We present and discuss results obtained in studies of the mechanisms underlying various feature size dependencies of SiO2 etching in inductively coupled fluorocarbon plasmas. The variation of the fluorocarbon deposition rate and the SiO2 etch rate with both feature size and rf bias power has been measured in a variety of constant aspect ratio features for both an etch stop (C3F6/H2) and a nonetch stop (CHF3) feedgas chemistry. © 2000 American Vacuum Society. [S0734-211X(00)02902-4]

I. INTRODUCTION

Directional etching of contact holes and trenches into dielectric layers is one of the most frequently employed processes in the fabrication of integrated circuits. Currently, the most widely used dielectric material is SiO2. The patterning of SiO2 layers is typically done by fluorocarbon plasma etching. An ideal fluorocarbon plasma etching process, selectively etches SiO2 to Si underlayers, SiN3 etch stop layers, and photoresistive masking layers at a relatively high rate that is independent of feature dimensions, while maintaining a vertical feature profile. In practice, the SiO2 patterning process often suffers from a variety of nonidealities, e.g., limited etching selectivity or feature dimension dependent SiO2 etch rate. Next to nonidealities the etch process may be subject to actual failure modes. The most dramatic failure mode is the "etch stop" phenomenon, in which a shift from etching to deposition occurs in features while on open surfaces etching continues.

In this article we present and discuss results obtained in a study of the effects of radio frequency (rf) bias power on various feature size dependencies of SiO2 etching in inductively coupled fluorocarbon plasmas. In particular, we present results on the SiO2 etch rate dependence on feature size and rf bias applied to the substrate. This was measured at a variety of constant aspect ratio features for both an etch stop (C3F6/H2) and a nonetch stop (CHF3) feedgas chemistry.

II. EXPERIMENT

The inductively coupled plasma (ICP) source setup used in this work is identical to the one described in an earlier article from this group. Briefly, a planar coil, supplied with 1400 W inductive power at 13.56 MHz, generates the plasma through a 19 mm thick quartz coupling window. A wafer is clamped electrostatically to a chuck that is cooled to 10 °C. To the backside of the wafer He at a pressure of 5 Torr is applied for thermal contact. The distance between the chuck and the induction coil is 8.5 cm.

The energy at which ions bombard the substrate is controlled by applying a rf bias voltage to the electrostatic chuck using a variable frequency power supply. Due to the different mobility of ions and electrons the substrate will develop a negative time-average offset voltage. This offset voltage is typically addressed as the self-bias voltage. In the ICP source used in this work self-bias potentials were determined using a high-voltage probe that contacts the wafer on the chuck. In Fig. 1, the measured self-bias voltages are plotted as a function of rf bias power in 6.4 mTorr, 40 sccm CHF3 plasmas at 600, 1000, and 1400 W inductive power. Figure 1 shows a linear relation between the self-bias potential and the rf bias power. This indicates that rf biasing is solely used to accelerate the ions over the sheath and does not significantly contribute to plasma generation, i.e., the ion energy and ion flux can be controlled independently in this process range. The floating potentials measured are about 20 V positive with respect to ground. The plasma potential measured at these process conditions using a Balzers PPM 422 plasma monitoring system ranged from around 25 to 35 V positive with respect to ground. Using an average value for the ion mass the electron temperature can be calculated from the Langmuir equations and is found to be around 3 eV in this process range. The results in Fig. 1 were obtained at a rf bias frequency of 3.4 MHz.

