Managing hazardous process exhausts in high volume manufacturing

Integrated sub-fab systems allow HVM fab operators to safely and efficiently implement new processes containing hazardous process chemicals.

BY ANDREW CHAMBERS, Edwards Ltd., Clevedon, UK

The relentless scaling of structures and reduction in thermal process budgets that characterize state- of-the-art integrated circuit (IC) production have resulted in the incorporation of many complex and hazardous materials into high-volume manufacturing (HVM) processes. In order to meet the need to deposit these materials at ever-lower temperatures, many of the new process chemicals have low vapor pressures, are highly reactive and present serious hazards to personnel and equipment. Many new CVD precursors and their associated reaction by-products are flammable, pyrophoric, toxic (harmful-to-health), corrosive or otherwise hazardous to personnel or destructive to equipment, and have a tendency to condense in pipe-work, including process exhausts.

In this article we will review the risks associated with these materials and describe methods for mitigating process exhaust pipe hazards in high-volume manufacturing. In particular, we will describe an approach based on the integrating vacuum pumps and point-of-use abatement systems with essential safety devices and monitoring systems into a complete sub-fab vacuum and abatement solution. Such modular integrated sub-fab systems ensure safe system operation, including mitigation of process exhaust hazards, and reduce exposure of service staff to hazardous materials.

Process gas and reaction product hazards

Clearly, exposure of staff and equipment to hazardous chemicals leaking from process exhausts is a serious concern and careful attention to the design, control, safety qualification and maintenance of process exhaust systems is essential in configuring a safe and reliable sub fab operations.
The properties of process chemicals may be altered significantly as they pass through a process tool, and reaction products found in process tool exhausts may differ markedly from the original process precursors. For example, while high flows of tetraethylorthosilicate (TEOS) are widely used in CVD processes for deposition of silicon oxide films, the concentration of residual unreacted TEOS in a CVD process tool exhaust is minimal [1]. Instead, the TEOS is decomposed in the process chamber to form a greater volume of mixed hydrocarbon gases (ethene and ethanol, for example [2]), which are then pumped out of the process chamber into the process exhaust. When the safety of process exhausts is evaluated in the design of protective measures, interactions and transformations of process gases such as this must be considered carefully.

Deposition of hazardous materials in exhausts

In some cases, the process by-products which pass into the exhaust pipe are condensable. Frequently encountered condensable by-products include aluminum chloride (AlCl3) in metal etch, ammonium chloride (NH4Cl) in LPCVD nitride, and ammonium hexafluorosilicate ((NH4)2(SiF6)) in PECVD nitride. Several of these condensates have also been found to incorporate partly-reacted hazardous materials. For example, partly-reacted silicon-containing compounds which condense in exhaust pipes during a PECVD process may react violently with fluorine gas which flows through the exhaust pipe during a subsequent chamber cleaning process. This has caused exhaust pipe fires and serious equipment damage in a number of cases (**FIGURE 1**).

FIGURE 1. Consequences of byproduct condensation in process exhausts; left: solid ammonium chloride blocks an LPCVD silicon nitride process exhaust; middle: flexible stainless steel bellows perforated by corrosive by-product condensate; right: flexible stainless steel bellows ruptured by detonation of reactive solid condensate.

In addition to the reactivity hazard posed by these materials, accumulation of condensed material during processing can block exhaust pipes, causing process tool downtime and possibly loss of production. Furthermore, the reaction of condensed fluorine- or chlorine-containing materials with atmospheric water vapor during removal and cleaning of exhaust pipes can release HF or HCl gas or other hazardous substances, posing a serious risk to service staff and requiring preventive measures.

A particularly serious example of harmful deposited materials in exhaust pipes is the condensation of extremely reactive polysiloxane materials in Si epi or Si-Ge epi exhausts [3]. These materials are particularly hazardous since they can react unpredictably and violently (explosively) on exposure to water vapor or air, or if they suffer a mechanical shock when the exhaust pipes are removed for cleaning. The consequences of process gases escaping through leaks in exhaust pipes and the tendency of materials to condense in process exhaust pipes should be carefully considered when a process exhaust system is designed. Indeed, the exhaust pipe should be considered as an important functional element of the whole sub-fab process tool support system, otherwise there may be increased risks of staff injury and process tool downtime.

