

# Self-Analysis of CCD Image Sensors using Dark Current Spectroscopy

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CCD image sensors are known to be very sensitive to contaminants in the fabrication process. "White spot defects," for example, are ascribed to heavy metals. We have exploited this sensitivity to develop a useful tool for investigating dark current in the image sensors themselves. By integrating over a number of frame times and analyzing pixel statistics, it is possible to observe quantized dark current from individual deep-level traps present in the imager, as shown in Fig. 1 [1,2]. These traps are Poisson-distributed among the imager pixels and may result from contamination in the starting substrates or the fabrication process. The detection sensitivity of this technique can be below  $10^9$  traps/cm<sup>3</sup>. By combining dark current analysis with investigations of deliberate imager contamination [3], we have found at least four deep-level traps and have identified three due to Au, Co, and Ni. We have measured the temperature dependence of these traps and determined their distinctive dark current generation rates. Our results show that as few as three Co or Ni traps in a pixel can produce a white spot or dim point defect that can affect device performance or yield.

Using this method of imager analysis, which we call dark current spectroscopy, one can nondestructively monitor production runs of imagers for the presence of such contaminants at levels below those currently thought to affect yield.

- [1] R. D. McGrath, J. Doty, G. Lupino, G. Ricker, and J. Vallerger, "Counting of deep-level traps using a charge-coupled device," *IEEE Trans. Electron Devices*, vol. ED-34, pp. 2555-2557, 1987.
- [2] W. C. McColgin, J. P. Lavine, J. Kyan, D. N. Nichols, and C. V. Stancampiano, "Dark current quantization in CCD image sensors," *IEDM Tech. Digest*, pp. 113-116, Dec. 1992.
- [3] W. C. McColgin, J. P. Lavine, J. Kyan, D. N. Nichols, J. B. Russell, and C. V. Stancampiano, "Effects of deliberate metal contamination on CCD imagers," *Mater. Res. Soc. Symp. Proc.* vol. 262, San Francisco, CA 1992, pp. 769-774.

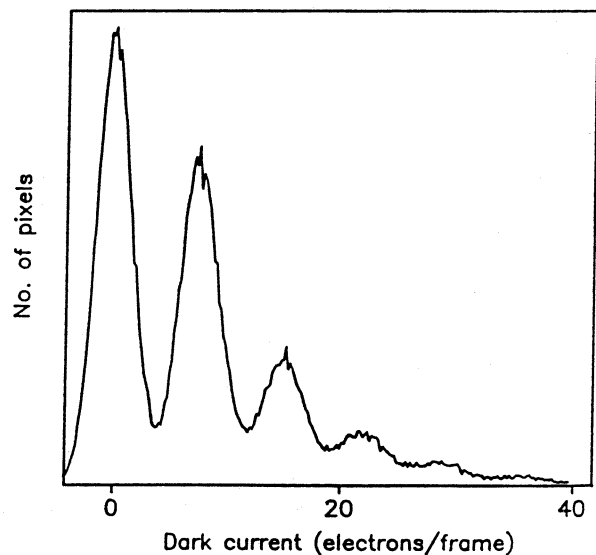


Fig. 1 Quantized dark current from a video interline-transfer CCD image sensor at 55°C. The histogram shows the number of pixels to be found at each value of the dark current (in electrons/33 msec frame time). A single type of trap contributing about 7 electrons per frame is responsible for the regularly spaced peaks.

# Controlling Process Equipment Contamination in the '90s

***By taking a 'total system' approach, it's possible to control the effects of processes and equipment on device performance and yield.***

Terry Francis, Director of Corporate Microcontamination, Applied Materials Inc., Santa Clara, Calif.

The basic philosophy of microcontamination is undergoing a major change. Considering the critical device requirements of the '90s, the classic definition describing contamination as "a particle of known size and shape measured on a wafer" is no longer comprehensive enough in scope. We now must revise the definition to include "any particle, chemical reaction, metal and mobile ion impurity, process or system procedure that can cause device degradation."

In a broad sense, device yield is the critical determinant. This broader and far more encompassing approach affects how the industry thinks of microcontamination issues and is crucial to controlling the effects of processes and process equipment on device performance and yield.

Design aspects related to decreasing device geometries continue to have a significant effect on contamination requirements (Table 1). Thinner oxide layers, for example, lead to more sensitivity in electrical characteristics. As geometries shrink, very small particles

and material impurities have a relatively greater effect on device degradation or shorting. Additionally, trace heavy metals and mobile ions can cause other forms of device degradation (Table 2).

Thus, in its broader definition which goes far beyond particulates, microcontamination can be considered to cause premature oxide breakdown, sub-threshold leakage, longer refresh cycles on the device, and other performance problems that have not historically been associated with microcontamination. But however broadly we define the problem, the industry must still aim for particle-free process chambers and particle-free chemistries.

### **Contamination food chain**

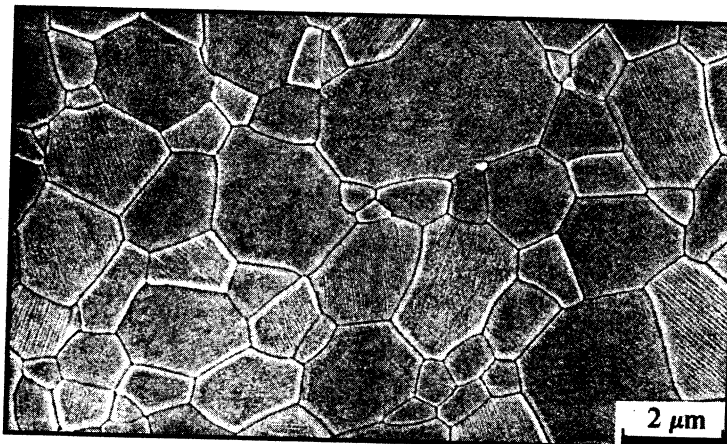
While the industry is moving toward a "total system" approach as the most effective method to resolve the spectrum of issues associated with device degradation, particles still remain the primary area of focus. Particle control might be broken down into three basic areas: generation, transportation, and

deposition onto the wafer (Fig. 2). There remains much opportunity to reduce particle levels through this approach. By viewing these areas as a sort of microcontamination "food chain," specialists in the field can work to efficiently eradicate the sources along the chain.

**Contamination generation** — This is simply the point at which a particle forms (as in a plasma), or is eroded from a material (as in material sputtered from hardware exposed to plasma).

The traditional approach involves redesigning the hardware, the system or the process to minimize or eliminate the particle source. Realistically, this is quite expensive and can only take place at certain times in a system's commercial lifetime.

Other solutions may provide faster, more efficient answers to controlling contamination at the point of generation. Process chemistry modification, changes in hardware materials, and modified pump and vent cycles are commonly used to control contamination



***Ceramics show promise as a new material for harsh process environments; however, the ceramic industry must work to improve material quality. SEM shows typical ceramic sample after polish and etch showing unacceptable, uneven grain size distribution.***

caused by gas phase nucleation, condensation, erosion, corrosion, or arcing. For example, simply changing o-ring material from Viton to Kalrez or Chemraz may lead to improved resistance to plasma environments.

*Particle transportation and deposition onto the wafer* — Efforts can be made to keep contamination that is normally generated in the system from being deposited on the wafer by either redirecting it to noncritical sites or removing it from the system. By carefully designing the hardware or by correctly managing electrical or magnetic fields, or flow variables, particles generated during processing can often be kept away from the wafer and swept out of the system.

In-process particles trapped in the plasma sheath boundaries, for example, can be convected away from the wafer by manipulating parameters such as gas flow, process pressure and rf power. In another instance, the gas flow field above the wafer may create a particle trapping recirculation zone. By modifying the gas distribution plate, the recirculation zone can be eliminated and pockets of particles can be avoided, particularly above the wafer.

#### Process considerations

The wafer itself is a significant contamination variable. It may have been exposed to moisture, have organic contamination, contain heavy metals from the silicon manufacturing process, or possess other contaminants as a result of processes performed prior to receiving the wafer into a given system. Thus, wafer cleaning and treatment is increasingly important prior to critical process steps. This might take the form of hydrogen heat treatment, sputter etching,  $\text{NF}_3$  or  $\text{CO}_2$  gettering, wet cleaning or other procedures. These cleaning steps must themselves also be kept extremely clean.

Particles generated during processing can be reduced by temperature, flow field management or controlling condensation. By keeping the wafer surface hot and maintaining a temperature gradient above and outward from the wafer surface (i.e. from hot to cold) thermophoretic force can be used to migrate particles toward colder environments and avoid contamination on the wafer.

More and more processing is now integrated within single, vacuum-iso-

Requirement	1993	1994	1995
Minimum design rule	0.5 $\mu\text{m}$	0.35 $\mu\text{m}$	0.35 $\mu\text{m}$
Overall defect density	0.5/cm <sup>2</sup>	0.10/cm <sup>2</sup>	0.05/cm <sup>2</sup>
Measurable defect size	0.15 $\mu\text{m}$	0.05 $\mu\text{m}$	0.05 $\mu\text{m}$
Outgassing	5 ppb	1 ppb	10 ppt
Heavy metal (atoms/cm <sup>2</sup> )	$10^8$ - $10^{11}$	$10^8$ - $10^{10}$	$10^8$
Mobile ions (atoms/cm <sup>2</sup> )	$10^8$	$10^8$	$10^8$
Metrology wafer particles (bare silicon wafer)	0.15 $\mu\text{m}$ (rf-on)	0.05 $\mu\text{m}$ — (total process particles) —	0.05 $\mu\text{m}$

Types of device degradation	Root causes
Particles	Abrasion, chemicals, gas phase nucleation
Corrosion	Chemicals used during process, moisture
Device leakage	Sodium contamination, deep-level defects
Minority carrier lifetime	Crystalline damage, metallic contamination, trapping sites
Volatile chemical contamination	Chemicals used during process, chemical impurities
Heavy metals	Corrosion, particles, materials
Oxide breakdown	Heavy metals, plasma damage

lated systems — raising the possibility that the results of one process will influence (and contaminate) the next. For example, residual chemicals from a previous process can potentially conta-

### **Microcontamination now includes (anything)...that causes device degradation**

minate the next processes' chamber, causing a system-wide shut down. Therefore, any "carryover" effects of integrated processing need to be thoroughly explored. By carefully designing these integrated processes, one can avoid cross-contamination by controlling pressure gradients and other parameters.

