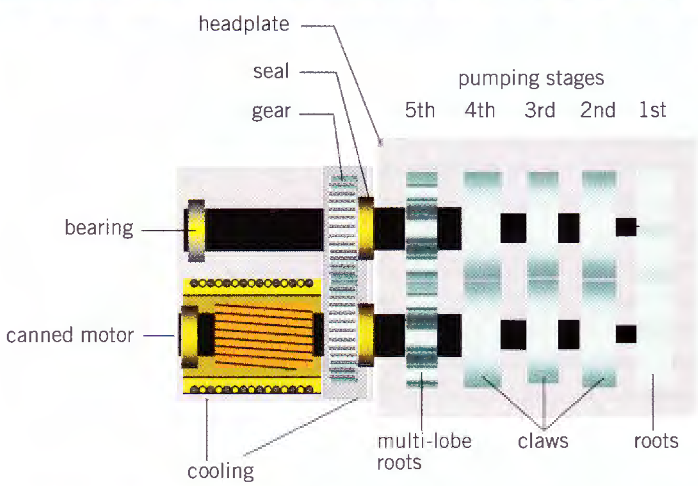
Dry pumps evolve to prevent contamination

Semiconductor manufacturers and other industrial users are demanding cleaner vacuum processing environments. Patrick Davis, Raul Abreu and Andrew Chew argue that dry pumps provide the ideal solution

Schematic of the iH80 pump



1 Schematic of the iH80 pump showing its cantilever-style design. The five pumping stages, the timing gears and the pump bearings are highlighted. Note that no bearings are located at the high-vacuum roots at the first stage of the pump.

Cleanliness is fast becoming an important factor in vacuum applications that range from semiconductor manufacturing to general industrial processing. Contamination can account for a yield loss of up to 16% in a typical semiconductor production line, with a potential profit loss of around $10 million per month.

Cleanliness is especially critical in the vacuum processing of semiconductor devices, where the main sources of contamination are submicron particles that are generated by the process tool. Other sources of contamination include moisture, process by-products and materials associated with the vacuum system, such as pump lubricants. Pumps that rely upon traditional mechanisms, such as oil-sealed rotary vane pumps and vapour pumps, are subject to a number of contamination-related issues. Not only are they sources of environmental contamination, but they also represent sources of possible contamination to the vacuum process.

When pump oils are exposed to low pressure it is normal for some of the oil, in the form of a vapour, to find a route back through the pump and appear as a contaminant in the vacuum lines. This process is known as "back-migration" and depends more on the type of lubricant than on the pump design. Vacuum applications that require a high degree of cleanliness can employ a number of techniques, such as liquid-nitrogen traps and molecular sieves, to counteract the effect of back-migration. Controlled gas bleeds at the pump inlet are also routinely used to halt back-migration and maintain clean vacuum lines.

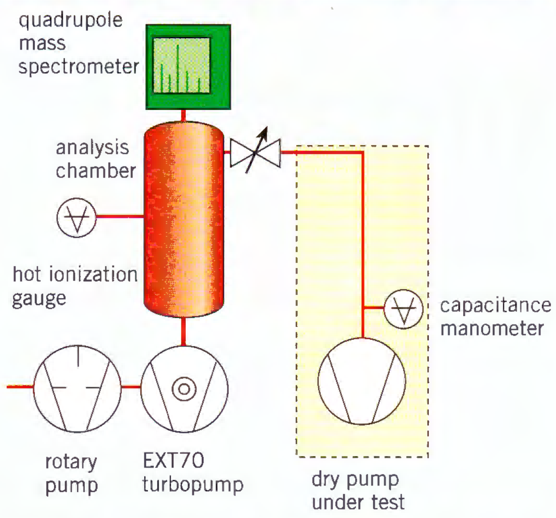
The evolution of dry pumps

The search for the ideal contamination-free semiconductor processing environment has been one of the major driving forces in the development of high-tech dry-vacuum pump technology. The generic term "dry pump" refers to those mechanisms that do not require lubricants to create a vacuum seal. This is achieved by non-contacting impellers manufactured with very close tolerances. The need to reduce lubricant contamination has resulted in the recent and rapid proliferation of dry pumping technologies based on mechanisms such as roots, claws and screws.

The swept volume of a dry pump is completely devoid of any lubricants or sealing fluids. However, these pumps do require a supply of oil and grease to lubricate mechanical components such as timing gears and bearings. The lubricating oils contained within the pump gearbox are isolated from the vacuum by high-performance dynamic or static shaft seals which prevent the transfer of vapour from the gearbox to the vacuum space. Under normal operating conditions, these seals can maintain a clean vacuum environment.

