by Jennifer Ouellette

Contamination Control in Vacuum

As silicon device densities increase and dimensions become ever smaller, the semiconductor industry is striving to control contamination in vacuum manufacturing environments to increase product yields and profit margins. Vacuum technology companies are exploring the use of magnetically levitated devices, which use unlubricated bearings to reduce friction between vacuum components, *in situ* monitoring systems, and experiments and computer simulations to better understand the behavior of particles in a vacuum processing system.

While vacuum technology is used primarily to provide the proper environment for certain manufacturing processes, its usefulness in contamination control cannot be overlooked. Controlling secondary contamination is particularly important for many manufacturing industries that use metal deposition and thin-film technology, such as tool coatings, architectural glass, camera and laser lens coatings, and aluminized plastic food packaging. It is also a key factor in surface science and high-energy accelerator physics applications, where even minute degrees of contamination disrupt measurements. In fact, the success of the $1.2 billion National Ignition Facility under construction at the Lawrence Livermore National Laboratory (LLNL) in Livermore, California, is highly dependent on both vacuum and atmospheric related contamination control, according to Howard Patton, a specialist in vacuum contamination control at LLNL.

In the semiconductor industry, contamination control is one of the key aspects of yield management, since improving a fabrication facility's yield by just a few percent can result in millions of dollars in increased profits. Allan Bowling, director of process development for Texas Instruments' R&D fabrication facility, reports that an estimated 80% of equipment failures in silicon wafer process lines arise from contamination-related defects. Since most wafer fabrication lines average an 80% yield, as much as 16% of the total loss of yield may be due to contamination. Each 1% yield loss can account for a profit loss of between $1 million and $5 million each month for a single fab line. Thus, using the more conservative estimate, a single fab line can lose $15 million each month from contamination-related defects.

Definitions of contamination and ways of controlling it depend on whether the application is high-tech, as in the particle accelerator and semiconductor industries, or low-tech, as in the consumer manufacturing and coating industry.

For low-tech industries there are essentially four different types of contamination associated with vacuum system technology, according to Mike McKeown of the Kurt J. Lesker Company (Clairton, PA): pump contamination arising from the oils used to lubricate the parts; residual air and finger grease; outgassing fixtures; and process materials or gases resulting from aluminum etch processes used in the semiconductor industry, such as the formation of contaminating particles as the gas reacts with other materials.

By comparison, contamination concerns in the semiconductor industry are more complex. These include: trace outgassing primarily of water vapor; permeation of water through O-rings, polymeric windows, and high-temperature quartz furnace walls; friction-generated wear between wafer handlers and wafers; particles flaking from deposition shields; particle generation from wafer clamps when moved; gas phase microscopic particle generated in deposition systems; plasma etch products, which condense and form particles; arcing in ion implanters; adiabatic expansion of water during pumping from the atmosphere, which forms a water aerosol; and electromagnetic trapping of particles in rings and domes above wafers in plasma-processing chambers.

Existing methods

Some contamination problems in low-tech applications are easily remedied. For example, many plastics used to manufacture parts in vacuum systems (such as Teflon) have high outgassing rates, as do certain metals, including the cadmium used in brazes or as plating. Overheating such a part may enhance this effect. Thus, only vacuumcompatible materials with relatively low outgassing rates are used in high-vacuum systems. These include glass, Pyrex, silicon quartz, and stainless steels using elements such as titanium as a stabilizer and avoiding alloys containing selenium or sulfur.

In contrast, contamination related to pumping mechanisms is more complex and difficult to remedy. Standard pumps use lubricants that often produce oil vapor, which then backstreams into the vacuum chamber. Liquid nitrogen traps or molecular sieves, for example, may be used to stop the oil vapor from the mechanical pump from getting into the high-vacuum pump, according to McKeown. A disadvantage of using a liquid nitrogen trap, which freezes the oil vapor and prevents it from backstreaming, is that it can become a secondary contamination source if it gets too hot.

In addition, foreline traps are used to prevent the etch effluent from condensing in the pump and destroying it. Etch residues, such as aluminum trichloride and boron trichloride, are usually solids below 70-80° C, so heat is needed to keep them in the vapor state until they are pumped out of the chamber and pumping lines between the chamber and the pump stack, as well as the pressure gauging lines.

Standard foreline traps typically employ either a knockdown plate—a perilous path into which the gas flows, settling out the particles as it flows through—cooling coils, or particle filters. Nor-Cal (Yreka, CA), a leading supplier of vacuum parts, has combined the knockdown plate and stainless steel particle filter aspects in their custom foreline traps, in conjunction with heater jackets, to reduce defects on silicon wafers. The jackets raise the temperature of the stainless steel vacuum components and valves on the exhaust end of the tool, reducing the number of particle-related surface defects per square inch on the wafer, as well as extending preventive maintenance intervals from 7 runs to as many as 21 runs.

While such solutions, properly implemented, are effective in controlling contamination for more low-tech vacuum applications, the semiconductor industry is increasingly seeking to avoid pump contamination problems by turning to dry pump technology, which employs little, if any, lubricating oil. This is hardly surprising, given the contamination problems associated with oil-lubricated pumps. In fact, many new wafer fabrication facilities are switching exclusively to dry pumps, according to Bowling, even though these can cost as much as 4 to 6 times more than equivalent-sized oil pumps.