#### Materials — a major concern

As contamination specifications become increasingly stringent, materials used in the construction of process equipment are emerging as an important area of concern. These materials

interact with the system's process chemistries, generating particles and other contaminants that tighter specifications now identify and require eliminating (Table 3).

Chamber and process kit materials, for example, may be the source of heavy metal contaminants created by long-term exposure to plasma. Corrosion related contamination is primarily a result of active species reacting with materials in process chambers. Particles are also generated by various cleaning methods, both wet and dry, as well as by simple abrasion. In order to eliminate these material-sourced particles, more plasma resistant materials and coatings need to be developed.

#### Ceramics: a solution?

Because they are relatively more resistant to plasma, ceramics and ceramic coatings are promising candidates in combating the erosion and corrosion issues associated with these harsh environments. However, since ceramics are not normally made for our industry's applications, (and as they are relatively new to the semiconductor equipment industry), concerns about purity, quality, and process control in the fabrication of ceramics need to be addressed. Therefore, ceramic vendors

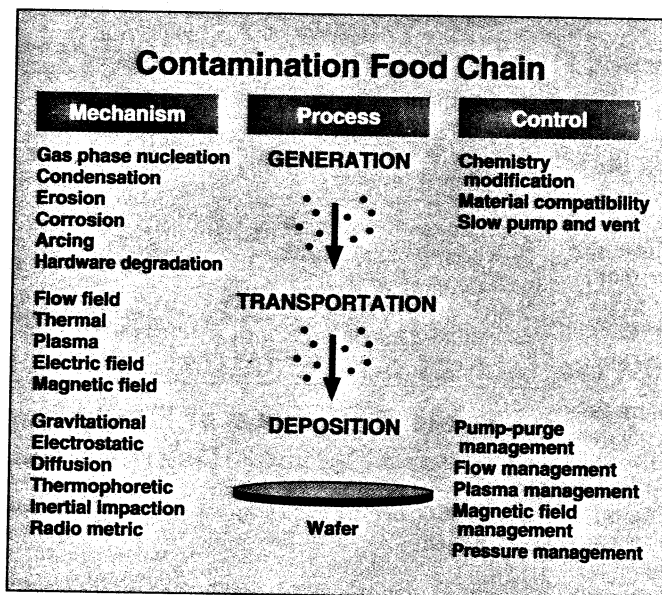
## Process Equipment Contamination

must be educated in how to meet our industry's unique requirements — including controlling the manufacturing process for repeatability.

Although perhaps not directly microcontamination related, other factors for ceramic manufacturing include grain size and distribution (see photo), uniformity, stress and binder concentrations. Thus far, ceramics have been successfully used in process kits, susceptors and shields. This durable material has shown the potential to reduce the number of consumables in chambers and extend the operating lifetime of critical components.

### Other materials issues

Sometimes — because of the



1. By looking at process contamination as a "food chain," particle sources can be eradicated before they are deposited on the wafer.

chemical process being performed — a certain material must be used. However, if it can be properly coated, or if the surface can be modified in some manner, this alone may offset a real or potential particle problem. Wear-resistant materials and coatings are of particular interest because they can not only mitigate particle problems but also extend the life of critical components. The steady progress in surface coating technologies has the potential to provide a real benefit in freedom from contamination; advanced anodization techniques are a promising starting point.

Other issues include the use of contamination free materials to combat metallic and ionic contaminants such

## Improving Particles in Existing Equipment

Continuous improvement in the microcontamination performance of installed equipment is a key economic issue for semiconductor manufacturers today. The requirements for process hardware materials are especially difficult to satisfy in high-selectivity oxide etching. A combination of high dc bias and a harsh, chemically active environment subject the hardware to severe erosion — limiting lifetime and introducing possibly undesirable reaction by-products into the chamber.

Applied Materials' Precision 5000 Oxide Etch system has undergone extensive particle-related development during the program leading to its latest model release, the Precision 5000 Etch. Root cause analysis identified the previous process kit's quartz clamp rings as the primary particle source. Particle "spikes" resulted from the degradation of the quartz in the plasma environment.

As potential alternatives, the development team evaluated both ceramic ( $Al_2O_3$ ) and Vespel SP-1, a polyimide polymeric material made by DuPont. Both materials interact with the oxide etch chemistry, but have different effects on the process, hardware and particle levels. Issues such as etch rates, uniformities, selectivities, profile control and microloading were carefully

monitored during evaluation. The ceramic clamp rings worked well in initial particle tests; however, the material exhibited process limitations that ultimately acted against its use in the oxide etch process.

The properties of Vespel were already known to the development team from that material's production use in several low-selectivity oxide etch applications on the system. Under the more extreme high-selectivity conditions, it showed much greater resistance to degradation than its quartz counterpart, but was found to erode rather quickly during the chamber's plasma dry cleaning stage following wafer etching — part of the high-selectivity oxide etch process. It had no problems with residue and showed improved particle performance.

As is common with such problems, the development team found that changing the process kit materials alone was only part of the solution; hardware design and process issues also played a part. To offset the Vespel's erosion problem during plasma clean, the cleaning process was modified to be more selective to the polymer on the chamber walls. Dry clean process time was also shortened, intentionally allowing polymer to build up slightly in non-

critical chamber locations.

Because process kit design also played a major part in particle levels, the team evaluated both the ceramic and Vespel materials in several new low-profile clamp ring configurations, as well as evaluating the effects of clamp ring force. With the previous quartz ring, particle trapping had been observed near the ring's "fingers" at the edge of a wafer; these trapped particles could drop onto the wafer surface when the rf is turned off.

To fully utilize improved material characteristics, the ring was re-designed with a much lower profile and a channeling effect, virtually eliminating particles trapped near the ring under rf/on conditions, and allowing rf/on particles to be pumped from the chamber. The force needed to hold the clamp ring in position also was lowered to about three-fourths of its earlier value.

In-process laser light scattering methodology has confirmed the absence of particle trapping. Besides a significant reduction in the frequency and amplitude of particle spiking, the median rf/on particle level also has been lowered, from 0.2/cm<sup>2</sup> before the program to its current 0.05/cm<sup>2</sup> (>0.3  $\mu$ m). □

# Process Equipment Contamination

as alkalis (sodium, potassium and lithium). This is a critical concern to chip-makers since this form of contamination ultimately can lower the breakdown voltage of the oxide layer in a film — reducing the leakage threshold in a device.

Using extremely high purity starting materials and coatings and establishing careful handling procedures can control heavy metal and mobile ion contamination. For example, improper handling of  $Al_2O_3$  and aluminum nitride ceramics can impart unacceptable levels of sodium, releasing these mobile ions during processing. Or, in the case of anodization processes, very high levels of trace elements can result from using commercial grade chemicals such as sulfuric acid.

Getting the necessary levels of purity in materials often requires a new level in the relationship between semiconductor equipment makers and materials vendors. Many commercially available materials simply do not exist in the purity level we increasingly need to meet our contamination requirements. This relationship will demand close interaction with materials vendors, including a careful analysis of the vendor's own manufacturing processes.

## Future contamination issues

As the industry continues to evolve, many peripheral issues are both technically challenging and show promise for materials, process and system management (including plasma management, modeling and nucleation).

Particle metrology, which may be considered the measurement of the total particles contributed by the complete process, is currently capable of about 0.1 to 0.2  $\mu m$  particle size detection on an unpatterned test wafer. Not only do shrinking device geometries cause very small scale particles (<0.1

**The wafer itself is  
a significant  
contamination  
variable.**

$\mu m$ ) to have an increasing impact on performance — electrical and speed requirements dictate that we measure all the contamination-related areas that negatively impact the device. This will require improvements in metrology, possibly in the following forms:

- *Variable incident angle lasers:* This technique promises to be effective because the surface variations and particles on a wafer tend to reflect back at different angles, giving more precise indications of particle locations.

- *Haze or microroughness measurements:* Current instruments may have difficulty separating actual particles from similar readings caused by haze or microroughness, resulting in poor measurement of particulate levels.

- *Total X-ray Reflection Fluorescence (TXRF) analysis techniques and inductively coupled plasma (ICP):* These measurements show promise in detecting concentrations in the range of  $10^8$  atoms/cm<sup>2</sup>.

## Process and system management

Plasma management can be improved in a number of ways, including detection and imaging capability. Laser light scattering technology is a promising avenue because the transportation of particles can be observed in situ. Process management can be enhanced by using a plasma particle purge, rf ramp-up, or magnetic field manipulation to reduce particle generation. Other options include hardware modifications that lead to plasma modifications (i.e. grooved clamp rings, focus rings and electrodes, antenna placement and addition, and modification of the dielectric material of the clamp ring).

