Development of an Anisotropic, Highly Selective Tungsten Silicide Dry Etch Process

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Abstract- The development of an anisotopic Tungsten Silicide etch that will provide good selectivity to photoresist as well as an underlying oxide has been studied. It has been found that by reducing the amount of fluorine (SF_6) in the system and increasing the chlorine concentration, slightly tapered sidewalls can be achieved without the use of a polymer forming gas. An optimum process was developed on an Applied Materials P-5000 MxP system. A condition of 10 sccm SF_6, 40 sccm Cl_2, 20 sccm HeO_2 at 30 mTorr, and 400W presents slightly tapered sidewalls with within wafer uniformity of 4.85%. The selectivity of Tungsten Silicide to photoresist and oxide is 0.89, and 3.07 respectively.

An experiment was also conducted in which comparable etch rates of 57Å/sec were obtained using a first order approximation of power densities between the P-5000 MxP and a GEC Plasma Cell located at the Rochester Institute of Technology.

1. INTRODUCTION

Refractory metal silicides have become increasingly important materials in the ULSI era. Materials such as $TiSi_x$, $MoSi_x$, WSi_x, and $TaSi_x$ have found uses in semiconductor manufacturing due to their low resistivity, high temperature stability, good electromigration resistance, and excellent optical and electrical properties. Refractory metal silicides have now found applications in a wide variety of technologies ranging from CMOS and BiCMOS to CCD applications. With silicides finding a wider range of applications in the semiconductor industry, new processes need to be developed for these materials. The development of an anisotropic WSi_x dry etch process that would provide high selectivity to oxide was the focus of this experiment.

A considerable amount of work has been done in developing etch processes for WSi_x using a wide variety of process conditions [1-3]. This project was restricted to a limited subset of useful process gases. It has typically been reported that the use of polymer forming gases (e.g. C_2F_6, CF_4), in a WSi_x etch process is the easiest way of achieving an anisotropic, highly selective etch. This experiment was designed using gas sources that did not contain polymer-forming agents. SF_6, Cl_2, HBr, and HeO_2 were the gases that were available. The initial experiment was processed on an Applied Materials Precision-5000 MxP Magnetically Enhanced RIE system (MERIE). A two level screening experiment was designed in which the etch rates and uniformities of photoresist, WSi_x, and SiO_2 was determined as well as selectivities of the WSi_x to the photoresist masking layer and the underlying oxide. Following the initial experiment, runs were selected based on the selectivities, and uniformities, and were etched to endpoint and the critical dimension and uniformity was measured and an optimum process determined. A process translation was then attempted between the P-5000 and the GEC Plasma Cell at the Rochester Institute of Technology (RIT).

2. PROCEDURE

The initial screening experiment was a six factor two level fractional factorial design for the P-5000 to examine the effect of gas flow, power, and pressure on a number of output responses. Table 1 below shows the experimental design. The design was

Table 1: Experimental Design for the P-5000

Input Parameters	*Levels*	*Output Responses*
Gas Flows		WSix Etch Rate
SF_6	10,60 sccm	WSix Uniformity
Cl_2	0,40 sccm	Photoresist Etch Rate
HBr	0,30 sccm	Photoresist Uniformity
HeO_2	0,20 sccm	Oxide Etch Rate
Power	200,400 W	Oxide Uniformity
Pressure	30,150 mTorr	WSi_x : Photoresist
Time	60 sec fixed	WSi_x : Oxide
Cathode Temp	10°C fixed	

created using the statistical software JMP. Three center point runs, (35sccm SF_6, 20sccm Cl_2, 15sccm HBr, 10sccm HeO_2, 90mTorr, 300W), were added to evaluate experimental error. Etch experiments were run at all of

the given process conditions on patterned resist masked samples of 6000Å of WSi_x sputtered on top of 5000Å of oxide formed from a TEOS precursor. Pre-etch step heights were measured at 25 sites using a KLA Tencor P-22 profilometer. With the initial step heights measured

