

## ABSTRACT

Koretechko, Kimberly. Solvent Free Post Metal Etch Veil Removal Process Development. (Under the direction of Dr. Jerome J. Cuomo)

As the feature size of advanced integrated circuits decrease, it has become necessary for the semiconductor industry to start investigating advanced methods of polymer residual removal. When metal lines shrink to 0.25um and beyond, the switching speed of the device becomes the limiting factor. In order to shrink the dimensions of the metal lines, advanced photo resist technologies such as the use of deep-UV photo resist are used which creates different post metal etch residuals. Residual polymers which are formed during metal etch processing prove to be more difficult to remove with these advanced photo resists. These residuals, commonly known as veils, become increasingly difficult to remove with the conventional wet chemical solvent systems. A new technology has emerged that moves away from wet chemical processing. The objective of this engineering project was to qualify this new technology. The qualification included tool purchase inputs and development of the new process. The Ulvac Enviro was the tool of choice for this process development. The Enviro provides a unique system which combines the chemistry of a very low-bias reactive ion etch and remote microwave plasma and fluorine gases resulting in enhancing the solubility of residues in solvents, acids or de-ionized water. The Enviro not only provides a solution to the removal of the residual polymers it also has a lower cost of ownership and fewer concerns with chemical waste disposal. A two step microwave/RF process was developed using an Enviro. The process consisted of the following gas flows;  $\text{NF}_3$ ,  $\text{N}_2/\text{H}_2(5\%)$  and  $\text{O}_2$ . These gases along with the microwave and RF parameters were the significant factors for this devel

process. A balance between fluorination, oxidation and physical ion bombardment was developed using the Enviro system. Corrosion, veil removal and metal line profiles were among the main factors that were measured and compared against a standard wet chemical cleaning process. The experimental work done with this new Enviro process proved to either match or exceed the existing chemical de veil process. The Enviro process actually showed an improved performance over the standard based on corrosion results. The Enviro also provided more than a 50% reduction in wafer processing cost, by completely eliminating the need for solvent processing. As a result it was determined that the Ulvac Enviro can provide an excellent alternative to the conventional chemical de veil process.

# **Solvent Free Post Metal Etch Veil Removal Process Development**

by  
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## 1. INTRODUCTION

In fabricating advanced integrated circuits, a multi-level interconnect scheme is commonly used, and plasma etch is applied to form metal lines and via holes. During the plasma etch, a sidewall polymer or veil is formed to control the etch profile. After the etch, the veil needs to be removed completely to ensure a good via contact resistance and zero leakage between adjacent metal lines. Typically, a very aggressive amine based chemical solvent is needed to clean up the sidewall polymer because of its heavy metallic contents.<sup>1</sup>

As metal interconnect technology moves toward 0.25 $\mu\text{m}$  and beyond, it becomes increasingly important to more thoroughly clean the residues (sidewall polymers and veils) left behind from the previous processing steps. The metal interconnects of these advance devices become the limiting factor for the switching speed of the device. As a result, post etch treatment must be recognized as an important step of the process. Some of the issues surrounding new design generations are listed below:

- As dimensions shrink down to 0.4 $\mu\text{m}$ , the commonly “allowed” 0.1 $\mu\text{m}$  of CD (critical dimension) loss is no longer valid, thus better control of post metal etch corrosion is required.
- The use of more complex material combinations in the process sequence, whether it is for ARC (anti-reflective coating), adhesion layer, electromigration or stress-relief barrier purposes, creates more complex post etch residues which are still expected to be removed in a minimum number of steps.
- The use of deep UV photo resists which were developed to achieve the requirements of these design rules. As a result the etch residues left on the



sidewall of the features etched are different in constitution and might require specific post etch treatment.<sup>2</sup>

With the increasing demands on these devices, new methods of residual polymer or veil removal are being investigated. One option is a residue solubilization system. This system combines the chemistry of a very low-bias reactive ion etch (RIE) and remote microwave plasma resulting in enhancing the solubility of residues in solvents, acids or DI water. In some cases this technology is able to completely replace the solvents and acids with simply a post DI water rinse. This technique provides a reduced consumption of acids and solvents while still meeting the demands for cleanliness on 0.25 $\mu$ m or smaller devices.

In the semiconductor industry the purchase and qualification of new processes are critical decisions. Tool cost of ownership and process capabilities are essential factors. Several tool manufacturers are evaluated. Factors that influence cost of ownership include initial cost of the tool, wafer through put, clean room space and mean time between maintenance. Test wafers are also sent out to tool vendors to provide initial process capabilities. Once a fab commits to a tool vendor and develops a process several millions of dollars are spent to install tools to meet the required wafer capacity needs of the manufacturing facility. Therefore, it is important that a well-informed discussion is made when purchasing a new toolset.

## **2. LITERATURE REVIEW**

In recent years there have been many studies related to veil removal process development. These studies investigated both solvent free and chemical deveil processes. Many of these studies were used to create the general understanding of the deveil process.<sup>3-11</sup>

### **2.1 Metal Interconnect Processing**

The manufacturing process steps that pertain to the metal interconnect technology and formation of metal lines for connecting devices are the focus of the solvent free strip procedure. The general procedure consists of depositing a metal film on a wafer, typically less than one micron thick; coating the film with photo resist; exposing the wafers to ultraviolet light through a mask; developing the resist thereby creating a protective pattern of photo resist on the metal where the metal lines will remain after the metal etch process. Fig 2-1 shows a diagram of the backend metal interconnect technology.

## Backend Design

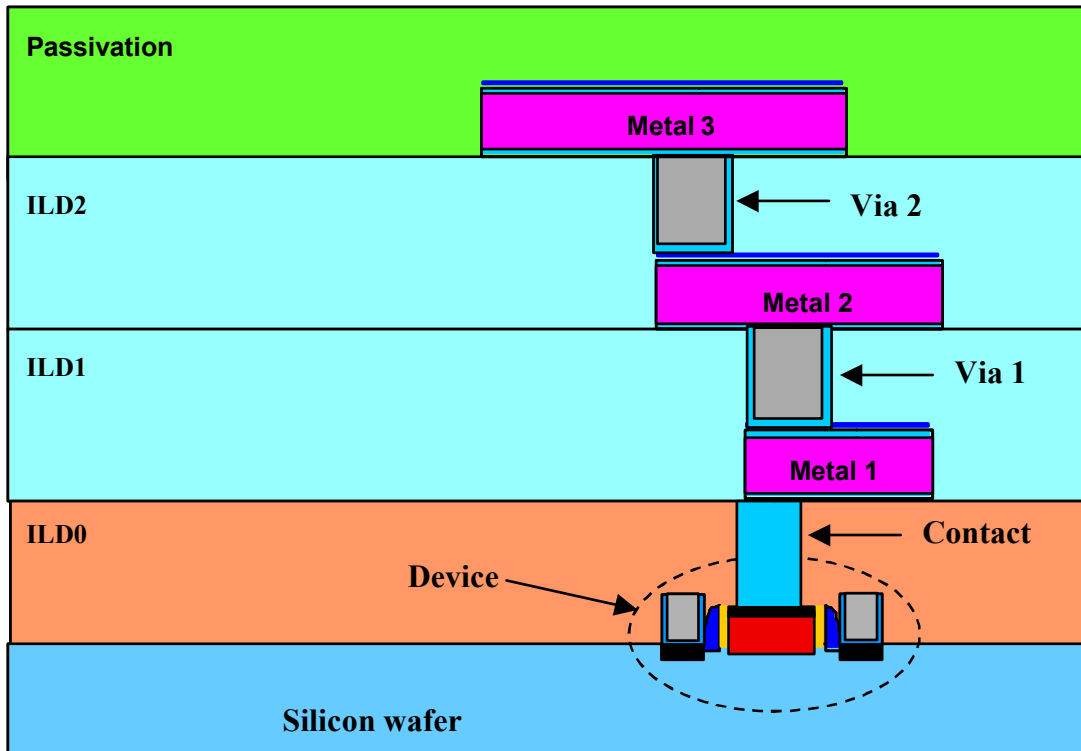


Fig. 2-1. The above diagram is a cross section of a typical backend semiconductor design. Once the device is formed a series of metal interconnects are formed. The first interlayer dielectric (ILD0) is formed using a stack film consisting of TEOS and BPSG. A contact is formed within this IDL0 layer to contact with the device. The ILD0 acts as a barrier layer between the device and the metal layers. The first metal layer is deposited on top of the ILD0 after the contacts are formed. Then another interlayer dielectric is deposited (ILD1). A via is formed within the IDL1 layer to provide contact to metal 1. This process is then repeated and a final passivation film is deposited to protect the device.

