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Reducing Capital and Labor Costs Using AMC Monitoring

Reduce capital and labor costs for 193 nm lithography monitoring of airborne molecular contamination (AMC) through proactive assessment and implementation of AMC monitoring techniques and strategies.

Because the lithography area is often at the cutting edge of semiconductor manufacturing processes, it is often the area that is most impacted by Airborne Molecular Contamination, or AMC. The transition to higher exposure energies (248 nm to 193 nm), use of chemical filtration and purge gases, and the increasing implementation of FOUP's, reticle pods, and reticle and wafer stockers have necessitated that the lithography area remains at the forefront of AMC monitoring strategies. Consequences can be dramatic if care is not paid to AMC levels. The energy content of this (193 nm) light can easily split molecules into reactive fragments, which can trigger chemical reactions and adhere to optical surfaces that can cost as much as $5 Million, as well as $10,000 per hour in downtime in cleaning or replacement.[1] However, relative to other contamination monitoring and control processes, such as defect inspection, AMC monitoring has lagged far behind leading to increased costs and lower efficiencies.

The semiconductor industry has done an exceptional job in recent years in refining their approach to wafer-based defect inspection. While there may appear to be many different choices in defect inspection equipment throughout the cleanroom, each piece of equipment has been carefully thought out and placed in the process flow for a specific reason. For example, un-patterned wafers which are coated with silicon dioxide or silicon nitride are cycled through process equipment on a regular basis, sent to the un-patterned defect inspection tool, and analyzed for non-process defect contribution. In addition, production wafers (patterned) are often inspected at regular intervals in the process to identify particulate contamination contributed from a single process or series of process. These wafers are run through patterned defect inspection systems that are either laser, optical, or scanning electron microscopy based. The choice of the inspection technique is not made hastily, but is thoughtfully considered based on, among other things, the strengths and weaknesses of the technique, the sensitivity requirements, the amount of time the wafers will require to allow a sufficient inspection, and the importance of the given process step. It is a balancing act to get the right combination of tools together which allows a sufficient frequency of inspection and detection of particulate contamination issues without significantly impacting the process flow. In essence, the defect inspection programs emphasize inspecting more often during the critical process steps, while de-emphasizing the inspection of wafers at less critical processing steps. In this way, semiconductor manufacturers constantly work to balance defect inspection cost with process efficiency and optimization.

It is interesting then, that monitoring for molecular contamination in cleanrooms often does not go through the same rigors of such a thoughtful process. In many cases AMC monitoring is performed based only on historical precedent, "this is how we have done it in the past", as opposed to determining the short and long-term needs of the particular situation. Perhaps this is because in many cases no one group officially "owns" the AMC monitoring process, resulting in too many groups "owning" AMC monitoring. Often in this case, AMC monitoring is such a small part of an individual's job responsibilities that only minimal effort is made to satisfy the most basic of needs. It may also be because only one group "owns" the AMC monitoring process, and applies a "one-size fits all" strategy. In this case, little information is shared, techniques are not customized to the problem at-hand, and the results are not likely to aid in accomplishing the objective. Regardless of the reason why this has occurred in the past, best-in-class semiconductor manufacturers have begun to look at their AMC monitoring strategies in a more thoughtful manner and some surprising new strategies are beginning to take shape.

Background

Besides organic AMC detection the most common compounds of interest in the lithography area are bases such as ammonia or amines and acids such as HCl, HF, Cl_2, and SO_2. Ammonia and amines negatively impact the chemically sensitive photoresist, and the combination of acids and bases in the exposure chamber will form haze contamination on optics and reticles when in the presence of high energy radiation.[2] For acid and base AMC, two monitoring techniques predominate: Impinger with Ion Chromatography analysis (Impinger-IC), and Ion Mobility Spectrometry (IMS).

