Characterization and comparison of fused silica etch processes in fluorocarbon based ICP chemistries

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Introduction

Dry etching by inductively coupled plasmas (ICP) of the many forms of silicon oxide, including fused silica continues to be vital in many applications including multilayer advanced integrated circuits, MEMS microfluidics, arrayed waveguide gratings, hybrid photonic devices, and most recently nanoimprint template fabrication. In this investigation, we compare three fluorocarbon chemistries (CHF_3, C_2F_6, and C_4F_8), along with the role of specific additives O_2, Ar and a novel CO_2 additive. Underlying mechanisms of each chemical etch system are proposed based on a detailed parametric study determined by the execution of a complex design of experiment (DOE). The influence of plasma parameters on fused silica etch rate, Cr mask selectivity, and profile evolution is examined. These mechanisms are studied at both microscale and nanoscale dimensions.

Experimental

100mm fused silica wafers of standard thickness 525µm were sputter deposited with 200nm chromium (Cr) for microscale etch studies, and 20nm for investigation at the nanoscale regime. Contact photolithography obtained minimum feature sizes of 1µm while electron beam lithography using negative resist resulted in feature sizes of 50-100nm. ICP etching using Cl_2/O_2 chemistry was used to pattern the Cr. The patterned Cr then served as the mask for the fused silica etching studies.

Etching experiments of the fused silica were carried out in an Oxford Instruments Plasmalab System 100 ICP tool. This features a cylindrical ICP source, independent substrate electrode bias and wide electrode temperature capability. See Figure 1. The high ion density, low pressure ICP etch regime provides excellent control over etched profiles [1].

The DOEs were formulated in a Taguchi L9 orthogonal matrix [2]. This enables a wide range of parameter space to be studied with relatively few process trials by means of an averaging procedure possible due to the symmetrical properties of the orthogonal matrix. The input parameters were gas ratio, pressure, ICP source power and electrode bias power. The output metrics consisted of fused silica etch rate, selectivity to Cr, and the resulting profile angle.