### 2.2 Metal Etch

An adequate metal etch process is required to etch through several different materials (Al and Ti/TiN barrier films) and result in an anisotropic etch with no residue, no corrosion, minimal undercut, good critical dimension control and minimal loss of material underlying the interconnect materials.<sup>12</sup> Typical fluorine-containing gases can not be used for the metal etch process due to the low vapor pressure of the etch by-product,  $\text{AlF}_3$ , at temperatures below  $100^\circ\text{C}$ . Chlorine containing gas such as  $\text{BCl}_3$ ,  $\text{CCl}_4$ ,  $\text{SiCl}_4$ ,  $\text{Cl}_2$ , are some of the gases used to etch aluminum films. The metal etch process consists

of an initial break through step, followed by a bulk Al step. The break through step is needed to remove the native oxide covering the aluminum and remove any moisture present in the chamber.  $\text{BCl}_3$  is the preferred source gas for the role of native oxide removal in many processes.  $\text{BCl}_3$  is a good getter of oxygen and water vapor, and it forms heavy ions that are effective in sputtering the native Al oxide.<sup>12</sup>

During the main etch step, chlorine is the primary chemical etchant. The ions generated from the  $\text{BCl}_3$  also act as the source of ions for physical bombardment. An anisotropic etch is achieved by an inhibiting layer generally referred to as sidewall polymer or veil on the aluminum surface. It is removed on directional surfaces by ion bombardment; however, the polymer remains on the side wall surfaces of the metal lines creating an anisotropic etch environment. Fig 2-2 illustrates the sidewall polymer before and after photo resist removal. These inhibiting layers are created from the formation of chlorocarbon polymers originating from the resist etch by-products. Often additional carbon containing gases are added to the process in order to enhance the protection of the Al sidewall from undercut. This formation of sidewall polymer becomes a challenge during post metal etch resist and polymer removal steps.

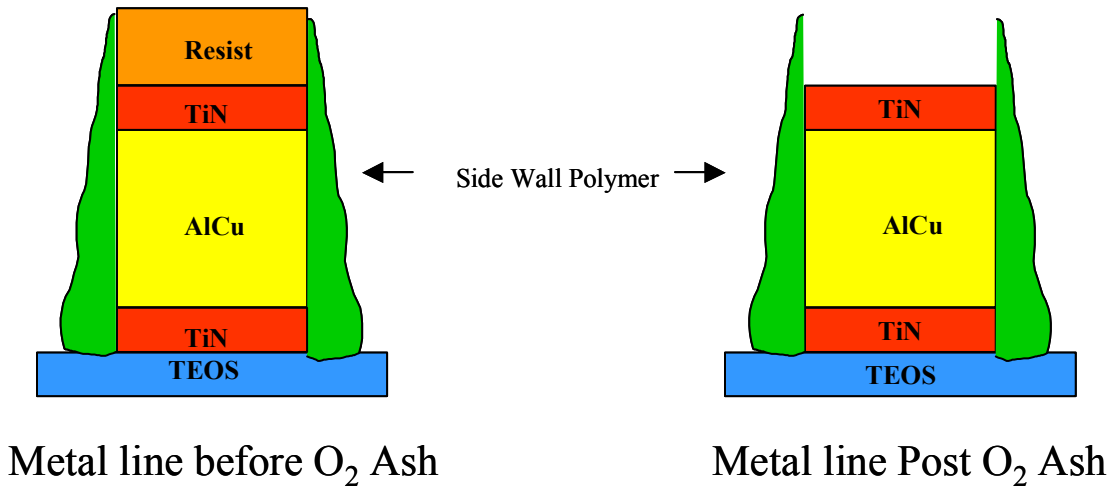


Fig. 2-2. The left diagram illustrates a metal line post metal etch. The film stack consists of underlying TEOS, metal line and resist on top of the metal line. The residue on the sides of the metal line is residual polymer or sidewall polymer created during the previous metal etch. The right diagram illustrates how the metal line and residual polymer appear post O<sub>2</sub> ash. The resist has been removed during the ash, however the sidewall polymer remains.

### 2.3 Post Metal Etch Residue

Once the wafer has completed metal etch, the next step is to remove the resist and polymer residue or veil. The first step is to remove the bulk resist from the surface. It is becoming more standard that the bulk resist removal takes place while still under vacuum within the metal etch tool. LAM 9600s and AMAT Metal DPS etchers are equipped with downstream stripping systems. Most ashers work on the same basic principles: bulk resist removal is achieved by reacting atomic oxygen atoms with the resist, which basically is a hydrocarbon polymer, to create volatile CO, CO<sub>2</sub> and H<sub>2</sub>O as the main by-product.<sup>2</sup> Usually the atomic oxygen is created by dissociating oxygen in a microwave plasma or RF plasma. Forming gas which is N<sub>2</sub> and H<sub>2</sub> is sometimes added to improve the ash performance and enhance the veil removal. Once the bulk resist is removed, then depending on the prior processing, i.e. metal or via etch, an additional wet

chemical clean is required in order to remove the polymers left behind after the resist strip.

The ash process step is conventionally followed by a wet chemical process which removes the polymer residues. As mentioned earlier, these residues or veils are generally created during the previous plasma processing in order to create an anisotropic etch environment. Polymer residues are also created during the previous ash step, known as resist popping. The resist temperature increases too fast and the solvents begin to bubble and pop off the surface of the wafer creating additional by-products on the wafer. Both of these residues are typically removed using a wet chemical clean process. Although the ash removes the bulk of the photo resist and some of the polymeric materials, a large amount of residual non-ashed material consisting of metals and complex metal-oxide organic compounds remain. Therefore, the use of solvent post ash processing is required to remove the remaining residues. Common solvents used for this application are N-methyl-pyrrolidone (NMP) containing an amine; an organic-aqueous solution containing ethylene glycol, ammonium fluoride, water and a surfactant; or a buffered hydroxyl-amine solution containing wafer and a chelating agent.<sup>13</sup> These solvents are costly to purchase, hazardous to use and must be disposed of through conventional hazardous waste-handling facilities. For each eight (8) inch wafer processed through a solvent step typically 0.20-0.40 liters of solvent are consumed. During the solvent process, wafers are first exposed to chemicals to remove the bulk residual for initial cleaning. Then the dirty bath is cycled out and a second clean bath is initiated to remove the remaining residuals or polymers on the surface of the wafers. Once the solvent clean is complete the wafers

then go through a series of rinse cycles to remove all remnants of solvents on the wafer surface. Often this process is done in a spray acid tool; the wafers are placed in a cassette and loaded into a chamber. This chamber rotates or spins the wafers while solvents are sprayed into the chamber. The spinning allows for equal dispersion of the chemicals. Once the wafers are cleaned, a drying cycle begins which spins the wafers in a nitrogen gas environment in order to dry the cassette and wafers prior to moving on to the next step.

The industry is now moving towards eliminating the wet chemical clean process with a microwave/RIE process, followed by a DI water rinse. This dry veil removal has proven to exceed the technical capabilities of the standard wet clean allowing for an increased process margin and considerable economic cost savings. The Ulvac Enviro is a tool that is capable of removing veil or polymer residue in a solvent free environment.

### **2.3 Ulvac Enviro System**

The Enviro system provides an alternative to the conventional post metal etch wet de veil process. The Enviro system is an advanced photo resist and polymer removal system which provides solvent free solutions for semiconductor processing. The Enviro de veil system offers more than a 50% reduction in process cost. The lower cost of the Enviro is attributable to the reduced use of chemicals compared to the conventional wet de veil process. Not only does the Enviro reduce chemical cost it also improves process yield by decreasing the amount of organic defects that remain on wafers post metal etch module.

