KINETICS OF PHOTORESIST ETCHING IN A LARGE AREA PLASMA SOURCE (LAPS)

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ABSTRACT

We report on photoresist etching experiments on the large area plasma source (LAPS) with an oxygen plasma. The etch rate rises to a maximum value and then falls with increasing gas pressure. Using a recently proposed etching model, this experimental result can be explained in terms of a simplified discharge kinetics model as well as our previous simulation results.

We find that the etching uniformity over the processing area of 40 cm x 50 cm decreases with increasing gas pressure. This can be explained by the experimental plasma profile results and our simulation results in which the plasma density profile becomes more non-uniform with increasing gas pressure. We also find that the standing wave pattern along the antenna coil can strongly influence etch process uniformity.
1. Introduction

We have developed a simplified oxygen discharge model corresponding to our large area plasma source (LAPS) geometry.\(^1\) For a specified gas pressure and absorbed power, we solved the particle and energy balance equations to predict the ion and O-atom densities and profiles and the electron temperature. Here we report on photoresist etching experiments on the LAPS with an oxygen plasma. The etch rate rises to a maximum value and then falls with increasing gas pressure. A simplified etch kinetics model is described in which the predicted ion and O-atom densities are used to explain the etch rate data. In order to gain an insight into the underlying physical mechanism, we also compare the etch rate data with the scaling behavior of the etch rate from a simplified analytical discharge kinetics model.

2. Experiments

The LAPS system used in these experiments has been described previously.\(^2\) For the measurements of photoresist etch rate, half of a four-inch silicon wafer with 2 \(\mu\text{m}\) (as measured by ellipsometry) of hardbaked photoresist was clamped at the center and (for uniformity measurements) at the edges of the processing area (40 cm \(\times\) 50 cm). Typical operating parameters are an oxygen gas pressure of between 1 mTorr and 100 mTorr and a rf power of between 500 W and 1500 W. No external bias was applied to the wafer during these experiments. 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. For these etching conditions, we also measured the plasma density profiles, and identified the achievement of launching a traveling wave using four voltage sensors 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 the same.

3. Results

Plasma density was determined from measurements of the ion saturation current with a Langmuir probe approximately 5 cm in front of the substrate holder. Figure 1 shows plasma density profiles for various oxygen gas pressures at an input power of 500 W. The eight vertical dashed lines in the figure indicate the positions of the eight copper rods. 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 mTorr and 100 mTorr) are somewhat embedded with the antenna pattern, which consists of four sets of two adjacent antenna rods each, connected in series in a
serpentine configuration. The plasma density has the peaks within the regions between each of the sets of two copper rods connected in parallel.

Figures 2 and 3 show plasma density profiles for various rf input powers at a gas pressure of 5 mTorr and 50 mTorr, respectively. For both pressures, the plasma density increases roughly linearly with the input power.

We next describe how the etch rate of photoresist changes depending on the oxygen gas pressure and rf input power. Figure 4 shows the etch rate at the center of the substrate holder as a function of both gas pressure and rf input 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 order to explain the data in Fig. 4, an etch model proposed by Joubert et al., along with our simulation results and analytical scalings for the discharge kinetics, will be introduced in the next section.

In Fig. 5, the etch rate is plotted along a vertical line (perpendicular to the antenna rods) within the chamber, for gas pressures of 1, 5, 20, and 50 mTorr at an input power of 1000 W. We see that the uniformity of the etch rate decreases with increasing gas pressure. This result can be explained by our simulation results for the ion fluxes to the substrate holder.

Figure 6 shows etch rate profiles along the vertical within the chamber, for a traveling wave condition and standing wave condition at a gas pressure of 20 mTorr. The corresponding voltage distributions along the antenna are shown in the inset. As seen in the figure, the profile for the standing wave condition is highly asymmetric and non-uniform. From this result, we see that the standing wave pattern can strongly influence etch process uniformity.

4. Discussion

We consider a simple model of photoresist etching to explain the etch rate data at the center of the substrate holder.