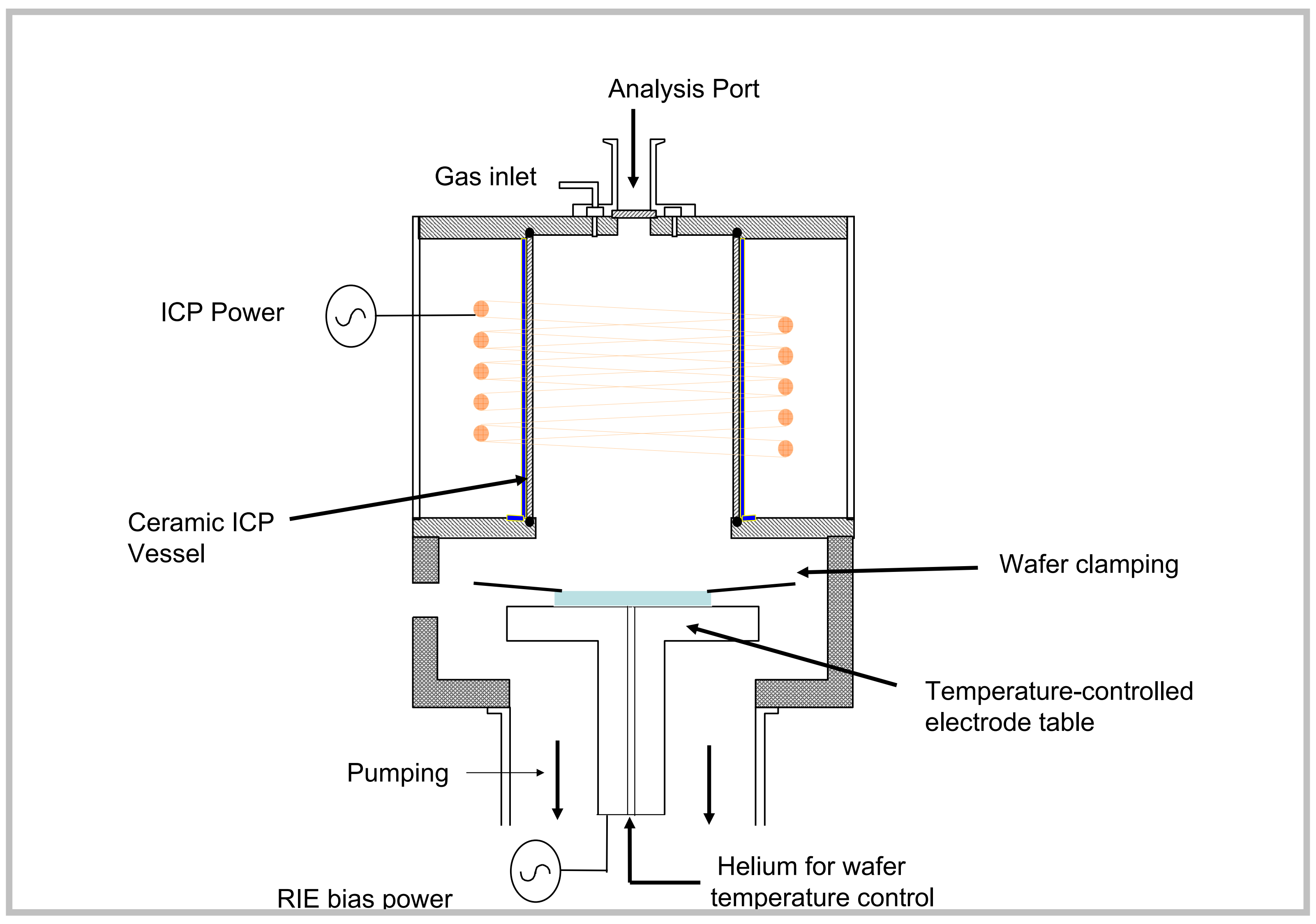

Figure 1: Plasmalab System100 ICP Schematic

Results and discussion

The specific gas chemistries studied were C_2F_6-Ar, C_2F_6-CO_2, CHF_3-Ar, CHF_3-CO_2, C_4F_8-CO_2 and C_4F_8-O_2. Space permits only 3 of the DOEs to be shown. See Figures 2 to 5 which include selected scanning electron micrographs (SEMs) of micro- and nano-scale features. Figure 2e shows one of the best results for the C_2F_6-CO_2 DOE (Run 5). The fused silica etch rate was 224nm/min, selectivity over Cr 105:1 profile was near vertical at 91°. Figure 4 shows SEMs of a particularly smooth etch (left hand image) and on the right, a deep nanoscale etch (68nm wide and 940nm deep – an aspect ratio >13:1). These results are from the C_4F_8-CO_2 DOE.

The overall mechanism of silicon oxide plasma etching consists of a complex interaction between simultaneous deposition and etch processes at the surface. Zhang, et al. [3] have modeled the ion sputtering, F atom etching, and ion assisted polymer substrate interactions. In the current study, the behavior of the CHF_3 chemistry appears to be quite dependent on the additive chemistry. The silica etch rate and profile are quite dependent on the CHF_3 percentage and pressure in the case of CO_2 addition, while in the case of Ar addition, the etch characteristics are more physical in nature. In the C_2F_6 chemistry, there is an overall stronger chemical influence on the etch rate and a stronger physical influence on the anisotropy with an Ar additive. Surprisingly, the addition of CO_2 to C_2F_6 is a physically dominated process from both an etch rate and profile perspective. The nature of the C_4F_8 fused silica etch is also dependent on the additive species. In the case of O_2 addition, the overall process is strongly ion energy and ion density dependent. However, when CO_2 is added to C_4F_8, the etch rate and profile evolution is highly chemically dependent on the percentage of highly polymerizing C_4F_8.

Conclusions

A detailed study of three fluorocarbon chemistries (CHF_3, C_2F_6, and C_4F_8) with different additives (O_2, Ar and CO_2) has been carried out using an orthogonal matrix methodology.

References

[1] A.L.Goodyear, D.L.Oylnick et al. J.Vac.Sci.Technol.B18-6(2000) 3471.
[2] G.Z.Yin and D.W.Jillie, Solid State Technology. May 1987 p127
[3] D.Zhang and M.Kushner, J.Vac.Sci.Technol.A 19(2), Mar/Apr 2001.