With the screening experiment analyzed, conditions which showed acceptable selectivity, and uniformity were chosen for endpoint detection. Wafers were run under the chosen process conditions for 400 sec. which allowed for endpoint detection. The endpoint detection system incorporated with the P-5000 was used. The endpoint system monitored by changes in intensity at a given wavelength. Previous work showed that the optimum wavelength to monitor the endpoint for WSi_x was a W line at 4010Å. Endpoint algorithms were established for each process condition based on the endpoint curve generated by the endpoint monitoring system. After an endpoint algorithm was established for each process. The conditions were repeated but stopped at endpoint with a fixed over etch time. CD measurements, (2μm opening), were collected on the selected wafers before and after each etch and strip. From this CD bias, or widening of the opening, and CD bias uniformity was determined. Oxide thickness measurements were also collected before and after each etch to examine the selectivity of each etch. SEM cross sections were also taken to determine the degree of anisotropy of each condition. The wafer that showed the best selectivity, and cross sectional profile with the minimum CD change was chosen as the optimum process which was then used in a higher level experiment that is discussed further in this report.

Based on optimum process conditions obtained on the P-5000 work was done to translate the etch process to a GEC Plasma Cell located at RIT. There is a considerable difference in the chamber design of the two tools which will result in a significant difference in the performance of the etch between the two tools. The P-5000 supports 6" wafer processing while the GEC has an electrode designed for 3" wafer processing. The brief list below shows some design variables that should be taken into account when either designing an etch process or trying to translate a process from one tool to another.

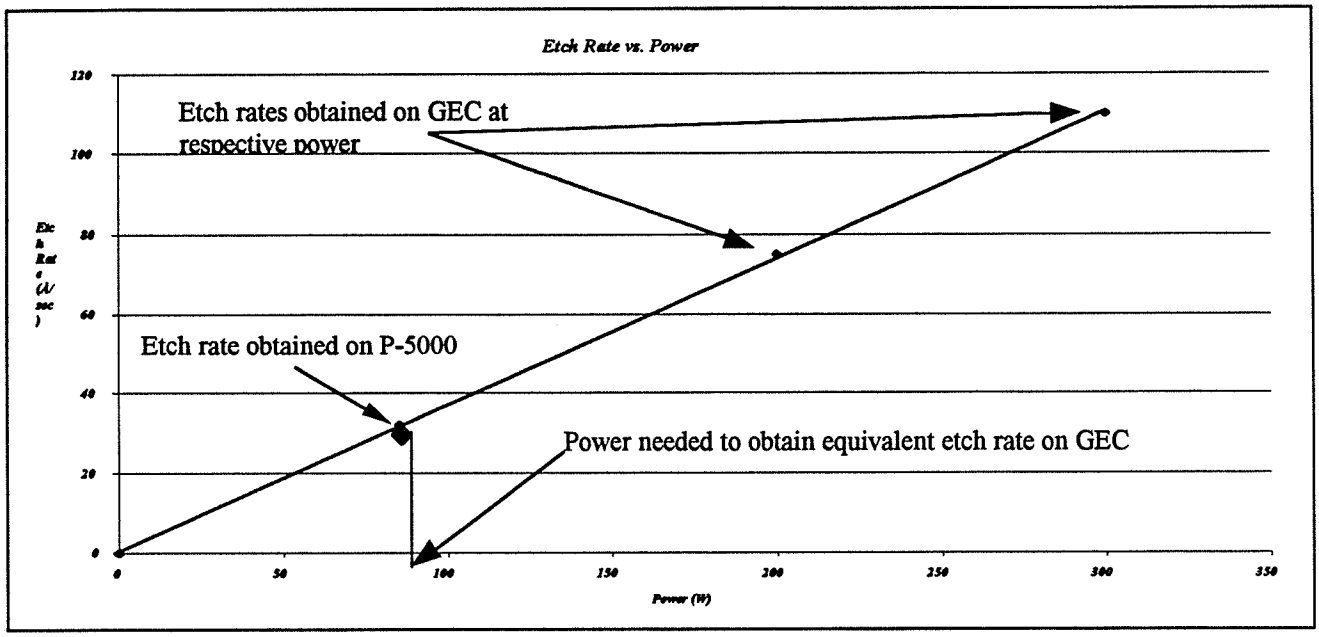
- Distance between electrodes
- Electrode Area
- rf power ramp rates
- Process pressure ramp rate(s)
- Gas flow ramp rates
- Electrode temperature
- Wall temperature (chamber)
- Shower head temperature
- Shower head pattern (gas distribution)
- Wafer cooling (He flow)
- Electrode materials exposed to plasma (excluding wafer)
- Conventional vs. electrostatic chuck
- Load lock pressure

