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Effect of Ion Energy on Photoresist Etching in an Inductively Coupled Large Area Plasma Source (LAPS)

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ABSTRACT

We report on the effect of ion energy on photoresist etching in an inductively coupled large area plasma source (LAPS) driven by a 13.56-MHz traveling wave with oxygen gas. To control the ion energy at the substrate surface, the electrode on which the substrate is placed is independently driven by a capacitively coupled 1-MHz power source. The ion energy is approximately the sum of the plasma potential (approximately 10-17 V depending on gas pressure) and the self-bias voltage (0 ~ -120 V in this experiment) induced by the 1-MHz power. The etch rate increases with increasing ion energy for gas pressure ranging from 1 mTorr to 100 mTorr. Ion-induced desorption rate constants (etch yields) are shown to be proportional to the square root of the ion energy. An increase in the ion energy leads to etch-uniformity improvement over the processing area of 40 cm × 50 cm, particularly at a low gas pressure of 5 mTorr. A modified photoresist etch kinetics model combined with a spatially-varying oxygen discharge model is used to explain these experimental results. The model and experimental results are generally in good agreement.

1. Introduction

In a previous report, we presented photoresist etching experiments in the LAPS with an oxygen plasma.[1] The etch rate rose to a maximum value and then decreased with increasing gas pressure. The etch uniformity over the processing area of 40 cm × 50 cm increased with decreasing gas pressure. No external bias was applied to the substrate holder electrode during these experiments. We introduced a simplified photoresist etch kinetics model in order to explain the experimental results.[1,2]

In this study, we investigate the effect of ion energy at the substrate surface on the photoresist etching for various gas pressures, changing the substrate self-bias voltage (V_{bias}) by a capacitively coupled 1-MHz power source. A modified photoresist etch kinetics model combined with a spatially-varying oxygen discharge model[1,3] is used to explain the experimental results.

2. Experiments

For the measurements of photoresist etch rate, half of a four-inch silicon wafer with 2 μm (as measured by ellipsometry) of hardbaked Novolak positive tone photoresist was clamped at the center and (for uniformity measurements) at the vertical edges of the processing area (±20 cm from the center). Typical operating parameters were an oxygen gas pressure of between 1 mTorr and 100 mTorr and an rf source power (13.56 MHz) of 1000 W. To control the ion energy at the substrate surface, the electrode on which the silicon wafers were placed was independently driven by a capacitively coupled 1-MHz power source, as shown in Fig. 1. Here, the impedance of the low-pass filter L and C are 628 Ω and 4 Ω, respectively, so that only 0.6 percent of the rf voltage appears across the capacitor, and the dc self-bias voltage on the electrode is directly measured with a high impedance voltmeter. The self-bias voltage induced by the 1-MHz power was in the range of between 0 V and −120 V. We measured the plasma density profiles for various gas pressures, changing the self-bias voltage. 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.

3. Results

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 electrode, and identified the achievement of launching a traveling wave using four voltage sensors equally spaced along the antenna coil. Figure 2 shows plasma density profiles for various self-bias voltages at a gas pressure of 20 mTorr. The plasma density increases only slightly with increasing self-bias voltage, which indicates that independent control of the ion/radical fluxes (through the source power) and the ion-bombarding energy (through the substrate electrode power) is achieved in this system.

Figure 3 shows the etch rate at the center of the substrate holder electrode as a function of gas pressure, with the self-bias voltage as the parameter, at a source power of 1000 W. The variation in the etch rate due to a change in the self-bias voltage depends on gas pressure. In the low pressure regime, increasing the self-bias voltage does not affect the etch rate much, whereas at higher pressures, increasing the voltage significantly increases the etch rate. In the low pressure regime, the etch rate is O-atom flux limited; therefore, increasing the self-bias voltage has little effect on the etch rate. In the high pressure regime, the etch surface becomes flooded with O atoms, and the etch rate is determined by the energetic ion flux striking the surface.

