

**Developing a Reliable Fluorinated Greenhouse Gas (F-GHG)  
Destruction or Removal Efficiency (DRE) Measurement Method for  
Electronics Manufacturing: A Cooperative Evaluation with Qimonda  
March 2008**



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## 1.0 Introduction

The purpose of this study was to accurately determine the Destruction or Removal Efficiency (DRE) of a Point Of Use (POU) abatement system or scrubber for process emissions containing perfluorinated compounds. A key component in accurately determining DRE was to determine the dilution of process exhaust occurring in the scrubber. This study used an experimental approach to measure the dilution across the scrubber by injecting a chemical tracer that could not react in the scrubber, or be produced as a by-product during scrubber operation. Krypton was used as the chemical tracer as it met the requirements for this application.

Testing was conducted in a fully functional semiconductor manufacturing facility, owned and operated by Qimonda in Richmond VA. Two tools, AMZ17 and AMZ18, each equipped with POU scrubbers were tested. Both tools ran the same process and used the same model of commercially available scrubber. The process evaluated was a contact etch process, which used PFC gases  $\text{CF}_4$ ,  $\text{CHF}_3$  and  $\text{C}_4\text{F}_6$ .

## 2.0 Experimental Setup

To carry out the objectives of this study it was necessary to monitor both process and scrubber emissions simultaneously, and determine scrubber dilution using chemical spiking. Process and scrubber emissions data were collected in parallel using Fourier Transform Infrared Spectroscopy (FTIR). Data used to determine scrubber dilution were collected using Quadrupole Mass Spectrometry (QMS). A schematic showing the experimental testing set up is shown in Figure 1.

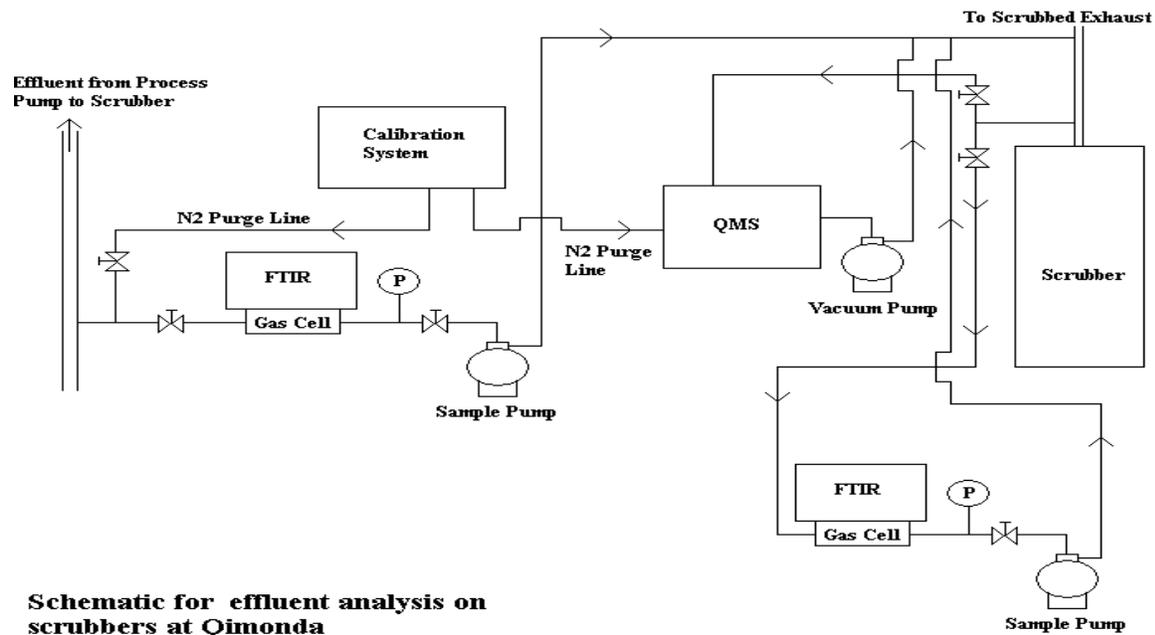
Two FTIRs were used to determine process and scrubber emissions. Both systems were MKS 2010 Multi Gas Analyzers equipped with liquid nitrogen cooled mercury cadmium telluride (MCT) detectors. One FTIR was equipped with a 10 cm path length single pass gas cell, and was used to sample process effluent. The other FTIR was equipped with a 5.6 m path length multi pass gas cell, and was used to sample scrubber effluent. Both FTIR were operated at  $0.5\text{cm}^{-1}$  resolution. Four scans were co-added for each data point yielding a sampling frequency of 2.2 sec.

A Balzers QMS system was used to sample scrubber effluent during dilution determination. The QMS was operated in Selective Ion Monitoring (SIM) mode and a secondary electron multiplier was used to enhance sensitivity. A 1 sec sampling frequency was used for each data point. To account for potential changes in QMS sensitivity, ion signals were normalized to the signal obtained for the nitrogen fragment ( $\text{N}^+$ ), which is formed during electron impact ionization of  $\text{N}_2$ .

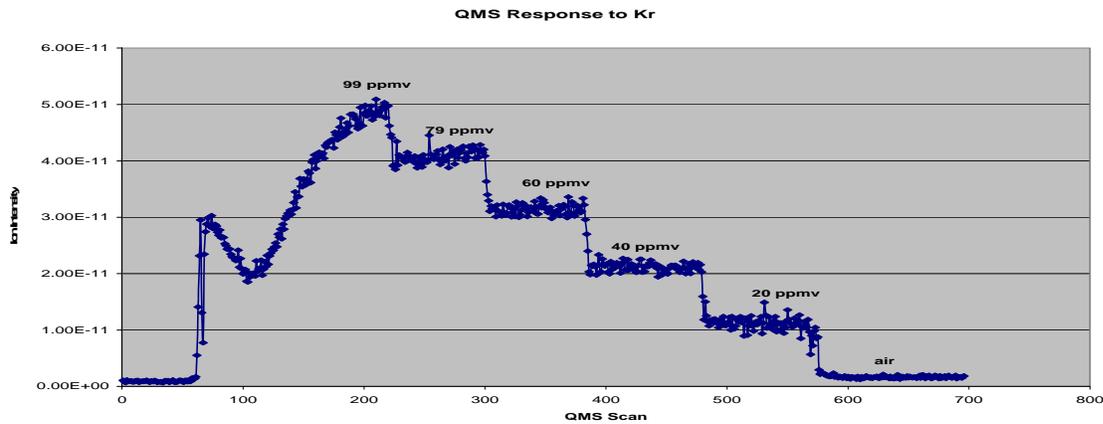
Sampling of effluent streams was done using metal bellows sampling pumps that were located after the instruments. The sample flow rate was controlled using adjustable flow rate valves. The sample line pressure for both FTIRs and the QMS were monitored using capacitance manometers. A filter was installed in the sample line used for monitoring scrubber emissions to ensure that particulate emissions from the scrubber would not coat the FTIR internal optics, or

the pressure reducing orifice used for the QMS. Since the scrubber DRE determination and the scrubber dilution determination were independent events, it was possible to use the same sample line for both operations. This was accomplished by switching the instrument inlet sample fitting from the FTIR to the QMS.

