AFFECTS OF CARBON DIOXIDE AND HELIUM ON REACTIVE ION ETCHING OF SILICON DIOXIDE

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ABSTRACT

A study of the etch characteristics of a thermally grown silicon dioxide etch in RIT's 2406 PLASMATRAC RIE was performed for a C_2F_6 / CHF_3 / CO_2 gas mixture. Correlations between the amount of CHF_3 and CO_2 introduced and SiO_2 etch rates and selectivity to polysilicon were investigated using a statistical experimental design. SiO_2 etch rates as high as 1018 A/min were achieved with a corresponding selectivity to polysilicon of 2.84:1. At a gas flow of 60 sccm C_2F_6, 171 sccm CHF_3, 48 sccm CO_2, 255 watts & 150 mtorr, an optimized etch for selectivity was found to give an SiO_2 etch rate of 910 A/min with a corresponding selectivity of 5.29:1. Uniformity of the etch rate across the wafer was found to be good for the SiO_2 etch with etch rates varying less than 5% across the wafer. Helium additions were found to improve the uniformity of polysilicon etch rates from their nominal value of 25% to 11% across the wafer.

THEORY

Due to the ever decreasing feature sizes of integrated circuits, recent trends in the semiconductor industry involving etching processes has been away from wet chemical processing to dry plasma etch systems. These systems offer better minimum resolution due to their anisotropic etching nature along with better control of sidewall profiles. Selectivity and throughput are, however, degraded as compared to wet etching techniques.

The etch rates and selectivities of thin films in a plasma system depends on several factors including the power and pressure of the plasma along with the gas composition. In the manufacture of silicon devices, SiO_2 is the most frequently etched material and therefore has the widest range of etching requirements [1]. When etching silicon dioxide it is often necessary to etch preferentially to polysilicon. SiO_2 can be etched in a plasma that produces fluorine atoms or which use feed gas mixtures that generate unsaturate-rich fluorocarbon species. Since polysilicon etching occurs when unattached fluorine

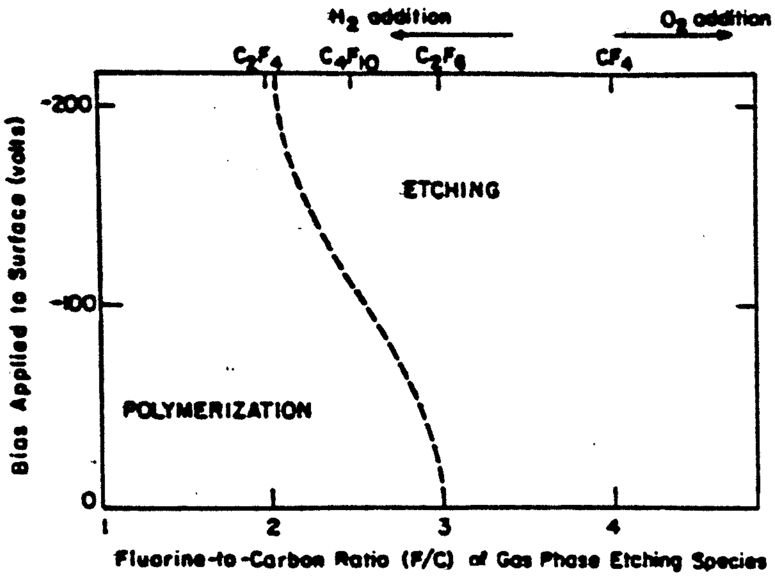

Figure 1: Boundary between polymerization and etching as influenced by the F:C ratio of the plasma [3].

radicals are present, for selective etching of SiO2 to polysilicon, an unsaturated gas feed is normally used [2].

This can be demonstrated for a C2F6 plasma. SiO2 etching will occur when C2F6 molecules collide with electrons to form CF3 radicals which in turn react to produce CFx radicals. A thin fluorocarbon layer is formed when these unsaturated species impinge on the wafer surface. The fluorine atoms in turn react with silicon and carbon reacts with oxygen forming volatile products which can be removed. Since no oxygen is available on the polysilicon surface, reactants are nonvolatile and a polymer forms. By lowering the fluorine to carbon ratio of the etchant gas, selectivity of SiO2 to polysilicon can therefore be enhanced due to the fact that different reactions are responsible for the etching of the two films. A gas combination used frequently to lower the F:C ratio of the plasma and enhance selectivity of SiO2 to polysilicon involves a C2F6/CHF3 mixture. This gas mixture is on the verge of polymerization as shown in Figure 1 [3], and due to this etch rates are lowered for both surfaces.