The etches were run for 60 sec. each and the step heights were remeasured. Knowing that the etch would actually remove some photoresist a second step height measurement was made after the samples were stripped in an O_2 plasma. The samples were again measured on the P-22, and now the etch rates of both the WSi_x and the resist were measured as well as the uniformity of each etch and the selectivity of WSi_x to photoresist for each process condition

The main differences that need to be accounted for in this work were the distance between the electrodes, and the electrode area. The difference between the electrode in the GEC cell is 1". The distance between the electrode spacing in the P-5000 is 3¼". The difference in electrode spacing between both tools will impact an etch with all other factors similar. The shorter the distance between electrodes the greater the average ion energy of the ions incident on the wafers. This will enhance the reactivity of the etch increasing the etch rate. Since this difference in the two tools was known it could be accounted for when performing the experiment and again will be addressed when the results are discussed. Since the electrode area exposed to the plasma could not be determined on the two tools due to the complexity of the two chambers, a method had to be devised to obtain comparable power densities in order to acquire equivalent etch rates between the two tools. It was thought by simply holding the gas flows and pressure constant and only varying the power it would be possible to extrapolate equivalent etch rates on the two tools. This was attempted by assuming that there is a linear relationship between etch rate and power. By running two conditions at two different powers on the GEC and obtaining etch rates for both conditions a straight line could be fitted to the data through the origin. A single condition could then be run on the P-5000 and the etch rate acquired from that run could be interpolated onto the line generated from the GEC data. The power needed to obtain an etch rate on the GEC comparable to the P-5000 could then be extracted. Figure 1 illustrates this procedure. The gas sources supplied to the two tools was another significant difference. SF_6 was the only common gas supplied to the two tools, therefore a complete process could not be translated once comparable etch rates had been achieved. Since SF_6 etches WSi_x isotropically, a process could not be developed in which SF_6 is the only gas supplied to the chamber and achieve the desired output. SF_6 is useful only with biased masks or when large ΔCD's do not pose a problem. However, the approach used to find the power needed on the GEC to give the

necessary etch rate found on the P-5000 work could be used to develop a process in which other gases like a fluorocarbon gas and some oxygen could be added to the system.. Using a polymer forming etch would minimize the lateral etching nature of SF_6 alone, and provide better selectivity to underlying oxide layers.

Figure 1 Relationship between etch rate and power, and proposed extraction of equivalent etch rates between the P-5000 and GEC.



3. EXPERIMENTAL RESULTS

A.) P-5000 Screening Experiment

With the design issues addressed, the initial screening experiment was done on the P-5000. Table 2 shows the process conditions run in this screening experiment. The process conditions were run on samples with photoresist patterned on 6000Å WSi_x on 5000Å TEOS oxide, and on samples with only 5000Å of TEOS. All samples had patterned 1.9μm resist masks to allow for accurate step height measurements. Etch rates, uniformity, and selectivity were determined for each process condition. Table 3 below shows the average etch rates for WSi_x, photoresist, and TEOS oxide as well as the selectivity between WSi_x and photoresist and WSi_x and oxide. It can be seen from Table 3 that there are