In Fig. 4, the etch rate is plotted along the vertical line within the chamber, with and without applying a self-bias voltage, for gas pressures of 5 mTorr and 20 mTorr. We see that, particularly at 5 mTorr, applying the self-bias voltage increases not only the etch rate but also the etch uniformity over the processing area.

In the next section, a modified photoresist etch kinetics model combined with a spatially-varying oxygen discharge model is used to explain these experimental results.

4. Discussion

Joubert *et al.* have proposed a model for oxygen plasma etching of polymers.4) The form of the rate expression is

$$E = K\frac{(\kappa p_O)(\sigma_S \eta j_i)}{\kappa p_O + \sigma_S \eta j_i}, \qquad (1)$$

where E is the etch rate, K is a rate coefficient, p_O is the O-atom partial pressure, κ is a thermodynamic adsorption constant for O atoms, σ_S is the density of adsorption sites for O atoms, η is an ion-induced desorption rate constant (etch yield), and j_i is the ion current to the wafer substrate. Based on Eq. (1), we have previously obtained an etch rate expression with our etch rate data and simulation results for O-atom density at the substrate surface ($n_{O\text{-}sub}$) in Fig. 5 and the flux of ions incident on the substrate ($\Gamma_{i\text{-}sub}$) in Fig. 6:1,3)

$$\frac{\dfrac{n_{O-sub}}{7.05\times10^{13}}\dfrac{\Gamma_{i-sub}}{1.93\times10^{15}}}{E} = \frac{n_{O-sub}}{7.05\times10^{13}}1.89\times10^{-2} + \frac{\Gamma_{i-sub}}{1.93\times10^{15}}1.72\times10^{-3}, \qquad (2)$$

where we have assumed that σ_S, η, and κ are constant for different gas pressures and 13.56-MHz source powers. We now make a new assumption that the rate constant η is an unknown function of

V_{bias}. Taking η at $V_{bias} = 0$ as the reference value, we have in place of Eq. (2)

$$\frac{\dfrac{n_{O-sub}}{7.05\times10^{13}}\,\dfrac{\Gamma_{i-sub}}{1.93\times10^{15}}}{E} = \frac{n_{O-sub}}{7.05\times10^{13}}1.89\times10^{-2}\frac{\eta_{ref}}{\eta} + \frac{\Gamma_{i-sub}}{1.93\times10^{15}}1.72\times10^{-3}, \qquad (3)$$

Equation (3) has one variable parameter η_{ref}/η which should be a strong function of self-bias voltage, and therefore ion energy at the substrate surface. The ion energy is approximately the sum of the plasma potential (approximately 10-17 V depending on gas pressure) and the self-bias voltage. A set of etch rate data and the corresponding self-bias voltages for various gas pressures can be used to obtain the functional dependence of η/η_{ref} versus ion energy.

Figure 7 illustrates the dependence of η/η_{ref} on ion energy for gas pressures of 20 mTorr, 50 mTorr, and 100 mTorr. Since as shown in Fig. 3 the η/η_{ref} values at low pressures of 1 mTorr and 5 mTorr vary widely due to their sensitivity to a small change in the measured etch rate, we ignore them. For the high gas pressures, it appears that η/η_{ref} varies approximately with the square root of incident ion energy. The extrapolated threshold energy is about 4 V, which is typical of ion-enhanced chemical sputtering thresholds.[5)] Figure 8 shows the etch rate data as a function of both gas pressure and self-bias voltage, and the predicted etch rate from Eq. (3) using the simulation results in Figs. 5 and 6 and the η/η_{ref} values at $V_{bias} = 0$ V and -80 V in Fig. 7. As seen in Fig. 8, Eq. (3) predicts a similar trend to the experimental data at 1 mTorr and 5 mTorr. These results demonstrate that the role of ion energy in photoresist etching can be explained in terms of the collision cascade approximation in which the ion-induced desorption rate constant is a linear function of the square root of the ion energy.[6)] The square-root dependence has been also confirmed by Barone and Graves[7,8)] to be valid for the low energy range of between 20 V and 200 V, and by Gray *et al.*[5)] in their beam study of fluorine etching of silicon.