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MATRIX EXPERIMENTS

Run	RIE bias	ICP	C2F6	Pre
1	20	1800	20	4
2	20	2200	25	8
3	20	2600	30	12
4	30	1800	25	12
5	30	2200	30	4
6	30	2600	20	8
7	40	1800	30	8
8	40	2200	20	12
9	40	2600	25	4

CONSTANT	
Total flow	50sccm
Etch time	10min
Temperature	10deg
Backside He	10Torr

MEASURED RESULTS

Run	ERSilica A/min	Ecr A/min	DC [-V]	Sox:cr	Profile
1	1447	67	92	22	93
2	1639	96	96	17	92
3	1788	28.7	96	62	93
4	1355	83	177	16	93
5	2238	21.4	105	105	91
6	1993	36.3	119	55	92
7	1931	69	184	28	91
8	1926	37	187	52	91
9	2549	22.4	121	114	91

PARAMETER LEVEL AVERAGES (PLOTTED ON GRAPHS)

Parameter	Level	ERSilica A/min	Ecr A/min	DC [-V]	Sox:cr	Profile
RF	20	1625	64	95	34	92.7
	30	1862	47	134	59	91.8
	40	2135	43	164	65	91.0
ICP	1800	1578	73	151	22	92.2
	2200	1934	51	129	58	91.3
	2600	2110	29	112	77	92.0
C2F6	20	1789	47	133	43	92.0
	25	1848	67	131	49	91.8
	30	1986	40	128	65	91.7
Pre	4	2078	37	106	80	91.7
	8	1854	67	133	33	91.7
	12	1690	50	153	44	92.2

Figure 2a L9 matrix, results and averages calculation for C_2F_6-CO_2.

