Process Control By Automated In-Process Wafer Inspection

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Abstract

This is the introduction of new technology developed specifically for the in-process pattern inspection and measurement of very large scale integrated (VLSI) wafers. There is a current need for significant improvements in pattern inspection instrumentation in order to tighten process control and achieve more competitive yields and therefore die costs. For the tedious and detailed task of pattern inspection and measurement, automation is the indicated solution. The future of computerized manufacturing requires, most fundamentally, the automation of the instrumentation and control function. In this paper, a system, designated the KLA 2020 Wafer Inspector, is described which incorporates the basic functions required to measure variations in the patterning process: linear and area dimensional measurements, registration error measurement, comparison for defects down to submicron in size. It is capable of inspecting in-process wafers in order to gain the most immediate process feedback. The speed with which it does each of these tests, less than a second, allows significant increases in sample size and therefore statistical control. It is this technology which will make computer-controlled photo processing possible.

Process control by the measured difference

The future of computer-controlled manufacture, of at least the microlithographic process, is dependent on computerized inspection instrumentation.

Absolutely fundamental to manufacturing of integrated circuits (ICs), or whatever, is to measure the current production output. If it exceeds tolerance, the process can be corrected. We call it process control by the measured difference.

Now it stands to reason that better measurements will allow a manufacturer to improve his process control and subsequently his manufacturing yield. This can be illustrated by comparing the sophisticated instrumentation and controls used in more mature industries and their current yields to their past practices and yields.

In the integrated circuit (IC) industry, microlithography is the single biggest factor in yield. The traditional methods of measurement and control allow for significant improvements. We have developed the technology which, for the first time, completely automates the pattern inspection function.

If I were to ask each of you the question [Q1] how do you control a microlithographic process? Essentially, you would say [A1] look at the wafers and do something about the problems you see. If I were to ask you a slightly different questions, which I have asked many of you, [Q2] how do you control a process well? That is to say, how do you control a process in such a way that it is stable and yield improvements are consistently achieved? [A2] We'd soon be talking of statistical sampling, inspection sensitivity, measurement speed, precision, and statistical trend plots which indicate where the most significant problems are developing. We have an idea of how it should be done, but have lacked the required tools.

The variability of the results from the versatile but erratic human don't lend themselves to tight statistical control. All of us who have sat at a microscope for hours know the tedium of the task and how much it needs to be automated. The high-lites from several tests illustrate the limitations of manual inspection.

One test indicated that operators with the same training, varied by a factor of 5 in interpretation of the same information.[1] One general inspection study indicated that manual inspection never gets better than 87% effectiveness on a shift basis.[2] We've been told by others that inspectors tend to consistently miss certain types of defects. Another study plots the catch rate of an operator over a shift as initially low, peaking about a third of the way into the shift and falling off the rest of the day. A paper presented at this conference on mask inspection, which included a comparison of manual to automated inspection, concluded that the (manual inspection) "sample plan becomes more effective in making discrimination between quality differences as the differences become greater" (that is to say they find the big problems) and that "visually estimated quality (was generally) 78% of the automatically (determined) quality.[3] If the eye brain is that inconsistent on high contrast, single level masks, just imagine how much is being missed on multi-level, low contrast wafer images today.

The benefits of statistics in process control are many and significant. A few itemized by AMI are: (1) The assessment or process capability, (2) The timely identification of problems, (3) The optimization of process targets, (4) The resulting reduction of rework and scrap, and (5) The eventual reduction of non-value adding measurement operations[4].

The gaping hole, however, in statistical process control and computerized quality control is the instrumentation with which to measure the differences. Without that tool, rigorous statistical analysis only yields very extensive 8 digit information.

Automated Inspection

What automated mask inspection has done to radically improve mask quality, automated wafer inspection is about to do for wafer quality.

This is a picture of the tool which we have developed to automate the measurement and control of a microlithographic process. It incorporates several functions developed specifically for, and capable of, inspecting and measuring multi-patterned, in-process production wafers.

The tool is instructed by the engineer how the inspection is to be done. A catalog of these "Inspections" is kept on disk memory. An operator simply selects the proper inspection and loads and unloads the wafers.

The functions incorporated in the Wafer Inspector are:

1. Automated transport, align and focus, which allow cleaner, fully automated and precise inspection.

2. Macro inspection of the full wafer checks for gross defects and patterning problems which affect many dice.

3. Linear and area dimensional measurement of all levels allow a process to be controlled to within a smaller envelope of error.

