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New Techniques Move In Situ Particle Monitoring Closer to the Wafer

In situ particle monitors evolve into semiconductor yield-enhancing process control tools.

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Key Technologies:

- **Contamination control**
- **In situ particle monitoring**
- **Process control**

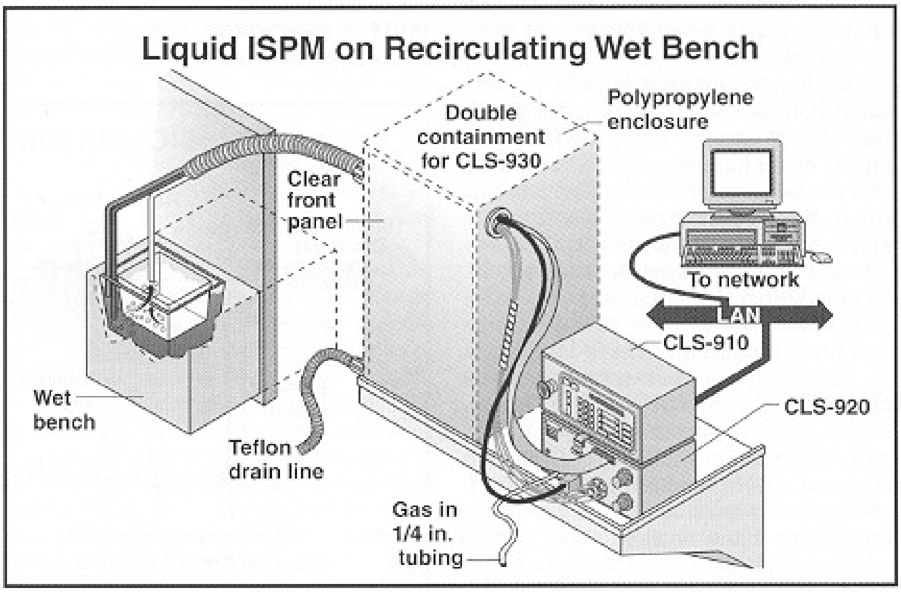
At A Glance:

The traditional particle monitoring done in cleanroom areas has changed from an integral part of improving process yields to a quality control (QC) measurement in order to ensure that the particle concentrations are below control limits. Real-time in situ particle monitors are a continuation of this evolution; technological advances permit their use in process control functions.

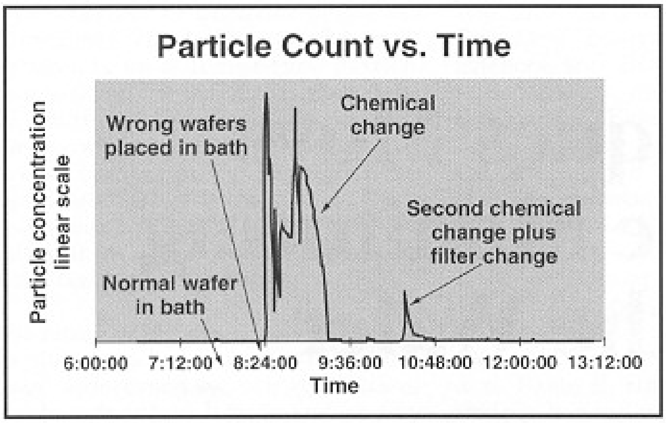
State-of-the-art cleanrooms and procedures used by semiconductor manufacturers have reduced particle levels to such low concentrations that yield loss resulting from particles in the cleanroom environment is almost negligible. Similarly, ultrapure water systems, raw gases and many of the process chemicals supplied to the manufacturers are exceedingly clean. The requirements of microcontamination control, however, are still evolving. Semiconductor fabricators are building or refitting manufacturing lines that use larger wafers; their increased value causes more money to be lost from the use of witness wafers, process tool downtime and product scrapped because of process anomalies. To reduce these costs, real-time monitoring of the process environment using in situ particle monitors (ISPMs) will be needed. Future emphasis in contamination control will change from a QC measurement to a process control measurement. This article reviews some recent technological developments with in situ monitoring, in particular its use as applied to liquid process chemicals and innovations in vacuum process sensors.