Equation (3) is also used to predict etch rate profiles along the vertical line with and without applying the self-bias voltage, using the simulation results for vertical n_{O-sub} and Γ_{i-sub} profiles in Figs. 5 and 6 and the η/η_{ref} value in Fig. 7. Figure 9 shows the predicted etch rate profiles at $\eta/\eta_{ref} = 4$ ($V_{bias} = -80$ V) and $\eta/\eta_{ref} = 1$ ($V_{bias} = 0$ V) for gas pressures of 5 mTorr and 20 mTorr. For a gas pressure of 5 mTorr, Eq. (3) predicts that the etch uniformity at $\eta/\eta_{ref} = 4$ is better than that at $\eta/\eta_{ref} = 1$. This result is in good agreement with the experimental data in Fig. 4. At a low pressure with a high η/η_{ref} value, the second term of the right-hand side of Eq. (3) dominates the first term, resulting in an etch profile similar to the O-atom density profile. As can be seen in Figs. 5 and 6, the O-atom density profile is more uniform than the ion flux profile, which leads to the better etch uniformity at 5 mTorr with $\eta/\eta_{ref} = 4$ than with $\eta/\eta_{ref} = 1$ as predicted in Fig. 9.

5. Conclusions

We have investigated the effect of incident ion energy on photoresist etching in the LAPS by applying a self-bias voltage to the substrate holder. The etch rate increases with increasing ion energy, and an increase in the ion energy leads to etch-uniformity improvement, particularly at a low pressure of 5 mTorr. In order to explain these experimental results, we have modified a previous photoresist etch kinetics model, introducing the functional dependence of the etch yields versus ion energy. The etch yields vary approximately with the square root of incident ion energy, indicating that the role of ion energy in photoresist etching can be explained in terms of the collision cascade approximation. We have compared the experimental etch data with the results predicted by the modified etch kinetics model. The model and experimental results are generally in good agreement, demonstrating that the modeling approach gives increased understanding of the effect of ion energy on the photoresist etch process.

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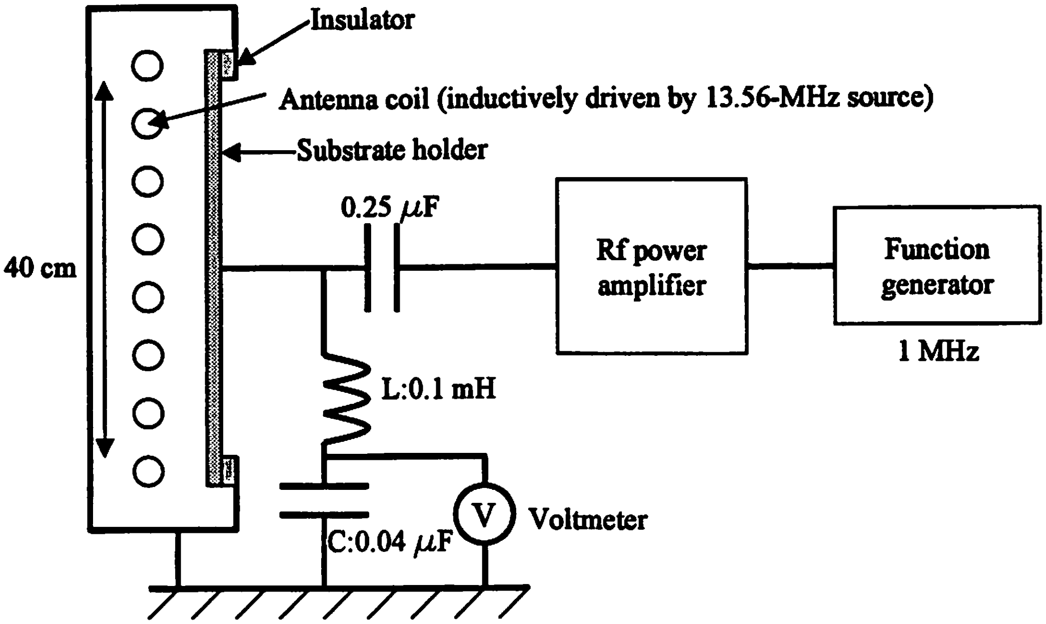

