Photoresist etching in an inductively coupled, traveling wave driven, large area plasma source

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We report on experimental and modeling results for photoresist etching with oxygen gas in an inductively coupled large area plasma source (LAPS). The source is driven by a 13.56 MHz traveling wave launched along a serpentine antenna embedded in the plasma and has a processing area as large as 40 cm × 50 cm. We describe a new series-parallel antenna coil configuration, and we present experimental observations for oxygen plasma density profiles, photoresist etch rates, and etch profiles. We introduce a simplified spatially varying oxygen discharge model corresponding to a two-dimensional LAPS geometry in order to account for the generation and loss of both etchant atoms (O atoms) and bombarding ions. The model and experimental results on plasma density are compared. A simplified photoresist etch kinetics model combined with the spatially varying oxygen discharge model is then described. The ion flux and O-atom density predicted by the model are compared with the etch rate data. In order to gain insight into the underlying physical mechanism, we also compare the data with the scaling behavior of the etch rates predicted by a volume-averaged (global) oxygen discharge model. The models and experimental results are generally in good agreement. © 2001 American Institute of Physics. [DOI: 10.1063/1.1331336]

I. INTRODUCTION

Inductively coupled plasma sources are known for their capabilities to generate high density plasmas under low pressures and achieve low voltages across all plasma sheaths at electrode and wall surfaces. These features enable us to increase the processing speed, minimize the contamination, and control ion/neutral fluxes and the ion-bombarding energy independently. Plasma sources suitable for processing 30 cm wafers, cylindrical in shape and driven by a planar coil, have been extensively studied in recent years. Inductively coupled large area plasma source (LAPS), driven by a 13.56 MHz traveling wave launched along an antenna embedded in the plasma. The LAPS provides a processing area of 40 cm × 50 cm for large-size wafers and glass substrates for thin-film transistor flat panel displays. Previously we characterized the LAPS for argon discharges, focusing on how various antenna coil configurations and the standing wave effects influence plasma density profiles over the large area. Plasma processes in which neutrals and ions at the substrate surface both play an important role, however, were not previously investigated.

In this article, we report on the operation of the LAPS for photoresist etching with oxygen gas. In Sec. II, after a brief description of the system configuration and a new antenna coil configuration, we give experimental observations for oxygen plasma density profiles, photoresist etch rates, and etch profiles over the processing area, depending on the operating conditions. In Sec. III, we introduce a simplified spatially varying oxygen discharge model corresponding to a two-dimensional LAPS geometry in order to account for the generation and loss of both etchant atoms (O atoms) and bombardment ions. The model and experimental results on plasma density are compared. In Sec. IV, in order to gain insight into the underlying physical mechanism, we also describe a volume-averaged (global) oxygen discharge model. In Sec. V, we develop a simplified photoresist etch kinetics model combined with the spatially varying oxygen discharge model. The ion flux and O-atom density predicted by the model are compared with the etch rate data and with the scaling behavior of the etch rates predicted by the global model. The models and experimental results are generally in good agreement. We give a brief conclusion in Sec. VI.

II. EXPERIMENTS

A. System configuration

The plasma chamber is a rectangular stainless-steel box (vertical length = 60 cm, horizontal length = 70 cm, depth = 20 cm) pierced horizontally by a planar line array of eight quartz tubes each 2.58 cm outer diameter, 1.7 mm thick, with center-to-center spacing of 7.65 cm. The rf-excited coil system consists of eight 6.35-mm-diam copper rods threaded through the interiors of the quartz tubes. A number of different connections of the rods to form the antenna were previously investigated in argon discharges. When all eight rods were connected in a series (serpentine) path, the total antenna length was found to be around half a wavelength of the rf.
power frequency (13.56 MHz), leading to a resonance in the tuning network. This caused significant power dissipation in the tuning elements. To eliminate the resonance, we have used a new antenna pattern, which consists of four sets of two adjacent antenna rods each, connected in series in a serpentine configuration, as shown in Fig. 1. Our theoretical analysis indicated that the matching elements and tuning elements could be chosen properly to obtain a good match with a traveling wave for this configuration. As shown in Fig. 1, in the new antenna configuration, the first series element of the matching network ($X_m$) must be an inductor, and the two capacitance elements ($B_{m1}$ and $B_{m2}$) can be varied to achieve the match. Since the tuning network consists of two variable capacitors connected in parallel with two fixed inductors, it provides either variable inductances or variable capacitances.