Benefits from ISPMs

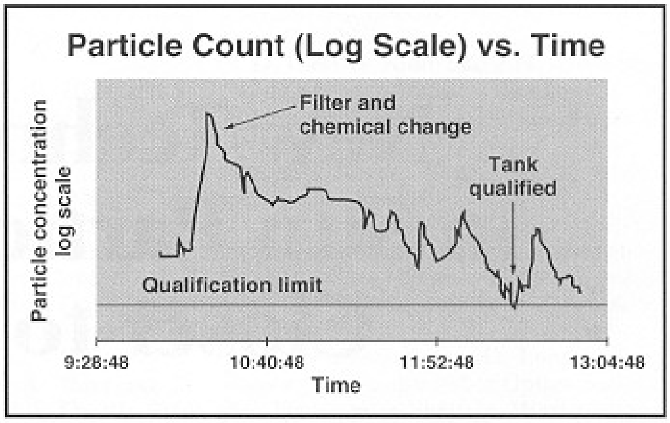
The financial benefits from using ISPMs can be separated into at least four broad categories. The first and most apparently lucrative category is yield enhancement. Data from ISPMs



1. Liquid ISPM on a recirculating wet bench.



2a. ISPM particle data detects improper wafers placed in bath.



2b. Clean up of HF bath after particle disaster.

is used to monitor, modify and control processes so the yield loss from particles is reduced. Although Pham et al. were able to correlate yield to ISPM data[1] using an exhaust line sensor, their study was an exception. The vast majority of studies have either not looked for a correlation to yield[4-6] or found no relationship.[2,3] Monitoring one tool used in a manufacturing process with hundreds of steps and expecting to see a correlation may be unrealistic for some tools.

A second cost savings comes from eliminating particle test wafers,[1] saving the cost of the test wafer and the time needed to run and inspect the test wafer. Larger test wafers are more expensive.[7]

A third cost advantage is throughput enhancement.[5] ISPMs can improve throughput by using particle data to lengthen maintenance cycles and by enabling faster requalification of tools after a PM.

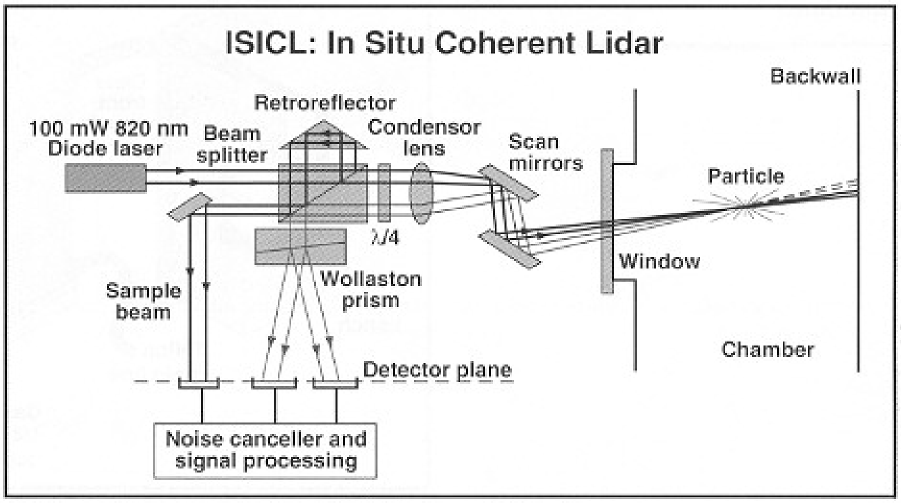
The fourth financial benefit is from the use of an ISPM as a disaster monitor.[2,4] When a tool is badly malfunctioning, it often happens that many particles are generated. Examples include a filter not seated properly on a wet bench, a broken wafer or a bad susceptor on a chemical vapor deposition tool. Several lots of product may be processed before a witness wafer is run and tested, and all of these lots might be scrapped; one disaster can cost as much as several ISPMs. ISPMs can detect gross contamination in real time and minimize product loss. This is a type of yield enhancement, even though focus is on identifying and fixing the problem with the tool before additional product is lost as opposed to modifying the process to improve yield. However, disasters can't be predicted, so the benefit of ISPMs as disaster monitors is difficult to quantify.

