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IN A LARGE AREA PLASMA SOURCE: O₂/Ar
MIXTURE PLASMA MODELING AND
PHOTORESIST ETCHING**

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Effect of Ar Addition to an O₂ Plasma in a Large Area Plasma Source: O₂/Ar Mixture Plasma Modeling and Photoresist Etching

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ABSTRACT

We report on the effect of Ar addition to an oxygen plasma on photoresist etching in the LAPS. We also develop a simplified spatially-varying O₂/Ar mixture discharge model corresponding to the LAPS in a two-dimensional geometry in order to account for the effect of Ar addition. A photoresist etch kinetics model and spatially-varying O₂/Ar mixture discharge model are used to explain the experimental data. We find that the addition of 50% Ar increases the plasma density and etch rate approximately by a factor of two. From the simulation, we find that argon metastables (Ar*) play an important role in the mixture plasma. The simulation predicts an enhancement in O-atom density ratio due to Ar addition over that due to the dilution of the feed gas. The experimental data and predicted etch rates from the simulation are generally in good agreement, indicating that the increase in the etch rate with Ar addition is due to both the increase in the plasma density and the enhancement in O-atom density attributable to the dissociation of O₂ by Ar*.

1. Introduction

For an inductively coupled, traveling wave driven, large area plasma source (LAPS), we have previously developed a simplified spatially-varying oxygen discharge model and photoresist etch kinetics model in order to explain the etch rate behavior dependence on the oxygen gas pressure.^{1,2}

Mixtures of reactive and rare gases are often used for thin film etching and deposition in microelectronics fabrication. Several studies have been conducted to determine the effect of adding rare gases to reactive gas plasmas. Bassett *et al.* have developed a Cl₂/Ar mixture discharge model and have found that argon metastables (Ar*) can induce the dissociation of chlorine when Ar is added to Cl₂.³ Booth *et al.* have observed that the addition of Kr to an O₂ plasma increases the degree of dissociation in their O-atom actinometry experiments.⁴

In this letter, we investigate the effect of Ar addition to an oxygen plasma on photoresist etching in the LAPS. We also describe a simplified spatially-varying O₂/Ar mixture discharge model corresponding to the LAPS in a simplified two-dimensional geometry in order to account for the effect of Ar addition. Specifically a 50% O₂-50% Ar discharge is compared to a pure O₂ discharge. The photoresist etch kinetics model and spatially-varying O₂/Ar mixture discharge model are used to understand the experimental data.

2. Experiments

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 equally spaced along the antenna coil.

Figure 1 shows O₂/Ar mixture plasma density profiles for different mixing ratios at a total gas pressure of 20 mTorr and an rf power of 1000 W. We see that the plasma density increases as the Ar fraction increases. The addition of 50% Ar increases the plasma density by a factor of 2. In a noble gas like Ar, the collisional energy loss per electron-ion pair created can be lower than for a molecular gas like O₂ at the same electron temperature, resulting in the higher plasma density.⁵

For the measurements of photoresist etch rate, half of a four-inch silicon wafer with 2 μm of hardbaked Novolak photoresist was clamped at the center of the processing area. Typical operating parameters were a total gas pressure of between 1 and 50 mTorr and an rf source power of 1000 W.

Figure 2 shows the dependence of the etch rate on the Ar fraction for a total gas pressure of 20 mTorr. Upon adding 50% of Ar the etch rate is increased approximately by a factor of two and further addition of Ar decreases the etch rate.

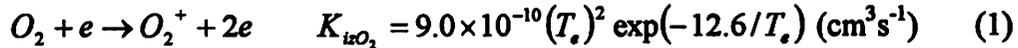
Figure 3 shows the etch rate as a function of both gas pressure and substrate bias voltage (V_{bias}), for a pure O_2 plasma (solid symbols) and an O_2/Ar mixture with 50% O_2 -50% Ar (open symbols). The effect of applying a substrate bias on photoresist etching has been previously reported.² We see that the addition of 50% Ar increases the etch rate for gas pressures of 1, 5, 20, and 50 mTorr. If the O-atom density were proportional to O_2 partial pressure, we would not see such an etch rate behavior. In order to explain the etch rate data in Fig. 3, a simplified O_2/Ar mixture discharge model are introduced in the next section.

3. O_2/Ar mixture discharge model

The O_2/Ar mixture discharge model we will describe below is similar to the previously developed oxygen discharge model,¹ except that reactions for Ar and Ar^* are included. For Ar^* loss processes, we include the collisional de-excitation with electrons and the dissociation of O_2 by Ar^* . We also include wall quenching, in which Ar^* is de-excited upon striking the chamber walls.

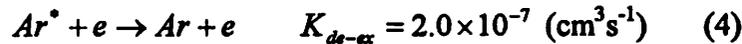
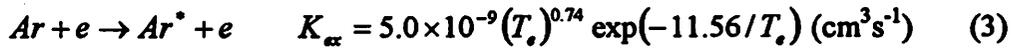
Assumptions of our model are listed below.

- (1) Steady state is assumed.
- (2) For simplicity, 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) The mixing ratio of $O_2/Ar = 1/1$ is assumed.
- (4) We take into account the following two reactions for the ionization process.^{5,6}



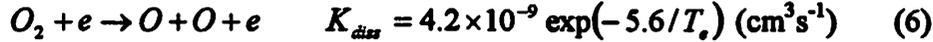
where K_{izO_2} is the molecular oxygen ionization rate constant and K_{izAr} is the argon ionization rate constant.

- (5) The following reactions for Ar and Ar^* are included.^{7,8}



K_{diss^*} has been estimated from similar reactions in Cl_2/Ar and F_2/Ar mixtures.^{3,7} By assuming K_{diss^*} is inversely proportional to the molecular bond strength, with $K_{diss^*}=4.7 \times 10^{-10} \text{ cm}^3\text{s}^{-1}$ for Cl_2 with bond strength 250 kJ/mol, and with $K_{diss^*}=6.2 \times 10^{-10} \text{ cm}^3\text{s}^{-1}$ for F_2 with bond strength 160 kJ/mol, we obtain for O_2 with bond strength 490 kJ/mol that $K_{diss^*}=2.4 \times 10^{-10} \text{ cm}^3\text{s}^{-1}$.

(6) In addition to reaction (5), the following reaction is included for the oxygen dissociation.^{5,6}



(7) The ion loss velocity is the Bohm velocity $u_B = (eT_e/M_{Av})^{1/2}$, where M_{Av} is the average ion mass.

(8) The ion temperature T_i and neutral species temperature T_n are assumed to be 0.05 V for gas pressures ranging from 1 mTorr to 100 mTorr.

Solving Eq. (7) as an eigenvalue problem with the proper boundary conditions gives the plasma density profile and the electron temperature:

$$\nabla^2 n(x, y) + n(x, y) \frac{K_{izAr} n_{Ar} + K_{izO_2} n_{O_2}}{D_a} \sum_{i=1}^8 \exp\left(\frac{R - r_i(x, y)}{\lambda_{iz-Av}}\right) = 0 \quad (7)$$

where $n(x, y) = n_i(x, y) = n_e(x, y)$ is the plasma density profile and $D_a = (T_e/T_i)^{1/2} u_B / (n_{O_2} + n_{Ar}) \sigma_i$ is the ambipolar diffusion coefficient, with $u_B = (2eT_e / (M_{Ar} + M_{O_2}))^{1/2}$ the mean Bohm velocity, $\sigma_i = 10^{-14} \text{ cm}^2$ the ion-neutral cross section, and n_{O_2} and n_{Ar} the gas densities. We incorporate an exponentially decreasing electron-neutral ionization around each quartz tube, where R is the radius of the quartz tubes, $r_i(x, y)$ is the distance from the center of each quartz tube, and λ_{iz-Av} is the average electron-neutral ionization length. For the mixture of $O_2/Ar = 1/1$, we use the following expression for the ionization length:

$$\lambda_{iz-Av} = \frac{\lambda_{iz(Ar)} + \lambda_{iz(O_2)}}{2} = \frac{125}{p(\text{mTorr})} + \frac{80}{p(\text{mTorr})} \text{ (cm)}, \quad (8)$$

which is consistent with previous expression used for argon and oxygen discharges.^{1,9}

Using the obtained electron temperature T_e and plasma density profile $n(x, y)$, we solve a diffusion equation (9) to determine the Ar^* density profile:

$$-D_{Ar^*} \nabla^2 n_{Ar^*}(x, y) = K_{ex} n_{Ar} n(x, y) - K_{de-ex} n_{Ar^*}(x, y) n(x, y) - K_{diss^*} n_{Ar^*}(x, y) n_{O_2} \quad (9)$$

with the following boundary condition (10):

$$-D_{Ar^*} \nabla n_{Ar^*}(x, y) |_{walls} = \frac{1}{4} n_{Ar^*}(x, y) \overline{v_{O_2-Ar, Ar^*}}, \quad (10)$$

where $D_{Ar^*} = \frac{\pi}{8} \frac{1}{(n_{O_2} + n_{Ar}) \sigma_{O_2-Ar, Ar^*}} \overline{v_{O_2-Ar, Ar^*}}$ is the diffusion coefficient with $\sigma_{O_2-Ar, Ar^*} = 5 \times 10^{-15} \text{ cm}^2$ the cross section and $\overline{v_{O_2-Ar, Ar^*}} = 8.2 \times 10^4 \text{ cm/s}$ the mean speed.