B. Vertical plasma density profiles

We measured plasma density profiles along a vertical line (perpendicular to the antenna rods) with a Langmuir probe approximately 5 cm in front of the substrate holder, and identified the achievement of launching a traveling wave using four voltage sensors (A, B, C, and D) equally spaced along the antenna coil. To launch a traveling wave, the tuning network was adjusted so that the voltages from the four sensors were almost the same. The probe is mounted on a vertical rod inside the chamber and is driven by a stepping motor. Ion saturation currents were used to calculate the plasma densities based on the orbital ion motion model for Langmuir probes.

Figure 2 shows vertical plasma density profiles for various oxygen gas pressures at a rf power of 500 W. For a traveling wave condition, the plasma density profiles are close to symmetric about the center and the plasma density increases with increasing gas pressure. We also see that the density profiles at high pressures (50 and 100 mTorr) are somewhat embedded with the antenna pattern. The plasma density has the peaks within the regions between each of the sets of two copper rods connected in parallel.

The plasma density was also found to increase roughly linearly with the rf power for powers between 500 and 1500 W. If the tuning network was adjusted so that the traveling wave condition was not met, then the plasma density profile was not symmetric and could be made to lean to one or the other side of the chamber.

C. Photoresist etch rates

We determined the etch rate of photoresist depending on the oxygen gas pressure and rf power. For the measurements, half of a 4 in. silicon wafer with 2 μm (as measured by ellipsometry) of hard-baked Novolak positive tone photoresist for i-line was clamped at the center and (for uniformity measurements) at the vertical edges of the processing area (40 cm in height). Typical operating parameters were an oxygen gas pressure of between 1 and 100 mTorr and a rf power of between 500 and 1500 W. No external bias was applied to the wafer. The thickness of photoresist film removed was divided by the etch time to determine the etch rate. We assumed that the etch rate was constant over the etch interval.

Figure 3 shows the etch rate at the center of the substrate holder as a function of both gas pressure and rf power. The etch rate rises to a maximum value and then falls with increasing gas pressure. The etch rate is clearly a nonlinear function of gas pressure. In Fig. 4, the etch rate is plotted along the vertical line within the chamber, for gas pressures...
of 1, 5, 20, and 50 mTorr at a rf power of 1000 W. We see that the uniformity of the etch rate decreases with increasing gas pressure.

In order to explain the etch rate data in Figs. 3 and 4, a simplified oxygen discharge model and photoresist etch kinetics model, along with an etch model proposed by Joubert et al., are introduced in Secs. III, IV, and V.

III. SPATIALLY VARYING OXYGEN DISCHARGE MODEL

A. Model formulation

In the photoresist etching processes with an oxygen plasma, ion and O-atom fluxes at the substrate surface are crucial variables. We develop a simplified spatially varying oxygen discharge model corresponding to the LAPS in a two-dimensional geometry. For a given gas pressure and absorbed power, we solve the particle and energy balance equations with proper boundary conditions in order to determine the electron temperature, ion, and O-atom density profiles, and their fluxes to the substrate surface. A finite element analysis is performed in two dimensions for the LAPS chamber. Due to symmetry of the chamber, only one quarter of the two-dimensional geometry. For a given gas pressure and absorption power, we solve the particle and energy balance equations with proper boundary conditions in order to determine the electron temperature, ion, and O-atom density profiles, and their fluxes to the substrate surface. A finite element analysis is performed in two dimensions for the LAPS chamber. Due to symmetry of the chamber, only one quarter of the two-dimensional area is used in the model. Assumptions of our model are listed in the following.