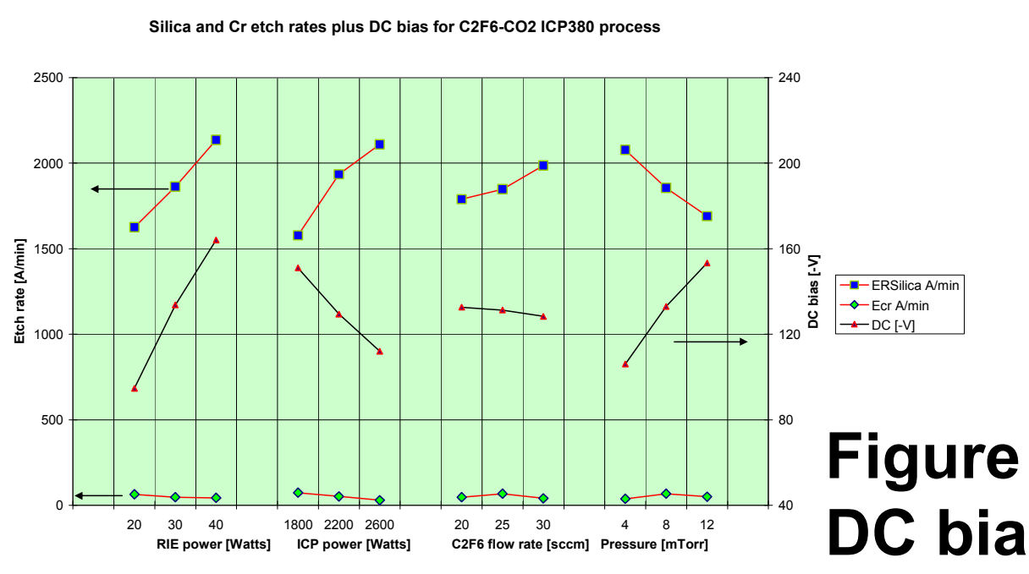


Figure 2b Etch rates and DC bias C_2F_6-CO_2

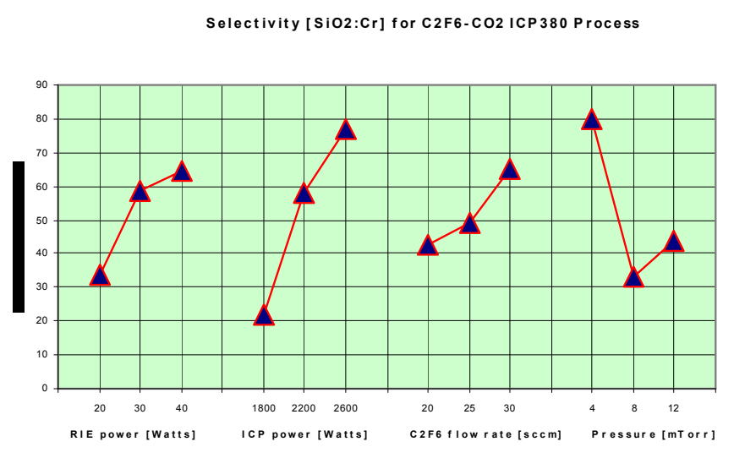


Figure 2c Selectivity C_2F_6-CO_2

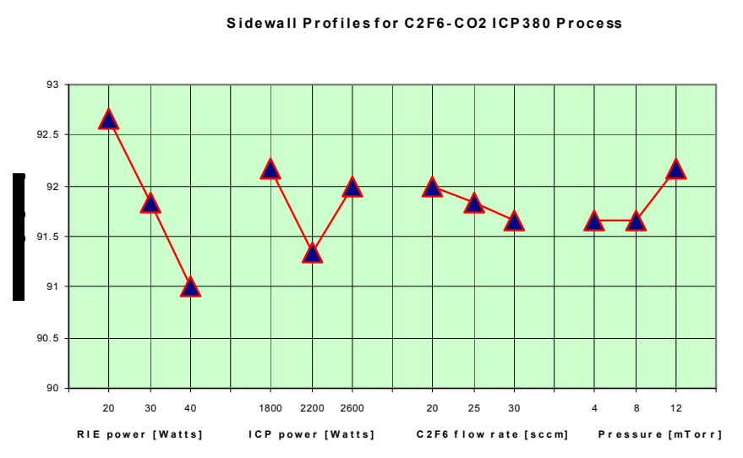
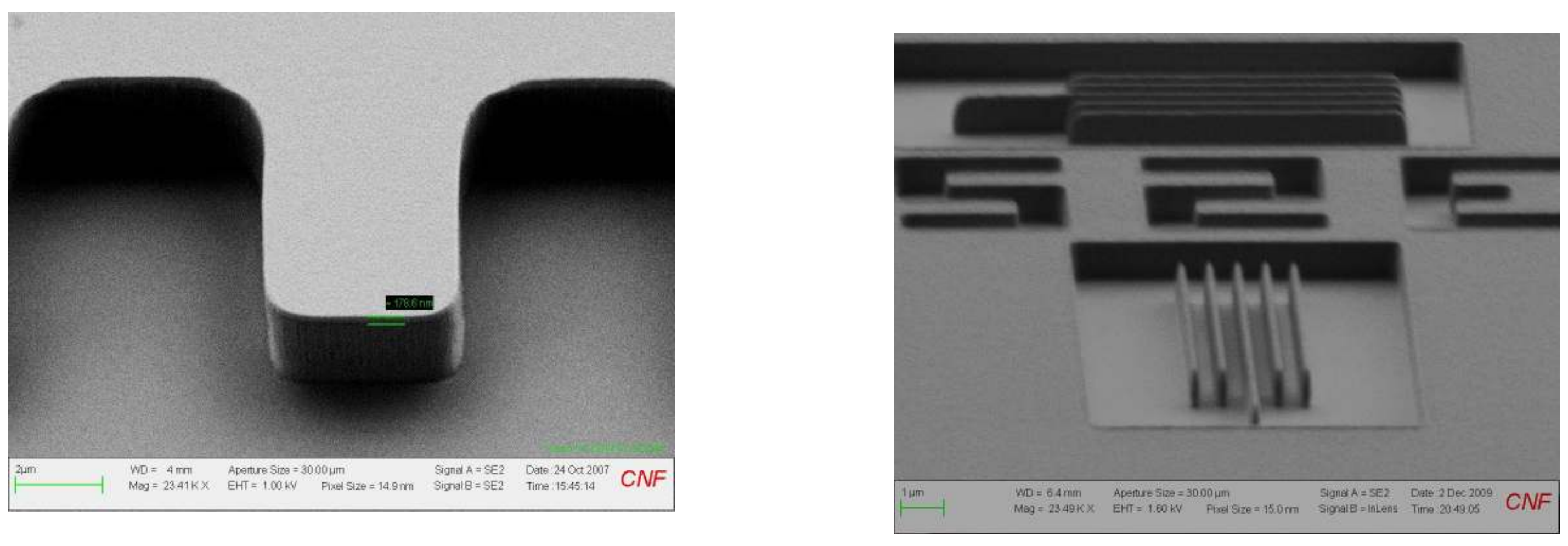