Modeling, or the application of advanced simulation is becoming imperative to effectively reduce the cycle time for designing new generation, low particle process chambers. The use of temperature field simulation in a 2-D or 3-D continuum for computational flow dynamics, particle transport modeling, or plasma modeling incorporating mass transport and kinetics, can provide an expedient and cost-effective method for addressing particle generation. These and other methods, including managing gas phase nucleation and refining the condensation process, can ultimately lead to the creation of a particle-free chemistry. □

**Table 3. Silicon Wafer Material Requirements\***

	1995	1998	2001
<b>Parameter</b>			
Device generation <sup>1</sup>	64Mb	256Mb	1 Gb
Design rule, $\mu m$	0.35	0.25	0.18
Wafer diameter, mm	200	200/300	300/300*
<b>Contamination</b>			
Light point defects <sup>2</sup> (/cm <sup>2</sup> )	0.032	0.003	0.001
Light point defects (#/waf)	10	1	1
Size ( $\mu m$ )	$\geq 0.12$	$\geq 0.05$	$\geq 0.03$
Metals (totals) (cm <sup>-2</sup> )	$\leq 10^{10}$	$\leq 10^9$	$\leq 10^8$
Oxygen (ppma)	29 $\pm$ 4	26 $\pm$ 2	23 $\pm$ 2
Denuded zone ( $\mu m$ )	—IC process/circuit dependent—		
<b>Electrical properties</b>			
Epi carrier concentration <sup>3</sup> (cm <sup>-3</sup> )	$10^{15}$	TBD	TBD
Substrate resistivity <sup>3</sup> (ohm-cm)	0.008-0.01	0.008-0.01	TBD
<b>Generation lifetime</b> ( $\mu sec$ )	300	500	1000

<sup>1</sup>DRAM equivalent

<sup>2</sup>Light point defects include: particles, haze, microroughness and stacking faults

<sup>3</sup>Epi and substrate resistivity are a function of circuit application

\*Source: SIA Semiconductor Technology, Working Group Reports (1993) p. 63. Available from SIA, 4300 Stevens Creek Blvd., Suite 271, San Jose, CA 95129

## Reader Interest Review

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# Equipment Generated Particles: Ion Implantation

*We know about 0.3  $\mu\text{m}$  particles at ion implant, but the work on smaller particles is just beginning.*

Pieter Burggraaf, Senior Editor

According to particle expert Benjamin Lui of the University of Minnesota, today's manufacturing processes and equipment each add about 38% to the total particle counts on semiconductor wafers; the remaining 24% comes from people and cleanrooms. By 1995, Lui predicts equipment and process particle percentages will shift to 25% and 40% respectively (Fig. 1).<sup>1</sup>

Clearly, equipment manufacturers are identifying and removing particle sources. Much of the continuing effort to find and eliminate equipment-generated particles concentrates on ion implanters (see "Implanter Particle Dynamics").

SEMATECH's Larry Larson tells us that particle control in implanters is well advanced, compared to other wafer processing steps. "But it is in the nature of implant, where a 1000 Å particle can obstruct the implant and contaminate the silicon surface, that no level of contamination can be tolerated. This means that much more work and improvement is necessary," says Larson.

Looking ahead to around 1995 and 0.35  $\mu\text{m}$  design-rule 64Mb DRAMs the "killer" defect size drops to near 0.035  $\mu\text{m}$ ; users will require a count of less than 0.035 particles/cm<sup>2</sup> added per wafer pass through process equipment. Mike Harris of Varian says, "Equipment manufacturers face a tough challenge in meeting these requirements. And manufacturers of particle measurement tools are equally challenged to improve the techniques used to measure particles."

Consider SEMATECH's goals, for example: For implant steps, the goal for 0.8  $\mu\text{m}$  CMOS is no more than one-half 0.3  $\mu\text{m}$  or larger particles/cm<sup>2</sup> and the 1995 goal for 0.35  $\mu\text{m}$  CMOS is no more than two-hundredths 0.1  $\mu\text{m}$  or

larger particles/cm<sup>2</sup>.

## The good news

Larson says, "It was one of the major eye-openers of my work with implanters that they are relatively clean and wafers entering an implanter carry a much more significant load of particles."

Jim Hart of Genus notes that the

cleanliness of wafers is crucial in establishing good particle performance. "For example, if the particles *added* are to be kept at <0.025/cm<sup>2</sup> then the starting wafer particle counts should be  $\leq 0.05$  particles/cm<sup>2</sup>," says Hart.

Although a clean ion implanter can actually remove particles from a wafer, experts advise not to count on this as a production practice because it mandates more frequent preventive maintenance cleaning cycles.

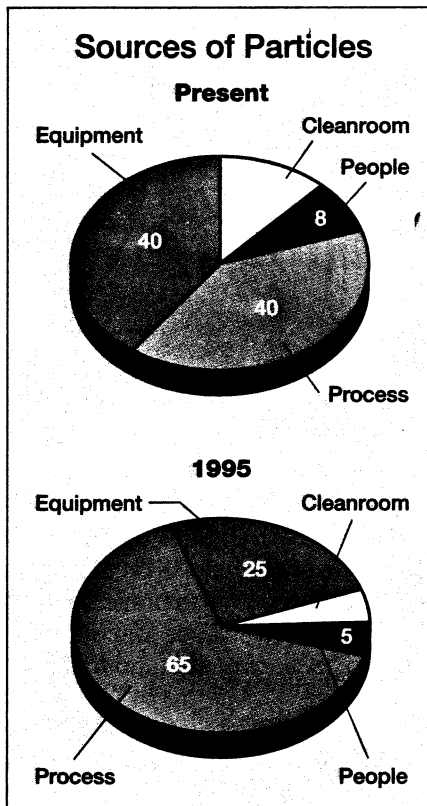
## Preimplant processing

What are the critical preimplant concerns? Walter Class of Eaton suggests that wafer-edge damage can be troublesome because most wafers coming to implant have seen an oxidation step. "The oxidation process causes stresses to develop around any minor microcracks near the wafer edge, making the edge prone to particle generation during post-oxidation handling," he says.

Good preimplant processing practices include elimination of sharp corners where the wafer perimeter and flat meet. It is also important to reduce edge-damaging wafer transport or holding operations in preimplant process equipment.

Even more important than wafer-edge damage control are preimplant steps that make implant-masking photoresist more resistant to implant particle generation. Typical steps include hard baking the photoresist and more complete removal of wafer resist edge-bead and backside resist.

It is standard fab procedure to optimize photo and develop processes for the following etch process, but such work is seldom done to optimize the resist to minimize particle generation at ion implantation. Larson says, "Such simple collaboration is a powerful possi-



**1. Data from Benjamin Lui at the University of Minnesota shows that equipment manufacturers are making progress reducing particles.<sup>1</sup>**

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Particle control is crucial in ion implanters. Here, a wafer is handed to the Eaton-1000 implant disk.

bility to improve implant particulate response. For example, engineers should set up control of track, exposure and, particularly, develop parameters where responses include the relative rate of particle generation at ion implant." Goals could include minimization of water vapor and hydrogen when an ion beam hits resist.

Other experts stress that backsides of wafers are important. Although we know that megasonic cleaning, for example, can remove backside particles, backside particle monitoring is tough. Larson says, "There is little technology available; the disturbing part is that it's a lovely source and we can't do anything about it, yet."

**Success with in situ monitoring**

Recent work at SEMATECH,<sup>2</sup> has shown the effectiveness of in situ particles monitoring at ion implantation. Engineers used in situ monitoring to optimize process chamber cleans — sequential pump-vent cycles. They found an increase in particle removal. In addition, this work identified problems due to the use of dirty dummy wafers and showed a potential reduction (>40%) in particle generation during processing.

In situ monitoring has also shown that photoresist is a key particle source in ion implanters.

In other work, in situ monitoring has shown that particle counts are roughly dependent on beam current.<sup>3</sup> Steve Moffatt of Applied Materials says, "We found that when a 'particle reservoir' — for example, electrodes, front plates and beamstop — is disturbed or under stress it can produce 10 to 200 particles. Then, when the disturbance is stabilized, particles may decrease or stay constant with time." Moffatt also notes that the ratio of in situ counts to particles measured on wafers indicates that most particles from the beamline do not stay on the surface of the wafers.

Peter Borden of High Yield Technology explains that in situ monitors can find particles close to 0.2  $\mu\text{m}$ . "We have found that such monitoring correlates well with surface monitors. This allows automation of particle testing, increasing productive time versus test time — an important factor in the cost of owning an implanter," says Borden.

**Looking at high current systems**

A presentation at the recent technical meeting of the Institute of Environ-

mental Sciences provided one look, using monitor wafers, into an ion implanter. This was the work of David McCarron of Eaton and Elaine Custodio-Williams a Motorola assignee to SEMATECH.<sup>4</sup>

Speaking to meeting attendees, McCarron explained their efforts to characterize particles added ("adders") to wafers processed through a high current implanter used in a Class 1 production area at SEMATECH. Specifically, these engineers classified the number and size of "adders" during automatic wafer handling, process chamber vacuum and vent cycles, and disk spinning with and without implant (Fig. 2):

- Only 2.8% of the "adders" came from automatic in-air wafer handling. Most of these particles were  $>1.0 \mu\text{m}$  and probably came from contact between wafers and cassettes, residues left by wafers, mechanical wear of parts and other mechanical origins.
- Only 2.9% of the "adders" came from the vacuum and vent cycle. These particles were all  $>0.5 \mu\text{m}$ . Reportedly, the aerodynamic forces introduced by this system's particular vacuum and vent cycles could move large particles, but did not disturb particles smaller than 0.5

## Ion Implantation

$\mu\text{m}$ . (Other work at Eaton has shown that particles moved by aerodynamic forces are very sensitive to the nature of the gas flow next to the surface on which the particle lies.)

- "Adders" from disk spinning without the beam amounted to 30% of the total. Here, the most significant increase was 0.3-0.5  $\mu\text{m}$  particles.

- Finally, 65% of the "adders" came from spinning and implanting wafers, mostly 0.3-0.5  $\mu\text{m}$  in diameter.

Overall, these engineers found that as the forces acting on particles in the process chamber and beamline increased, the particles added to wafers increased: Particles added from mechanical and aerodynamic forces are minimal and typically  $>0.5 \mu\text{m}$ . On the other hand, inertial forces from the spinning disk increased "adders" relative to the prior mechanical transport steps. Directly proportional to the mass of particles, larger particles are preferentially removed and transported to the wafer in comparison with the smaller particles that remain on the disk. Finally, electrostatic forces, target sputtering or ablation, and beam potential are combined to transport 0.3-0.5  $\mu\text{m}$  particles to the wafer.