1. Steady state is assumed.

2. We ignore negative ions. We thus take \( n = n_{i} = n_{e} \), where \( n \) is the plasma density, \( n_{i} \) is the positive ion density, and \( n_{e} \) is the electron density.

3. We take into account the following two reactions for the ionization and dissociation processes:

\[
\begin{align*}
O_{2} + e & \rightarrow O_{2}^{+} + 2e, \\
K_{iz} & = 9.0 \times 10^{-10}(T_{e})^{2} \exp(-12.6/T_{e}) \text{ cm}^{3} \text{s}^{-1}, \\
O_{2} + e & \rightarrow O + O + e, \\
K_{diss} & = 4.2 \times 10^{-9} \exp(-5.6/T_{e}) \text{ cm}^{3} \text{s}^{-1},
\end{align*}
\]

where \( K_{iz} \) is the ionization rate constant, \( K_{diss} \) is the dissociation rate constant, and \( T_{e} \) is the electron temperature.

4. The ion loss velocity is the Bohm velocity \( u_{B} = (eT_{e}/M)^{1/2} \), where \( e \) is the electronic charge and \( M \) is the oxygen ion mass.

5. The ion temperature \( T_{i} \) and O-atom temperature \( T_{O} \) are assumed to be 0.05 V for gas pressures ranging from 1 to 100 mTorr.

6. The metal (stainless steel)-surface and quartz-surface recombination coefficients for O atoms are assumed to be 0.1 and 0.0001, respectively.

7. The ion and O-atom densities are assumed to be proportional to rf power. This assumption seems to be reasonable from the experimental results.

Ion particle balance is obtained from the following diffusion equation:

\[
\nabla^{2} n(x,y) + n(x,y) \frac{K_{iz}}{D_{e}} n_{O} \sum_{i=1}^{8} \exp \left( \frac{R - r_{i}(x,y)}{\lambda_{iz}(O_{2})} \right) = 0,
\]

which is consistent with a previous expression used for argon. The boundary conditions for Eq. (3) are

\[
\nabla n(x,y) |_{\text{walls}} = - \frac{u_{B}}{D_{e}} n(x,y),
\]

\[
\nabla n(x,y) |_{\text{plasma}} = 0,
\]

where the subscript “walls” stands for the substrate holder metal, side metal, and quartz surfaces, and the “plasma” stands for the plasma boundary of the calculation area, as shown in Fig. 5.

Partial differential equation (3) is solved numerically using the finite element method for eigenvalue problems. Since \( u_{B} \) and \( D_{e} \) are functions of \( T_{e} \), we need a value of \( T_{e} \) to solve Eq. (3). Assuming an initial value of \( T_{e0} \), we solve Eq. (3) to obtain a solution \( n(x,y) \) and eigenvalue. With given
$D_a$ and $n_{O_2}$, the eigenvalue gives $K_{iz}$. We then compare the obtained $K_{iz}$ with our initial $K_{iz0}$ which is estimated by substituting the initial $T_{e0}$ into Eq. (2). We iterate our solution until the $K_{iz}$ given by the eigenvalue becomes reasonably close to our initial estimate $K_{iz0}$, indicating that the plasma parameters are found within the accuracy of the calculation. This procedure gives numerical values for the electron temperature $T_e$ and plasma density profile $n(x,y)$, depending on the gas density $n_{O_2}$. It should be noted that $n(x,y)$ gives the plasma density profile and does not give information on the absolute magnitude of the density. The latter is obtained from energy balance considerations.