Figure 2d Profile C_2F_6-CO_2



Figures 2e Micro- and nano-scale features for Run 5 of C_2F_6-CO_2 DOE

MATRIX EXPERIMENTS

Run	RF	ICP	CHF3	Pre
1	40	2000	10	4
2	40	2500	15	8
3	40	3000	20	12
4	60	2000	15	12
5	60	2500	20	4
6	60	3000	10	8
7	80	2000	20	8
8	80	2500	10	12
9	80	3000	15	4

CONSTANT	
Total flow	50sccm
Etch time	10min
Temperature	50deg
Backside He	10Torr

MEASURED RESULTS

Run	ERSilica A/min	Ecr A/min	DC [-V]	Sox:cr	Profile
1	1605	19.4	117	83	91.0
2	2133	10.6	118	201	90.9
3	2043	58	120	35	90.6
4	1887	29.8	210	63	91.8
5	2083	3.1	147	672	90.6
6	2132	10	141	213	91.3
7	2407	9.9	236	243	90.5
8	2373	15	220	158	91.0
9	2621	15	157	175	90.8

PARAMETER LEVEL AVERAGES (PLOTTED ON GRAPHS)

Parameter	Level	ERSilica A/min	Ecr A/min	DC [-V]	Sox:cr	Profile
RF	40	1927	29	118	106	90.8
	60	2034	14	166	316	91.2
	80	2467	13	204	192	90.8
ICP	2000	1966	20	188	130	91.1
	2500	2196	10	162	344	90.8
	3000	2265	28	139	141	90.9
CHF3	10	2037	15	159	151	91.1
	15	2214	18	162	146	91.2
	20	2178	24	168	317	90.6
Pre	4	2103	13	140	310	90.8
	8	2224	10	165	219	90.9
	12	2101	34	183	86	91.1

