Effects of radio frequency bias frequency and radio frequency bias pulsing on SiO₂ feature etching in inductively coupled fluorocarbon plasmas

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The effect of radio frequency (rf) bias frequency on SiO₂ feature etching using inductively coupled fluorocarbon plasmas is investigated. It is found that the rf bias frequency can have an important effect on SiO₂ feature etch rate, microtrenching phenomena, and SiO₂-to-photoresist etch selectivity. In addition, the effect of rf bias pulsing on inductively coupled fluorocarbon plasma SiO₂ etching has been studied and a model that describes the data well is presented. The model assumes that fluorocarbon deposition occurs while the rf bias is off, fluorocarbon etching occurs during the first part of time that the bias is on, and substrate etching occurs once the fluorocarbon material has been removed from the substrate. © 2000 American Vacuum Society.

I. INTRODUCTION

In semiconductor device manufacturing inductively coupled fluorocarbon plasmas are often used for pattern transfer from photoresistive masking layers into SiO₂ layers. Inductively coupled fluorocarbon plasma etching processes, however, often suffer from limited etching selectivity to Si, Si₃N₄, and photoresist masks. Further, feature dimension dependent SiO₂ etching effects, such as (RIE) lag and/or etch stop phenomena, may cause complications. Additionally, problems exist with feature sidewall tapering and enhanced etching close to the feature sidewalls that causes microtrenching. In order for an etching process to be successful in a manufacturing environment, all process parameters need to be tuned and controlled such that the above nonidealities are minimized. Often, however, insight into the role of certain process parameters is limited. Therefore, systematic studies of the effects of these process parameters on the etching process are required.

In a companion article we described the effects of the radio frequency (rf) bias power process parameter, which is a measure of the average ion energy, on SiO₂ feature etching in inductively coupled fluorocarbon plasmas. In this article we report results from a study of the influence of the rf bias frequency process parameter, which can have a significant effect on the ion energy distribution. Further, the effect of pulsing the rf bias power on the etching process is presented and discussed in this work.

II. EXPERIMENTAL SETUP AND PROCEDURES

The inductively coupled plasma source setup used in this work is identical to the one described in earlier articles from this group. Important to this work is that the electrostatic wafer holder is connected through a matching network to a rf power supply (0–250 W) that amplifies a signal received from a variable frequency (0.4–40 MHz) rf function generator. The operating pressure was kept at 6 mTorr and inductive power was 1400 W for all experiments.

In the first part of this article the rf bias frequency is varied in the range of 1–10 MHz. The rf bias power level was varied to induce a self-bias potential in the range of −85–−120 V. The samples that were processed consisted of 0.7 μm thick photoresist patterns on 4 μm thick silicon dioxide films on Si (100). The lateral dimensions of trenches ranged from 0.2 to 1.0 μm. The samples were etched for 300 s in a 40 sccm CHF₃ plasma to a depth of 1.40–2.55 μm into the SiO₂ for the various conditions. The samples were analyzed by scanning electron microscopy (SEM).

In the second part of the article blanket SiO₂, Si, resist, and deposited fluorocarbon films and 3 μm thick SiO₂ samples with 900 nm thick patterned resist masks were etched in 40 sccm CHF₃ and C₂F₆ plasmas, while pulsing the rf bias power. For this work we introduced an analog switch (LF13202N-ND) between the rf function generator and the rf power supply, which could be opened by sending a trigger voltage from a pulse generator. The pulse cycle time, i.e., pulse period, on the pulse generator was varied from 900 ms (maximum period) down to 1 ms. The duty cycle has been varied from 99% (which more or less represents a continuous mode operation) down to 29%. The rf bias frequency was kept constant at 3.4 MHz for this work.

III. RESULTS AND DISCUSSION

A. rf bias frequency effects

In this section we report results from a study of the influence of rf bias frequency on SiO₂ feature etching. First, a short description is given of the role of rf bias frequency on the ion energy distribution. Next, we will compare the fea-
ture size dependence of the (time integrated) SiO$_2$ etch rate, microtrenching, and photoresist erosion behavior at various rf bias frequencies in the 1–10 MHz range in 40 sccm CHF$_3$ plasmas at 1400 W inductive power and 6 mTorr operating pressure.