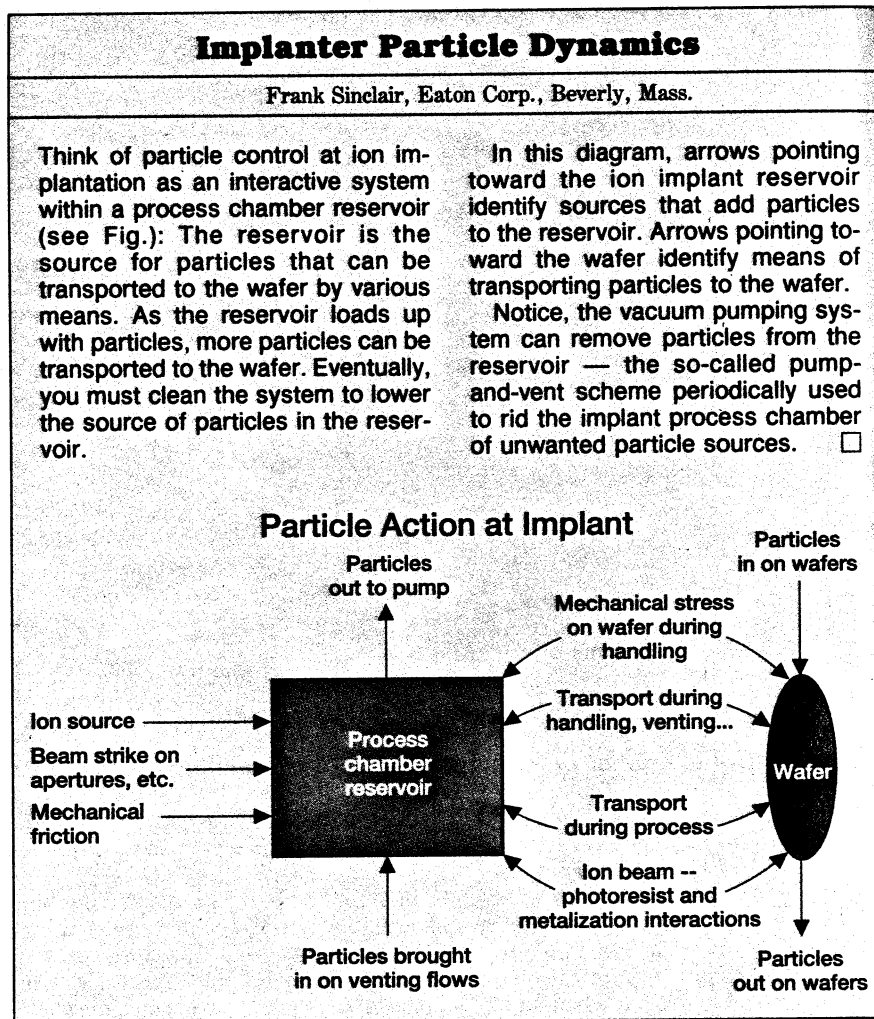
McCarron said, "The results of this testing clearly points out the need to monitor smaller particle sizes —  $>0.2 \mu\text{m}$ . At the particles per wafer levels we measured — roughly five particles  $>0.3 \mu\text{m}$  — small changes in the mean are difficult to detect."

### Particles and ion beams

Photoresist- and beamline-generated particles can be present in both high- and medium-current implanters:

- During ion implantation, photoresist degradation occurs by interaction between the ion beam and the resist: Research has shown that ion damage can release hydrogen from the resist polymer structure thereby partially carbonizing the resist and making it very difficult to strip from the wafer surface. At moderately high implant temperatures this hydrogen accumulates as small bubbles that burst to shower resist particles over the nearby wafer surfaces.

- Beamline sources of particles are usually beamline parts that become particle generators when struck by the ion beam. For example, McCarron and Custodio-Williams found the striker plate of the mass analysis magnet was a prob-



lem with  $\text{B}^+$  implants from a  $\text{BF}_3$  source gas. Apparently, many unwanted ions separated from the beam by the mass analysis process hit this plate. In turn, these emitted particles became entrained in the ion beam and transported to wafers.

These effects are less significant in medium current implanters where beam power densities and implant doses are usually lower. Robert Simonton of Eaton notes that with medium current implants it is rare to see measurements that show particles added from exposure to the beam. "These systems use lower current and power densities. So, we see fewer particles coming from beamline components and less photoresist degradation at the wafer, than with high current systems," he says.

Simonton notes that the most contaminating events in medium current

implanters are loadlock venting and roughing and wafer clamping, especially to resist-coated wafers.

### Controlling particles

Over the past several years implanter manufacturers have found that atmospheric and pumpdown control in loadlock is a key in controlling particles in both medium- and high-current implanters. Here, researchers have found that particles down to 0.005  $\mu\text{m}$  can act as condensation nuclei for water vapor during the initial pumpdown phase.

The conclusion about this phenomenon is now different from earlier conclusions: Ron Eddy of Varian, says, "Turbulence was thought to be the only contributor. However, tests with vent manifolds — where the vent speed is as fast as possible, but the turbulence is as low as the lowest vent speed —



## Ion Implantation

show there is still improvement to be made in particle control by controlling the atmosphere of the chamber before pumpdown."

Class adds, "With time-profiled evacuation and vent-back, load-locked and nonload-locked systems can limit particle contamination contribution to about 0.001 particles/cm<sup>2</sup>."

In other related work, engineers at SEMATECH have optimized the cleanroom ambient versus the vent-evacuation cycle.

### Wafer holding

In high-current implanters wafers spin on a disk during implant. Although some high-current systems use clamps to hold wafers on the disk, the most common method uses clampless centrifugal force. Class notes, "Here, clampless holding has resulted in a substantial reduction in particle generation."

Medium-current implanters use wafer clamps during implant. Thus, particle contamination can come from clamp ring contact with the front edge of the wafer. In addition, particles are transported from the clamp ring to the wafer by the forced contact itself.

Simonton explains that the design techniques used in advanced medium current implanters, and the use of resist processing edge-bead removal, can allow the added particle contamination level from all implant process steps to be <0.06 particles/cm<sup>2</sup> for  $\leq 0.5 \mu\text{m}$  diameter particles in production environments using photoresist coated wafers.

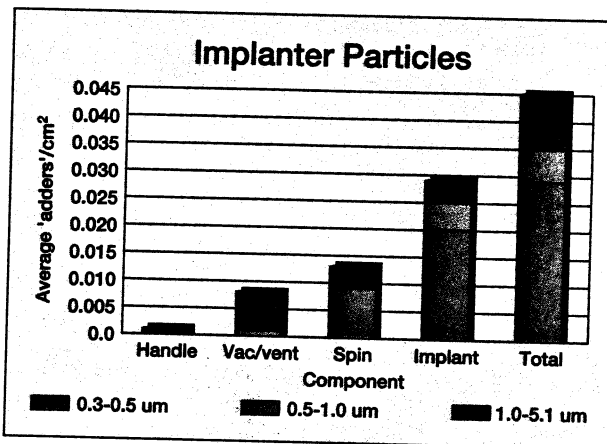
"Longer term, however, clampless hold-down technology must be implemented onto medium current machines, as it already has been on high current machines," says Simonton.

### Future needs . . .

We know of two major contributors of particles during ion implantation:

- particles added from the ion beam, beam size and energy, potentially 5-100 >0.3  $\mu\text{m}$  particles, and
- particles added from wafer handling, potentially 5-25 >0.3  $\mu\text{m}$  particles.

Michael Current of Applied Materials summarizes, "By improving beam optics and appropriate conditioning, both for particles and high voltage, we can reduce the first category to <5-10 particles. Most particles added, due to this mechanism, are in the 0.3-0.5  $\mu\text{m}$  range."



2. Data shows that as the forces acting on particles in a high-current implanter increase, the particles added to wafers increase.<sup>4</sup>

Then, by improving the materials used in wafer handling parts, the cleaning procedure and autoclean cycle, we can reduce the wafer handling particles to <5," says Current.

Larson says, "I don't think that the large body of incremental improvements should be minimized. We, and the implanter manufacturers, have learned a lot about wafer handling, vacuum loadlock design and implant beam-line construction." He believes these incremental improvements have taken particulate control from a "black art" to a well known field where there is a large body of knowledge available to the concerned.

But for the future, Larson says, "Unfortunately, one part of the knowledge is that what we've done is not yet enough and that even more work needs to be done to keep in phase with the needs of advanced processes."

Class reminds us, "As the detectability of the particle counters increases, a whole new body of knowledge will emerge about sources of and control of particulate contamination. My impression is the work has just begun."

Clearly, a long-term strategic approach to particle reduction in implant is necessary. Moffatt says, "We don't think we are going to get beyond 64Mb technology unless we make some radical, revolutionary changes in the way we do things. For the 64Mb to 256Mb devices, we are going to have to be very well calibrated at 0.1  $\mu\text{m}$  and low 0.002/cm<sup>2</sup> densities."

Moffatt believes that yield arguments point to the need for fundamental changes in ion implantation in the next few years. These revolutions could include, new ways of transporting a beam

to reduce contact with implanter surfaces, improvements in the way implanters are cleaned and wafers are handled (including use of standard cassettes) and minimizing exposure of the wafer, perhaps by introducing it at the very last moments before actual implant. □

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3. S. Leung, et al, *Nuclear Instruments and Methods in Physics Research*, B55 (1991), p. 35.
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## DESIGNING PARTICLES OUT OF THE DEPOSITION PROCESS - TITANIUM NITRIDE FILMS.

