$ values calculated by using the measured $R_1$ and $X_1$ are shown. After three wafers are processed, the process chamber is opened to the atmosphere for several tens of minutes. After the chamber is evacuated again, the etching process is restarted. The $R_1$
slightly decreases immediately after the chamber is opened, whereas the $X_L$ markedly decreases, and then gradually returns to the initial value. Figure 2(d) shows the peak-to-peak voltage, $V_{pp}$, applied to the powered electrode. The $V_{pp}$ also significantly changes after opening the chamber, and then gradually returns to the initial value. As shown in Fig. 2(c) and 2(d), the changes in $|Z_L|$ and $V_{pp}$ are well interrelated. The increase in $|Z_L|$ arising from exposure to the atmosphere causes the increase in $V_{pp}$ because the input rf power is not changed during the experiments; that is, a higher $V_{pp}$ is required when the load impedance increases. $V_{pp}$ is also related to $X_L$. Here, the load impedance, $Z_L$, can be expressed as \(^{31}\)

\[ Z_L = R_L + jX_L \]

\[ \sim R_p - j \frac{1}{\omega C_L} \]

where $R_p$ is the resistance of bulk plasma, $\omega$ is the frequency of the rf power supply, $C_L$ is the combined capacitance of the sheath and inner wall material including the deposited film, $S$ is the equivalent area of the plates of this combined capacitor; $d_i$, $d_e$, and $d_d$ are the thickness of the sheath, inner wall material, and deposited film; and $\varepsilon_0$, $\varepsilon_i$, and $\varepsilon_d$ are the dielectric constant of a vacuum, the inner wall material, and deposited film, respectively. According to the Child law sheath, the relationship between $d_i$ and the sheath voltage, $V_s$, can be expressed as \(^{39}\)

\[ d_i = \frac{2}{3} \frac{\lambda_D}{\lambda} \left( \frac{2V_s}{kT_e} \right)^{\frac{3}{4}} \]

where $\lambda_D$ is the Debye length, $k$ is the Boltzmann constant, and $T_e$ is the electron temperature. $d_i$ depends on $V_s$, which is estimated as half $V_{pp}$ at the cathode sheath in CCP discharge. \(^{21}\) The dielectric constant of the film $\varepsilon_d$ increases when the film absorbs moisture because the dielectric constant of moisture ($\sim 80$) is much larger than that of TiF$_4$ ($\sim 2.6$). \(^{30}\) From the Fig. 2(b) and Eq. (1), the thickness $d_d$ must also increase due to the moisture absorption because the increase in the $\varepsilon_d$ leads to the increase in $X_L$, which is the opposite direction of the change shown in Fig. 2(b): hence, the decrease in $X_L$ is mainly caused by the increase in $d_d$, which decreases the combined capacitance, $C_L$. Equation (2) indicates that $d_i$ at the powered electrode increases when $V_{pp}$ increases. Therefore, the decrease in $X_L$ is caused by both the increase in the $d_i$ owing to moisture absorption and the increase in the $d_d$ due to the increase in $V_{pp}$. As we discuss later, the gradual returns of $|Z_L|$ and $V_{pp}$ after the chamber open result from the baking effect at the deliquescing deposited film owing to plasma discharge. Accordingly, the monitoring system can detect the change in the load impedance caused by the change in the inner wall condition of the process chamber.

### 3.2 Relationship between the load impedance and plasma discharge condition

The change in the load impedance detected in the previous section would reflect not only the change in the inner wall condition but also that in plasma discharge condition. Therefore we investigate the relationship between the load impedance and the plasma discharge condition by using OES. Figure 3 shows the monitoring result in the range from 620 to 680 nm of emission wavelength. Similar to the experiment in the previous section, the process chamber is opened to the atmosphere during etching experiment. In the Fig. 3, three wafers are processed, and the chamber is opened after the wafer of No. 1 is etched; that is, No. 2 and 3 wafers are processed after the open to the atmosphere. The intensity of the emission spectrum of No. 2 apparently decreases than that of No. 1, and the emission spectrum of hydrogen (656 nm; Balmer series of spectrum of hydrogen atom) is observed. This is caused by the baking effect at the deliquescing deposited film and the outgassing from the film because the process gas does not con-
tain hydrogen atom; hence the result provides evidence that the changes in Fig. 2(a)–2(d) are actually caused by the moisture absorption and the baking effect. The spectrum of No. 3 wafer returns toward that of No. 1 wafer, and the spectrum of hydrogen atom is not observed. The decrease in the intensity of No. 2 than that of No. 1 indicates the electron density decreases because the baking effect and the outgassing from the film owing to plasma discharge causes recombination reaction. The slight decrease in the $R_L$ shown in Fig. 2(a) can be caused by the increase in the electron density and the decrease in the electron temperature since the $R_L$ is inversely proportional to electron density and proportional to collision frequency. Therefore, Fig. 3 indicates the slight decrease in the $R_L$ results from not the increase in the density but the decrease in the electron temperature.