The form of the rate expression proposed by Joubert et al. is

\[ E = K \frac{(\kappa \rho_0) \sigma_s \gamma \bar{j}_i}{\kappa \rho_0 + \sigma_s \gamma \bar{j}_i} \]  

where \( E \) is the etch rate, \( K \) is a rate coefficient, \( \rho_0 \) is the O-atom partial pressure, \( \kappa \) is the thermodynamic adsorption constant for O atoms on the photoresist, \( \sigma_s \) is the density of adsorption sites for O atoms, \( \gamma \) is an ion-induced desorption rate constant, and \( \bar{j}_i \) is the ion current to the wafer substrate. In order to obtain values for the constants in Eq. (1), we use the simulation results for O-atom density at the substrate surface \( (n_{\text{O-sub}}) \) and the flux of ions incident on the substrate \( (\Gamma_{\text{i-sub}} = n_{\text{i-sub}} u_B) \).
Since $p_0$ is proportional to $n_{O_{sub}}$, $p_0$ can be redefined as

$$P_0 = P_{O\text{ref}} \frac{n_{O_{sub}}}{n_{O_{sub}\text{ref}}} = P_{O\text{ref}}C_1 \quad (2)$$

Similarly, since $j_i$ is proportional to $\Gamma_{i_{sub}}$, $j_i$ can be redefined as

$$j_i = j_{i\text{ref}} \frac{\Gamma_{i_{sub}}}{\Gamma_{i_{sub}\text{ref}}} = j_{i\text{ref}}C_2 \quad (3)$$

It is convenient to rearrange Eq. (1) into the following form

$$\frac{C_1C_2}{E} = \frac{C_1}{K\alpha_2} + \frac{C_2}{K\alpha_1} \quad (4)$$

where $\alpha_1$ is the product $\kappa p_{O\text{ref}}$ and $\alpha_2$ is the product $\sigma S\eta j_{i\text{ref}}$. We assume that $\sigma S$, $\eta$, and $\kappa$ are constant for different gas pressures and rf powers. Taking $n_{O_{sub}}$ and $\Gamma_{i_{sub}}$ at 20 mTorr, 500 W as the reference values, we have

$$\frac{7.05 \times 10^{15}}{1.93 \times 10^{15}} \frac{1}{E} = \frac{n_{O_{sub}}}{7.05 \times 10^{15}} \frac{1}{K\alpha_2} + \frac{\Gamma_{i_{sub}}}{1.93 \times 10^{15}} \frac{1}{K\alpha_1} \quad (5)$$

Using the etch rates for 20 mTorr and 1 mTorr at 500 W in Fig. 4, we have the following simultaneous equations with respect to $1/K\alpha_2$ and $1/K\alpha_1$.

$$\frac{1}{48.5 \text{nm/min}} = \frac{1}{K\alpha_2} + \frac{1}{K\alpha_1} \quad \text{at 20 mTorr}$$

$$\frac{3.26 \times 10^{15}}{4.27 \times 10^{15}} \frac{1}{22.4 \text{nm/min}} = \frac{3.26 \times 10^{12}}{7.05 \times 10^{13}} \frac{1}{K\alpha_2} + \frac{4.27 \times 10^{15}}{1.93 \times 10^{15}} \frac{1}{K\alpha_1} \quad \text{at 1 mTorr}$$

This equation yields 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 7 shows the etch rate data as a function of both gas pressure and rf input power, and the predicted etch rate from Eq. (5) with the above two constants and the simulation results for 1, 5, 20, 50, and 100 mTorr taken from reference 1. Here we have also assumed that $n_{O_{sub}}$ and $\Gamma_{i_{sub}}$ are proportional to rf power. This assumption seems to be reasonable from the experimental results in Figs. 2 and 3. Equation (5) predicts a somewhat lower rate than the experimental data for a high rf power of 1500 W, but does predict the general trend.

Equation (5) is also used to predict vertical etch rate profiles for various gas pressures, using the simulation results for vertical $n_{O_{sub}}$ and $\Gamma_{i_{sub}}$ profiles taken from reference 1. The results are shown in Fig. 8. For a gas pressure of 5 mTorr, Eq. (5) predicts a somewhat steeper profile than the experimental result in Fig. 5, but the general trends are similar, with the uniformity decreasing with increasing
pressure. The somewhat steeper etch profiles at 5 mTorr could be explained in terms of the metal-
surface recombination coefficient for O atoms ($\gamma_{\text{O-metal}}$). We have taken $\gamma_{\text{O-metal}} = 0.1$ in the
simulation.\textsuperscript{1} If we took a lower value as the recombination coefficient, the O-atom density profile
would become flatter, resulting in a more uniform etch profile.