The addition of hydrogen to the etchant gas, decreases the F:C ratio in the plasma even further since it reacts with fluorine radicals forming HF thereby eliminating a polysilicon etchant gas. The addition of an oxidant such as carbon dioxide to the plasma should result in pulling the chemically reactive species toward the etch side of Figure 1, resulting in higher etch rates and increased throughput. This added oxygen will also tend to remove the polymer formed on the surface of the polysilicon thereby promoting polysilicon etching. Although the selectivity of SiO2 to polysilicon will diminish with oxygen addition due to the fact that oxygen is already abundant in the region of the SiO2 and any further additions are diluted by that already present, it may be compensated by the amount of hydrogen existing in the plasma from CHF3.

With the advent of larger diameter wafers, the uniformity of etch rates has become an important concern. For certain etchant processes, etch rates are required to vary less than 5% over the entire wafer. Helium may be a suitable additive to an optimized etch gas to achieve desirable uniformity. Non uniformity can result from poor gas flow or non uniform electric fields or currents [4]. With the addition of a light, inert gas such as helium, etch rates should not be affected and due to the dilutive nature of the helium in the plasma, high concentrations of etch species in certain areas will be less likely to occur, eliminating plasma concentration gradients which result in arcing. Due to this phenomenon, uniformity will increase since the areas where arcing occurs consumes the majority of the available power resulting in nonuniform etch rates [5].

This experiment studied the etch characteristics of a SiO2 etch preferentially to polysilicon for a C2F6/CHF3/CO2 plasma. Correlations between the amount of CHF3 and CO2 introduced and SiO2 etch rates and selectivity to polysilicon were investigated and a statistical experimental design used to determine an optimal process for both SiO2 etch rate and selectivity with respect to polysilicon. Helium was then added to the optimal process found for selectivity and its effects on etch rates and uniformity determined.

EXPERIMENT

Twenty-five 3 inch wafers were prepared for this experiment. The wafers were dipped in HF to remove any oxide present and then RCA cleaned. Approximately 5000A of SiO2 was thermally grown and approximately 7000A of polysilicon deposited via LPCVD. The polysilicon was lithographically patterned using KTI820 and a stripped mask which defined 1 cm wide lines of alternating polysilicon over SiO2 and SiO2 lines. The wafers were rotated 90 degrees and KTI820 photoresist was patterned in the same manner, resulting in perpendicular lines of photoresist over polysilicon and SiO2.

This study utilized a 2406 PLASMATRAC RIE to determine the effects of CO2 and helium on a C2F6/CHF3 plasma etch of silicon dioxide. Carbon dioxide was added in various amounts to a C2F6/CHF3 plasma optimized previously for selectivity of SiO2 to polysilicon. A suitable baseline for CO2 addition was determined and a faced central composite statistical design was used to enhance the etch rate of SiO2 and its selectivity to polysilicon. The CHF3 flow was varied from 137 to 205 sccm, CO2 from 32 to 48 sccm, power from 204 to 306 watts and pressure from 120 to 180 mtorr. Response variables included the etch rate of SiO2, its selectivity with respect to polysilicon and uniformity of the SiO2 etch.

Film thicknesses were measured using a Nanospec and polysilicon thicknesses verified with an alphastep since the Nanospec program used was calibrated for polysilicon over 1000A

of SiO2. Measurements of SiO2 were absolute while those of polysilicon were, therefore, relative. The uniformity of the etch across the wafer was found from the formula

$$(\text{High Reading} - \text{Low Reading})/2 * \text{Average} \qquad (1)$$

Measurements were taken at the top, center, flat, left and right sides of the wafer so that uniformity could be measured. After an optimized SiO2 etch process was found, it was verified and helium was then added to the optimized C2F6/CHF3/CO2 etchant gas from 100 sccm to 250 sccm in increments of 50 sccm and its effects on the response variables noted.

RESULTS/DISCUSSION

A summary of the process conditions and results of the faced central composite statistical design can be found in Table 1 in Appendix A.