To further understand the change in the plasma discharge condition, the ion saturation current $J_{is}$ and floating potential $V_f$ are measured as shown in Fig. 4(a) and 4(b) by using a Langmuir probe. In this experiment, the electrode gap is set at 80 mm to insert the probe. The eight wafers are processed and the chamber is opened for several minutes after the three wafers are processed. As shown in the Fig. 3, the electron density decreases owing to the outgassing, so that the ion density and the $J_{is}$ should also decrease. However, Fig. 4(a) shows the $J_{is}$ increases when the forth wafer is processed after the chamber open. Hence, the increase would be caused by the decrease in the negative ion density due to the decrease in the electron density and the decrease in the electron temperature since the $R_L$ is inversely proportional to electron density and proportional to collision frequency. Therefore, Fig. 3 indicates the slight decrease in the $R_L$ results from not the increase in the density but the decrease in the electron temperature.

Figure 5(a) shows the time variation of the film deposited on the ground electrode. The film thickness is measured after processing every 30 wafers, that is, after an etching time of 7.5 min. The average values of four concentric measurement points are shown. Several hundred wafers have been etched before the experiment; therefore, substantial amounts of the etching reaction product are already deposited on the inner wall (~84 μm). As shown in Fig. 5(a), the thickness of the film increases as more wafers are etched and etching reaction product is deposited on the inner wall.

3.3 Monitoring of the change in the thickness of deposited film

Figure 5(a) shows the time variation of the film deposited on the ground electrode. The film thickness is measured after processing every 30 wafers, that is, after an etching time of 7.5 min. The average values of four concentric measurement points are shown. Several hundred wafers have been etched before the experiment; therefore, substantial amounts of the etching reaction product are already deposited on the inner wall (~84 μm). As shown in Fig. 5(a), the thickness of the film increases as more wafers are etched and etching reaction product is deposited on the inner wall.

Figure 5(b) and 5(c) show the time variation of the real and imaginary parts of the load impedance. $R_L$ shown in Fig. 5(b), hardly changes, whereas $X_L$ shown in Fig. 5(c), gradually decreases as more wafers are processed and the deposited film thickens. $R_L$ mainly depends on electron density and electron temperature, so that plasma discharge conditions remain constant during the
etching experiment. Compared with the increase in the thickness of the deposited film of approximately 6 μm in Fig. 5(a), $X_L$ in Fig. 5(c) decreases by approximately 0.2 Ω during the experiment. The result indicates that the change in the film thickness is mainly reflected by the imaginary part, $X_L$. The load impedance, $Z_L$, is expressed as Eq. (1). The thickness of the inner wall material, $d_i$, remains unchanged during the experiment. The thickness of the sheath, $d_d$, is treated as unchanged because the plasma discharge conditions do not change. Only the thickness, $d_d$, changes because of the film deposition, and this causes the change in $X_L$. On the other hand, $X_L$ can also change because of the change in the floating potential (sheath potential) as shown in Eq. (1) and (2). We investigate the change in the floating potential at the inner wall by using the VP-Probe to clarify whether the change in $X_L$ reflects the change in the potential. Figure 5(d) shows the peak-to-peak voltage of the amplitude of the VP-Probe signal. The amplitude remains almost constant, so that the change in $X_L$ does not reflect the change in the floating potential. Therefore, the decrease in $X_L$ is caused by the increase in $d_d$. The dispersion of the change in $X_L$ from a monotonic decrease would result from variations in the impedance of each wafer, the slight dispersion of the amplitude of the floating potential shown in Fig. 5(d), and particle generation due to film detachment.

According to the results, the system can detect an increase in the thickness of the deposited film of several micrometers as the decrease in $X_L$ on the order of $10^{-1}$ Ω; that is, the system has sufficient sensitivity to detect changes in the thickness of the film of several micrometers. Currently, although the sensitivity has not been quantified, it is important that the change in the thickness of the film deposited on the inner wall is detected in real time by using the external monitoring method under mass-production condition. In future work, we will investigate the sensitivity of the system in more detail, and detect flaking of the deposited film and particle generation.

4. Conclusions

A monitoring method for films deposited on the inner wall of plasma etching chambers has been demonstrated. We use a load impedance monitoring system, which can be installed without remodeling mass-production equipment, to monitor the film deposition. The results reveal that the imaginary part of the load impedance mainly decreases owing to the decrease in the capacitance component in the impedance as the film on the inner wall thickens. We have demonstrated that the real-time system detects the change in the film thickness from a 50 Ω transmission line. This practical method is expected to improve production yield and OEE, and can be used to develop a predictive maintenance method for mass-production lines. In future work, we will attempt to detect flaking of the deposited film and particle generation.

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