Using the obtained plasma density profile $n(x, y)$ and Ar^* density profile $n_{Ar^*}(x, y)$, we solve another diffusion equation (11) to determine the O-atom density profile $n_O(x, y)$:

$$-D_O \nabla^2 n_O(x, y) = 2K_{\text{dis}} n(x, y) n_{O_2} + 2K_{\text{dis}^*} n_{Ar^*}(x, y) n_{O_2}, \quad (11)$$

with the same expression for D_O and boundary conditions as in the previous work,¹ in which the metal-surface recombination coefficient γ_{metal} is assumed to be 0.1 and quartz-surface recombination coefficient γ_{quartz} is assumed to be 0.0001.

The overall discharge energy balance can be expressed as

$$P_{\text{abs}} = e \oint_{\text{walls}} E_T \Gamma_i dS, \quad (12)$$

where P_{abs} is the power absorbed by the plasma, E_T is the total energy loss, dS is the area element for particle loss, and Γ_i is the ion flux to the wall surfaces. E_T is the sum of the collisional energy loss per electron-ion pair created and kinetic energy carried to the walls by electrons and ions.⁵ After the density profiles are computed from Eqs. (7), (9), and (11), Eq. (12) is solved to determine the absolute magnitude of the densities in the system.

4. Discussion

We first describe how the computed plasma density and T_e change depending on the plasma gas composition. Figures 4(a), (b), and (c) show the computed plasma density profiles for a pure Ar, O₂/Ar mixture, and pure O₂ discharges, respectively, at a gas pressure of 20 mTorr. The corresponding electron temperature is also shown in the figures. For the pure Ar plasma, Eq. (7) was solved with $n_{O_2}=0$. For the pure O₂ plasma, Eq. (7) was solved with $n_{Ar}=0$. As seen in these figures, the variation of plasma density is similar to the experimental result in Fig. 1, with the plasma density increasing with increasing the Ar fraction. We also see that T_e decreases with increasing Ar fraction. This result physically means $K_{\text{izAr}} / D_{a(\text{Ar})} > K_{\text{izO}_2} / D_{a(\text{O}_2)}$ for the T_e with zero Ar fraction, where $D_{a(\text{Ar})}$ and $D_{a(\text{O}_2)}$ are the ambipolar diffusion coefficients for the pure Ar and O₂ plasmas.

Figures 5(a) and (b) show the computed Ar* density profiles for a pure Ar plasma and an O₂/Ar mixture with 50% O₂-50% Ar, respectively, at a total gas pressure of 20 mTorr. The Ar* density for the pure Ar plasma is higher by a factor of 50 compared to that for the mixture. The same trend has been observed for a Cl₂/Ar discharge simulation³ and laser-induced fluorescence (LIF) measurement,¹⁰ in which the Ar* density was estimated to be $\sim 10^{11}$ cm⁻³ for pure Ar and a drop in the LIF intensity by an order of magnitude was observed for the Cl₂/Ar mixture. Figure 5(c) shows the computed Ar* density profiles for an O₂/Ar mixture with 50% O₂-50% Ar at a total gas pressure of 5 mTorr. Comparing Fig. 5(b) and 5(c), the Ar* density is higher at the lower gas pressure. The similar trend has been observed for a Cl₂/Ar discharge simulation³. For the pure Ar plasma, the primary loss mechanisms of Ar* are

collisions with electrons and wall quenching, while for the mixture it is collisions with O₂.

Figure 6 shows the dependence of computed T_e on total gas pressure for a pure O₂ plasma and an O₂/Ar mixture with 50% O₂-50% Ar. The trends are similar, with T_e decreasing with increase pressure.

Figures 7(a) and (b) show the computed O-atom density profiles for a pure O₂ plasma and an O₂/Ar mixture with 50% O₂-50% Ar, respectively, at a gas pressure of 20 mTorr. From Eq. (11) with the results in Figs. 4(b), (c), and 5(b), the predicted O-atom density ratio for 20 mTorr scales as

$$\frac{n_o(O_2/Ar)}{n_o(O_2)} \approx \frac{2K_{diss}(O_2/Ar)n(O_2/Ar)n_{O_2}(O_2/Ar) + 2K_{diss}n_{Ar^*}n_{O_2}}{2K_{diss}(O_2)n(O_2)n_{O_2}(O_2)} \approx 0.6,$$

which is in good agreement with the ratio seen in Figs. 7 (a) and (b). Figures 8(a) and (b) show the computed O-atom density profiles for a pure O₂ plasma and the mixture, respectively, at a gas pressure of 5 mTorr. The O-atom density ratio for 5 mTorr is estimated to be ~0.8, which is larger than that for 20 mTorr. The larger enhancement in O-atom density ratio for 5 mTorr due to Ar addition over that due to the dilution of the feed gas can be attributed to the changes in the Ar* density and the electron temperature, which in turn affect the generation and loss for the O atoms.

Figure 9 shows the computed ion flux to the substrate surface (Γ_{i-sub}) at various gas pressures for the pure O₂ plasma and the mixture. We see that Γ_{i-sub} is higher for the mixture than the pure O₂ plasma, which is consistent with the results in Figs. 4(b) and (c).

Figure 10 shows the computed O-atom density at the substrate surface (n_{O-sub}) at various gas pressures for the pure O₂ plasma and the mixture. As the total gas pressure decreases, the difference in n_{O-sub} between the pure O₂ plasma and the mixture becomes small, which is consistent with the results in Figs. 7 and 8.

Using the simulation results in Figs. 9 and 10, we predict the photoresist etch rate based on a previously developed expression (13):²

$$\frac{n_{O-sub}}{E} \frac{\Gamma_{i-sub}}{1.93 \times 10^{15}} = \frac{n_{O-sub}}{7.05 \times 10^{13}} 1.89 \times 10^{-2} \frac{\eta_{ref}}{\eta} + \frac{\Gamma_{i-sub}}{1.93 \times 10^{15}} 1.72 \times 10^{-3}, \quad (13)$$

where η_{ref}/η is the relative etch yield depending on substrate bias voltage. Figure 11 illustrates the etch rate data as a function of both gas pressure and substrate bias voltage (V_{bias}), for the O₂/Ar mixture with 50% O₂-50% Ar, and the predicted etch rate from Eq. (13) with the simulation results in Figs. 9 and 10. Equation (13) predicts a somewhat lower etch rate than the experimental data for $V_{bias}=0$ V, but does predict the general trend, with the etch rate increasing with Ar addition as seen in Fig. 3. If we solve only Eq. (7) and Eq. (11) without the second term on the right-hand side, ignoring the Ar* contribution,

then the predicted etch rates becomes still lower than those in Fig. 11. The increase in the etch rate with Ar addition is, therefore, due to not only the increase in Γ_{i-sub} but also the enhancement in n_{O-sub} attributable to dissociation of O₂ by Ar*. Ar* has a relatively high energy and also a long lifetime because its transition to the ground state is forbidden. Consequently, Ar* can influence actively the plasma chemistry and therefore the etch processing.

5. Conclusions

The effect of Ar addition to an O₂ plasma on photoresist etching has been investigated in the LAPS. We have also developed a simplified spatially-varying O₂/Ar (O₂ : Ar = 1 : 1) mixture discharge model corresponding to the LAPS in a two-dimensional geometry in order to account for the effect of Ar addition.

The mixture plasma density increases as the Ar fraction increases. The addition of 50% Ar increases the plasma density by a factor of two. The addition of Ar increases the etch rate for gas pressures of 1, 5, 20, and 50 mTorr. Particularly, for $V_{bias}=0$ V, the etch rate is approximately doubled by the addition of 50% Ar. From the simulation results, we have found that argon metastables (Ar*) play an important role in the mixture plasma. The simulation predicts an enhancement in O-atom density ratio due to Ar addition over that due to the dilution of the feed gas depending on the total gas pressure. This can be attributed to the changes in the Ar* density and the electron temperature. The experimental data and predicted etch rates from the simulation are generally in good agreement, indicating that the increase in the etch rate with Ar addition is due to both the increase in the plasma density and the enhancement in O-atom density attributable to the dissociation of O₂ by Ar*.