Figure 3a L9 matrix, results and averages calculation for CHF_3-Ar

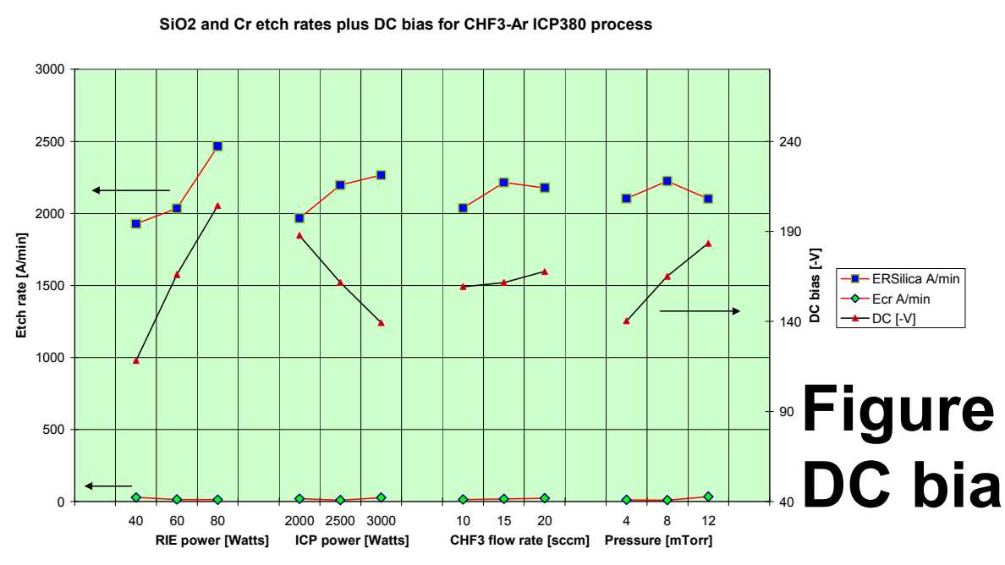


Figure 3b Etch rates and DC bias CHF_3-Ar

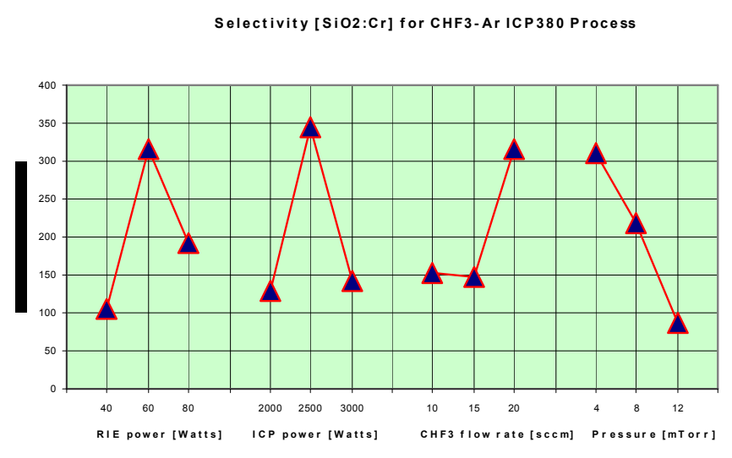


Figure 3c Selectivity CHF_3-Ar

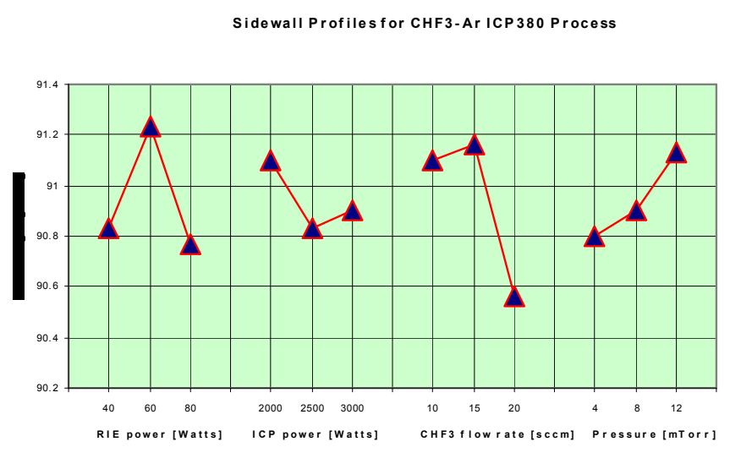


Figure 3d Profile CHF_3-Ar

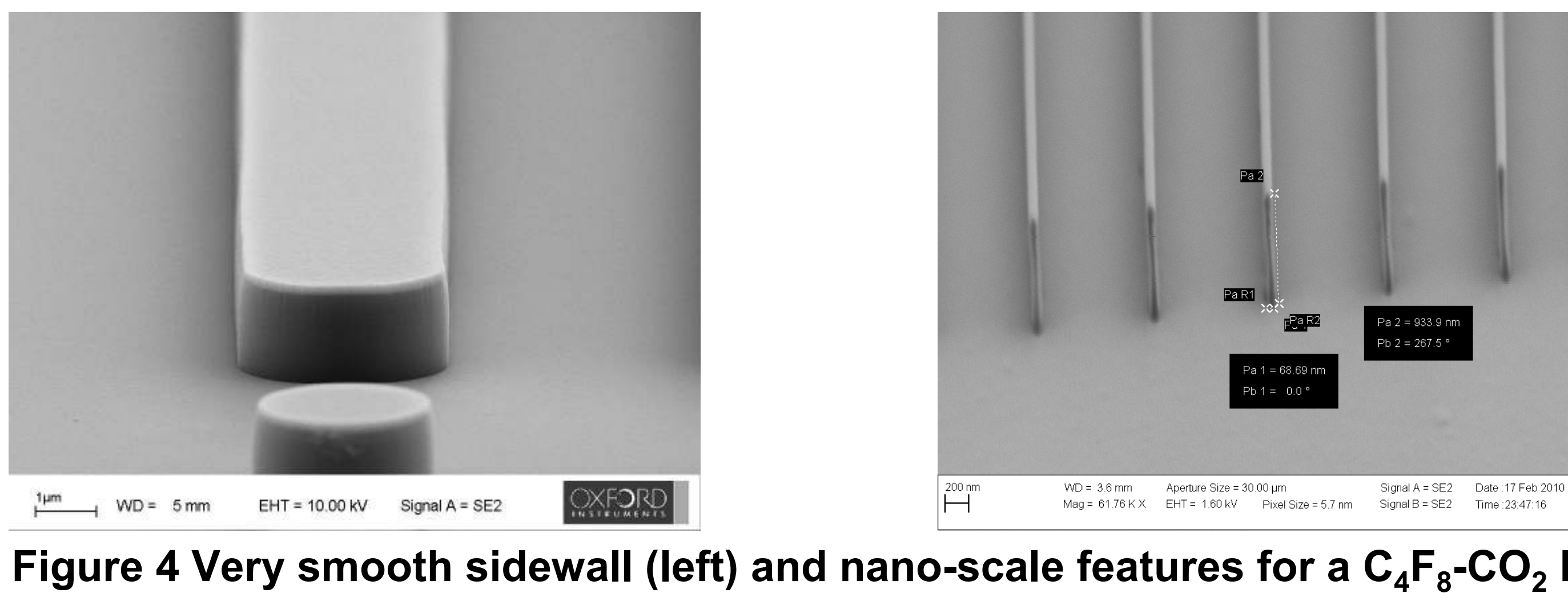


Figure 4 Very smooth sidewall (left) and nano-scale features for a C_4F_8-CO_2 DOE Run

MATRIX EXPERIMENTS

Run	RF	ICP	C4F8	Pre
1	20	1800	20	4
2	20	2200	25	8
3	20	2600	30	12
4	30	1800	25	12
5	30	2200	30	4
6	30	2600	20	8
7	40	1800	30	8
8	40	2200	20	12
9	40	2600	25	4

CONSTANT	
Total flow	50sccm
Etch time	10min
Temperature	**25deg**
Backside He	10Torr

MEASURED RESULTS

Run	ERSilica A/min	Ecr A/min	DC [-V]	Sox:cr	Profile
1	1613	18	80	90	91.0
2	1602	19.7	85	81	91.8
3	1562	41.4	84	38	92.0
4	1333	110	128	12	90.3
5	2120	5	97	424	90.3
6	2149	27	100	80	91.30
7	1723	38	143	45	90.5
8	1973	78	143	25	90.80
9	2598	9	112	289	91.0

PARAMETER LEVEL AVERAGES (PLOTTED ON GRAPHS)

Parameter	Level	ERSilica A/min	Ecr A/min	DC [-V]	Sox:cr	Profile
RF	20	1592	26	83	69.55	91.60
	30	1867	47	108	171.90	90.63
	40	2098	42	133	119.77	90.77
ICP	1800	1556	55	117	49.02	90.60
	2200	1898	34	108	176.87	90.97
	2600	2103	26	99	135.33	91.43
C4F8	20	1912	41	108	64.83	91.03
	25	1844	46	108	127.37	91.03
	30	1802	28	108	169.02	90.93
Pre	4	2110	11	96	267.43	90.77
	8	1825	28	109	68.75	91.20
	12	1623	76	118	25.05	91.03

