3.5 PROCESS DIAGNOSTICS

Page

3.5.1 Current Industry Characteristics

(Shaded Material is unreleased)

3.5.0 PROCESS DIAGNOSTICS

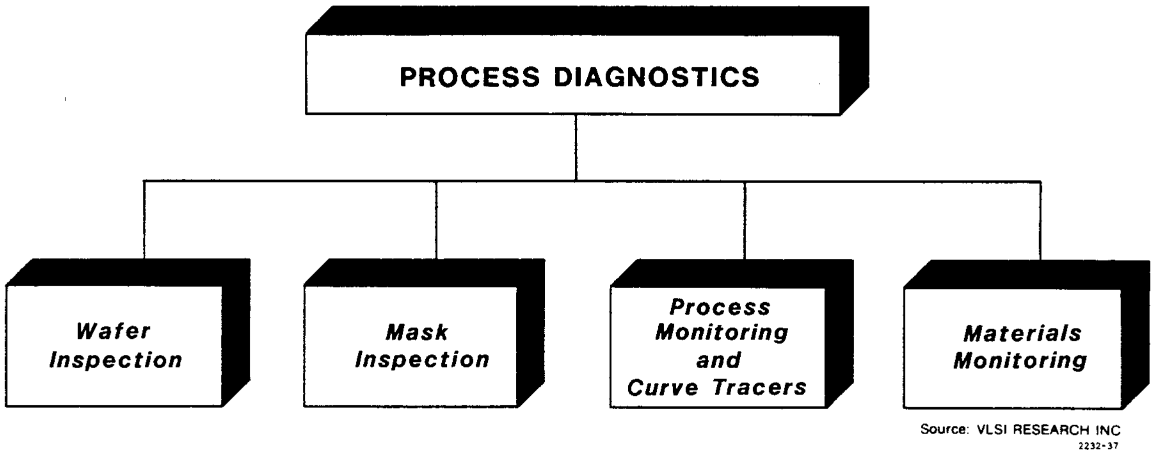
Process diagnostic equipment is critical to semiconductor manufacture. Though this equipment is not used to directly manufacture devices, it serves to verify consistent and in-control manufacturing processes.

Equipment for process diagnostics includes wafer inspection, mask inspection, process monitoring, curve tracers and materials monitoring, as shown in Figure 3.5.0-1. While wafer inspection uses microscopes, the microscope industry is not covered since it is so broad and not endemic to semiconductors. Rather, microscopes serve virtually all segments of industry and science, so no purpose would be accomplished by covering them here. More importantly perhaps, microscopes themselves have become OEM components within VLSI manufacturing equipment, more often being sold as an equipment accessory rather than as an end item. Finally, vacuum instrumentation is excluded also, as this segment can be more properly described as instrumentation within a vacuum system. Such instrumentation has no separate market in and of itself.

In the mid-eighties the process diagnostics market exceeded $450M. The process diagnostic industry for semiconductors is characterized by a fragmented market, with fragmented products, and fragmented competition. It encompasses research scientists, manufacturing specialists, quality control and assurance engineers, and failure analysis diagnosticians. It spreads across academic, industrial, and government institutions. Its products incorporate technologies ranging from simple optics to sophisticated X-ray techniques, with vast differences sometimes existing even within single categories. More than twenty-six different types of inspection equipment are used to perform inspections in semiconductor lines. They are supplied by more than 100 different manufacturers. Competition comes from both numerous small companies as well as a few large diversified companies. Many leading suppliers of individual instruments have overall sales of less than $5M.

Users of process diagnostic equipment for semiconductor manufacture consist of production, research, quality control and failure analysis personnel. Applications can be divided into four process areas: military and R&D lines, captive modules and pilot lines, average size manufacturing modules, large modules and giant modules. In the mid-eighties, the average size semiconductor manufacturing process module started about 2500 wafers per week. Almost ten times that quantity of inspections are made weekly in a typical module—some 24,725 per 2500 wafer starts per week. Large modules start 5000 wafers per week, while giant modules start 7000 wafers per week. The quantity of inspections increases accordingly, with a slight slowdown in larger modules due to economies of scale.

Figure 3.5.0-1



Captive modules, R&D lines, pilot lines and military lines all share the common characteristic of being underutilized. Most are designed for a capacity of about 1000 wafer starts per day, for it is uneconomical to make them any smaller. However, by-and-large, these lines will seldom process more than 100 wafers per day. This is equivalent to about 500 wafers per week. Thus, they usually run at 50% capacity or less.

3.5.1 CURRENT INDUSTRY CHARACTERISTICS

(Shaded material is unreleased)

3.5.1 Current Industry Characteristics

The process diagnostic industry has become a critical subindustry to semiconductor manufacturing. As the cost to operate equipment and complexity of devices increases, it is essential that process quality be monitored to correct problems as early as possible in order to sustain yield and control costs.

Growth in the process diagnostic market has been driven by the need to build-in quality as well as by the need to design and build devices correctly the first time. Classical automatic test equipment can only test-out poor quality at the end of the process. It cannot add to intrinsic device quality. Test equipment costs and test times sky-rocketed during the seventies and eighties. It has thus become too costly just to inventory and test-out defective devices with test equipment. A closed-loop factory which waited upon test results for yield corrections would build up costly stockpiles of defective products. If something were to go wrong in processing, it could take months before a problem is identified through test data. With typical lines of the mid-eighties, it was possible to start more than eleven million dollars worth of potentially defective product if the line was being solely controlled from test data. No semiconductor manufacturer could afford such a scheme.

This is why many of the recently built factories have been designed more as open-loop or loose-loop systems rather than as a tightly controlled feed-back loop system. The elementary systems themselves are closed loop, and there are some closed-loop islands within the factory. Equipment which diagnoses processing errors that are essential for these islands to avoid yield loss are needed. Process diagnostic equipment has become essential in filling this need and in monitoring the fabrication process in order to eliminate such costly yield losses.

3.5.1.1 Development Of The Industry

Some of the technologies for the materials monitoring segment have been in existence since the early 1940's. These technologies eventually became employed in the semiconductor manufacturing environment.

The curve tracer is one instrument whose market dates back to before the time of the first transistor. It was developed for the vacuum tube industry. But traditional curve tracers could not perform versatile programming and could not store data. This eventually led to the development of modern process monitoring equipment.

Optical inspection has also been a critical element of semiconductor manufacturing since its beginning. The first types of inspection equipment consisted of microscopes. In the early-eighties automated microscopes appeared on the scene.

The wafer inspection market evolved from the mask inspection market. The first automated mask inspection equipment was introduced in the mid-1970's by KLA.

3.5.1.1.1 Development of the Wafer Inspection Industry

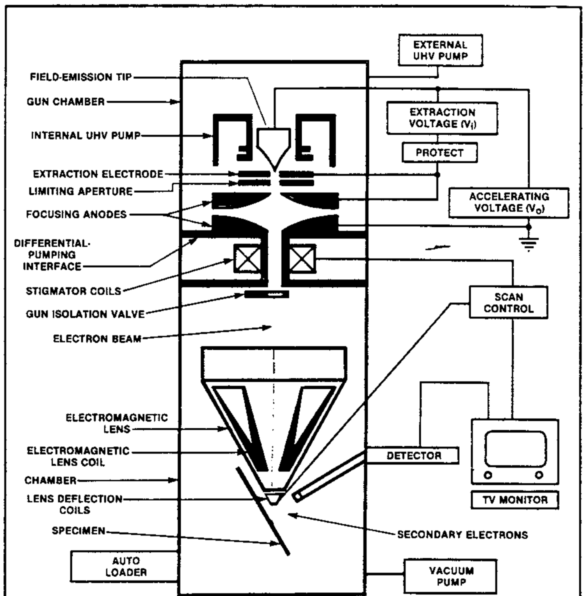
Inspection has been an integral part of semiconductor manufacture since its inception. The first versions of inspection equipment were non-automated microscopes with simple x-y stages.

Nevertheless, this was to change as device complexity increased. The manual operation of microscopes proved too susceptible to human error. Consequently, the semi-automated inspection market began to grow at a much faster rate in the late seventies.

Classically, the role of inspection has been to guarantee quality conformance and quality assurance. The former is generally inward looking while the latter is generally outward looking. That is to say, quality conformance is an effort on the part of the manufacturer to protect himself by lowering his cost of waste through improved manufacturing quality. Quality assurance is an effort to ensure that the customer receives a reliable, quality product which can be anticipated to continue functioning for its expected lifetime. Another way of saying this is that quality control works to the manufacturer's advantage while quality assurance works to the customer's. Responsibilities for quality conformance and quality assurance lie within the quality control department.

Early concepts of inspection included elementary quality control tests for form, fit and function. However, the world of integrated circuits has grown too complex and too abstract for such elementary items. As time elapsed and integrated circuits increased in complexity, quality control departments found themselves unable to cope with the real-life complexities of integrated circuits. They gradually abrogated inspection functions in the factory, and manufacturing took over. QC/QA has since generally limited itself to manufacturing control through statistical inference via lot sampling procedures. Consequently in the early-eighties, inspection became a manufacturing function. Moreover, inspection has also changed from the role of lot sampling and has become, in a few instances, full in-line, automated, inspection. Figure 3.5.1.1-1 gives brief drawings of wafer inspection systems.