Impingers with Ion Chromatography

The technique known as Impinger with Ion Chromatography (Impinger-IC) is a manual sample collection method whereby an operator draws an air sample through a liquid filled vial for a certain period of time and subsequently sends the sample to a laboratory for analysis of the liquid solution. Most semiconductor manufacturers send the samples to an external laboratory for IC analysis, but some large semiconductor manufacturers have the capability to perform IC analysis at their site. It is assumed that all water soluble acid and base molecules will be captured in the solution with a theoretical 100% efficiency and reported via IC analysis.

Ion Mobility Spectrometry

Ion Mobility Spectrometry is an automated sample collection and detection technique housed within a small analyzer enclosure. IMS draws an air sample into a detection cell, and ionizes polar molecules within the air sample. A drift tube is periodically pulsed open and closed, allowing the ions to drift under the influence of an electric field towards a detector. Each ion will impact the detector at a specific time based on its mass and size. Therefore, a unique spectrum can be obtained for acid and base compounds. This is a gas-phase sample technique, meaning the air sample is always in the gas phase and never impacts a liquid solution. It is also a real-time measurement achieved through the sampling and detection of eight unique air samples every second.

As Table 1 notes below, there are some major differences between these two techniques. Given that these techniques identify the same compounds in slightly different ways, there is a potentially significant incentive to explore how each technique can best be utilized as part of a comprehensive monitoring program, and determine if there is a financial incentive to utilize each or both of these techniques in complementary ways.

Another major consideration besides those listed in the Table 1, is the cost to purchase the equipment and implement the sample collection and analysis. IMS is hardware that is purchased one time, and implemented to detect a single class of compounds at a single point-of-use location. Initial up-front costs are higher but there are no consumable or laboratory analysis costs after the fact. Impinger-IC analysis requires less up-front cost, but ongoing expenses are high for the consumables, labor, and lab analysis in order to obtain the results. Table 2 documents the approximate costs for each technique.

Table 1: Strengths and weaknesses of common acid/base AMC monitoring techniques

	Sample Duration	**Sensitivity (ppt_v)**	**Time to Results**	**Speciation**	**Labor Intensity**
IMS	5 minutes	70	Immediate	Medium	Low
Impinger-IC	4 – 24 hours	10	2 – 7 days	Medium/High	High

Definitions for the table:

- Sample Duration: Length of time sample is collected for analysis
- Sensitivity: Specification of minimum detection limit (part-per-trillion)
- Time to results : Length of time between sample collection and sample analysis
- Speciation: Level to which technique will tell you what compound is present

Medium = Class or group of compound (acid or amines)
Medium/High = Ion species such as Cl^-, F^-, SO_4^{2-}

Table 2: Cost of common acid/base monitoring techniques

	Compound Detected		
	Acids Only	**Bases Only**	**Acids & Bases**
Equipment Cost: IMS	$10,000	$10,000	$20,000
Labor Cost: IMS	Minimal	Minimal	Minimal
Total Cost: IMS	$10,000	$10,000	$20,000
Equipment/Analysis Cost: Impinger-IC (External Lab)	$240/sample	$240/sample	$480/sample
Labor Cost: Impinger-IC	$80/sample	$80/sample	$80/sample
Total Cost: Impinger-IC (External Lab)	$320/sample	$320/sample	$560/sample

NOTE: Both IMS and Impinger-IC will have some labor cost associated with the review and analysis of the data. This cost will be nearly equal regardless of the technique. The labor cost associated with Impinger-IC referenced in Table 2 is the use of an individual to obtain the solution, set up the sample collection apparatus at the beginning of the test, dismantle the sample collection apparatus at end of the test, and ship the sample to an external lab for analysis.

In some cases, semiconductor manufacturers have their own in-house analytical labs, which can bring down the ongoing IC analysis cost significantly (Table 3), however the startup costs of an IC lab are extraordinarily high given the price to outfit the lab with equipment, maintain the lab with the gases and chemicals, and to hire the appropriate staff (PhD level) to run the lab and equipment. The actual cost of ongoing in-house analysis varies due to the above considerations as well as cumulative analysis needs of the company, such as the ongoing analysis of ultra-pure water, high purity chemicals, and other resource draining tasks. Because this cost is proprietary, an 80% cost savings is assumed for the in-house analysis relative to the analysis cost when using an external lab.