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### ABSTRACT

Particulate contamination becomes a leading risk to high yield submicron VLSI manufacturing as design rules continue to shrink. At the same time that titanium nitride films are gaining favor as effective barrier and antireflection layers, evidence is mounting to support the belief that the very nature of the reactive sputtering process has the potential to generate large numbers of particles. This paper explores the source of this particle generation through statistical design of experiments. The results show that the particles are generated at the target surface rather than at the wafer surface. Source design and titanium nitride process parameters exercise a strong effect on the number of particles generated. By optimizing the process parameters, target erosion profile and the shielding design, the particle density measured on wafer surfaces (for 0.5  $\mu\text{m}$  and over) has been reduced by a factor of 16 from a previous average of 2.3 particles/ $\text{cm}^2$  and its stability demonstrated. A brief discussion on particle measurement gauge capability and caution in interpretation of the particle data on TiN films is also presented.

### INTRODUCTION

In accordance with the achievement of higher performance in VLSI technology, manufacturing development has worked toward the realization of greater cleanliness and reliability in deposition technology. In particular, increased packing density and improved yield call for a complete control of particle contamination. Contamination is generally attributed to : people, environment, tool/processes, and feedstreams. However, with the cleanliness achieved by today's state of the art clean room, human, environment, and process feedstreams are no longer the yield limiting factors. Most particle contamination comes from individual process steps, namely the equipment, process and material interactions. Reactive sputter deposition of Titanium Nitride is a key example.

Reactive sputtered titanium nitride is known to be an excellent diffusion barrier in VLSI IC metallization [1,2]. Nevertheless, it is only recently that TiN has gained favor as a diffusion barrier and antireflection layer in high volume submicron device production [3-6]. At the same time evidence is mounting to support the belief that the very nature of the reactive sputtering process has the potential to generate a large number of particles. This requires excessive preventive maintenance to ensure consistent quality films. Current manufacturing solutions

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are to halt the process every 25 to 50 depositions. Pure titanium is then deposited on monitor wafers to coat internal parts of the chamber, or sequentially deposit Ti/TiN to clean the poisoned target. This approach helps maintain a low particle level, but is not a cost effective solution.

In this study, the source of this particle generation is examined. It is shown that the particles are generated at the target surface, and process parameters exercise a strong effect on the number of particles generated. By optimizing the process parameters, target erosion profile and shielding design, the particle density (for 0.5  $\mu\text{m}$  and over) can be reduced to a manufacturable level. This study also necessitated the development of particle measurement capability. Below, we discuss this capability and precautions required in interpretation of the particle data for sputter deposited TiN films.

### EXPERIMENTAL PROCEDURE

The TiN films were deposited in a multi-chamber single wafer deposition system as illustrated in *Figure 1*. It is a fully automatic and highly integrated system that included vacuum batch degas load locks, wafer transfer module, RF etch module, three deposition modules with the Smartsan(TM) DC magnetron source [7], and sensor/ response software flexibility which allows for multi-step depositions. The system software controls the batch degas temperature, wafer temperature and chamber pressure prior to wafer processing.

The TiN layers were deposited on silicon substrates of <100> orientation by reactive sputtering a high purity titanium target (99.993%) in an ambient of argon and nitrogen, with flow rates adjusted to vary the film stoichiometry. The thickness of the TiN films varied from 250 to 1000  $\text{\AA}$ . The base pressure of the modules were  $\leq 2 \times 10^{-8}$  torr with wafer batch degas set at 200  $^{\circ}\text{C}$  in the load locks. The processing parameters, as summarized in *Table 1*, were obtained through experimental designs. The main difference between the two processes is: in the standard process the  $\text{N}_2$  (30%) and Ar are introduced at a cathode power of 3.5 KW with deposition occurring on the wafer. In the modified process, titanium is deposited on the shutter for 10 sec at cathode power of 3.5 KW,  $\text{N}_2$  is then introduced at 95% and cathode power increased to 5.6 KW with TiN deposition occurring on the shutter for 5 sec and then on the wafers. Henceforth, in the article these two processes will be referred to as PROCESS A (standard) and PROCESS B (modified), respectively.

The resistivity, reflectivity, and composition of the deposited TiN films were characterized. The reflectivity measurements

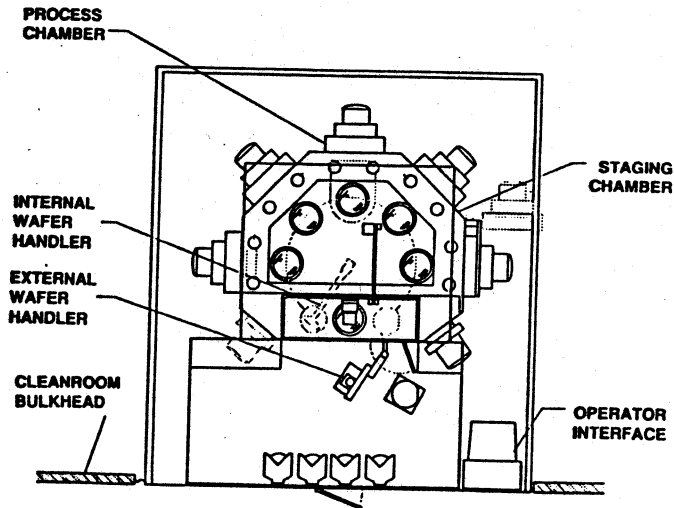


Figure 1: Schematic of the multi-chamber deposition system.

Parameters	Standard Process A	Modified Process B
Cathode Power (KW)	3.5	5.6
Platen Temperature (C)	275	275
Platen Bias (watts)	200	0
Process Pressure (mTorr)	5	5
Nitrogen Ratio (%)	30	95
Pre Sputter Time (sec)	10	10
Deposition Time (sec)	30	30
Base Pressure (x10-8 Torr)	< 2	< 2

TABLE 1: Process Parameters for the two deposition processes.

were obtained using an aluminum reference and were performed at 440 nm on a Nanometrics Nanospec 215 using a 19 points per wafer mapping routine. The sheet resistivity was measured on Prometrix Rs50/e with 6 mm edge exclusion and 49 points per wafer. AES and RBS depth profiles were used for composition and thickness analysis. Microstructure and topography of the films and particles were analyzed using SEM and TEM techniques.

### PARTICLE MEASUREMENT AND CAPABILITY

All the particle measurements were performed on bare silicon substrates and on TiN films using a Tencor Surfscan 5500. To understand the stability of the Surfscan, a gauge capability study was performed. This included: calibration of the Surfscan to reference standards, performing repeatability and reproducibility studies and understanding system adequacy relative to parameter specification. Two VLSI standard wafers with  $479 \pm 10\%$   $1.091 \mu\text{m}$  and  $1070 \pm 10\%$   $0.364 \mu\text{m}$  latex spheres deposited on bare silicon wafers were used as standards. The Surfscan records particle measurement in  $\mu\text{m}^2$ , the laser scattering cross-sectional area. For example, a  $1.091 \mu\text{m}$  sphere measured  $0.93 \mu\text{m}^2$  and  $0.364 \mu\text{m}$  sphere as  $0.20 \mu\text{m}^2$ .

The long term stability results on these two standard size spheres is summarized in Table 2. A good agreement between the observed and the nominal cross-sectional values demonstrate the stability and repeatability of the Surfscan for measurement of particles  $0.3 \mu\text{m}$  and over on bare silicon wafers.

Once capability for particle measurement on bare silicon substrates was established, capability for titanium nitride films was evaluated. For this purpose, TiN films of different thicknesses and compositions were deposited on silicon substrates and their acceptable threshold values were determined. Thin films produce significant background noise level and therefore it was essential to evaluate the background noise threshold. After obtaining the threshold values, latex spheres of known diameter were spun on these TiN films. Table 3 shows the results obtained.

The detection size obtained for bare silicon substrate is in good agreement to that observed earlier (Table 2). However, for TiN films due to film grain texture and haze characteristics (background noise level), the two processes gave different results. The degree of contribution of the background noise level for the two processes was quite different and this is reflected in the cross-sectional values obtained. For PROCESS A, the cross sectional values on an average were 47% higher than those obtained on bare silicon substrates, while for PROCESS B, these were only 12% higher. The threshold value obtained for bare silicon substrate and PROCESS B was identical, but it was  $\approx 100\%$  higher for PROCESS A. In order to measure  $0.3 \mu\text{m}$  size particles, the Surfscan detection limit had to be set at 0.12-

Parameter	Units	STD 1	STD 2
Sphere Diameter	$\mu\text{m}$	1.091	0.364
Nominal Value	$(\mu\text{m})^2$	0.93	0.2
Observed Value	$(\mu\text{m})^2$	0.929	0.204
+/- 1 Sigma (x 10-3)	$(\mu\text{m})^2$	6.04	1.02
Process Potential	Cp	5.52	1.63

TABLE 2: Surfscan gauge capability study for standard spheres on bare silicon.

Sphere Diameter ( $\mu\text{m}$ )		Cross-Sectional Area ( $\mu\text{m}^2$ )		
Nominal	Actual	Bare Si	Process A	Process B
0.3	0.309	0.11	0.15 (a)	0.12 (b)
0.5	0.508	0.45	0.701	0.533
1.0	1.091	1.05	1.554	1.15
Threshold Value		0.004	0.008	0.004
% Reflectivity (c)		52	30-35	20-30
Film Thickness (A)		-	500	500
Composition (Ti:N ratio)		-	1.05	0.95

- (a) High substrate haze interference observed
- (b) Slight haze contribution at this level
- (c) Reflectivity with reference to Aluminum at 440 nm

TABLE 3: Surfscan capability for TiN films with 0.3, 0.5, and 1.0  $\mu\text{m}$  spheres.

0.15  $\mu\text{m}^2$ . This low level is at the bottom of the Surfscan detection limit for particle measurement in the 0.3  $\mu\text{m}$  range for sputter TiN films. It was also observed that the particle count data collected at this size was highly exaggerated due to substrate haze contribution, though the degree was much higher for PROCESS A as compared to PROCESS B. Therefore, to overcome this difficulty and improve comparison of the two TiN processes, a lower detection limit of 0.5  $\mu\text{m}$  was used. Here the contribution of the background noise level was negligible. Below, we present particle data on TiN films for 0.5  $\mu\text{m}$  and over.

