

# Airborne Molecular Contamination Control in Semiconductor Fabs: A Practical Approach

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## ABSTRACT

**A**s semiconductor device geometry continues to decrease into the deep sub-micron level, chemical contamination has become as important as particulate contamination. Airborne molecular contamination (AMC) can impact almost all aspects of sub-micron device fabrication, from overall fab operation to final device performance.

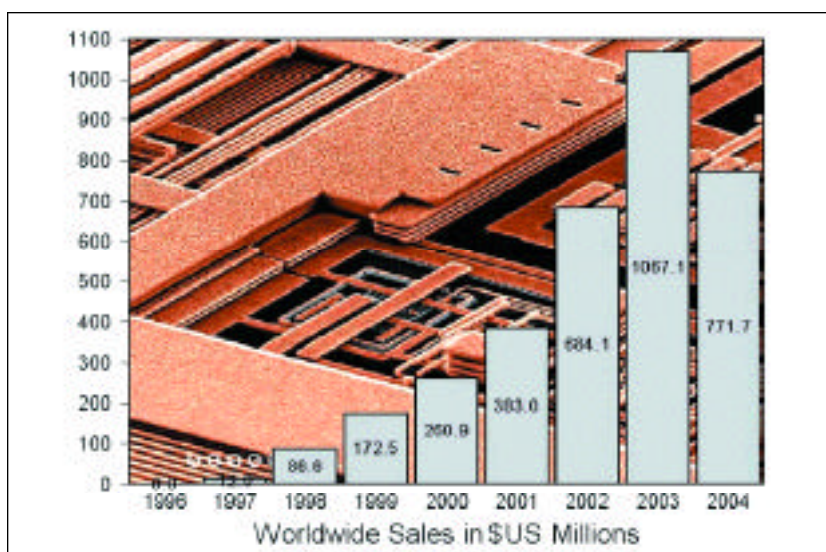
**A**ccording to SEMATECH's International Technology Roadmap for Semiconductors [1], the percentage of process steps affected by non-particulate or molecular contamination is expected to increase. Pre-gate oxidation, salicidation, contact formation, and DUV photolithography have been identified as particularly sensitive production steps. New chemistries introduced to manufacturing processes have also been shown to cause unforeseen AMC-related effects. Hydrogen sulphide, for example, poses a significant threat to the metallisation process as the transition is made from aluminium to copper.

**A**s copper appears ready to become the main on-chip conductor for all types of integrated circuits, it is showing up in the plans of chip and production equipment makers worldwide (Figure 1) and is quickening the shift to AMC-free manufacturing environments.

## WORLDWIDE SALES IN US\$ MILLIONS

As AMC pushes to the forefront in the minds of process and facilities engineers, they continue to seek answers to a number of basic questions:

- What types and levels of AMC are problematic to my manufacturing operations?
- How do I know what I have in my fab?
- If I implement AMC control, what increases in productivity and/or yield can I expect?



- How can I be assured that I am meeting my AMC control criteria?

Figure 1  
Worldwide sales of copper

Even with ongoing research, more and more manufacturers are turning to outside sources for the answers to these questions. Companies that can supply an entire package of AMC control and monitoring services are becoming increasingly viable and important sources of information. They are being used in a quasi-consulting role to keep their clients abreast of developments in AMC monitoring and control across the industry.

Control of AMC has evolved into a 3-step process. The first is an assessment of the air quality both outside and inside the fab to identify potential target contaminants. The second is the selection and qualification of an AMC control system. The final step is ongoing monitoring of the controlled environment and the performance of any AMC control systems.

## AMC ASSESSMENT

Before a determination can be made as to whether AMC control is warranted, the environment must be characterised as to its potential for AMC-induced damage or failures. This can be done with real-time gas monitors although this does not necessarily provide an indication of the potential effects of these contaminants. Unless a specific contaminant has been characterised as to its effect(s) on materials and processes, one can only speculate as to what its presence will mean to product reliability and yield. Even if a specific contaminant has been well characterised, e.g. ammonia in lithography processes or chlorine in metallisation and

Figure 2  
An Environmental Reactivity  
Coupon



salicidation, its control alone does not ensure that the process or device will be defect-free. Direct gas monitoring does not take into account the possible synergies – positive and negative – between different chemical species.

Reactivity monitoring, however, can show the effects of AMC on materials and is being used in fabs to perform air quality assessments. Environmental classifications using reactivity monitoring are designed to

characterise the destructive potential of an environment and have been accepted as a viable alternative to direct monitoring of low-level gaseous contaminants [3,4,5]. Reactivity monitoring is being used for the characterisation of makeup air, identification of AMC hot spots, and to track AMC incidents within a fab with the ultimate goal of establishing the cause-and-effect relationship between AMC and product yields/losses.