Fig. 1. Dc self-biasing system and probe with L and C sized for 1-MHz operation.

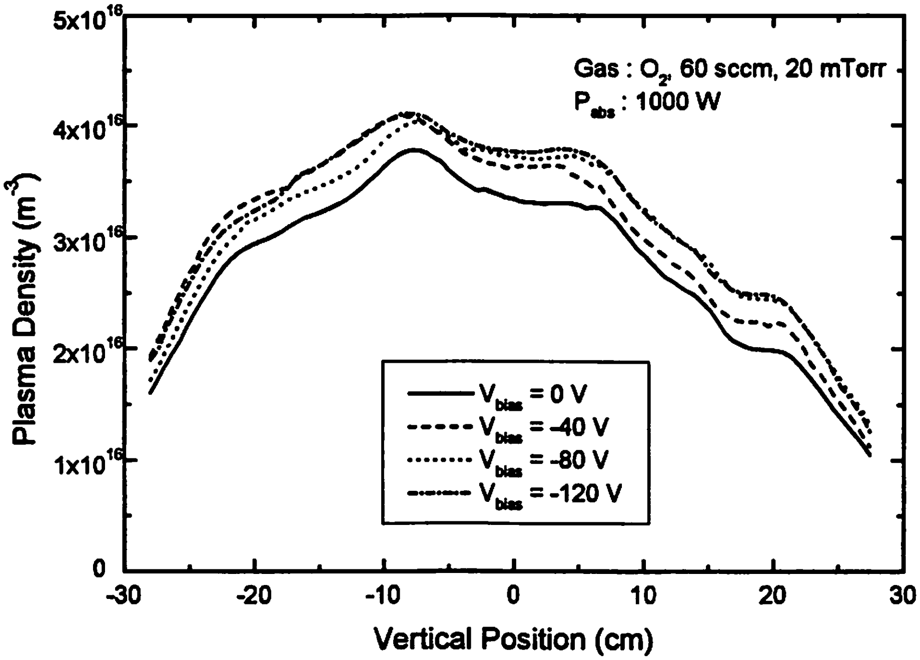

Fig. 2. Plasma density profiles for various self-bias voltages at a gas pressure of 20 mTorr.