We next discuss the etch rate behavior in Fig. 4 in terms of a simplified discharge kinetics and its
scalings. The discharge power balance at the substrate holder can be written

$$P_{\text{sub}} = A_{\text{sub}} e E_T n_{\text{i-sub}} u_B$$  \hspace{1cm} (6)

where $P_{\text{sub}}$ is the power dissipation at the substrate holder, $A_{\text{sub}}$ is the substrate holder area (60 cm x 70
in), and $E_T$ is the total energy lost per electron-ion pair created.\textsuperscript{5} The ion flux to the substrate is
determined from Eq. (6) as

$$\Gamma_{\text{i-sub}}(n_{O_2}) = n_{\text{i-sub}} u_B \frac{P_{\text{sub}}(n_{O_2})}{e A_{\text{sub}} E_T(n_{O_2})}$$  \hspace{1cm} (7)

As has been seen in the simulation results,\textsuperscript{1} both $P_{\text{sub}}$ and $E_T$ depend on the gas pressure $n_{O_2}$. The ion
flux $\Gamma_{\text{i-sub}}$ thus also varies with $n_{O_2}$ as seen in Eq. (7).

For the production of O atoms by dissociation of the oxygen feedstock, the steady-state rate
equation is\textsuperscript{5}

$$A_{\text{sub}} \frac{d n_{O_2}}{dt} = 2 A_{\text{sub}} l K_{\text{diss}} n_i n_{O_2} - \gamma_{\text{sub}} 2 A_{\text{sub}} \frac{1}{4} v_o n_{O-\text{sub}} = 0$$  \hspace{1cm} (8)

where $l$ is a discharge thickness.

Solving Eq. (8) for $n_{O-\text{sub}}$,

$$n_{O-\text{sub}} = \frac{2l}{\gamma_{\text{sub}} 2 \frac{1}{4} v_o} K_{\text{diss}} n_i n_{O_2}$$  \hspace{1cm} (9)

and using $n_i \approx n_{\text{i-sub}}/h_i$ with $n_{\text{i-sub}}$ given by Eq. (7), we have

$$n_{O-\text{sub}}(n_{O_2}) = \frac{2l}{\gamma_{\text{sub}} 2 \frac{1}{4} v_o} \frac{K_{\text{diss}}(n_{O_2}) P_{\text{sub}}(n_{O_2}) n_{O_2}}{u_B(n_{O_2}) E_T(n_{O_2}) h_i(n_{O_2})}$$  \hspace{1cm} (10)

where $h_i$, a ratio of edge-to-center density, can be expressed as\textsuperscript{6}

$$h_i = \frac{0.86}{\left[ 3 + \frac{l}{2 \lambda_i} + \left( \frac{0.86 l u_B}{n D_a} \right)^2 \right]^{1/2}}$$  \hspace{1cm} (11)

This general $h_i$ factor can be used for transitions from low to high pressure. Since $K_{\text{diss}}$, $P_{\text{sub}}$, $u_B$, $E_T$, and
\( h_i \) depend on the gas pressure, \( n_{\text{O-sub}} \) also is a complicated function of gas pressure as seen in Eq. (10). The values that depend on the gas pressure are summarized in Table 1.

<table>
<thead>
<tr>
<th>( p ) (mTorr)</th>
<th>( \lambda_i ) (cm)</th>
<th>( u_B ) (cm/s)</th>
<th>( D_a ) (cm²/s)</th>
<th>( T_e ) (V)</th>
<th>( K_{\text{dis}} ) (cm³/s)</th>
<th>( E_T ) (V)</th>
<th>( h_i )</th>
<th>( n_{\text{O2}} ) (cm⁻³)</th>
<th>( P_{\text{sub}}/P_{\text{abs}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.0</td>
<td>( 3.21 \times 10^4 )</td>
<td>( 5.10 \times 10^5 )</td>
<td>3.40</td>
<td>( 8.1 \times 10^{10} )</td>
<td>120</td>
<td>0.34</td>
<td>( 3.3 \times 10^{13} )</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
<td>0.61</td>
<td>( 2.83 \times 10^4 )</td>
<td>( 7.95 \times 10^5 )</td>
<td>2.65</td>
<td>( 5.1 \times 10^{10} )</td>
<td>200</td>
<td>0.18</td>
<td>( 1.7 \times 10^{14} )</td>
<td>0.56</td>
</tr>
<tr>
<td>20</td>
<td>0.15</td>
<td>( 2.67 \times 10^4 )</td>
<td>( 1.76 \times 10^5 )</td>
<td>2.35</td>
<td>( 3.9 \times 10^{10} )</td>
<td>260</td>
<td>0.073</td>
<td>( 6.6 \times 10^{14} )</td>
<td>0.44</td>
</tr>
<tr>
<td>50</td>
<td>0.061</td>
<td>( 2.62 \times 10^4 )</td>
<td>( 6.80 \times 10^4 )</td>
<td>2.27</td>
<td>( 3.6 \times 10^{10} )</td>
<td>290</td>
<td>0.035</td>
<td>( 1.7 \times 10^{15} )</td>
<td>0.30</td>
</tr>
<tr>
<td>100</td>
<td>0.030</td>
<td>( 2.61 \times 10^4 )</td>
<td>( 3.38 \times 10^4 )</td>
<td>2.25</td>
<td>( 3.5 \times 10^{10} )</td>
<td>300</td>
<td>0.017</td>
<td>( 3.3 \times 10^{15} )</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Using the scaling Eqs. (1), (7), and (10), with the values in Table 1, we predicted the etch rate in the same way as has been done with the simulation results. Figure 9 shows the results. The result from the simplified discharge kinetics model is also in good agreement with the experimental data.