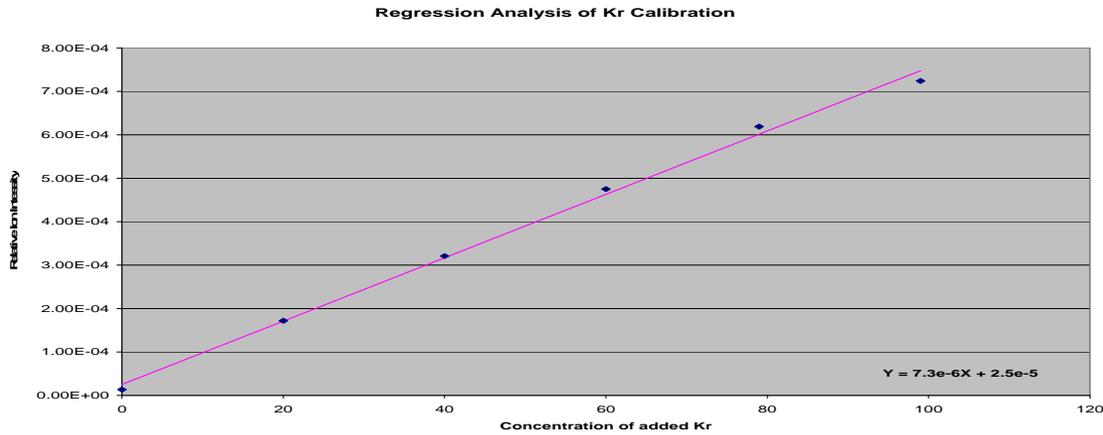
The QMS was calibrated to determine its response to Kr on site using a dynamic dilution blending system. Test atmospheres containing Kr, were created by blending a calibration standard containing 1% of Kr in N<sub>2</sub> with N<sub>2</sub> diluent. The QMS response to <sup>84</sup>Kr during calibration is shown in Figure 2. From regression analyses of these data a calibration curve was generated and is shown in Figure 3. This calibration was repeated for both tools tested.



**Figure 1: Sampling schematic used for testing TPU PFC DRE**



**Figure 2: QMS Response to <sup>84</sup>Kr during calibration.**



**Figure 3: Regression analysis of calibration data shown in Figure 2**

### 3.0 Data Analysis

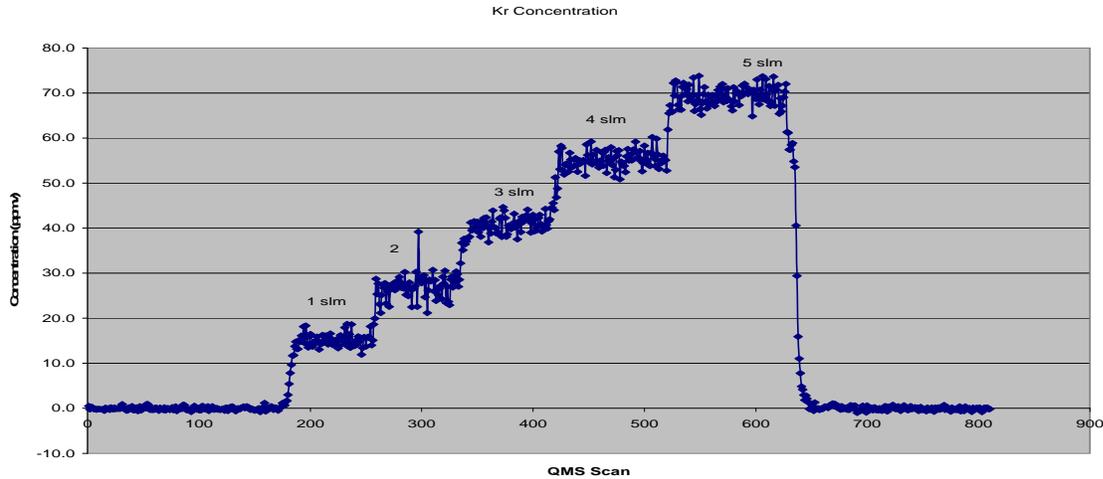
#### 3.1 Determination of Scrubber Dilution

One of the primary goals of this study was to accurately determine the dilution that occurs when gas emitted from the process chamber passes through the scrubber. Dilution can occur from many sources including effluents from other chambers, combustion gases and by-products added to and generated within the scrubber, vapors added as the gas stream passes through the water scrubber portion of the system, in-board leaks, and back diffusion from main headers. The method of determining dilution in this study was to use a purely experimental approach where a chemical was spiked into the gas stream entering the scrubber at a known flow rate, and determined in the scrubber effluent stream. From the determined concentration and the controlled flow rate added to the process exhaust duct, a total flow from the scrubber could be calculated:

$$TF = S_f / (C_{an} \times 10^{-6}) \quad (1)$$

Where  $S_f$  represents the spike gas flow and is reported in liters per minute, and  $C_{an}$  represents the analyte concentration reported in ppmv.

The experiment conducted to determine dilution for the scrubbers on AMZ17 and AMZ18 consisted of using the calibration system shown in Figure 1 to add calibration gas into the process effluent through the FTIR sample line where the process effluent was monitored. While calibration gas was being added, the QMS was used to sample scrubber effluent. The flow of calibration gas was controlled with a 0 – 5 slm Mass Flow Controller (MFC) that was calibrated for nitrogen. Five flow rates were added to the scrubber: 1, 2, 3, 4 and 5 slm. The concentration profile for Kr determined from QMS data during this experiment are shown in Figure 4 for AMZ17.



**Figure 4: Kr concentration determined for AMZ17 scrubber during spiking experiment. Flow rates of calibration gas are indicated on the graph.**

Applying Eq. 1 to the data obtained for the scrubbers on AMZ17 and AMZ 18 yielded the total flows contained in Table 1. The average total flow for each scrubber is also contained in Table 1.