The term "in situ particle monitor" historically has primarily referred to monitors on exhaust lines of vacuum process tools. However, exhaust line sensors currently account for only a small percentage of total particle monitoring equipment, perhaps because users cannot simply purchase an exhaust line sensor, plug it in on a new application and use it as they had the more traditional particle counters. Almost every tool and every process recipe dictates a different set of requirements for an ISPM. Having to optimize ISPM performance for each tool slows the growth of their widespread use. A large number of successful applications have been developed, however, and this number continues to increase.

ISPMs for wet processes

Although particle monitors for liquids have been used for some time on chemical delivery and reprocessing systems, their application to wet benches is a relatively recent development; the first published work on the subject (by Hess et al.[9]) appeared this year. Liquid particle monitoring systems are able to monitor particles in a fluid that is in intimate contact with the wafer, and they make it possible to sample the fluid very close to the wafers being processed. The particles that are counted, therefore, are likely to be of interest. Measurements in liquids can be made in units of particles per unit volume so data can be compared from tool to tool. Liquid monitors are easy to install since there is no need to shut down a tool, break vacuum and fit a sensor into a vacuum system. All one needs is enough space to insert a sample line and a return line into the bath.

Many liquid processes use corrosive fluids, including HF and H_2SO_4, often at elevated temperatures. Liquid



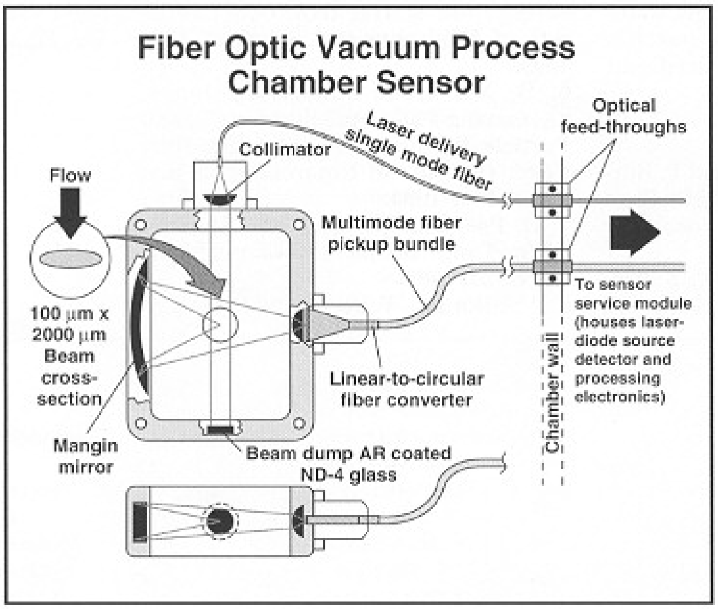
3. Schematic representation of in situ coherent lidar.[11]

particle counters must be compatible with these chemicals at temperatures up to 150°C. Safety issues become a very important design consideration. All of the liquid handling must be done in a double containment vessel and the vessel purged with N_2. Sensors need to continually monitor the liquid level at several points; if any anomalies are detected the instrument is immediately placed in a safe condition and shut down.

Other requirements are similar for all ISPMs. The counters should be sensitive to particle sizes near 0.3 µm; as feature sizes decrease the sensitivity needs to be improved to 0.1 µm. Since ISPMs run almost continuously, they must operate unattended. The data obtained must be available over a network or by some other remote means so that contamination control personnel don't need to enter the cleanroom to monitor the process. A sensor must be very reliable; for an ISPM to decrease tool uptime is unacceptable.

Obtaining samples

There are two ways to extract samples from wet benches. The first way is called the "sampling" method, in which a sampler extracts the sample fluid from the bath, pressurizes the sample and then injects it into the particle counter. The sample must be pressurized to prevent the formation of bubbles which occur in effervescent fluids such as hydrogen peroxide. Bubbles appear to most optical particle counters as particles and therefore must be eliminated.