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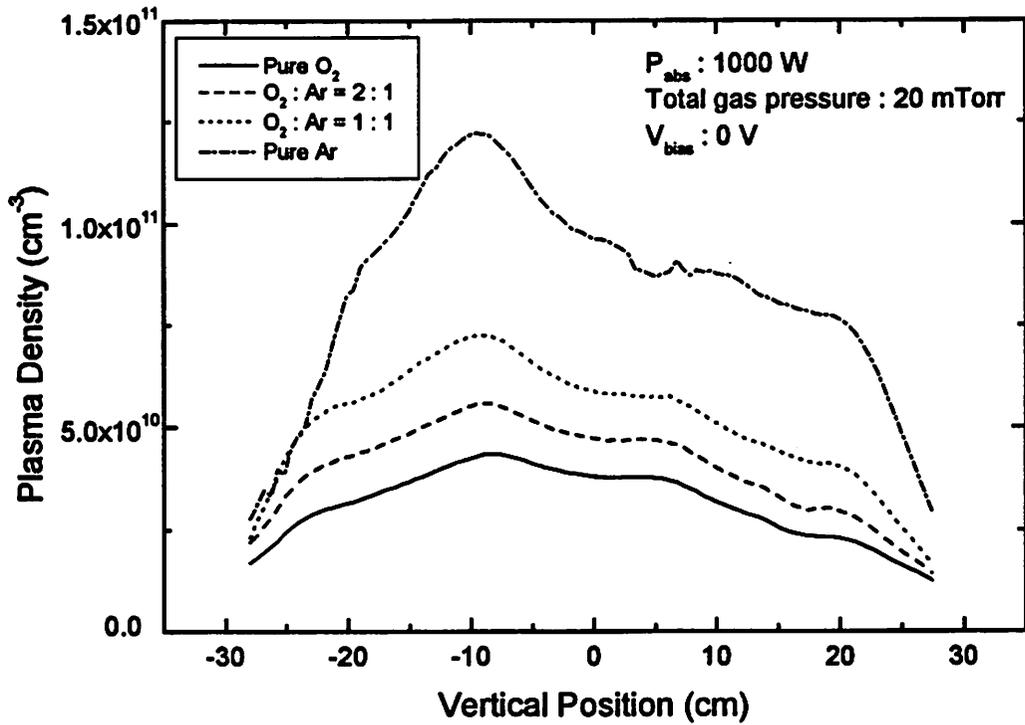


Fig. 1. O₂/Ar mixture plasma density profiles for different mixing ratios.

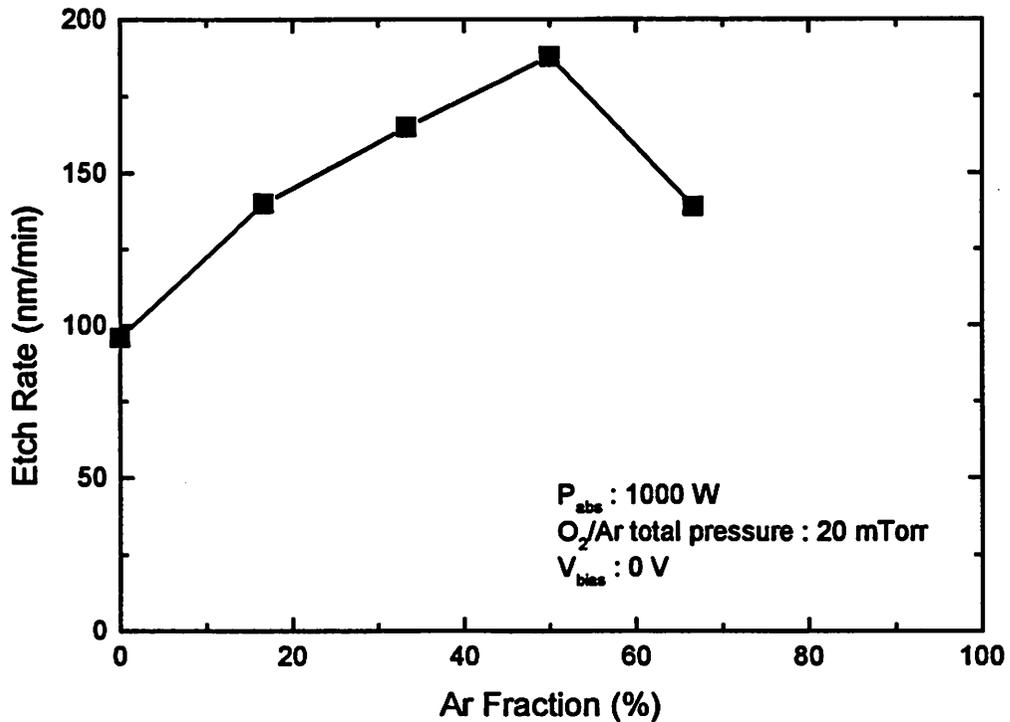


Fig. 2. Dependence of the etch rate on Ar fraction for a total gas pressure of 20 mTorr.

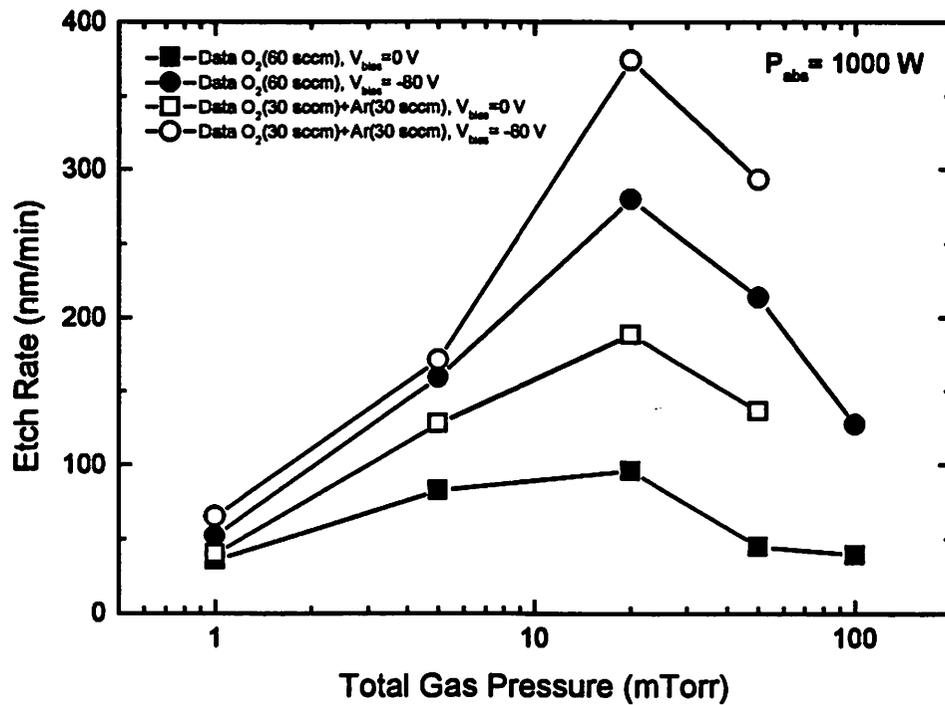


Fig. 3. Etch rate as a function of gas pressure for a pure O₂ plasma and O₂/Ar mixture with 50% O₂-50% Ar.

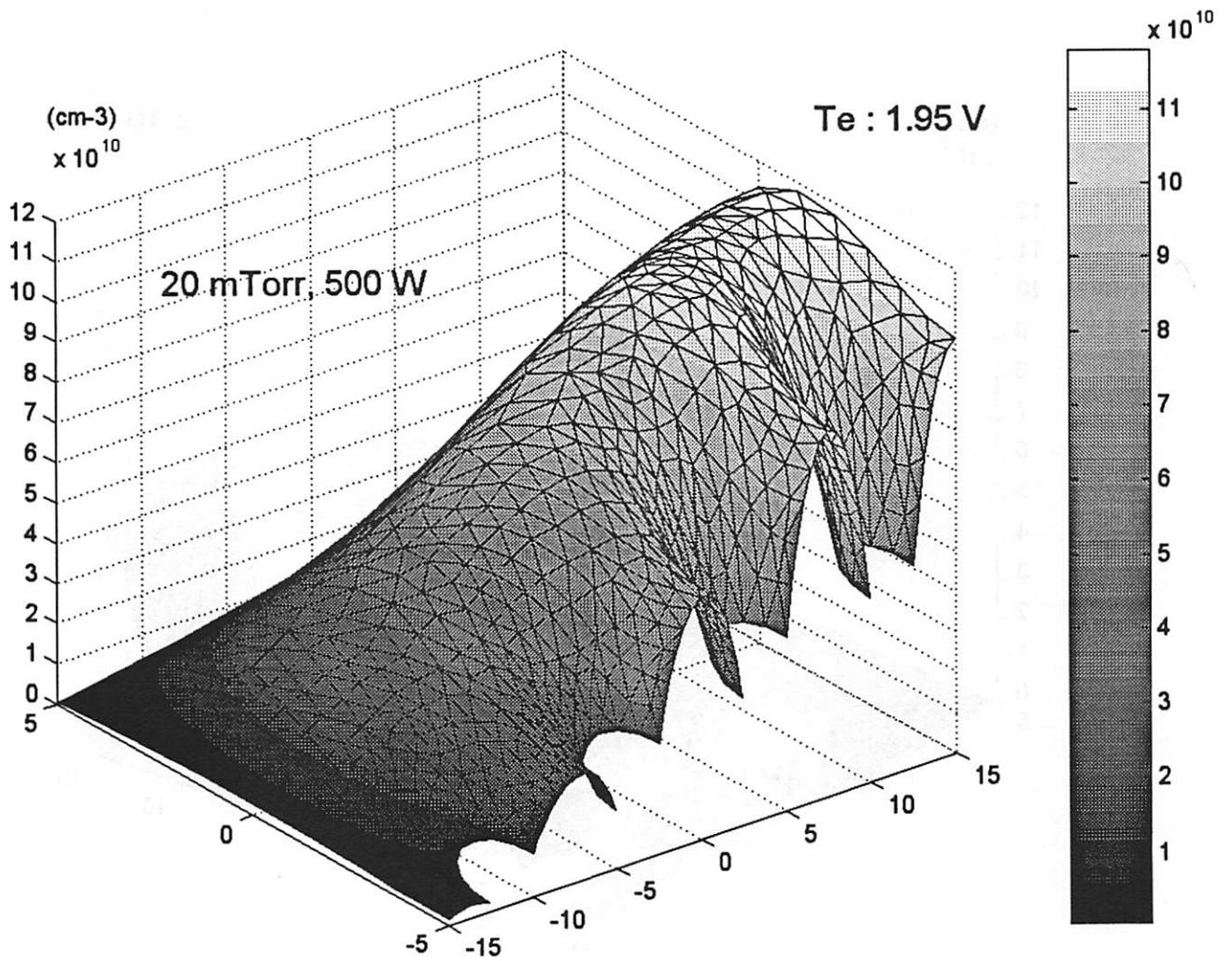


Fig. 4(a). Plasma density profile for a pure Ar discharge.