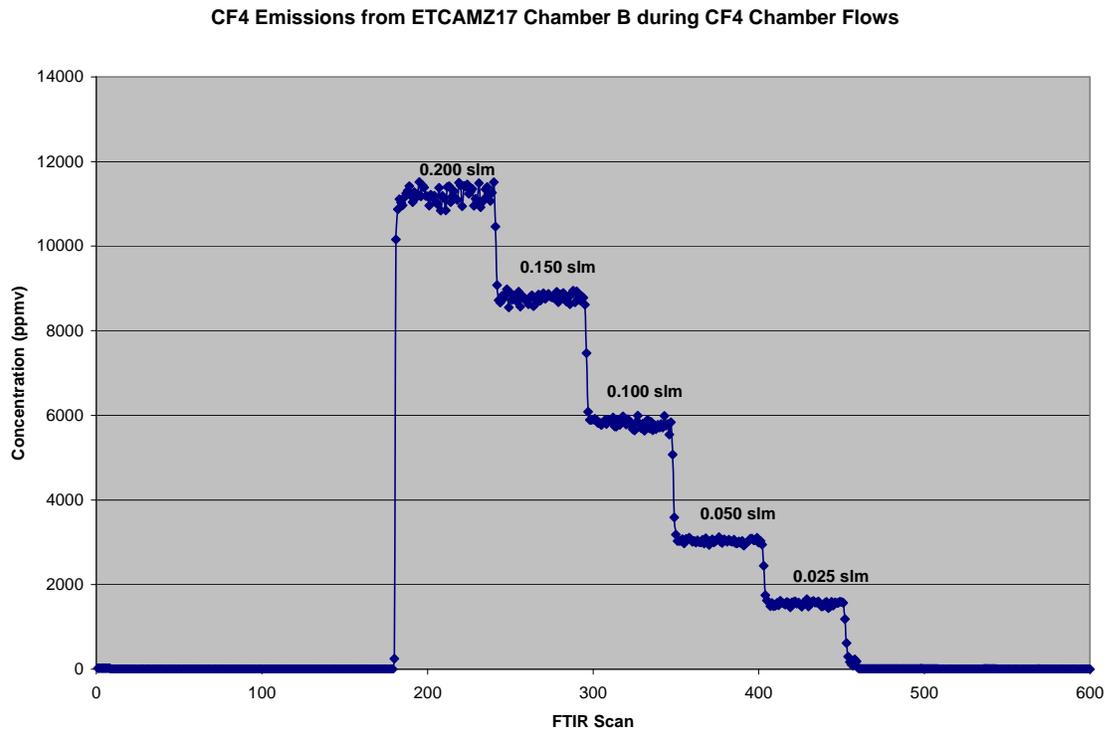
**Table I: Data used to determine the total flow emitted from TPU systems on AMZ17 and AMZ18.**

AMZ17 System Total Cal Gas Flow (slm)	Equivalent Kr Flow (slm)	Kr Concentration measured at TPU Outlet (ppmv)	Total Flow (slm)
1.0	0.010	15.1 ± 1.4	662 ± 61
2.0	0.020	27.1 ± 2.7	738 ± 74
3.0	0.030	40.8 ± 1.8	735 ± 32
4.0	0.040	55.5 ± 1.9	723 ± 25
5.0	0.050	69.5 ± 2.0	719 ± 21
AMZ18 System Total Cal Gas Flow (slm)			Ave. Total Flow for AMZ17 System 721 ± 2
1.0	0.010	14.1 ± 1.6	709 ± 80
2.0	0.020	25.5 ± 1.7	784 ± 52
3.0	0.030	38.8 ± 1.7	773 ± 34
4.0	0.040	52.2 ± 1.9	766 ± 28
5.0	0.050	65.8 ± 2.4	760 ± 28
			Ave. Total Flow for AMZ18 System 765 ± 2

The total scrubber flow data can be combined with the flow from the process chamber and pump, which go into the scrubber and is referred to as the total process flow, to determine the dilution that occurs as the process effluent passes through the scrubber. This calculation requires measuring the dilution that occurs as gases from the etch chamber are pumped out of the chamber and fore line and sent into the corrosive scrubber exhaust. The experiment to measure the dilution of AMZ17 and AMZ18 chamber effluent consisted of flowing  $CF_4$  into the chamber with the RF power in the chamber turned off at several flow rates. The determined  $CF_4$  concentration in the effluent could be used to calculate the total process flow entering the scrubber from the following equation:

$$TPF = PG_f / (C_{PG} \times 10^{-6}) \quad (2)$$

Here the total process flow (TPF) is determined from the ratio of the process gas flow (slm) divided by the measured concentration ( $C_{PG}$ ) in ppmv. The values obtained for  $CF_4$  on AMZ17 are shown in Figure 5. From these data the total process exhaust flows for both AMZ17 and AMZ18 were calculated and are contained in Table II.



**Figure 5:  $CF_4$  emission concentrations determined from AMZ17 chamber B while  $CF_4$  was flowed through chamber B with RF power off.**

**Table II: Total chamber and process pump effluent flow from chamber B on AMZ17 and AMZ18. Values determined from the average concentration measured during each CF<sub>4</sub> flow using Eq. 2**

ETCAMZ17			ETCAMZ18		
CF <sub>4</sub> Flow (slm)	CF <sub>4</sub> Conc. (ppmv)	Total Effluent Flow (slm)	CF <sub>4</sub> Flow (slm)	CF <sub>4</sub> Conc. (ppmv)	Total Effluent Flow (slm)
0.200	11,211 ± 183	17.8 ± 0.3	0.200	12,134 ± 195	16.5 ± 0.3
0.150	8780 ± 55	17.1 ± 0.2	0.150	9652 ± 121	15.5 ± 0.2
0.100	5784 ± 109	17.3 ± 0.3	0.100	6477 ± 48	15.4 ± 0.1
0.050	3024 ± 43	16.5 ± 0.2	0.050	3297 ± 32	15.2 ± 0.2
0.025	1554 ± 48	16.1 ± 0.5	0.025	1681 ± 61	14.9 ± 0.5

The data in Table II yielded an average total flow of  $17.0 \pm 0.7$  slm for AMZ17 and  $15.5 \pm 0.6$  slm for AMZ18. The process flow into the scrubber combined with the total flow from the scrubber yielded the experimentally measured dilution for each scrubber:

$$\text{System Dilution} = \text{TF}_{\text{out}}/\text{TF}_{\text{in}} \quad (3)$$

For AMZ17: Dilution =  $721 \pm 2/17.0 \pm 0.1 = 42.4 \pm 2$

For AMZ18: Dilution =  $765 \pm 2/15.5 \pm 0.1 = 49.4 \pm 2$

Equipped with these dilution factors and total flows into and out of the scrubbers it is now possible to determine the scrubbers DRE for the gases used and by-products formed during wafer processing.

### 3.2 Scrubber DRE Determinations

Determination of the scrubber performance was done using two different testing conditions. The first was to measure the scrubber effluent of the etch process gases during the total process flow calibrations and the second was to measure the scrubber effluent during wafer processing.