Using the electron temperature $T_e$ and plasma density profile $n(x,y)$, we solve a second diffusion equation to determine the O-atom profile:

$$-D_O \nabla^2 n_{O}(x,y) = 2 K_{diff}(T_e) n(x,y) n_{O_2}. \quad (7)$$

Equation (7) expresses the O-atom particle balance, where $D_O$ is the diffusion coefficient for O atoms due to collisions with O$_2$ molecules, $n_{O}(x,y)$ is the O-atom density profile, and $K_{diff}(T_e)$ is the dissociation coefficient as defined in Eq. (2). The diffusion coefficient $D_O$ is taken to be

$$D_O = \frac{\pi}{8} \lambda_{O,O_2} \overline{u_{O,O_2}}, \quad (8)$$

where $\lambda_{O,O_2} = 1/n_{O_2} \sigma_{O,O_2}$ is the mean free path and $\overline{u_{O,O_2}} = (8 e T_e / \pi M_{O_2})^{1/2}$ is the mean speed with the reduced mass $M_{O_2}$. We take the cross section $\sigma_{O,O_2} = 3.0 \times 10^{-15}$ cm$^2$, which is somewhat smaller than that ($\sigma_{O_2,O_2} = 5.0 \times 10^{-15}$ cm$^2$) for self-diffusion of O$_2$ molecules due to collisions with O$_2$ molecules. The boundary conditions for Eq. (7) are

$$\Gamma_{O-metal} = -D_O \nabla n_{O}(x,y)|_{metal} = \gamma_{metal} \frac{1}{2} n_{O-metal}(x,y) \overline{v_{O}}, \quad (9)$$

$$\Gamma_{O-quartz} = -D_O \nabla n_{O}(x,y)|_{quartz} = \gamma_{quartz} \frac{1}{2} n_{O-quartz}(x,y) \overline{v_{O}}, \quad (10)$$

$$-D_O \nabla n_{O}(x,y)|_{plasma} = 0, \quad (11)$$

where $\Gamma_{O-metal}$ is the O-atom flux at the metal surfaces, $\Gamma_{O-quartz}$ is the O-atom flux at the quartz surfaces, $\overline{v_{O}} = (8 e T_e / \pi M_O)^{1/2}$ with $M_O$ the O-atom mass, $\gamma_{metal}$ is the metal-surface recombination coefficient, and $\gamma_{quartz}$ is the quartz-surface recombination coefficient. A previous study indicated that $\gamma_{metal}$ ranges from 0.1 to 0.5 in oxygen discharges depending on the plasma condition. We take $\gamma_{metal} = 0.1$ because a higher value would not be consistent with the etch rate data shown in Fig. 3. A value of $\gamma_{metal} > 0.1$ leads to an O-atom density that is too low to be consistent with the low pressure etch rate data, even if we assume a reaction probability $\gamma_{react} = 1$ for the O-atom flux on the photoresist. We take $\gamma_{quartz} = 0.0001$ since $\gamma_{quartz}$ has been reported to be much lower than $\gamma_{metal}$. For chlorine (Cl) atoms, which are considered to have a higher recombination coefficient than O-atoms, $\gamma_{quartz}$ was found to be around 0.01. Our assumption for O atoms thus seems to be reasonable.

Partial differential equation (Poisson’s equation) (7) is also solved numerically using the finite element method. The solution gives the numerical value for the O-atom density profile $n_{O}(x,y)$, depending on the plasma density profile $n(x,y)$ and gas density $n_{O_2}$. We note that $n_{O}(x,y)$ is the O-atom density profile and does not give information on the absolute density.

We next consider the energy balance for oxygen discharges. The collisional energy loss per electron–ion pair created, $E_i(T_e)$, which is a function of the electron temperature, is an important quantity. In addition to $E_i(T_e)$, electrons and ions carry kinetic energy to the walls. For Maxwellian electrons, the mean kinetic energy lost per electron lost $E_i(T_e)$ can be expressed as

$$E_i = \frac{T_e}{2} + \frac{T_e}{2} \ln \left( \frac{M}{2 \pi m} \right), \quad (12)$$

where $m$ is the electron mass and $M$ is the ion mass. The second term accounts for the energy gained by ions falling across the plasma sheath. In oxygen plasmas, we find $E_i = 5.1 T_e$. Summing the three contributions yields the total energy lost per ion lost from the system:

$$E_T = E_e + E_{i-e} + E_i = E_i(T_e) + 2 T_e + 5.1 T_e. \quad (13)$$

At low pressures for which the ion loss velocity is the Bohm velocity $u_B$, the overall discharge energy balance can be expressed in terms of $E_T$ as

$$P_{abs} = e \int \frac{E_T \Gamma_i}{s} dS, \quad (14)$$

where $P_{abs}$ is the power absorbed by the plasma, $dS$ is the area element for particle loss, and $\Gamma_i$ is the ion flux at the walls expressed as

$$\Gamma_i = -D_a \nabla n(x,y)|_{walls} = n(x,y) \overline{u_B} = n_{i-s}(x,y) u_B, \quad (15)$$

where $n_{i-s}(x,y)$ is the ion density at the plasma-sheath edge. In our system configuration, Eq. (14) can be written as

$$P_{abs} = e \int \frac{E_T \Gamma_i}{s} dS + e \int \frac{E_T \Gamma_{i-s}}{s} dS + e \int \frac{E_T \Gamma_{i-s}}{s} dS. \quad (16)$$

The three terms on the right-hand side of Eq. (16) account for the energy loss at the four quartz tube surfaces, at the substrate holder surface, and at the chamber side surface, shown in Fig. 5. After the density profiles are computed from Eqs. (3) and (7), Eq. (16) is solved to determine the absolute magnitude of the densities and fluxes to the substrate surface.

B. Results and discussion

1. Plasma density and O-atom density profiles

Figure 6 shows the dependence of electron temperature on gas pressure. As seen in Fig. 6, the variation of electron
temperature is similar to that in the literature, with $T_e$ decreasing with increasing pressure. With the variation of $T_e$, $E_T$ in Eq. (13) ranges from 120 to 300 V with increasing gas pressure.

Figures 7 and 8 show the plasma density profiles for oxygen gas pressures of 1 and 20 mTorr, respectively, at a rf power of 500 W. The density profiles roughly follow a sinusoid pattern in general, which is typical for a diffusion dominated plasma discharge. The plasma density 5 cm in front of the substrate holder increases with increasing gas pressure, which is generally similar to the trend of the experimental results in Fig. 2. We see that, as the gas pressure increases, the plasma density profile becomes steeper in the middle and flatter at the metal surfaces. We also see that considerable diffusive loss occurs in the small annular regions surrounding the quartz tubes with increasing gas pressure.

Figures 9 and 10 show the O-atom density profiles for oxygen gas pressures of 1 and 20 mTorr, respectively, at a rf power of 500 W. Since the mean free path $\lambda_{O_2}$ is less than the characteristic size of the plasma, gas-phase O atoms created within the plasma are transported to the surfaces by diffusion. We see that, as the gas pressure increases, the O-atom density profile becomes steeper in the middle and flatter at the metal surfaces, as has also been seen for the plasma density profile. O atoms are not depleted near the quartz tubes since we have taken $\gamma_{quartz}=0.0001$, indicating that almost all the O atoms entering the quartz surfaces leave the surfaces without surface recombination.

2. Ion flux and O-atom density at the substrate surface

Equations (15) and (9) are solved to determine the absolute flux of ions incident on the substrate holder ($\Gamma_{i-\text{sub}}$) and the absolute density of O atoms at the substrate holder ($n_{O-\text{sub}}$), respectively. Figure 11 shows the flux of ions incident on the substrate holder as a function of the distance from the center of the substrate holder. We see that, with increasing pressure, $\Gamma_{i-\text{sub}}$ monotonically decreases and becomes more nonuniform over the substrate holder. The nonuniformity at high pressures can be explained by diffusive loss at the substrate and quartz tube surfaces. In oxygen dis-
charges, $E_T$ in Eq. (16) increases with increasing pressure, resulting in the decrease in $\Gamma_{i-\text{sub}}$ with pressure seen in Fig. 11.