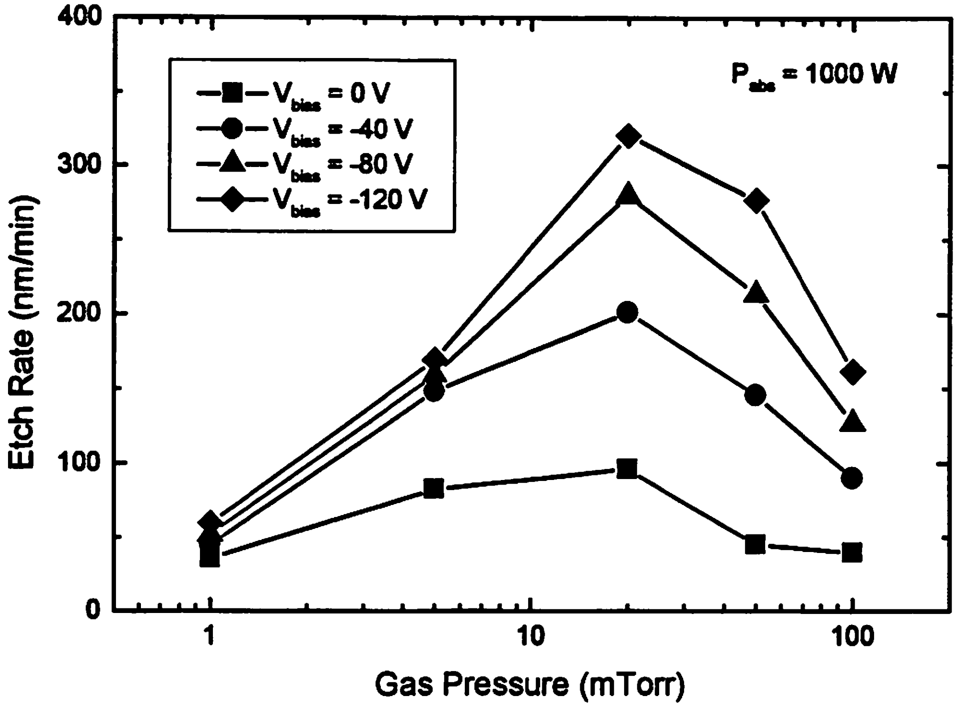

Fig. 3. Etch rate at the center of the substrate holder as a function of gas pressure for various self-bias voltages.

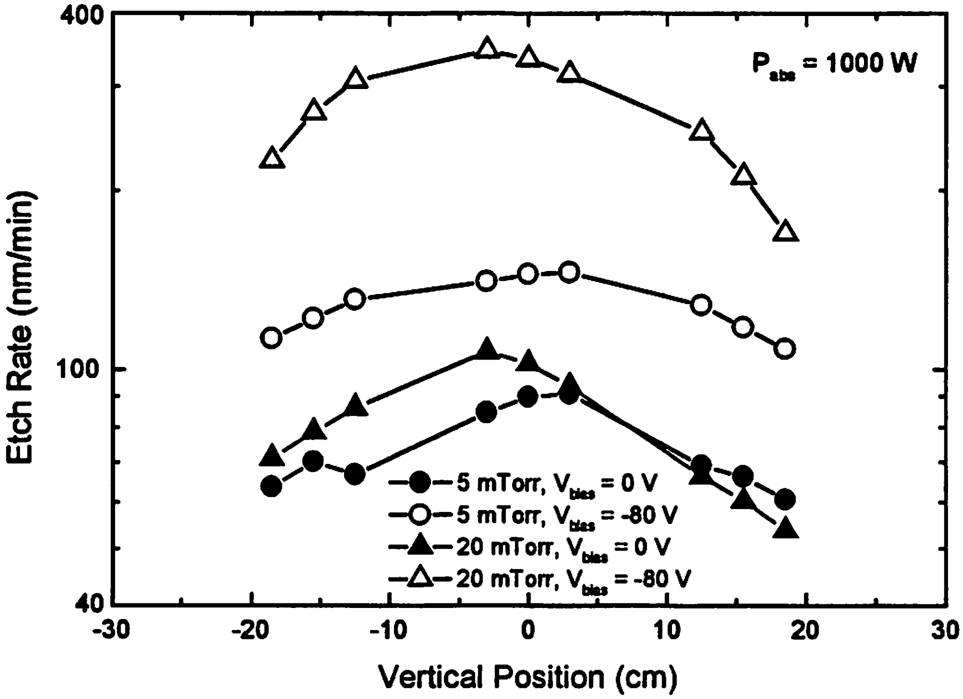

Fig. 4. Vertical etch rate profiles with and without applying a self-bias voltage for gas pressures of 5 mTorr and 20 mTorr.