Table 3: Cost of Impinger-IC technique to those who benefit from an in-house analysis laboratory

	Compound Detected		
	Acids Only	**Bases Only**	**Acids & Bases**
Equipment/Analysis Cost: Impinger-IC (Internal Lab)	$48/sample	$48/sample	$96/sample
Labor Cost: Impinger-IC	$80/sample	$80/sample	$80/sample
Total Cost: Impinger-IC (Internal Lab)	$128/sample	$128/sample	$176/sample

Representative AMC Monitoring Scenario in Lithography

In order to present a representative monitoring strategy/case some assumptions are made to allow us to achieve a financial perspective. It is assumed that a single 193 nm lithography process bay containing four 193 nm Scanner and Track modules needs to have a strategic AMC monitoring program implemented. It is desired to have some level of monitoring at the points noted below:

- Each individual exposure chamber needs to be monitored for both acids and bases.
  This is typical in order to proactively monitor for compounds that contribute to optical and reticle hazing, while also providing an indication when chemical filters need to be replaced as this monitoring location is downstream of the filters.
- Each individual track needs to be monitored only for bases.
  This is typical to identify base contamination levels which may interfere with chemically sensitive photoresist.
- The process bay needs to be monitored in two locations for both acids and bases.
  This is typical to determine the contribution of AMC from the make-up and re-circulated air handling systems that feed the air into the lithography bay. It is also representative of the air being fed into the upstream side of any chemical filters (allowing for AMC removal efficiency to be understood in conjunction with the downstream data). Because air is generally well mixed and molecules at room temperature are diffuse, a smaller number of monitoring locations are needed in the process bay to understand overall contamination levels.

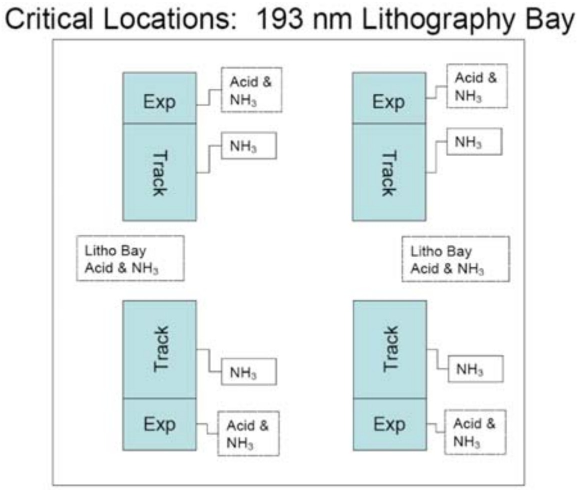

Figure 1. Reference Case: AMC monitoring locations within a 193 nm Lithography Bay.

As shown in Figure 1, there are 10 individual sample points of interest. Of these 10 points 6 are within the track and the process bay, and require data on two AMC compounds (acids and bases). Therefore, a total of 10 Impinger samples need to be collected, assuming that the DI water is the Impinger collection fluid and that the same DI water sample can be used for both the acids and base analysis where needed. This is an assumption that provides for a slightly lower cost monitoring scenario and sacrifices some Impinger-IC performance as the DI water sample volume increases which thereby decreases the lower detection limit. To monitor the 10 individual sample points 16 IMS analyzer are required (10 to monitor for amines, and 6 to monitor for acids).

Given that this represents a typical strategy for capturing AMC data at specific locations the next strategic step is to evaluate how often AMC data is needed in order to provide sufficient decision-making information. Sample collection frequency is generally defined as the number of times a sample is taken for AMC analysis in a day. strategies for AMC sample collection frequency have historically varied widely across manufacturers. To simplify, we can imagine 4 potential monitoring scenarios: continuous, daily, weekly, and quarterly. Within the cost table below, the lowest cost solution is highlighted in green for each scenario.