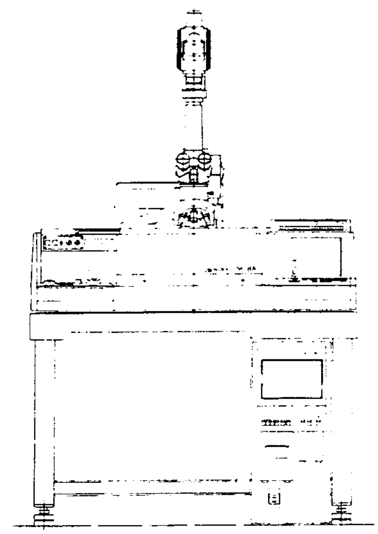
The reason for this changing role was elementary: Each and every semiconductor device manufactured is inspected and tested individually



Ref: Nanometrics

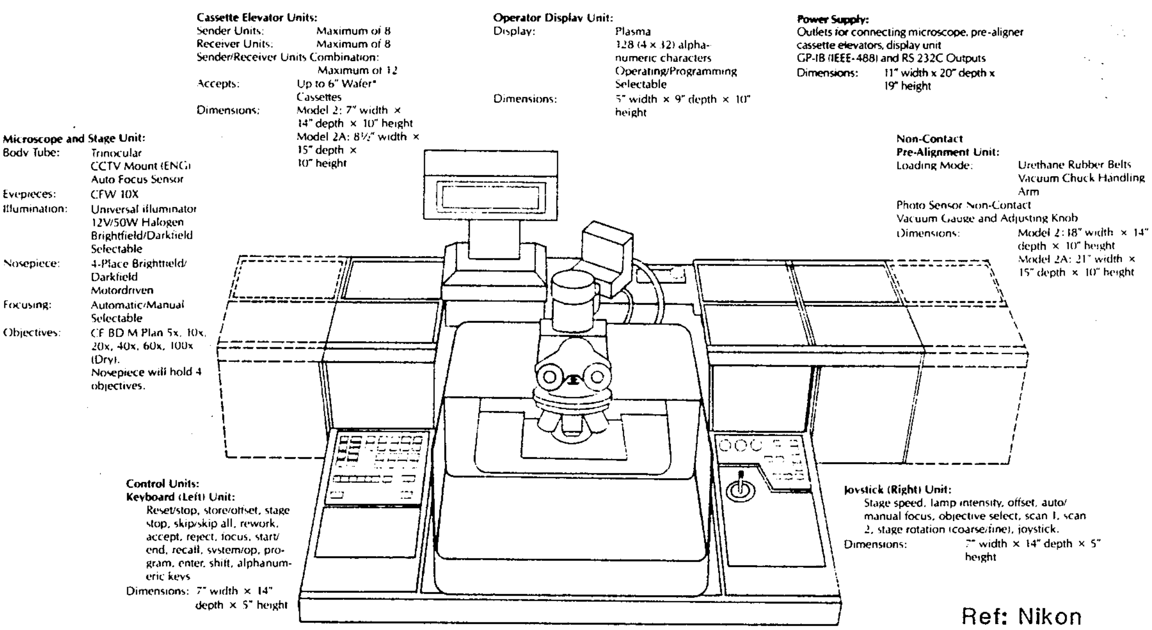
Block/schematic diagram of typical field-emission SEM. Electrons from field-emission tip (blue) are accelerated, focused by electromagnetic lens (yellow), and scanned across specimen in raster pattern by lens deflection coils. Resulting secondary electrons are detected, and corresponding signal intensity-modulates monitor that is raster-scanned in synchronism with electron beam.

Nanometrics's SEM



Ref: Nidek

Nidek's IM-8A Inspection Microscope



Ref: Nikon

2232-39

Nikon's Optistation IC Wafer Inspection Station

Figure 3.5.1.1-1

TYPICAL WAFER INSPECTION EQUIPMENT

at several points in the process. Contrast this with the manufacture of other devices wherein lots are only sampled on a periodic basis. When sample tests are made, there is little economic pressure to stress the utility or the speed of the inspection, so long as the method is accurate. But when 100% inspection is performed, classical manufacturing pressures develop to simplify, to speed up, and to improve inspecting methods. Semiconductor inspection equipment thus found itself in a role similar to that of other manufacturing equipment.

As this occurred, the role of inspection gradually changed from a role of inspecting the product, per se, to a role of inspecting the manufacturing process itself. Inspection then evolved into process monitoring, and ultimately into process control. More complex instrumentation became integrated into inspection during this evolution.

Much of the original instrumentation equipment was designed either for, or by, semiconductor research laboratories as instrumentation for extending the limits of materials research. Subsequent production requirements for those newly-introduced materials or processes often resulted in more widespread need of this instrumentation. Small specialty companies thus sprang up to fill the market. As of the mid-eighties, the market remained very fragmented, and was still supplied by such small companies. Only a very few of the larger companies took sufficient interest to strongly promote instrumentation.

Resistivity measuring equipment is a case in point. The methodology was one of the first to be developed for semiconductor use. But for almost two decades, resistivity methods lay virtually untapped in incoming inspection departments. There it was used to measure the doping range of wafers being received from outside vendors. Resistivity instruments first began to be used in production to monitor so-called test wafers in diffusion. These are unpatterned wafers. One test wafer is used to accompany each lot of wafers that are being processed. It receives all of the same processing that the others receive, but because it is not patterned, large wafer areas can be measured. Resistance on the test wafer is measured after implantation or diffusion to determine the correct doping concentration. Thickness of deposited films is also measured after deposition. These films are subsequently stripped from the test wafer and resistivity tests are retaken. As a result, resistivity film thickness, together with other instrumentation equipment, moved from the quality control department into production.

As is indicated in Section 3.5.9, the inspection equipment market has followed a trend that can be said to be typical of the semiconductor capital equipment industry: the older equipment suppliers with manual instrumentation have grown at a relatively slow pace, while the suppliers with integrated systems have captured newer market share.

The market for a particular type of instrument remains small when it is not used in production on a wafer-by-wafer basis. But once some justification can be made for performing wafer-by-wafer tests, the market quickly develops.

There are four major categories of inspection. They are outlined in Table 3.5.1.1-2. These four categories can be further segregated into seventeen different sub-categories of inspection. Altogether, there are twenty-five distinct types of equipment to address these. They are shown in Table 3.5.1.1-3. They are essentially instruments.

Inspection instruments are used mainly to measure one or two physical characteristics on a wafer. The main categories of inspection instruments are:

- line width measuring
- film thickness measuring
- wafer flatness mapping
- surface profiling
- wafer measuring

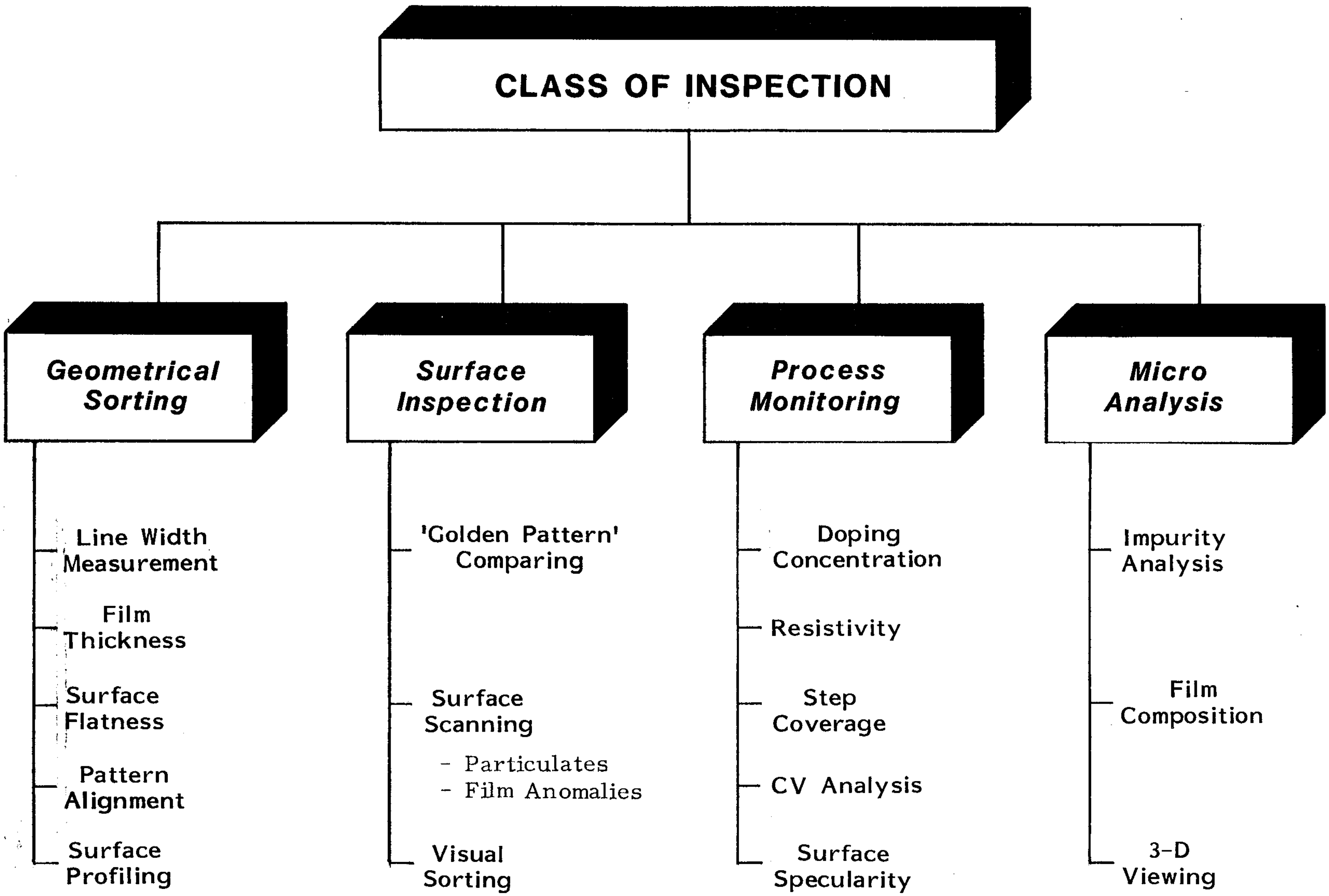
Line width measuring instruments are used to scan across a wafer surface and measure patterned linewidths. Typically, the operator locates any disparities between required linewidths and inspected linewidths. Film thickness instruments measure the thickness of films deposited on wafers. They use either light, sound or beta backscattering. Wafer flatness mapping instruments measure wafer flatness in the optical plane across the surface of a wafer. Surface profiling instruments, as the name implies, give a profile of surface of the wafer. Wafer measuring instruments measure characteristics such as taper, warpage, and bow.

Process monitor clusters consist of clusters of discrete equipment hooked together and used to measure electrical characteristics on wafers. There are two basic categories:

- CV Instruments and Plotters
- Miscellaneous Monitoring Instruments
  - Four and Six Point Probes
  - Deep Level Transient Spectroscopy (DLTS)
  - Eddy Current (ED) Measuring Instruments

CV plotters are used to measure the shift in capacitance versus voltage and temperature in semiconductor devices. Critical doping properties of the device can be detected by the voltage shift corresponding to capacitance flat bands. In this inspection process, an initial CV plot is conducted at ambient temperature. Test devices are put under stress voltages and elevated in temperature. The temperature and voltage are removed. A CV plot is conducted once again at ambient temperature.