1. Role of rf bias frequency

When varying the rf bias frequency while maintaining a specific rf bias power, the average ion energy may not vary significantly, as found from voltage measurement on rf biased wafers, but significant changes in the ion energy distribution may result.\textsuperscript{5–8} Namely, if the ion transit time through the plasma sheath is large with respect to the time of one rf cycle (high bias frequency), the majority of the ions entering the plasma sheath will arrive at the substrate with the time-averaged sheath potential (i.e., plasma potential minus the self-bias voltage). The ion energy distribution is narrowly spaced around the time-average sheath potential. If the ion transit time is short with respect to one rf cycle (low bias frequency), an ion will arrive at the substrate with an energy corresponding to the sheath potential at the time that the ion enters the sheath. The resulting ion energy distribution is wide and bimodal.

At the current conditions it can be expected, based on recent experiments by Sobolewski et al.\textsuperscript{6} in a similar system, that the ion energy distribution at around 1 MHz is dominantly bimodal, while at 10 MHz the ions will typically bombard the surfaces with energies close to the average sheath potential.

2. Microtrenching

Figure 1 shows SEM micrographs of 1 $\mu$m trenches etched at conditions with self-bias voltage and rf bias frequency of: (a) $-85$ V and 1.3 MHz, (b) $-120$ V and 1.3 MHz, (c) $-85$ V and 10.5 MHz, and (d) $-120$ V and 10.5 MHz.

The etched trenches had, dependent on the biasing condition, sidewall angles ranging from 86.5$^\circ$ to 88$^\circ$. More vertical sidewalls are observed at the higher rf bias power level. Further, it is observed that the SiO$_2$ etch rate is typically enhanced at positions close to the feature sidewalls, which produces microtrenching.

Figure 2 shows the amount of microtrenching (depth of microtrench relative to the total etched depth) versus the initial trench width of the structures etched for 300 s at various bias powers at both 1.3 and 10.5 MHz rf bias frequency in 40 sccm CHF$_3$, 6 mTorr operating pressure, and 1400 W inductive power discharges.
3. Etch rates

Results of SEM analysis of trenches etched at various rf bias powers and frequencies are summarized in Fig. 2. The etched depth into SiO$_2$ after 300 s of etching is plotted as a function of initial trench width at various bias powers at both 1.3 and 10.5 MHz bias frequency. The etched depth both measured at the center of the bottom of the feature and measured at the top of the microtrench is plotted. For the condition where no microtrenching is observed, only one depth is plotted. The data in Fig. 2 show if the etched depth is measured at the bottom of the microtrench in the 1.3 MHz case that no significant aspect ratio dependence exists for the etch rate under these conditions. If the etched depth is measured in the middle of the feature, inverse RIE lag was observed. The inverse RIE lag behavior can in this particular case be explained by the fact that as the feature width decreases, the microtrenches from the two sidewalls start to overlap. This also explains why the observed inverse RIE lag is more significant at higher bias powers, see Fig. 2.

4. Photoresist erosion

Figure 3 shows the erosion rates of photoresist masks measured at $-85$ and $-120$ V self-bias at both 1.3 and 10.5 MHz bias frequency. The erosion rate of the resist mask is roughly a factor of 2 lower for 10.5 MHz than for 1.3 MHz rf bias frequency. This observation is consistent with results recently reported by Doemling et al. who find that in this inductively coupled plasma source for high inductive power levels (>600 W) the photoresist etch rate is determined by the energy of the individual ions rather than the total energy flux to the resist substrate. Since the highest energy for a 1.3 MHz ion energy distribution is greater than in the 10.5 MHz case (due to narrowing of the ion energy distribution with increasing frequency) one would expect the resist erosion rate to be elevated in the low frequency case. Figure 3 in combination with SiO$_2$ etch rate results (see Fig. 2) shows that the SiO$_2$-to-resist selectivity may indeed be increased by increasing the rf biasing frequency, i.e., lowering the maximum ion energy while keeping the total energy flux to the substrate at a constant value.

B. rf bias pulsing effects

This section summarizes results obtained in an investigation of the effects of inductively coupled fluorocarbon plasma etching while pulsing the rf bias to the wafer. First, we will show results obtained when measuring the wafer voltage while pulsing the bias power. Next, we show results obtained while etching various materials under pulsed bias conditions. Finally, the experimental observations are quantitatively explained by a simple model that includes fluorocarbon deposition during the part of the duty cycle when the bias is off, fluorocarbon etching during the first part of the duty cycle when bias is on, and substrate etching during the rest of the duty cycle.