Within the design space, RS1 calculated an optimized silicon dioxide etch rate process to give 1045 A/min with a 3.48:1 selectivity to polysilicon. An optimized selectivity to polysilicon process also was calculated, giving an SiO2 etch rate of 827 A/min with a selectivity of 6.41:1. From extrapolation of the data outside of the original design space, RS/1 predicted that a high SiO2 etch rate at both low and high values of CO2 concentration can be achieved. This is, however, contrary to data obtained from establishing a CO2 baseline and when these results were attempted to be verified it was found that the predicted RS/1 values for the data outside of the design space could not be replicated, however, verification was achieved for the RS/1 results within the statistical design. These findings are summarized in Table 2.

RS/1 Optimization

	Within Design Space		Outside Design Space	
	Etch Rate SiO2	Selectivity to polysilicon	Etch Rate SiO2	Selectivity to polysilicon
C2F6	60 sccm	60 sccm	60 sccm	60 sccm
CHF3	173.89 sccm	171 sccm	215 sccm	125 sccm
CO2	48 sccm	48 sccm	70 sccm	15 sccm
Power	282.54 watts	255 watts	300 watts	300 watts
Pressure	120 mtorr	150 mtorr	120 mtorr	120 mtorr
Predicted:				
E SiO2	1045 A/Min	827 A/Min	1800 A/Min	1200 A/Min
Selectivity	3.48:1	6.41:1	3.6:1	1200:1
Actual:				
E SiO2	1018 A/Min	909.8 A/Min	915 A/Min	905.2 A/Min
Selectivity	2.84:1	5.29:1	2.48:1	3.12:1

Table 2: Actual & predicted etch rates and selectivity and their respective etch chemistry.

Figures 2 and 3 are contour plots of the Taylor series models for SiO2 and polysilicon etch rates versus CO2 concentration, CHF3 concentration, power and pressure. From these it can be seen that the etch rates of both SiO2 and polysilicon decrease with increasing concentrations of CHF3 as predicted from Figure 1. With increased CO2 concentrations, the etch rate of SiO2 increases steadily, while that of polysilicon increases until approximately 40 sccm of CO2, then declines. This results in the highest selectivity of SiO2 to polysilicon at higher values of CO2 concentration. Figure 3 shows that both SiO2 and polysilicon etch rates increase with decreased pressure. This is due to the fact that lower pressures result in longer mean free paths for the plasma's ions, which in turn leads to more ionic bombardment, removing any fluorocarbon buildup and facilitating etching. With increased power, etch rates of SiO2 peak at approximately 280 watts, while those of polysilicon increase slowly but steadily. Since SiO2 does not require extensive ion bombardment to remove any polymer formation due to the presence of oxygen, its etch rate reaches a maximum. This oxygen is not present at the polysilicon surface and therefore, increased power results in greater ionic bombardment facilitating etching as described previously.

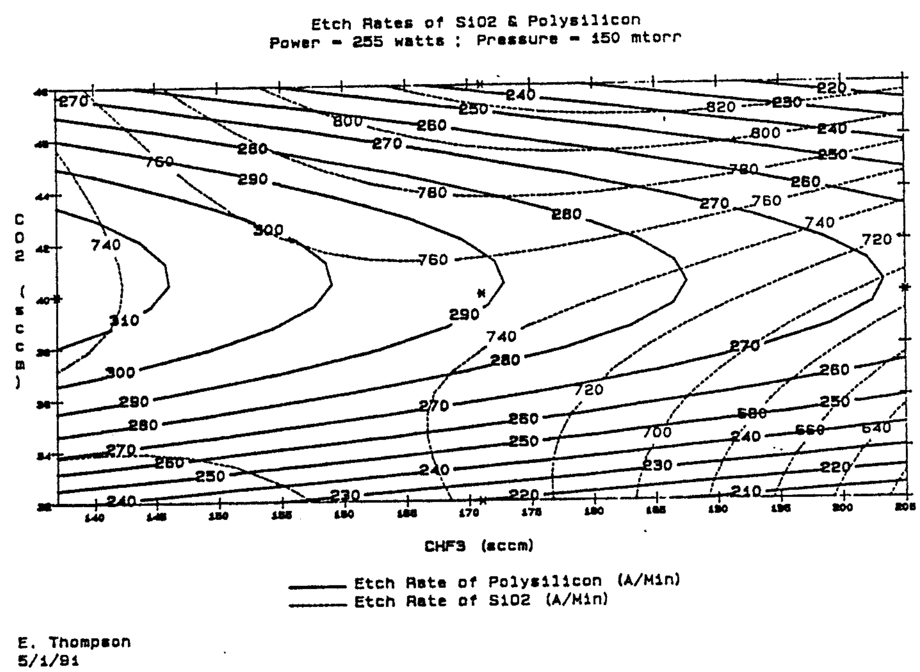

Figure 2: CCF Response Surface Model for fixed Power and Pressure.