The classification scheme shown in Table 1 directly correlates corrosion rates to environmental classifications. These classifications – both in terms of the classification level and the corresponding reactivity rates – are being refined based on the results of testing, input from manufacturers, and the specific needs of the industry [6,7].

Individual corrosion films can be quantified and used to further characterise the environment, and assist in determining the proper AMC control strategies. Relevant acceptance criteria have been determined and these take into account total corrosion as well as the relative contribution of each individual corrosion film (Table 2). These specifications are more general in their application and are often used for the characterisation of an environment prior to the implementation of specific AMC control measures.

Environmental reactivity coupons (ERCs, Figure 2) employing copper and silver coupons may be used to indicate the presence of many different types of AMC including acids, bases, and solvents – all of which have been cited as the cause of a number of AMC-related process effects. ERCs are commonly used for evaluating long-term air quality trends inside and outside a facility and in performing environmental surveys as part of the development of an AMC control programme. They can also be used to differentiate

**TABLE 1. ENVIRONMENTAL CLASSIFICATIONS FOR SEMICONDUCTOR CLEANROOMS**

Copper Reactivity			Silver Reactivity		
Class	Air Quality Classification	Reactivity Rate	Class	Air Quality Classification	Reactivity Rate
C1	Pure	<90Å / 30 days	S1	Pure	<40Å / 30 days
C2	Clean	<150Å / 30 days	S2	Clean	<100Å / 30 days
C3	Moderate	<250Å / 30 days	S3	Moderate	<200Å / 30 days
C4	Harsh	<350Å / 30 days	S4	Harsh	<300Å / 30 days
C5	Severe	>350Å / 30 days	S5	Severe	>300Å / 30 days

**TABLE 2. GENERAL REACTIVITY MONITORING ACCEPTANCE CRITERIA FOR SEMICONDUCTOR CLEANROOMS**

Copper Reactivity Acceptance Criteria		Silver Reactivity Acceptance Criteria	
Copper Corrosion Reaction Products	Reactivity Rate	Silver Corrosion Reaction Products	Reactivity Rate
Copper Sulphide, Cu <sub>2</sub> S	0Å / 30 days	Silver Chloride, AgCl	<50Å / 30 days
Copper Oxide, Cu <sub>2</sub> O	<150Å / 30 days	Silver Sulphide, Ag <sub>2</sub> S	0Å / 30 days
Copper Unknowns	0Å / 30 days	Silver Oxide, Ag <sub>2</sub> O	<50Å / 30 days
Total Copper Corrosion	<150Å / 30 days	Total Silver Corrosion	<100Å / 30 days

between classes of chemical contaminants and to provide estimates of AMC concentrations.

The main limitation in the use of ERCs is their inability to provide a continuous environmental classification. To address this, reactivity monitoring has been taken a step further through the development of a real-time monitoring device employing metal-plated quartz crystal microbalances (QCMs) [8,9]. These micro-processor-controlled devices are able to measure the total environmental corrosion attributable to AMC and can detect changes in AMC at levels <1 ppb. This is regarded as one of the main requirements for any real-time AMC monitoring protocol used in semiconductor manufacturing applications [10]. To date, there is only one commercially available environmental reactivity monitor (ERM, Figure 3) that provides real-time information on AMC, conforms to industry standards, and is currently in wide use in semiconductor manufacturing facilities [11].

Both ERCs and ERMs are being incorporated into standard operating procedures and manufacturers are working to determine what reactivity levels should be the cause for actions to be taken. The preventive and corrective measures for which ERCs and ERMs are being used include:

- Installation in processing areas to identify specific sources and types of fugitive chemical emissions.
- Installation in tool inlet/exhaust and recirculation air handlers to monitor AMC levels.
- 100% inspection of in-process materials during AMC episodes to determine product failure/defect rates due to specific levels of AMC.

Data has been collected from both ERCs and ERMs that supports the use of both passive and real-time reactivity monitoring in performing environmental assessments in semiconductor manufacturing applications [5,7,12]. Examples of this are shown in Table 3 and Figure 4.

**AMC CONTROL**

AMC control has become an essential design requirement for all new fabs – as well as a large number of existing facil-



Figure 3  
An Environmental Reactivity Monitor

ities. In semiconductor manufacturing, the control of corrosive gases (acids and bases) in the cleanroom manufacturing environment is of primary concern. Other contaminants such as dopants, condensables, VOCs, etc., can affect various processes and materials and are often included as part of an AMC control strategy.