In order to study feature size dependent etching effects we used two types of samples. The first type of samples consisted of 3 μm thick SiO2 (BPSG) films deposited on a crystalline silicon wafer, covered with a 950 nm thick photoresist mask. The resist features have diameters ranging from 400 to 1200 nm. The second type of samples are 3.5 μm thick SiO2 (BPSG) films deposited on a crystalline silicon wafer, covered with a 300 nm thick polysilicon hardmask. The features in the silicon hardmask have diameters ranging from 400 to 1200 nm. The SiO2 underneath the silicon hardmask was pre-etched to a depth of approximately 2200 nm. In order to determine actual feature size dependent etch rates as a function of rf bias at a constant aspect ratio, we exposed the

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Effect of radio frequency bias power on SiO2 feature etching in inductively coupled fluorocarbon plasmas

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samples for only a relatively short period of time to the process under investigation. When exposing the samples to an etching process we typically etched around 500 nm of SiO$_2$ on a blanket surface as measured by in situ ellipsometry. In a deposition process we typically deposited 150 nm of fluorocarbon material on a blanket surface (Note: for significantly thicker fluorocarbon films an overhang may form that pinches off the smaller diameter features.) Since the exposure time is relatively short, the feature aspect ratio remains nearly constant during the process. In order to determine etch and deposition rates at the center of the feature bottom, cross-sectional scanning electron micrographs of samples before and after exposure to the process were compared.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. SiO$_2$ patterning in CHF$_3$

This section summarizes the feature etching results obtained in CHF$_3$ discharges. The first part discusses the SiO$_2$ etch rates as a function of rf bias power. The second part discusses observed trends in fluorocarbon deposition at 0 W rf bias power.

1. SiO$_2$ etching versus rf bias

Figure 2 shows SiO$_2$ etch rates as a function of rf bias measured for various (constant) aspect ratios in a 40 sccm CHF$_3$ plasma at 1400 W inductive power and 6 mTorr operating pressure. Similar to etching of blanket SiO$_2$ surfaces (see Rueger et al.\textsuperscript{11}) a transition from fluorocarbon deposition at low rf bias to SiO$_2$ etching at high rf bias occurs in features. It shows, however, that the fluorocarbon deposition rate at conditions where no rf bias is applied (floating substrate) decreases rapidly with increasing aspect ratio in the regime 0.8–2, where resist features were used for the experiment. In features with larger aspect ratios, where typically pre-etched silicon hardmask samples were used, no significant fluorocarbon deposition was observed at the feature bottom. Interestingly, in the aspect ratio range where the fluorocarbon deposition at the feature bottom shows significant changes, the SiO$_2$ sputter rate at high rf bias does not show any significant aspect ratio dependence (see Fig. 3). In the high aspect ratio (AR) range (AR>2), however, where the fluorocarbon deposition does not change (i.e., deposition rate is constantly around zero), the SiO$_2$ etch rate shows a decrease with increasing aspect ratio.

From the strong decrease of the fluorocarbon deposition rate with increasing AR one would expect that with increasing AR an increase in the SiO$_2$ etch rate, which is a result of a balance between fluorocarbon deposition, fluorocarbon etching, and SiO$_2$ etching\textsuperscript{3} would occur. However, the absence of this expected inverse RIE lag behavior can be explained by reductions in the flux of species responsible for

![Figure 1](image1.png)

**Fig. 1.** Self-bias voltages as a function of rf bias power in a 6.4 mTorr, 40 sccm CHF$_3$ plasma at 600, 1000, and 1400 W inductive power.

![Figure 2](image2.png)

**Fig. 2.** SiO$_2$ etch rates as a function of self-bias voltages in a 6 mTorr, 40 sccm CHF$_3$ plasma at 1400 W inductive power measured in features with for aspect ratios ranging from 0.8 to 6.
etching as the AR of the feature increases. These reductions could possibly result from conductance limitations in features or neutral etch precursor shadowing. The corresponding reduction in fluorocarbon polymer etch rate, can (for a limited range of aspect ratios) compensate for the inverse RIE lag expected from a reduction in fluorocarbon deposition. The SiO2 etch rate, which results to a certain extent from a balance between fluorocarbon deposition and etching, will therefore not suffer from a feature size dependence. Also the effect that the ion energy flux to the bottom of features with the current dimensions is reduced with respect to a blanket surface due to differential charging effects could account for this compensation.