TABLE 3.5.1.1-2



Source: VLSI RESEARCH INC.
2232-40

TABLE 3.5.1.1-3

Instruments For Inspection

Type of Inspection / Type of Equipment	Geometrical Sorting: Line Width Measurement	Geometrical Sorting: Film Thickness	Geometrical Sorting: Surface Flatness	Geometrical Sorting: Pattern Alignment	Geometrical Sorting: Surface Profiling	Surface Inspection: Golden Pattern Comparing	Surface Inspection: Surface Scan -Particulates	Surface Inspection: Surface Scan -Pattern Anomalies	Surface Inspection: Visual Sorting	Process Monitoring: Doping Concentration	Process Monitoring: Resistivity	Process Monitoring: Step Coverage	Process Monitoring: CV Analysis	Process Monitoring: Surface Specularity	Micro Analysis: Impurity Analysis	Micro Analysis: Film Composition	Micro Analysis: 3-D Viewing
Acoustical Microscope		•	•				•		?E								
Beta Backscatter		•															
Conductance Gauge															•		
CV Analyzer										•			•				
CT Analyzer										•					•		
DLT Spectrometry										•			•		•	•	
Eddy Current Gauge		•								•	•						
Ellipsometer		•															
FTIR		•						?						?		•	
Four Point Probe										•	•				•		
Gas Chromatograph															•		
Interferometer		•	•														
Ion Chromatograph															•		
Laser Probe			•		•	•	•	•						•			
Microspectrophotometer		•													•		
Optical Microscope	•	•		•		?E	•	•	•					•			
Plasma Spectrometer															•		
Scanning Electron Microscope	•	•		•	?E	?E	•	•	?E			•					•
Sonic Reflectometer																	
Six Point Probe										•	•						
Stylus Microprobe					•												
Thermal Wave Microscope	?F	•				?E				•	•	?F			•	-	
X-Ray Fluorescence		•					•	•		•				?	•	•	
Video Micrometer	•	•		•		•	•	•	•								

E: Economical Limitations F: Feasibility Undemonstrated

Source: VLSI RESEARCH INC. 231-102

The resulting shift in flat band voltage of the two plots correlates to moving ionic contamination.

Four point probes and six point probes are used to measure resistivity. In four point probe applications, the probes are first brought into contact with the wafer. Current is then forced into the two outside probes. The voltage developed at the two inner probes is then measured. Six point probes are similar to four point probes, but the two additional probes are placed on the backside surface of the wafer. Six point probes can be used to better measure injection currents at a probe contact. One drawback with contact probes is that they are destructive to wafers.

Deep level transient spectroscopy (DLTS) measures dopant impurity concentrations by monitoring donor or acceptor ions in the substrate. These impurities may have resulted from defects in the crystal lattices (dislocation defects), they may have been process induced (radiation damage), or they may be generated from device failure. Deep level impurities are significant because they alter the electrical and optical properties, thereby reducing device lifetime. One method of measuring this type of impurity is to rapidly pulse the bias voltage, thereby filling the deep level traps temporarily. A current transient occurs at the end of the pulse. The transient is monitored as a function of pulse rate and temperature of the sample.

Another noncontact method of monitoring makes use of eddy currents. In this process the wafer is inserted between the poles of an inductance coil. The coil is part of an RF tank circuit. The wafer changes the load on the RF tank via electromagnetic coupling and detunes the RF circuit. The amount of detuning is directly related to the resistance of the wafer and can be used via conventional tuned circuit formulae to measure resistance.

Inspection systems are large stand-alone stations that automatically pre-align and position a wafer at the correct point for inspection. There are four basic classifications for inspection systems:

- Wafer Inspection Stations
- Image Processing Systems
- In-Process SEM's
- Surface Particulate Scanners

Wafer inspection stations mechanically move a wafer onto the chuck and scan across its die permitting the operator to observe defects. Operators then key-in both the type and location of defects. Process engineers can then analyze the resulting data and make corrections to manufacturing processes.

Image processing systems perform these functions automatically, inspecting for defects and measuring characteristics such as linewidth and film thickness. These systems inspect without the aid of an operator. This equipment quickly gained in popularity due to its ability to obtain consistent detection of defects. In-process SEM's are scanning electron microscopes sold to the semiconductor industry. SEM's allow for detection and measurement of submicron images. Some of these systems are destructive while others are not.

Surface particulate scanners automatically scan blank wafers for particulates and map their location.

Exotic equipment species measure various properties of wafers, using exotic measurement techniques that cannot be easily categorized elsewhere. This market has three basic categories:

- Energy dispersion systems
- FTIR
- Miscellaneous

Most energy dispersion systems use an X-ray technique to examine contamination in coatings. Fourier transform infrared spectrometers (FTIR) measure film composition and film thickness via infrared light generated by a laser.

The miscellaneous classification is used to include various types of exotic microscopes such as ultrasonic and thermosonic ones. Other exotic techniques used in the semiconductor industry are scanning laser microscopes, thermal wave microscopes, ion chromotography instruments and others.

By the mid-eighties, inspection equipment manufacturers had begun to address several aspects of semiconductor manufacture. These were:

- contamination control
- increasing wafer sizes
- yield enhancement and productivity
- smaller geometries
- automation

Contamination control became a major issue for all manufacturers. As awareness of the need for better contamination control grew, so too did the need for automation. Contamination control is directly traceable to yield. The manual methods that were used for inspecting wafers were found to contaminate wafers. The people performing the inspection were another leading cause of contamination. Some of the contamination problem was solved by reducing the operator's exposure to the wafer. By employing some forms of automation, inspection errors attributed to the operator were reduced. For example, manual linewidth measurement is found to vary widely from operator to operator. Automated measurement eliminates these variances in linewidth inspection. New generations of equipment with automation have thus developed.

The trend toward increased wafer size is not new. The increased size resulted in the upgrade of older inspection equipment models. For instance, many companies had introduced inspection equipment available for 8 inch wafers. However, as wafer size increases, it also increases inspection equipment demand. Precision must also be improved. It is much harder to control process specifications across an eight inch wafer. Moreover, larger wafers have greater value because they have more die than do smaller wafers. Yield loss due to non-uniformities defeats the purpose of using larger wafers. Consequently, the use of more sophisticated inspection equipment is justified as wafer size increases. As wafers became larger, warpage and bow also became a greater issue. Equipment used to detect these features thus experienced increased demand.

The market for inspection equipment experienced unusually high growth in the mid-eighties as shown in Section 3.5.9. There were two primary reasons for these phenomenal growth rates. They were:

- Yield Enhancement
- Productivity

As the semiconductor industry progressed, it placed an ever-increasing burden on both inspection equipment and its operators. Smaller geometries made inspection more difficult, yet without inspection, yields dropped off drastically. For example, the problem of locating defects rose to horrendous proportions. A one micron defect might lie in any of over eight million points covering a four inch wafer. The magnitude of this problem was clearly pointed out by Gordon Moore, of Intel. He noted:

> "Finding a defect...is like finding a matchstick in a field of hay."

This problem is compounded by the need for multiple inspection steps. Wafers are typically inspected following photoresist develop, following etch and after the photoresist stripping. About 35% of all wafers go through these steps.

The typical inspection of a wafer consists of a back and forth 'Z' scan at between 100 and 200 power. Afterwards, the inspector will check the test die and several adjacent die for misalignment and other defects. These are performed at higher magnifications (400X - 600X).

Table 3.5.1.1-4 outlines inspection methods in greater detail at each of the major inspection points in wafer processing.

Inspection data is usually of a form called 'attributes' data rather than 'variables' data. Attributes data consists of a set of tally points that are pigeon-holed by disposition. One example might be the quantity of components which pass inspection at a given point, together with the quantity which fail. Variables data consists of a set of measured data points associated with the units, or the dimensions, of the item being inspected. One example might be the length of a cable when measured in meters, another might be the temperature of a process in degrees. By way of contrast, equipment manufacturers have been more accustomed to such 'variables' data. But individuals in semiconductor manufacturing seldom deal with such variables data except at in-process monitoring.

The extent and frequency of measurement is an important definition to be aware of. The concept of inspection is usually associated with the concept of examining some portion of the surface of a wafer. But the total surface area of a wafer is seldom examined or measured. Usually only a few measurements are made and these are made at a limited number of points—say 5 to 15. These, in turn, may be performed on all wafers—i.e. 100% wafer inspection, or they may be performed on just a few. If inspection is only to be performed on a few wafers, it must be known whether those few are inspected in each lot, or if the lots themselves are to be sampled. Figure 3.5.1.1-5 gives a mid-eighties distribution of inspection at several different points.

It should be noted that there is no simple one-to-one relationship between an inspection instrument and its market. For example, there are twelve kinds of instruments used for thickness measurements. Most of these are used for other purposes as well.

Smaller geometries have challenged the industry to devise more accurate ways to inspect wafers. Scanning electron microscopes are now commonly found in fab areas. Some of these are used in in-process applications. In the past they were used dominantly for analytic purposes rather than inspection purposes. In order to be used for inspection, scanning electron microscopes needed to overcome three limitations: 1) they need to be non-destructive, 2) they must be able to preserve the address of the defect inspected in order to be able to return later to the defect, and 3) they must be able to work in an unsteady, vibrating, manufacturing environment.

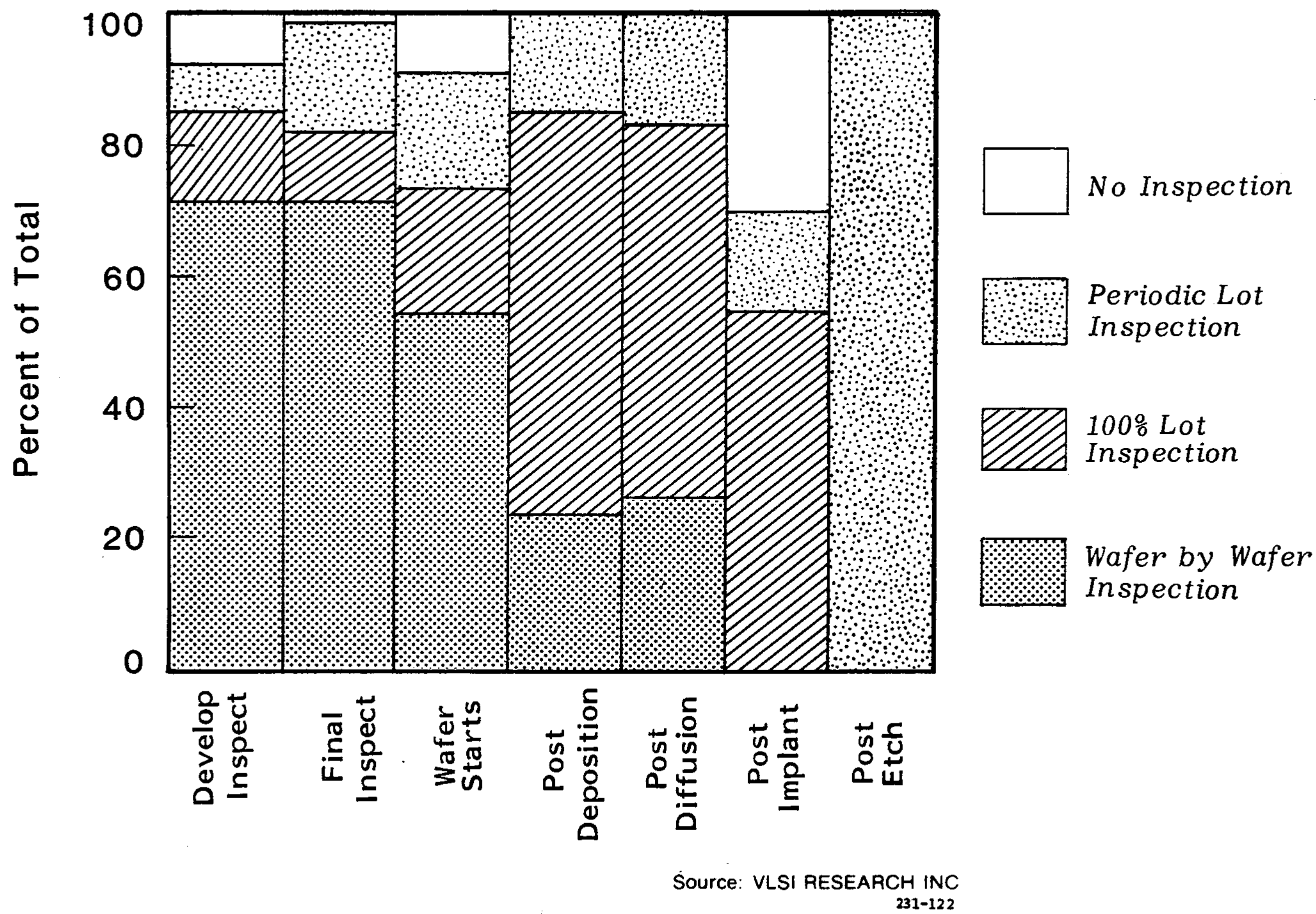
Through the early-eighties, the outlook for fully-automated, non-human wafer inspection was very discouraging. There was no foreseeable means at hand for replacing the human operator. Pattern recognition had not advanced sufficiently to replace the operator, while a myriad of