4. Registration measurement allow misregistration to be quantifiably monitored to control this key parameter of a lithographic process. Statistically significant and precise data can be obtained for problem isolation and yield correlation.

5. Patterning problems and random and repeating defects can be inspected for automatically, thoroughly, and fast.

6. Data management and graphical presentation will provide process trends to be perceived, and reacted tok sooner rather than later.

While we have demonstrated capability of each of these major functions, those being reported on today are fully automatic wafer transport and alignment, critical dimension measurement and automatic defect detection.

Automated Transport

It is critically important that an inspection system find problems, not add to them. Wafer quality can be degraded by direct damage or merely by adding micro-defects. It is generally well understood that cleaner wafers yield better results.*

The wafer transport system (Figure 1) moves wafers from input cassette elevators onto a wafer chuck for inspection. After inspection, the wafer is removed in the reverse fashion. Care has been taken in the mechanical design to handle wafers gently and only by touching the backside. The wafer is moved from the macro position to the micro position by a pivoting arm. This transfer arm and wafer chuck are mounted on a high speed (20 cm/sec.) X-Y stage.

*K. Harris, P. Sandland, R. Singleton, Wafer Inspection Automation: Current and Future Needs, Solid State Technology, pp. 199-204, August 1983.

WAFER TRANSPORT

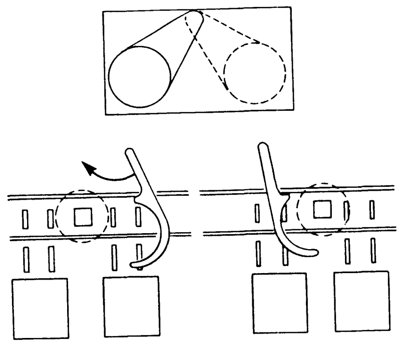

Figure 1

It is critically important that an inspection system find problems, not add to them. Wafer quality can be degraded by direct damage or merely by adding micro-defects. It is generally well understood that cleaner wafers yield better.

Improved wafer cleanliness during inspection is provided relative to manual means by automation. A micro environment has been created by forcing high efficiency particulate air (HEPA) into the enclosed inspection chamber. In addition, the system integrates numerous functions, thereby minimizing wafer handling required for these inspection tasks.

Automated Alignment

In order to automate the inspection function, it is fundamental that the patterns be acquired automatically by the system.

In the macro position, the wafer flat and then the pattern is optically aligned. The wafer is moved to the micro position where it is aligned globally. All alignments are done without the need for any special or unique targets. The Inspector drives to the address of the micro test and then uses its pattern recognition capability to do a site alignment, with subpixel accuracy, of the individual features to be measured, or to line up the candidate and reference pattern for comparison for defects.

Focus

To do micro tests reproducibly, it is critical that the focus be reproducible. The proprietary focusing system design focuses on the pattern, rather than just maintaining a fixed gap.

The focus is done over a large part of the field of view to normalize the effect of individual features. This nominal position is repeated to within a fraction of the depth of focus for a given objective. At the highest magnification, 0.1μm has been demonstrated. Additionally, a unique and optimal focus position can be selected by the engineer as each micro test is specified. The system will remember the position designated, as on offset from nominal, and use that position each time it executes that particular test.

Dimentional Measurement

The preferred process monitor is to measure critical dimensions; it is a quantitative and objective meausre of the patterning process variations. This more sensitive monitor allows one to control the process within a smaller envelope of error by making small adjustments as needed, rather than to fix the process by making large corrections after bad patterns have been produced.

A significantly larger sample size is possible due to the speed at which measurements are done; less than 1 second per measurement. This includes a nominal movement. For example, if one were to only do a dimensional measurement, at a frequency of 50 measurements per wafer, an estimated throughput of 120 wafers per hour would be possible.

The improvements in this equipment over the current state-of-the-art are (1) fully automated dimensional meausrement, and (2) at least an order of magnitude increase in measurement speed.

Illustrated in this photomicrograph is a vertical gap between two resist bars, at DI of poly mask (Figure 2). Measurements with any angle orientation are also possible with this system.