Leak integrity of process exhausts

Escape of process gases or reaction products from leaking process exhaust pipes presents serious risks to fab operations. For example:

• Flammable gas escaping from exhaust pipes may mix with air in closed spaces to create a fire risk
• Toxicgasesleakingoutofnon-enclosedexhaustpipes present an injury risk to fab personnel
• Corrosive gases leaking out of non-enclosed process exhausts can harm personnel and cause severe damage to fab equipment
• Process gas odors may cause complaints from fab staff or local residents

Typically, area gas detectors are deployed in fabs to warn of process gas leaks. These are very effective in detecting escaping process gas, but when they are activated process operations are interrupted and fab output affected. Furthermore, gas detectors cannot detect inward leaks into reduced pressure pump exhausts, such as air entering exhaust pipes where it could mix with flammable process gases to form flammable mixtures. In the worst case, a flammable process gas / air mixture could be ignited by a local ignition source, such as a dry-pump or point-of-use abatement system, and cause an exhaust pipe fire.

Configuring the vacuum/abatement/exhaust components as a single coherent system can increase staff safety and manufacturing efficiency by reducing the risk of hazardous process gas escape and ensuring appropriate action if a leak is detected In particular, integrated sub fab systems enable the use of extracted secondary enclosures around vacuum pumps, point-of-use abatement systems, fuel gas delivery systems and all interconnecting pipework to contain escaping gas, while ownership, maintenance and integrity of the process exhaust pipes becomes the responsibility of the system supplier, rather than remaining undefined.

Exhaust dilution

A standard safety precaution widely used to avoid the possibility of fires in process exhausts is the dilution of flammable gases below their Lower Flammable Limit (LFL). However, there are risks with this strategy. Considering the previously cited example, if the required dilution flow is calculated based only on the volume of TEOS gas in the exhaust pipe, it will be insufficient to dilute the larger volume of hydrocarbon decomposition products below their LFL. A related risk is formation of a flammable mixture in the exhaust if there is an air leak into the exhaust pipe coincident with the TEOS being decomposed by the process chamber.

As noted above, the process dry-pump and point-of- use abatement system are both ignition sources that could ignite the hydrocarbon / air mixture and cause an exhaust pipe fire.

To operate process exhausts containing flammable gases safely using this strategy, not only must the dilution flow be calculated appropriately, but the vacuum and abatement system controller must include a capability to shut off the flammable gas flow from the process tool if the dilution flow should drop below some critical level, or if a fire occurs in the exhaust pipe, as required by semiconductor industry safety standards such as SEMI S18 [4].

In recent times, the risks associated with flammable and pyrophoric gases have become more severe as highly reactive compounds such as disilane and trimethyl aluminum have become more widely used in CVD processes. Some of these materials have extremely low LFLs – for example, disilane has a published LFL of 0.2% [5], and trimethyl aluminum is known to be extremely flammable though specific LFL data appears not to be widely available [6]. This characteristic makes their dilution to safe levels costly and inefficient from an operational efficiency perspective. For example, the low LFL of disilane requires a very large volume of nitrogen required to dilute it to a safe level, increasing the direct cost of the nitrogen and putting additional load on the fab facilities. The resulting high gas flow in the process exhaust increases the total cost of abatement by requiring larger, more expensive equipment, more sub-fab floor space, and a higher utility consumption. Finally, the abatement efficiency of highly-diluted process gases may be degraded, creating an environmental concern if emissions of process gas that exceed permitted levels.

Temperature control of process exhaust pipes

The risks posed by the condensation of process by-products in exhaust pipes can be mitigated by controlling the temperature of the exhaust pipes at a suitably high value (**FIGURE 2**). Commercial products are widely available to perform this function, but when selecting a suitable system, its capability to maintain a uniform temperature throughout the exhaust system should be considered carefully – in particular, cold spots caused by inadequate thermal insulation or lack of adequate real-time temperature control can cause localized by-product condensation and pipe blockage. At the other extreme, if exhaust pipes are heated to an excessively high temperature, unused CVD precursors may react, depositing solid materials in the exhaust pipe. Ideally, temperature will be actively and precisely controlled within a specified range.

FIGURE 2. Heating elements and thermal insulat
enclose pump exhaust lines leading to the abateme
to maintain exhaust gases at a temperature high er
prevent condensation.

Integrated sub-fab systems

Integration of the process exhaust pipe assemblies together with dry-pumps and point-of-use abatement into a complete sub-fab system by the equipment manufacturer permits an optimization of safety, performance, efficiency and cost that cannot be achieved in the installation of discrete units by individual suppliers.