- Continuous monitoring is monitoring non-stop at a particular sample point. Measurements occur at 5 minute intervals or less and this monitoring process is repeated non-stop.
- Daily monitoring samples 1 time per day at a particular sample point (365 samples collected and analyzed at one particular sample point in a given year).
- Weekly monitoring samples 1 time per week at a particular sample point (52 samples collected and analyzed at one particular sample point in a given year).
- Quarterly monitoring samples 1 time per quarter at a particular sample point (4 samples collected and analyzed at one particular sample point in a given year).

Analysis

Each technique has financial implications for the execution of a given scenario, as documented in Table 4. However, a broader view must be taken to understand the quality and usefulness of data that comes through the use of a given technique for a given scenario. The analysis below considers two of the above scenarios: continuous and weekly monitoring. Questions posed at the end of each section below are to provoke thought in the consideration of these techniques and scenarios in relation to how an optimal and efficient AMC monitoring program might be implemented.

Cost of Technique

If continuous data is desired at these critical lithography points the IMS technique is clearly the lowest overall cost solution. Over a long-term period (5 years), the cost to implement an IMS monitoring program is 40 times less than an Impinger program with an in-house lab analysis and 130 times less than an Impinger program which requires analysis by an outside laboratory (nearly $34 Million!!!). IMS is also the lowest cost solution when viewed from a short-term (1-year) and medium term (3-year) daily monitoring program strategy. When considering a weekly monitoring strategy IMS continues to be the low-cost leader in the long-term (5-year) or cost-equivalent in the medium term (3-year). When considering short term monitoring (1-year), the Impinger-IC using an in-house analysis lab is the low-cost leader with IMS and IC-Impinger (external lab) having equivalent costs.

Table 4: Cumulative cost over time for common acid/base AMC monitoring techniques

	Cumulative Cost for Analysis Technique ($,000)			
	Continuous	**Daily**	**Weekly**	**Quarterly**
1-Year IMS	$160	$160	$160	$160
1-Year Impinger-IC (External Lab)	$6,780	$1,690	$241	$18
1-Year Impinger-IC (Internal Lab)	$2,290	$572	$82	$6
3-Year IMS	$160	$160	$160	$160
3-Year Impinger-IC (External Lab)	$20,340	$5,070	$723	$54
3-Year Impinger-IC (Internal Lab)	$6,870	$1,716	$246	$18
5-Year IMS	$160	$160	$160	$160
5-Year Impinger-IC (External Lab)	$33,900	$8,450	$1,200	$90
5-Year Impinge- IC (Internal Lab)	$11,450	$2,860	$410	$30

NOTE: For the continuous scenario, we assume that an Impinger-IC sample is taken every 6 hours.

The total 3 and 5 year cost for IMS is the same cost as the first year in all cases because the equipment has already been purchased. The Ion Mobility Spectrometer monitors continuously over the 3 or 5 years with no additional hardware investment required. In addition, the cost for continuous IMS monitoring is the same as the cost for daily, weekly, and quarterly scenarios. The IMS has the capability to monitor continuously regardless of how often the data actually needs to be viewed or used. On the other hand, because the Impinger-IC technique is a consumable-intensive technique using laboratory analyses, the costs incurred in the first year will also be incurred in each subsequent year.

- What monitoring cost is reasonable within a photolithography area?
- Is photolithography critical to process yield or quality?
- Are there significant cost implications if AMC impacts these areas (optical hazing, resist poisoning)?
- Does the overall benefit of the AMC monitoring technique and data received exceed the cost?
- Can the expense and labor resources saved by utilizing one technique be more efficiently put into use in another area?

Quantity of Data Available for Analysis & Decision Making

For a weekly monitoring program the Impinger-IC technique provides 52 data points at each sample location over the course of a year. For a continuous monitoring program, assuming Impingers are taken at each location every 6 hours, the Impinger-IC technique provides slightly more than 1,000 data points at each sample point for the year. In all scenarios the IMS technique provides over 525,000 data points at each sample point per year (using a 5 minute sample interval). The IMS analyzer is typically used to monitor in 5 minute intervals, however the equipment has the capability to be programmed at much lower intervals (5 seconds) to much higher intervals (1 day) so more or less data can be collected as needed. Regardless of the interval chosen there is no additional cost to obtain the additional data from using a lower sample interval.