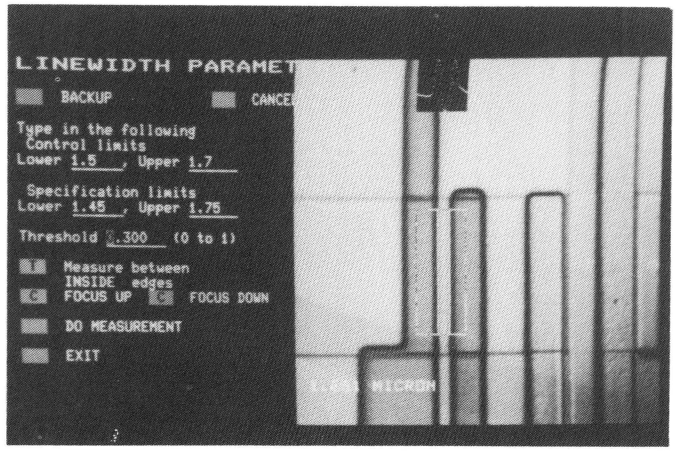

Figure 2. CD Measurement - Resist Gap at Poly Mask

The details of the optics and electronics used will be published at a future time. Suffice it to say that a 3 sigma precision of less than 0.03μm has been demonstrated.

Micro Comparison for Defects

It was determined early in the development that to be effective, the Wafer Inspector would require different image processing technology than mask inspection. This is due to the low contrast images and multilayer patterns on production wafers. A single objective is used to acquire the image which is compared to a stored image to find any abnormalities. Dedicated high speed electronics have been developed which does the comparison for defects four orders of magnitude faster than the general purpose computer which was used to demonstrate the inspection algorithms initially.

Multiple bright field/dark field objectives are mounted in the automatic indexing turret with fields of view from 1 mm to 100 μm with magnification from 130x to 1300x, as viewed on the monitor. The pixel size is a function of the field of view selected (Figure 3). The sensitivity is approximately one to two times the pixel size and is a function of the illumination (bright field/dark field), the substrate graininess, and the defect type and location. The pixel size and sensitivity can be pre-selected from 2 microns down to submicron.

MICRO-COMPARISON SENSITIVITY

FIELD OF VIEW	PIXEL SIZE	APPROXIMATE* SENSITIVITY
1,000μm	2.1μm	2.1 - 4.2 μm
500	1.0	1.0 - 2.0
250	0.5	0.5 - 1.0
100	0.2	0.5 - 1.0‡

*LOCATION, FILM GRAININESS, BRIGHT/DARK FIELD
‡DIFFRACTION LIMITED

Figure 3

The system was designed to monitor production wafers. Therefore, a tolerance to dimensional variations and registration error is built into the algorithm.

For the image comparison, there are three basic reference options possible. They have been designated as: wafer reference, standard reference and design reference (a future option). Wafer reference and standard reference were selected at the beginning of the project as being more immediately useful for process control. With both, an actual wafer image (it can be multi-level etc.) is stored. The difference is that the wafer reference is a temporary storage (random access memory - RAM) while standard reference is a long term storage (disk). Design reference is when a singel level test wafer is compared to a synthetic image which has been derived from a design tape, similar to a reticle mask inspector.

There are three difference types of defects which must be inspected for: patterned defects, random point defects, and repeating point defects.

Patterned defects are those that are associated with either topology and/or minimum feature size. Examples are bridging when the minimum design rule is used, step coverage problems, poor focus, etc.

Point defects are defective areas which do not correspond to pattern or topology. Point defects can either be random, from various sources, including masks or resist, or repeating, which is unique to a stepper with a defective reticle.

When the different references are compared based on the different types of defects one wishes to find, the optimal selection for different applications can be made (Figure 4). The reason why the wafer reference and standard reference were developed first, becomes apparent.

DEFECTS FOUND VS. REFERENCE

DEFECT TYPE	WAFER	STANDARD	DESIGN
Patterning	Often	Yes	No
Random	Yes	Yes	Yes
Repeating	Yes*	Yes	Yes

*If multi-die reticle

Figure 4.

Patterning problems often vary on different parts of the wafer, therefore using a Wafer Reference might be adequate to find patterning problems, but not always. By contrast, the Standard Reference has been inspected by the engineer and determined to have no patterning problems; a standard to which other wafers could be compared. The Design Reference, however, is by definition a comparison of a single level on a monitor wafer. This idealized wafer is not susceptible to the same type of topographical variations, reflection due to various films and edges, and other factors which contribute to patterning problems. Therefore, Design Reference is inadequate to monitor for patterning type defects.

Random defects can be found either by using the Wafer Reference, the Standard Reference, or the Design Reference. The actual defect position can be determined when using the Wafer Reference by having this microtest done at 3 locations, taking a vote and assigning the defect to the die which is different from the other two. With Standard and Design Reference, a defect and its location are known directly, by comparing just one other field it can be determined to be repeating or not.