The Enviro solvent free process benefits from the fact that most of the metallic compounds incorporated into the polymers or veils are water soluble for example; aluminum chloride,  $\text{TiCl}_4$  and  $\text{TiF}_4$ . The process maintains a low operating temperature which prevents oxidation of the metals. At the same time, it is able to ash effectively rendering the entire remaining material soluble in a simple DI water rinse.<sup>13</sup> A series of plasma chemistry process steps at low temperatures are used for this process. The plasma chemical treatment includes steps with reactive ion etch (RIE) and remote or downstream microwave plasma treatment, often in combination in order to achieve a dry water soluble residue.

The Enviro consists of the following features<sup>14</sup>:

- Substantial cost savings over conventional wet processing
- Solvent free processes in production since 1998
- Patented microwave and RIE plasma source in same reactor
- High throughput dual reactor processing
- Vacuum isolated (load lock) reactor
- Flexible process chemistry with 6 MFC's
- Window's NT based graphical user interface



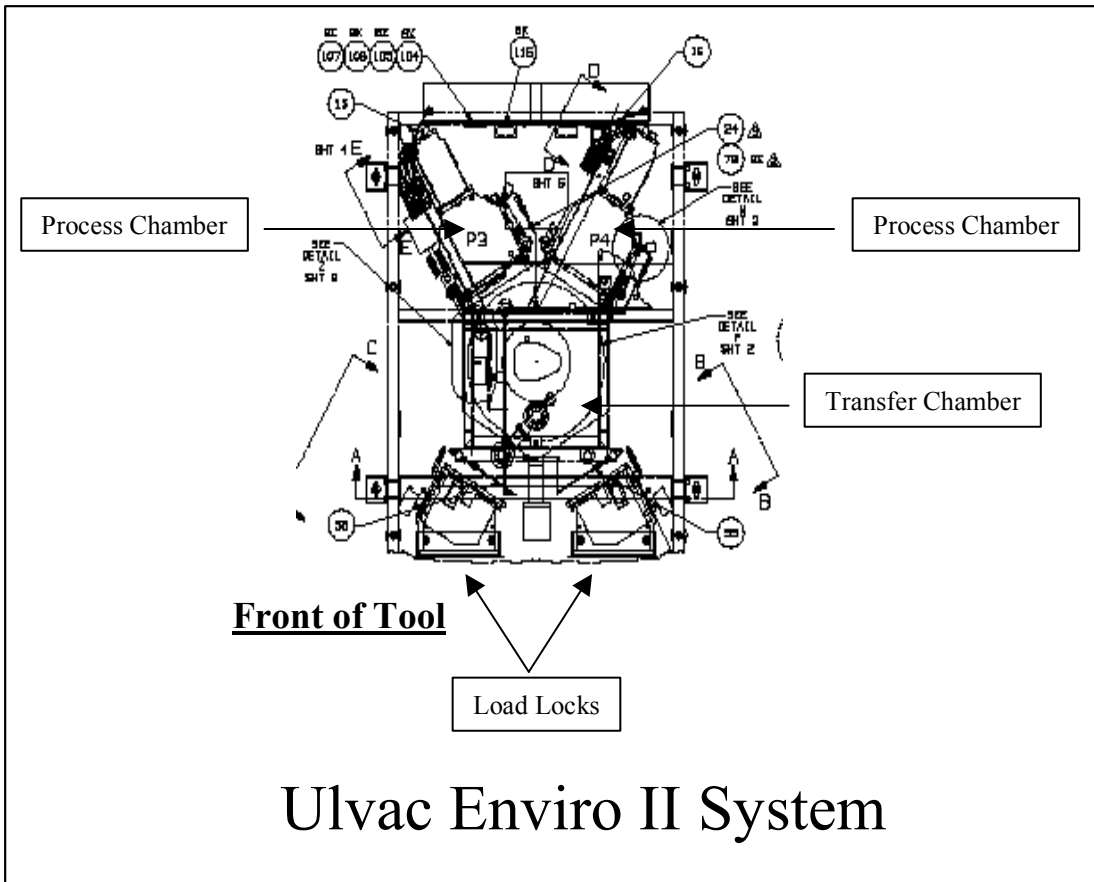


Fig 2-3 The above diagram is a top down cross section of the Ulvac Enviro II System. The front of the tool is bulk head mounted to the operations bay, while the remaining portion of the tool is housed in the gray space (equipment area). The two load locks are accessible through the front of the tool. The transfer chamber houses the robot which transfers the wafers between the load locks and process chambers. Two process chambers are located in the rear of the tool.<sup>14</sup>

The tool consists of two (2) processing chambers and two (2) load lock chambers, which allows for high wafer throughput. The tool can be configured for either a streaming or parallel mode. The “streaming” mode allows the operator to continuously load and unload wafers from one load lock while continuing to process wafers from the other load lock allowing. This enables maximum tool utilization and an over all lower cost of ownership.

Depending on the length of the process and tool configuration, the Enviro is capable of obtaining a throughput of up to 50% greater than conventional wet processing. For process flexibility, the Enviro is equipped with both a hot plate and a cold plate. The hot plate allows for wafer processing from room temperature to 300C. These higher temperature processes are typically used to remove high dose implant photo resist. The cold plate provides processing capabilities from 0 – 90C, this temperature range is typical for backend applications such as via and metal de veil processes. The Enviro plasma source consists of both a Microwave (2.5kW, 2.45 GHz) and RF (650W, 13.56MHz) capability. The microwave source provides the ability of an increased chemical environment within the chamber, while the RIE process is more of a physical ion bombardment environment.<sup>14</sup>

### **3. EXPERIMENTAL WORK**

The objective of the following experimental work was to develop a dry metal de veil process using the Ulvac Enviro II System. The standard process used a Semitool system with NOE to chemically remove the veil from the wafers. NOE, which stands for neutral oxide etch, consist of ethylene glycol and ammonium fluoride.

#### **3.1 Device Summary**

All experimental work was done on wafers from CDR1 (critical design rules) technology, which uses a CMOS flow. CMOS (complementary, metal, oxide silicon) process is designed to build both N-type and P-type channel transistors. The design rule set for

CDR1 is applicable to new designs intended to be manufactured with the minimum feature sizes of 0.4 micron. Both logic and nonvolatile memory devices are processed using the CMOS technology. A typical CDR1 device uses three layers of metal, and polysilicon for both the transistors and flash module. The metal layers are each separated by an inter layer dielectric (ILD). The purpose for the ILD is to decrease capacitance between metal lines and to reduce cross talk between the metal lines. Metal 1 and 2 are the same thickness, where as metal 3 is thicker.

CDR1 is a planar process which allows for smaller feature size. The planarization process is done by a chemical mechanical polish procedure. The CDR1 technology also contains unlanded via's which makes the control of CD's (critical dimension of metal line width) more critical.

Metal resistance of the lines is very important. Veil removal or the lack of it can slow the device down. The resistance becomes very critical for devices that require speed. Also in very tight features, veils can cause leakage from one metal line to the next. Veils can also cause defectivity issues in the subsequent clean steps, resulting in metal line shorts.

Veil residue can be a source of corrosion. Corrosion is an extremely critical parameter due to the fact that it becomes a reliability issue. Reliability can be measured by electromigration testing. The electromigration rule is that if 50% of the Al line is missing in a cross section then that line is a reliability risk in the field.

Basically there are two types of corrosion:

- 1) By-product – Chlorine is still reacting with the metal and leaving by-product. Generally this type of corrosion results in the wafer getting scrapped.
- 2) Standard corrosion – The corrosion reaction has stopped and there is a void in the metal line. This type is not as serious as by-product. The 50% rule applies to this type of corrosion.

### 3.2 In-Line Success Criteria

During the development of the metal deveil process, the following in-line success criteria had to be met before committing a product lot to the new process. The objective was to match or exceed Enviro in-line data to the current wet processing in-line data. The success criteria was defined according to the CDR1 design limits.