Among semiconductor manufacturers, the most popular dry pump technology for vacuum applications includes the claw, scroll, and screw pumps, which do not use oil as a seal or lubricant inside the vacuum pump and can withstand the corrosive gases and contaminating particles that may be deposited inside them during the vacuum process. Dry piston pumps, which are lubricated by coating one surface with Teflon and the other with aluminum, are no longer used much by the semiconductor industry. Not only do they have a lower pumping speed and require more frequent cleaning, but they tend to generate large amounts of particles themselves. Diaphragm pumps also have low pumping speeds and are typically used as back-ups for more high-vacuum primary pumping systems, according to McKeown.

Future solutions

The vacuum industry has demonstrated a growing interest in developing magnetically levitated devices. An important advantage of magnetically levitated pumps is that, like dry pumps, they eliminate the need for oil lubrication while still reducing friction between vacuum system components. For example, Edwards High Vacuum International (Wilmington, MA) offers oil-free turbomolecular pumps in which the rotor is suspended entirely by magnetic bearings. This eliminates the need for hydrocarbon lubricants and prevents contamination of the vacuum process from the pump.

“All contact between the rotor and the remainder of the pump is eliminated,” said Mike Mangione, the company’s marketing communications specialist. “In addition to giving very low vibration, the elimination of contact means no bearing wear and no requirement for consequent pump maintenance." To avoid particulate deposition, a problem encountered in many semiconductor deposition processes, a temperature management system must be used to maintain the internal surfaces of pumps and pumping lines at sufficiently high temperatures to prevent condensation of by-products such as aluminum trichloride. With no countermeasures, by-products would build up in the lower compression stages of the turbopump rotor, leading to pump failure, according to Mangione.

Lesker offers a levitated sample positioner, and Patton reports that such industry giants as Intel, Toshiba, and Hewlett-Packard are considering using hermetically sealed, pressurized cylinders instead of motorized sample positioners inside vacuum chambers to avoid the outgassing contamination usually associated with motors. However, Bowling said that for the most part, the semiconductor industry is relying on proven technology for contamination control. "People are certainly thinking about new approaches to levitation, but I don't think any of them are seriously viable yet," he said.

Advanced Fluid Systems (Dallas, TX) offers a wide range of magnetic fluid seals for vacuum systems. These use magnetic particles suspended in a carrier fluid which, when subjected to a magnetic force, can be made to form a liquid O-ring around a rotating shaft, producing a hermetic seal without damaging the vacuum or reducing the process purity. When installed adjacent to a bearing in vacuum systems, the seals protect bearings from the ingress of particles or gases. Furthermore, since the sealing method doesn't create friction between parts, there is no shaft wear from the seal. Lip seals, in contrast, rely on rubbing for their sealing capability, which ultimately causes wear-generating debris.

AFS is developing this technology for use in the robotic arm that transports silicon wafers within cluster tools, a movement that must not generate particles between the vacuum chambers in the fab line. Another emerging application is in the dry high-vacuum mechanical pumps favored by the semiconductor industry. The seals can protect the pumps from corrosive gases and exclude contaminating particles from the pump's bearing.

The use of in-chamber robotics is another area of interest for the future. Most wafer fabrication facilities currently employ several optically based wafer inspection systems in their process lines, in which a laser beam is scanned across the surface of a wafer to detect contamination defects in the patterning. According to Bowling, the industry is also interested in developing *in situ* particle monitoring systems to reduce contamination in real time within the vacuum chamber itself. Texas Instruments has implemented such monitors in pumping lines to measure particles in the gas streams emitted from the vacuum chambers. However, "We would love to be able to figure out how to actually measure the contaminants coming to the wafer surface during the processing itself, but we don't have adequate tools to do that just yet," said Bowling. "Once we understand the fundamentals, we may be able to implement some additional control mechanisms within the vacuum chamber."

Gary Selwyn (Los Alamos National Laboratory) is one researcher who is making significant strides in understanding particle behavior, especially those produced in plasma etch processing systems used by the semiconductor industry. Specifically, he has developed detection techniques using laser scattering to monitor the movement and behavior of particles inside the plasma chamber. For example, he discovered that the plasmas used for processing tend to generate particles suspended above the wafer surface, which are then deposited on the wafer when the gas flow and the plasma are turned off simultaneously. By changing the gas flow as the plasma is turned off, he found that it could be used to sweep the particles out of the region so that they are not deposited on the wafer.

Mark Kushner, a professor at the University of Illinois, Urbana-Champaign, has used Selwyn's experiments as the basis for his computer models of the mechanisms of contamination control in vacuum systems. While in general there has been good agreement between the observed behavior of particles and the predictions made by the computer simulations, "The computer model is only as good as the physics, and the physics hasn't been all that well understood," said Selwyn. Nevertheless, improvements are constantly being made to make the computer models more accurate.

While large particles in the range of 1 to 50 microns can still pose problems in the semiconductor industry, Selwyn believes that the focus will shift to *in situ* monitoring of very small submicron particles in the future, for which there are no existing detection techniques. This poses significant challenges for the computer modeling of such behavior, since a particle less than 0.1 micron has very few negative electrical charges that govern its behavior, unlike a 1-micron particle, which can have as many as 10^4 electrical charges. Because of this, the natural fluctuations that occur during processing could change to no charge or even a positive charge during various parts of the cycle, dramatically impacting the predictions of the models.