## RESULTS AND DISCUSSION

To capture the particle contribution due to sputter tool wear out, process feedstreams, human errors etc., bare silicon monitors were routinely run through the system at regular intervals. The process recipe used was similar to the film deposition recipe as outlined in Table 1, except the cathode power was turned off. This way all the components were activated to simulate the actual process. Typically, the particle density was  $\leq 0.05 \pm 0.03$  particles/cm<sup>2</sup>.

### PROCESS A (STANDARD)

The particle performance at various stages for PROCESS A is illustrated in Figure 2. As mentioned earlier, the current manufacturing practices require coating the internal surfaces of the chamber with titanium by cycling 15 - 25 wafers. It also helps clean the "poisoned target surface". Following this, particle monitor wafers (typically, 3-5 wafers) are processed and particle data collected. If the particle density is within the "process specifications", the tool is said to be qualified for production. However, if the particle density is still high, several more wafers are cycled. This procedure is repeated until the tool is qualified. This approach does help keep the particle density low. But, it not only introduces a sense of uncertainty in the performance of the process, it is costly and reduces tool utilization capability. Figure 2 also illustrates this by processing 25 monitor wafers (production batch size is 25 wafers/lot), the particle count is < 50 particles for first few wafers, but increases drastically thereafter and reaches as high as >350 at

the end of the 25th wafer. The data also show that, the more titanium deposition is used to clean the target, the longer it takes for the TiN particles to increase. The number of production wafers that can be processed with a clean set up is approximately 25 - 40 wafers before particles ( $\geq 0.5 \mu\text{m}$ ) go above 100 or 0.7 particles/cm<sup>2</sup>.

### PROCESS B (MODIFIED)

The process parameters and details of this process are given in Table 1. These set points were arrived at from design of experiments run to characterize the TiN process. It is beyond the scope of the present paper to discuss the details. These along with other electrical results will be subject matter of a future publication. In summary, the results showed that there was significant interaction between process factors and particle density. Higher flow of the reactant gas and deposition rate produced films with lower defect density. These results together with tool hardware features such as: shutter capability and multi-step deposition options were utilized in generating the particle performance data for this modified process (Figure 3). As seen in Figure 3, a dramatic improvement is observed in the particle performance and on average < 22 particles are added, as compared to PROCESS A (where the average was  $\approx 350$  particles added). Although some wafers had >50 particles added, the baseline was low and no signs of any upward trend was observed, even after processing more than 175 wafers. We would like to mention here that all these >175 wafers were processed in sequence with no intentional coating of the internal surfaces or target cleans. In summary, the modified PROCESS B yielded 16 times reduction in particle density ( $\geq 0.5 \mu\text{m}$ ) or < 0.15 particles/cm<sup>2</sup>, improvement in the process/tool utilization, and no adverse effect on film properties.

### TARGET PERFORMANCE

The results discussed above demonstrate that the most likely source of the particles is the target surface (i.e., poisoning of the target). To understand this in more detail, the target surface and the appearance in general were observed after performing these tests. For example, after PROCESS A was completed and

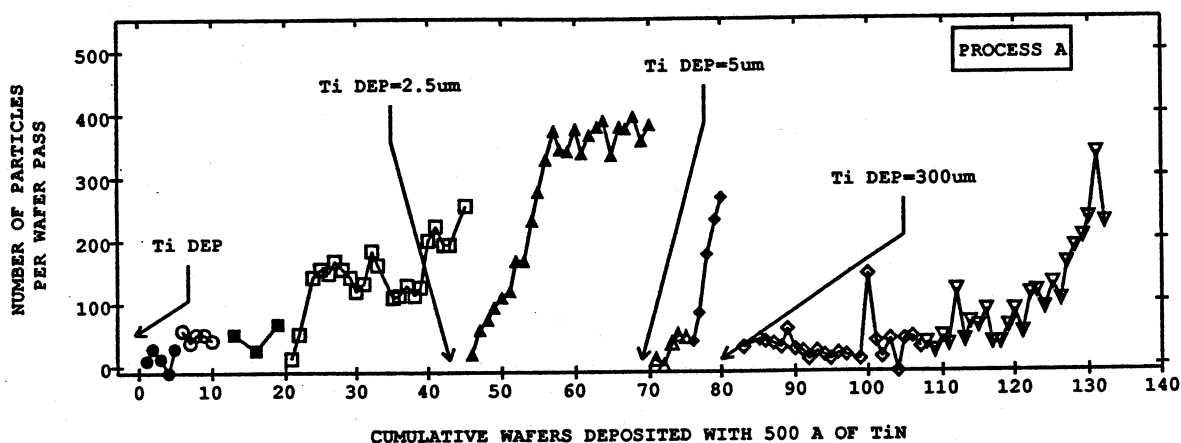


Figure 2: Trend plot for individual particles per wafer pass on monitor wafers with TiN deposition (PROCESS A) as a function of the number of TiN deposition. The effect of titanium deposition to clean the target surface on TiN particles is also shown. Particles  $\geq 0.5 \mu\text{m}$ .

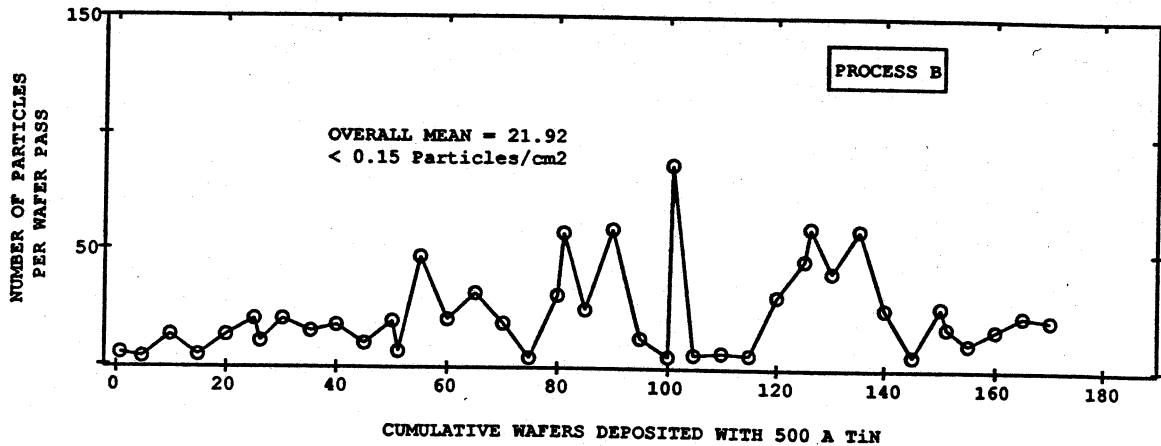


Figure 3: Trend plot for individual particles per wafer pass on monitor wafers with TiN deposition (PROCESS B) as a function of the number of TiN deposition. Particles  $\geq 0.5 \mu\text{m}$ .

chamber opened, a buildup of fine brownish material was observed on the target surface. This material was both loose on the target surface and embedded in it. SEM analysis is shown in Figure 4. The material appears to be very porous and columnar, with a very small attachment point to the target. This coupled with its porosity, suggest that it could easily "blow" off onto the wafer. Also, the target had pockets of yellow and silver gradations across the face. Subsequent tests on the target to qualify the titanium process showed that the recovery of titanium mean resistivity and uniformity was very slow. These results are shown in Figure 5, for number of 1000 Å titanium per wafer run. Even after 250 wafers the resistivity and uniformity values for titanium are not achieved.

Similar evaluation was also performed for PROCESS B. Even after sputtering several microns of TiN, the target surface remained clean and metallic. The surrounding shields were also quite clean and charcoal grey in color. Due to low number of particles, it was difficult to easily collect samples for SEM cross sections. The titanium process recovery is shown in Figure 6. As noticed, within 5 wafers of 1000 Å titanium on each, the mean resistivity and uniformity values were achieved. These results indicate that the detrimental target poisoning effects that occur during PROCESS A, do not appear to occur with PROCESS B.

### CONCLUSIONS

We have demonstrated a reactive sputtering process for deposition of high quality TiN films. Continuous process/hardware improvement has enabled achievement of a robust TiN production process in VLSI manufacturing. The source of the particles produced during reactive sputtering has been identified. Analysis of the results indicate that the particles are produced at the target surface and are a strong function of the process parameters. By optimizing the process parameters the particle density on the TiN films has been reduced by a factor of 16, from a previous average of  $> 2.3$  particles/cm<sup>2</sup> to  $\leq 0.15$  particles/cm<sup>2</sup> for particles  $0.5 \mu\text{m}$  and over. Further refinement of the process has the potential to reduce the particle density to  $< 0.1$  particles/cm<sup>2</sup>.

It has also been the intent of this article to demonstrate the gauge capability study of the Surfscan. The present study, however, raises one question in the author's mind, "How realistic is the reported data on particles on reactive sputtered TiN films at  $0.3 \mu\text{m}$ , is it really  $0.3 \mu\text{m}$ ?"

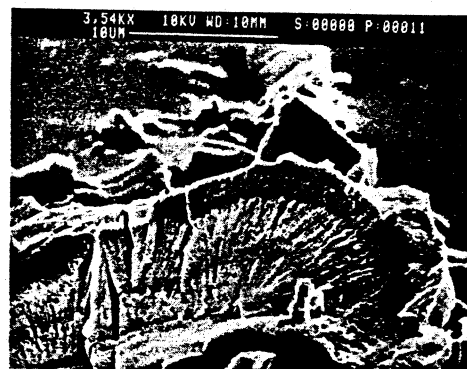
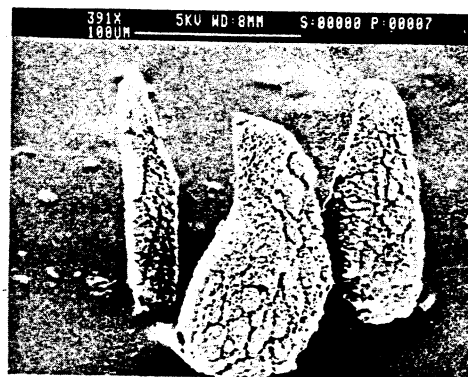


Figure 4: (a) SEM cross-section of particles removed from anode. They are sitting upside down. Note the porous surface. (b) Particle pulled from edge of target. The ring is TiN deposition from PROCESS B on top of TiN deposition from PROCESS A.