Table 3.1  
In-Line Success Criteria

Category	Spec	Procedure
Corrosion defects	Zero corrosion defects	Wet Box: KLA M2 @ 0.25 $\mu$ m
Veil removal	100% removal of polymer w/DI rinse only	SEM, center and edge
CD Loss	+/- 10nm loss	CD SEM
Profile	Match existing process	X-section and top down SEM, center and edge
Oxide (TEOS) loss	< 250 Å	Prometrix, UV1050 or equivalent
TiN Arc loss	< 50 Å or match existing process	Prometrix, SEM
Ti, TiN, TEOS undercut	< 100 Å or match existing process	TEM or SEM
Particles	< 50 adders of 0.18 $\mu$ m or greater particle size	Tencor 6100 particle analyzer
Contamination	Match existing process	SIMS/TXRF
Visual Inspection	Match existing process	Microscope inspection/ in-line SEM

## Test Wafers

The above in-line success criteria was tested using a variety of test wafers. The particle test and contamination testing were completed with bare silicon wafers. All particle measurements were taken using a Tencor 6100 series instrument. Initial particle counts for particle testing were below 50. Then the wafers were processed through the Enviro on the 2 step deveil process. Wafers were then re-measured on the same Tencor and particle adders were calculated. The wafers used for contamination testing were virgin wafers that had not seen any processing. A control wafer was tested from the same lot to ensure no incoming contaminants on the wafers.

Oxide loss was measured on test wafers with 16K Å of plasma enhanced TEOS film. There was no pattern on the oxide test wafers. Resist etch rates were measuring using 1.87µm resist coated wafers. Both of these etch rates were used to monitor the daily tool performance.

Corrosion defects, veil removal, CD loss, metal profiles and Ti/TiN/TEOS undercut were all tested on short flow test wafers and product wafers. The short flow consisted of 16KÅ underlying TEOS, metal photo pattern, and metal etch. Test wafers were created for each of the three metal layers. From previous testing it was known that the second metal layer (M2) was most sensitive to the corrosion wet box testing, therefore all corrosion testing was completed at the M2 layer on both short flow test wafers and product.

### Wet Box

A wet box test is an accelerated corrosion test. The wafers are run through a given process (dry deveil), then wafers are immediately placed in a sealed wafer box for 24 hours. The wafer box consists of a wafer cassette and dampened cloths to provide a humid environment. If chlorine is still present on the wafers the chlorine will react with the moisture and form hydrochloric acid, which attacks the Al. A control wafer from a known good process was also placed in the wet box to ensure validity of the test. Fig 3-1 represents typical corrosion that might occur post deveil processing if all of the chlorine is not completely removed.

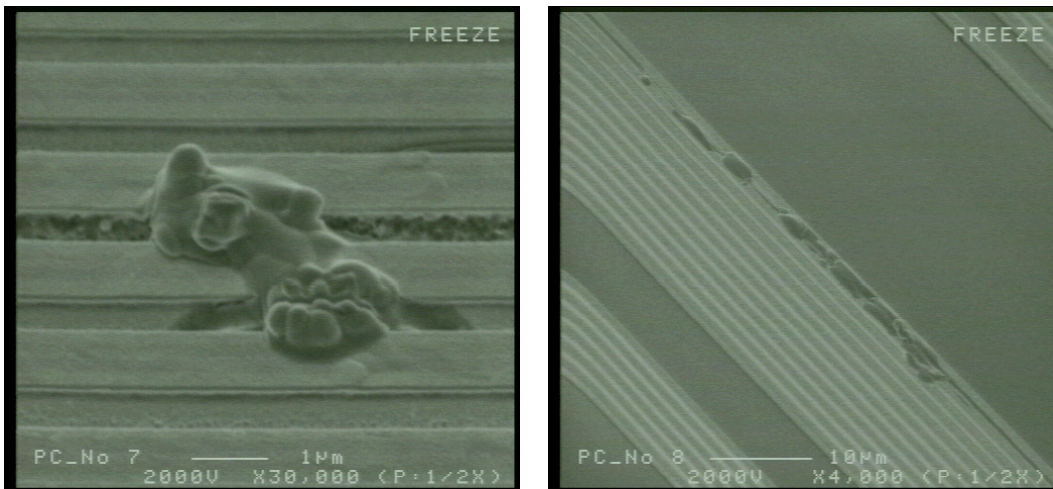


Fig 3-1. Examples of metal corrosion occurring post deveil processing. SEMs were taken after 24 hours wet box test for corrosion.

### Veil Removal

The in-line success criteria requires a 100% removal of the polymer post DI rinse. The polymer inspection is done using an in-line SEM. The wafer is inspected top down at about a 30 degree angle at both the center and edges of the wafers. The veil is generally most visible along the top surfaces of the metal lines. Fig 3-2 shows SEM taken prior to a deveil step, polymer is still present on the metal lines.

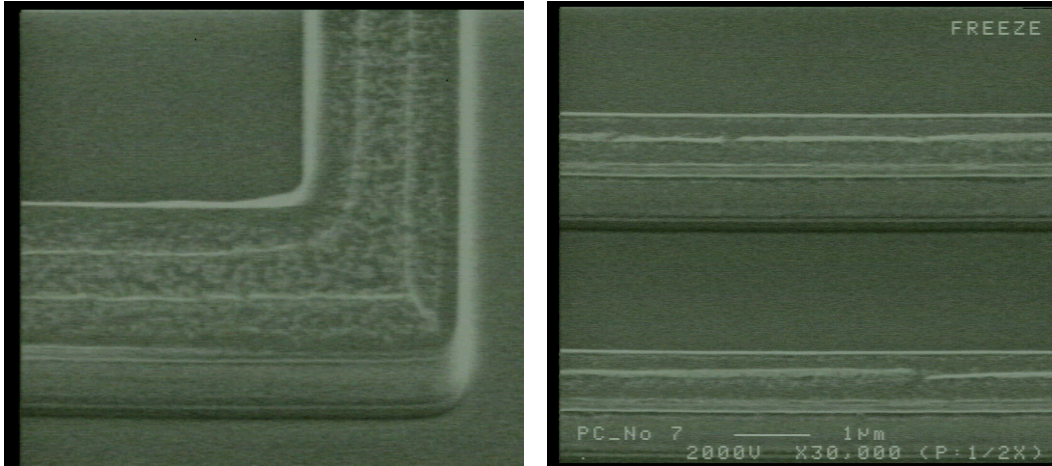


Fig 3-2. Examples of metal lines with polymer residuals post metal etch and O<sub>2</sub> ash prior to deveil processing.

### 3.3 Initial Process Development (Design of Experiment)

The first step towards optimization and development of a process is to determine the important variables using screening experiments. These experiments are designed to examine a large (greater than 5) number of input factors simultaneously in the same experiment. The objective is to screen out the factors that have a no significant influence on the response within the range of experimentation.

An initial review of all previous dry metal deveil experimental work was completed prior to designing the experiment in an attempt to narrow down the potentially important variables. Patterned wafers were also sent to Ulvac Technologies for preliminary process development. These test wafers were sectioned into pieces in order to provide multiple resources; therefore, the effects on full wafers could not be evaluated prior to the initial screening experiment. The initial development information indicated that the process was most effective using a 2 step microwave / RIE process. The first step of the process

was a less aggressive, microwave power based. During this micro step, the majority of the fluorination of the veils and chlorine exchange occurs. The second step is a more aggressive, power based step used to physically bombard the remaining veil from the top surfaces of the metal lines.

Ulvac Technologies was able to provide a best known method (BKM) process using the short flow patterned wafers that were sent to them. Using Ulvac's BKM process, two screening design of experiments were generated. The experiments tested the two step process separately. The first experiment was based around the first micro step while keeping the second RF step constant at the BKM parameters. The objective was to generate an optimal set of parameters for the micro step. Then a second design of experiment was run to determine the optimal set points for the RF step. During these experiments, the parameters for the micro step were set to the optimized set points obtained from the initial experiments

### Experimental Design

The objective of the initial design of experiment is to determine significant factors from the initial seven factors associated with the first step of the dry metal de veil process. The initial seven factors are as follows:

- Time
- Pin Height
- Microwave power
- Temperature
- $\text{NF}_3$
- $\text{N}_2/\text{H}_2(5\%)$
- $\text{O}_2$



The responses for the screening experiments are corrosion, oxide loss and veil removal. Each of these responses have a different level of importance. Corrosion has the most stringent specification therefore, making it the response that is primary concern. Oxide loss and veil removal are of secondary concern, due to wider spec limits.

