Designing Safe, Low-cost Vacuum and Exhaust Management Systems for Semiconductor Processes

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Overview

Vacuum and exhaust gas management are critical components of semiconductor manufacturing. While these systems are usually hidden away out of sight—and out of mind—in the process tool or the sub fab, they are vital to efficient and safe manufacturing. Vacuum systems remove potentially hazardous process gases and manufacturing byproducts from process tools and pump them to abatement systems, which break these substances down for safe disposal. Both vacuum and abatement systems are undergoing continuous improvements, lowering the cost of ownership while improving performance. However, to achieve maximum productivity and minimize risk, the entire vacuum and exhaust management system must act as an integrated whole that is customized for each specific process and for each fab's needs.

Background

Vacuum and exhaust management is very simple in concept *(Figure 1).* Pumps create the appropriate vacuum environment required for semiconductor applications such as physical or chemical vapor deposition (PVD and CVD) and pull process gases or byproducts from the process tool, delivering them to abatement systems. The abatement systems treat the gases or byproducts, often with high heat, making these safe to release into the environment. A water scrubber may also be required to remove particulates from the treated gas stream and to capture acid gases such as HF for subsequent concentration and treatment in a waste water stream.

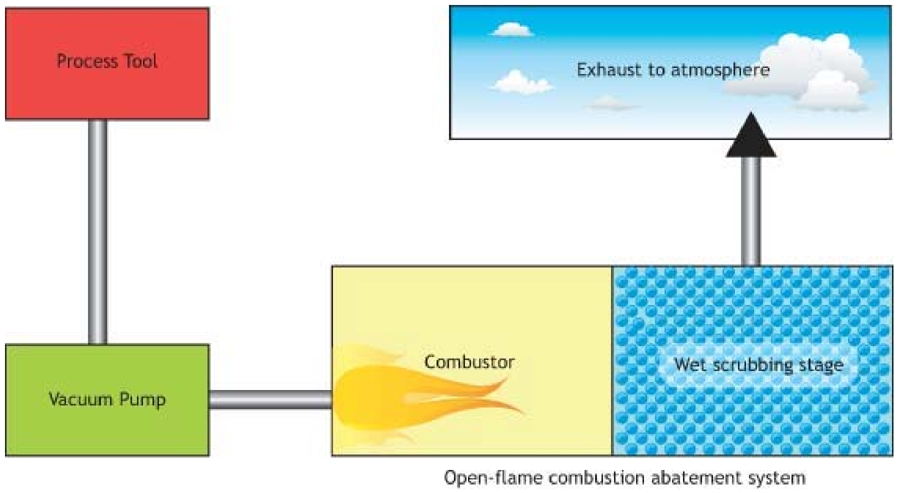


Figure 1: Basic vacuum and exhaust management systems require a vacuum pump to remove gases from the process tool and an abatement system that treats the process gases and byproducts so they can be disposed of safely.

However, designing exhaust management for a fab is complex. There are an enormous number of choices for vacuum pumps, which vary in size, cost, energy usage, maintenance requirements, and technology. In addition, many of these pumps require booster or backing pumps for optimal operation. On the abatement side there are also many choices, and it is critical to select the right technology for the process application, not only to achieve a low cost of ownership, but also to reduce safety risks.

Without proper planning, fab-wide vacuum and exhaust management systems can end up consisting of dissimilar equipment from a variety of manufacturers—and can turn the sub fab into a rat's nest of equipment and piping. This approach makes it difficult to isolate a problem to a particular piece of equipment or vendor, and, even when the faulty component has been found, makes it difficult to access and service. More importantly, it can be challenging to identify the existence of a problem, so undetected leaks or malfunctions could be hazardous to fab personnel or the environment. A final concern is that there may be space and access issues when new equipment is required to meet changing regulations or to accommodate advanced processes.

To prevent these types of problems, some manufacturers install monolithic fab-wide abatement systems. These may offer advantages for troubleshooting and identifying appropriate service technicians, as well as offering cost savings from economies of scale. However, this approach reduces flexibility, can be expensive to retrofit for changing needs, and may require large scale construction projects for expansion. There is also a significant risk that this type of system will reduce overall productivity, as the entire manufacturing process must be halted to perform routine maintenance or in the case of a malfunction. Also, dangers can arise from mixing of incompatible gases from different process tools in the pipelines feeding into the fab wide abatement unit.