Chemical filter systems specifically designed for the control of these materials are being used in all critical process areas. Today's chemical filtration technology is capable of controlling targeted AMC to specified levels and, subsequently, chemical filters in many forms are being used in makeup and recirculation air handlers, mini-environments, fan filter units, and process tools. Whether it is adsorption, chemisorption, ion exchange, bulk granular or loaded nonwoven media, critical AMC control can be accomplished with one or more media. As a minimum, the broad guidelines for applying AMC control at the deep submicron level are:

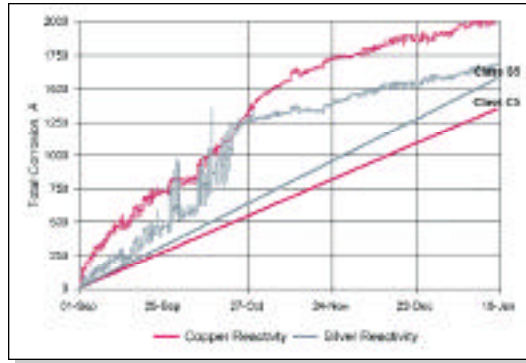
1. all makeup air units serving process areas and
2. all recirculating systems serving areas where wafers are processed, stored, or handled.

**TABLE 3. SITE SURVEY ERC DATA – FRESH AIR INLET**

Monitoring Period	Copper Reactivity Data*					Silver Reactivity Data*				
	Cu <sub>2</sub> S	Cu <sub>2</sub> O	Cu-Unk	Total	Class	AgCl	Ag <sub>2</sub> S	Ag-Unk	Total	Class
Sept. 4–18, 2001	794	310	0	1104	C5	212	367	605	1184	S5
Sept. 9–Oct. 9, 2001	1419	104	0	1522	C5	164	212	109	485	S5
Aug. 31–Oct. 24, 2001	2591	107	0	2698	C5	253	204	164	621	S5
	1745	160	0	1905	C5	202	275	123	599	S5
	1763	114	0	1877	C5	274	294	82	649	S5
Oct. 24–Nov. 7, 2001	818	464	0	1282	C5	137	943	609	1689	S5
Sept. 4–Nov. 20, 2001	1453	398	0	1851	C5	183	491	338	1012	S5
Oct. 24–Dec. 12, 2001	1357	343	0	1701	C5	671	570	214	1455	S5
Oct. 24–Dec. 19, 2001	1237	220	17	1474	C5	137	442	124	703	S5
<b>Averages</b>	<b>1464</b>	<b>247</b>	<b>2</b>	<b>1713</b>	<b>C5</b>	<b>248</b>	<b>422</b>	<b>263</b>	<b>933</b>	<b>S5</b>

\* all ERC data is reported angstroms/30 days

Figure 4  
Copper Reactivity vs Silver  
Reactivity



At times semiconductor manufacturers have become so focused on the control of a single contaminant, e.g., ammonia in lithography, chlorine in metallisation, that they sometimes forget or ignore other contaminants that could cause entirely different problems from those being singled out. For instance, many ion exchange products are sold for the control of ammonia but have little if any effect on amines and NMP. Another filter material is selective for chlorine but is ineffective against other acids. Targeting single critical contaminants will improve yield; however, all AMC must be considered when designing an AMC control programme. Even if they do not have any noticeable effect on processes or materials, they could very well have an unintended effect on the particular chemical filter products in use.

Improving production, fewer defects, and less rework all point to an increased requirement for reducing and maintaining low AMC levels. Assuming that reducing or eliminating AMC can help achieve these goals and that optimum AMC control will be achieved through direct (removal control) rather than indirect means (dilution control, etc.), recent experience has identified 4 important points that must be addressed by the facility designer:

- Identification of the air handling systems that should have AMC control systems in place
- Characterisation of the different requirements for makeup and recirculation air handler systems
- Specification of the AMC control equipment, and
- Performance verification, ongoing metrology, and detection limits.

#### AMC MONITORING

Once an AMC control strategy has been decided upon and implemented – whether it involves the use of chemical filtration or not – one must be able to monitor the success or failure of meeting specified AMC control criteria. Where chemical filtration is being used, an AMC monitoring programme must be able to provide the following.

- Information as to the type(s) of contaminants present and their relative levels.

- Air quality information correlated to specific air cleanliness classifications.
- Chemical filtration system performance assessment.
- Verification of the attainment of specified or standard AMC levels.

Generally speaking, air quality in critical process areas should be a minimum of Class C2 / S2, without evidence of active sulphur or inorganic chlorine compounds. This most often indicates an environment sufficiently well-controlled as to prevent AMC-related process effects and direct control of AMC may not be required. Where chemical filtration is being employed to control AMC, reactivity rates <15-20 /30 days have routinely been attained. Subsequent gas monitoring has indicated that pollutant levels are at or below the limits of detection for the analytical techniques employed. If an environment exhibits reactivity rates corresponding to a C1 or S1 classification, there is little else that can be done, economically, to improve the environment (see Table 4).