There are seven factors in the experiment, all of which are continuous. Levels for each factor were set using the best known method (BKM) as the target values. For each factor, 3 set points were run; target bkm value, 15% above target BKM value and 15% below bkm value. This is the recommended procedure when setting up an initial screening experiment. It is important to carefully consider the high and low set points because if the levels are too close the interactions may not occur. Similarly, set points are too far out the experiment may skip over potential interactions.

The experiment assumes 3 factor interactions are negligible. This will be important as we look at the “confounding structure”. Confounding structure means that there are estimates of how each factor influences response are added together into one number and can not be separated out in the analysis.

The initial experimental design proposed for the first micro step of the dry metal de veil process consisted of 35 separate runs. The second RF step experimental design consisted of an additional 16 runs. Once both screening experiments were complete and analyzed, additional experiments would be needed in order to fully optimize the process. Each experimental run absorbs a large quantity of resources; cost of silicon, cycle time of test

wafers, analytical tool time and personnel. In a manufacturing environment, new process development is often considered a lower priority; therefore, it was not possible to run the full experimental design suggested in the above sections. Small portions of the experiments were run. Trends and interactions were determined from these modified experiments. Refer to Appendix A for the original design of experiments that were generated for the initial testing of the first and second processing steps.

### Trend and Interaction Summary

#### *Step 1 (Microwave power step):*

The experimentation suggested that the most significant variables in the micro step were interactions between the microwave power,  $\text{NF}_3$ ,  $\text{N}_2/\text{H}_2(5\%)$  and  $\text{O}_2$ . The amount of veil increased as temperature of the chamber was increased. Time and pin height were non-significant variables. In line SEMs results showed a clear improvement of the veil removal as the microwave power increased. However, corrosion wet box testing indicated high levels of corrosion. An interaction between higher microwave power and increased  $\text{NF}_3$ ,  $\text{N}_2/\text{H}_2(5\%)$  and  $\text{O}_2$  gas flows produced clean and smooth metal line surfaces and extremely low levels of corrosion. The corrosion levels were monitored post wet box testing. However, it was found that if the  $\text{O}_2$  flow was too high more oxidation occurs than fluorination. From these results, a two level full factorial DOE was designed in order to optimize the recipe.

*Step 2 (RF power step):*

Oxide loss was the main response evaluated while conducting the RF step testing. It was determined that  $\text{CF}_4$  had no effect on the oxide loss. Higher RF power set points increased the amount of oxide removed due to the increased amount of ion bombardment. When process time and RF were increased, the amount of residual visible on the top of the metal lines increased. This was probably attributed to the etching of the TiN surface. However, if the RF was too low, veil type material was present. It was determined to use the Ulvac bkm for second step of the process and concentrate on the optimization of the microwave step.

Optimization of Microwave Step

*Step 1  $\text{NF}_3/\text{N}_2/\text{H}_2(5\%)$  Experiment*

The goal of this experiment was to determine the optimal flow rates and interaction between  $\text{NF}_3$  and  $\text{N}_2/\text{H}_2(5\%)$ . A  $2^2$  full factorial design was created, including one center point. For both of the factors three set points were run: target, 15% above target and 15% below target. The pattern column in Table 3.2 indicates the set points for each parameter. For each run, the symbols +, -, and 0 stand for 15% above target value, 15% below target value and the target value, respectively. The experimental runs were generated using the JMP software, statistical design software.

Table 3.2

Ulvac Deveil Experimental runs for Step 1, varying NF<sub>3</sub> and N<sub>2</sub>/H<sub>2</sub>(5%).

Run Order	Pattern	NF <sub>3</sub> sccm	N <sub>2</sub> /H <sub>2</sub> (5%) sccm	Center Point	Veil Removed (Response)	NF <sub>3</sub> -C	N <sub>2</sub> /H <sub>2</sub> (5%) -C	STD Run order
1	-+	160	650	0	4.8	-1	1	3
2	--	160	550	0	4.8	-1	-1	1
3	00	170	600	1	3.75	0	0	5
4	++	180	650	0	4.0	1	1	4
5	+-	180	550	0	3.5	1	-1	2

Veil Removal was the response. The following scale was used to determine the wafer cleanliness (Veil removed response):

- 1 – No veil removed
- 2 – Most veil remaining on wafer
- 3 – Moderate veil removed
- 4 – Trace amounts of veil present
- 5 – No veil present

It was determined from the experimental results that NF<sub>3</sub> has the largest effect on the veil removal. Parameter estimate tables and prediction profiles were generated through the use of JMP statistical discovery software. Refer to Appendix B for both parameter estimate tables and prediction profiles. The results for the experiment indicate that lower NF<sub>3</sub> flow produces cleaner wafers. It was also determined that when NF<sub>3</sub> flows at a lower set point, i.e. 160sccm, N<sub>2</sub>/H<sub>2</sub>(5%) does not have an effect on veil removal. From these results it was determined to set the NF<sub>3</sub> flow to 160sccm and N<sub>2</sub>/H<sub>2</sub>(5%) flow to 600sccm. Fig 3-3 are SEMs of both the Enviro process and standard deveil process.

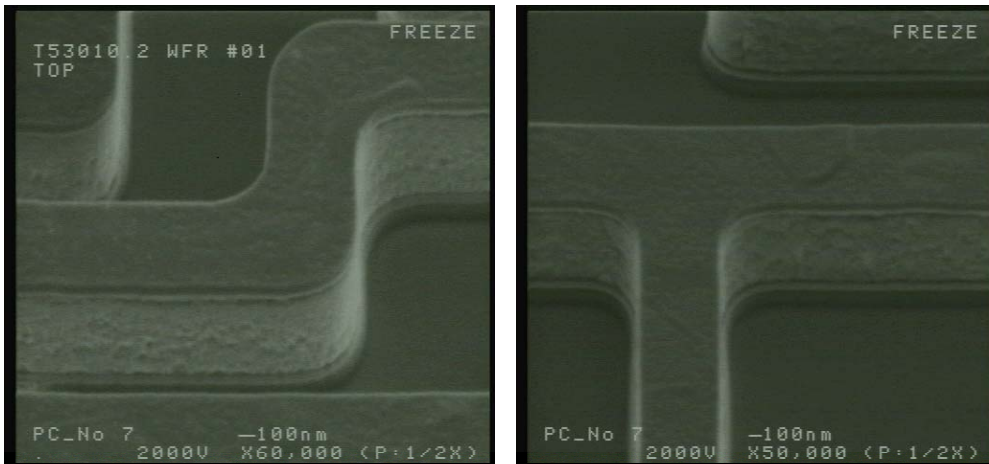


Fig. 3-3. Both figures are top down SEM pictures. The left SEM was taken post Enviro deveil processing. The right SEM was taken post the standard deveil processing.

### 3.4 In-Line Success Criteria Results

All in-line data was collected using the optimized process.

#### Corrosion

Corrosion (24 hour wet box) testing was completed on the optimized process. Two product wafers from both the standard wet deveil process and experimental dry deveil process were placed into the same wet box cassette to ensure there was no variability with the wet box procedure. The wafers were tested for corrosion after the metal 2 layer; previous data has indicated that the metal 2 layer is most sensitive to corrosion.

Table 3.3 Metal 2 Corrosion Wet Box Testing Results

Wet Box Test		
Wafer ID	Process	Corrosion Results
1	STD	28 Corr_BP
7	STD	38 Corr_BP
9	ULVAC	0
12	ULVAC	0

The Enviro results showed no by-product corrosion. Both wafers from the standard group showed by-product corrosion.

Critical Dimension (CD) Loss

Metal line width post etch and cleans processes is critical in order to maintain device speed requirements. To monitor the metal line width after etch and cleans, a SEM is used for measurement. Two product wafers from both the standard wet deveil process and experimental Enviro dry deveil process were measured on an in-line SEM for critical dimension (CDs) or metal line width post metal etch. All four wafers were measured after each metal etch and cleans processing. Table 3.4 gives the critical dimension at each metal layer. M1, M2, and M3 represent the first, second, and third metal layers, respectively. The success criteria was for the CD average of each metal layer to be within +/- 10nm. There were 9 sites measured on each wafer, the below table is an average of the 9 sites.