Table 2: Initial screening experiment on P-5000

Condition	SF6	Cl2	HBr	HeO2	Pressure	Power	CP
1	35	20	15	10	90	300	1
2	60	0	30	0	150	200	0
3	10	40	0	0	150	200	0
4	60	0	0	0	30	400	0
5	60	40	0	0	150	400	0
6	60	40	30	0	30	200	0
7	60	0	30	20	30	400	0
8	10	40	30	20	150	200	0
9	10	0	30	20	30	200	0
10	60	40	30	20	150	400	0
11	60	40	0	20	30	200	0
12	10	0	0	0	30	200	0
13	10	0	0	20	150	400	0
14	10	40	0	20	30	400	0
15	10	40	30	0	30	400	0
16	60	0	0	20	150	200	0
17	10	0	30	0	150	400	0

significant variations in etch rates of the three films. This is due to a number of factors, and the statistical software package JMP was used to see what effect each input parameter had on the output responses defined in the beginning of this report. Table 4 shows the impact the increase in each input factor has on each output response. From the screening experiment, conditions were selected for endpoint detection.

A.) Endpoint Detection and CD Bias Analysis

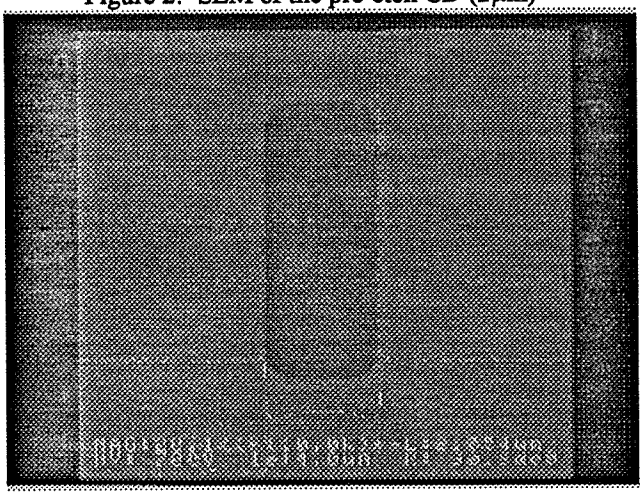
Nine process conditions were selected based on selectivity and uniformity. These conditions are shown in bold font in Table 2 as well as Table 3. These conditions were run for 400sec. while the endpoint monitoring system on the P-5000 monitored the intensity of the plasma at a specified wavelength, of 4010Å. With the endpoint traces obtained, seven process conditions were chosen for CD bias measurements. These conditions can be found in bold and italic font in Table 2. Conditions 7 and 8, in Table 2, were removed from the original nine because they showed no signs of endpoint in the 400sec.

Table 3: Etch rates and Selectivity

	WSix ER	*PR ER*	*Oxide ER*	*WSix: PR*	*WSix:Oxide*
1	**32.50**	**23.69**	**13.19**	**1.372**	**2.4641**
2	**71.32**	**17.51**	**16.81**	**4.073**	**4.2425**
3	**46.54**	**14.77**	**6.81**	**3.152**	**6.8346**
4	60.89	53.40	22.61	1.140	2.6930
5	**106.95**	**78.55**	**27.47**	**1.362**	**3.8932**
6	15.00	11.71	6.44	1.281	2.3290
7	**28.13**	**24.78**	**15.34**	**1.135**	**1.8335**
8	**14.57**	**5.99**	**3.22**	**2.431**	**4.5240**
9	8.85	8.66	4.36	1.023	2.0300
10	**54.53**	**35.93**	**18.26**	**1.518**	**2.9862**
11	29.26	25.25	7.96	1.159	3.6764
12	20.46	21.96	10.07	0.932	2.0322
13	31.31	33.94	17.13	0.922	1.8278
14	**34.30**	**38.73**	**11.16**	**0.886**	**3.0734**
15	15.46	16.63	8.91	0.930	1.7351
16	**77.77**	**27.46**	**15.4**	**2.832**	**5.0503**
17	21.53	14.88	13.1	1.447	1.6435

etch time. Due to possible throughput issues an etch that exceeds 400sec. is not considered a viable process. Therefore, with the seven conditions chosen endpoint algorithms were created for each. The process programs were then set up to etch to endpoint instead of for a given time. This allows for the etch to automatically stop when each condition reaches what the programmed endpoint algorithm defines as endpoint. With the endpoint algorithms established pre-etch CD measurements were taken on a Hitachi S-6200H scanning electron microscope. Figure 2 below is a sample SEM of a CD that was measured.