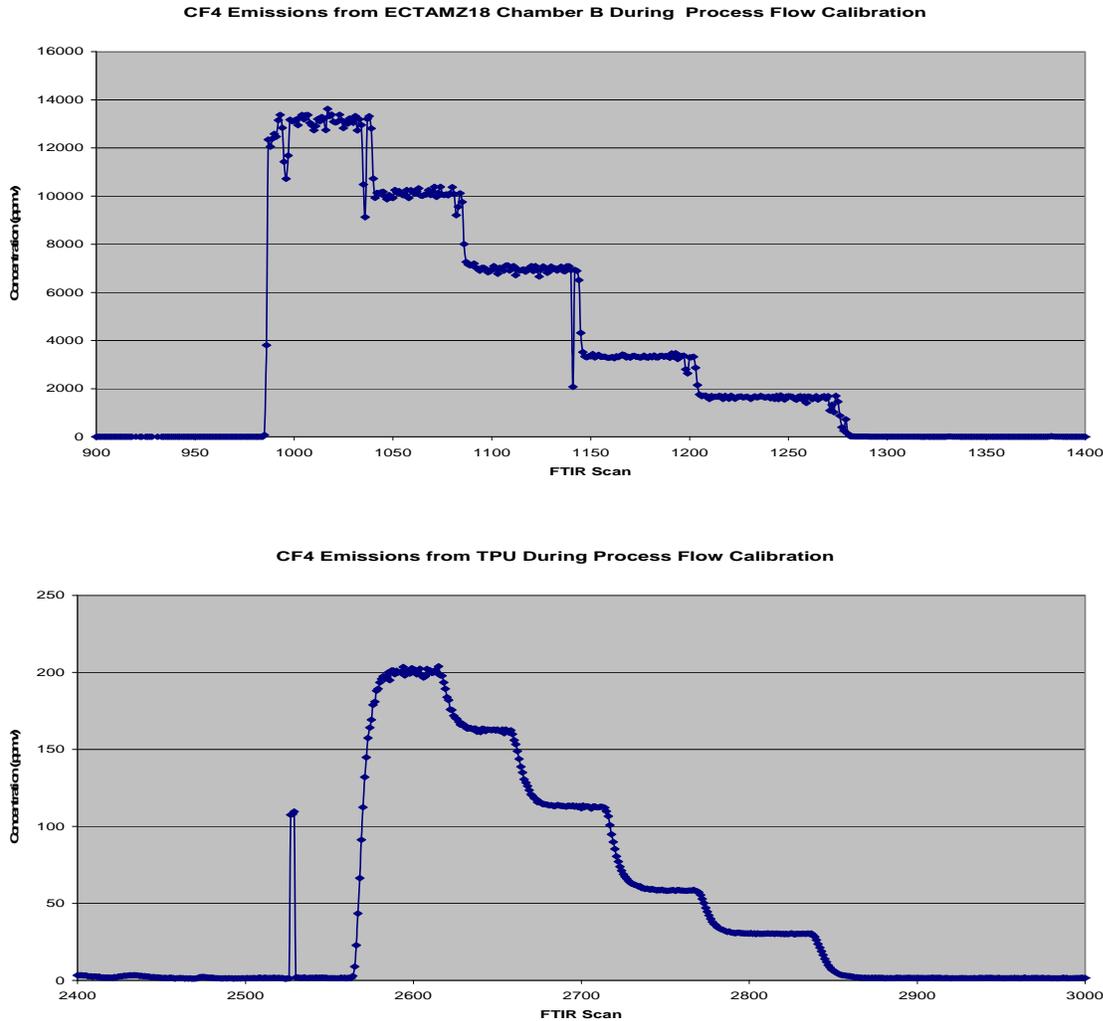
#### 3.2.1. DRE Determination During Process Calibration Flows

The scrubber DRE for CF<sub>4</sub>, CHF<sub>3</sub> and C<sub>4</sub>F<sub>6</sub> was determined during total process flow calibrations by comparing the steady-state inlet and outlet concentrations during the flow of each gas, and adjusting for the scrubber dilution. From these data a direct calculation of the scrubber DRE could be made. Figure 6 shows the scrubber inlet and outlet CF<sub>4</sub> concentrations determined for AMZ18 while CF<sub>4</sub> was flowing through the chamber. (These were the data used to calculate

the AMZ18 process dilution.) These data were used to calculate the scrubber DRE for CF<sub>4</sub> using the following equation:

$$\text{DRE} = 1 - ((\text{CF}_{4\text{out}} \times \text{Dilution}) / \text{CF}_{4\text{in}}) \quad (4)$$

Here CF<sub>4out</sub> and CF<sub>4in</sub> represent the average CF<sub>4</sub> concentrations determined for each flow shown in Figure 6. Using this method of comparing concentrations into and out of the scrubber, CF<sub>4</sub> DRE values for AMZ17 and AMZ18 are tabulated and contained in Table III.

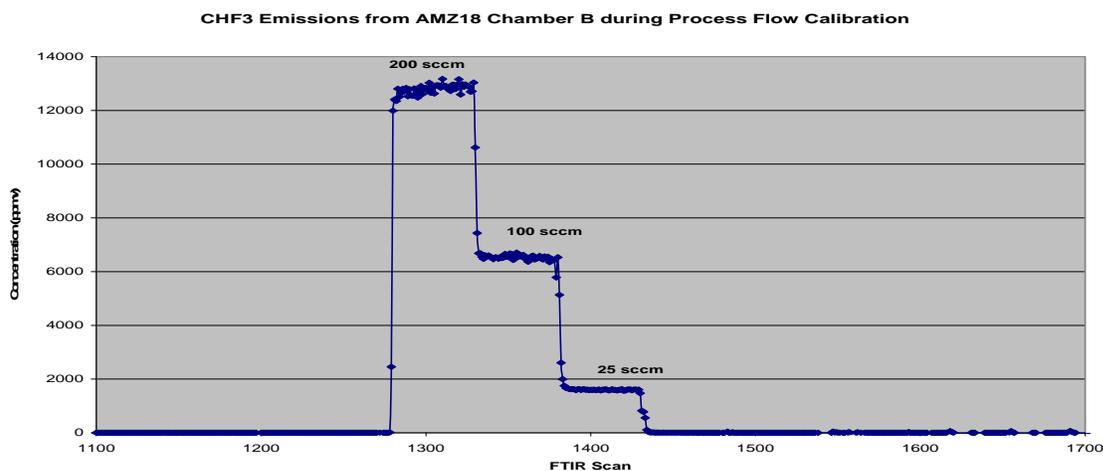


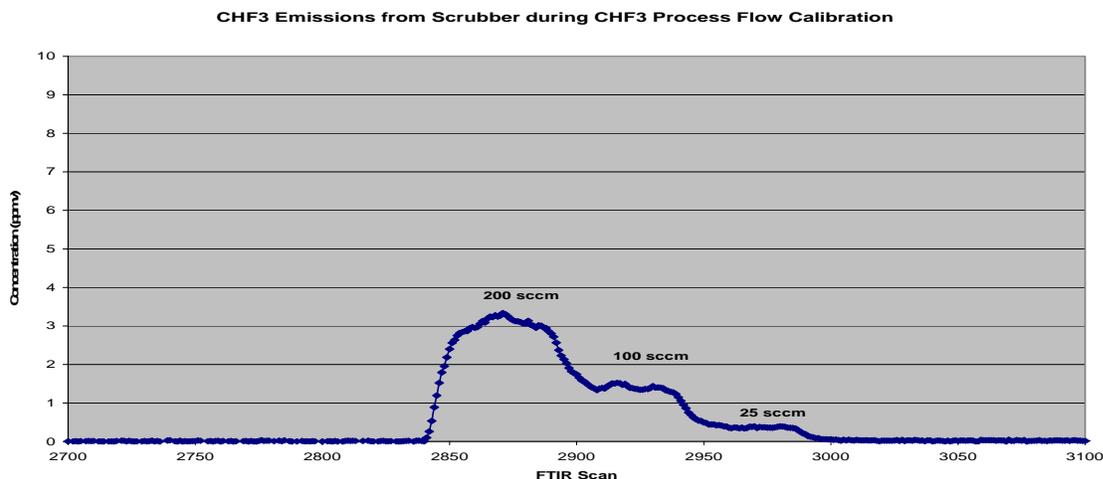
**Figure 6: CF<sub>4</sub> emission profile from AMZ18 chamber B (top) and from TPU (bottom) during process flow calibration. Each level of concentration is equivalent to a specific CF<sub>4</sub> flow rate thru the process chamber.**