A better solution is to use a distributed network of integrated vacuum and abatement systems, each designed to provide an optimized solution for a specific process module (*Figure 2)*. This approach offers a low cost of ownership:

- Minimizes equipment costs by selecting the most cost effective combination of equipment to efficiently and safely handle the exhaust gases
- Speeds installation, reducing costs and enabling a faster ramp to high volume production
- Lowers operating costs with energy efficient components designed to work with each other
- Reduces maintenance costs and delays as a single vendor with the appropriate knowledge and expertise can quickly return the system to production
- Up to 70% smaller size.

With integrated systems, risk mitigation is also built in. The vendor is responsible for the full system, understands the risks involved, and continuously monitors the system for hazardous conditions. Whearas the piping between separate vacuum and abatement systems brings very high risk. Dilute, sub-atmospheric gases are compressed and heated in the vacuum pump. This can create a flammable, explosive, and/or condensing mixture in the piping that is very dangerous.

This article will discuss details of both vacuum and exhaust gas management systems and how their integration can offer significant benefits.

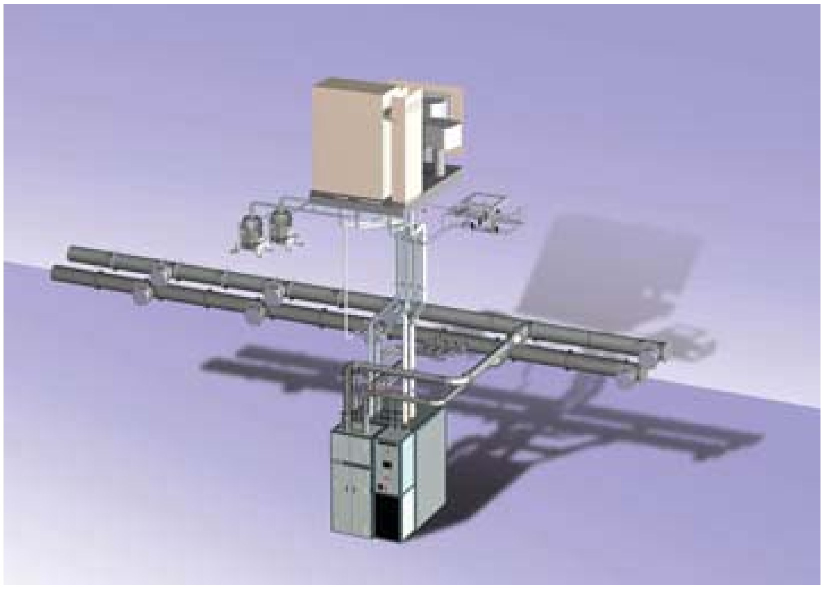


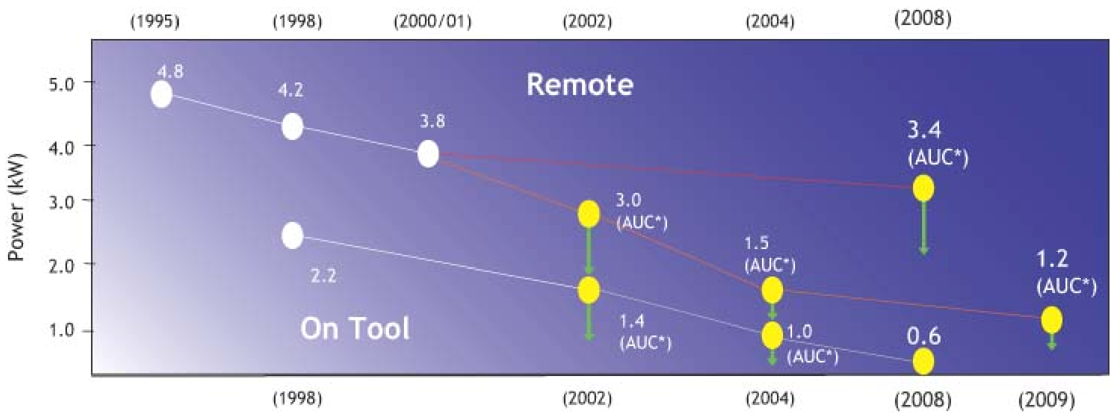
Figure 2. Integrated systems optimized for specific process modules offer a safe, cost-effective, and energy efficient solution for vacuum and exhaust gas management. Note the single vendor is responsible not only for the vacuum pump and abatement module, but also for the piping between the two components.