We next consider how the absorbed power is distributed to the three surface regions [three terms on the right-hand side of Eq. (16)], depending on the gas pressure. Figure 12 shows the dependence of fractional power distribution on gas pressure. As the gas pressure increases, the power dissipated at the four quartz walls increases while the powers dissipated at the substrate holder wall and chamber side wall decrease.

The O-atom density at the substrate holder surface ($n_{O-\text{sub}}$) is determined from Eq. (9) as

$$n_{O-\text{sub}} = \frac{4\Gamma_{O-\text{sub}}}{\gamma_{\text{metal}} V_O}$$

(17)

Figure 13 shows the density of O atoms at the substrate holder as a function of the distance from the center of the substrate holder. With increasing pressure, $n_{O-\text{sub}}$ greatly increases and becomes more nonuniform over the substrate holder. These simulation results for the ion flux and O-atom density are compared in Sec. V with the etch rate data.

IV. VOLUME-AVERAGED OXYGEN DISCHARGE MODEL

In order to gain insight into the underlying physical mechanism, we describe a simplified volume-averaged discharge model to determine the scalings for the ion flux and O-atom density at the substrate surface. The discharge power balance at the substrate holder can be written:

$$P_{\text{sub}} = A_{\text{sub}} e E_T n_{i-\text{sub}} u B,$$

(18)

where $P_{\text{sub}}$ is the power dissipation at the substrate holder, $A_{\text{sub}}$ is the substrate holder area (60 cm x 70 cm), and $n_{i-\text{sub}}$ is the plasma density at the sheath edge at the substrate surface. The ion flux to the substrate is determined from Eq. (18) as

$$\Gamma_{i-\text{sub}}(n_{O_2}) = n_{i-\text{sub}} u B = \frac{P_{\text{sub}}(n_{O_2})}{e A_{\text{sub}} E_T(n_{O_2})}.$$  

(19)

As has been seen in the simulation results, both $P_{\text{sub}}$ and $E_T$ depend on the gas pressure. The ion flux $\Gamma_{i-\text{sub}}$ thus also varies with $n_{O_2}$ as seen in Eq. (19). Equation (19) is the scaling equation for the ion flux at the substrate surface.

For the production of O atoms by dissociation of the oxygen feedstock, the steady-state rate equation is

$$\text{FIG. 10. O-atom density profile for an oxygen gas pressure of 20 mTorr and a rf power of 500 W.}$$

$$\text{FIG. 11. Ion flux profiles incident on the substrate holder surface for various gas pressures at a rf power of 500 W.}$$

$$\text{FIG. 12. Dependence of the fractional power dissipation on gas pressure.}$$

$$\text{FIG. 13. O-atom density profiles at the substrate holder surface for various gas pressure at a rf power of 500 W.}$$
\[ A_{\text{sub}} \frac{dn_O}{dt} = 2A_{\text{sub}}K_{\text{dis}}n_i n_O - \gamma_{\text{sub}} 2A_{\text{sub}} \frac{1}{4} V n_O n_{O-\text{sub}} = 0, \]  

(20)

where \( l \) is a discharge thickness (20 cm), \( n_i \) is the ion (and electron) density in the bulk plasma, and \( \gamma_{\text{sub}} = \gamma_{\text{metal}} \) is the substrate holder metal-surface recombination coefficient. Solving Eq. (20) for \( n_{O-\text{sub}} \),

\[
n_{O-\text{sub}} = \frac{l}{\gamma_{\text{sub}} \frac{1}{4} V} K_{\text{dis}} n_i n_O, \]

(21)

and using \( n_i = n_{i-\text{sub}} / h_1 \), with \( n_{i-\text{sub}} \) given by Eq. (19), we have

\[
n_{O-\text{sub}}(n_O) = \frac{l}{\gamma_{\text{sub}} \frac{1}{4} V} \frac{K_{\text{dis}}(n_O)p_{\text{sub}}(n_O)n_O}{u_B(n_O)^2 E_T(n_O)h_1(n_O)}, \]