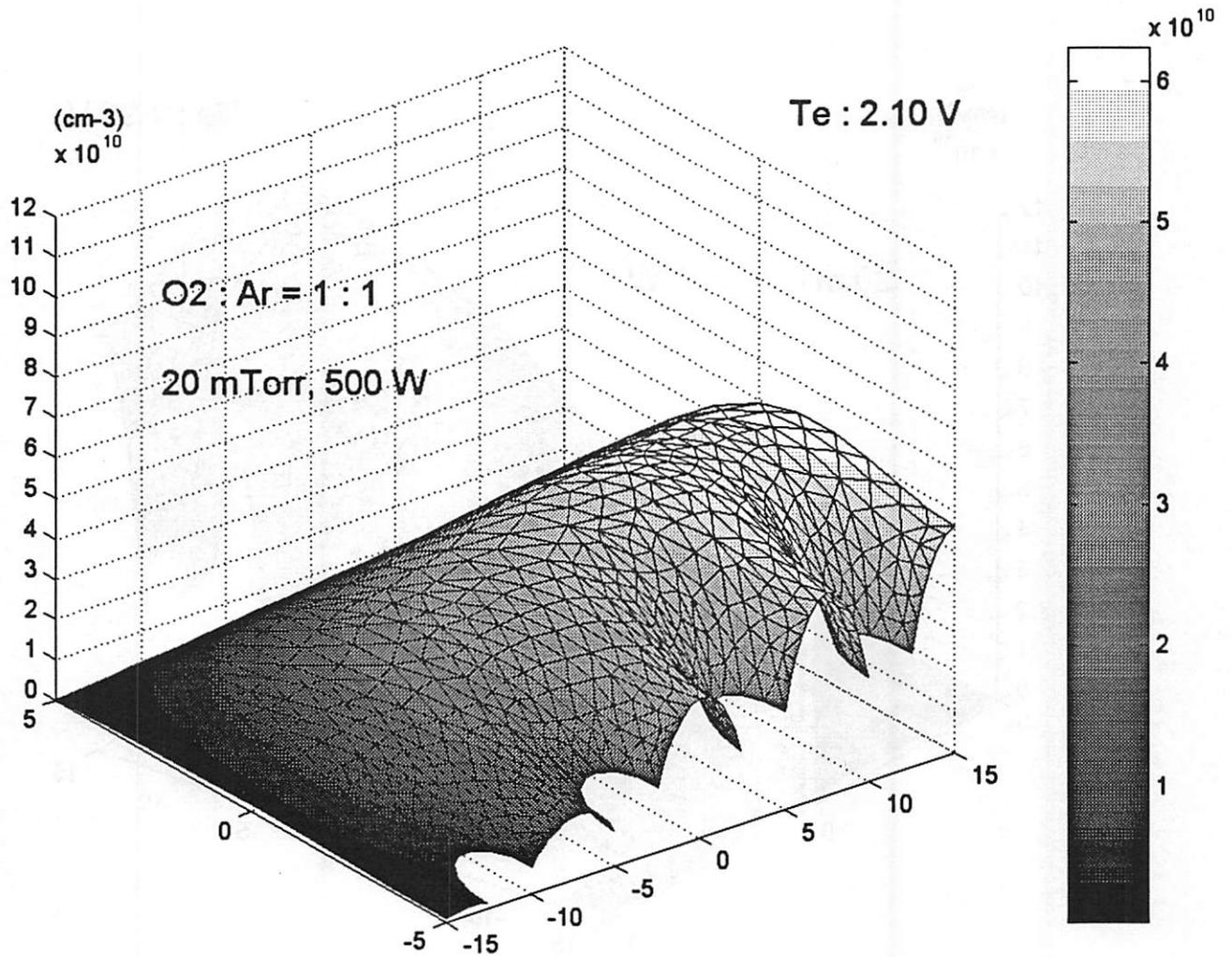


Fig. 4(b). Plasma density profile for an O₂/Ar mixture discharge.

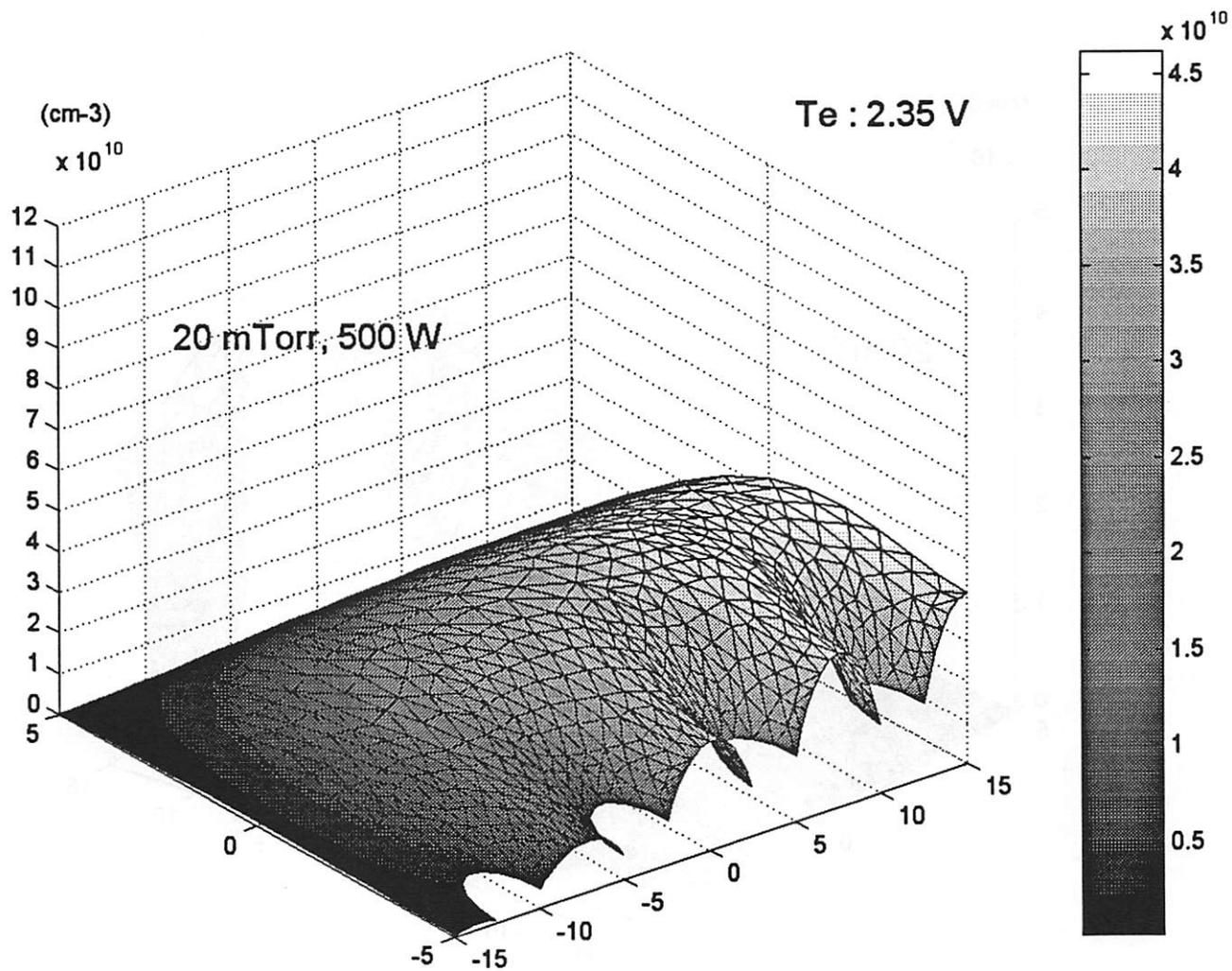


Fig. 4(c). Plasma density profile for a pure O₂ discharge.