Vacuum Systems

Vacuum pump uses range from clean processes such as metrology to complex processes such as CVD where particulate, condensable, and corrosive by-products are present. Depending on the application, the pump may be installed inside the process equipment, near the equipment, or in a remote location. Pump applications include: load lock and transfer, metrology, lithography, implant source, PVD processes and pre-clean, RTA, strip/ash, oxide, silicon, and metal etch, CVD and MOCVD, and ALD. Choosing an effective pump with a low cost of ownership for each application requires a thorough understanding of both the process involved and the pump options available.

Pump energy consumption is a key concern. As much as 20% of a fab's energy expenditure may be attributed to process pumps. Recent design improvements have significantly reduced the amount of energy consumed per pump while simultaneously improving performance *(Figure 3).* Pump designs offer a number of opportunities to improve efficiency.

- Motor and inverter matching can be optimized for the application
- Thermal control systems can improve reliability while minimizing water usage
- Vacuum stator and rotor profiles as well as the number of pumping stages can be selected for specific compression and pumping performance profiles
- The design of non-contact seals, bearings, lubrication and gears can all reduce losses.



* Speed control / Active Utility Control (AUC) can give reductions ~20%.

Figure 3. Continuous improvements have significantly reduced vacuum pump energy consumption over the last ten years.

Significant advances have also been made to reduce maintenance and simplify pump use. Dry vacuum pumps often function continuously for two years or longer, eliminating the regular maintenance required for oil changes in wet pumps. Even more impressively, turbomolecular pumps can run for up to five years without maintenance as their magnetically levitated bearings are virtually friction free, minimizing vibration and wear. New corrosion resistant, high-temperature materials are available that help to prevent byproduct gases from condensing in the pump mechanism and work in corrosive environments such as conductor etch. Pumps can also incorporate intelligent monitoring systems that connect to fab networks to enable rapid identification and response to pump performance excursions.

Although advances in pump technologies are impressive, pumps can not be considered in isolation from the rest of the vacuum system. For example, PVD processes require a high level of vacuum that can be achieved with several different types of pumps, each of which requires backing pumps. Cryogenic pumps can be used for this application and offer significantly higher water vapor pumping speed than most competing technologies. However, in some applications the use of a turbomolecular pump is favored either because it is a smaller, more energy efficient device or for more fundamental reasons such as safety when pumping materials such as oxygen that can be hazardous when trapped as a liquid in a cryogenic pump. Distribution of the components is also critical to maximize performance. Moving booster pumps closer to the process chamber improves pumping speed while reducing requirements for inlet pipe size, booster pump size, and backing pump size.

To specify the most cost effective and energy efficient vacuum pumps requires knowing the abatement and process tool vacuum requirements as well as the distribution of the vacuum system. For relatively simple applications such as etch, less expensive, lower torque pumps can be used that offer excellent energy efficiency. For more challenging CVD applications, pumps may require pipe heaters or heating jackets, or even use active gas injection into the exhaust stream to convert compounds into gases that can be transported through the vacuum system they can also require high torque motors to transport high intermittent powder loads. The initial investment for such advanced pumps may be high, but payback is achieved with higher process tool reliability and productivity.

Abatement Systems

A well designed vacuum system will safely and efficiently remove gases and process byproducts from the process tools and main fab. However, abatement systems are required to treat these substances before disposal, as many are toxic, or pose other risks to the environment such as containing greenhouse gases that contribute to global warming. The choice of abatement system is dependent on several variables including the process, local regulations, and the availability of fuels.

CVD and Epitaxial Processes

Gases and process byproducts generated by CVD and epitaxy include pyrophoric, flammable, and toxic substances including SiH_4, PH_3, F_2, NF_3, SF_6, NH_3, HF, HCl. Proper abatement is critical for safety. Abatement can be achieved by running the process gas stream through a reagent mixture at high temperatures, typically around 800C. Thermally activated reactions break the gases into safe components. Silicon based components such as silane or TEOS are oxidized into silica, and fluorine is reduced to form HF. Both can then be removed from the waste water stream in a final wet scrub phase and the remaining gases can be released into the atmosphere.

In an open flame combustion abatement system, the high heat required for CVD and epitaxial abatement is generated by passing the process gases directly through a flame consisting of methane or other hydrocarbon fuel. While this method is simple, it permits formation of undesirable byproducts such as NO_x and perfluorocarbon greenhouse gases. With an open flame combustion system, it is difficult to ensure sufficient temperature uniformity across the burner. Where the temperature is too low, the desired reactions will not be complete. Where the temperature is higher, often in excess of 1600C, NO_x may be formed—this pollutant can contribute to respiratory problems and acid rain, and its emissions are often regulated.