1. Wafer potentials

In order to measure the response of a surface exposed to a plasma to a sudden application of a rf voltage, a high voltage probe was attached to the surface of the wafer that was being biased in pulses (49% duty cycle, 1 ms period). The signal from the wafer probe was fed to a digital storage oscilloscope. The storage oscilloscope was triggered simultaneously with the Analog Switch that controls the rf bias pulsing. In this fashion we were able to monitor the initial stages of the self-bias voltage development on a wafer.

Figure 4 shows how the self-bias voltage on the wafer develops. In the first eight rf cycles (at 3.4 MHz bias frequency) the wafer collects net negative charges during every cycle (due to the higher mobility of electrons than of ions). The negative charge collected on the wafer in each one of these initial cycles repels plasma electrons from the wafer surface, i.e., the electron current to the wafer during each
following rf cycle is lower than the previous one. This continues until the electron current to the wafer equals the ion current to the wafer during one rf cycle, such that no net charge is being collected. The net charge on the wafer no longer changes and steady-state conditions are achieved. The average potential of the wafer at this point is the self-bias voltage. (Note: the fact that it takes about 2–3 μs to establish the self-bias voltage, indicates that not the full plasma thermal electron current is collected during the positive peaks of the initial rf cycles. If the full plasma thermal electron current would be collected one expects for the current conditions that the self-bias voltage would be established within a few nanoseconds.)

In the most extreme pulsing case that will be addressed in this work, the pulsing period is 1 ms and the duty cycle is 29%. The total time that the rf bias is switched on in one cycle is in this case 290 μs. The self-bias, on the other hand, is being developed in eight rf cycles, i.e., 2.35 μs. Since the self-bias voltage adjustment time is less than 1%, we will neglect this effect in the discussion of the results to be presented.

2. Etching of blanket samples

Etch rates on blanket samples of SiO₂, Si, resist, and deposited fluorocarbon material were measured for various conditions using in situ He–Ne ellipsometry. Figure 5 shows the SiO₂ etch rates in 40 sccm C₂F₆ discharges at 1400 W inductive power and 6 mTorr operating pressure as a function of self-bias voltage. The data were obtained for 99%, 49%, and 29% duty cycle and the period of one cycle is 1 ms or 900 ms. It shows that the duty cycle significantly influences the SiO₂ etch rate, while the length of the period has only little influence in the investigated range.

Similar data were obtained for Si and resist etching. Again decreasing the duty cycle significantly reduces the Si and resist etch rate, while the length of the period has only little influence. The fact that both SiO₂ and Si or resist etch rates decrease in a similar fashion with duty cycle, does not allow for optimizing the SiO₂-to-Si or SiO₂-to-resist selectivity by means of bias pulsing.

3. Mathematical description of blanket etching

The results presented in the previous section showed that all substrate materials have the same etch rate dependence on the duty cycle, and depend only little on the length of one pulse period. This general behavior can be mathematically described with a simple model, similar to a model by Boswell et al. that describes the etching of Si in a pulsed SF₆ discharge.22,23 In the present case, the model consists of a set of equations that describe the fluorocarbon deposition during the part of the duty cycle when the bias is off, fluorocarbon etching during the first part of the duty cycle when bias is on, and substrate etching during the rest of the duty cycle.

First, the amount of fluorocarbon material DMCFx deposited during the part of the pulse cycle that the bias is off is equal to:

$$DM_{CFx} = DR \cdot t_{per} \cdot (1 - dc) \cdot t_{per}.$$  

(1)

where DR the (continuous mode) fluorocarbon deposition rate at 0 W rf bias power, tper the length of the pulse cycle (pulse period), and dc the part of the pulse cycle that the bias is on, i.e., the duty cycle. At the point that the bias is switched on, the deposited fluorocarbon material needs to be removed from the surface through a fluorocarbon etch process. The time trem required to remove the deposited fluorocarbon material from the surface by a fluorocarbon etch process with a (continuous mode) etch rate ER CFx is equal to:

$$t_{rem} = DM_{CFx} / ER_{CFx}.$$  

(2)

Once most of the fluorocarbon material has been removed from the surface, substrate etching can occur at the rate ER sub-CW that is normally measured in continuous wave (cw) experiments. The time tsub that is left during one pulse cycle to etch the substrate is equal to:

$$t_{sub} = t_{per} \cdot dc - t_{rem},$$  

(3)

and the amount of substrate material EMsub removed during this time is equal to:

$$EM_{sub} = ER_{sub-CW} \cdot t_{sub}.$$  

(4)