4. Schematic representation of fiber optic sensor.

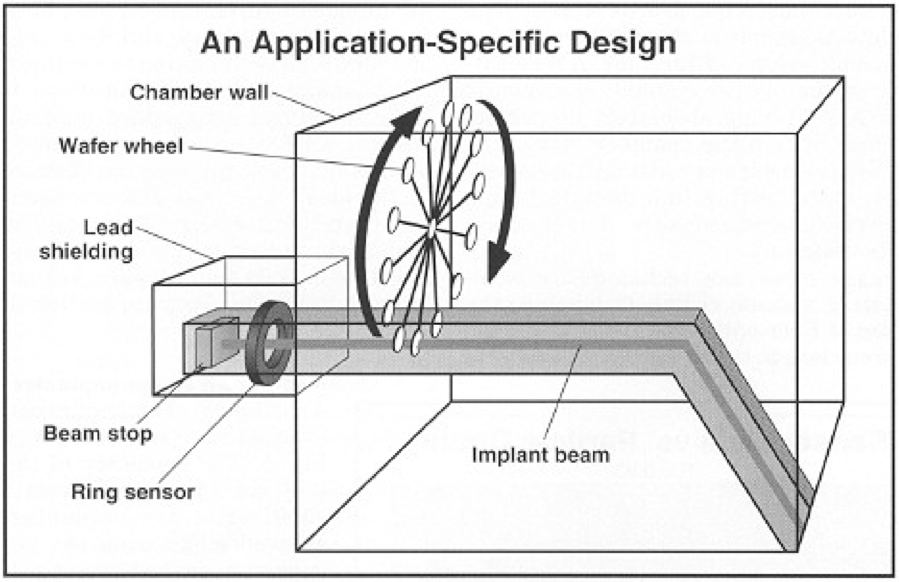
The second method, the "in-line" method, consists of plumbing the counter in-line in the recirculation system so that sample is pressurized by the recirculation pump. However, pressurizing the sample requires the counter to be downstream of the pump — and pumps produce particles. To eliminate these pump-produced particles the particle counter must be downstream from a filter which is between the sensor and the pump. A fraction of the particles will penetrate the filter so the data will still give an indication of the number of particles in the bath; however, the number of particles is greatly reduced. This technique is only suitable for process baths like SC1 that contain high particle concentrations. HF baths are relatively particle free and are less suitable for an in-line sampling system. Also, the data from an in-line system is a superposition of the filter performance and the number of particles in the bath so the particle data varies as filter performance changes over the life of the filter. Since the filter acts as a reservoir for both fluid and particles, time response deteriorates and short duration events get smoothed out.

For a single-sensor system, the in-line type can be the less expensive method. Fluid samplers and controllers are sophisticated devices that can cost almost as much as a sensor. For multiple sensor systems the cost of the controller can be spread over several sensors, so a sampling system cost becomes similar to that of an in-line system. Since the sample is taken immediately after the filter, particle data may be able to predict filter breakthrough. The continuous nature of the sampling is also preferable for some applications. The advantages of sampling are that no filter is needed upstream from the sensor so cleaner baths can be monitored, the time response is much faster, and data measurement does not depend on the filter performance. Sampling systems provide flexibility in the sampling location and the timing of the sampling can be coordinated with tool events. A sample can be drawn from the area that has the highest particle concentration for a worst case, or from an area close to the wafers being processed. Using a sampling system, non-recirculating baths can be monitored; controlling flow rate and pressure and reducing bubbles is more straightforward.

Description of a sampling system

Figure 1 illustrates a liquid ISPM using a sampler on a recirculating wet bench. The sample is drawn out of the bath by the sampler, which in this case is shown as a Particle Measuring Systems CLS-930 chemical fluidics module. This module contains the sampler plumbing and a particle sensor. The selection of the particle sensor is based on the sensitivity, resolution and flow rate required. Fluid passes through a sample buret and overflows into an overflow chamber, flushing any remaining particles from the sample buret and eliminating contamination problems associated with a liquid-gas meniscus layer. When the buret is filled, the inlet valve is closed and the overflow chamber is allowed to drain. Once the overflow chamber is drained, the sample is held under pressure to force any remaining bubbles back into solution. After a compression delay to let the sample reach perhaps 60 psi (depending on the sample chemistry) the sensor valve is opened and the sample is forced through the particle spectrometer at a known flow rate and pressure. When this is completed the sensor valve is closed and the pressurized lines are vented. All fluids are returned to the recirculation system of the chemical bath. The fluidics module is controlled by two other modules that communicate with the wet bench, coordinate the sampling and transmit data to the remotely located data collection system.