An additional consideration is that the supply of methane may be limited in certain locations. High growth rate economies may face shortages of natural gas and some governments have given priority to residential usage over industrial. ("Policy on natural gas streamlined," *Shanghai Daily*, 2007-9-4). Semiconductor fabrication facilities in these regions will need to focus on the efficient combustion of process by-products to minimize fuel consumption or will need to look for alternate non-fuel solutions.

An elegant solution is the inward fired combustor design that separates the fuel gases from the process gases (*Figure 4*), thus preventing the unwanted cross reactions. The inward fired design creates isothermal conditions throughout the reaction chamber, virtually eliminating the risk of incomplete reactions or NO_x formation. Because the gas flow is constrained within the reactions chamber, the inward fired combustor guarantees complete combustion even at high flow rates. Other benefits include:

- Reducing the abatement system's footprint and energy requirements
- Minimizing maintenance as the constant temperature prevents accumulation of solid residues that can reduce throughput and require frequent removal in open flame systems

Thermal abatement systems that use electric power provide an attractive alternative in locations where fuel is unavailable.

Figure 4. With the inward fired combustor design, the heating fuel gases remain outside the interior reaction chamber. This significantly improves the ability to control temperature compared to open flame systems, thereby improving abatement performance.

Challenges for Compound Semiconductor CVD Processes

Compound semiconductor (CS) manufacturing, which is experiencing explosive growth tied to demand for new light emitting diodes (LEDs), brings unique challenges to abatement. Many of the materials used to process CS are highly toxic, so abatement is essential but solutions must be extremely cost effective as LEDs are sold into price-sensitive consumer markets. Primary gases requiring abatement are hydrogen, ammonia, phosphorous, phosphine, and arsine. In addition, as with traditional CVD, care must be taken not to generate NO_x.

Conventional approaches applied separate technologies for individual substances. Wet scrubbing has been used effectively with sodium hypochlorite for phosphide processes or sulfuric acid for nitrides. For phosphide processes, the phosphorous is usually removed from the exhaust stream to prevent deposit buildup on the vacuum pumps or lines—these deposits combust spontaneously when exposed to air, making periodic cleaning of phosphorous traps a dangerous job. Hydrogen does not dissolve in water and has often been allowed to escape into the atmosphere, but this poses a considerable risk of explosion, even in relatively low concentrations.

Combustion based abatement using the inward fired combustor design offers an attractive alternative. High temperature vacuum pumps and heated vacuum lines can transport phosphorous laden exhaust, minimizing the risk of condensing solids. Manufacturers have found that eliminating the need for phosphorous removal provides an immediate 10% increase in process tool uptime and allows more wafers to be processed. Hydrogen is immediately oxidized, minimizing the risk of explosion. Combustion based systems can simultaneously handle high hydrogen and ammonia flow rates from multiple process tools, reducing initial capital expenditure. As a final benefit, in many applications, the hydrogen and ammonia from the process can be used as the primary fuel for combustion, drastically reducing fuel costs.

Etch Processes

Metal Etch

Metal etch processes use corrosive gases such as Cl_2 and BCl_3, as well as global warming (PFC) gases. Abatement can be performed with inward fired combustion, as described above, or with hot bed reactor technology. Both can be very effective and the choice depends on application and fab specifics. In a hot bed reactor, gases react at high temperature with inorganic granules contained in a stainless steel cartridge. The gases are completely converted to inert salts that are locked in the cartridge for easy disposal. Compared to competing technologies, hot bed reactors are dry, making them immune to moisture corrosion issues, convert a wider spectrum of gases than cold bed reactors, have lower energy and utility requirements, and generate no toxic waste.

Dielectric Etch

Dielectric etch processes also use PFCs and corrosive gases, including HBr. Although combustion abatement has been used for this application, the stable PFCs created with dielectric etch require significant amounts of energy and often high supplemental hydrogen flow rates. A better solution is to use microwave atmospheric plasma to dissociate the PFC molecules. Advanced microwave plasma technologies are extremely energy efficient, have a small footprint, and offer low installation and maintenance costs.

Integrating Vacuum and Abatement Systems

The previous sections have just begun to touch on some of the complexities and interdependencies that must be considered when designing vacuum and exhaust management systems. A further complicating factor is that the process tool suppliers may have certain vacuum elements inside their equipment, so the remainder of the design must accommodate those devices.

