Asymmetric microtrenching during inductively coupled plasma oxide etching in the presence of a weak magnetic field

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When fabricating microscopic features in SiO$_2$ layers using low pressure, high-density fluorocarbon plasmas, microtrenching has commonly been observed. Microtrenching has been explained either as due to ion scattering from sloped sidewalls or negative charging of the sidewalls by electrons, and the influence of the associated electric field on ion trajectories. In this work, we show that a weak magnetic field produces a significant asymmetry in microtrenching. Our results demonstrate unambiguously that electron-based sidewall charging is to a significant extent responsible for microtrenching, and, more generally, that differential charging is an important effect in microstructure fabrication using high-density plasmas. © 1998 American Institute of Physics.

When forming microstructures in thin films the formation of small trenches at the bottom corners of the feature being etched is commonly observed. Microtrenching has frequently been explained by ion scattering from sloped feature sidewalls. On the other hand, for etching of dielectric films differential charging of microstructures has also been suggested to produce microtrenching. Differential charging has been proposed to occur as a result of the difference in angular distribution for ions and electrons. The ion angular distribution is highly anisotropic, whereas the electron angular distribution is nearly isotropic. On microscopic features electrons will mainly arrive at the surface portions near the top of the feature, and are prevented from reaching the bottom, whereas ions will reach the bottom of the feature. This differential charging produces local electric fields inside the feature, which will lead to changes in ion and electron trajectories until electron and ion currents eventually are balanced everywhere along the surface. Surface discharge mechanisms have also been suggested to play a role in the balancing of ion and electron currents. Microtrenching can directly result from ion deflection by negatively charged sidewalls, see Fig. 1(a).

We propose here to use a weak magnetic field (~$10^3$ G) to distinguish between these two mechanisms. If the differential charging mechanism is to a significant extent responsible for microtrenching, asymmetric microtrenching should occur if a weak magnetic field is applied, see Fig. 1(b). On the other hand, if ion scattering is primarily responsible for microtrenching, the etch profile should not be significantly affected by the introduction of a weak magnetic field since ions are too immobile to be influenced. Even if a perturbation of the ion trajectories should occur, the deflection should be opposite to that predicted for electrons, allowing us to determine the dominant mechanism. In this letter results obtained in the above experiment will be presented. Our results strongly support the differential charging mechanism.

The inductively coupled plasma reactor used here has been described by Rueger et al. 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. The plasma is fed with 40 sccm of trifluoromethane (CHF$_3$) at the operating pressure of 6 mTorr. A wafer is clamped electrostatically to a wafer holder cooled to 10 °C. A 5 Torr He backside pressure is applied between the chuck and the wafer. The distance between the chuck and the induction coil is 7 cm. The chuck is connected through a matching network to a variable frequency (0.4–40 MHz) rf power supply (0–250 W), which allows for rf biasing of the wafer independently from the plasma generation.

For this work, a small magnet ($l \times w \times h = 2.2 \text{cm} \times 0.5 \text{cm} \times 0.4 \text{cm}$) was placed in the center of the 125 cm diameter wafer. Patterned samples located relative to the magnet as shown in Fig. 2, were chosen for analysis. The samples consisted of a 900 nm thick patterned resist mask on top of 1600 nm thick oxide (BPSG) film on silicon (100). The diameter of the contact holes is 600 nm. The samples were etched for 10 minutes.

![FIG. 1.](image)

FIG. 1. (a) Schematic view of the differential charging mechanism in the presence of a magnetic field. The local electric fields in the feature deflect ions from the center towards the negatively charged sidewalls, resulting in symmetric microtrenching. (b) Schematic view of differential charging in the presence of a magnetic field. The Lorentz force $F_L$ deflects electrons, resulting in an asymmetric electron angular distribution, resulting in asymmetric microtrenching.
150 s at a self-bias voltage of \(-125\) V (150 W rf bias power) at 3.4 MHz, to a depth of around 1000 nm into the oxide. The thickness of the resist mask after etching is 700 nm. The etched structures were examined by scanning electron microscopy (SEM).

Figure 3(a) shows a micrograph from a feature for which the magnetic field runs parallel to the cross section. The symmetric microtrenching profile seen in this case is identical to that seen in separate experiments where no magnetic field had been applied. For comparison, Fig. 3(b) shows a scanning electron micrograph taken from the cross section of a feature that was located close to the north pole of the magnet, see Fig. 2. The magnetic field line is perpendicular to the cross section and pointing out of Fig. 3(b). The feature etched significantly deeper on the right hand side than in the middle or on the left hand side of the feature. At this orientation of the magnetic field relative to the SEM cross section electrons are deflected to the right, whereas positive ions are either not affected or would be deflected to the left.

The microtrenching profiles change in a systematic fashion with the orientation of the magnetic field relative to the SEM cross section. The microtrenching asymmetry will be defined in this letter as the oxide depth measured in the right microtrench \(d_r\) minus the oxide depth measured in the left microtrench \(d_l\). The difference is plotted as a percentage of the depth measured in the middle of the trench \(d_m\):

\[
\text{Microtrenching Asymmetry} = \left( \frac{(d_r - d_l)}{d_m} \right) \times 100\%.
\]

When moving along a sample that is cracked for SEM analysis, the orientation of the magnetic field with respect to the cross section changes, see Fig. 2. In this fashion the microtrenching asymmetry was measured as a function of the orientation of the magnetic field line with respect to the cross section of the feature. Figure 4(a) shows the microtrenching asymmetry measured as a function of angle \(\theta\).
between the magnetic field $B$ and the magnetic field component that is perpendicular to the cross section $B'_{\perp}$,

$$\theta = \arccos \left( \frac{B_{\perp}}{B} \right).$$

The magnetic field $B$ and its components were calculated as a function of position from the magnet, assuming that the magnet acts as a magnetic dipole. For samples placed too close to the magnet this assumption is only qualitatively correct, and Fig. 4(a) should be interpreted in this fashion. A clear trend in the microtrenching asymmetry is observed in Fig. 4(a). When the magnetic field component perpendicular to the cross section dominates, a severe microtrench asymmetry can be observed. If the magnetic field is parallel to the cross section, symmetric microtrenching can be observed.

Figure 4(b) shows schematically how the results obtained from the cross sectional views need to be interpreted in a three dimensional fashion. Dependent on the orientation of the magnetic field, there will be a certain area on the bottom of the feature that is flat, i.e., a plateau that extends towards the sidewall on one side in the feature. Around the plateau there is an area where microtrenching occurs. The microtrench is deepest on the side opposite of where the plateau extends towards the sidewall, and in a direction that is expected for electron deflection by the magnetic field.

In summary, the results presented in this letter demonstrate that differential charging of microstructures contributes significantly to microtrench formation. More generally, we conclude that differential charging is an important effect in microstructure fabrication using high-density plasmas and should be included when explaining other microstructuring phenomena, e.g., the slowdown of the etch rate with feature size.\(^7,8\)

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