The system shown is outside the wet station and mounted above the wet bench to prevent the possibility of siphoning in the event of a catastrophic failure. A Teflon drain line connects the double containment vessel to the existing drain system of the wet bench;



5a. Schematic diagram of Applied Materials' 9500 series implanter and position of ring sensor.

the particle sensor is purged with nitrogen. Liquid ISPMs can be integrated into wet process tools to simplify system plumbing and fluid containment.

A case history

As an example, ISPM systems were installed on several of a semiconductor manufacturer's HF tanks as a tool to increase productivity. Prior to installing the ISPM systems, qualifying the tank required calling in a person from contamination control to bring down a liquid particle counter and check the bath; the tool remained idle until the check was complete. The company required the tanks' particle concentration to be below a control limit after a process chemical change. Now the dedicated ISPM automatically checks the particle concentration in the bath; as soon as the concentration is below the control limit the technician can run product. The downtime of the bath was minimized and the work load for the contamination control group was reduced. In some cases tank process chemical changes can occur as often as every four hours, so reducing downtime after a change can significantly affect the throughput of a tool.

Disaster monitoring with ISPMs

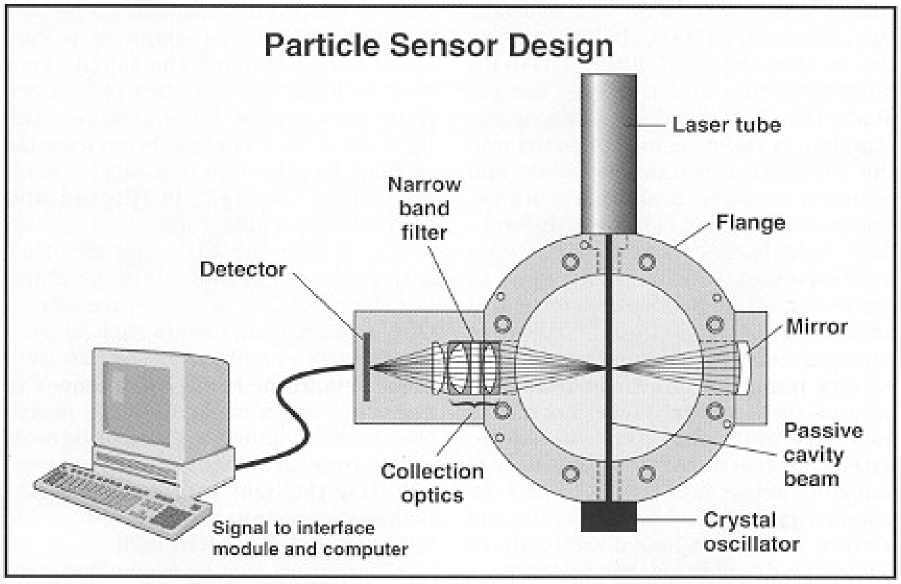
In addition to increased productivity the ISPM serves as a real-time disaster monitor (Fig. 2). The particle background is very low in Fig. 2a until the wrong type of wafers were placed in the bath; then the concentration increased dramatically. An ISPM detected the problem and no additional lots were run until the chemical was changed; the particle counts then dropped dramatically. Without the ISPM several lots of product would have been processed before the problem was detected. The savings from this incident alone was more than five times the cost of the ISPM.

The data for the second chemical change in Fig. 2a (the small peak on the right) is replotted on a log scale in Fig. 2b. After the chemical change the concentration slowly dropped to the qualification limit and product was processed shortly thereafter. In a similar way a sensor can be used to minimize the interval between processing lots. The purchase of the ISPMs was justified by the increased productivity; the savings from detecting process anomalies was an additional bonus.

These examples show that liquid ISPMs are already more than QC instruments and that they are currently used in process control. Their role in process control will be expanded as users gain experience with them.