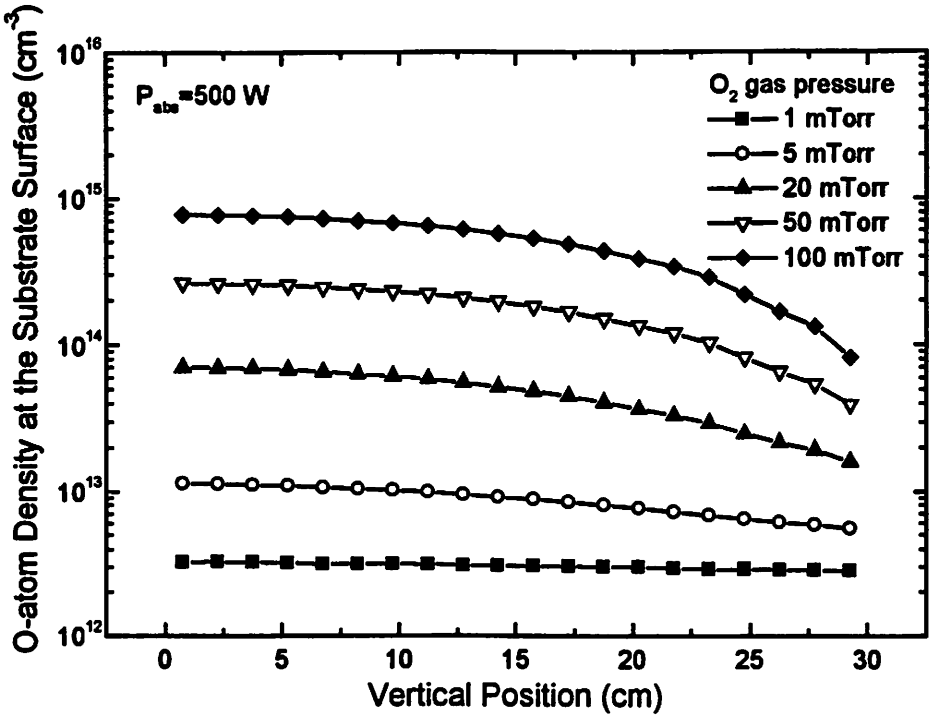

Fig. 5. Vertical O-atom density profiles at the substrate surface for various gas pressures (simulation results).

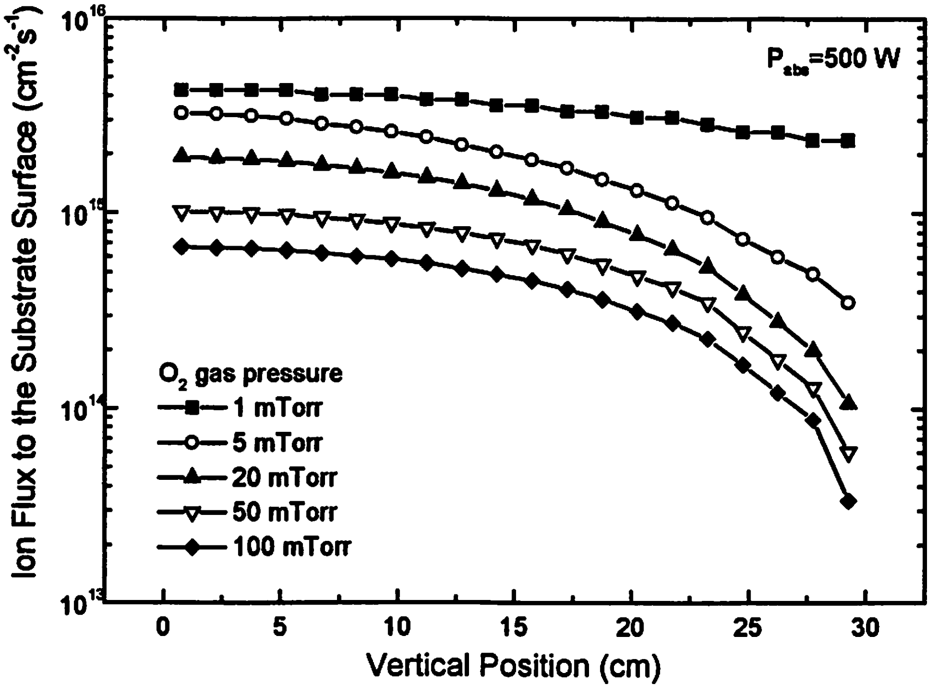

Fig. 6. Vertical ion flux profiles incident on the substrate surface for various gas pressures (simulation results).