Figure 2: SEM of the pre-etch CD (2μm)



Wafers were etched under each process condition until the endpoint algorithm determined endpoint. A short over etch was done but was not optimized sample to sample. The resist was then removed, and post-etch CD measurements were taken. Oxide loss measurements were also taken using a KLA Tencor UV-1280. Table 5 below shows the CD bias, CD bias uniformity, and the oxide loss for each sample.

It can be seen in Table 5 that there is a considerable amount of variation in the CD bias for the various etch conditions. This is due in a large part to the chemistries used for the different process conditions. The by-product formations that occur during the etch have extremely different volatilities, which play a major role in etch rates and CD bias. Fluorine-based plasmas have a significantly higher volatility of reaction products than chlorine-based plasmas do, allowing for increased etch rates and a much more chemically reactive etch [4][5]. To promote the desorption of the silicon chlorides and tungsten chlorides so etching can occur, ion assisted reactions are necessary in chlorine-based plasmas which will effectively decrease the etch rate and make for a much more physical etch process. However, this enhances the etching anisotropy, since the sidewall of the etched film is not subjected to energetic ion bombardment. Oxygen is often added to enhance the etch rates of these gases [4].

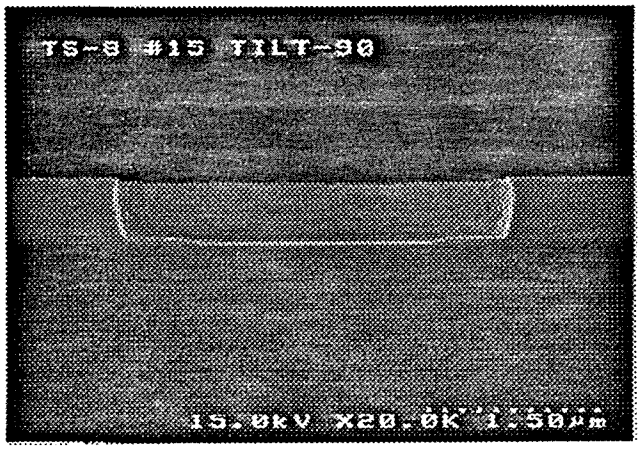
Table 5: CD bias, CD bias uniformity and oxide loss

	CD Bias	CD Unif.	Oxide Loss	*Endpoint Time (sec)*	*Over Etch (sec)*
1	0.031	1.737	1000.91	213.3	10.6
2	0.379	3.259	860.84	116.9	5.8
3	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
5	0.303	12.205	1694.44	88.3	4.4
10	0.035	0.923	1173.04	*N/A*	*N/A*
14	-0.074	4.589	646.73	182.5	27.3
16	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
3	0.096	3.090	721	258.2	12.9
10	0.009	2.351	879.31	143.3	7.1
16	1.249	7.064	975.42	135.4	6.5