In situ monitors for vacuum tools

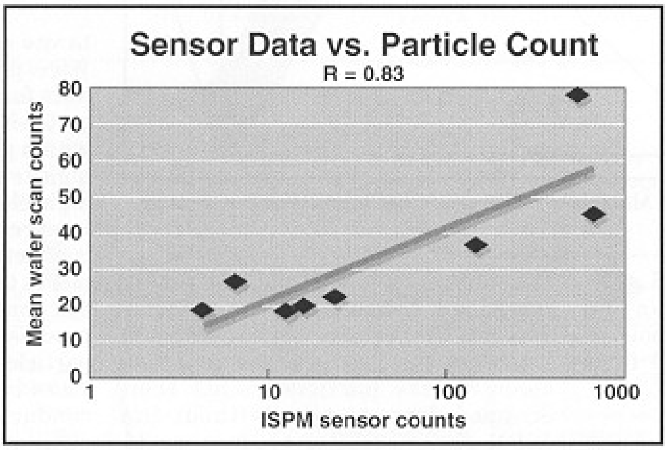
Widespread application of in situ monitors for vacuum tools has been limited by their technology. The environment within process tools can be very harsh; high temperatures, corrosive species, high electromagnetic fields and very low pressures are found in many semiconductor vacuum processes. Instruments that are currently used to monitor contaminants in semiconductor processes use light scattering to size particles. The type of light source for these instruments is typically a semiconductor diode laser (SDL). While other sources can be used, these lasers are chosen because of their low cost, small size and relatively high brightness. SDLs, however, are not able to withstand the harsh environment inside of many semiconductor process tools. In particular, high temperature severely shortens the life of SDLs: an operating temperature of 60°C will



5b. The ion beam goes through the center of this beamline sensor in this design.

reduce the life of an SDL by a factor of ten.[10] This limits the location of monitors that use these lasers and thereby the usefulness of the instruments.

A particle counter's ability to monitor contamination in process tools is determined by the particle size detection limit, the size of the sample zone and the location of the sample zone. It is generally believed that best results are produced by monitoring particles in close proximity to the wafer being processed. Since SDLs cannot withstand the harsh environments found within many process tools, the location of the sample area must be moved so the SDL can be located outside of the process tool and directed through a window into the process environment. This usually means the particle counter is located in an exhaust line, far from the wafer being processed. The exhaust line is useless for low pressure applications because particles are not transported by the remaining gas; instead, the particles simply fall (due to gravity) or are transported by electric fields. If a particle monitor is not located near the semiconductor wafer being processed it may not be able to see any particles that could affect the wafer.



6. Particles added to test wafers (as a result of an implant process) vs. ISPM counts.

There are at least two techniques now being developed to address the shortcomings of vacuum ISPMs. One was developed by IBM[11] and called in situ coherent LIDAR (ISICL). All of the in situ coherent lidar (LIDAR= light detection and ranging) components (Fig. 3) remain outside of the chamber. A laser beam is directed into the chamber through a window and scanned to form a sample volume. Coherent detection is used to differentiate light backscattered by particles from other extraneous light, such as scattering off of chamber surfaces and process generated light.[11] Because backscattering is used only one small window is needed; the windows used on process tools typically are more than adequate and could even be shared with other instruments such as optical endpoint detectors. The beam can be scanned in any desired direction and pattern so one can look directly above the wafer. In addition, the instrument is capable of mapping the location where particles are detected. The detection limit is about 0.3 μm with a sample volume of 30 cc/min. A schematic of the optical system[11] is shown in Fig. 3. Having absolutely no components within the chamber makes the ISICL sensor very attractive; however, more testing in a manufacturing environment needs to be done to assess its usefulness.

The other new technique for monitoring vacuum chambers involves the use of fiber optics to move the sample area close to the wafer.[12] A representation of the fiber sensor is shown in Fig. 4. The output from a laser diode is coupled into a single mode fiber which carries light through a vacuum feedthrough into the chamber. There the light emerges from the fiber, is rectangularly shaped by means of a lens, and is directed through a sample area. Particles falling through the sample area scatter light which is focused onto a fiber bundle. The bundle carries the light out of the chamber through another fiber feedthrough to a service module where the light is filtered and focused onto a detector.

By moving the SDL and all other active components outside of the chamber the reliability problems are solved. Only passive components such as lenses are in the chamber and they are able to withstand the harsh conditions. The remote location of the detector makes the system immune to electromagnetic noise generated by some processes. Filtering the light before the detector makes the system insensitive to noise from process generated light.

Fiber optics may be used effectively with various sensor designs. Each tool has unique requirements for size, form factor and sensitivity. Building only one sensor and attempting to shoehorn it into many different applications is difficult and may not produce optimum results. As a result, a unique sensor head is designed for each application. In the ideal case these sensors would be integrated into the process tool. The components outside of the chamber, the interface module and software, remain basically the same from application to application.