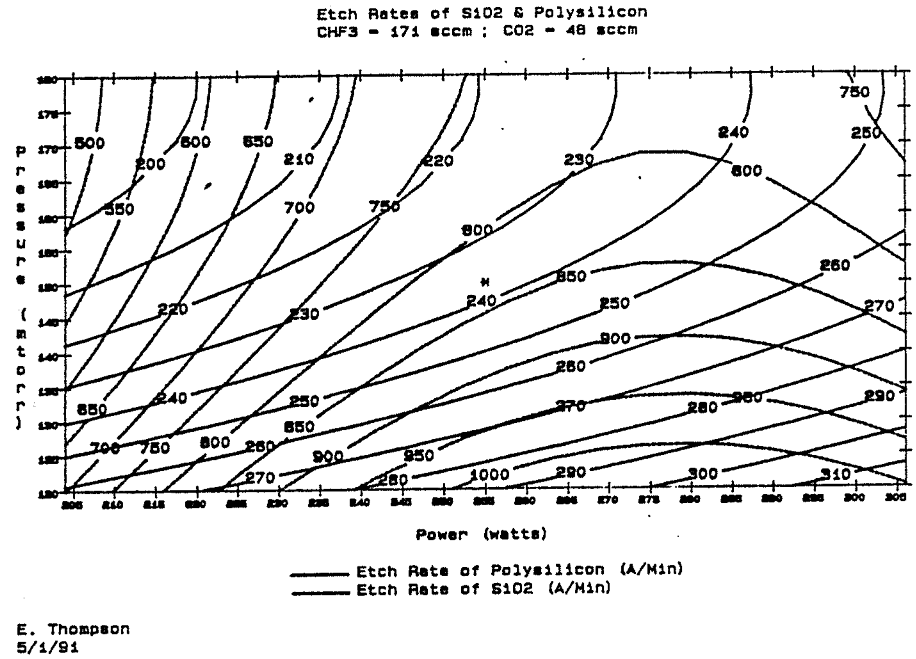

Figure 3: CCF Response Surface Model for fixed CO2 and CHF3 concentrations.

Figure 4 shows the effects of helium additions to the etchant chemistry optimized for selectivity. The uniformity of polysilicon seems to be improved at a helium addition of 150 sccm , however, higher polysilicon etch rates are the cost. This can be explained by the fact that although helium is light, it still can enhance ionic bombardment, leading to higher polysilicon etch rates.