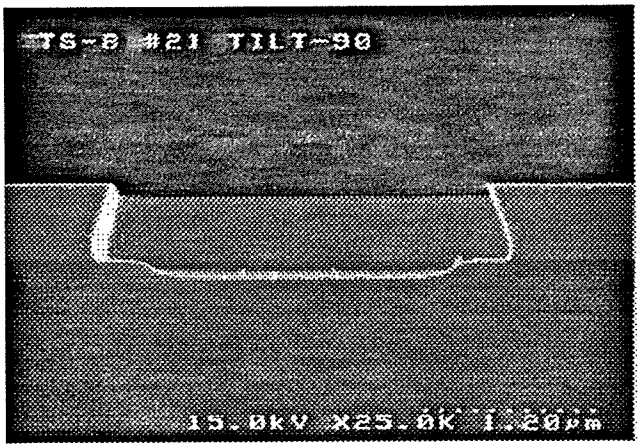
This phenomena can be seen in the selected cross-sectional SEM micrographs found in Figure 3 a-c. It can be seen that the CD bias was relatively low in Fig. 3b and 3c. This is most likely due to the fact that chlorine was added to the system. Figure 3a shows the effect of a predominately fluorinated plasma. It can be seen that there was severe lateral etching resulting in a CD bias of ~1.25μm. Although this sample was etched in a mostly fluorinated plasma it should be noted that this sample was also run at a fairly high pressure, (150mTorr), which will also aid in the isotropic nature of the etch. Figure 3c is what was determined to be the optimum etch process for the experiment presented. As can be seen a slightly tapered sidewall has been obtained with relatively good selectivity to the underlying oxide; only losing ~647Å. It is important to point out that this etch was processed in a plasma that contained a only 10sccm of SF_6 while 40sccm of Cl_2 was added with 20sccm of HeO_2. By examining the Fig. 3c it can be seen that by flowing more Cl_2 than SF_6, that an anisotropic profile was obtained. This is due to the fact that the more chloride compounds were formed requiring more ion assisted reactions, which as described above allows for a more anisotropic etch. However, since a predominately chlorine based plasma was used, the time needed to reach endpoint was lengthened. However, since HeO_2 was added, the oxygen was able to speed up the etch rate and result in only a 30 sec. difference in etch time. The HeO_2 also allowed for the tapered sidewall due to the fact the erosion of the photoresist by the its oxygen component. This is important because the etch time needed to endpoint was kept to the point where throughput would not be an issue. Since throughput is sufficient and an optimum etch profile was now obtained on the P-5000 the next phase of the experiment was initiated.

Figure 3: a) 60 sccm SF_6, 20 sccm HeO_2, 150 mTorr, 200W b) 60 sccm SF_6, 40 sccm Cl_2, 150mTorr, 400W, c) 10 sccm SF_6, 40 sccm Cl_2, 20 sccm HeO_2, 30 mTorr, 400W.

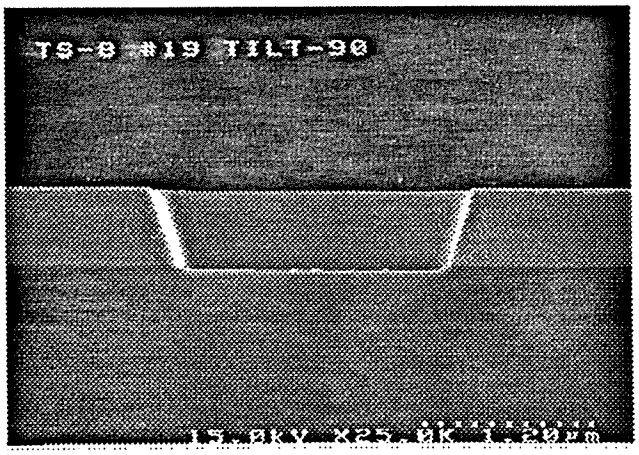
(a)



(b)



(c)



