Does it matter what type of source is used for plasma etching of semiconductors?

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Comparison of CF_4 plasma SiO_2 etch rate data in three different types of etch tools (ECR, ICP and HRF) shows that etch rate depends on a limited number of plasma parameters at the wafer surface. The data show that identical values of ion energy flux and fluorine concentration result in identical etch rates. Differences in selectivity are expected because of differences in free radical to fluorine concentrations for identical SiO_2 etch rates . Most of the chemical reactions do not appear to be important.

Introduction

Plasma etching of semiconductor features < 0.3 micron now appears to requires the use of high density-low pressure tools. This category of plasma tools operate with neutral pressures 0.1 mTorr < p < 10 mTorr corresponding to neutral densities $n_o \approx 3 \times 10^{12} \rightarrow 3 \times 10^{14}$ cm^{-3} and electron densities $10^{11} \rightarrow 10^{12}$ cm^{-3}. Such plasmas have the characteristic that plasma-wafer sheaths are thin compared to ion neutral collision lengths. This means that ion anisotropy is unlikely to be affected by ion collisions in the plasma-wafer sheath.

High density-low pressure plasmas can be obtained with electron cyclotron resonant (ECR), inductively coupled (ICP) and helicon (HRF) etch tools. The electron temperature T_e increases in a similar way with decreasing neutral pressure in all three types of tools. All employ RF (often at 13.56 MHz) to "self bias" insulating substrates to negative potentials (relative to the plasma) the order of tens of volts and use similar wafer chucks. This means that ion velocity distribution functions (IVDF) at the wafer will be comparable. All three employ similar chemistries to achieve the same goals. However, there are some obvious differences. These include the operating frequency: 2.45 GHz for ECR, usually 13.56 MHz for ICP and HRF; the electron heating mechanism (resonant E fields for ECR, wave and collisional heating for HRF, inductive E fields for ICP); the presence or absence of B fields - present in the ECR and HRF, absent in the ICP. The three types of tools provide the plasma with different combinations of conducting and insulating boundaries. For identical input power, flow rate and pressure, the relative concentrations of ion and neutral species also differ. In this paper we consider the questions: Does it matter what type of plasma source is used? What are the differences? Are there any important differences?

Etching depends on plasma parameters at the wafer surface

Plasma etching takes place at the wafer surface so it only depends on the plasma and neutral species parameters at the wafer surface.

It appears to be obvious that plasma etch rates will be tool independent if plasma etch tools are operated with *identical* plasma parameters at the wafer. It is not clear that this condition can ever be satisfied especially when it is realized that in comparing different sources it is important to consider both the charged particle and neutral species. Even for relatively simple etching systems, there are often dozens of equations and species which are present, and apparent when for example the optical emission is monitored.

Is it necessary to consider *all* neutral and charged species? Our experiments suggest that plasma etching characteristics are similar in all three types of sources when only a *limited number of plasma parameters are identical* at the plasma-wafer sheath boundary. Once these parameters are identified, it is not necessary to determine the others, except perhaps in very general ranges.

The variation of the electron temperature T_e with pressure is determined by the balance of plasma production with plasma loss. This can be written:

$$n_e < \sigma_i(T_e) v_e > n_o V \approx n_e c_s A_{loss}, \qquad (1)$$

where $c_s = \sqrt{\frac{T_e}{m_i}}$. Note that the plasma density n_e drops out. Eq. (1) implies that T_e is a function of neutral pressure and species mix and of geometry and not a function of input power. The assumption of Maxwellian electron energy distribution functions (EEDF) gives a reasonable approximation for calculating σ_i in Eq. (1).

Etch rates are sensitive to the ion energy E_i at the wafer surface:

$$E_i = e(-V_{sb} + \Phi_p) \qquad (2)$$

where V_{sb} is the wafer self bias voltage and Φ_p is the plasma potential far from the wafer.

In high density-low pressure discharges, sheath thicknesses at the wafer (the order of $(E_i/T_e)^{3/4}\lambda_D$, where λ_D is the electron Debye length) are much smaller than the ion-neutral or ion-ion collision length so ion motion through the sheath is collisionless. Almost all of the ion energy at the wafer is picked up by the ions in falling through the plasma-wafer sheath. Ions take approximately ω_{pi}^{-1} to fall through the sheath, where ω_{pi} is the ion plasma frequency. The details of the IVDF depend on the amplitude and frequency of the self bias voltage rather than the type of tool.