A typical integrated sub-fab system is designed to incorporate dry-pumps, point-of-use abatement systems, exhaust pipe assemblies, temperature management systems (TMS), together with all necessary safety devices, into a single entity which also includes a supervisory control system and all process tool and fab interfaces. Since all individual functional elements are integrated into a single unit, typically only one connection for each fab utility is required – not only does this reduce the overall installation cost of the sub-fab equipment, it also occupies less valuable sub-fabspace.Each such integrated system is typically used to support a single process tool, and is usually designed to fit conveniently within the “shadow” of the process tool in the sub-fab.

This close integration of the individual sub-fab functional elements into a unified system enables a reduction in risks associated with exhaust pipe leaks by continuously monitoring the leak status of the exhaust pipes, by monitoring the air extraction rate in secondary enclosures, and by monitoring the temperature and pressure in the process exhaust pipes. In the event of an excursion by any of these parameters into a critical condition, an integrated system can be designed to initiate shut-down of the process gas through its interfaces to the process tool, and alert the fab MES through its interface to a central monitoring system (CMS). Furthermore, real-time collection and processing of data from all the functional elements in the integrated system allows events leading up to previous alerts to be analyzed. Predictive algorithms can then be developed that can enable the CMS to antic- ipate or predict future failure events.

Provided the safety features of an integrated sub-fab system are properly designed, including those which specifically monitor the condition of the exhaust pipes, it becomes practical to reduce dilution rates of flammable gases safely, leading to significant reductions in required abatement capacity, capital equipment investment, utilities consumption and total operating costs in a high volume manufacturing environment (**FIGURE 3**).