It is interesting to note that inverse RIE lag has indeed been observed earlier by Doemling et al. in this ICP tool at a process condition similar to the condition in Fig. 2 (40 sccm CHF3, 1400 W inductive power) except for the operating pressure, which was 20 mTorr. At this higher pressure the fluorocarbon deposition rate at 0 W rf bias is higher in CHF3, while the ion current density is lower. The strong reduction of the fluorocarbon deposition rate with AR apparently has at the 20 mTorr condition a more dominant effect on the SiO2 etch rate than the etch rate reducing effects.

For the aspect ratio range larger than 2, where no significant change in the fluorocarbon deposition rate at the feature bottom occurs, but where the SiO2 etch rates are found to decrease, the latter may be explained by either of the etch rate reducing mechanisms mentioned above. Since in low pressure reactors SiO2 is typically found to be etched through a mechanism that relies on direct ion impact, we consider the differential charging mechanism to be more likely responsible for the etch rate reduction in this aspect ratio range. Experimental proof of the differential charging mechanism at the current process conditions has been reported in an earlier publication from this group. Also, the fact that the rates measured in the 400 nm diam (aspect ratio 2.4) photoresist features do not completely line up with the rates in the 1200 nm diam (aspect ratio 2) hardmask feature could be consistent with differential charging, since the charging mechanism is to some extent dependent on actual feature diameter in addition to aspect ratio.

2. Fluorocarbon deposition

In the experiments discussed above it was found that in the low aspect ratio range the fluorocarbon deposition rate strongly decreases with increasing aspect ratio (see Fig. 3). The strong decrease of the deposition rate with increasing aspect ratio seems consistent with the fact that the isotropic neutral flux arriving at the feature bottom decreases rapidly. As an example, Fig. 3 shows the aspect ratio dependence of the direct neutral flux arriving at the center of the feature bottom. If one includes multiple (cosine distribution) reflections of neutral species on feature sidewalls and one chooses the reflection coefficients properly, one can match the neutral arrival aspect ratio dependence to the aspect ratio dependence of the fluorocarbon deposition rate. In the above fluorocarbon deposition mechanism, however, ions are assumed to play an insignificant role. This is inconsistent with results obtained by Oehrlein et al. who performed double-grid deposition experiments in fluorocarbon electron cyclotron resonance (ECR) discharges and found that the fluorocarbon deposition rate is reduced in cases where ions are being repelled from the surface with respect to the case where ions arrive at the surface. The ECR discharges, however, differ from ICPs in that they operate at significantly lower pressures and the fluorocarbon deposition mechanism could therefore be quite different as well.

In order to evaluate whether ions also play a significant role in the fluorocarbon deposition mechanism for the current conditions, we performed an experiment in which we measured the fluorocarbon deposition profiles obtained in a 1400 W, 6 mTorr, 40 sccm CHF3 discharge while no rf bias was applied for three different sample configurations. In the first configuration, an 8 cm long c-Si sample was placed in the center of the wafer and exposed for approximately 50 s to the discharge. In the second configuration, a 2.5 cm high Teflon wall was placed next to a similar 8 cm long c-Si sample and again the sample was exposed to the discharge for the same amount of time. In the third configuration, a magnet was placed behind the Teflon wall and once again an 8 cm long sample was exposed to the discharge for 50 s. Figure 4 shows the three normalized fluorocarbon deposition profiles. It clearly shows that in the second configuration the deposition rate is reduced close to the Teflon wall with respect to the first configuration where no Teflon wall was present. Apparently, the Teflon wall “shadows” the sample from deposition precursors at the positions close to the Teflon wall. When a magnet is placed behind the Teflon wall in the third configuration the fluorocarbon deposition rate is even further reduced. In order to verify that the enhanced deposition reduction was not dependent on the wall material, we also performed an experiment in which the magnet was
placed behind an aluminum wall and again we saw an enhanced deposition reduction, indicating that the reduction in deposition rate is solely a result of the presence of the magnetic field. These results are consistent with results obtained by Maruyama et al.\textsuperscript{22} who also finds a decrease in fluorocarbon deposition rate in the presence of a magnetic field. The results may be explained in terms of ion deflection by the magnetic field, due to the Lorenz force