Additional gas ballast can also be used to maintain a barrier between the gearbox and the vacuum space. The gas ballast facility admits a controlled flow of either atmospheric air or a dry inert gas to points in the pump where condensation is likely. This increases the proportion of non-condensable gas, ensuring that the pumped vapour never exceeds its saturated vapour pressure and hence no condensation of material occurs. The benefits of using gas ballast are twofold: the gearbox is protected from possible

Residual gas analysis measurement



2 Schematic showing the equipment used to perform residual gas analysis measurement of the vacuum environment above commercial dry pumps.

contamination by process effluent and the vacuum space is protected from gearbox oil vapours. Such measures eliminate the possibility of back-migration at source.

An issue of even greater concern in many dry-pump designs is the presence of grease-lubricated bearings in the high-vacuum stage of the pump. This is common to more traditional pump designs, where the rotors are supported by bearings located at the extreme ends of the pump. The bearings at the high-vacuum end of the pump are indirectly exposed to the inlet high vacuum. Under these conditions it may be possible for some of the bearing lubricant – in the form of a vapour – to find a route, via back-migration, through the pump and appear as a contaminant in the vacuum lines. Reporting in volume 6 of the *Journal of Vacuum Science and Technology A* (1988), W Wong and colleagues have shown that a small inlet gas flow can be used to maintain clean vacuum lines and to suppress back-migration completely.

The contamination problems normally associated with lubricated bearings have been eliminated completely in the more advanced turbomolecular pumps. In these pumps the rotors are supported entirely by magnetic bearings which require no lubrication. The pumps are therefore completely oil-free.

Recent advances in conventional dry-pump technology have led to the development of pumps with no bearings in the high-vacuum stages. The cantilever-design pump rotors allow the two rotor-support bearings to be located inside the timing gearbox. This design is incorporated in the BOC Edwards iH and iL range of dry pumps (figure 1, page 33). The bearings are isolated from the vacuum space by a combination of shaft seals and gas ballast injection ports. Bearing-related contamination of the vacuum space is greatly reduced because the bearings are located towards the exhaust end of the pumps. The cleanliness achieved by pumps with cantilever rotors is such that no oil contamination can be detected in the vacuum using standard residual gas analysis techniques.

Contamination can account for a yield loss of up to 16% in a typical semiconductor production line

Technological advances in scroll-pump design have also resulted in much-improved general vacuum cleanliness. Pumps of this design operate with low noise and vibration; however, they do have a number of significant disadvantages. Traditionally, the orbital scroll mechanism is driven with a shaft through the central axis of the pump. This means that the shaft bearings and associated lubrication are exposed to the vacuum space, which could lead to contamination problems. This design also exposes the bearings to attack from condensed vapours and, in traditional scroll pumps, the use of gas bleeds or continuous gas ballast usually addresses these issues. A further problem associated with traditional scroll pumps is that the shaft seal used can wear over time, resulting in a pump that is not hermetically sealed.

The new BOC Edwards XDS dry-vacuum pump overcomes all these issues thanks to a number of new features in orbital scroll-pump design. The XDS has an orbiting scroll mounted eccentrically on a crank on the motor shaft. The shaft is retained by a patented bearing shield mechanism. Unlike other scroll pump designs, the motor shaft does not penetrate the vacuum space and as the bearings are held at atmospheric pressure, they are totally isolated from the vacuum space. This design ensures that the vacuum is not contaminated by oil vapour, and shields the bearings from attack by condensable materials.

Measuring pump cleanliness

Technological advances in pump design bring with them the need to evaluate improvements in the cleanliness attained. There is also the need to assess any improvements in cleanliness that come about from the inclusion of other features, such as foreline traps, purges and gas ballast. There is currently no recognized standard method to quantify the cleanliness of the vacuum generated by any particular pump. To plug this gap, BOC Edwards has developed a technique to quantify the relative amount of contamination generated in the vacuum atmosphere due to the back-migration of oil vapours from the pump.

The traditional method of measuring pump cleanliness is to use a residual gas analyser (RGA) to obtain a mass spectrum of the vacuum atmosphere at the pump inlet. The contamination is estimated from the partial pressures of contaminating species. However, measurements performed in this manner are subjective and susceptible to changes in pump ultimate pressure, temperature fluctuations and drift of the analyser signal.

A standardized residual gas analysis technique has been developed to measure the relative cleanliness of

There is at present no recognized standard way to quantify the cleanliness of a vacuum

the vacuum atmosphere. This provides a means to quantify the effectiveness of steps taken to improve the cleanliness of the vacuum atmosphere. It also allows different pumps to be directly compared.