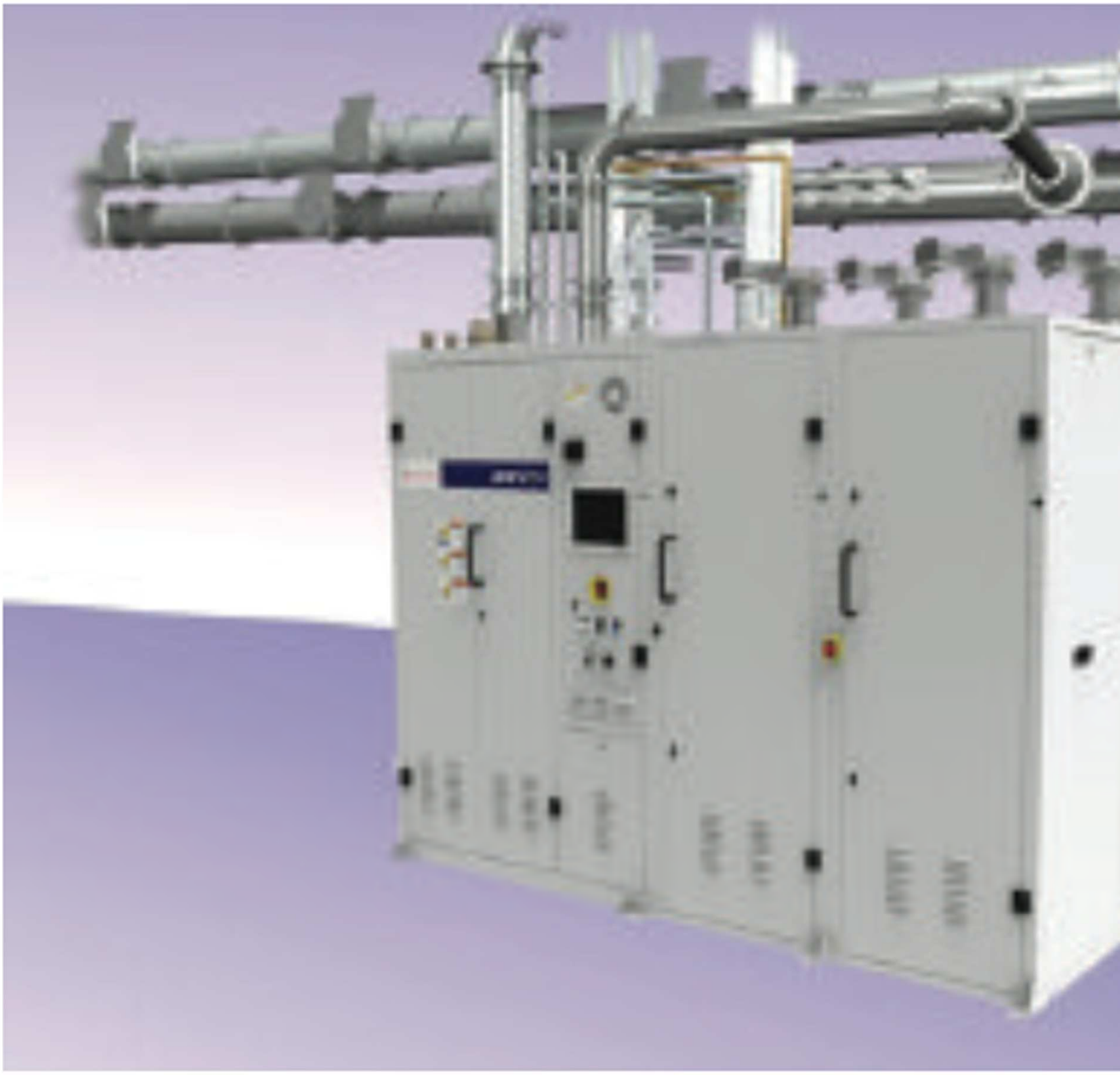

FIGURE 3. Complete integration of vacuum pur
abatement systems can lead to significant reducti
required abatement capacity, capital equipment in
utilities consumption and total operating costs in a
manufacturing environment. Note in particular the
number of utility connections required to support
pumps and a point-of-use abatement system in th
example of an integrated system.

Implementation of Best Known Methods (BKMs)

Integrated sub-fab systems are typically built, installed and serviced by a single supplier, who takes responsibility for the complete system design, including all necessary safety functions and external interfaces. Safe sub-fab system operation is normally assured by a comprehensive safety assessment of the integrated system design and by compliance with global semiconductor industry safety standards such as SEMI S2 [7].

However, to ensure the most efficient operation it is also necessary to set-up the sub-fab system according to a Best Known Method (BKM) for each process tool. Application of process BKMs ensures that each integrated sub-fab system is fit-for-purpose to meet the specific require- ments of its allocated process tool, and shortens the time required to qualify the tool for process. Typically, sub-fab equipment suppliers use know-how based on experience of similar processes in other HVM facilities to define their own BKMs and set-up equipment properly. Once an integrated system is operational, service support, applications support and continuous improvement programs (CIP) are all available from a single source which ensures that all critical safety systems are properly maintained and comply with the latest BKMs (**FIGURE 4**).

FIGURE 4. An example of continuous improvement and application of best known methods in a point-of-use abatement system: in a TEOS CVD process the standard inward-fired burner (left, after 9k wafers) was replaced with a shortened version (right, after 26k wafers). The resulting increase in surface firing rate greatly reduced unwanted deposition, improving the mean time between service (MTBS) from 10K wafers to 42K wafers.

Summary

The concept of integrated sub-fab systems is a valuable tool that allows HVM fab operators to safely and efficiently implement new processes containing hazardous process chemicals. The integrated function- ality and comprehensive safety systems guard against hazardous process gas escape, leakage of air into exhausts containing flammable gas, and condensation of a wide range of hazardous materials in exhaust pipes. Collectively these attributes enable the safest and most efficient sub-fab operation for HVM.

References

1. Edwards Ltd. – unpublished data
2. M.G.M. Van Der Vis, E. Cordfunke, R. Konings: The thermody-
namic properties of Tetraethoxysilane and an infra-red study of its decomposition, Journal de Physique IV, 1993, 03 (C3), pp.C3-75-C3-82
3. Safety Applications Procedure SAP 00-01 – Pumping Reduced Pressure Epitaxy (RP Epi) Applications, Edwards Ltd.
4. SEMI S18-0312 Environmental, Health and Safety Guideline for Flammable Silicon Compound, SEMI
5. MSDS #1038 (Disilane) Air Products, Pub #320-708
6. MSDS #257222 (Trimethylaluminum) Sigma-Aldrich product
#257222
7. SEMI S2-0715, Environmental, Health and Safety Guideline for
Semiconductor Manufacturing Equipment, SEMI

ANDREW CHAMBERS currently holds the position of Senior Product Manager at Edwards Ltd., Clevedon BS21 6TH, UK andrew.chambers@edwardsvacuum.com