TABLE 3.5.1.1-4

EXTENT OF INSPECTION IN THE TYPICAL PROCESS

Operation	Typical Point by Point Inspections	Typical Surface Inspections
Develop Inspect	Critical Dimensions 3 Places/Wafer 3 Wafers/Lot (50W Typ)	Microscope at 100X in Z Pattern Scan or Individual Die in 4 Quadrants and Center. 200X Used for Detail When Required.
Final Inspect	Critical Dimensions 3 Places/Wafer 3 Wafers/Lot (50W Typ)	Microscope at 100X in Z Pattern Scan or Individual Die in 4 Quadrants and Center. 200X Used for Detail When Required.
Wafer Starts	Point by Point Inspection Is Not Typically Performed	Unaided Eye Inspection Under Bright Light – Dark Field Microscope Used for Detail When Required.
Post Deposition	V/I 3 Places/Test Wafer (TW) 3 TW/Load (100W Typ)	Unaided Eye Inspection Under Bright Light – Dark Field Microscope Used for Detail When Required.
Post Diffusion	V/I 3 Places/Test Wafer (TW) 3 TW/Load (100W Typ)	Unaided Eye Inspection Under Bright Light – Dark Field Microscope Used for Detail When Required.
Post Implant	V/I 3 Places/Test Wafer (TW) 1 TW/Lot (50W Typ)	Unaided Eye Inspection Under Bright Light – Dark Field Microscope Used for Detail When Required.

Source: VLSI RESEARCH INC
231-121



INSPECTION FREQUENCY

topologies and materials were involved. Moreover, some degree of three dimensional perspective was needed as well.

That all changed in early 1984 when KLA announced its Model 2020 wafer inspector. This was the first true image processing system that the industry had produced. And it replaced the human inspector. It operates at 110 wafers per hour and it brings an objective measurement approach to an otherwise quite subjective inspection point. It was the freshest and most original piece of inspection equipment to emerge. It's impact on the wafer inspection market size can be seen in Section 3.5.9. Insystems Corporation later introduced an image processing system that employs holography. Insystems claims this new system has the ability to inspect an entire wafer in one-sixth of the time taken by other methods.

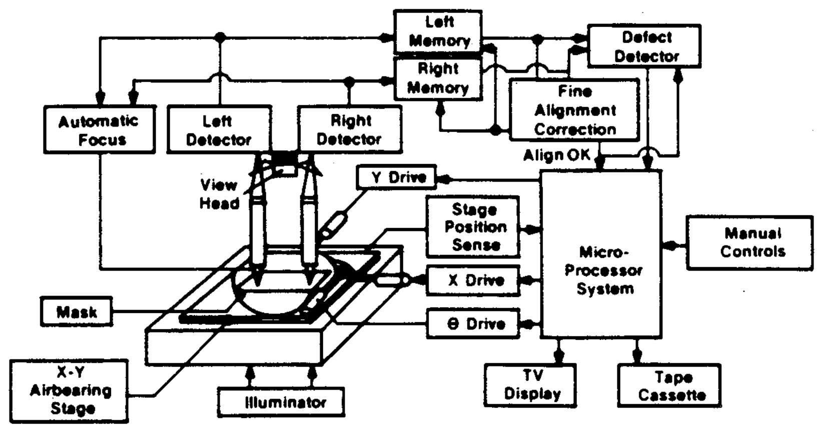
The reason for the success of image processing was thus found to be related to both economics and to yield improvement. An image processing system provides an unbiased eye for inspection. It also automates data collection so that yields could be improved over time via engineering analysis.

3.5.1.1.2 Development of the Mask Inspection Industry

Originally, masks were inspected manually, just as wafers. There was no market. Microscopes and other special optical tools were used for both tasks. The first true mask inspection system was introduced by KLA in 1976. Other systems, as well as mask repair systems—which could make use of the computer outputs from inspection systems—then evolved. Today, the market for mask inspection equipment can be segmented into four distinct types:

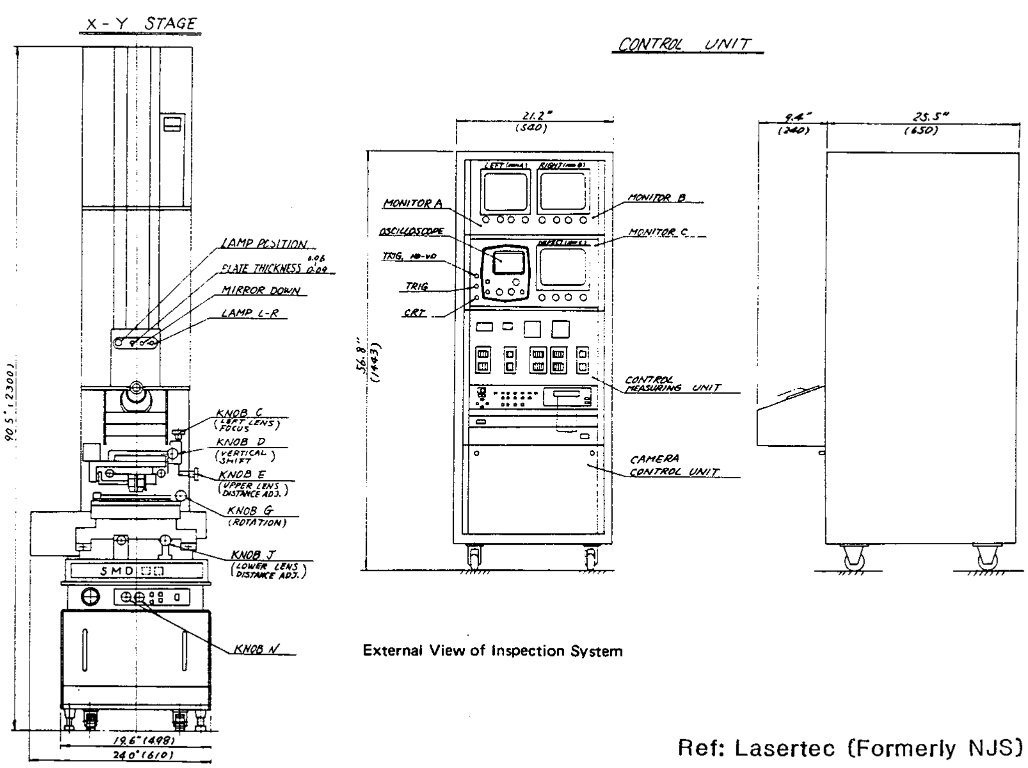
- Master Inspection Systems
- Reticle Inspection Systems
- Production Qualification Systems
- Mask Repair Systems

Brief drawings of mask inspection equipment are given in Figure 3.5.1.1-6. Master mask inspection systems compare a newly created mask with its computer-generated database. The computer database contains a digitized pattern of the mask, as derived from the original mask design generated in a CAD system. The advent of reticle use with steppers created mask inspection problems. First, there was often only one die, on each reticle, so a comparative die-to-die inspection could not be made. Second, the masks had to be perfect. One defect



Ref: KLA Instruments

KLA-100 Block Diagram



External View of Inspection System

Ref: Lasertec (Formerly NJS)

2232-44

The Lasertec 5MD22 Mask Inspection System

Figure 3.5.1.1-6

TYPICAL MASK INSPECTION EQUIPMENT

would subsequently print on all dice and ruin them all. Clearly, a new type of inspection system was needed at the time.

NJS (now Lasertec) introduced the first reticle inspection equipment in 1981. It was soon followed by KLA. The reticle inspection market took off even more rapidly than the master mask inspection market had.

Production qualification systems are dedicated to qualifying a reticle before it is used in production. Reticle qualification systems are used to qualify previously used reticles just before use. At issue is the integrity at the moment of use, for the reticle may have deteriorated since its initial inspection and a repeating defect may have appeared.

There are several approaches to qualifying reticles. KLA offers one solution. The KLA method uses chrome glass wafers for qualification. These glass wafers are first exposed by the aligner. They are then passed through a standard KLA inspection equipment and treated as if they were a mask. Micromanipulators offers another solution via a specialized manual inspection system. This utilizes a proprietary filter that enables users to actually see defects in pellicle membranes. It also highlights residual dust particles left on the mask when a pellicle as being attached.

As mentioned, the first automatic mask inspection equipment was introduced by KLA in 1976. This was quickly followed by Lasertec's (formerly NJS) unit. Such equipment proved to be very accurate. At the 1978 Kodak Microelectronics Seminar, David Angel and P.H. Johnson of AMI astounded the lithography world with some of the first results from having used the KLA system. They had purchased the system and set out to use it merely as a means for improving manufacturing via automation. What they found instead was an incredible number of defects not previously thought to have existed. Here is what they reported:

> "...The initial results from the equipment produce a situation entirely different than anticipated. Upon inspection of 'thought-to-be-perfect' photomasks for projection printing manufactured internally as well as from outside sources, the equipment indicates defect levels from two to ten defects per square inch.
>
> The equipment prints the coordinates of all anomalies. Upon a thorough review of all reported anomalies at 600X magnification it was verified that in greater than 95 percent of the cases, the reported anomaly was indeed present. At this point one notes a change in terminology; that is the use of the word anomaly rather than defect. At the risk of jumping subjects, considerable work lies ahead in defining and categorizing unintended material on the photomask and its effects upon yield at 6 microns, 5 microns, 4 microns, 3 microns,

and downward feature sizes. A reported anomaly may be a killer defect with 3 microns design rules, however, may not be as significant with 5 microns design rules. But the first conclusive statement that we may take regarding automatic inspection equipment is that the reported foreign or unintended matter on the photomask is indeed present.