Repeating defects can be found using a glass wafer on currently available mask or reticle inspectors or with either of the three references mentioned using silicon wafers. The Wafer Reference can be used in the most common application of qualifying a multi-die reticle by comparing the die within the reticle field. The Design Reference can be used to determine that the printed image is similar to what was designed and expected to work. The Standard Reference is an image of the actual pattern which, in the first place, is known to be a good print and is stored in such a way as to be free of random defects. It has been inspected for repeating defects. Subsequent probe results can certify this stored pattern to be that of an electrically functional device.

To illustrate the speed of the Wafer Inspector, I am going to flash 5 fields of view on the screen and ask you to find the defects . . . Now, those fields of view came up about 1 every second with about 250k pixels in each field to be considered. Most people require several seconds to do an examination with any pretense of thoroughness. By contrast, the Wafer Inspector inspects at about twice the rate at which you just saw the imates.

Now lets look at some of the defects that have been found on a variety of different substrates (Figures 5A, 5B, 5C, 5D). Notice that most of them are on multi-level wafers just as most of the wafers in your fab area are multi-level.

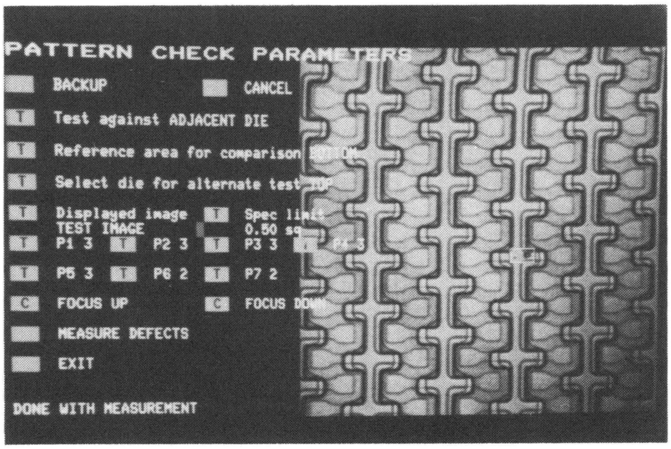

Figure 5A

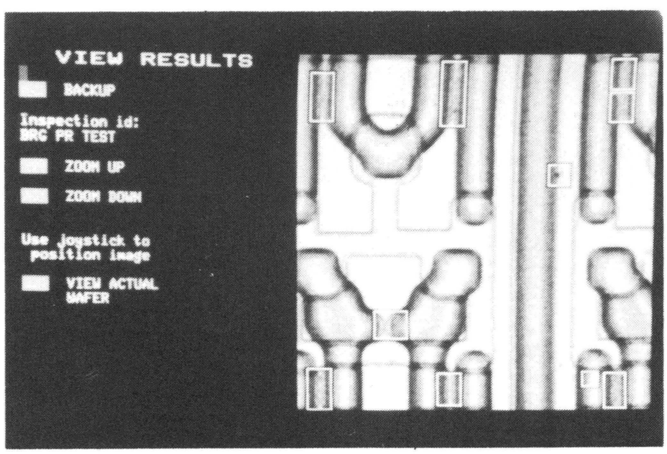

Figure 5B

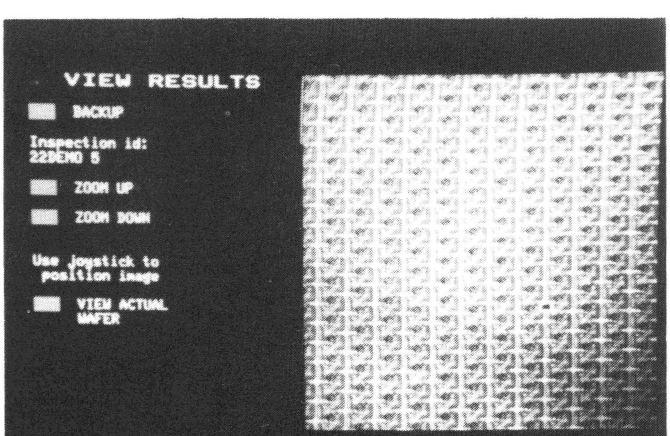

Figure 5C

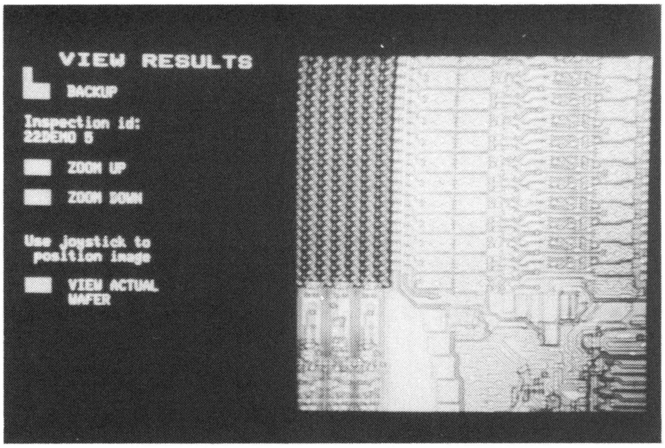

Figure 5D

Examples and Throughput

Obviously, the capability to find defects of different types and measure critical dimensions can be used in different ways.

One application of this new technology will be Stepper Qualification, including inspection for Repeating Defects.

Stepper time is expensive. Time spent on stepper set-up can be reduced by using the Wafer Inspector to do the tests with some very specific inspection sequence: The dimensional measurement function can be used to quickly determine the optimum focus/exposure position of the standard focus/exposure matrix. (The stepping precision or site-by-site alignment can also be determined using the registration micro test which has a precision of 0.03μm (3σ). The lens distortion or how the reticles stack can also be quickly determined.)

Automated inspection of a reticle field for repeating defects has many obvious potential advantages of both thoroughness and speed. Every pixel in every sub-field of the reticle is checked for fatal defects, in a matter of minutes. The inspection rate for contiguous fields of view using the Standard or Wafer Reference is shown in Figure 6.

APPROXIMATE INSPECTION RATES

PIXEL SIZE (μm)	RATE (min/cm²) WAFER REFERENCE	STANDARD REFERENCE