(22)

where \( h_1 \), a ratio of edge-to-center density, can be expressed as

\[
h_1 = \left[ 3 + \left( 1/2 \lambda_i \right) + \left( 0.86 l u_B / \pi D_a \right)^2 \right]^{1/2}. \]

(23)

This general \( h_1 \) factor can be used for transitions from low to high pressure. Since \( K_{\text{dis}} \), \( p_{\text{sub}} \), \( u_B \), \( E_T \), and \( h_1 \) depend on the gas pressure, \( n_{O-\text{sub}} \) also is a complicated function of gas pressure as seen in Eq. (22). Equation (22) is the scaling equation for O-atom density at the substrate surface. The scaling Eqs. (19) and (22) are used in Sec. V in order to explain the etch rate behavior in Fig. 3.

V. KINETICS OF PHOTORESIST ETCHING

We consider a simplified model of photoreesist etching to explain the etch rate data shown in Figs. 3 and 4 proposed by Joubert et al. \( ^{15} \)

\[ E = K \left( \kappa p_O (\sigma_j \eta_j) / K \sigma + \sigma_j \eta_j \right), \]

(24)

where \( E \) is the etch rate, \( K \) is a rate coefficient, \( p_O \) is the O-atom partial pressure, \( \kappa \) is a thermodynamic adsorption constant for O atoms, \( \sigma_j \) is the density of adsorption sites for O atoms, \( \eta_j \) is an ion-induced desorption rate constant, and \( j_i \) is the ion current density to the wafer substrate. In order to obtain values for the constants in Eq. (24), we use the simulation results for O-atom density at the substrate surface \( (n_{O-\text{sub}}) \) and the flux of ions incident on the substrate \( (\Gamma_{i-\text{sub}}) \). Since \( p_O \) is proportional to \( n_{O-\text{sub}} \), \( p_O \) can be written as

\[ p_O = p_{O(\text{ref})} n_{O-\text{sub}}(\text{ref}) = p_{O(\text{ref})} C_1, \]

(25)

where \( p_{O(\text{ref})} \) and \( n_{O-\text{sub}}(\text{ref}) \) are the reference values for \( p_O \) and \( n_{O-\text{sub}} \), respectively. Similarly, \( j_i \) is proportional to \( \Gamma_{i-\text{sub}} \), \( j_i \) can be written as

\[ j_i = j_{i(\text{ref})} \Gamma_{i-\text{sub}}(\text{ref}) = j_{i(\text{ref})} C_2, \]

(26)

where \( j_{i(\text{ref})} \) and \( \Gamma_{i-\text{sub}}(\text{ref}) \) are the reference values for \( j_i \) and \( \Gamma_{i-\text{sub}} \), respectively. Inserting Eqs. (25) and (26) into Eq. (24), it is convenient to rearrange Eq. (24) into the following form.

\[
\frac{C_1 C_2}{E} = \frac{C_1}{K \alpha_2} + \frac{C_2}{K \alpha_1},
\]

(27)

where \( \alpha_1 \) is the product \( \kappa p_{O(\text{ref})} \) and \( \alpha_2 \) is the product \( \sigma_j \eta_j \). We assume that \( \sigma_j \), \( \eta \), and \( \kappa \) are constant for different gas pressures and rf powers. Taking \( \Gamma_{i-\text{sub}} \) and \( n_{O-\text{sub}} \) at 20 mTorr, 500 W in Figs. 11 and 13 as the reference values, we have

\[
\frac{n_{O-\text{sub}}}{7.05 \times 10^{13}} (\Gamma_{i-\text{sub}}/1.93 \times 10^{15}) \frac{1}{E} = \frac{1}{7.05 \times 10^{13}} \frac{1}{K \alpha_2} + \frac{1}{1.93 \times 10^{15}} \frac{1}{K \alpha_1},
\]