Fortunately, it is not necessary for each fab to develop the expertise required to optimize their vacuum and exhaust management systems. Complete sub systems, such as *Edwards Zenith™ line*, integrate both vacuum components—often including those installed in process equipment—and abatement. These are now available, are customized for specific applications, minimize safety risks, and lower the cost of ownership.

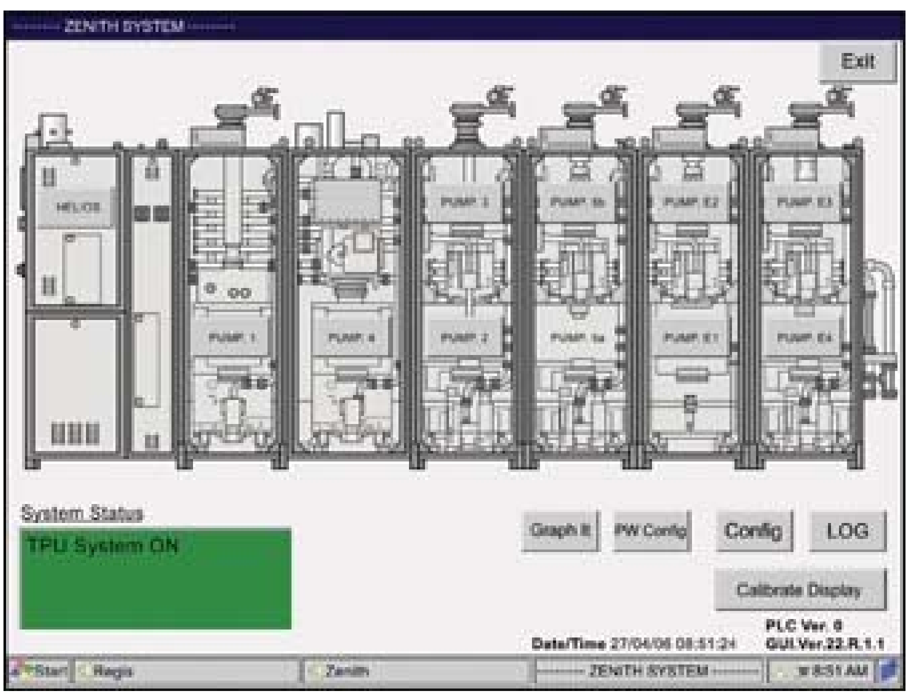


Figure 5. Edwards Zenith™ line of integrated vacuum and abatement systems provides a single user friendly control and monitoring interface for all components.

In these integrated systems, components are selected for compatibility with the process and each other to ensure safe and effective treatment of process precursors and byproducts. Total footprint is reduced by up to 70% compared to individual components, simplifying access and freeing sub-fab floor space. Vacuum pumps are sized for maximum efficiency with the given layout. A single, user friendly interface *(Figure 5)* provides detailed information on individual components and the entire system, helping to eliminate down time and reduce operator errors, as well as continuously monitoring for safety hazards.

Installation is simplified. Integrated systems have fewer than half the number of hookups compared to separate components and pipe work is leak checked at the factory. The systems can be pre-certified to meet the most stringent industry standards. In addition to reducing costs, faster installation allows the associated process tools to become productive sooner.

Integrated systems also reduce maintenance. Advanced vacuum pump designs eliminate the need for frequent maintenance, such as oil and filter changes, with service intervals ranging from two to five years. Similarly, new abatement designs significantly decrease the need for cleaning to remove solid build up.

Integrated systems can be engineered to communicate with the process tool so that utility consumption can be modulated and their function optimized to the requirements of each process steps. Hence, integrated systems are able to offer significant power, water and nitrogen savings, thereby reducing overall operating cost. The initial cost of an integrated system is often found to be competitive compared to the cost of individual components. In fact, when the integrated system's ability to handle high flow rates allows it to work with two or more process tools, the up front costs are much lower. Then factor in lower installation, maintenance, energy costs, and ease of use and integrated systems are clearly a very attractive choice.

Conclusion

Vacuum and gas exhaust management systems are key factors for safe and efficient semiconductor manufacturing. While there are a wide variety of pumps and abatement tools and technologies, the crucial factor is that system components must match the specific application. Choosing the wrong solution can not only be costly, lives may be endangered if the hazardous gases are not properly removed and disposed of. Integrated systems, carefully engineered for safety and efficiency, can minimize risks and achieve a low cost of ownership.