Table 3.4 Critical Dimension Measurements for Metal 1,2 and 3

<b>Wafer ID</b>	<b>Process</b>	<b>M1 CD μm</b>	<b>M2 CD μm</b>	<b>M3 CD μm</b>
03	STD	0.615	0.717	0.708
20	STD	0.609	0.717	0.717
17	ENVIRO	0.613	0.717	0.719
14	ENVIRO	0.611	0.712	0.712

Oxide (TEOS) Loss

Oxide loss was measured on blanket flat film for 30 consecutive days after processing on the Enviro. During this time frame no intrusive chamber maintenance was performed on the tool. The upper control limit for the in-line success criteria was oxide loss < 250Å.

The data below shows all oxide loss measurements were below the upper control limit. A

test wafer with 16K Å of TEOS was pre measured on a Tencor UV1050. Then the oxide test wafer was run through the Enviro on the optimized deveil process. The test wafer was then post measured on the same UV1050. The oxide loss was calculated from the pre and post measurements.

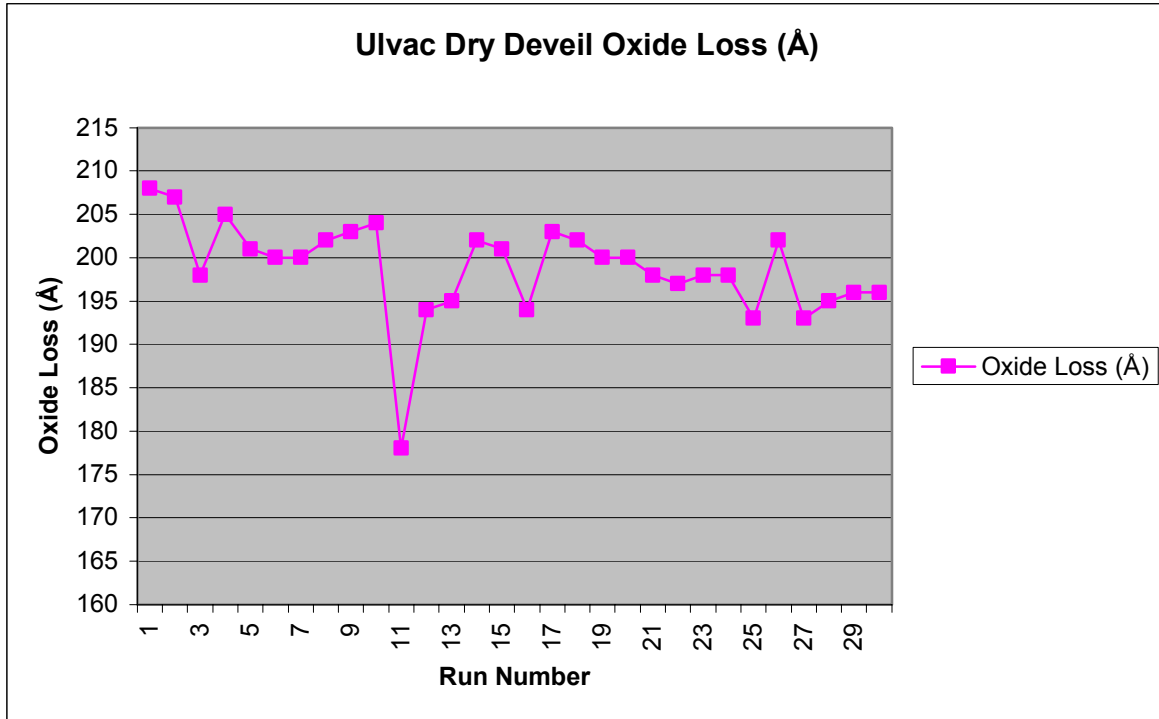


Fig. 3-4. The amount of oxide loss during a 30 day period on the Enviro system.

Profile (TiN Arc loss and Ti, TiN, TEOS undercut)

The Ulvac profiles match the standard wet deveil process. No significant undercut is seen on either of the profiles. Fig 3-5 are cross sections that were taken from two production wafers at the end of line. The SEM was taken of the metal 2 line.

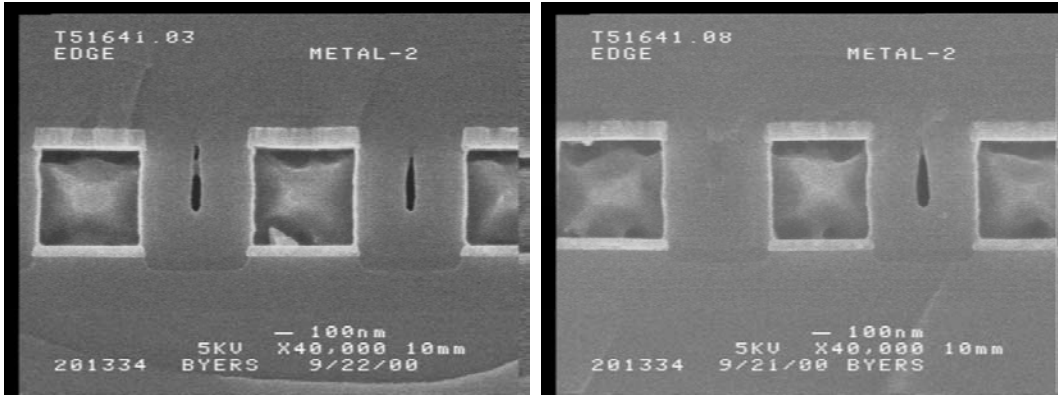


Fig 3-5 The right figure received the Ulvac deveil processing and the figure on the left received the standard wet deveil processing. SEMs were taken of the second metal stack layer.

### Particles

Particles were tested on the tool over a 3 month period. The upper control limit for the particles is 50 adders for particle sizes 0.18 $\mu$ m or greater. Both the pre and post particle readings were taken on a Tencor 6100 tool. Figure 3-6 illustrates the particle qualification data results.

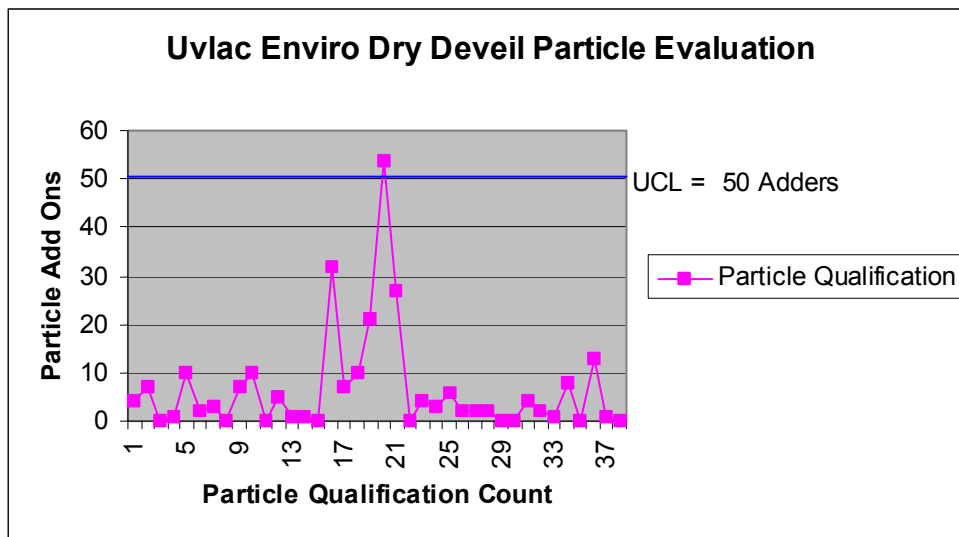


Fig. 3-6. Enviro dry deveil particle evaluation over a 3 month time period.



Particle counts started to increase after 6 weeks of testing. The process chamber was opened and inspected. We found that the quartzware in the process chamber was beginning to shed particles on the wafers during processing. The quartzware was replaced and the chamber was wet cleaned. A chamber wet clean involves wiping out the chamber with DI dampened cloths to remove any residual particles in the chamber. Once the maintenance was completed, the chamber was qualified for particles. The particle counts returned to normal levels. In order to prevent a future particle excursion, we began wet cleaning the process chamber every 15,000 wafer counts. During each wet clean the quartzware was inspected and replaced if it showed signs of degradation.