The ion anisotropy (i.e. the ratio of etch rate perpendicular to parallel to the surface), depends on $E_\perp$, the ion energy transverse to the wafer, measured at the wafer surface.

$$E_\perp \approx \text{presheath energy} \approx \frac{T_e}{2} \qquad (3)$$

Etching of SiO_2 and Si etching with $CF_4/CHF_3/C_2H_2F_4/Ar/H_2/O_2$

Semiconductor etching is a chemical process. We have considered as a model etching system: $CF_4/CHF_3/C_2H_2F_4/Ar/H_2/O_2$ etching of $SiO_2$and Si. We have employed many in-situ diagnostics of plasma and neutral species.

Experimental SiO_2 etch rate data obtained in the **ECR tool** [1] are graphed in Fig. 1. Equal etch rate contours are contours are identified on a graph of fluorine concentration vs ion energy flux. The fluorine concentration was determined with argon actinometry. The ion energy flux was determined by measuring the ion saturation current to a probe near the wafer.

These data suggest that only two rate limiting parameters matter. These are the ion energy flux J_iE_i and the fluorine density (really the fluorine flux). It is apparent that for sufficient fluorine density, the etch rate only depends on the ion energy flux while for too little ion energy flux, the etch rate depends only on the fluorine concentration. We have shown [2] that the etch rate R (shown in Fig., 1) and higher pressure (40 mtorr) capacitively coupled RIE data can be described by:

$$R \approx \frac{K_{es}\, J_i\, E_i\, [1 - C_{sp}(\frac{J_d}{J_e})^2]}{1 + A_s \frac{J_i\, E_i}{J_e}} \qquad (4)$$

where E_i = ion energy at the wafer, J_d = deposition species flux , J_e = etching species flux, J_i = ion particle flux and K_{es}, C_{sp}, and A_s are constants. The term $[1-C_{sp}(\frac{J_d}{J_e})^2]$ in the numerator of Eq. (4) accounts for polymer deposition and can be negative indicating net deposition. With CF_4 plasmas, this term was only found to be significant in describing etching in the RIE tool.

Equation 4 has the property that for $\frac{J_i\, E_i}{J_e} >> 1$, $R \propto J_iE_i$, while for $\frac{J_i\, E_i}{J_e} << 1$, $R \propto J_e \propto n_F$. The former result is interesting because the etch rates observed in these tools are much greater than can be attributed to physical sputtering and are almost certainly the result of energy assisted chemical reactions.

Etch rate data obtained in a homemade helicon (HRF) tool are graphed in Fig. 2. For comparison, the 1000 A/min etch rate contour, determined for the ECR data is also graphed in Fig. 2. It is apparent that the HRF data are generally consistent with the ECR data. Representative etch rate data for the three types of tools are given in Table 1.

A better comparison is given in Fig. 3 in which data from the MCICP and HRF tools are added to data from the ECR tool, which has been fit to equation (4). It is evident that Eq.(4), derived from fitting ECR data, fits MCICP and HR F data as well the ECR data. This is a remarkable result since the details of the three types of sources are quite different.

Selectivity in etching follows from Eq.(4) because different substrates have different coefficients. Polymer formation (determined by C_{sp} and J_d/J_e) which inhibits etching is particularly important. For CF_4 plasmas, $J_d/J_e \propto \frac{n_{CFx}}{n_F}$, where n_{CFx} and n_F are the concentrations of fluorine and CFx and x = 1,2,3. We are not certain which x is most important because all three have very similar behavior with power, pressure, etc. Our data suggest that the ratio $\frac{n_{CFx}}{n_F}$ varies considerably from tool to tool. This in turn suggests that it is unlikely that different tools can achieve identical plasma parameters at the wafer surface.

Uniformity of both etch rate and anisotropy depend on the uniformity of: n_e, ϕ_p, T_e, wafer chuck-cooling, free radicals and self bias across the wafer surface. For etch rate, Eq. (4) says we only need to know:, E_i, n_e, n_F, n_{CFx}. We do not need to know about all of the neutral species. In addition, we only need to know the electron density n_e rather than the individual densities of each of the ion species.

Eq. (4) does not depend on electron energy distribution function (EEDF) or the electron velocity distribution function (EVDF). Fig. 3 shows that etch rate does not depend on the type of tool or on the presence or absence of a B field. Selectivity and anisotropy depend on the ability to produce particular ratios of $\frac{n_{CFx}}{n_F}$, which do depend on the type of tool.

It is tempting to attribute the differences in $\frac{n_{CFx}}{n_F}$ to differences in the electron heating mechanism or to the presence or absence of magnetic fields. However, it is also likely that much of the differences can be attributed to interactions with neutral species at the walls. Each of the three tools we have studied provides a different combination of wall materials. The walls of the ECR tool are a combination of anodized aluminum and stainless steel. The MRF walls are a combination of quartz and aluminum while the MCICP is as combination of stainless steel and quartz. We found that changing the ECR wall material from aluminum to stainless steel resulted in a reduction in the relative fluorine concentration. Although wall material is not important in determining the etch rate, it can be important in determining the selectivity. It may matter what the walls are made more than the type of tool.

