In-line Atomic Force Microscope for Semiconductor Process Evaluation

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OVERVIEW: To support the coming ubiquitous information society from the bottom up, semiconductor devices must be capable of high-speed processing and low-power consumption. A device structure that satisfies these performance requirements will have to have higher levels of integration as device miniaturization progresses, be capable of high-step-height processing due to multilevel structures, and employ new materials different than those of conventional devices. At the same time, the use of large-area silicon wafers (ϕ300 mm) is increasing with the aim of improving productivity and lowering costs. As a consequence, processes such as embedding and the planarization of high step heights have come into use in addition to traditional etching in semiconductor manufacturing. The management of such processes requires high-accuracy measurement of flatness over the entire chip and measurement of process depth in nanometer units, for example. In addition, the conventional method of breaking a wafer to examine its profile is losing favor due to cost considerations as large-diameter wafers come into use. Against this background, the AFM (atomic force microscope) having a resolution of 0.1 nm has been attracting interest as a new type of in-line evaluation equipment that can satisfy the above requirements. Such AFM equipment is already demonstrating its effectiveness in in-line use including operation on a ϕ300-wafer line (see Fig. 1).

INTRODUCTION

THE AFM takes measurements from a position above the sample and can obtain fine 3D (three-dimensional) shapes and cross sections in a non-destructive manner, an accomplishment not possible by other techniques. Nevertheless, various technical issues that hinder the widespread use of AFMs still remain.

With the aim of solving these issues, Hitachi has

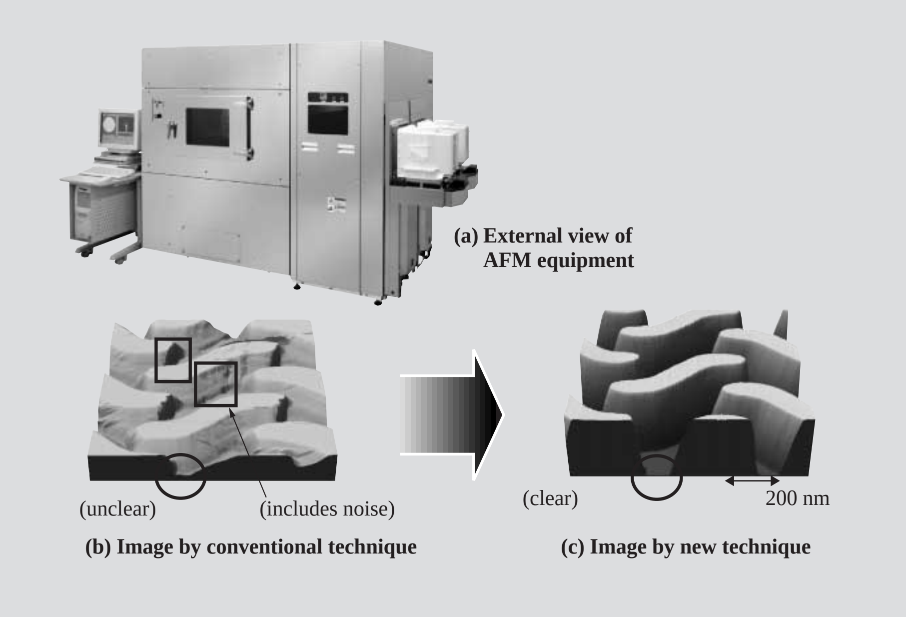


Fig. 1 —AFM Equipment (a) and Image Quality in Conventional and New Systems.
A faithful image (c) can be obtained using the step-in mode. This AFM equipment is now in use on a ϕ300-wafer line. The new step-in mode provides a faithful image of a sample with respect to STI (shallow trench isolation), as shown in (c).

developed an easy-to-control, WA (wide-area)-AFM[1] for semiconductor-process evaluation. We have also developed several application examples of this equipment in semiconductor manufacturing processes by adding a function that can perform wide-area scanning and precise measurement.

This report describes the WA-AFM for semiconductor-process evaluation.