A sensor on an ion implanter

An example of an application specific design is shown in Fig. 5. The geometry of the tool, an Applied Materials 9500 series ion implanter, allowed monitoring the ion implant beam and keeping all the active components outside the chamber without having to use fiber optics. The 9500 series operates at a pressure of about 10-7 Torr, so particles either fall due to gravity or are transported by the electrostatic forces of the ion beam. A spoked wheel is used to hold the wafers; as the wheel spins the implant beam alternately strikes the wafers and passes through to the beam stop. A ring sensor was inserted between the wheel and the beamstop, as shown in Fig. 5a. The sensor is shaped like a flange or ring, as shown in Fig. 5b; the ion beam goes through the center of the ring. The particle sensor incorporates a HeNe laser which pumps a passive cavity that has a circulating power of about 3-5 W (i.e. the resonant cavity increases the illumination on the particle to that of a 3-5 W laser). This type of system is used in aerosol particle counters because the high optical power produces good size sensitivity and the passive cavity is very reliable. Scattered light from the particle is collected, collimated, filtered by a narrow band optical filter to reject the glow from the implant beam and then focused onto a detector.

Results from a prototype are shown in Fig. 6; the sensor data is plotted against particles added to wafers. Three witness wafers were used for each test in Applied's development lab; the number plotted is the average of the three wafers in eight tests for a total of 24 wafer scans. With just a few data points a correlation coefficient

R = 0.83 was obtained between the mean number of particles added (as determined from before and after measurements on a Tencor-type particle counter) and the ISPM particle counts. In addition to the wafer data, the sensor was able to identify particle related events such as arcing of the implant beam, mis-tuning of the implant beam and spin-up of the wafer wheel. This initial data appears very promising; more testing is in progress.

The future of ISPMs

In situ particle monitors will become more widespread as their applications are broadened to liquids and as new technologies enable effective vacuum chamber particle monitoring. As wafer diameters increase, in situ particle monitoring provides accelerated cost advantages.

References

1. H.D. Pham, M. Elzingre and P. Borden, "LSI Logic Proves Yield Gain Using In Situ Monitor," *Semiconductor International*, April 1995.
2. B. Fardi, B.S. MacGibbon, S. Tripathi and F. Moghadam, "Feasibility of an in situ Particle Monitor on a Tungsten LPCVD Reactor," *Proc. of 41st Tech. Conf.*, Institute of Environmental Sciences, May 1995.
3. B. Fardi, C. Sirovy, B. Huff and F. Moghadam, "Feasibility of an in situ Particle Monitor on a PECVD Reactor," *Proc. of 41st Tech. Conf.*, Institute of Environmental Sciences, May 1995.
4. T. Winter, R. Woodward, P. Niemyski and T. Fu, "AMT P5000 W CVD Reactor Diagnosis and Control with ISPM," *Proc. of 41st Tech. Conf.*, Institute of Environmental Sciences, May 1995.
5. S. Fang, B. Hallet, A. Merriam, C. Musilli, P. Foglieti and T. Fu, "In Situ Particle Monitor at LPCVD Poly Furnace," *Proc. of 41st Tech. Conf.*, Institute of Environmental Sciences, May 1995.
6. D. McCarron and M. A. Jones, "Achieving Full Capability from in situ Particle Monitors," *Proc. of 39th Tech. Conf.*, Institute of Environmental Sciences, May 1993.
7. O. Port and W. Winkler, "Running Wafer Thin," *Business Week*, pp. 82-83, March 25, 1996.
8. P. G. Borden, Y. Baron and B. McGinley, "Monitoring Particles in Vacuum-Process Equipment," *Microcontamination*, Oct. 1987.
9. D. Hess, S. Klem and J.M. Grobelny, "Using in situ Particle Monitoring to Optimize Cleaning Bath Performance," *Micro*, Jan. 1996.
10. *1994 Laser Diode User Manual*, Sharp Electronics.
11. P.C.D. Hobbs, "ISICL: In Situ Coherent lidar for Particle Detection in Semiconductor-Processing Equipment," *Applied Optics*, Vol. 34 No. 9, March 20 1995.
12. R.G. Knollenberg, D. Long and S. Lopez, "An in situ Fiber Optics Sensor for Monitoring Particle Microcontamination During an IBS Optical Coating Process," *OSA Technical Digest*, Vol. 17, 1995.

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