Conclusion

Does it matter what type of source is used for plasma etching of semiconductors? Identical plasma parameters at the sheath-wafer boundary give rise to identical etching, independent of tool type. The processes depend on rate limiting steps and so depends on the plasma density or a particular free radical density. The surface reactions at the wall can be critical to tool operation, especially the selectivity. The etch rate also depends on the wafer chuck design, especially the cooling capability. What doesn't matter? Curiously, most of the chemical reactions and perhaps the type of tool.

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References

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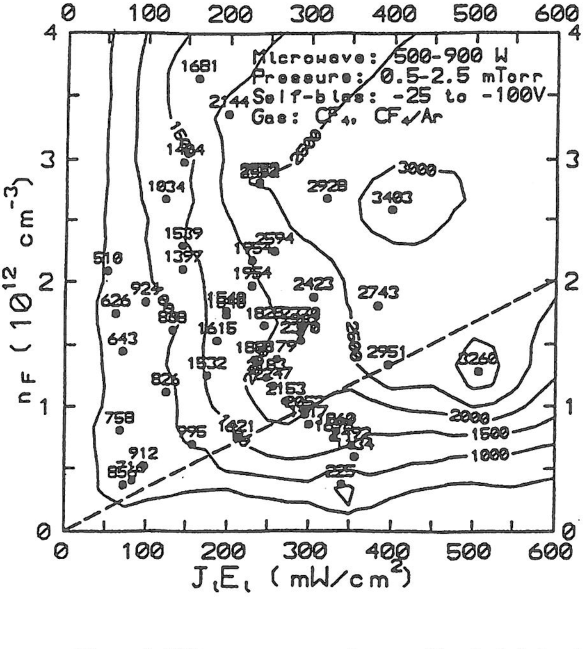

Figure 1. Contour Plot of SiO_2 average etch rate (A∞/min) in the ECR tool as a function of ion energy flux to the wafer surface and the F atom density.

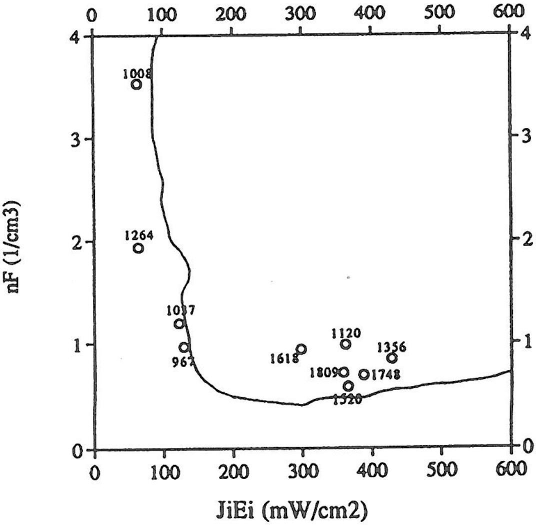

Figure 2. Contour Plot of SiO2 average etch rate (A∞/min) in the HRF tool as a function of ion energy flux to the wafer surface and the F atom density.

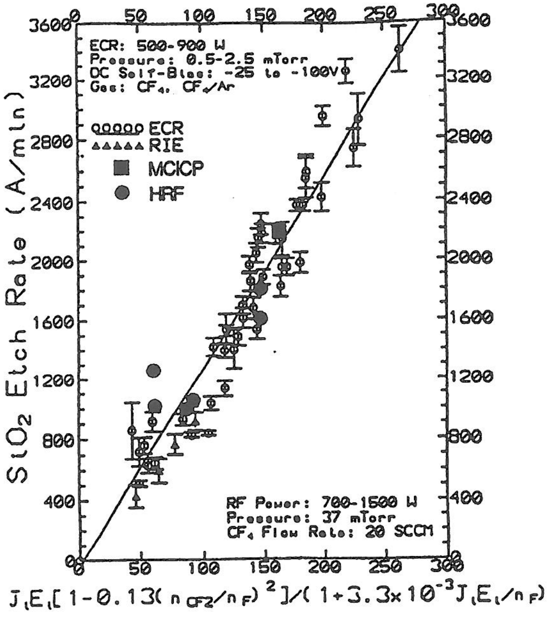

Figure 3. Etch rate data from the ECR, HRF, MCICP and RIE tools fit to Eq.(4).