Figure 2 on page 34 provides a schematic of the equipment used to measure the vacuum atmosphere at the pump inlet. Residual gas analysis is performed using a quadrupole mass spectrometer (QMS). A BOC Edwards EXT70 turbomolecular pump, backed by an alumina-trapped two-stage rotary pump, is used to evacuate the analysis chamber. The chamber is connected, via a fine leak valve (FLV), to a 1 m flexible foreline that is in turn connected to the opposite end to the pump inlet. A capacitance manometer pressure gauge is connected to the foreline and used to monitor the ultimate pressure attained by the pump. The vacuum atmosphere in the foreline is continuously sampled at approximately 7.0×10^{-5} Torr l s^{-1}. All the vacuum system components, fittings and gauges are clean at the start of each test.

The low-vapour pressure greases and lubricating oils used in modern vacuum pumps are predominantly of the perfluoropolyether (PFPE) variety. The mass-spectra cracking patterns for these lubricants are quite distinctive and readily identifiable. A relative measurement of pump cleanliness is obtained by measuring the partial pressure at the lubricant's main mass-spectral peak corresponding to CF_3^+ at mass 69.

A reference partial pressure of hydrogen – present in all vacuum systems – is measured at mass 2. Hydrogen provides an ideal reference because PFPE lubricants do not contain any hydrogen, and therefore do not contribute to partial pressure measurements at mass 2. Furthermore, the partial pressure measured at mass 2 in the vacuum atmosphere above a selection of dry pumps, of disparate construction but comparable ultimate pressures, has been found to be similar.

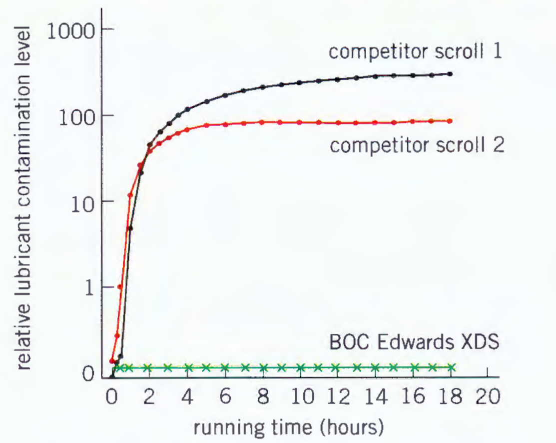
The vacuum atmosphere at the pump inlet is monitored over a number of hours from a cold start, and the partial pressures at masses 2 and 69 are measured continuously. The pump-related contamination will stabilize to equilibrium after several hours at the system's ultimate pressure.

Pump comparisons

The BOC Edwards XDS dry pump has been compared with two scroll pumps from other companies. All three pumps were run in accordance with the manufacturer's recommended operating parameters, and ballast and seal purges were activated where fitted. The vacuum atmosphere attained by each pump was monitored from a cold start followed by 18 hours at ultimate pressure. The relative cleanliness – the ratio of partial pressure at mass 69 to that at mass 2 – was calculated and the results plotted in figure 3.

The cleanliness achieved by the XDS dry pump is such that the relative cleanliness measurement remained at the background level throughout the exercise. In contrast, the competitors' scroll pumps,

Lubricant contamination



3 Comparison of the relative lubricant contamination measured in the vacuum environment above three different commercial scroll pumps, from a cold start-up to a total of 18 hours running at ultimate pressure.

which have bearings exposed to the vacuum space, showed significantly higher levels of contamination in the vacuum atmosphere.

In order to confirm the reliability of the results presented in figure 3, a number of conventional mass-spectra measurements were taken after the 18-hour period. These included measurements of the vacuum atmosphere above the pump called "scroll 1" and the XDS dry pump. The partial pressures measured at mass 2 are of the same magnitude. However, the partial pressure measured at mass 69 is undetectable to the order of 10^{-10} Torr in the vacuum atmosphere above the XDS. This is in stark contrast to the partial pressure of 2.7×10^{-9} Torr measured at mass 69 above "scroll 1". It is clear that the XDS generates an extremely clean vacuum when compared with scroll pumps of a more traditional design. Cleanliness is around a thousand times greater when using a hermetically sealed vacuum space.

This cleanliness-measurement technique is relevant across the range of dry-pump products. It has been used successfully to measure the vacuum environments generated by a wide range of pumping mechanisms and provides a reliable method to qualify improvements due to pump design, manufacture and use. Development and application of the technique were recently detailed in a presentation and scientific paper at the American Vacuum Society's 46th International Symposium 1999 in Seattle (*"Dry Vacuum Pumps – A Method for the Evaluation of the Degree of Dry", R.P. Davis, R.A. Abreu and A.D. Chew*). Our work continues to formalize this approach and to produce a fully standardized model.

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