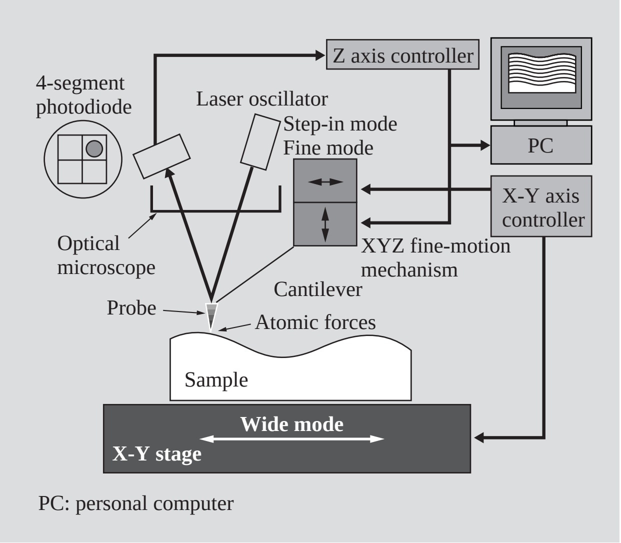
CONVENTIONAL AFM AND WA-AFM

AFM Overview

Fig. 2 shows a block diagram of the WA-AFM.

A conventional AFM scans the surface of a sample using a probe attached to the tip of a cantilever equipped with an X-Y-Z scanner, and obtains 3D positional information from X-Y position signals and Z up/down motion signals. This information is then used as a 3D image and a profile image of the sample surface at any location. Two types of atomic forces are used in detection: Van der Waals attractive forces and repulsive forces. Specifically, the AFM detects the magnitude of cantilever deflection induced by repulsive forces using a highly sensitive optical lever system, and automatically controls the probe along the Z-axis using a servomechanism so that the deflection angle remains constant.

The AFM uses the (X, Y, Z) positions of the probe generated by this control process as 3D data. In the above way, the AFM is capable of taking pictures of atoms and writing the world's smallest characters, and for achievements such as these it has become a symbol of advanced technology. Conventional AFM equipment, however, while proving useful in the laboratory, suffers from low reliability and durability in industry. There are three main reasons for this, as described below.



PC: personal computer

Fig. 2—Block Diagram of WA-AFM.
The WA-AFM scans the surface of the sample while detecting the atomic forces equivalent to the spring constant of the cantilever. It controls the drive mechanism so that the difference between detected and set values is zero.

Issues with Conventional AFM and Their Solutions by WA-AFM

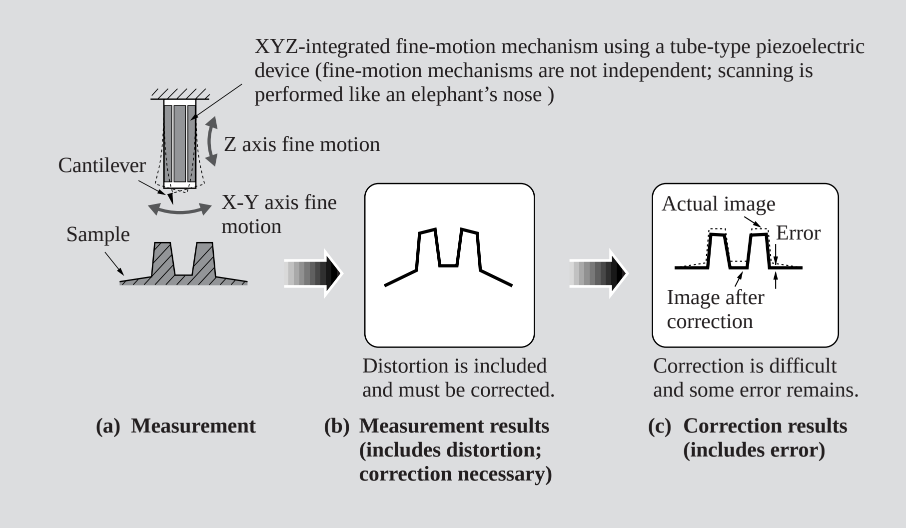
The first issue concerns the method of determining scanning speed for taking measurements. Up to now, it has usually been determined for each sample surface on a trial-and-error basis. The process, however, is affected by the skill of the AFM operator, and operators with low levels of proficiency can generate highly erroneous results. In some cases, for example, an image cannot even be obtained. This problem has hindered the application of AFM equipment.