Figure 5a L9 matrix, results and averages calculation for C_4F_4-O_2

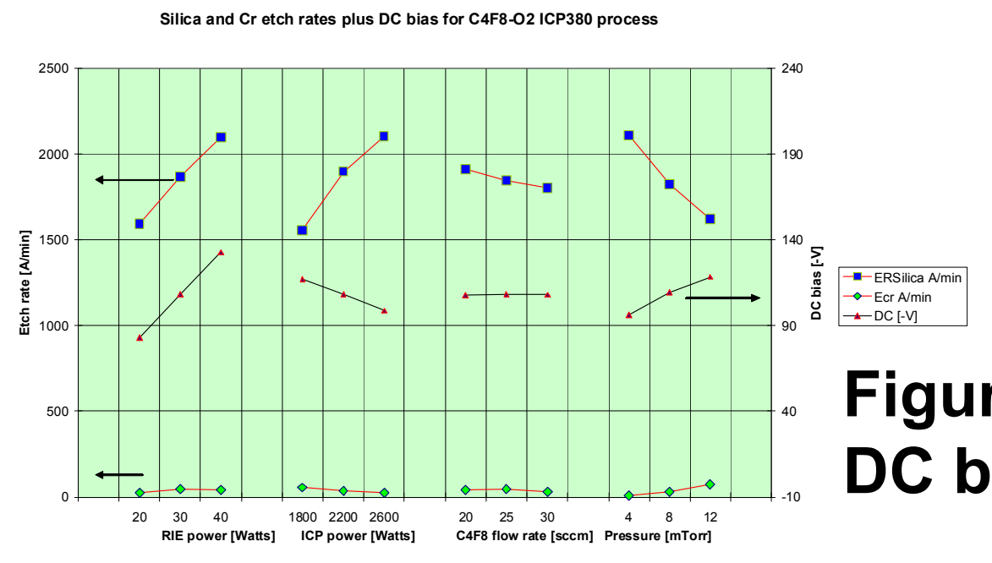


Figure 5b Etch rates and DC bias C_4F_8-O_2

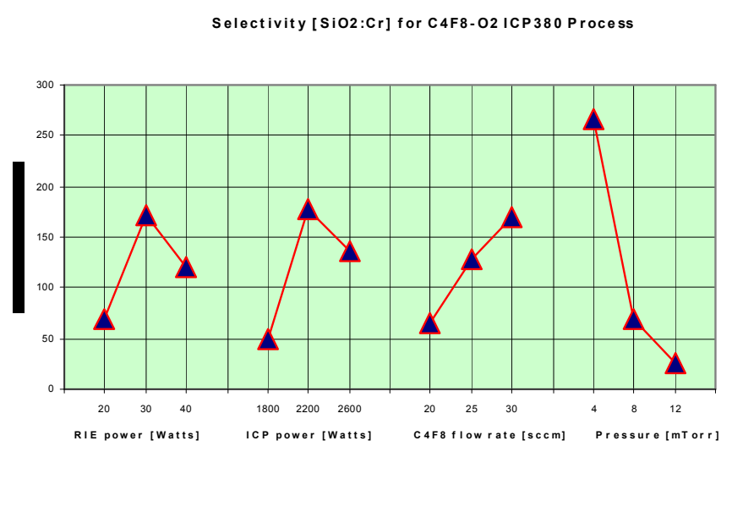


Figure 5c Selectivity C_4F_8-O_2

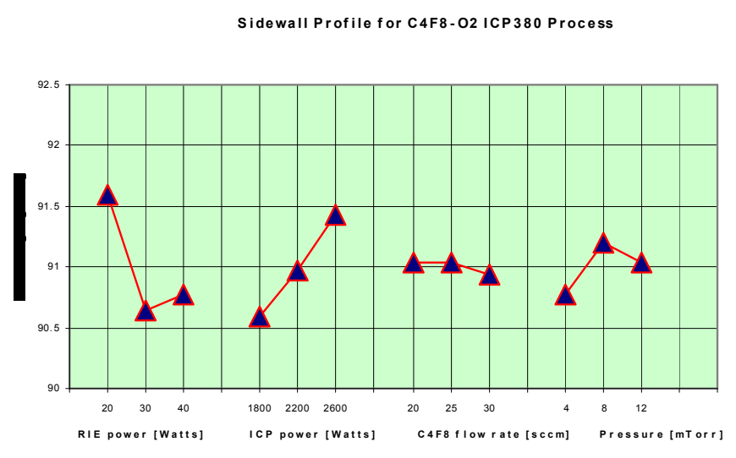


Figure 5d Profile C_4F_8-O_2

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