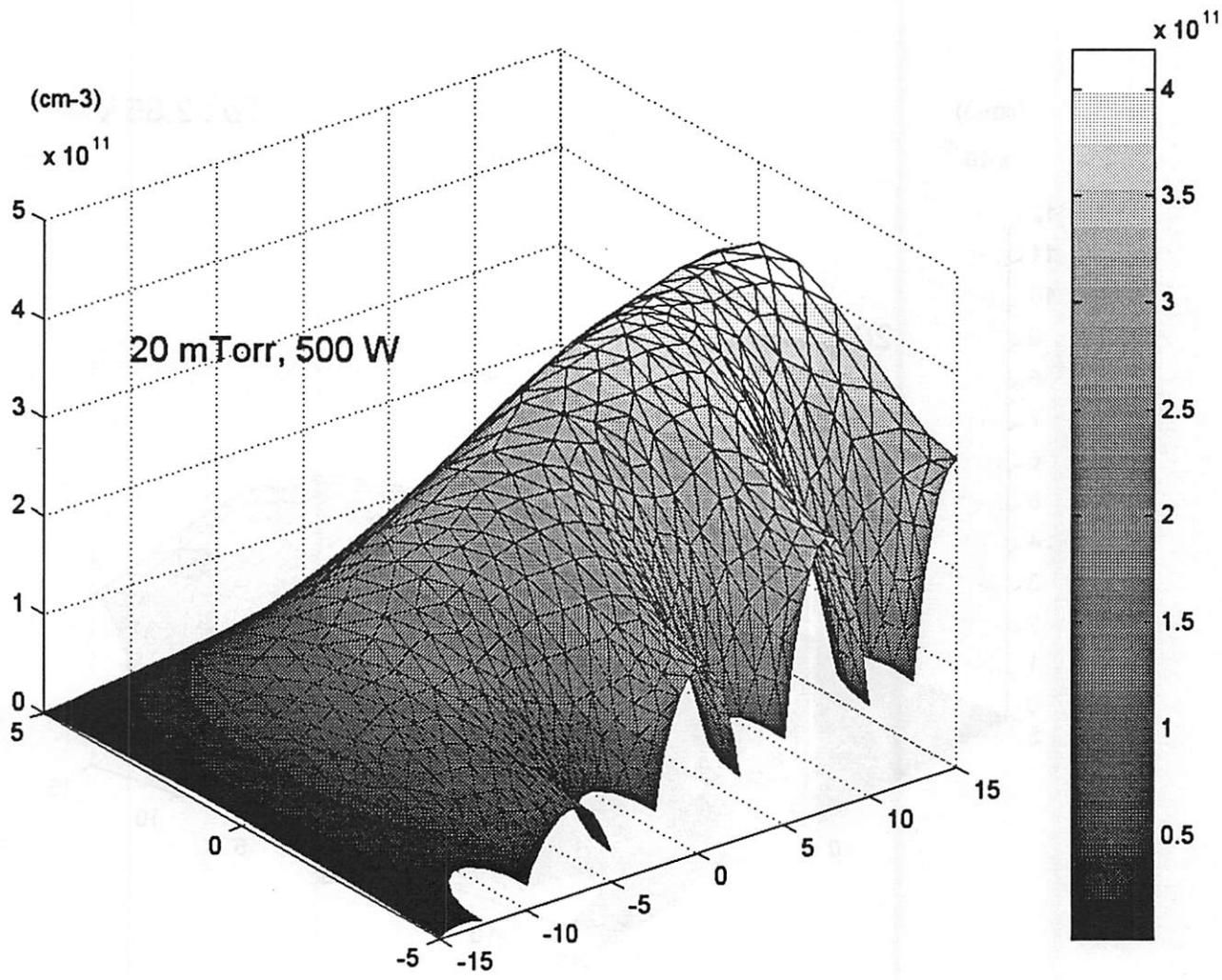


Fig. 5(a). Ar* density profile for a pure Ar discharge at 20 mTorr.

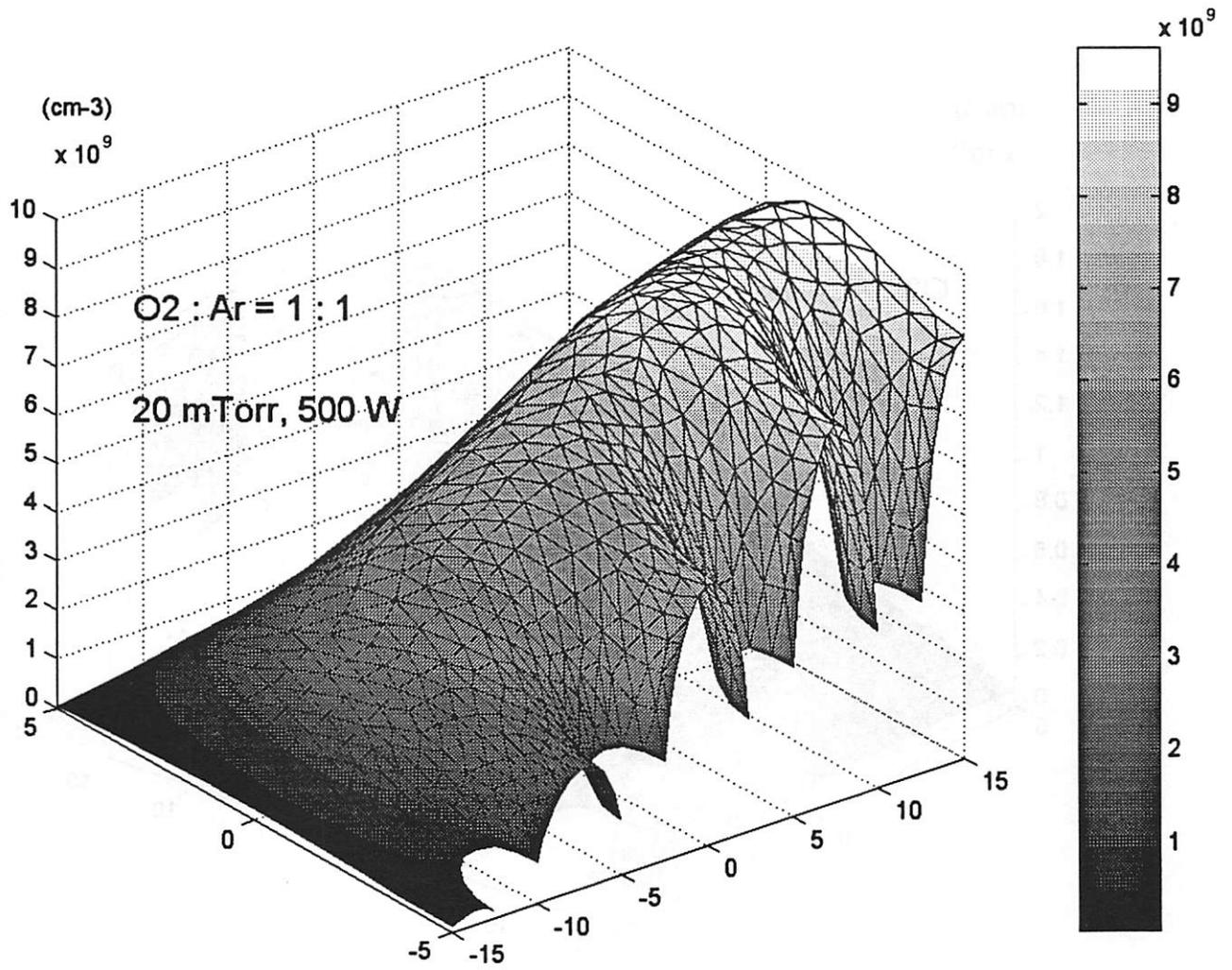


Fig. 5(b). Ar* density profile for an O₂/Ar mixture discharge at 20 mTorr.