The second feature of automatic inspection equipment is the sensitivity. The sample masks were obtained from:

1. The AMI photomask operation;

2. Generally respected, independent photomask suppliers;

3. The internal photomask operation of other semiconductor companies; and

4. E-beam created photomasks.

All masks were considered to be "master or projection print" grade. All masks had the multiple hours visual inspection and laser repair (if necessary) associated with "perfect" grade masks. In short, the masks represented the best effort of several credible photomask operations. Obviously, there was considerable dubiousity when so high a defect count was reported. However, once a skilled operator, who had previously inspected the masks and failed to find the anomaly, became aware of the coordinate location of the anomaly, the inspector could verify the existence of the anomaly with moderate to reasonable ease, even in the submicron region—albeit in that situation with difficulty. So it may be concluded that automatic inspection has a detection sensitivity several orders of magnitude greater than the human eye with considerable speed advantage."

Angel and Johnson's results were soon repeated elsewhere. The industry had thus begun a long and successful drive to implement mask inspection at all sites. It was quickly accepted as a replacement for manual inspection with microscopes. The market size doubled each year thereafter from 1977 through 1980.

Mask inspection equipment operates by comparing two dice. It has two objectives. Each is focused over the same segment of two different die. The mask pattern is viewed by the microscope objective and digitized by electro-optical transducers. The digitized data is then processed by a micro-computer. The processed data is compared against the original pattern. A "best fit" digital pattern analysis is made. The "best fit" methodology eliminates extraneous defects such as mask run-out, mechanical errors, and operator misalignment. Any other geometric differences between dice are considered to be defects; their size and location are logged and stored. The Lasertec (formerly NJS) system converts patterns to video signals and uses a high speed flying spot scanner to compare corresponding segments of two die.

Issues concerning mask inspection in semiconductor manufacturing have been quite different from those encountered in wafer inspection. There are several reasons. First, throughput is not an issue in mask inspection, as it is in wafer inspection. Masks do not need to be inspected after each exposure, only when they are changed. Quality of inspection becomes of paramount importance in mask inspection however, because it will affect each and every wafer product.

Six types of mask defects impact yield:

- Lead Breaks
- Bridging across leads
- Lead intrusions
- Pinholes or pinspots
- Missing geometries
- Glass fractures or seeds

All of these must be smaller by one-half than the minimum pattern geometry sizes in order to avoid yield losses and should be even less than that.† Most individuals in masking would prefer that an individual defect be no more than 10% of the minimum geometry, but manufacturing practice will often allow 33% to 50%. Recent evidence however indicates that defects do not scale linearly, so even 10% may become unacceptable for tight geometries. At 25%, defects as small as one-half micron must be detected and eliminated when using two micron technology. Mask inspection systems must be able to accurately find such small defects.

Manually locating sub-micron defects is virtually impossible on a five inch mask. The use of automatic inspection is critical. Studies have shown that automatic inspection systems consistently detect as many as five times the defects detected on a manual system using human inspectors. Consequently, automatic mask inspection has become the favored approach.

Most early problems with mask inspection equipment have now been resolved. Few people feel that there is an issue in mask inspection equipment. Automated master and reticle inspection has taken place. It has been proven to work well because of defect discrimination techniques.

The advent of pellicles had a significant impact upon mask inspection.

† D. Angel and P. Johnson, "Effects of Mask Defects on Reliability and Yield," Semiconductor International, March 1980

Pellicles are protective membranes placed just above the mask surface. Their purpose is to optically remove dust particles, rather than to physically remove them. The pellicle is optically transparent, and is positioned about three millimeters (75 microns) from each mask surface. Dust particles falling upon the pellicles are held at the pellicle, and are thus outside the focal depth of the aligner's lenses. So they're not seen. The effect is much like dust on a pair of eye glasses. Dust can be seen when the glasses are examined closely. However, the dust only appears as minor distortions when wearing glasses because it too is far outside the focal depth of the eyes. This proved to have a tremendous positive impact upon yield: defect densities decreased by as much as 30% to 50%. Yield increased correspondingly.

Pellicles also extend mask life, the masks don't get as dirty or need not be cleaned as often. Consequently, pellicles have proven to be as important as was the advent of the stepping aligner and the projection aligner.

Other issues of the mid-eighties centered on defect density as a function of size, detection ability and the ability to repair defects. These issues were critical to the future advances in 1X lithography.

Table 3.5.1.1-7 lists defect density versus size for both opaque and clear defects. This table presents amalgamated results from several published sources. It shows that particles above 10 microns in diameter are virtually nonexistent: Modern clean rooms are effectively filtering out such large particles. Opaque defect densities are seen to increase gradually with decreasing size. There is a shallow dip in the one to two micron region and then a heavy peak between 0.5 and 0.75 micron. In contrast, clear anomalies tend to peak in the 6-10 micron range and then again in the submicron range.

By the early-eighties, inspection systems were catching 100% of the defects above about one to two microns in diameter. Below that size the capture rate decreased appreciably. The systems were only about 35% effective on particles below one half micron.†

> Data used in the above discussion dealing with defect density was taken in the 1983 time frame. Since then, the capture rate of mask inspection systems has improved dramatically. For example, the KLA 208 and 218 models had an improved capture rate of 0.95 at one-half micron, while the KLA 209 and 219 models achieved 0.95 capture rates as low as 0.35 micron. Unfortunately, while the data on these new capture rates is available, newer data on as-made densities and repair rates is still unavailable. Therefore, more recent post-repair defect densities are unavailable as well. Should the data become available, post-repair defect density can be calculated from this formula:
>
> $$\textit{density after repair} = D\left[1 - P_c \cdot P_r\right] \qquad [\#/\text{unit square}]$$
>
> Where:
>
> *D is the as-made defect density,* P_c *is the capture rate, and* P_r *is the repair rate.*

TABLE 3.5.1.1-7

OVERALL MASK DEFECT DENSITY & REPAIR RATE
(circa 1983, domestic USA)

Particle Diameter (micron)	Inspection Capture Rate (%)	OPAQUE ANOMALIES			CLEAR ANOMALIES		
		Density As Made (#/Sq.In.)	Repair Rate	Density After Repair (#/Sq.In.)	Density As Made (#/Sq.In.)	Repair Rate	Density After Repair (#/Sq.In.)
>10µ	100	0.01	100%	0	0.50	100%	0
8-10µ	100	0.10	100%	0	1.50	100%	0
6-8µ	100	0.50	100%	0	0.80	100%	0
4-6µ	100	0.50	100%	0	0.50	100%	0
2-4µ	100	0.30	100%	0	0.30	100%	0
1-2µ	100	0.25	100%	0	0.25	100%	0
0.75-0.99µ	94	2.0	75%	0.6	0.5	100%	0
0.50-0.74µ	73	5.0	25%	4.1	0.5	75%	0.23
<0.5µ	35	3.5	Ø	3.5	1.5	10%	1.45
TOTAL		12.2	-	8.2	6.35	-	1.68

Source: VLSI RESEARCH INC.
231-130

Even then, not all of the small particles were repaired. Roughly 25% of opaque defects between three quarters of a micron and one micron are left unrepaired. About 75% of those below one-half micron are left unrepaired.

Overall, unrepaired masks have an opaque defect density of about twelve defects per square inch and a clear defect density of about six, as measured in the 1983 time frame. After repair this reduces to about eight and two defects per square inch, respectively.

The defects that go unrepaired do so for two reasons—first, inspection systems are generally inefficient at submicron regions; and second, laser repair beams typically used by the industry do not get below 0.7 micron. Some laser houses claim they can get down to 0.4 micron but they do so by using apertures to close off the beam. This reduces power and the sharp edge definition. A Gaussian energy profile results. Ion beam repair systems were introduced as a way to achieve submicron repair. They can repair defects as small as 0.1 micron.

However, another issue is the defect density that is actually printed on the wafer. This is shown in Table 3.5.1.1-8 for devices using a 1.5 micron linewidth (i.e.—a three micron pitch). It can be seen from this table that printed defects for 10X reticles is different from that for 5X and 1X reticles. This is because the effective on-wafer defect size is reduced by the stepper's reduction lens. For example, a one micron defect will appear as a one micron defect in 1X reticles. But it will only appear as 0.2 micron or 0.1 microns in size, respectively, under 5X or 10X reduction. Consequently, larger defects which might be reduced and go unnoticed for 10X and 5X reticles can be fatal in 1X reticles.

As mentioned, most designs call for repairing defects which are 25% of the minimum line size or smaller. Consequently, at a 3 micron pitch any defect above 0.375 micron would be repaired. However, not all of these defects would be fatal. An experienced operator could determine which ones might not be fatal. Many production houses raise the lower limit of 25% to 33.3% and try to work around the difference. This brings the defect size to 0.5 micron at a 3.0 micron pitch. It also takes those defects which must be repaired to just within the threshold of an inspection machine's detection capability.

It is important to note that 1X reticles only become an issue at three micron pitches and below. About one half of all critical defects can be repaired on 1X reticles and on 1X projection masters in which a three micron pitch was used. Reticles for 5X and 10X steppers will be defect-free. In fact, a defect-free one micron pitch could, conceivably, be achieved with a 5X stepper. Defect-free four micron pitches are achievable with 1X systems. Consequently, a three micron pitch provides a good dividing line.