(28)

where we have assumed that the O-atom flux at the photoreesist surface is equal to that at the stainless-steel substrate holder wall since the photoreesist area is much smaller than the steel-wall area. Using the etch rates for 20 and 1 mTorr at 500 W in Fig. 3 and the simulation results for \( \Gamma_{i-\text{sub}} \) and \( n_{O-\text{sub}} \) in Figs. 11 and 13 at these two pressures, we obtain two equations (one for 20 mTorr, the other for 1 mTorr), which we solve to determine values of \( 1.89 \times 10^{-2} \) min/nm for \( 1/K \alpha_2 \) and \( 1.72 \times 10^{-3} \) min/nm for \( 1/K \alpha_1 \). Figure 14 shows the etch rate data as a function of both gas pressure and rf power, and the predicted etch rate from Eq. (28) with the above two constants and the simulation results in Figs. 11 and 13. Here we have assumed that \( n_{O-\text{sub}} \) and \( \Gamma_{i-\text{sub}} \) are proportional to rf power, resulting in a linear relationship between the etch rate and rf power. Equation (28) predicts a somewhat lower rate than experimental data for a high rf power of 1500 W, but does predict the general trend.

Equation (28) is also used to predict etch rate profiles along the vertical line within the chamber for various gas pressures, using the simulation results for vertical \( \Gamma_{i-\text{sub}} \) and \( n_{O-\text{sub}} \) profiles in Figs. 11 and 13. The results are shown in Fig. 15. For a gas pressure of 5 mTorr, Eq. (28) predicts a somewhat steeper profile than the experimental result in Fig. 15.
4, but the general trends are similar, with the uniformity decreasing with increasing gas pressure. The somewhat steeper etch rate profile at 5 mTorr could be explained in terms of the metal-surface recombination coefficient for O atoms (\( \gamma_{\text{metal}} \)). We have taken \( \gamma_{\text{metal}} = 0.1 \) in the simulation. If we took a lower value as the recombination coefficient, the O-atom density profile would become flatter, resulting in a more uniform etch rate profile.

Using the scaling Eqs. (19), (22), and (24) from the simple volume-averaged model, we also predicted the etch rate in the same way as has been done with the finite element model simulation results. Figure 16 shows that the result from the simplified volume-averaged discharge model is also in good agreement with the experimental data. In the low pressure regime (low \( p_O \)), from Eq. (24), a linear relationship between the etch rate and \( p_O \) can be observed. The etch rate therefore increases linearly with \( n_{O,\text{sub}} \) defined in Eq. (22). From Eq. (22), \( n_{O,\text{sub}} \) increases with gas pressure, resulting in an increase in the etch rate with gas pressure. On the other hand, in the high pressure regime (high \( p_O \)), a linear relationship between the etch rate and \( j_i \) can be observed. The etch rate is thus proportional to \( \Gamma_{i,\text{sub}} \), defined in Eq. (19). From Eq. (19), \( \Gamma_{i,\text{sub}} \) decreases with gas pressure, leading to a decrease in the etch rate with increasing pressure. The good agreement between the experimental data and the volume-averaged discharge model gives increased understanding of the photoresist etch process and its scaling with process parameters.

VI. CONCLUSIONS

We have investigated the oxygen plasma density and photoresist etch rate profiles for various gas pressures and rf powers. We have found that the plasma density profiles are close to symmetric about the center of the chamber for a traveling wave condition. The plasma density increases with increasing gas pressure and increases roughly linearly with rf power. For the photoresist etching, we have found that the etch rate at the center of the substrate holder rises to a maximum value and then falls with increasing gas pressure. The etch rate uniformity over the processing area increases with decreasing gas pressure. In order to explain these experimental results, we have developed a simplified spatially varying oxygen discharge finite element model corresponding to the LAPS in a two-dimensional geometry and applied a simplified photoresist etch kinetics model. We have also compared the experimental data with the scaling behavior of the etch rates predicted by a volume-averaged oxygen discharge model. The models and experimental results are generally in good agreement, indicating that the basic modeling approach captures much of the essential physics for the oxygen discharge and photoresist etching in the LAPS.

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