Measurements of mass dependent ion flux, radical concentrations and polymer film growth during the etching of SiO_2 and Si with high density fluorocarbon plasmas*

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For fluorocarbon based plasma etching of silicon, the parent gases are dissociated into ions and neutrals which deposit polymer films as well as provide chemically active species that etch silicon. High density sources such as an electron cyclotron resonance (ECR) or an inductive coupled plasma (ICP) tool require gas 'recipes' that differ from capacitive parallel plate devices to obtain good selectivity as well as etch rate. The parent gases are more extensively dissociated and there is enhanced ion to neutral flux on the wafer surfaces. Data from both an ECR and an ICP will be given in this report. Good selectivity of SiO_2 to Si has been found with CHF_3/H_2 and $C_2H_2F_4/O_2$ feed gases while pure CF_4 and CHF_3 have little selectivity. An FTIR is being used to monitor the breakup of the parent gases and provide a measure of the polymer film growth rates and composition. The relative composition of the ionic flux is being monitored by a differentially pumped in-line quadrupole mass analyzer. A measure of the radical concentrations of CF_3 and CF_2 is given by an IR diode laser. The latter two diagnostics have been used solely on the ECR. FTIR measurements as well as Langmuir probe, etch rate and uniformity and etching selectivity have been done on both tools. CF_4 and CHF_3 are predominately dissociated for typical input powers (500-1500 Watts) and neutral densities (1-5 mTorr) in both the ECR and the ICP tools. With CHF_3/H_2 in the ECR, the selectivity increases as the hydrogen percentage is increased until the etching rate drops to zero for both SiO_2 and Si. The CF_2 concentration drops by a factor of two and the ion data suggests a shift towards hydrogen containing species and lower mass molecular ions. For $C_2H_2F_4/O_2$ increasing the oxygen percentage reduces the selectivity while the CF_2 concentration decreases by a factor of 10. The latter data is consistent with the model that the CF_2 concentration correlates with polymer growth and polymer growth is essential for selectivity while the CHF_3/H_2 results do not follow the model. CF_3 and CF concentrations parallel the CF_2 concentration and thus give no indication of which species more directly affects polymer growth.

Polymer film growth on KBr windows near the wafer stage have been measured with the FTIR for pure CF_4 and CHF_3 in the ICP. The film growth is much larger with the CHF_3 plasma as expected. This indirect method of measuring film growth on the wafer will be used with the more selective gas recipes to aid in generating a model of the etching process.

Etching processes in the semi-conductor industry often have multiple requirements: high etch rate for a particular layer (e.g. SiO_2), good selectivity (e.g. etch SiO_2 but not Si or SiN), high anisotropy (straight side walls when etching trenches or VIA's), low damage and excellent process stability over many wafers. As critical dimensions (CD) have decreased these requirements have all become more difficult and yet more important to attain. High plasma density, low neutral pressure sources have been one avenue along which the industry has traveled. Once a tool has been constructed, the time honored methods of trial and error have been used to quickly and efficiently find the gas composition, flow rate, pressure, RF power and wafer bias power that fulfill these needs. The tool itself might be "tweaked" by changing the inductive coil design, the composition and temperature of the sidewalls, and the thickness of the plasma above the wafer. Afterwards, extensive measurements are required to completely elucidate the physical phenomena that are occurring. This report gives a short synopsis of data taken to assist in understanding the etch rate phenomena of one process, SiO_2 etching in fluorocarbon gases in high plasma density low neutral pressure tools, an ECR (Electron Cyclotron Resonance) and an (Magnetic Confined Inductively Coupled Plasma) MCICP. Reasonable etch rates (2000-5000 A/min), good selectivity (> 100:1 SiO_2/Si), and good CD control (.25 microns) have been attained on test wafers. On the MCICP, etch rate uniformity's of better than 3% have been achieved over a 10 cm diameter by proper antenna and wafer chuck design. The present ECR source cannot attain this uniformity.

Neither tool is a production model but has excellent diagnostic access and retains the basic features of the production tools. Both the MCICP and the ECR tools have turbomolecular pumps, monopolar electrostatic chucks with Helium backside cooling and a load lock. The ECR is a two magnet coil ASTEX system with a resonance magnetic field of 860 Gauss and a field at the wafer of about 150 Gauss. Maximum microwave power is 1.5 kW. A multiple path length infrared diode (IR) laser is permanently mounted on this tool and is used to measure concentrations of molecular species averaged over a radial volume just above the wafer using known absorption lines and their spectroscopic absorptivity. An in-line, magnetically shielded and differentially pumped quadrupole mass analyzer can be inserted in place of the wafer chuck assembly in order to monitor ion and neutral flux to a simulated wafer surface. A microwave interferometer is used to measure the source plasma density along with Langmuir probes. The MCICP is a large diameter ICP tool with a

surface multi-dipole magnetic field produced by permanent magnets outside a thin stainless steel vacuum chamber. The radial plasma density profile is uniform over a larger radial dimension with the magnets present then without. However obtaining etch rate uniformity of < 3% required slightly modifying the inductive coil and changing details of the electrostatic chuck as well as having good plasma density uniformity. Both tools can be monitored by a single pass FTIR (Fourier Transform Infrared) spectrometer and an OMA (Optical Multichannal Analyzer).