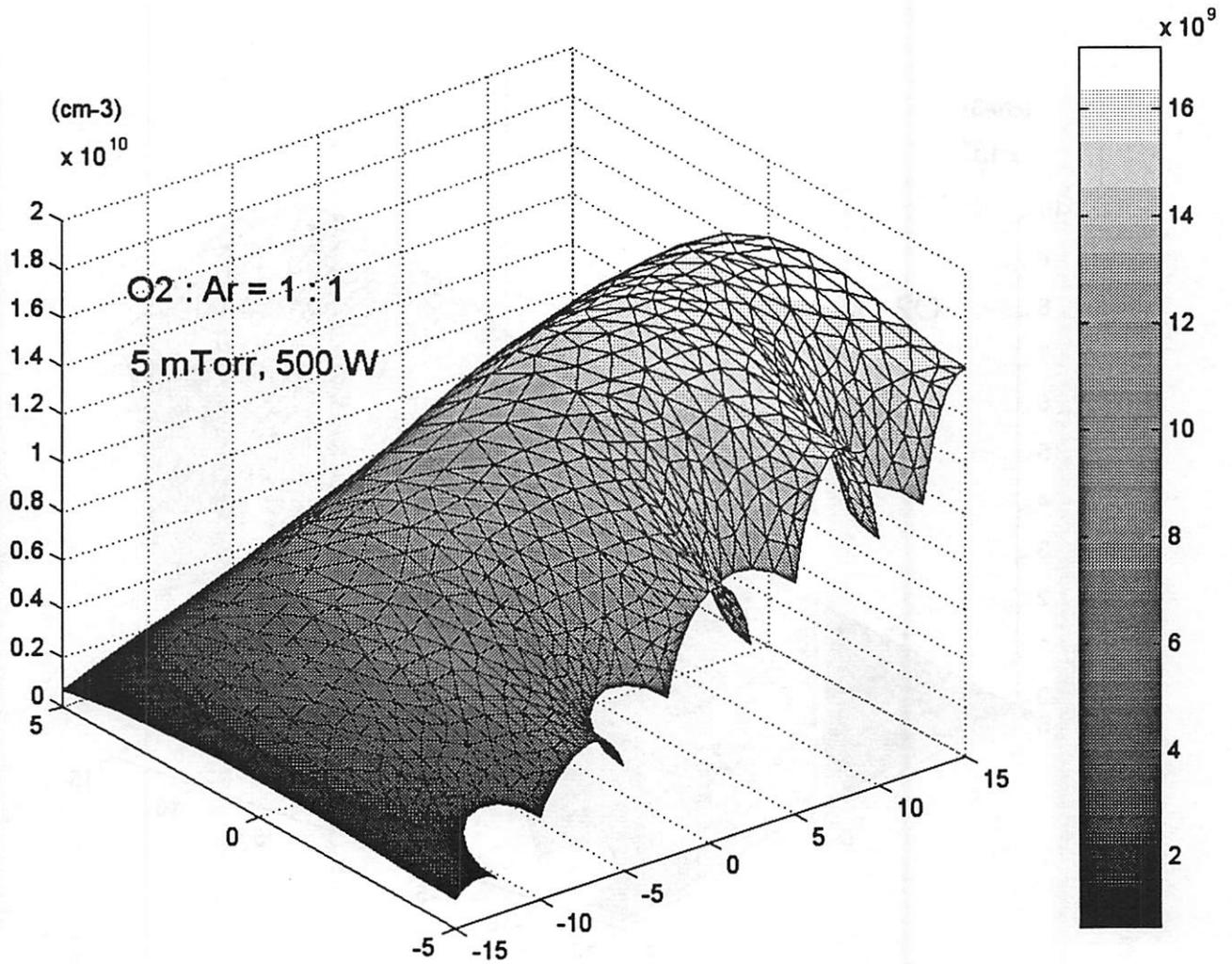


Fig. 5(c). Ar* density profile for an O₂/Ar mixture discharge at 5 mTorr.

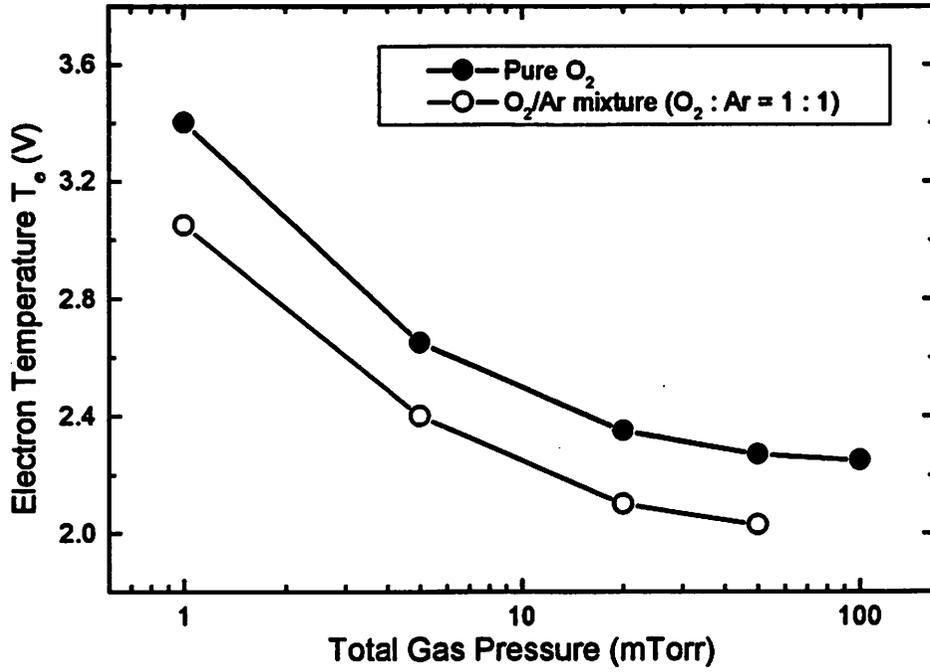


Fig. 6. Dependence of computed T_e on total gas pressure for a pure O_2 plasma and O_2/Ar mixture with 50% O_2 -50% Ar.

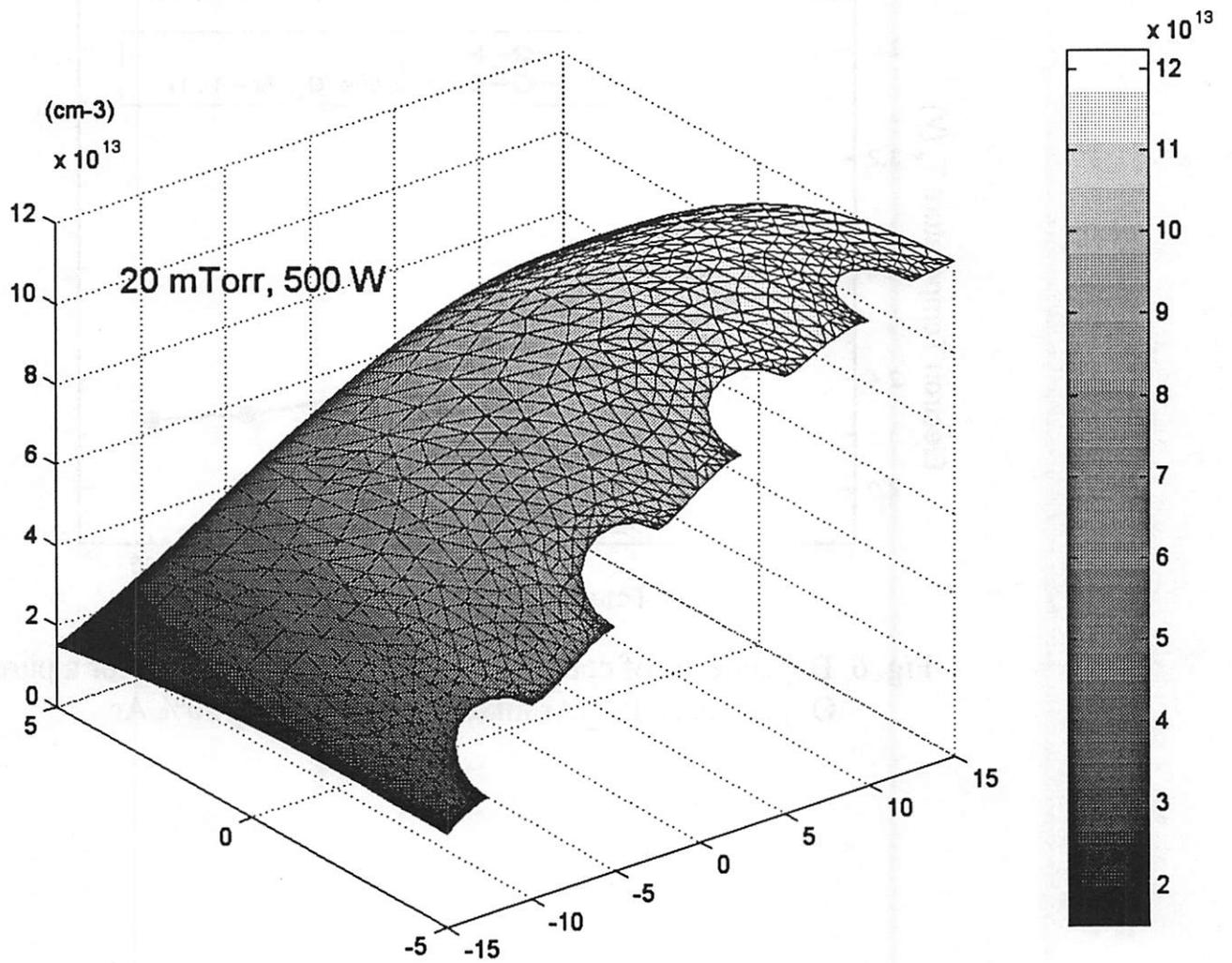


Fig. 7(a). O-atom density profile for a pure O₂ discharge at 20 mTorr.