In order to determine the average etch rate during one pulse cycle, the amount of removed substrate material needs to be divided by the time of one pulse period:

$$ER_{sub-DC} = EM_{sub} / t_{per} = ER_{sub-CW} \cdot dc \cdot (1 - dc) \cdot \left( \frac{DR_{CFx}}{ER_{CFx}} \right).$$  

(5)

Equation (5) shows that the ratio of etch rate in the pulsed case ER sub-DC to etch rate in the continuous mode ER sub-CW, i.e., the relative etch rate, is only a function of the duty cycle dc, the fluorocarbon deposition rate DR CFx and the fluorocarbon etch rate ER CFx. The time of the pulse period drops out
of the equations, which is consistent with our observations that the pulse period only has a small influence on the etch rates. Also consistent with our observations is that the relative etch rate is independent of the substrate material. Figure 6 shows the calculated dependence of the relative etch rate on duty cycle for a variety of ratios of fluorocarbon deposition rate to fluorocarbon etch rate.

It should be noted that during continuous bias a steady-state fluorocarbon film, with a thickness equal to or larger than roughly 1 nm, is present on the surface of the various substrates. On the other hand, the amount of fluorocarbon material deposited during the “bias off” period at 1 ms pulsing period is roughly 0.01 nm. It is clear that this thickness increase does not prevent etching of the substrate during the first part of the “bias on” period such that the previously deposited amount of fluorocarbon material can be removed, as suggested in the derivation of Eq. (5). Instead, as soon as the bias is turned on substrate etching occurs, while simultaneously the small amount of deposited fluorocarbon material is removed. When mathematically deriving an expression for the substrate etch rate under pulsed bias condition, however, one also ends up with Eq. (5).

Finally, it should be noted that another mechanism that could be active is covered by the above equations, namely the mechanism that assumes that deposition of fluorocarbon material is a result of low energy ions. In this mechanism fluorocarbon material is being deposited during the bias on as well as the bias off part of the pulsing period. However, since the above equation only effectively compares the pulsed bias to the continuous bias condition, there is no need to especially adapt Eq. (5) to this mechanism. The deposition during the bias on period is already captured in the balance between deposition and etching that ultimately results in the continuous bias substrate etch rate.

In order to validate the above model we compared the calculations of the dependence of the relative etch rates to the relative etch rates measured when either etching or depositing fluorocarbon material in a 40 sccm C₂F₆ discharge for which DR<sub>cfx</sub>/ER<sub>cfx</sub>-CW = 0.3 or a 40 sccm CHF₃ discharge for which DR<sub>cfx</sub>/ER<sub>cfx</sub>-CW = 2.2 at 1400 W inductive power and 6 mTorr operating pressure (note: ER<sub>CFₓ</sub>-CW determined at −100 V self-bias in continuous mode).

Further validation of the above model is done by comparing calculations of the etch rates of oxide, silicon, resist, and fluorocarbon material in C₂F₆ discharges at 49% and 29% duty cycle to the measured values. Figure 7 shows the measured values as a function of the calculated values for: (a) 900 ms period and (b) 1 ms period. (1400 W inductive power, 6 mTorr operating pressure).
very well with the calculations. The 1 ms experimentally determined rates are typically slightly higher than the calculated values. This etch rate enhancement might be explained by the fact that the 1 ms period does not allow the fluorocarbon etch rates or substrate etch rates to achieve steady-state conditions. The values for the etch and deposition rates inserted into Eq. (5) are therefore possibly underestimated.

4. Etching of features

Patterns in a 900 nm thick resist mask were transferred into SiO$_2$ using a 40 sccm C$_2$F$_6$ discharge at 1400 W, 6 mTorr, and a pulsed $-100$ V self-bias at 99%, 49%, and 29% duty cycle. The samples were etched for 120 s and subsequently analyzed by SEM. The investigated structures included 1200 and 400 diam vias, and the initial aspect ratio (AR) thus varied from 0.8 to 2.4. Marginal selectivity of SiO$_2$ to the resist mask is achieved at these conditions, as was already clear from blanket etching. This results in roughly a constant aspect ratio throughout the etch process, i.e., the initial and final AR are roughly the same.