B.) Process Translation from P-5000 to GEC Cell

To begin the process translation the differences in chamber design of the two tools needed to be understood. The many variables that needed to be addressed were previously listed in the Procedure section of this report. Again the main differences that needed to be understood and accounted for were the electrode spacing in the two tools and the exposed electrode area. In both cases these variables could not be controlled and were fixed for the experiment. Since the GEC has a much shorter distance between the electrodes, and a smaller electrode surface area it was clear that the power density would be significantly higher on the GEC at equal powers. This is due to the fact that a shorter distance between electrodes leads to a higher plasma potential, or higher ion energy. It should also be noted that a smaller area leads to a higher current or power density. With these differences in mind, it was determined that the way to achieve comparable power densities was to obtain comparable etch rates. To do this all parameters were held constant and only the power varied. As previously described there should be a linear relationship between etch rate and power. Gas flows, and pressure was chosen at 35 sccm of SF_6 and 150mTorr. Again only SF_6 could be used due to the fact that it was the only common gas supplied to both tools. This process condition was run on the P-5000 at 150W for 60sec. and rendered an etch rate of 57.3Å/sec was obtained. Two samples were then run on the GEC at 200W and 300W for 60 sec. yielding etch rates of 98.6Å/sec and 100.3Å/sec, respectively. As can be seen there was not a significant difference in etch rates found on the two samples processed in the GEC. This is due to the fact that the reactivity of the etch was so high under each process condition that the WSi_x was completely removed before the 60 sec. etch time was completed. It therefore, etched through the WSi_x and was slowly reacting with the underlying oxide making it impossible to calculate an accurate WSi_x etch rate. It was therefore determined that the power and time of the etches on the GEC needed to be lowered. A 20 sec. etch time at 150W and 50W was randomly selected to ensure that endpoint was not reached before the etch timed out. After the etches were run under the new conditions etch rates were calculated. For the 150W etch an etch rate of 102.3Å/sec was obtained while the 50W etch yielded an etch rate of 56.75Å/sec. The data from these two etches are shown in Figure 4. With the etch rates determined for the two conditions run on the GEC Cell, the power needed on the GEC to give an etch rate of 57.3Å/sec found on the P-5000 was estimated. To do this a line was fit using the two GEC etch rate data points. The etch rate from the P-5000 was then placed on that line and the power needed on the GEC was extrapolated. Coincidentally, it was found that to obtain an etch rate of ~57Å/sec on the GEC it needed to be run at 50W which was one of the original process conditions. With equivalent etch rates found on two tools it is now possible to run a comparable etch on the two tools provided the gas chemistry and pressure remain constant.

Following the approach used to obtain similar etch rates determined it would now be possible to extend the experiment completely onto the GEC and develop an etch process which would yield comparable etch profiles and selectivities as the optimum process described in the previous section. However, with the gas sources supplied to the two tools being different this is not possible. The GEC would require the addition of Cl_2 or a polymer forming gas (i.e. C_2F_6, CF_4), to allow for anisotropic etching, and acceptable selectivity to the underlying oxide. By adding the polymer forming gas to the system the addition of oxygen is then required to remove the organic polymer from the sidewalls so an organic etch stop is not formed.