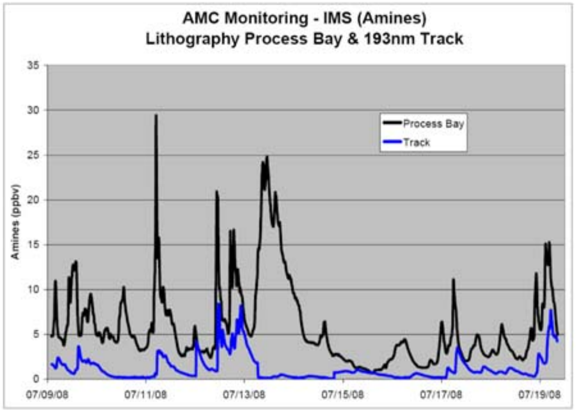

Figure 2. IMS results from Amine monitoring of a 193 nm Lithography process bay and chemically filtered track.

Figure 2 is an example of 10 days of monitoring for Amines contamination in a couple of locations similar to our scenario. One sample point is monitoring for Amines in the general 193 nm Lithography process bay and another sample point is monitoring for Amines within the track attached to a 193 nm Lithography tool. Chemical filtration is being utilized at the top of the track to scrub the air entering the track. By using IMS both baseline data is captured to compare to historical techniques and contamination event data is captured which allows for immediate alarm reporting. Considering another alternative, such as Impinger-IC using a weekly sample scenario, there are two possible outcomes:

- The Impinger was taken during normal conditions (low concentration), leading to the assumption that because one data point was in-control the concentration during the entire week was also in control.
- The Impinger was taken during the tallest spikes in contamination (either upstream or downstream). The probability of capturing high concentration data consistently in this manner is a risky monitoring strategy which relies on luck in choosing the appropriate time of day and day of week to sample. In addition, because the Impinger samples for long periods of time, even spikes in contamination will be time-averaged out of the final analysis. Therefore, the results will not distinguish between a spike in contamination and a slightly higher concentration reading that is stable over the sample interval time.

Because Ion Chromatography is a lab analysis technique, the turnaround of results is also not a rapid process. External labs will charge an additional "expedite" fee if results are needed within 48 hours (not factored into the financial considerations and analysis above). Otherwise, 5 - 10 business-day turn around for IC results is common.

- How often is data needed for these locations?
- How long will it take to obtain results from the sample collection?
- Is the amount of data provided statistically significant?
- Will enough data be available to make clear decisions?

Speciation of Compounds

The Impinger-IC technique does provide more finely separated analysis of the compounds when directly compared to IMS. Ion species such as Cl^-, SO_4^{2-}, F^-, etc. represent a typical ion output from an Ion Chromatograph. However, exact speciation is lost (did the Cl^- come from Cl_2, HCl, CH_3Cl….did the HF come from F_2 or HF…..did the SO_4^{2-} come from SO_2, SO_3, H_2SO_4, etc.).

IMS also speciates compounds to a degree, but in a more general sense. For example, an Acids IMS analyzer will output acids concentration as calibrated to SO_2 gas. However, the IMS also reacts to HCl, Cl_2, Br_2, and HF among others. The data output from the detection of these compounds is reported relative to SO_2. In a similar fashion, the Amines IMS analyzer is calibrated to ammonia gas, but reacts with a majority of primary and secondary amines seen in semiconductor cleanrooms.

- Does the partial speciation of compounds provide value given that there are many fewer samples analyzed using IC when compared to IMS?
- Does the partial speciation of the IC make troubleshooting any easier than IMS if exact speciation is not obtained?
- Is information on the concentration changes from the general class of compounds (acids, ammonia, amines) detected by IMS sufficient to make ongoing decision?