Etch rates measured at the center of the bottom of the features using SEM analysis are summarized in Fig. 8. It shows that at 99% duty cycle, the etch process suffers from some forward RIE lag, i.e., high aspect ratio features etch slower than low aspect ratio features. At 49% duty cycle, the etch process shows a slight inverse RIE lag behavior. When the duty cycle is further reduced to 29%, the inverse RIE lag increases such that the 2.4 aspect ratio feature etches around a factor of 3 faster than the 0.8 aspect ratio feature.

5. Mathematical description of feature etching

In order to explain the etch rates in features with the model presented in the blanket study, Eq. (5) needs to be modified. There are three parameters that could depend on the aspect ratio, namely the etch rate of the SiO$_2$ substrate

$$ER_{\text{sub-AR}} = ER_{\text{sub}} \cdot f(\text{AR}),$$

the fluorocarbon etch rate

$$ER_{\text{CF,AR}} = ER_{\text{CF}} \cdot g(\text{AR}),$$

and the fluorocarbon deposition rate

$$DR_{\text{CF,AR}} = DR_{\text{CF}} \cdot h(\text{AR}).$$

The calculated ratio of the SiO$_2$ etch rate at a particular duty cycle and aspect ratio to the SiO$_2$ etch rate in the continuous mode on a blanket sample, i.e., relative etch rate, is plotted as a function of aspect ratio for various duty cycles in Fig. 9(a). The calculations show good correspondence with the data in Fig. 8, i.e., the inverse RIE lag increases with decreasing duty cycle. Since the etch rate of the resist mask (AR=0) decreases more rapidly than the SiO$_2$ etch rate inside features, the SiO$_2$-to-resist selectivity increases with decreasing duty cycle and increasing aspect ratio. Figure 9(b), in which the measured and calculated SiO$_2$-to-resist selectivities for various duty cycles are plotted as a function of aspect ratio, shows this effect. According to the calculations in Fig. 9(a), the curve for 23% duty cycle shows that it is even possible to have no etching on a blanket surface, i.e., AR=0, while still allowing for SiO$_2$ etching inside the features. In other words, at this point where there is no net substrate etching on blanket surfaces, the fluorocarbon deposition is just winning the competition between etching and deposition, while in features the etching still dominates. Since it does not matter in the case of no net etching what type of substrate is not being etched it is clear that at 23% duty cycle no etching of, for example, the top of the resist mask will occur, while etching of SiO$_2$ in features will still continue. The above implies that infinite SiO$_2$-to-resist selectivity can be achieved when etching features.

6. Critical dimension mechanism

Figure 10 shows results from SEM analysis on the critical dimension (CD), i.e., the width at the bottom of the feature, of the processed samples. Also included are the dimensions of the unprocessed resist features. The CD of the features,
and correspondingly the sidewall angle, is found to decrease with decreasing duty cycle. This observation may be explained by the fact that a significant amount of the fluorocarbon material that needs to be removed during one pulse cycle can redeposit on the resist feature sidewall. If the fluorocarbon material redeposits at the sidewall, it can act as a mask for the underlying SiO₂, i.e., lead to a reduction in critical dimension. Since more fluorocarbon material needs to be removed at low duty cycles, the CD and the sidewall angle will be reduced to a greater extent.

IV. SUMMARY AND CONCLUSIONS

The dependence of SiO₂ etch rate on feature size, microtrenching effects, and SiO₂-to-photoresist selectivities were measured and compared at 1.3 and 10.5 MHz rf bias frequencies for otherwise identical conditions. The results presented here show that microtrenching decreases in this frequency range with increasing bias frequency, while the SiO₂-to-resist selectivity can be significantly increased.

Further, results from a study on the effects of rf bias pulsing were presented. It is found that the etch rate of any blanket substrate depends only on the pulse duty cycle and the ratio of fluorocarbon deposition rate to fluorocarbon etch rate. The pulse period does not have a significant effect on the substrate etch rates. In the etching of features it is found that inverse RIE lag effects increase with decreasing duty cycle. The inverse RIE lag effects can be explained by the strong aspect ratio dependence of the fluorocarbon deposition rate at the bottom of features. Since the etch rate of the resist mask, i.e., aspect ratio zero, decreases more rapidly than the SiO₂ etch rate inside features, the SiO₂-to-resist selectivity increases with decreasing duty cycle and increasing aspect ratio. Feature sidewall angles and critical dimensions, however, are significantly reduced as the duty cycle is decreased.

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