1.0	3	5
0.5	13	20

Figure 6

For example, if a single large die reticle of 30 square millimeters were inspected using Standard Reference, and the 0.5μm pixel, it would take 6 minutes. If a multi die reticle were inspected using wafer reference and if one used 0.5μm pixel, then all of a 10:1 field (1 cm x 1 cm), could be inspected in 13 minutes.

Sample Inspections

One of the most powerful applications of the Wafer Inspector, is the monitoring of on-going process quality. Inspections of this type, which sample the products at Develop Inspection and Final Inspection, we have designated as Sample Inspections. The sample consists of a series of micro tests done at various locations or areas of the wafer: for example, registration measured at two locations on each wafer, dimensional measurement being done at three locations on every fifth wafer and micro comparison for defects being done at five locations on every wafer. The position and frequency, as well as the pass/fail criteria, can be tailored by the engineer to suit individual requirements. Once determined and taught to the system, they will be done repeatedly and consistently as specified for the individual products and mask levels.

The possible combinations of available micro tests, frequencies and locations are almost infinite. The following illustrate several typical examples and their respective calculated throughputs.

SAMPLE INSPECTION

FULL WAFER MACRO

DIMENSIONAL MEASUREMENT: 3 ON EVERY 4TH WAFER

REGISTRATION MEASUREMENT: 2 ON EVERY WAFER

MICRO COMPARISON FOR DEFECTS:

0.5 μm PIXEL SIZE
4 FOV IN EACH AREA
5 AREAS PER WAFER

THROUGHPUT:

110 WAFERS PER HOUR (32 SECONDS PER WAFER)
OR 150 WAFERS PER HOUR WITHOUT MACRO

PROCESS QUALIFICATIONS

(INDIVIDUAL WAFER INSPECTION)

FULL WAFER MACRO INSPECTION

DIMENSIONAL MEASUREMENT: 5

REGISTRATION MEASUREMENT: 9

MICRO COMPARISON FOR DEFECTS

0.3 cm^2 DIE, 5 DIE IN TOTAL
WAFER REFERENCE, 1.0 μm PER PIXEL

THROUGHPUT:

5 MINUTES (vs 30 TO 45 MINUTES MANUALLY)

Summary

An automated system as described, is ideally suited for the repetitive and detailed task of wafer inspection. The Wafer Inspector that has been briefly described, incorporates several test functions required for microlithographic process control. Throughput appears adequate for production applications. This advanced technology is fundamentally a new way to measure the difference and control the patterning process. It will allow the user to discern smaller changes in the process and to define the process problems more clearly and to find better solutions faster than is possible with conventional means. This improved process control by automation will have a direct impact on yield, die cost and quality. It is this technology which will make computer controlled photo processing possible.

Acknowledgements

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