TABLE 3.5.1.1-8

TARGET DEFECT DENSITY VERSUS TYPE OF RETICLE
(for a three micron pitch)

Defect Diameter (micron)	Total Defect Density As Made (#/Sq. In.)	*CRITICAL DEFECT DENSITY AS PRINTED*		
		10X Reticle	5X Reticle	1X Projection Master
		Qty	Qty	Qty
>10μ	0.60	0	0	0
8-10μ	1.60	0	0	0
6-8μ	1.30	0	0	0
4-6μ	1.00	0	0	0
2-4μ	0.60	0	0	0
1-2μ	0.50	0	0	0
0.75-0.99μ	2.5	0	0	0.6
0.50-0.74μ	5.5	0	0	4.33
<0.5μ	5.0	0	0	5.0
Critical Defects #/Sq. In.	18.6	0	0	9.93

Source: VLSI RESEARCH INC
231-131

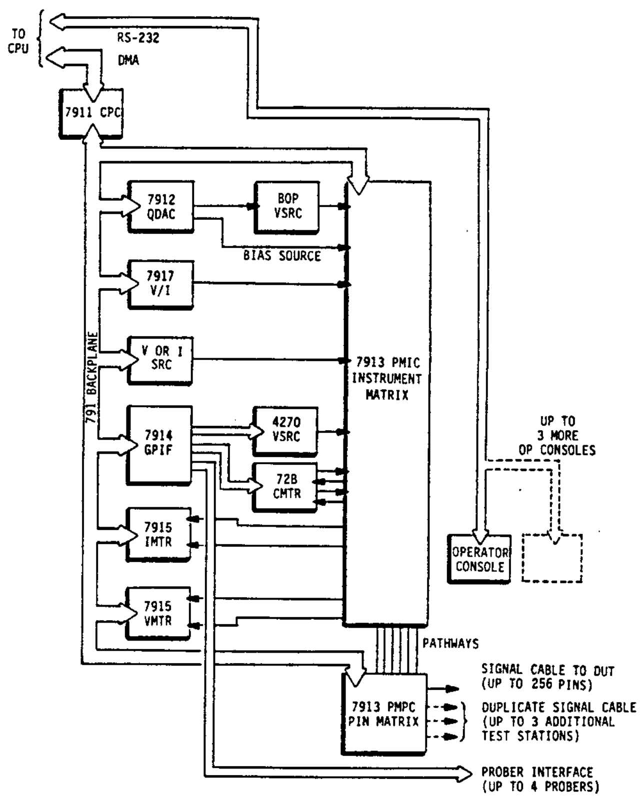
3.5.1.1.3 Development of the Process Monitoring and Curve Tracing Industry

Process monitoring equipment is used exclusively to monitor electrical parameters of test chips. It is not presently used to directly monitor data from the process or the process equipment itself. As an example, it does not take readings from a diffusion furnace. Process monitoring equipment tests parametric variables on an actual wafer. As such, it is distinctly different from automatic process control equipment. The latter uses monitoring sensors buried in the equipment, while automatic process monitoring equipment keeps track of the electrical parameters on the wafer which change during each step. In that sense, it tests the process, not the device. So it should not be confused with the DC parametric test capability of automatic test equipment. This is used to test the device. Curve tracers serve a similar function. Brief drawings of these types of equipment are shown in Figure 3.5.1.1-9.

The basic roots of the process monitoring equipment market were firmly entrenched well before the first transistor was made, having grown out of the curve tracing equipment market. Curve tracers are a very old type of equipment, that were developed for use by the vacuum tube industry. Over the years, curve tracing equipment had been brought to an advanced enough state that its use could be freely adopted by the transistor industry. Curve tracing equipment also laid the groundwork for the automatic test equipment industry. Prior to 1974, curve tracing equipment was the only electrical semiconductor process monitoring equipment available.

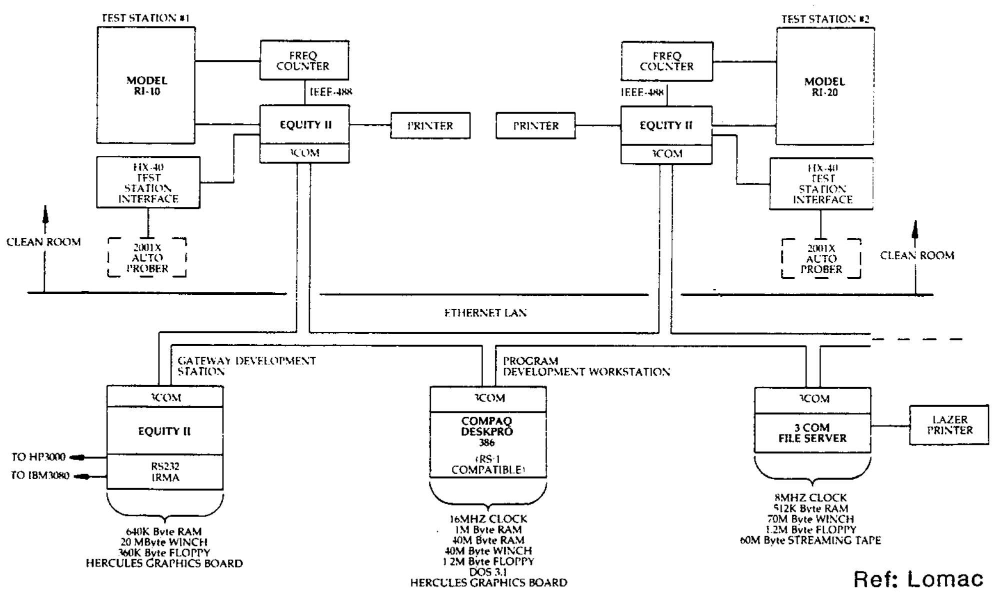
Older types of curve tracers had typically lacked the capability to store data. It was necessary to visually measure and calculate test parameters. This took time, slowed the throughput capabilities of curve tracers and contributed errors in the data. It prompted development of process monitoring systems. In 1974, Lomac introduced such a digitized test system for wafer monitoring. This machine was a radical departure from the curve tracer. It did not have the CRT display format typical of a curve tracer; instead it used computerized data reduction and computer printouts. It was the first automated process monitoring system. Another advantage was gained by Lomac by making use of computer control: The tester could be automated and customized for each users needs. Additionally, data storage and data reduction capabilities could be added. Moreover, process monitoring equipment offered throughput advantages as high as 180 times that offered by curve tracers.

Process monitoring soon emerged as the new star in inspection equipment market. Even though it performed many of the DC parametric tests of an automatic test system, its application was-and-is entirely different. For automatic process monitoring equipment is placed right in the middle of the wafer process line. Therefore it, and its companion optical inspection equipment, resistivity monitoring equipment



Ref: Keithley

Keithley Model 350 Process Monitor



Ref: Lomac

2232-49

Lomac Series RI-10/20 Process Monitor

Figure 3.5.1.1-9

TYPICAL PROCESS MONITORS & CURVE TRACERS

and film thickness gauges serve as judge and jury over each masking level. They are used early enough in the manufacturing cycle so that quick changes are possible when process variations are detected. It is this ability to test between masking levels and just after processing that gives process monitoring equipment its powerful ability to quickly detect yield degradations. Classical automatic test equipment cannot offer this, for wafer probing lies at the end of wafer processing. Once a wafer has reached wafer probe testing, the investment that has been made at each masking level is committed and no further changes can be made thereafter without stripping the entire upper surface of the wafer and starting over.

In the eighties, most VLSI fabs used process monitoring as a measure of that fab's performance. Traditionally performance has been measured dominantly on counting wafers-out and by yield. However, yield is a function both of defects and of many other process variables. It is better to monitor the cause (the variables) rather than the effect in order to prevent "yield crashes". This entails developing a set of test devices on a test die which will indicate the state of the process. Limits can then be set on process variance and closely tracked. This entails long-term measurements, long-term data collection and statistical correlation to probe and to final test. This analysis is typically done off-line. Multi-equation non-linear optimal control models are used. Once the parameters and the process limits have been set, the systems are used to monitor the process.

Process engineering uses this information to determine precisely where the process is at any given time. It uses histograms, trend analysis, and variance plots of detailed data. Product engineering uses the information to enhance yield and to determine the causes of yield crashes. Consequently, process monitors must track the data device type and lot number as well as tracking time trends.

Perloff's method is one way in which engineers have expanded the use of the process monitor. It is used to keep alignment equipment within specifications. Its development, by Dave Perloff of Signetics Corporation, proved to be an important advancement in improving aligner registration. This is accomplished by processing special test wafers containing Van der Pauw resistors. This is a special resistor made in the form of a cross. Current is forced between two adjacent corners of the resistor. Voltage is then measured between a tap on the opposite side of the corners and on each of the other corners. This structure causes the resistor to act like a highly sensitive voltage divider. Following one measurement, the direction of current is then reversed. Alignment misregistration across a wafer can be determined to within 0.01 micron in both the X and the Y directions by Perloff's method. If these techniques are then used periodically, aligners can be tracked within very tight tolerance margins. For example, NCR reported at

1982's SPIE conference that it had been able to keep its TRE steppers consistently within ±0.1 micron registration.

The use of test wafers for 100% wafer mapping looked to become more prevalent as a result. Martin Buehler of JPL (Jet Propulsion Lab) has described using pin-hole-array capacitors for mapping oxide integrity. The advantage of using test wafers is that potentially bad lots can be weeded out of the process flow as early as possible. This effectively increases a plant's capacity as well as reduces raw material costs.

While these advances were being made, it cut into the curve tracer market heavily enough to stimulate new developments there. Some people might ask—Why would anyone want to buy a curve tracer anymore? However, old applications don't die easily.

Some users prefer curve tracers for evaluation engineering and failure analysis. Evaluation engineering applications are dominantly used by end users of semiconductors for incoming inspection. The purpose is to determine that device specifications meet manufacturing requirements.

Discrete semiconductors most commonly evaluated by curve tracers and for approximately 71% of all curve tracer applications. The most frequently tested parameters are breakdown voltage and leakage. These are followed DC Beta, input/output characteristics, gain and junctions.

For several years, Tektronix had enjoyed a virtual monopoly of the curve tracer market with its manual system. In 1982, Hewlett-Packard introduced the 4145—a programmable version that also stored data for future analysis. Tektronix countered with the introduction of its model 370 in 1985. These newer machines have kept the curve tracer market alive.

3.5.1.1.4 Development of the Materials Monitoring Industry

The materials monitoring industry is segmented into three categories:

Solid Monitoring Systems
Liquid Monitoring Systems
Gas Monitoring Systems

They will be discussed in this section.

Solid particles suspended in a gas—typically in air—are called Aerosols. Hence, solid monitoring consists of simultaneously analyzing both material phases at once. Solid particles below ten microns are invisible to the eye. In fact, particles smaller than 0.3 microns are invisible to optical microscopes. Consequently, the monitoring of aerosols relies upon techniques such as the detection of scattered light via electronic photo detection.

There are two critical aspects of aerosol monitors—the light source and the gas flow rate. Light sources used in mid-eighties designs consisted of helium-neon lasers. The wavelength of these lasers is 633 nanometers. This wavelength gives maximum intensity of incident light. Lasers with helium-neon light can accurately detect 0.2 micron particles. The flow rate of the instrument is directly related to its sensitivity. The slower the flow rate the more sensitive the reading will be. High flow rates create gas molecule scattering. The scattered light is incorrectly detected and indicated as particles. However, for clean room monitoring, a high flow rate is necessary in order to get statistically significant counts. Clean room air with 10 countable aerosol particles/per cubic foot generates about 10 counts in 1 minute at a flow rate of 1 cu. ft./min.