The etch rate of SiO_2 has been found to be dependent on ion energy flux with correction terms for the amount of etchant available versus ion energy flux and the etchant versus deposition precursors[1]. So a high plasma density source with a reasonable RF generated wafer bias voltage gives high etch rates. Selectivity (SiO_2 to Si) is most dependent on the 'chemistry' and the gas composition above the wafer. For CF_4 based etching processes, where hydrogen is added to decrease Si etching or oxygen is added to increase it, the selectivity is poor. Higher carbon containing species e.g $C_2H_2F_4$, are required in these high density sources to obtain high selectivity. The question is :'What is the deposition precursor?" Etch rates for SiO_2 and Si using CHF_3;H_2 and $C_2H_2F_4$;O_2 taken in the ECR are shown in Fig. 1. For these conditions, [CF_2] concentrations were measured with the IR diode laser as well as actinometry measurements of [F]. The [CF_2] concentrations are given in Fig. 2. It was found that [CF] follows the same general trends as [CF_2] (see fig 2) and [CF_3] has a concentration lower than the detection limit of $1X10^{11}$ cm^{-3}. Therefore, a particular [CF_x] deposition precursor cannot be identified. The ratio of [CF_2]/[F] for this data (see Fig. 3) shows good correlation with selectivity when oxygen is added but fails for the cases with hydrogen. The absorption spectrum of the film deposited on a KBr window in the MCICP during pure CHF_3 operation shows several features including CF stretching vibration around 1250 cm^{-1} (see fig.4). However, all the features have not been identified as yet. Measurements of the ion flux with the in-line QMS diagnostic reveals a tendency for lower mass ions and more 'break up" of the ionic species as hydrogen and more deposition (increased selectivity) occurs in the CHF_3 plasma.

1 J. Ding, J-S Jenq, G-H Kim, H. L. Maynard, J. S. Hamers, N. Hershkowitz, and J. W. Taylor, J. Vac. Sci. Tech. A11,1283(1993).

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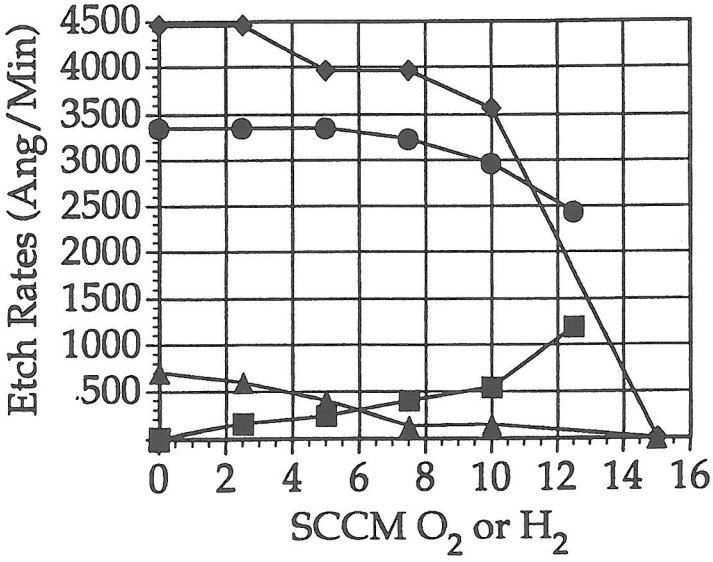

Fig . 1 Etch rates versus flow rates of additives - H_2 & O_2 in sccm where main gas flow rate is 25 sccm. ECR tool, at 1000W, 3mT. and 150 W RF on wafer chuck. ■ Si -$C_2H_2F_4/O_2$; ●SiO_2-$C_2H_2F_4/O_2$; ▲Si -CHF_3/H_2; ◆SiO_2-CHF_3/H_2 .