Alarm and Troubleshooting

With the Impinger-IC technique the extended time needed for sample collection, shipment of sample, and laboratory analysis does not provide sufficient data to alarm to real-time AMC events. The total time from the start of the Impinger sampling to when the IC results are obtained can range from 2 – 14 days. Timing of employee shift work, weekend, and holidays provides another layer of complexity. IMS data obtained every 5 minutes provides the capability to react to contamination events as they occur or shortly thereafter (within 1 sample interval) in the process bay, track, or exposure chamber. In addition, IMS is not shut down or delayed due to shift-work, weekends, or holidays.

- Does an alarm need to be generated in real-time?
- What exposure to risk is there if evidence of an AMC excursion or problem is not identified for several days?
- Does the alarm have to be tied to data from a single compound or is an alarm caused by an excursion of any number of compounds valuable?
- Can the analyzer be used for real-time troubleshooting, for example, to track down the source causing a high excursion?

Trends from Best-In-Class Semiconductor Manufacturing

As is hopefully apparent from the information above, choices made about an AMC monitoring strategy can have significant financial, time, and resource efficiency implications. Companies who have recognized this are now implementing AMC monitoring strategies which allow for maximum results given the constant pressure on these constraints.

First, companies are viewing the choice of an AMC monitoring technique, such as Impinger-IC or IMS, as not an all-or-nothing proposition. Companies are utilizing the technique or combination of techniques that maximize value for their needs. Even though the IMS speciation of compounds is not as detailed as Impinger-IC companies are implementing IMS in critical locations to provide real-time, continuous, and high-sensitivity data for a given class of compounds. When an excursion is seen an immediate decision can then be made to determine whether an Impinger sample should be collected that will better identify the specific compound or if the IMS sample tube should be moved around to pinpoint the exact location causing the excursion. The strategy to use continuous monitoring data which then triggers the use of another technique is one best-practice that leading semiconductor manufacturers are implementing. These two techniques are not viewed then as being mutually exclusive, but are viewed as mutually beneficial when used in cooperation with each other to provide an effective overall monitoring strategy.

Second, companies are realizing that there are critically important areas of a cleanroom to monitor and there are other areas which are not as important (or non-critical). The critical areas often require the most attention as the effect from AMC is often the highest at these locations (Photolithography is one such area). Generally speaking, in these critical areas, more data is better than less, continuous data is better than periodic data, and data from the point-of-use (or point-of-concern) is more valuable than general process bay data. Non-critical points on the other hand, may only require periodic data for baseline purposes and can often use general monitoring at a smaller number of locations in order to provide representative data of a larger area.

Third, companies are transitioning from AMC monitoring techniques which output only periodic data to techniques which provide data in real-time. This is occurring because periodic techniques generally are highly susceptible to not identifying the problem due to sample frequency or due to time-averaging of the results. Without real-time data it is not possible to understand if molecular contamination levels observed in the air or on optics, reticles, and wafers represent stable background conditions, a contamination event, or a low or high phase of a daily contamination cycle.[3]

Finally, companies are recognizing that there are a significant amount of resources available who deal with the same issues when it comes to implementing or optimizing an appropriate AMC monitoring strategy. World-class companies are efficient at utilizing their resources, and where a lack of strength in AMC monitoring is apparent they are not hesitant to bring in expert consultants or vendors to review best practices or even help implement appropriate AMC monitoring programs.

Summary

AMC monitoring strategies over the past few years have not advanced in line with other process strategies for a number of reasons. The lack of ownership of AMC monitoring programs or the historical mindsets in implementing monitoring technologies are but a few of the reasons why AMC continues to cause damage. Thoughtful consideration of AMC monitoring strategy for a particular area or location will show that an AMC monitoring program can be effectively enacted despite some common constraints. In doing so, financial, time, equipment, and labor resources are all balanced to provide AMC data that works to the advantage of all stakeholders.

Ion Mobility Spectrometry is one tool that stands alone in its ability to satisfy the monitoring requirements of today's sub-65 nm technology nodes. IMS allows a financially efficient monitoring program to be created which is centered on providing real-time and continuous AMC data with high sensitivity at the critical locations where AMC causes damage. When complimented at times with other AMC monitoring techniques an AMC monitoring program is achieved that reduces long-term capital and labor resources.

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