Poisson statistics are typically used to describe clean room aerosol particle data.† The standard deviation of Poisson statistics varies as the square root of sample size. Hence, accurate statistics require maximum flow rates. Instruments commonly used in the eighties optimized air flow at 1 cu. ft./min., thereby achieving the best balance between sensitivity and statistical accuracy.†† Even at optimized flow rates, the issue of accuracy remains open however. In practical applications, the need for statistical calibration of aerosol particle counters has been a recurring problem.†††

One instrument on the market is Particle Measuring Systems Inc.'s LPC525. This aerosol monitor uses a helium-neon laser with 0.5 mW of power. A complex set of elliptical mirrors are used to collect the light scattered by particulates. The mirrors provide a one-to-one magnification relay system from the laser to the solid-state photodetector. The optical system collects light scattered over a wide solid angle, with 95% transmission efficiency. Figure 3.5.1.1-10 shows a sketch of the system. The smallest particle detectable by such an instrument is 0.2 micron.

† Van Slooten, R.A. "Statistical Treatment of Particle Counts in Clean Gases," Microcontamination, February, 1985, Vol. 4, No. 2, pp. 32-38.

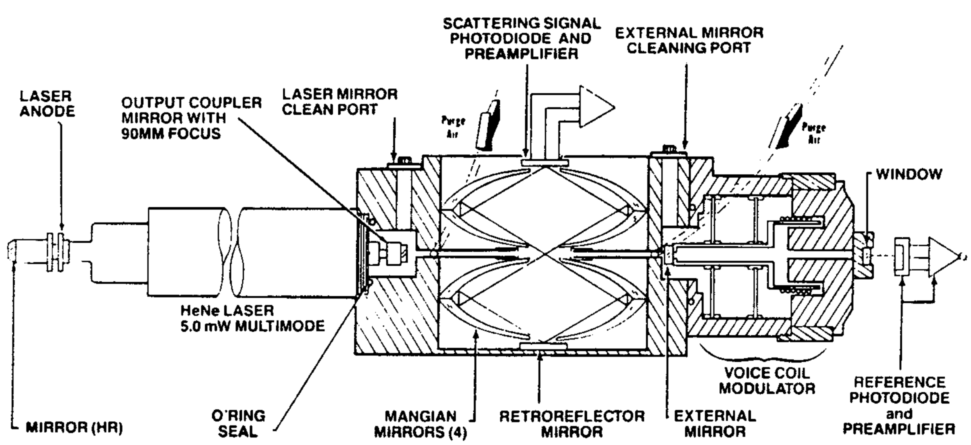
†† Donovan, R.P.; Locke, B.R.; Ensor, D.S. "Real Time Measurements of Single Submicron Aerosol Particles in Clean Rooms," Solid State Technology, September, 1985, Vol. 28, No. 9, pp. 139-148.

††† Peacock, S.L.; Accomazzo, M.A.; Grant, D.C.; Meier, P.M. "A Comparison of Particle Shedding from Different Chemical Filtration Products," pp. 1-17

For even smaller particles, TSI Inc. markets a Condensation Nucleus Counter. This instrument is capable of particulate detection down to 0.01 microns in diameter. A vacuum pump draws samples at 0.01 cu. ft./min. through a condenser tube. The tube is set to operate at +10°C. However, the tube is saturated with butanol vapor at a temperature of 35°C. Consequently, vapor condenses on air particles in the sample. The particles grow by condensation, becoming droplets measuring approximately 12 microns across. This enlarged "particle" is used to produce a large signal when the droplet passes through an optical sensing zone. The technique works as follows: As each particle passes through the sensing zone, it scatters light. A collecting lens forces the light onto a photodetector, which then converts the pulse of light energy into a voltage pulse. This pulse is then detected and counted electronically. The power of the CNC is in its ability to detect extremely small particles. The principal drawback of the CNC is its inability to determine the size of particles.

Figure 3.5.1.1-10

OPTICAL SYSTEM DIAGRAM FOR LASER BASED AEROSOL MONITOR



Optical System Diagram

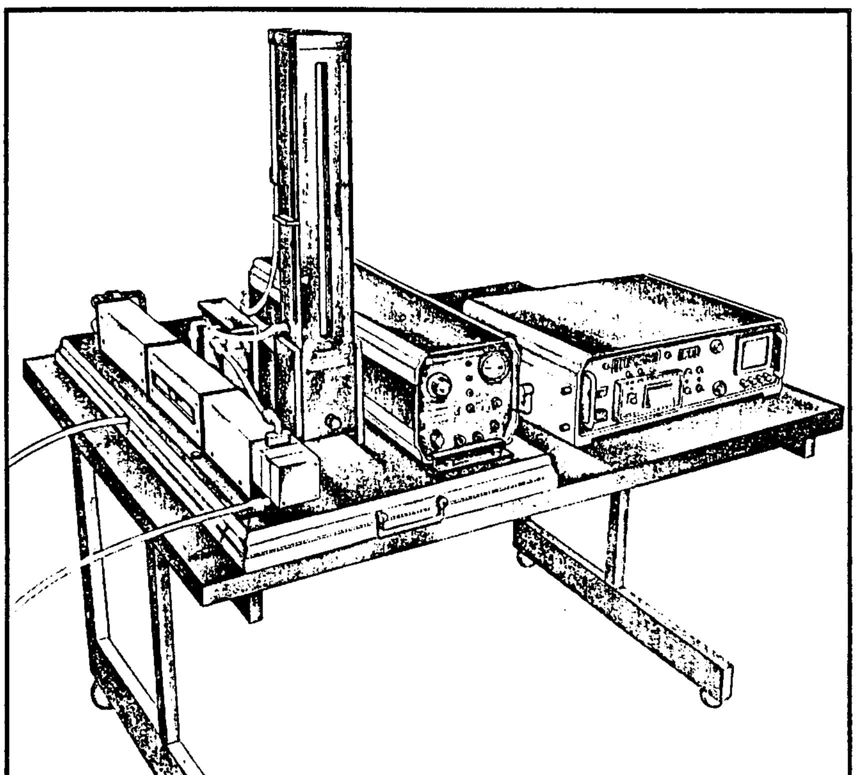
Reference: Particle Measuring Systems Inc.

By the mid-eighties, three types of instruments were available for liquid particle monitoring. One instrument type was based on optical scattering techniques. A second instrument type was based on ultrasonic measurements techniques. A third one utilized chromatographic techniques.

Particle Measurement Systems marketed the Model CLS-100 liquid contamination monitor equipped with a laser spectrometer. The system could be used with liquid-in-line, liquid-point-of-use, and liquid volumetric sensors. The sensors utilize laser fed illumination with a high resolution optical system collecting light from 5-60°. The transmitted laser beam is independently monitored and serves as a reference to compensate for changes in illumination level. Sizing is accomplished in-situ via light scattering and pulse height analysis. Standard particle size range is 0.5 to 7.5 microns. Figure 3.5.1.1-11 shows the Particle Monitoring System's CLS-100 and the accompanying LLPS-X spectrometer.

Figure 3.5.1.1-11

PMS'S LIQUID CONTAMINATION MONITORING SYSTEM



MODEL CLS-100
CORROSIVE
LIQUID SAMPLER

with

MODEL IMOLV
VOLUMETRIC
SENSOR

and

MODEL LLPS-X
SPECTROMETER
DATA SYSTEM

Reference: Particle Measuring Systems Inc.
2232-51

A typical ultrasonic monitoring system is manufactured by the MicroPure Company. MicroPure's MPS-3000 is a real-time liquid monitor. The unit is capable of particulate detection in virtually any liquid. There are three major components of the system—a RF Pulser/Multiplexer, a Receiver Monitor, and a computer controller. Sensors come in a variety of lens material for chemical compatibility with virtually any liquid. Upon direction from the computer, the RF pulser emits a 2 microsecond burst of RF energy. This energy is converted to an acoustic wave and focused by an acoustic lens in the transducer to provide maximum sensitivity. Reflected acoustic energy from solids, oils, bacteria, or even suspended gases in the liquid stream is received by the transducer. The acoustic signal is converted to electrical energy, amplified and processed by the receiver monitor at the rate of 200 times per second. The transducers in the system require occasional calibration against AC Fine Test Dust. This instrument can detect particles greater than 0.8 microns.

Another liquid monitoring technique is known as ion chromatography. As the name implies, the technique is applicable to those substances that ionize in the liquid. An instrument based on ion chromatography is manufactured by Dionex Inc. The Dionex ion chromatograph is an analytical instrument used for the separation and quantification of ionic species in the sub micro gms/liter (sub ppb) to micrograms/liter (ppm) range. The technique of Ion Chromatography utilizes ion exchange to accomplish the separation of analytes, followed by eluent suppression and conductivity detection.

A liquid sample is introduced at the top of the separator column. The ionic eluent pumped through the ion chromatograph causes differential migration of ions down the separator column as a result of different thermodynamic factors. Thus, analyte ions are separated into discrete bands. A second column, the suppressor, chemically modifies ionic eluent and converts it to a low conductive form. At the same time, in a complementary fashion, the supressor modifies the analyte ions to highly conductive acids or hydroxides. The detection is performed by a highly sensitive conductivity detector as shown in Figure 3.5.1.1-12.

The identification and quantification is performed by comparing retention times and peak heights respectively, in the sample and standard solution. Data reduction may be done manually or by using electronic integration.

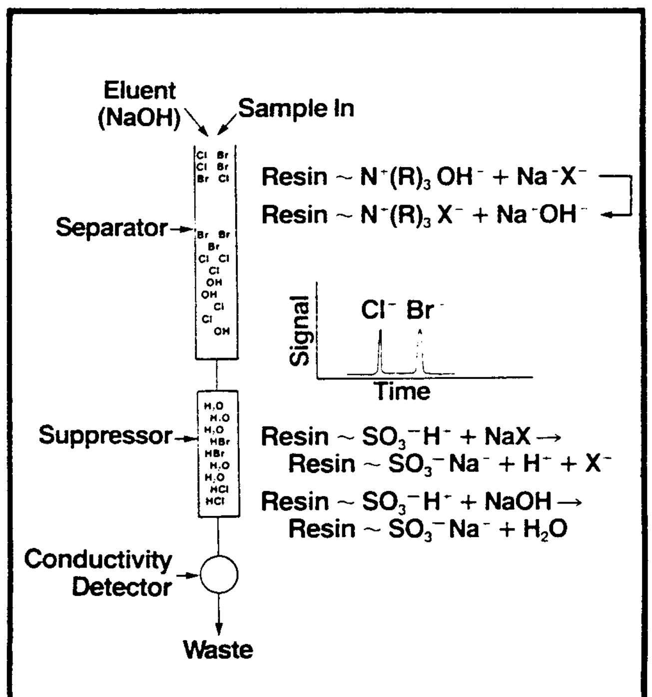
A number of technologies exist for detecting gas contamination. Moisture has been the leading contaminant for years. Consequently, various moisture detection methods exist. One method, termed the resistance method is based on changes in the resistivity of hygroscopic phosphorous pentaoxide, $P_2 0_5$. A somewhat similar moisture detection method relies on moisture induced changes of capacitance in hygroscopic aluminum hydraoxide. The analyzer using this technology consists of aluminum oxide plated on a gold electrode and configured to form an aluminum oxide dielectric capacitor. Yet, another moisture detector relies on a piezoelectric crystal that changes its frequency of oscillation when moisture is absorbed in the hygroscopic polymer.