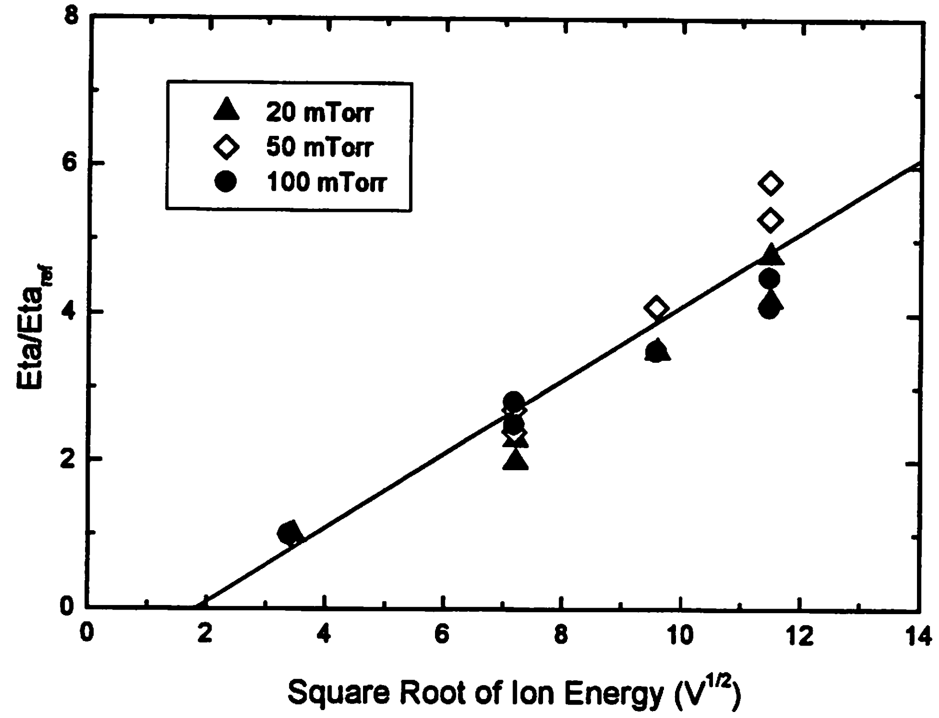

Fig. 7. Dependence of η/η_{ref} on ion energy for gas pressures of 20 mTorr, 50 mTorr, and 100 mTorr.