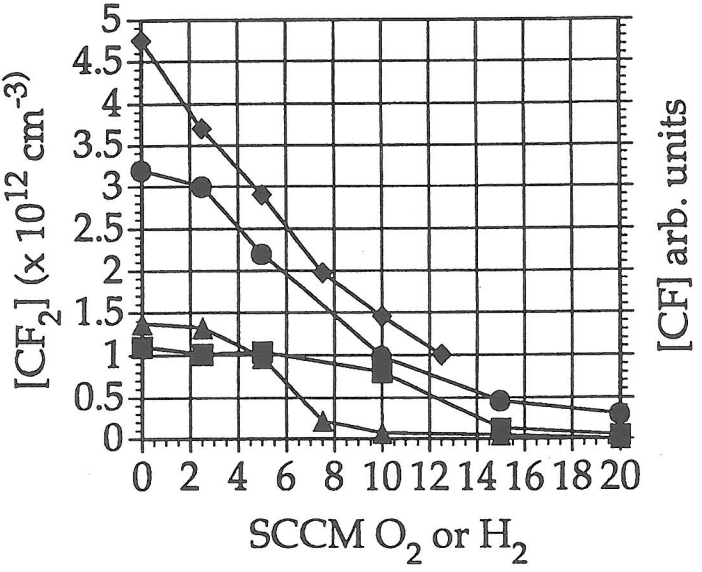

Fig. 2 $[CF_2]$,and [CF] versus flow rates of additives - H_2 & O_2 in sccm where main gas flow rate is 25 sccm. ECR tool, at 1000W, 3mT. and 150 W RF on wafer chuck. ■ $[CF_2]$ -$C_2H_2F_4/O_2$; ●$[CF_2]$ -CHF_3/H_2 ; ▲[CF]-$C_2H_2F_4/O_2$; ◆[CF]-CHF_3/H_2 .

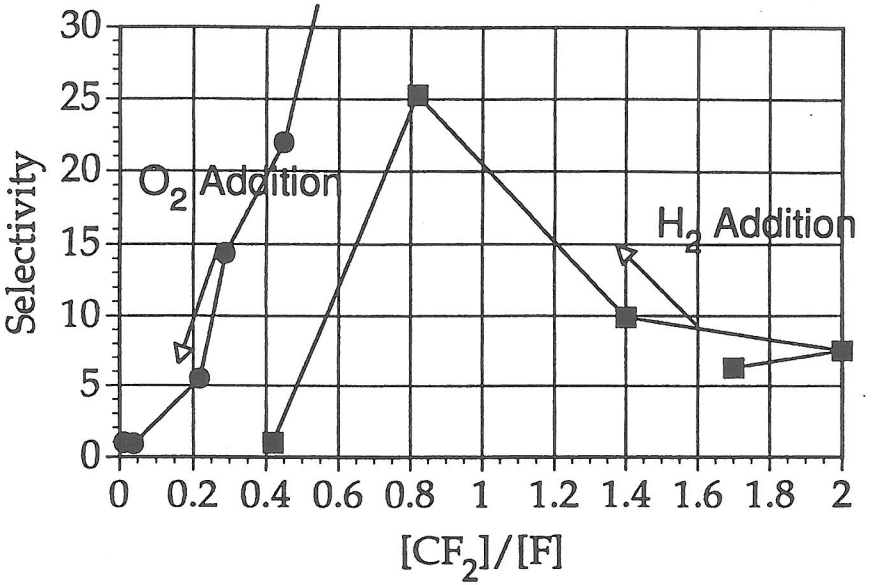

Fig. 3 Selectivity versus $[CF_2]/[F]$ for ■ H_2 added to CHF_3 & ● O_2 added to $C_2H_2F_4$. ECR tool, at 1000W, 3mT. and 150 W RF on wafer chuck.

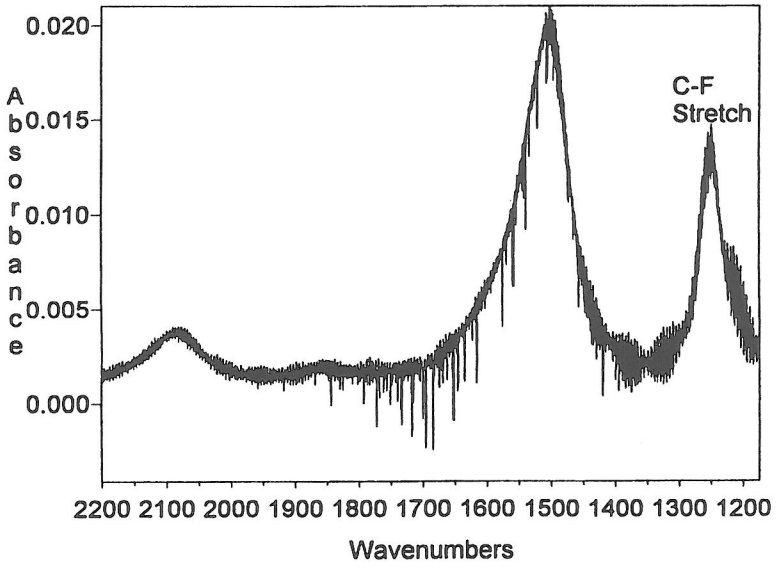

Fig. 4 Absorption spectrum of film deposited on KBr window during pure CHF_3 operation in the MCICP.