We consider the scaling behavior of the etch rate from Eqs. (1), (7), and (10). In the low pressure regime (low \( p_0 \)), from Eq. (1), a linear relationship between the etch rate and \( p_0 \) can be observed. The etch rate therefore increases linearly with \( n_{\text{O-sub}} \) defined in Eq. (10). From Eq. (10) with the values in Table 1, \( n_{\text{O-sub}} \) increases with gas pressure \( (n_{\text{O2}}) \), resulting in an increase in the etch rate with gas pressure, as seen in Fig. 9. On the other hand, in the high pressure regime (high \( p_0 \)), a linear relationship between the etch rate and \( j_i \) can be observed. The etch rate is thus proportional to \( \Gamma_{\text{i-sub}} \) defined in Eq. (7). From Eq. (7) with the values in Table 1, \( \Gamma_{\text{i-sub}} \) decreases with gas pressure \( (n_{\text{O2}}) \), leading to a decrease in the etch rate with increasing pressure, as seen in Fig. 9.

The fact that both the simulation and analytical discharge kinetics results are in good agreement with the experimental data confirms the assumptions of the model.

5. Conclusions

From the photoresist etching experiments on the LAPS with an oxygen plasma, we have found that the etch rate rises to some maximum value and then falls with increasing gas pressure. Using a recently proposed etching model, the experimental result can be explained in terms of the analytical scalings for discharge kinetics as well as our previous simulation results. This agreement confirms the validity of the various approximations in our model.

For the etching uniformity, we have found that the uniformity over the processing area of 40 cm \( \times \) 50
cm decreases with increasing gas pressure. This result can be explained by the experimental results and our simulation results in which the plasma density profile becomes more non-uniform with increasing gas pressure. We also have found that the standing wave pattern along the antenna coil can strongly influence etch process uniformity.

The maximum etch rates were limited to between 100 – 150 nm/min due to power supply and vacuum pumping limitations. We expect the maximum etch rate to increase linearly with rf power. For a large photoresist area, in the O-atom flux limited regime where the etch rate is proportional to \( n_{O_{sub}} \), we will undergo a reduction in the etch rate due to the loading effect. To minimize the loading effect, high gas flow rates will be required, leading to a reduction in depletion of etchant O atoms over the substrate area.

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Fig. 1. Plasma density profiles for various oxygen gas pressures at an input power of 500 W.

Fig. 2. Plasma density profiles for various rf powers at a gas pressure of 5 mTorr.
Fig. 3. Plasma density profiles for various rf powers at a gas pressure of 50 mTorr.

Fig. 4. Dependence of etch rate at the center of the substrate holder on the gas pressure (experimental data).
Fig. 5. Vertical etch rate profiles for various gas pressures at an input power of 1000 W.

Fig. 6. Vertical etch rate profiles for a traveling wave condition and standing wave condition.
Fig. 7. Plots of etch rate vs gas pressure for various rf powers. The fits are from Eq. (5) with the simulation results.

Fig. 8. Predicted vertical etch rate profiles for various gas pressures at 1000 W. The fits are from Eq. (5) with the simulation results.
Fig. 9. Plots of etch rate vs gas pressure for various rf powers. The fits are from the scaling Eqs. (1), (7), and (10).