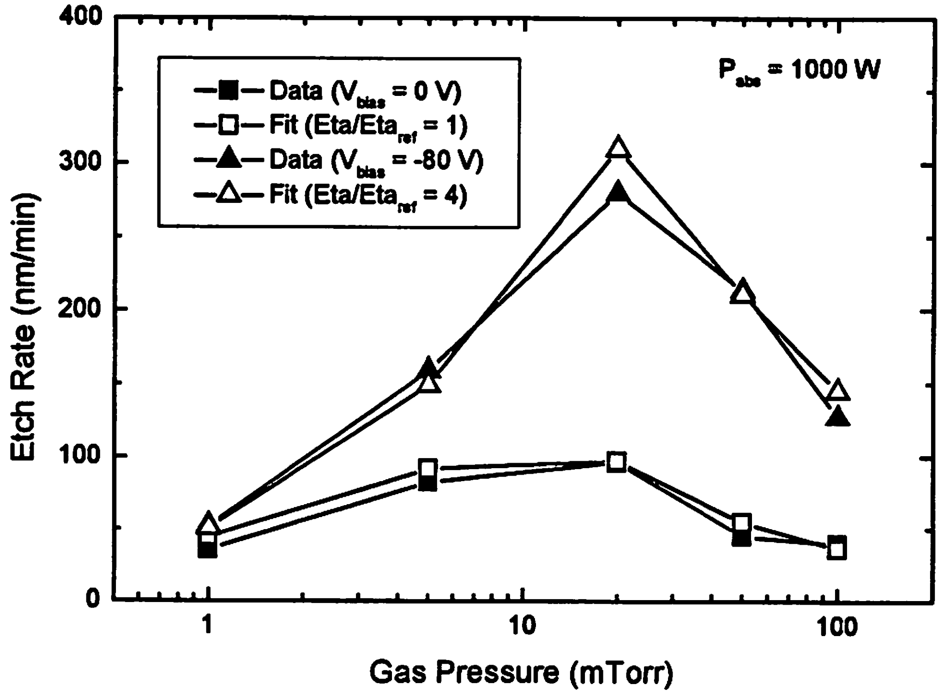

Fig. 8. Plots of etch rate at the center of the substrate holder vs gas pressure. The fits are from Eq. (3), with the simulation results and the η/η_{ref} values in Fig. 7.

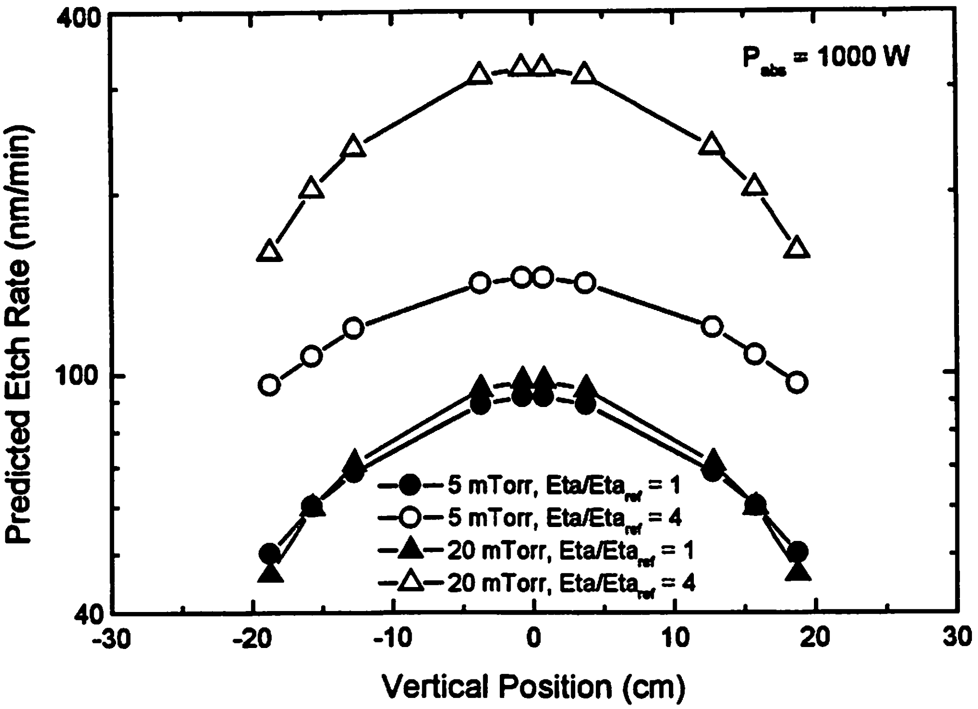

Fig. 9. Predicted etch rate profiles at $\eta/\eta_{ref} = 1$ and $\eta/\eta_{ref} = 4$ for gas pressures of 5 mTorr and 20 mTorr.