\[
\frac{m_{\text{ion}}v_{\text{thi}}^2}{R_{\text{Larmor}}} = qv_{\text{thi}}B,
\]

where \(m_{\text{ion}}\) is the ion mass, \(v_{\text{thi}}\) is the thermal ion velocity perpendicular to the magnetic field, \(q\) is the ion charge, and \(B\) the magnetic field strength. The ions will spiral around the magnetic field, and the radius of the spiral is called the Larmor radius \(R_{\text{Larmor}}\).

\[
R_{\text{Larmor}} = \frac{m_{\text{ion}}v_{\text{thi}}}{qB}.
\]

When using the magnetic field strength shown in Fig. 4 one finds for a typical singly ionized ion of 50 AMU at 0.1 eV thermal velocity that roughly at distances smaller than 1 cm from the wall the Larmor radius is smaller or equal to the magnet wall height. The c-Si sample is then effectively being shielded from positive ions by the magnetic field. This indicates that ions also play a role in the deposition mechanism in inductively coupled fluorocarbon plasmas.

From the above experiments one may also conclude that when explaining the aspect ratio dependence of the fluorocarbon deposition rate in the low aspect ratio range, one should include the ion arrival at the feature bottom. A simple model that includes a role for ions is presented below and is partly similar to mechanisms suggested by Bariya et al.\textsuperscript{23} and Arai et al.\textsuperscript{24} The model assumes that (reactive neutral) deposition precursors require active sites for adsorption, which are being created by (low energy) ion impact. After absorption of the reactive neutral these sites are lost. The following active site balance describes this situation:

\[
\frac{d\theta}{dt} = \Gamma_{\text{ion}}Y_{\text{sc}}(1 - \theta) - \Gamma_{n}\theta = 0,
\]

where \(\Gamma_{\text{ion}}\) is the ion flux, \(Y_{\text{sc}}\) is the site-creation yield of the low energy ions (i.e., sites created per ion), \(\Gamma_{n}\) is the neutral deposition precursor flux, and \(S\) is the sticking probability of the neutral deposition precursors. Solving this balance for steady-state deposition conditions results in a steady-state active site density of

\[
\theta = \frac{1}{1 + \left(\frac{\Gamma_{n}S}{\Gamma_{\text{ion}}Y_{\text{sc}}}\right)}.
\]

The fluorocarbon deposition rate \(DR\) can now be written as follows:

\[
DR = \frac{1}{\rho} (\Gamma_{n}S\theta) = \frac{1}{\rho} \left(\frac{\Gamma_{n}S}{1 + \left(\frac{\Gamma_{n}S}{\Gamma_{\text{ion}}Y_{\text{sc}}}\right)}\right),
\]

where \(\rho\) is the density of the fluorocarbon material.

Equation (5) nicely shows that both neutral deposition precursors and (low energy) ions are required for deposition. For example if the term \(\Gamma_{\text{ion}}Y_{\text{sc}}\) was relatively small with respect to \(\Gamma_{n}S\), one could neglect the constant 1 in the denominator, whose result in turn is that the \(\Gamma_{n}S\) terms cancel out and thus the deposition rate turns out to be linearly dependent on the ion flux. Similarly, if \(\Gamma_{n}S\) is relatively small, the ratio of \(\Gamma_{n}S\) to \(\Gamma_{\text{ion}}Y_{\text{sc}}\) can be neglected. The deposition rate is then linearly dependent on the neutral flux.