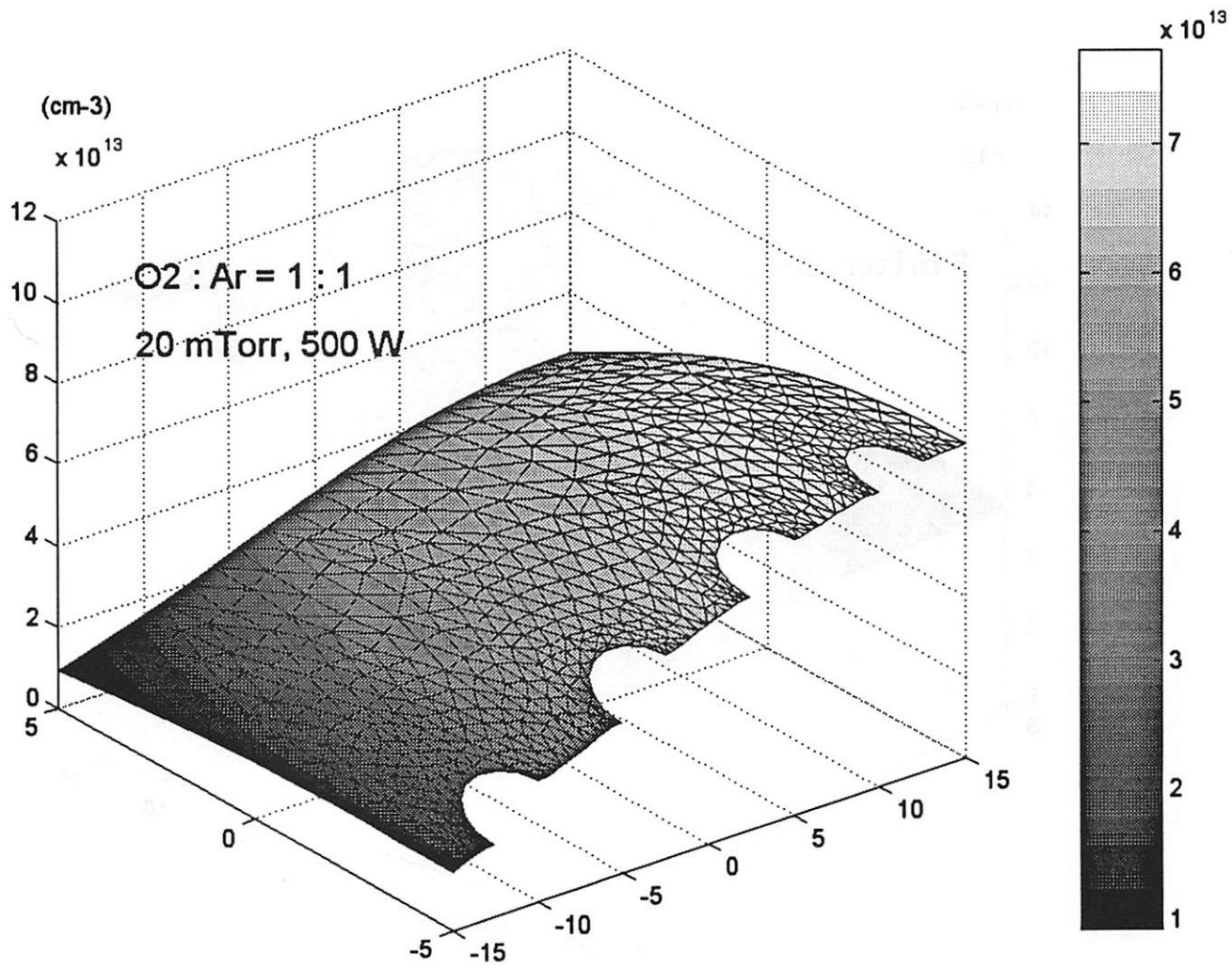


Fig. 7(b). O-atom density profile for an O₂/Ar mixture discharge at 20 mTorr.

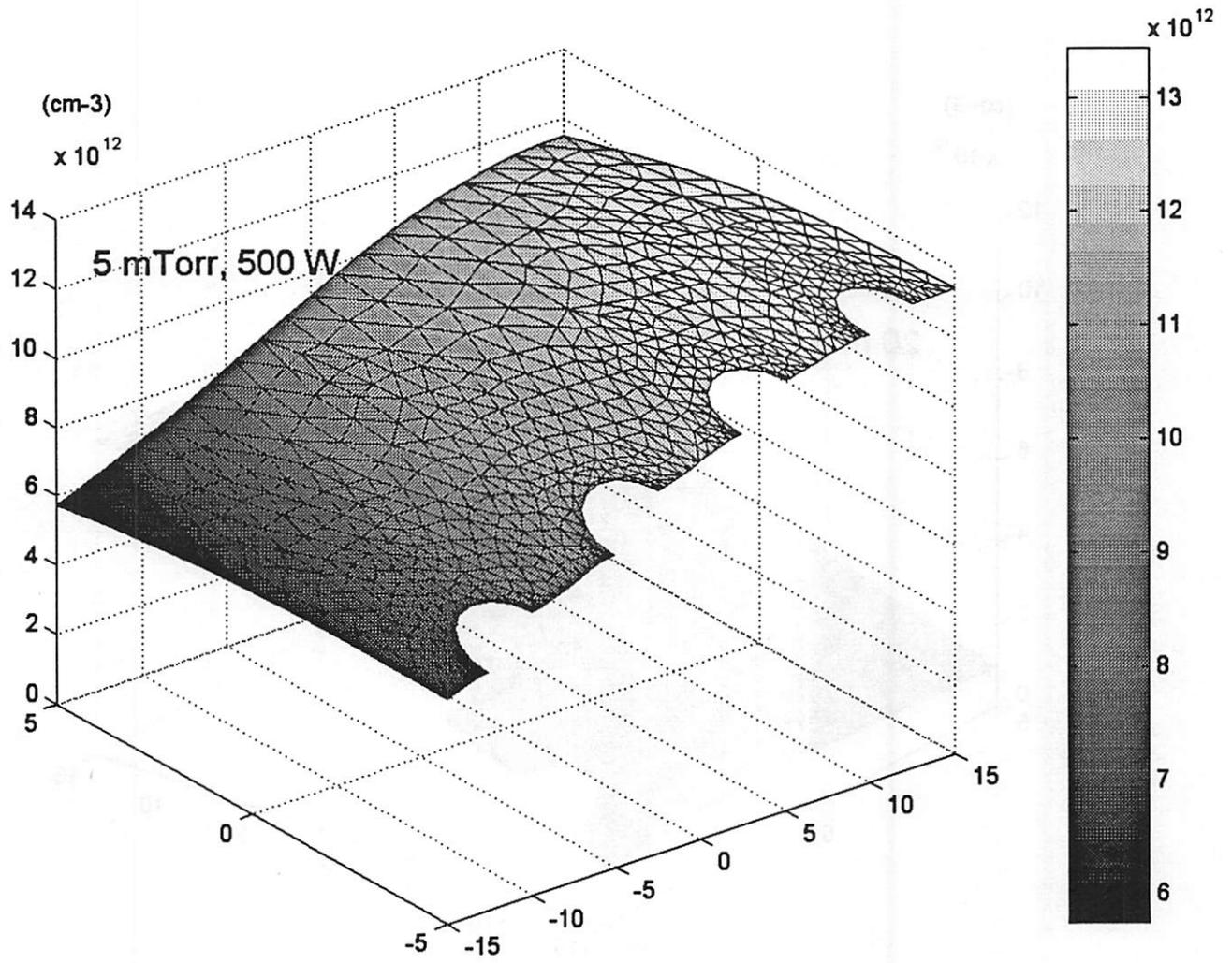


Fig. 8(a). O-atom density profile for a pure O₂ discharge at 5 mTorr.