**Table III: CF<sub>4</sub> DRE values determined during process flow calibrations.**

AMZ17				
CF <sub>4</sub> Flow (slm)	Ave Process Emiss. Conc. (ppmv)	Ave Scrubber Emiss. Conc. (ppmv)	Dilution Adjusted Concentration (ppmv)	DRE (%)
0.200	11,121 ± 183	191 ± 2.5	8098	27.8 ± 0.6
0.150	8783 ± 55	151 ± 1.5	6402	27.1 ± 0.4
0.100	5811 ± 109	104 ± 0.6	4410	23.6 ± 0.5
0.050	3028 ± 43	51 ± 0.4	2162	28.5 ± 0.5
0.025	1551 ± 48	27 ± 0.5	1145	26.3 ± 1.0
AMZ18				
0.200	12,134 ± 195	200 ± 2.0	9880	18.6 ± 0.4
0.150	9652 ± 121	162 ± 0.8	8005	17.1 ± 0.2
0.100	6477 ± 48	113 ± 0.5	5582	13.8 ± 0.2
0.050	3297 ± 32	59 ± 0.3	2915	11.6 ± 0.2
0.025	1681 ± 61	30 ± 0.2	1482	11.8 ± 0.5

From the data contained in Table III the scrubber CF<sub>4</sub> DRE appears higher for the AMZ17 scrubber relative to the AMZ18 scrubber. Results for CHF<sub>3</sub> indicated that AMZ17 abated CHF<sub>3</sub> sufficiently to yield a concentration below the detection limit of the FTIR equipped with a 5.6m cell, while relatively low emissions of CHF<sub>3</sub> were detected from AMZ18 scrubber. The CHF<sub>3</sub> inlet and outlet profiles determined during CHF<sub>3</sub> flows through chamber B on AMZ18 are shown in Figure 7. Both scrubbers abated C<sub>4</sub>F<sub>6</sub> sufficiently to yield an outlet concentration not detected by the FTIR.





**Figure 7: CHF<sub>3</sub> emissions from process (top) and scrubber (bottom) during CHF<sub>3</sub> process flow calibration.**

From the data shown in Figure 7, the AMZ18 scrubber DRE was calculated for CHF<sub>3</sub> during the total process flow calibration and is contained in Table IV. These data indicate a relatively high DRE for CHF<sub>3</sub> on AMZ18 scrubber. The AMZ17 scrubber had a higher DRE as CHF<sub>3</sub> was not detected in the effluent during the CHF<sub>3</sub> flow calibration.

**Table IV: CHF<sub>3</sub> DRE for AMZ18 scrubber based on data shown in Figure 7.**

CHF <sub>3</sub> Flow (slm)	Ave Process Emiss. Conc. (ppmv)	Ave Scrubber Emiss. Conc. (ppmv)	Dilution Adjusted Concentration (ppmv)	DRE (%)
<b>0.200</b>	<b>12,820 ± 170</b>	<b>3.1 ± 0.1</b>	<b>153</b>	<b>98.8</b>
<b>0.100</b>	<b>6538 ± 74</b>	<b>1.4 ± 0.06</b>	<b>69</b>	<b>98.9</b>
<b>0.025</b>	<b>1601 ± 15</b>	<b>0.4 ± 0.01</b>	<b>20</b>	<b>98.8</b>

The DRE for C<sub>4</sub>F<sub>6</sub> was high for both AMZ17 and AMZ18 scrubbers. The estimated detection limit for C<sub>4</sub>F<sub>6</sub> was 0.5 ppmv with the 5.6m gas cell based on a signal to noise ratio of 3. Thus, based on a 0.100 slm process flow (0.100 slm was the maximum flow possible with the installed MFC), which yielded an average process emission of 6474 ± 59 ppmv on AMZ18, the minimum DRE would be 99.6 %.

### 3.2.2 Determination of DRE during Wafer Processing

Determining the scrubber DRE under wafer processing conditions can be much more challenging, particularly if the PFC effluent concentration does not reach a steady state condition (here a steady state condition is defined as  $dC/dt = 0$ , where the concentration (C) is not changing over a relatively short period of time, as shown in Figure 6). Under these conditions it may be

necessary to numerically integrate the PFC concentration over time to yield an emission volume, which can be compared to the integrated process emission volume entering the scrubber for a given analyte. To convert measured concentrations into volumes, the following equation was used:

$$V_{EM} = \sum C_i T_f \Delta t \quad (5)$$

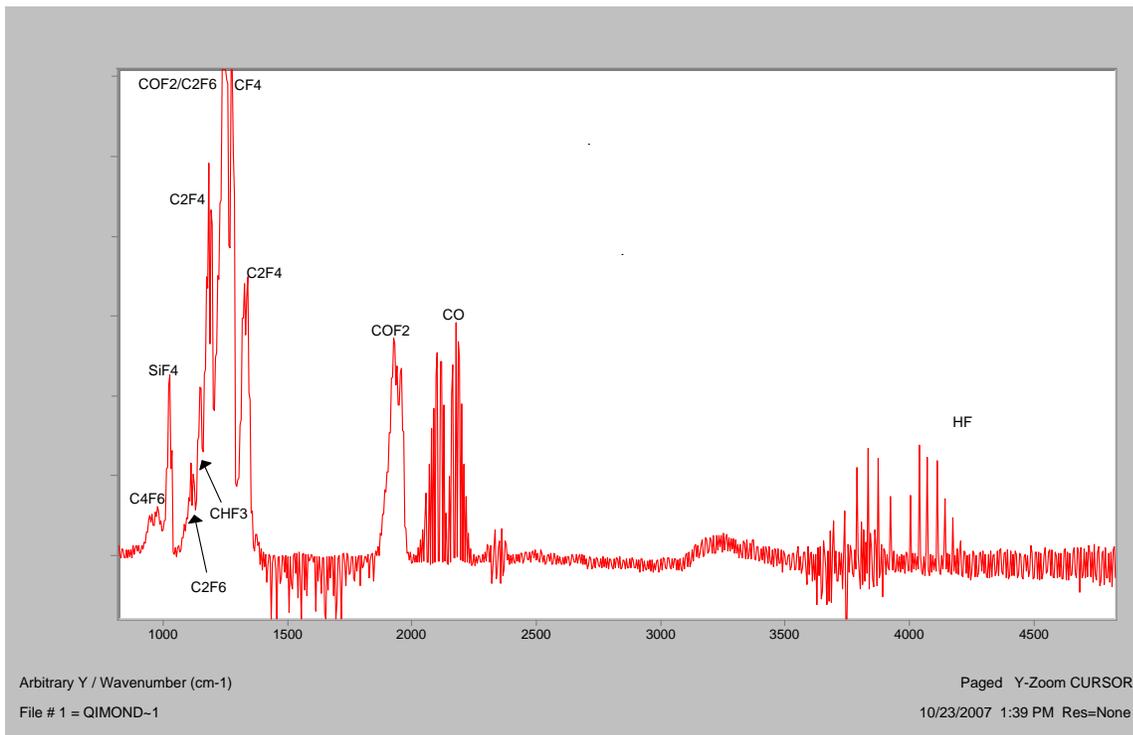
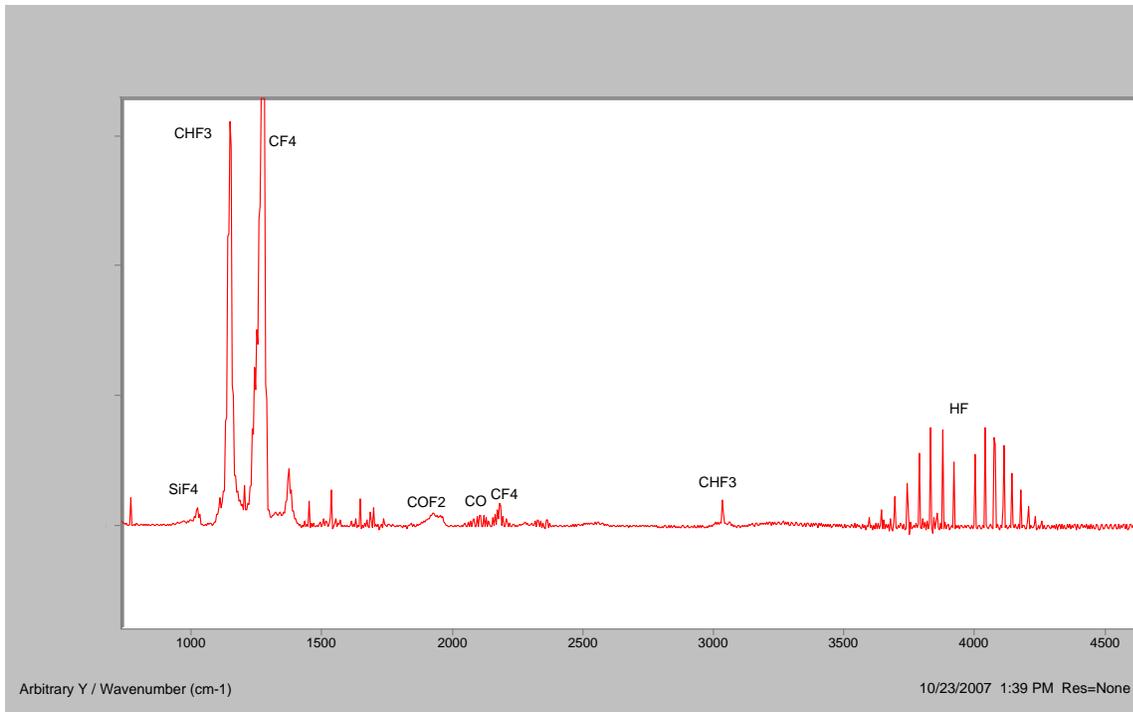
Where the total emission volume ( $V_{EM}$ ) is the summation of each FTIR data point where the concentration of analyte C is determined during time interval  $\Delta t$  and multiplied by the total flow ( $T_f$ ). The summation of the entire emission profile provides an emission volume for a given analyte during the process. During this study, these calculations were performed using standard spreadsheet software (Microsoft Excel). Use of this technique reinforces the importance of accurately determining the total process and scrubber flows as described in the sections above.

The process tested on AMZ17 and AMZ18 was a dielectric etch process that had two distinct etch steps. The approximate process recipes were as follows:

**Step 1 Arc Etch: 160 sccm CF<sub>4</sub>; 100 sccm CHF<sub>3</sub>; 150 sccm Ar; 20 sccm O<sub>2</sub> 35 sec**  
**Step 2: Main Etch: 60 sccm C<sub>4</sub>F<sub>6</sub>; 1000 sccm Ar; 45 sccm O<sub>2</sub> 65 sec**

In addition to the etch times listed above, up to 5 sec of additional chamber stabilization time is required to turn the process gases on and set the chamber pressure prior to turning on the process plasma.

During the etch processes etch gases CF<sub>4</sub>, CHF<sub>3</sub> and C<sub>4</sub>F<sub>6</sub> could be detected in the process effluent. Many etch by-products were also detected. These included SiF<sub>4</sub>, HF, COF<sub>2</sub>, C<sub>2</sub>F<sub>4</sub>, C<sub>2</sub>F<sub>6</sub> and CO. Figure 8 shows the FTIR spectrum of process emissions for each etch step.



**Figure 8: FTIR spectra of emissions from arc etch (top) and contact main etch (bottom)**

Typical emission profiles for the etch process are shown in Figure 9. These data were acquired on AMZ18 chamber B during the etching of test wafers. The top graph shows PFC process gas emissions during both etch steps for three wafers. The bottom graph shows the etch by-products

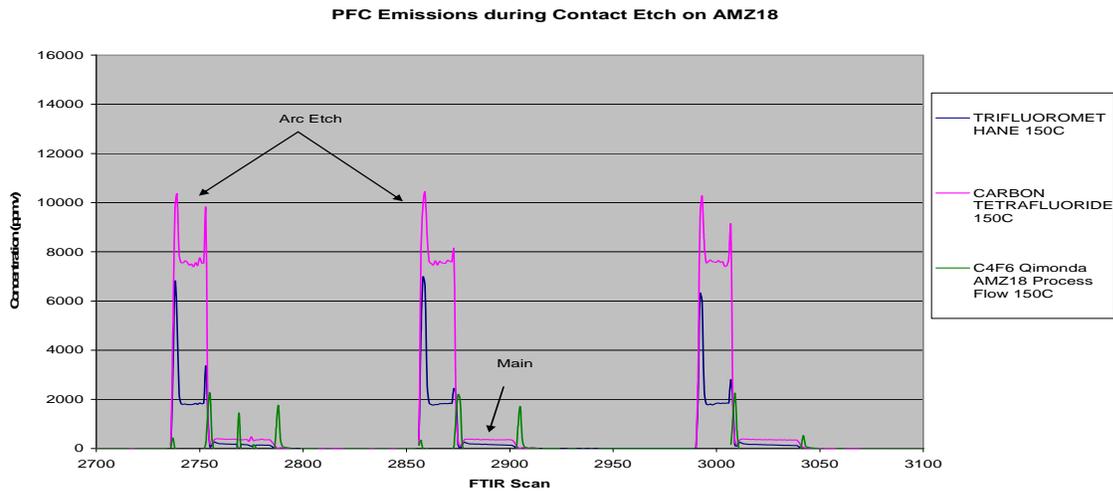
formed in the plasma during the process. The spikes observed in the process gas emissions are attributed to the stabilization flow at the beginning of the etch process, and the chamber purge of residual gases after the plasma has been turned off at the conclusion of etching.