## Yield Analysis Software Solutions

*We are seeing an array of major software products that can quickly evaluate the vast amount of data gathered in advanced IC processing.*

Pieter Burggraaf  
Senior Editor

### Key Technologies:

- Defect inspection
- Wafer probe
- Yield software

### At A Glance:

*Clearly, yield management for semiconductor manufacturing is moving into a new realm. In the past such engineering has been hardware based; the industry's defect detection tools gathered the data, the defect size and location, while process engineers pounded out process and yield related correlations. Today's revolution surrounds the accelerating emergence of software that can automatically do the "pounding out," quickly correlating physical events (i.e., particles and defects) to electrical events (i.e., probe data). These software solutions are very valuable additions within expensive wafer fab operations. Most experts agree that the industry's trend is to more software driven solutions that ease the burden of manipulating the vast amount of data produced during the processing of a single wafer.*

Leading semiconductor manufacturers have been doing yield analysis since the early 1980s. Mature companies that had significant manufacturing experience in nonsemiconductor products did not accept low yields common in early semiconductor processes and did the engineering required to make the technology manufacturable. Younger companies often pursued more aggressive process technology that offered unique products, but their ability to manufacture at a high yield was limited. In those days the mature operated at a high yield on mainstream devices; the aggressive made more challenging products at much lower yields.

Bob Clifford, director of new business development at KLA PRISM, noted, "It is no accident that IBM had mainframe-based software systems that stored a vast quantity of data relating to process and test results, and

not only did ad-hoc engineering correlation, but did extensive overnight data processing to find problems without hands-on involvement by engineering." In fact, he noted, an early partnership between IBM and Intel gave Intel one of its first real glimpses into the value of world class capabilities to analyze process and yield information.

Subsequently, all major IC manufacturers recognized the value of yield analysis and put "home grown" systems in place. Commercial software suppliers, including Consilium, Promis and others, started offering engineering analysis modules, but these products did not provide effective processing of die level data from wafer probe.

### Emerging commercial support

Tencor Instruments was an early player in defect data analysis. Tencor established itself with the Surfscan



Increasingly, software solutions are providing process engineers with greater ability to analyze the massive amounts of defect data gathered in wafer fabrications. (Source: KLA PRISM)

## Yield Analysis Software Solutions

SWIFT/Station, which is now installed at more than 100 sites. SWIFT/Station automatically collects defect data from multiple sources throughout a fab and then integrates the information into a single database for analysis and correlation. Importing data from multiple sources, SWIFT/Station can update all user-defined display charts, calculate and display defects added between assigned process levels, and identify out-of-control wafers or lots, alerting an operator with an alarm. In addition to the speed required for immediate process feedback, the SWIFT/Station also supports long-term defect reduction efforts. For example, lots can be inspected at key partition points to source defects to their first point of occurrence, which is critical for identifying true yield limiting defects. (At press time, Tencor had extended the capabilities of its defect inspection technology. See sidebar titled "Just Released: Another Defect Data Management Tool.")

According to Glyn Davies at Tencor, "At one U.S. fab where SWIFT/Station was used, a persistent defect problem was selected for a defect reduction task force." Initial attempts at isolating the defect mechanism were unsuccessful. "By using the SWIFT/Station's contributor algorithm, the fab was able to isolate the defect mechanism to a process step that, if evaluated by defect count alone, appeared to be within control limits," he said. Identifying the source of the defect mechanism allowed the problem to be tracked and fixed, resulting in an immediate yield impact.

"Because of corporate protection of perceived proprietary technology," KLA's Clifford said, "it took about 10 years until semiconductor manufacturers began to partner with commercial suppliers to produce externally supported variants of in-house yield analysis systems."

For example, KLA's Discovery product is a commercialized version of an in-house system developed at Motorola. Clifford related that Motorola calculated that any proprietary competitive edge based on internal development was more than offset by the advantages of having a system of this nature sustained, enhanced and supported by a commercial supplier. The costs asso-

ciated with the ongoing support and development of such a complex system must be amortized over many installations. Consequently, a commercial supplier can better justify the magnitude of resources required to develop complex yield analysis products.

Today, most IC manufacturers have some type of yield analysis system.

time they occur as possible."

### LPA's DES

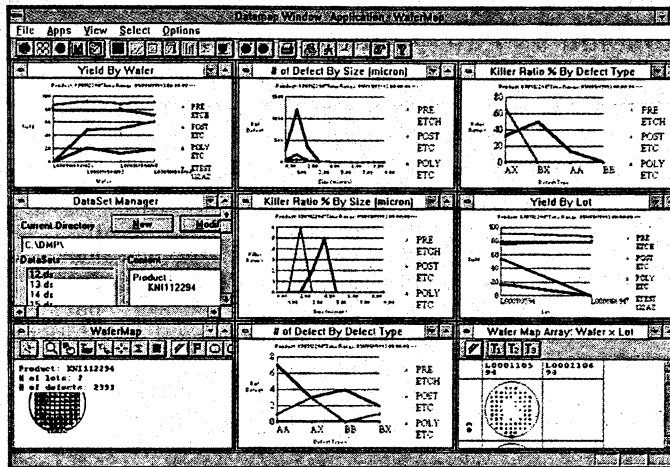
LPA's DES (defect evaluation system) software, one of today's commercial solutions, ties together multivendor automatic defect inspection equipment, optical defect review stations, scanning electron microscopy (SEM), focused ion beam (FIB) tools and probe and test data. Receiving defect inspection data, DES runs in-line with short-loop feedback, applying sampling techniques and custom yield models to defect data, and notifies process experts of problems through e-mail alarms. In addition, DES will automatically shut down defect producing equipment if necessary, and DES data can be used to drive SEM and FIB analysis tools where operators can add defect classification and even digital pictures to the

DES database. Riley further explained, "DES calculates defect-limited yield based on three different yield models and all defect data pertinent to yield management is stored in an SQL database where it is available for review through defect analyzer engineering analysis software. The test data can also be used to drive review and analysis stations to enable an engineer to do visual verification of electrical faults."

When National Semiconductor (S. Portland, Maine) added VLSI production, DES was part of its plan to improve yield management techniques via a short-loop in-line system. According to Pam Partow, section head in National's Integrated Yield Management Group, the new integrated yield management system had three goals:

- to gather inspection defect data in-line with immediate problem alerts,
- to apply consistent data sampling and yield modeling techniques to automatic defect inspection data and
- to catch defects missed by providing the ability to overlay in-line, short-loop data with the long-loop electrical test data available at the end of the manufacturing process.

Partow said, "In the past, electrical tests at the end of the line were sufficient. If unexpected problems arose, skilled process engineers were enough to determine problems and make



### 1. YieldBook, part of Knights Technology's YieldManager, enables process engineers to customize yield data reporting and statistical analysis.

Some in-house systems are state-of-the-art. Venu Menon, worldwide contamination free manager at Texas Instruments (Dallas, Texas), stated, "We have not been standing still and have been filling our needs internally. One advantage with an internal system is that we can tune it to our process, making it more effective for our products."

Other in-house yield analysis systems, however, are based on older hardware platforms and database technology. Most older systems need substantial upgrading to handle today's larger data volumes, visual defect images and correlation at the sub-die level, leaving a difficult decision. Those in charge of internal analysis programs now have to decide whether to continue to develop in-house solutions or work with the new breed of commercial suppliers.

Stuart Riley, technical consulting manager at LPA Software Semiconductor Solutions, noted, "Commercial yield management systems today include hardware and software tools to help rapidly improve and maintain yields by assisting the identification of problems in-line. It is critical that process engineers are alerted to all yield-limiting problems as close to the

## Yield Analysis Software Solutions

decisions. But today, it is no longer possible for process engineers to do this. They need access to data provided by new automatic defect inspection equipment to determine problems they can no longer see." However, the data alone can be inconsistent and overwhelming. "Overlaying of in-line data with electrical test defects through DES is very powerful. For example, looking at fails and overlaying particles, we can determine how many faults are not being detected. We can also determine what particles have higher kill ratios, and we can make a Pareto on the defect types based on the kill ratios, or actual faults they cause," she said.

"If manufacturing tools had a complete self-check procedure, that would be great. But, that will never happen," Partow explained. "Instead, you must have in-line data to catch defects as they happen and prevent situations where you have to scrap the whole lot. Real learning, real productivity improvement, comes when you have a system that includes DES, where you can predict failures before they happen, capture defects as they happen, and compare data with actual electrical test to ensure you do not miss any defects along the way."

### Knights YieldManager

Knights Technology YieldManager is data integration and engineering analysis software that brings in data from design, inspection, electrical test, failure analysis, and factory-wide information systems; this software provides yield-based decision-making through automatic and customizable routines. For example, automated defect partitioning determines which defects were added to the wafer during each process step. Among other capabilities, YieldManager's cluster analysis feature determines the random and nonrandom nature of the defects and selects properly weighted samples for yield review. YieldManager software can also automatically spot and report repeater defects by comparing each defect's relative location within its respective die to all other defects. For process control, defect results can be automatically uploaded to the factory SPC system or to YieldManager's incorporated SPC module for charting. And yield excursions outside a user-defined tolerance can be automatically reported to engineers through e-mail. Paul Proctor, director of yield products

at Knights Technology, said, "After a wafer lot has completed the fabrication process, automatic correlation of the in-line inspection results with electrical test data helps to determine which defects are 'killers.' By linking to the design database, the exact or approximate location of the failing defect can be determined." YieldManager also provides custom links to factory-wide databases, including KLA's Discovery (discussed later), which is being done

### KLA's Discovery and QUEST

KLA has two fab-wide analysis products - Discovery and Quest. Both of these systems run on scalable relational databases running on UNIX multi-processing servers, providing true fab-wide analysis capability.