In order to apply the above model to the data in Fig. 3 one needs to know the aspect ratio dependence of both the neutral and ion flux. In order to estimate the aspect ratio dependence of the ion flux, one may look at the SiO\textsubscript{2} etch rate at sufficiently high self-bias voltage. The etching of SiO\textsubscript{2}, namely, is directly proportional to the ion flux since it relies on chemical sputtering.\textsuperscript{11} As shown in Fig. 3, the SiO\textsubscript{2} etch rate does not show a significant aspect ratio dependence, indicating that the ion flux to the bottom of the features is relatively constant. The neutral flux dependence, on the other hand, can be quite difficult to estimate. For simplicity we use only the direct neutral flux arriving at the center of the bottom of the feature, which has the typical \(1/(1 + 4\text{AR}^2)\) dependence for contact holes\textsuperscript{13,25} (see Fig. 3). The normalized deposition rate NDR can in this case be written as follows:

\[
\text{NDR} = \frac{1 + \left(\frac{\Gamma_{n0}S}{\Gamma_{\text{ion}}Y_{\text{sc}}}\right)}{1 + \left(\frac{1}{1 + 4\cdot\text{AR}^2}\right)},
\]

where \(\Gamma_{n0}\) is the neutral flux to a blanket surface. The term \(\Gamma_{n0}/\Gamma_{\text{ion}}Y_{\text{sc}}\) can be treated as one single parameter that can be used to fit the model to the data in Fig. 3. When performing a least squares fit of the model to the data (see the dashed line in Fig. 3) one finds a value of 10.4 for the parameter
This value seems physically reasonable since the neutral deposition precursor flux can easily be a factor of 10–100 times larger than the ion flux at the corresponding conditions and values of 0.1–1 for $S$ and/or $Y_{\text{sc}}$ seem possible.

In the above model it is assumed that only the direct neutral flux significantly contributes to the fluorocarbon deposition mechanism. If this assumption were correct, then one would expect asymmetric deposition at the feature bottom if the direct flux is shadowed by, for example, a Teflon wall. Therefore, in order to test to what extent the above assumption is valid, we deposited fluorocarbon material into resist features close to a Teflon wall. Figure 5 shows micrographs of features that were exposed to the 1400 W, 6 mTorr, 40 sccm CHF$_3$ plasma. The Teflon wall was located to the left of the cross section in (a) and to the right in (b). The dotted line indicates the interface between the fluorocarbon and the resist mask, while the solid line indicates where the SiO$_2$ underlayer is located.

The fact that asymmetric fluorocarbon film deposition occurs at the bottom of the feature seems to support the assumption that the direct neutral flux contributes a significant amount to the fluorocarbon deposition at the feature bottom. This conclusion can, however, only be drawn if the ion flux across the feature bottom remains uniform.

In order to test how the ion flux distribution varies across the feature bottom, we also performed an etching experiment close to the Teflon wall (see Fig. 6). It shows that the SiO$_2$ features are etched asymmetrically in the presence of the Teflon wall. Surprisingly, the side that is being shadowed from an isotropic flux by the Teflon wall, i.e., the side where the deposition rate is lowest, etches slower than the other side. This asymmetric microtrenching effect was observed in a similar experiment in an $\alpha$-Si:H plasma deposition environment. (Note: if one takes a micrograph of a cross section in the 90° rotated direction, regular symmetric deposition profiles at the feature bottom are obtained.)

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an earlier study in which a weak magnetic field was employed to alter the electron angular distribution. This resulted in asymmetric differential charging.\textsuperscript{14} The observations made in this experiment are possibly due to the same effect. The electron angular distribution in this experiment may be altered by the electron shadowing due to the Teflon wall. The feature sidewall that is not being shadowed will charge up more negatively than the other sidewall, and ions will be more strongly deflected toward the nonshadowed sidewall.

It can be concluded from the above experiment that the ion flux across the bottom of the feature during etching is nonuniform in the presence of the Teflon wall. Unambiguous evidence of the direct neutral flux being the only neutral component of significance to the fluorocarbon deposition mechanism was not found, since the ion flux can also be altered by the asymmetric differential charging effects during deposition.