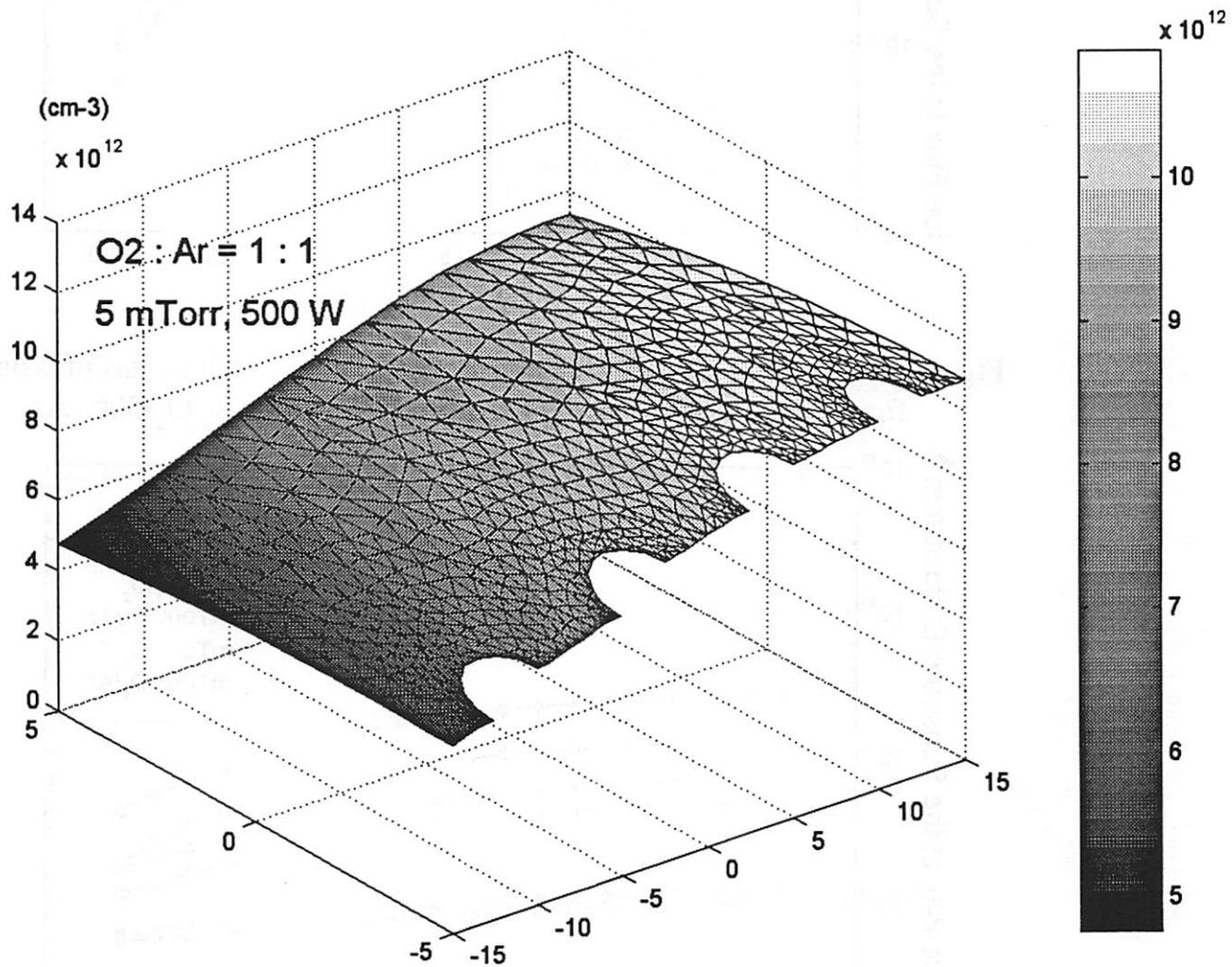


Fig. 8(b). O-atom density profile for an O₂/Ar mixture discharge at 5 mTorr.

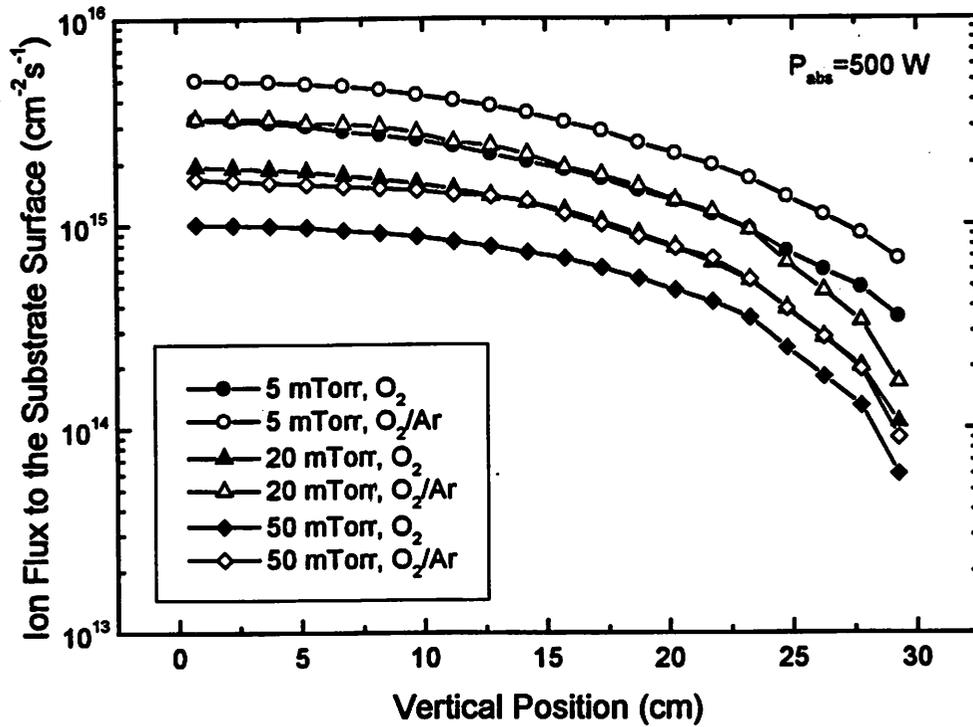


Fig. 9. Computed ion flux to the substrate surface at various gas pressures for a pure O_2 plasma and O_2/Ar mixture with 50% O_2 -50% Ar.

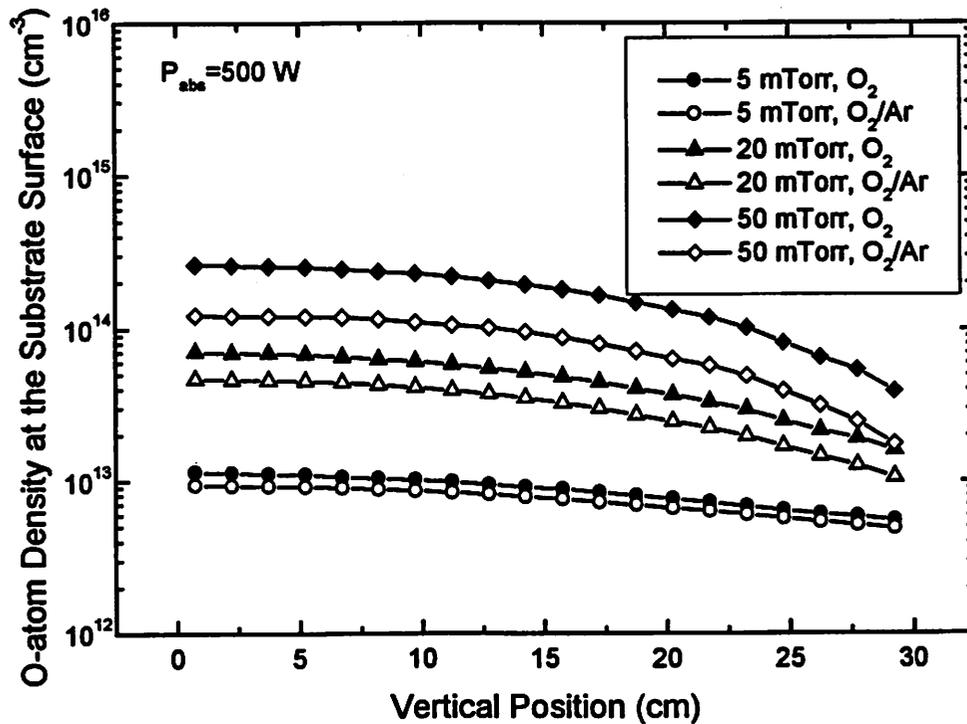


Fig. 10. Computed O-atom density at the substrate surface at various gas pressures for a pure O_2 plasma and O_2/Ar mixture with 50% O_2 -50% Ar.

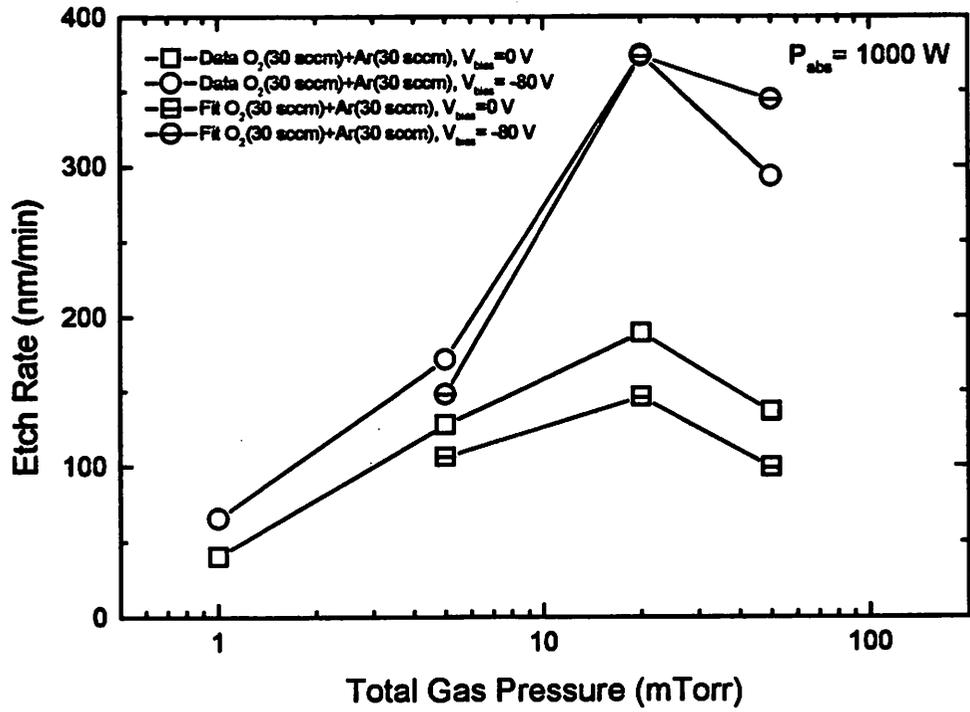


Fig. 11. Plots of etch rate vs total gas pressure. The fits are from Eq. (13) with the simulation results in Figs. 9 and 10.