4. CONCLUSION

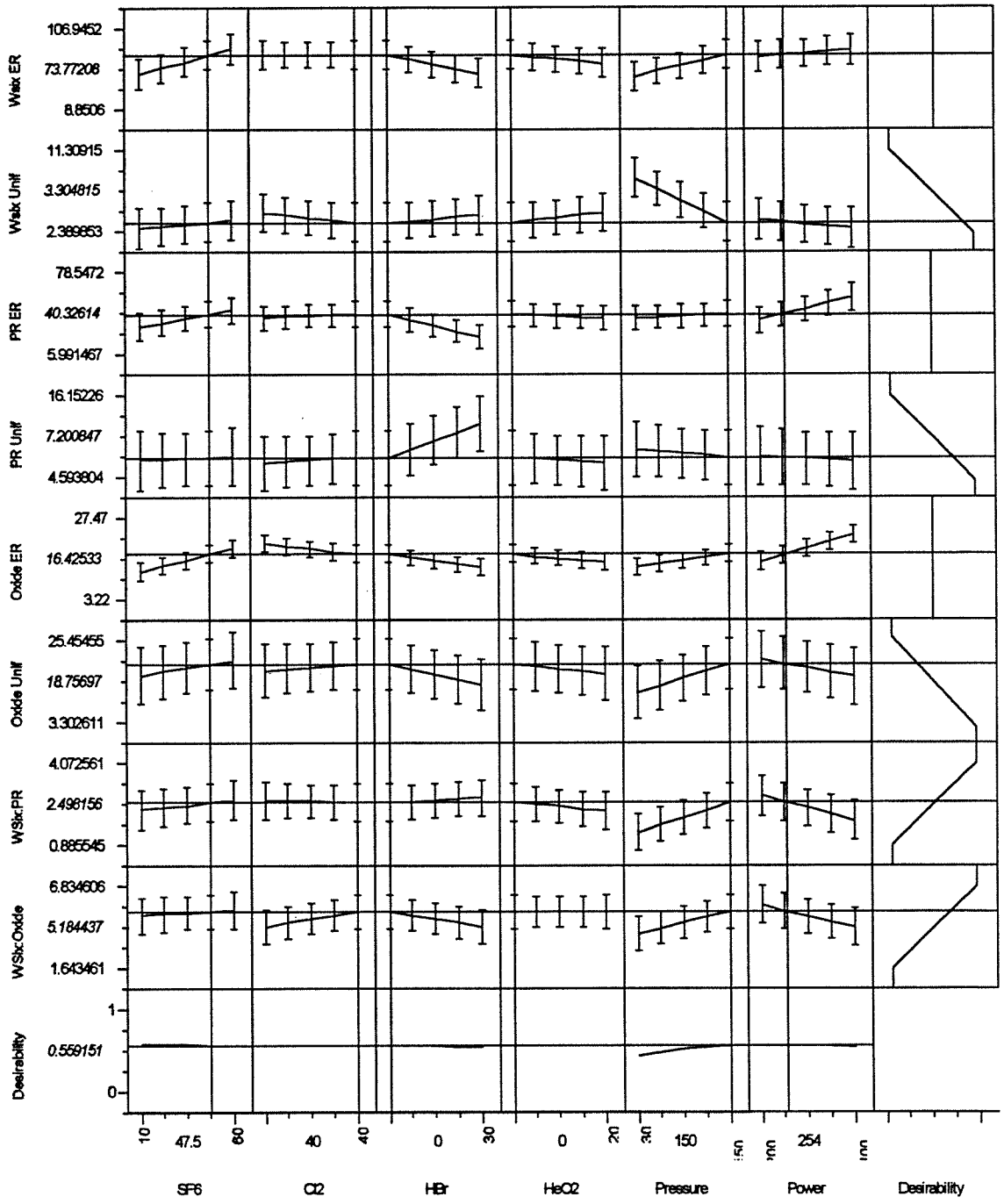
An in depth study of plasma etching for Tungsten Silicide has been presented. An optimum etch process for tungsten silicide was developed on a P-5000 MxP and the factors that control the process were explained. The etch yielded tapered sidewalls as well as good uniformity, (i.e. 4.85%), and good selectivity to the underlying oxide, (i.e. WSi_x:oxide=3.07). It was found that the addition of chlorine plays a significant role in allowing for an etch to be anisotropic as well as highly selective to the underlying oxide, especially when not using a polymer forming gas.

An initial experiment was also completed in which ion energies and power densities of both the P-5000 and the GEC were matched, to a first order, allowing for similar etch rates to be obtained. This experiment showed that chamber design plays a major role in the design of an etch process, and a process transfer from one tool to another.

Future work is planned to further optimize the process on the P-5000 MxP. The use of the magnetic field capabilities on the etch process will be evaluated; as well as the implementation of alternate focus rings to improve the etch uniformity. A Focus ring is a glass "cup" that surrounds the cathode and allows for a uniform distribution of the gas species over the substrate surface.

A process will be proposed for the GEC in which C_2F_6 or CF_4 will be used to generate anisotropic sidewalls as well as improve selectivity to an underlying oxide, by forming a polymer on the sidewalls.

Table 4: Two level screening experiment results generated in JMP



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5. ACKNOWLEDGMENTS

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