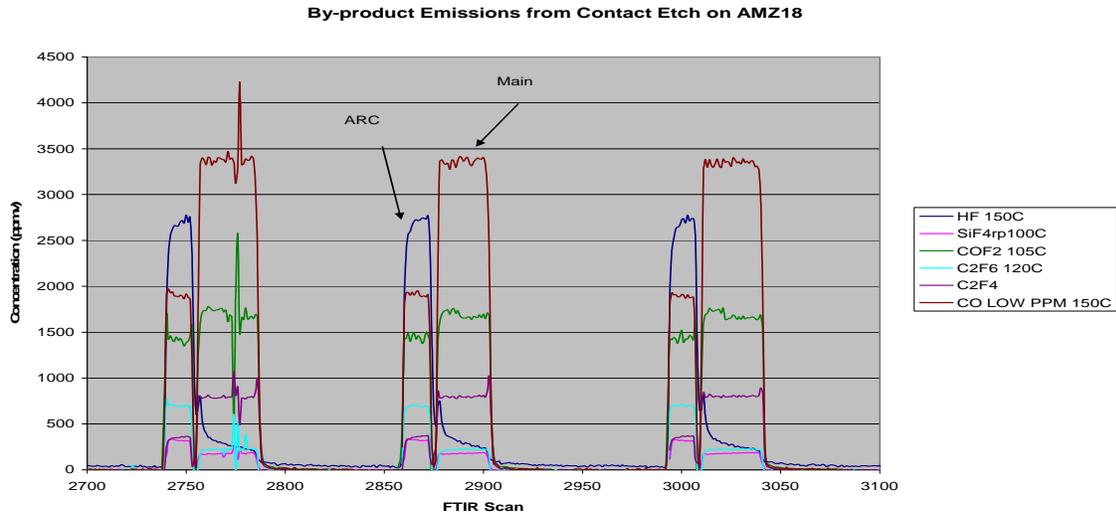
The PFC emissions data shown in Figure 9 (top) were integrated to determine the total emission volume for each gas, and used to calculate the process utilization for each molecule. Using the process recipe shown above the following PFC plasma utilization values were obtained for CF<sub>4</sub>, CHF<sub>3</sub> and C<sub>4</sub>F<sub>6</sub>:

**Table V: Process Utilization for etch gases used in contact etch. The volumes reported as being used were calculated from the process recipe and assumed a stabilization flow of 5 seconds. Data reported per wafer processed.**

CF <sub>4</sub> Used for Process (sl)	CF <sub>4</sub> Emitted from process (sl)	CF <sub>4</sub> Process Utilization (%)
0.107	0.088	18
CHF <sub>3</sub> Used for Process (sl)	CHF <sub>3</sub> Emitted from process (sl)	CHF <sub>3</sub> Process Utilization (%)
0.067	0.032	52
C <sub>4</sub> F <sub>6</sub> Used for Process (sl)	C <sub>4</sub> F <sub>6</sub> Emitted from process (sl)	C <sub>4</sub> F <sub>6</sub> Process Utilization (%)
0.070	0.005	93

The data contained in Table V include emissions for both etch steps of the process. Approximately 10% of the total CF<sub>4</sub> emission was observed during the C<sub>4</sub>F<sub>6</sub> process step, where CF<sub>4</sub> was formed as a by-product.





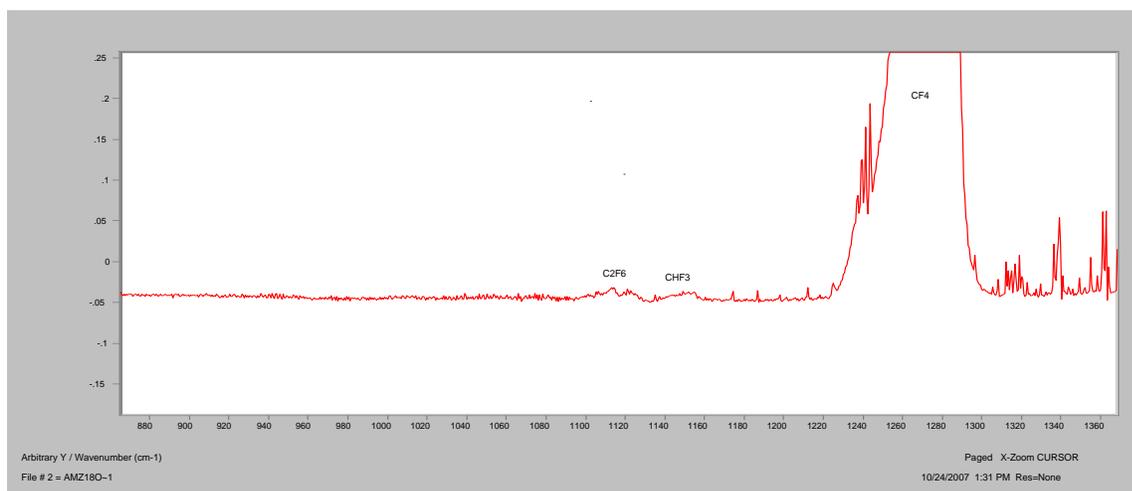
**Figure 9: Emission profiles for PFC process gases (top) and plasma by-products (bottom) during contact etching of test wafers on AMZ18 chamber B. The ARC and Main etch portions are labeled in the figures.**

Emissions from the scrubber during wafer processing included primarily  $\text{CF}_4$ . Figure 10 shows an FTIR spectrum obtained during test wafer processing on AMZ18. Low level  $\text{CHF}_3$  and  $\text{C}_2\text{F}_6$  emissions were detected. The  $\text{CF}_4$  emission profile from the scrubber is shown in Figure 11. Only the data for the test wafers was used to calculate a DRE as emissions from multiple chambers confound the DRE determination if the scrubber loading from other chambers is not accounted for.  $\text{CF}_4$  emissions from the test wafers were integrated and used to calculate DRE by comparing to the integrated process emissions reported above. Figure 12 shows  $\text{CF}_4$  emissions from AMZ17 scrubber. Again multiple chambers were being used on the tool.  $\text{CF}_4$  emissions for the last 9 wafers were integrated to yield total  $\text{CF}_4$  emission for 9 wafers and compared to the integrated process emissions for the same 9 wafers. The results for both scrubbers are contained in Table VI below:

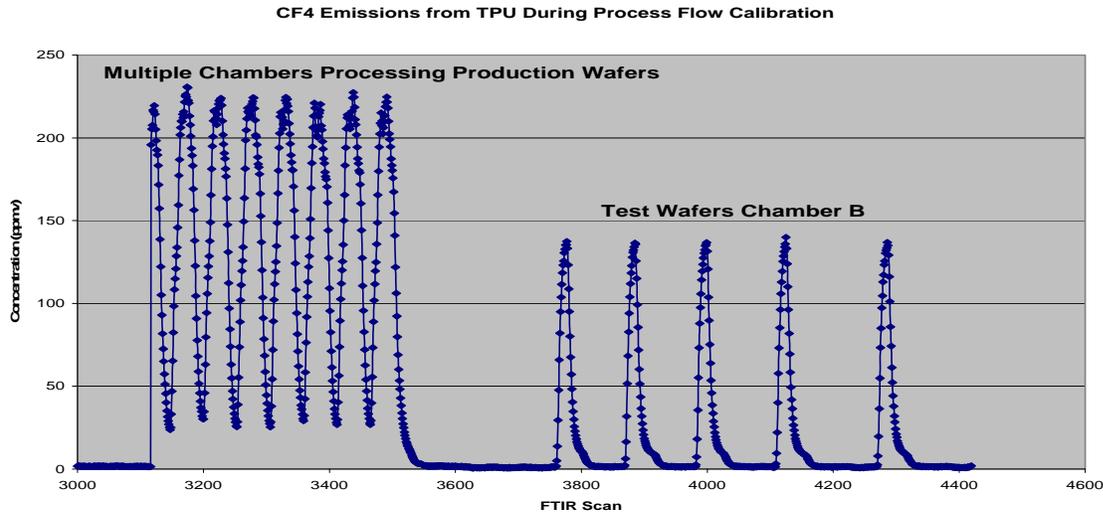
**Table VI: CF<sub>4</sub> DRE determined for each scrubber by comparing inlet and outlet emission volumes.**