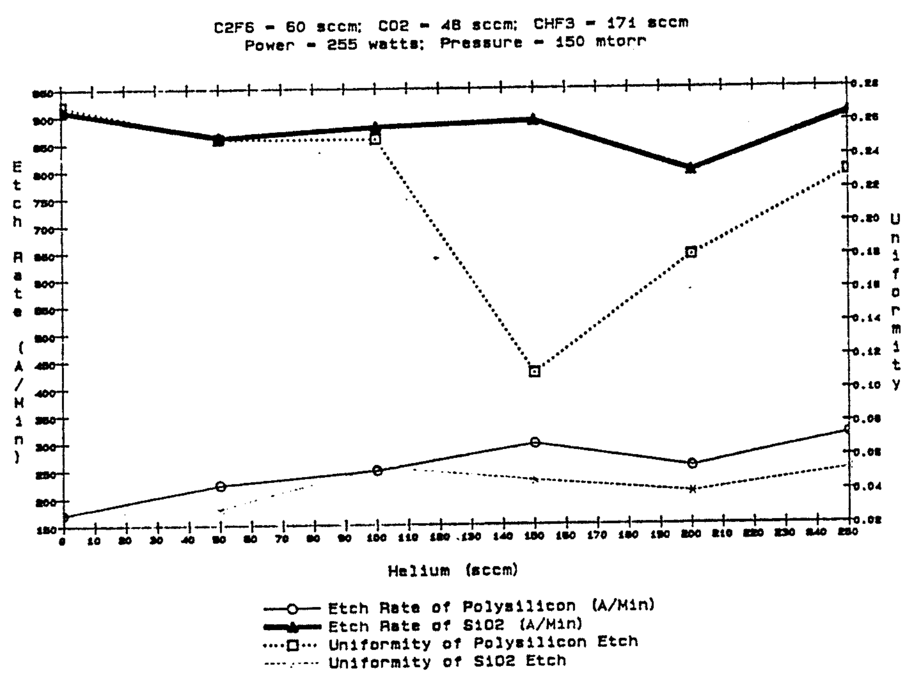

Figure 4: Helium addition to a C2F6/CHF3/CO2 Etch

CONCLUSIONS

This experiment provided valuable information on the effects of CO_2 on a C_2F_6/CHF_3 etchant gas. A previously optimized C_2F_6/CHF_3 etch resulted in SiO_2 etch rates of 612 A/Min with a selectivity to polysilicon of 6.3:1 [6]. By adding CO_2, etch rates of SiO_2 can be improved to approximately 910 A/Min with a selectivity to polysilicon of 5.29:1. If the desired SiO_2 etch rate is high, then this gas mixture is optimal with little loss of selectivity to polysilicon. Helium additions were found to improve, otherwise poor polysilicon uniformity, however, the added helium was seen to increase polysilicon etch rates in the process.

ACKNOWLEDGMENTS

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APPENDIX A

Run Number	CHF3 (sccm)	CO2 (sccm)	Power (watts)	Pressure (mtorr)	E SiO2 (Å/min)	E POLY (Å/min)	Uniformity SiO2 Etch	Uniformity Poly Etch
1	205.00	40.00	255.00	150.00	727.70	298.70	0.03	0.210
2	205.00	32.00	204.00	120.00	637.40	293.60	0.02	0.154
3	205.00	32.00	204.00	180.00	433.30	173.20	0.04	0.215
4	171.00	40.00	255.00	150.00	783.00	321.75	0.05	0.190
5	205.00	48.00	204.00	180.00	465.40	206.50	0.03	0.100
6	171.00	40.00	255.00	150.00	827.00	129.10	0.05	0.100
7	205.00	32.00	306.00	120.00	361.30	179.50	0.04	0.378
8	171.00	40.00	204.00	150.00	445.00	222.00	0.04	0.260
9	171.00	40.00	255.00	150.00	784.00	322.70	0.05	0.164
10	171.00	40.00	255.00	150.00	771.00	324.70	0.04	0.170
11	171.00	40.00	255.00	180.00	772.70	333.60	0.03	0.110
12	137.00	32.00	306.00	120.00	1018.70	358.00	0.08	0.100
13	137.00	32.00	306.00	180.00	577.00	314.20	0.04	0.158
14	205.00	32.00	306.00	180.00	573.80	181.00	0.05	0.180
15	137.00	48.00	204.00	180.00	433.20	215.17	0.04	0.115
16	137.00	48.00	204.00	120.00	630.20	298.00	0.05	0.135
17	171.00	40.00	255.00	150.00	724.00	333.40	0.05	0.145
18	171.00	40.00	306.00	150.00	712.00	283.80	0.03	0.120
19	205.00	48.00	204.00	120.00	651.60	249.10	0.04	0.365
20	205.00	48.00	306.00	120.00	1006.30	291.60	0.01	0.135
21	137.00	32.00	204.00	120.00	660.60	215.00	0.05	0.313
22	171.00	40.00	255.00	150.00	755.00	327.00	0.04	0.215
23	137.00	48.00	306.00	120.00	955.90	422.00	0.02	0.155
24	137.00	40.00	255.00	150.00	674.00	215.00	0.03	0.166
25	171.00	32.00	255.00	150.00	717.60	255.00	0.04	0.106
26	137.00	48.00	306.00	180.00	545.00	289.10	0.04	0.073
27	171.00	40.00	255.00	150.00	783.70	325.00	0.05	0.100
28	171.00	40.00	255.00	120.00	818.50	212.40	0.05	0.142
29	137.00	32.00	204.00	180.00	445.20	170.60	0.05	0.121
30	171.00	40.00	255.00	150.00	712.00	297.70	0.04	0.135
31	205.00	48.00	306.00	180.00	734.10	192.60	0.06	0.168