Discovery automatically gathers data from multiple sources throughout a wafer fab, integrates it into a single database for correlation and analysis, then stores it for future use. KLA's CIMA software automates wafer probing operations and handles collection and transfer of die level bin and parametric data, which is the single most important data source for the Discovery system.

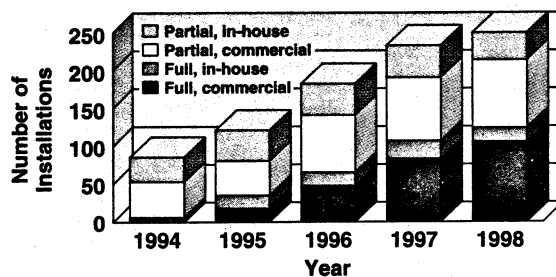
Quest, based on technology licensed from Defect and Yield Management (DYM), is a totally integrated defect data management system specifically developed to enable both in-line and end-of-line monitoring and analysis of defect related yield excursions. From a wide

variety of defect detection systems, review stations and SEMs, it provides comprehensive defect data correlation to various possible causes. The system's open architecture automatically collects process data from any combination of patterned wafer inspection tools and review stations, and sends it to a centralized ORACLE database. In-line monitoring provides immediate notification of problems. The system correlates, analyzes, clusters and partitions data to isolate killer defects.

Clifford said, "In one case study where Discovery was used, an etcher that was producing product that was out-of-specification was identified through routine correlation of yield with process equipment." Here, one chamber of an etch system was consistently producing lots with 8% lower average yield, even though nothing unusual was caught by the SPC system monitoring the etcher's performance. This 8% yield loss resulted in an estimated weekly revenue loss of \$86,000. If this problem would have gone unsolved for 12 weeks, more than \$1 million in product would have been lost.

Another case study involved fab-wide correlation analysis and resulted in finding unexpected longterm yield problems. "A poly-one sheet resistance to bin speed correlation was found by accident in a live demonstration of KLA's Discovery system to a potential customer," Clifford said. "Engineers stated the system

### Worldwide Defect Data Management Installations



**2. The growth in worldwide use of defect data management systems will be composed of four elements - partial integration with in-house software, partial with commercial solutions, full integration with in-house software and full integration with commercial software solutions.** (Source: Laird Durham Co.)

at Motorola's MOS-13 and LPA's DES. "A fab is not forced to abandon its investment in existing systems," Proctor said.

YieldManager has been successfully installed and is operational at SEMATECH (Austin, Texas) where it is being used to investigate engineering problems for member companies. YieldManager has also been successful at Motorola's MOS-11 fab and has also been purchased by Chartered Semiconductor, TSMC and National Semiconductor. Proctor noted, "In each case, Knights will be developing custom links to integrate the system into the existing fab architecture." For example, Chartered Semiconductor (Singapore) already had a CIM system that was integrating data from the inspection and test equipment when they purchased YieldManager. Rather than duplicating that process, YieldManager draws data from the CIM system for automated or ad hoc yield analysis in real time. YieldManager's modular design also allows for continued customization and upgrading as new equipment and processes are added.



## Yield Analysis Software Solutions

### Just Released: Another Defect Data Management Tool

As this article was going to press, Tencor Instruments introduced SwiftAccess, its next-generation defect data management tool. Keeping the intuitive user interface of its existing SWIFT/Station analysis product, SwiftAccess is designed to operate in a sophisticated distributed networking environment. UNIX-based with an X-Windows architecture, the SwiftAccess system allows data analysis simultaneously at the primary SwiftAccess station, at remote stations outside the fab and directly at Tencor's new Surfscan AIT in-line defect inspection system. In addition, SwiftAccess can integrate electrical test data, allowing fabs to correlate defect data to yield.

Speaking about the direct interface between SwiftAccess and Surfscan AIT, Tencor's Glyn Davies said, "Operators can automatically review and analyze data in the form of control charts directly on the inspection systems, almost immediately after a wafer or lot has been inspected. This gives them rapid feedback on the disposition of a lot, and on the status of a process step." Currently, Davies said, operators must go to a dedicated data analysis workstation and call up the control charts for the results of the latest inspection step. "If a wafer or lot is out of control, the delay between inspection and corrective action can result in significant additional wafer loss. By making review and analysis part of the process flow, operators will see the results in real time and respond more rapidly."

SwiftAccess is currently under beta test at a major United States fab.

must be wrong since there was no known correlation of poly-one sheet resistance to device speed, but subsequent analysis identified an unknown layout problem." The identification of this particular problem, occurring in a random sample into the customer's

database, was worth significant incremental revenue per month to the potential customer, an amount sufficient to pay for the entire system investment within a few weeks. "If random analysis of the customer's data uncover yield relationships such as this

during a demo, imagine the value of such a system running full time," emphasized Clifford.

### Inspex DMS

Inspex's DMS-II is a distributed client-server computing system with ORACLE relational database and user interface for complete metrology overlay analysis and yield control. The DMS II includes a library of proven data-normalization software that converts the defect and electrical test data to a common coordinate system. All data types, physical defect files, video and spectra files for images and electrical test data are logically stored and managed by the DMS II server. Process engineers have immediate access to all data from anywhere within a wafer fab.

Case studies from the 15 installations of DMS worldwide show the value of yield analysis software. For example, a major memory manufacturer in Japan installed DMS II to assist them in starting a manufacturing operation. DMS II identified the sources that were creating an unacceptable level of defects at the oxide isolation level. In another example, at a wafer fab of a

There are two ways to thoroughly inspect wire bonds.

### Manually...

- |                                     |   |
|-------------------------------------|---|
| <input checked="" type="checkbox"/> | Measure each ball size, both long and short axes                            |
| <input checked="" type="checkbox"/> | Determine each ball's distortion ratio                                      |
| <input checked="" type="checkbox"/> | Measure how far each ball has shifted from bonding pad's center             |
| <input checked="" type="checkbox"/> | Measure how far each ball projects off bonding pad                          |
| <input checked="" type="checkbox"/> | Determine what percentage of each ball is off bonding pad                   |
| <input checked="" type="checkbox"/> | Measure every crescent size   |
| <input checked="" type="checkbox"/> | Measure distance from where each crescent should be... to where it truly is |
| <input checked="" type="checkbox"/> | Measure amount of curve in each wire  |
| <input checked="" type="checkbox"/> | Measure intervals between all wires   |
| <input checked="" type="checkbox"/> | Measure height of each wire at apex   |

or



major North American telecommunications chip manufacturer, the advanced process development engineering group was able to isolate a low yield situation to a metal clean operation; here DMS II provided data visualize tools that presented the problem graphically. Michael Laine, product manager at Inspec, said, "In both these cases a conservative ROI was estimated just for the wafer fab at over \$225,000 based on improved wafer start yields."

**Yield management tomorrow...**

What is the importance and future of more powerful yield management? Clifford noted: "It has been said that yield is the least predictable factor in IC manufacturing. Thus, yield management is necessary both to predict yield to meet supply requirements and to increase yield to maintain profitability in a highly competitive global market."

Trends certainly indicate that this is a technology of the future. According to an independent market study commissioned by Knights Technology,<sup>1</sup> by the end of 1998, 125 fabs worldwide will have fully integrated defect data management systems installed (Fig. 2).

Here, fully integrated means that all in-line and off-line inspection and analytical tools and databases can be accessed through a single user interface. The report details that 100 of these systems will be provided by outside suppliers rather than written in-house. Proctor noted, "Because the ROI for a fully integrated defect data management system is high, almost all semiconductor fabs can easily justify \$500,000 for such a system, and a plurality can justify \$1 million."

And there seems to be another significant role: using yield management software to determine the cost effectiveness of inspection and inspection equipment. Today, industry estimates are that inspection and measurement account for about 13% of the \$1 billion budget for an advanced fab. Laura Peters at Integrated Circuit Engineering (Scottsdale, Ariz.) has reported, "Yield management must enable process engineers to be able to understand and evaluate the trade-offs between the cost of an inspection and the potential cost of lost product if an excursion remains undetected for any significant amount of time."<sup>2</sup> □

**References:**

1. "The Outlook for Defect Data Management Systems," prepared by The Laird Durham Co., Pittsburg, Calif.
2. *Cost Effective IC Manufacturing 1995*, Integrated Circuit Engineering, Scottsdale, Ariz., 1995.

For more information directly from the suppliers of yield analysis software mentioned in this article, please circle the appropriate number on the reader service card at the back of this issue.

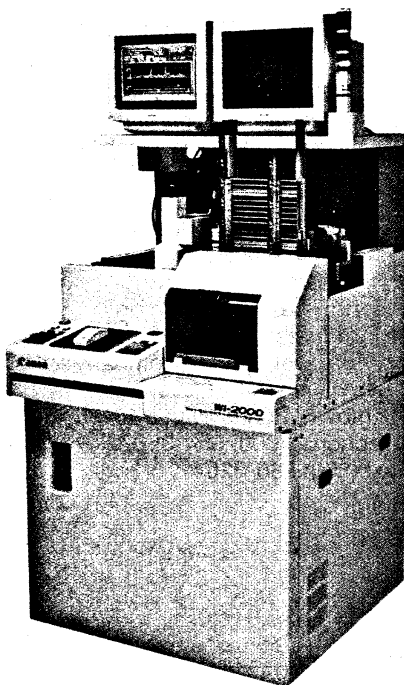
Company	Circle No.
Defect & Yield Management (DYM)	222
INSPEX	223
KLA PRISM	224
Knights Technology	225
LPA Software	226
Tencor Instruments	227

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**Introducing a better automated wire bond inspection system.**



**Faster, more accurate**

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