<i>AMZ17</i>		
<b>Integrated CF<sub>4</sub> Process Emissions for 9 wafers (sl)</b>	<b>Integrated CF<sub>4</sub> Scrubber Emissions for 9 wafers (sl)</b>	<b>Scrubber CF<sub>4</sub> DRE (%)</b>
<b>0.920</b>	<b>0.716</b>	<b>22</b>
<i>AMZ18</i>		
<b>Integrated CF<sub>4</sub> Process Emissions for 5 test wafers (sl)</b>	<b>Integrated CF<sub>4</sub> Scrubber Emissions for 5 test wafers (sl)</b>	<b>Scrubber CF<sub>4</sub> DRE (%)</b>
<b>0.445</b>	<b>0.425</b>	<b>4</b>

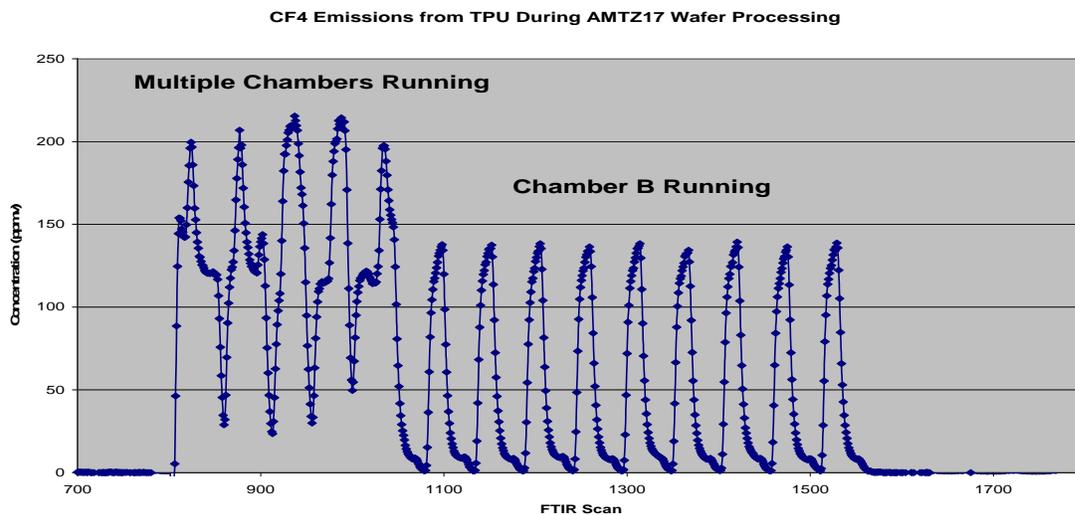
Emissions of C<sub>2</sub>F<sub>6</sub> and CHF<sub>3</sub> from the AMZ18 scrubber during test wafer processing were integrated and used to estimate minimum DRE values of > 98 % for C<sub>2</sub>F<sub>6</sub> and > 98.7 % for CHF<sub>3</sub>. Actual DRE values are presumed to be higher. The minimum DRE for C<sub>2</sub>F<sub>6</sub> is based on an integrated per wafer process emission of 0.010 sl and an integrated scrubber emission of < 0.001 sl. The minimum DRE for CHF<sub>3</sub> is based on an integrated per wafer process emission of 0.033 sl and an integrated scrubber emission of < 0.001 sl. CHF<sub>3</sub> and C<sub>2</sub>F<sub>6</sub> were not detected in the effluent of the scrubber on AMZ17.



**Figure 10: FTIR spectrum of AMZ18 scrubber emissions during test wafer processing.**



**Figure 11: CF<sub>4</sub> emission profile from AMZ18 scrubber during processing of test wafers on Chamber B, and during processing of production wafers on multiple chambers.**



**Figure 12: CF<sub>4</sub> emission profile from AMZ17 scrubber during processing of production wafers on Chamber B, and during processing of production wafers on multiple chambers.**

**III: Comparison of CF<sub>4</sub> DRE Determinations:**

Both methods of determining the scrubber DRE for CF<sub>4</sub> on AMZ17 and AMZ18 are compared in Table VII. Both methods are in reasonable agreement and both indicate a relatively low DRE for CF<sub>4</sub> on the scrubbers tested. Higher DRE were obtained for etch gases CHF<sub>3</sub> and C<sub>4</sub>F<sub>6</sub>, and process by-product C<sub>2</sub>F<sub>6</sub>. The AMZ17 scrubber appears to be more effective at abating all PFCs. It was noted during testing that the AMZ17 scrubber was operating at a higher reported temperature than the AMZ18 scrubber, however, temperature data were not collected.<sup>1</sup>

<sup>1</sup> Observations of temperature during the study indicated that AMZ17 was running at approximately 885 to 905 °C, whereas, AMZ18 was running at approximately 800 to 815 °C. It is believed that the noted temperatures refer to the external wall temperature of the combustion chamber within the abatement device.

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**Table VII: Comparison of two methods used to determine CF<sub>4</sub> DRE on scrubbers for AMZ17 and AMZ18**

<b>Scrubber</b>	<b>CF<sub>4</sub> DRE determined from Process Gas flow Calibrations (average of 5) (%)</b>	<b>CF<sub>4</sub> DRE from Integrated Process Emissions (%)</b>
<i>ETCAMZ17</i>	<i>27</i>	<i>22</i>
<i>ETCAMZ18</i>	<i>15</i>	<i>4</i>

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## **4.0 Conclusion**

Determination of the DRE of PFCs by POU scrubbers has been conducted for a contact etch process at Qimonda. Two scrubbers of the same make and model were tested. The processes tested were the same on each tool. The results indicated very high DRE for most PFC process gases and PFC by-products. Only CF<sub>4</sub> was determined to have a low DRE on both systems.

One key element of this study was to accurately determine the dilution that occurs to process effluent as it passes through the scrubber into the corrosive scrubber exhaust duct. In this study, the dilution was determined by using a chemical tracer, Kr, which was injected into the scrubber inlet of one process chamber, and subsequently determined in the scrubber effluent. The effluent Kr concentration was determined by using a QMS, which was calibrated on-site for its response to Kr. The choice of Kr for chemical spiking was dictated by the need for a tracer that would not react in or be produced by the scrubber.

Two methods of determining process gas DRE were investigated. Use of a continuous flow of PFC gases permitted a steady state emission of PFC from both the process chamber and scrubber (provided the DRE was < 100%). This allowed direct comparison of emission concentrations from tool and scrubber after scrubber effluent data were corrected for dilution. Wafer processing emissions were also used to calculate DRE by integrating the emission concentrations over time and total flow to yield emission volumes into and out of the scrubber. The comparison of these methods yielded DRE values that were in reasonable agreement. The latter method could be needed in cases where the effluent data do not appear to reach a steady state, particularly for the scrubber effluent. The fundamental difference between the two methods is that etch by-products would be present in method 2, whereas they would not present in method 1. This would include any particulates that may be present in the etch effluent stream.