Even if chemical filtration is not employed as part of a facility’s overall AMC control programme, continuous monitoring of the environment is necessary to assure compliance with any air quality criteria. As monitoring tools, ERCs and ERMs are capable of providing information on AMC levels as low as 1 ppb.

ERMs have proven especially useful for establishing AMC baselines and identifying AMC episodes and their sources. They can be incorporated into a facility’s overall preventive maintenance programme and help reduce the number of AMC-related incidents that are reported and logged. They can also help reduce the number of reported health and safety incidents by allowing proactive investigation of potential problems with the ultimate goal being to eliminate production down-time due to AMC.

Performance monitoring of chemical filter systems is perhaps where ERCs and ERMs gained their widest acclaim. Their use allows for timely changeout of the media/filters and reduces the cost-of-ownership for these systems. Proper maintenance of these systems also ensures that air quality goals are being met, and AMC-related process effects are significantly reduced or eliminated altogether.

#### SUMMARY

AMC continues to grow in importance as a barrier to semiconductor manufacturers as they transition towards 300 mm wafers, 100-nm linewidths and copper interconnects. It represents a wide range of chemical types that can result in a large number of potential processing problems. However, many fabs have only recently begun to actively address AMC and the effects of specific contaminants on individual processing steps are still not very well understood. Direct correlations between process yield and individual contaminant concentrations, although one of the current Holy Grails of

TABLE 4. SUMMARY OF CHEMICAL FILTER PERFORMANCE

ERM Monitoring Location	CopperReactivity	Reduction	Class	SilverReactivity	Reduction	Class
Fresh Air Inlet	579		C5	484		S5
Chemical Filter Discharge	21	96.37%	C1	11	97.73%	S1
Mechanical Room	70	87.91%	C1	33	93.18%	S1
Cleanroom	10	98.27%	C1	10	97.93%	S1

contamination control, are either rare or not published.

With the rapid pace of technological advancements, semiconductor manufacturers have fully recognised the fact that sensitive electronic and electrical components and equipment will be damaged if exposed to AMC. The International Technology Roadmap for Semiconductors has proposed that AMC will be the next technical challenge to overcome in order to maintain high reliability and yield for semiconductor devices. Next generation semiconductor devices will require the strict control of AMC in order to assure productivity, competitiveness, and profitability. Manufacturers are actively addressing AMC and its control, each according to the specific requirements of their own manufacturing processes and concerns.

An assessment of outdoor air quality should be one of the first steps towards establishing any AMC control programme. In review of reactivity monitoring data from semiconductor fabs around the world, there are very few areas today where the outside air quality would meet specific area quality requirements with respect to AMC. Even ambient levels are high enough to be of concern.

As the industry's knowledge about the damaging effects of AMC on processes and materials continues to increase, more facilities are implementing AMC control programmes. Suppliers of specialised chemical filtration systems are being asked to assist in determining the types of AMC present, the specific control system(s) required, how best to determine if the systems are working and, if so, whether they are meeting specific design requirements.

An air quality classification scheme has been established for use with reactivity monitoring and it has gained wide acceptance throughout the semiconductor industry. Reactivity monitoring can provide information as to the types and relative concentrations of many contaminants problematic to manufacturing processes. It can provide the information required to determine if direct AMC control is indicated and, if so, what form it should take. At the very least it now appears that incorporation of chemical filtration into makeup air handlers will become a requirement for these facilities.

As the necessity to control chemical contamination increases, more information and feedback from semiconductor manufacturers is going to be required for continuous improvement of AMC monitoring and control technologies. Intellectual property, new technology, and competitive considerations must be protected, but the suppliers of monitoring and control technologies must be able to address AMC issues with as much information as possible at their disposal. Only then can we be assured that we will keep pace with AMC.

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## ABOUT THE AUTHOR

Chris Muller is the Technical Services Manager for Purafil, Inc., a manufacturer of chemical filtration media, equipment, and AMC monitoring instrumentation. He has written and spoken extensively on the subject of AMC control and monitoring and counts more than 45 papers and articles, and 3 design guides to his credit. He is a senior member of the IEST and is a member of working group WG-CC035: Design Considerations for Airborne Molecular Contamination Filtration Systems and contributes to WG-CC008: Gas-Phase Adsorber Cells. He chairs ASHRAE's Standard Project Committee 145P which is developing industry standards for assessing the performance of chemical filtration systems.

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