B. \textit{SiO}$_2$ patterning in $C_3F_6/H_2$

This section summarizes the etching results obtained in $C_3F_6/H_2$ discharges in constant aspect ratio features. Similar to the previous section, the first part discusses the \textit{SiO}$_2$ etch rates as a function of rf bias power, while the second part discusses observed trends in fluorocarbon deposition.

1. \textit{SiO}$_2$ etching versus rf bias

Figure 7 shows \textit{SiO}$_2$ etch rates as a function of rf bias measured for various aspect ratios in a 25 sccm $C_3F_6/15$ sccm $H_2$ plasma at 1400 W inductive power and 6 mTorr operating pressure. Similar to the CHF$_3$ results the transition from deposition to etching is observed. Also the strong decrease of the fluorocarbon deposition rate at 0 W rf bias (electrically floating substrate) is observed. The deposition rates, however, are significantly higher than for CHF$_3$ at the same process conditions. Also the threshold bias required for net etching is significantly higher. Again for the aspect ratio range where no significant changes in the fluorocarbon depo-
Therefore, a two-step etch process may be used to avoid etch stop in applications that require the use of feedgas chemistries prone to etch stop, e.g., in the production of high-aspect ratio self-aligned contact features which rely on high SiO$_2$-to-Si$_3$N$_4$ etch selectivity. In the first step, a nonetch stop condition, e.g., high bias condition or CHF$_3$ chemistry, could be used to etch the features beyond the critical aspect ratio. In the second step the highly selective SiO$_2$-to-Si$_3$N$_4$ condition, that for smaller aspect ratios would result in etch stop, can be used to complete the etching of the structure.

2. Fluorocarbon deposition

Figure 8 shows the results of a more detailed study of the fluorocarbon deposition rate as a function of AR and rf bias in C$_3$F$_6$/H$_2$ discharges. At 0 W rf bias the fluorocarbon deposition rate shows an AR dependence very similar to that observed at 0 W bias in CHF$_3$ discharge (see Fig. 3). If the fluorocarbon deposition is performed in C$_3$F$_6$/H$_2$ under biased conditions, however, a different dependence is observed. The fluorocarbon deposition rate on a blanket surface seems to decrease faster with increasing bias than the fluorocarbon deposition rate inside features. This may be explained in a similar fashion to that of the etch stop, i.e., the fluorocarbon removal rate inside features is lower than at a blanket surface, e.g., due to differential charging effects, neutral etch precursor shadowing, or even due to enhanced deposition inside the features as a result of redeposition. The latter effect implies that reaction products have difficulty leaving the features.

IV. SUMMARY AND CONCLUSIONS

Results on the SiO$_2$ etch rate feature size dependence as a function of rf bias applied to the substrate in a nontime-averaged fashion for both an etch stop (C$_3$F$_6$/H$_2$) and a nonetch stop (CHF$_3$) feedgas chemistry are presented. The observed feature size dependencies, such as the etch stop phenomenon, may be explained in terms of decreasing fluorocarbon deposition and fluorocarbon etching rates with increasing aspect ratio, resulting from differential charging and neutral shadowing. Based on the experimental observations it is suggested that etch stop occurs at a condition specific “critical” aspect ratio. A two step process that etches beyond the critical AR using a nonetch stop process in the first step and then switches to an etch chemistry prone to etch stop is suggested to prevent etch stop problems in critical applications.

Results from fluorocarbon deposition experiments are also presented. The results indicate that both ions and neutrals are important for fluorocarbon deposition on blanket samples and in features. A simple site creation model, which includes the ion flux and the direct neutral flux to the bottom of the feature, is able to explain the experimental results well. In addition, we showed that asymmetric fluorocarbon deposition and SiO$_2$ etching occurs when depositing fluorocarbon material and etching SiO$_2$ in features if an obstacle, such as a wall, that shadows isotropic neutrals and electrons is located near the samples.

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D. Cooperberg and V. Vahedi (private communication, 1998).


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