### Contamination

Three wafers were submitted for contamination testing (TXRF and SIMS). The test wafers initially had 1000Å of TEOS on the surface, then were etched back to approximately 800Å after the Ulvac de veil process. The control wafer was submitted with the initial 1000Å of TEOS and no additional processing.

First the samples were analyzed using Total Reflection X-Ray Fluorescence (TXRF). The instrument used was the TREX 610T, using the tungsten rotating anode X-ray source. Five sites were analyzed for each wafer. The x,y coordinates for sites analyzed are (0.01,0.01) and (-57,57). These coordinates are given for the wafer oriented notch down.

The results indicate no difference between the controlled wafer and the processed wafers.

Table 3.5  
TXRF Results

Wafer #	pos	S	Cl	K	Ca	Ti	Cr	Mn	Fe	Ni	Cu	Zn
T35916 #14	cntr	1000	--	--	--	--	--	--	--	--	--	--
EF01DVLA	edge	900	--	--	--	--	--	--	--	--	--	--
T35916 #15	cntr	760	--	--	--	--	--	--	--	--	--	--
EF01DVLB	edge	680	--	--	--	--	--	--	--	--	--	--
T35916 #13	cntr	630	--	--	--	--	--	--	--	--	--	--
Control, no process	edge	710	--	--	--	--	--	--	--	--	--	--
Detection limits		19	13	6	6	3	2	1	1	1	1	2

Units are in  $e10 \text{ atoms/cm}^2$  (Area densities)

The 3 samples were then analyzed for alkali metals using the Camera IMS-5f. An oxygen primary beam accelerated to 12.5kV (8keV net impact energy) was used to sputter the sample. To optimize sensitivity, positive secondary ions were detected. The site analyzed was from the center of the wafers. The SIMs results were all within the process control limits

Table 3.6  
SIMS results

Wafer	Description	Li	Na	K
T35916 #14	Processed in EF01DVLA	1e9	2e10	4e9
T35916 #15	Processed in EF01DVLB	9e8	1e10	2e9
T35916 #13	Control, no process	<5e7	6e9	<5e7

Units are in  $\text{atoms/cm}^2$  (Area densities)

#### 4.0 CONCLUSION

As advances are made in the world of semiconductor devices it is imperative that the industry keeps up with the aggressive pace of new design rules and features. Veil

removal was once considered a non-critical process step, but with the advances in photo resist and etch processing, veil removal following metal etch has become a challenge to the semiconductor industry. There is a trend toward moving away from the traditional aggressive amine based wet chemical processing to a residual solubilization system which does not require wet chemical processing. This paper explored one of the many possible solutions for this de veil process conversion.

The Ulvac Enviro system provides a unique system which combines the chemistry of a very low-bias reactive ion etch, a remote microwave plasma and fluorine gases resulting in enhancing the solubility of residues in solvents, acids or DI water. A two step microwave/RF process was developed on the Enviro rendering the residual soluble in DI water. This process was subjected to a series of in-line success criteria and compared with the standard chemical de veil process. Out of all of the input parameters involved in the Enviro process the gases ( $\text{NF}_3$ ,  $\text{N}_2/\text{H}_2(5\%)$  and  $\text{O}_2$ ), microwave power and RF power had the greatest impact on the output parameters. By optimizing these conditions a balance between fluorination, oxidation and physical ion bombardment was developed. For example, as mentioned previously, if the  $\text{O}_2$  flow was too high more oxidation occurred rather than fluorination. It was also found that if the RF power was set too high the physical ion bombardment would begin to etch away the TiN surface on the tops of the metal lines.

Flat film test wafers, short flow test wafers and product wafers were used to compare in-line test results to the existing wet chemical de veil process. Corrosion was considered

most critical success criteria. Wet box corrosion testing showed an improvement from the standard processing. Veil removal, metal line critical dimensions, oxide loss and metal line profile matched the standard deveil process. Overall, the experimental work done with this new Enviro process proved to either match or exceed the existing chemical deveil processing. Along with processing improvements, the Enviro provided more than a 50% increase in wafer throughput, decreasing the processing cost. However, the majority of the cost reduction was due to the elimination of wet chemistries and disposal of the chemical. As a result, it was determined that the Ulvac Enviro can provide an excellent alternative to the conventional chemical deveil processing.

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## 5.0 APPENDICES

### Appendix A

The initial screening design of experiment for the micro step was designed with the following seven factors: time, pin height, microwave power, temperature, and gas flows. For each of the factors three set points were run; target, 15% above target value and 15% below target value. The pattern column in Table A.1 indicates the set points for each parameter. For each run, the symbols +, -, and 0 stand for 15% above target value, 15% below target value and the target value, respectively. The experimental runs for the design of experiment were generated using the JMP software, a statistical design software. The table below lists the experimental runs generated by JMP for the screening experiment. This experiment consists of 35 runs, which includes 3 center points.

Table A.1  
Screening design of experiment for step one

Run Order	Pattern	NF3 Sccm	N2/H2(5 %) sccm	O2 sccm	Pin Height	Time sec	Temp C	MW Power	Center Pnt
1	+-+-+-	170	425	10350	1	35	40	1725	0
2	+++++	170	575	7650	1	25	40	1725	0
3	+-----	170	425	10350	3	35	60	1275	0
4	+++++	170	425	10350	3	25	40	1725	0
5	+-----	170	425	7650	3	35	40	1275	0
6	++++-	170	575	10350	3	25	40	1275	0
7	-----	130	425	7650	1	25	40	1725	0
8	000000	150	500	9000	2	30	50	1500	1
9	-+-+-+-	130	575	10350	1	35	40	1725	0
10	--+--	130	425	10350	1	35	40	1275	0
11	+---+	170	425	7650	3	25	60	1725	0
12	---+-	130	425	7650	3	25	60	1275	0
13	+++--	170	575	10350	1	35	40	1275	0
14	-++--	130	575	10350	1	25	60	1275	0
15	-++++	130	575	10350	3	25	40	1725	0
16	+++--	170	575	7650	3	35	40	1725	0
17	000000	150	500	9000	2	30	50	1500	0
18	+---+	170	425	7650	1	35	60	1725	0
19	-++++	130	575	10350	3	35	60	1275	0
20	+--+-	170	425	10350	1	25	60	1275	0
21	-+---	130	575	7650	1	35	60	1725	0
22	-+---	130	575	7650	1	25	40	1275	0
23	-+-++	130	575	7650	3	25	60	1725	0
24	++-+-	170	575	7650	3	25	60	1275	0
25	-----	130	425	10350	3	35	60	1725	0
26	---++	130	425	7650	3	35	40	1725	0
27	--+++	130	425	10350	1	25	60	1725	0
28	+++--	170	575	10350	1	25	60	1725	0
29	--+++	130	425	10350	3	25	40	1275	0
30	000000	150	500	9000	2	30	50	1500	1
31	----+	130	425	7650	1	35	60	1275	0
32	+++++	170	575	10350	3	35	60	1725	0
33	-+---	130	575	7650	3	35	40	1275	0
34	+-----	170	425	7650	1	25	40	1275	0
35	+++--	170	575	7650	1	35	60	1275	0

The initial design of experiment for the second step of the process was set up varying the following factors: time RF power, CF4 and N<sub>2</sub>/H<sub>2</sub>(5%). An experiment with sixteen runs including 2 center points was generated from JMP software, refer to Table A.2.



Table A.2  
Design of experiment for step two

Run Order	Pattern	CF4 Secm	RF Power watts	Time sec	N2/H2(5%) secm	Center Pnt
1	--+-	30	290	35	395	0
2	-+--	30	290	25	535	0
3	0000	35	250	30	465	1
4	+++	40	290	25	535	0
5	-+--	30	290	25	395	0
6	+++	40	290	25	395	0
7	---+	30	210	25	535	0
8	--++	30	210	35	535	0
9	+--	40	210	35	395	0
10	+++	40	210	25	535	0
11	+--+	40	210	35	535	0
12	----	30	210	25	395	0
13	--+-	30	210	35	395	0
14	+++	40	290	35	395	0
15	0000	35	250	30	465	1
16	-+++	30	290	35	535	0
17	+---	40	2210	25	395	0
18	++++	40	290	35	535	0

As noted earlier, due to the manufacturing environment in which this experimental work was being conducted in, it was not possible to run both of the experimental designs. However, if the above experimental runs were run, the following steps would have been taken to analyze the result.