A very different detection technology is gas chromatography. Gas chromatography involves the injection of the sample gas into a flowing stream of carrier helium. Together the gases flow through a coiled column with a solid support medium that separates the sample gas into its components, which are in turn passed through detectors. Detectors can be selective—e.g. flame ionization for hydrocarbons, or detectors can be general purpose. Although accurate, sensitive (to the sub ppm range) and reliable, gas chromatography needs pure helium and the piping-in of sampling gases.

Another gas detection technology is infrared spectroscopy. This technology involves comparing the sample gas with capsules of known contaminants, by passing infrared light through both. This system is quite accurate and sensitive; though it does require keeping capsules of any contaminants that need detection. In the eighties, the most powerful broad spectrum detection technology is centered around the quadrupole mass spectrometer, QMS. This technology converts molecules of the gases to be sampled into ions. The ions are then passed through a magnetic field. This field deflects the ions in proportion to their atomic mass units. The deflected ionic current is then measured. The current measurements are subsequently converted into atomic mass units (AMU) of the gases sampled. Beginning in 1984, a particular application of mass spectroscopy gained popularity in the semiconductor industry. The

Figure 3.5.1.1-12

SCHEMATIC REPRESENTATION OF ION CHROMATOGRAPHY



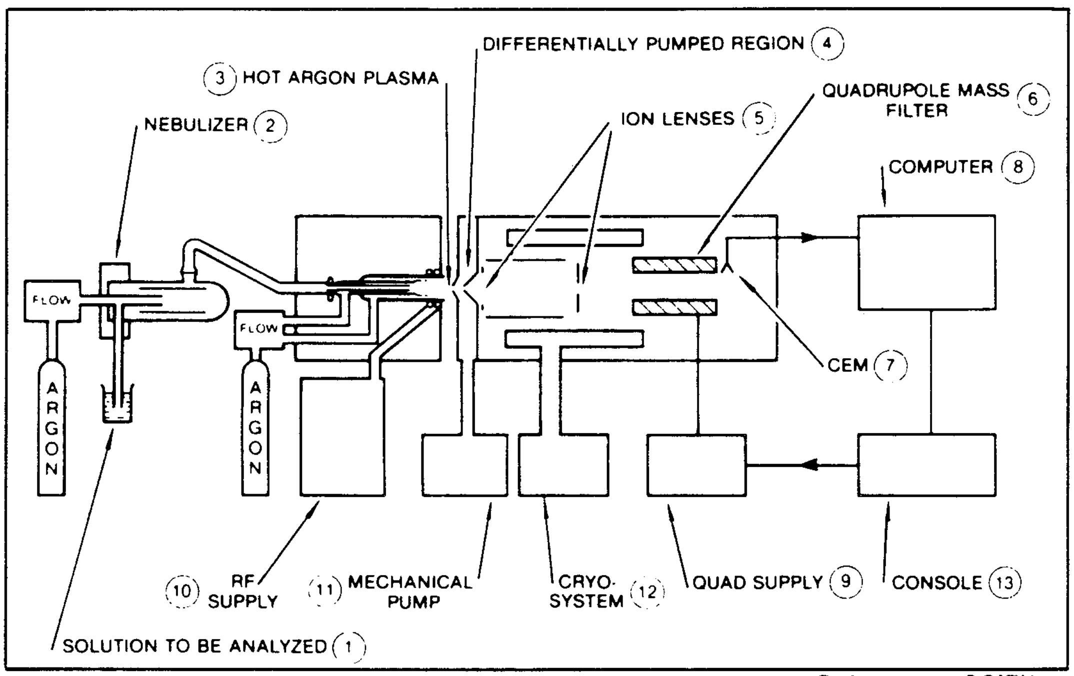
Reference: Dionex Corp.
2232-52

technique works by nebulizing the sample to be monitored into a high temperature argon plasma. Ions produced in the argon plasma are sampled through a differentially pumped interface linked to a quadrupole mass spectrometer. Ions are first separated then registered using a high sensitivity pulse counting system. Figure 3.5.1.1-13 shows a schematic for an ICP/MS unit.

The inductively coupled plasma (ICP), while first conceived in the 1940's, did not receive analytical application until the 1960's. It was not until the 1970's that ICPs were made available commercially.

Figure 3.5.1.1-13

SCHEMATIC FOR AN INDUCTIVELY COUPLED PLASMA MASS SPECTROMETER



Reference: SCIEX
2232-53

The ICP has several distinct advantages over other atomic spectroscopic techniques. These are:

- low detection limits
- wide linear dynamic range
- freedom from chemical interferences
- capability to analyze several elements simultaneously.

The ICP offers high probability of atomizing and exciting a sample, since the sample is introduced concentrically through the plasma. The high temperature of the plasma (8-10,000K) also ensures higher probability of atomization and excitation. Finally, multielemental analyses can be performed with the mass spectroscopy technique. A concentration of up to 60 elements can be monitored simultaneously. Sciex has marketed an ICP/MS unit capable of ppb levels of gas contamination detection.

The most significant disadvantage of using ICP/MS as an instrument for on-line analyses is that the ICP does not analyze alkali metals very well. With a conventional sample introduction system, detection limits range from 0.02 ppm for sodium to 5 ppm for potassium.

Other technologies capable of detecting contamination at the ppb level continued to emerge through the eighties. Of these technologies are helium ionization, ultrasonic mass detection, and chemi-luminescence.

Helium ionization involves the use of gamma radiation to elevate helium to a metastable energy level of 17eV. In a subsequent reaction, helium returns to the ground state by transferring its energy to the sample gas molecules which are ionized in the process. These sample gas ions are then collected and detected accurately at the ppb level. Two companies, Valco and Antek, both located in Texas, are pursuing this technology.

Another technology is ultrasonic mass detection. This technology uses ultrasonic energy instead of ionic currents to detect the amu of gas molecules. It is marketed by Tracor of Texas. The company claims that the technology has the similar universality but much greater sensitivity than QMS.

Chemi-luminescence is effective as a super sensitive hydrides detector. The process operates by optically detecting the reaction between ozone and the hydride. The optical reaction is photomultiplied and then measured for an accurate reading. Ideal Gas Products, a subsidiary of Liquid Air Corp., markets this technology.

3.5.1.2 Technology Of Process Monitoring Via Electrical Instrumentation

The production of semiconductor devices relies upon very complex technology. Monitoring is required at numerous points in the production process. A typical device might undergo 500 individual manufacturing steps. Wafer fabrication is the central element of device production. A typical wafer undergoes 200 to 300 individual steps in its fabrication. Wafer fab processes can be divided into seven major categories. These categories are deposition, epitaxy, lithography, develop/bake, etch/strip, implant, and diffusion. Wafers are monitored numerous times while undergoing processing in each of these categories. Monitoring via electrical instruments is of specific concern here. Almost half of all such monitoring occurs at diffusion. One-fifth of monitoring occurs at deposition. Epitaxy related monitoring constitutes 14% of the total. The remaining seventeen percent of monitoring activity is scattered across lithography, develop/bake, etch/strip and implant. CV plots are involved in almost one-half of all electrical measurements. Other common measurements made are resistivity and parametric test measurements. Exotic measurements such as trap analysis and SEM analysis are used in process monitoring. CV plots are discussed first. DLTS systems are discussed next. Exotic monitoring was discussed in Section 3.5.1.

Virtually all CV plots are performed on MOS devices. The plots are a convenient and widely used technique for evaluation of the properties of semiconductor insulator interfaces. Most MOS-type measurements require comparison of the experimentally measured CV curve with an ideal CV curve. This is usually time consuming because ideal characteristics are represented by rather complicated functions that need to be calculated separately for each value of doping, oxide, film thickness and voltage. Consequently, automated systems have been developed over the years to automatically plot capacitance as a function of voltage over a range of time and temperature parameters.

Generally, the objective is to obtain quantitative information about charge concentration at the oxide-silicon interface. The value of capacitance obtained is a direct function of background doping density and surface charge. Surface charge is a function of anomalous impurities either in the oxide or at the interface. Mobile ion contaminants exist in the oxide. Trapped charges, usually referred to as traps, exist in the silicon. In CV plotting, a voltage is applied to a sandwich capacitor made of the silicon, the oxide and the aluminum metallization. If the voltage is slowly varied, while capacitance is being measured, a characteristic S-shaped curve is obtained. A typical measurement cycle consists of an initial CV plot at ambient temperature. The capacitor is then subjected to a selected stress voltage at an elevated temperature. This bias-temperature stress condition is maintained for a selected period of time. The temperature is returned to ambient, the stress voltage is removed, and a second CV plot is made. The shift in flat-band voltage of the two plots correlates to mobile ion contamination.

Deep Level Transient Spectroscopy, or DLTS, is a measurement approach fundamentally similar to CV plots. In the simplist application of DLTS, a voltage pulse is superimposed over the DC voltage. The difference in capacitance at different temperatures is read again. Here the similarity between DLTS and CV plots ends. DLTS is an approach more than a measurement. DLTS identifies a well-established class of techniques for the characterization of electronic defects in semiconductors. It provides depth profiled measurements that CV plots are incapable of generating. In the broadest sense, DLTS refers to the spectroscopic measurement of deep level traps in semiconductor devices by transient electrical techniques. While some transport techniques, such as minority-carrier-lifetime measurements, are extremely sensitive to the presence of deep levels (e.g., recombination centers), DLTS has the advantage of combining high sensitivity with spectroscopic detection.

The DLTS concept is rooted in device physics. Electronic defects introduce localized electronic states in the semiconductor forbidden energy band. The interaction of free carriers with such defects generally causes a degradation of device performance. For example, defects can be inadvertently introduced as contaminants during device fabrication. If such defects are located in a depletion layer of a device and have energy levels near midgap, then they are particularly efficient as carrier generation centers as manifested by junction leakage currents. Defects are also intentionally incorporated to controllably modify the electrical or optical properties of semiconductors. Examples are gold and platinum in silicon which contribute efficient recombination centers for high-speed switching and indium in silicon for extrinsic optical absorption in the far infrared spectrum.

The presence of traps is indicated by positive or negative decaying voltage peaks of the pulse. The heights of these peaks are proportional to trap concentration. The sign of the peak indicates whether it is due to majority or minority carrier traps. Using DLTS, it is possible to measure the thermal emission rate, activation energy, concentration profile, and capture rates of traps. However, the highest potential use of DLTS measurements is for contamination analysis. The rise of DLTS goes hand in hand with the growing requirement for the quantification of contamination.

Notes