Analyze the Results

The following is a 9 step process that can be used to analyze and interpret any fractional factorial screening experiment using the JMP software.

- 1) View the data: Look for any unusual events that may have happened in the collection or the data entry. Make a few simple graphs to get the big picture. For example, use an outlier box plot or a normal quantile plot to look for outliers in the data set. A time order plot should be used to focus on the time sequence of the center point responses. The center points are the only true replicates in the experiment, and a time order plot of the center points should exhibit stability over time.

- 2) Create the Model: At this point JMP software is used to fit model. Once the responses have been generated and inputted into the original model, fit model can be generated by using all of the main effects and two-factor interactions.
- 3) Fit the Model: Examine the tables and graphs, including summary of fit, analysis of variance, lack of fit and parameter estimates.
- 4) Perform Residual Diagnostics: Create plots of residuals to test assumptions including: independence of residuals, stability of residuals, equal variance of residuals and normality of residuals.
- 5) Check for possible transformations: Use the Box-Cox approach. If a transformation is needed it is necessary to go back to the create model step and continue the analysis with the transformed response.
- 6) Remove non-significant terms/refit the model: Use the parameter estimates table generated in step 3 to remove non-significant terms. Once removed it is important to recreate the model excluding the non-significant terms.
- 7) Chose the improved model: Once the best model has been chosen, the prediction equation for that model must be saved
- 8) Interpret chosen model: Use the prediction profile and desirability function to choose an optimal level of input factors. Validate the model results with engineering and scientific knowledge of the process. Then draw conclusions and make recommendations.
- 9) Continue Experimentation / Make Confirmation Runs: If experiment is to be stopped, then run confirmation tests at current optimal settings for the input factors. However, if the optimal region has not been reached, then continue experimentation using a response surface model.

## Appendix B

Parameter estimate tables and prediction profiles were generated through the use of JMP statistical discover software from the results of the  $2^2$  full factorial design that was created for the optimization of the  $\text{NF}_3$  and  $\text{N}_2/\text{H}_2(5\%)$  gas flows for step one of the process.

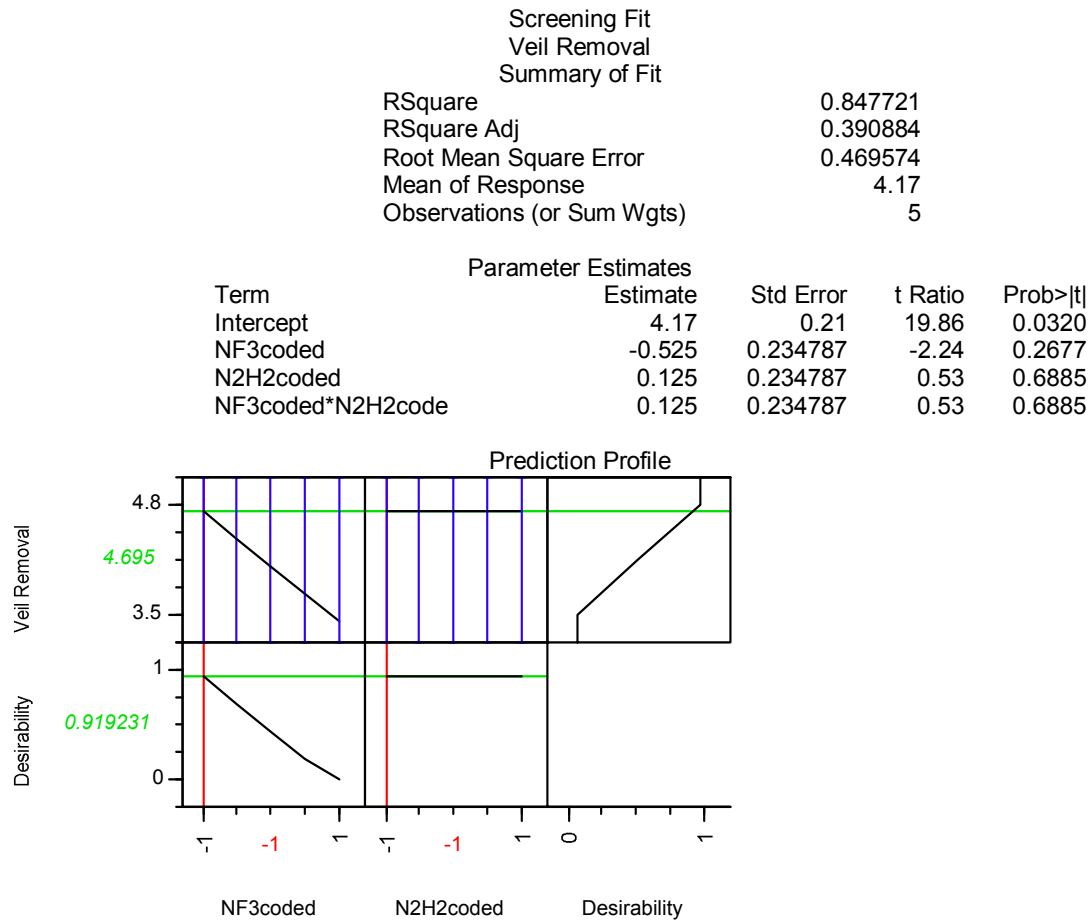


Fig. B-1 The above Parameter of Estimates and Prediction Profile was generated with the data created from the  $\text{NF}_3$  and  $\text{N}_2/\text{H}_2(5\%)$  design of experiment using JMP statistical software.

It was determined from the DOE results that  $\text{NF}_3$  has the largest effect on the veil removal. The parameter estimates table indicates that all variables are not statistically

different. However, the prediction profile illustrates that the lower the  $\text{NF}_3$  flow produces cleaner wafers. The profile also shows that when  $\text{NF}_3$  is at the low end,  $\text{N}_2/\text{H}_2(5\%)$  flow does not have an effect. This is illustrated in the prediction profile below.

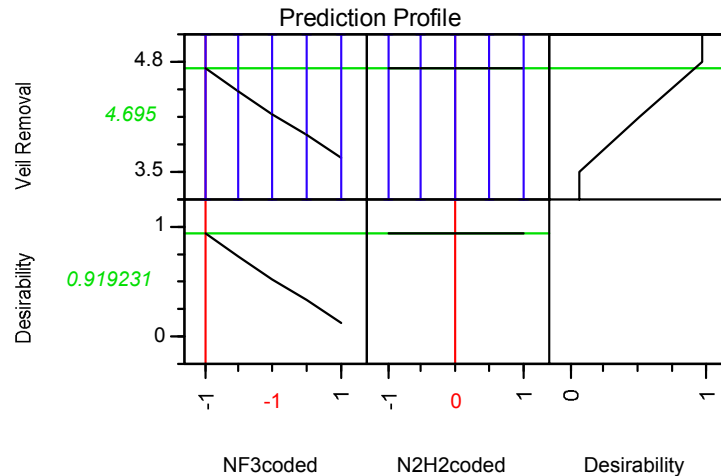


Fig. B-2. The above Prediction Profile was generated with the data created from the  $\text{NF}_3$  and  $\text{N}_2/\text{H}_2(5\%)$  design of experiment using JMP statistical software. The desirability index for each of the factors was set to give the most optimal response.

The  $\text{NF}_3$  flow was kept at “-1” set point and  $\text{N}_2/\text{H}_2$  was moved to the center point. The desirability number still remains 0.92. It was decided to use  $\text{NF}_3 = 160\text{sccm}$  and  $\text{N}_2/\text{H}_2(5\%) = 600\text{sccm}$  flow set point for the remaining in-line testing. We choose the center point for  $\text{N}_2/\text{H}_2$  since it did not have an effect on veil removal when  $\text{NF}_3$  was set to 160sccm.