In the WA-AFM, the development of a step-in mode, a new measurement-control technique, has made it possible to obtain data independent of measurer's skill. This technology has also provided a base for automating the measurement scanning process.

The second issue concerns the accuracy of scanning. To improve nonlinearity of a conventional scanner, the parallel-plate mechanism has been developed to drive probe scanning in the X and Y directions. In this mechanism, each of the X and Y axes provides independent translation making for highly accurate measurements.

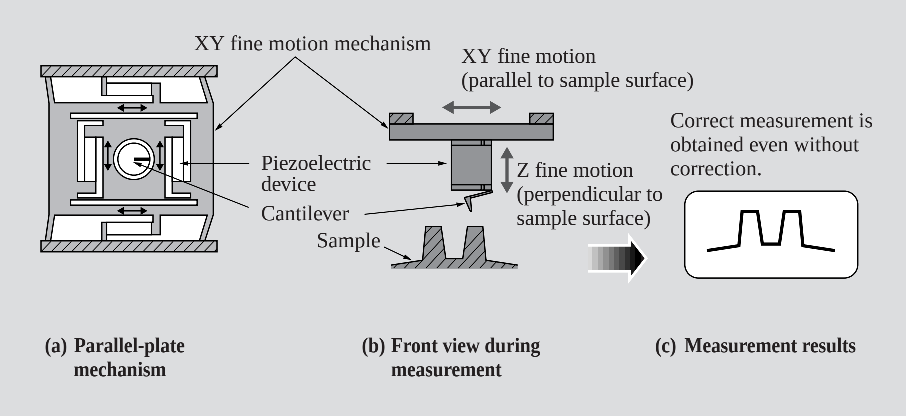
Conventional AFM equipment used in research and development generally used a tube-type XYZ scanning mechanism as shown in Fig. 3. The main feature of this mechanism is that the probe can be manipulated as desired despite its simple structure in a manner much like an elephant's nose. On the other hand, the arc-like motion of the mechanism's neck generates distortion in obtained images. This distortion has been corrected on the basis of operator's insight with respect to the sample surface. Nevertheless, as the measured surface is not in a state conforming to numerical formulas, the data after correction could only be taken to be approximate values. Correction is naturally dependent on the operator's experience, which means that results can easily differ between operators.

In response to this problem, the WA-AFM adopts the parallel-plate scanning mechanism and, for the Z-axis, the fine-motion piezoelectric device shown in Fig. 4 (a, b). This makes it possible to keep the horizontal



(a) Measurement **(b) Measurement results (includes distortion; correction necessary)** **(c) Correction results (includes error)**

Fig. 3—Measurement by Conventional AFM.
Distortion occurs in measurements using an XYZ-integrated fine-motion mechanism. Despite of correcting the data, error still remains after correction.



(a) Parallel-plate mechanism **(b) Front view during measurement** **(c) Measurement results**

Fig. 4—Measurement by WA-AFM.
Incorporating a parallel-plate fine-motion mechanism enables high-accuracy, distortionless measurements to be obtained even without correction.

motion of the cantilever parallel to the sample surface and its up/down motion perpendicular to the surface thereby solving the problems of the past mechanism. This WA-type XYZ scanning mechanism increases rigidity at the same time and achieves more stable operation than before. The data so obtained does not require correction; high-accuracy measurement results can be obtained without correction as shown in Fig. 4 (c).

The third issue concerns expansion of the measurement range. The measurement of conventional AFM equipment has been limited to a range from 10 to 100 μm due to limitations of the XY scanning mechanism of tube type probe. For the WA-AFM, an ultra-flat X-Y stage has been developed (see Fig. 2) making it possible to expand the measurement range to 25.6 × 25.6 mm^2. This, in turn, has made it possible to measure flatness of the entire chip surface at the level of AFM performance (see Fig. 5). This is not possible in conventional AFM equipment. In other

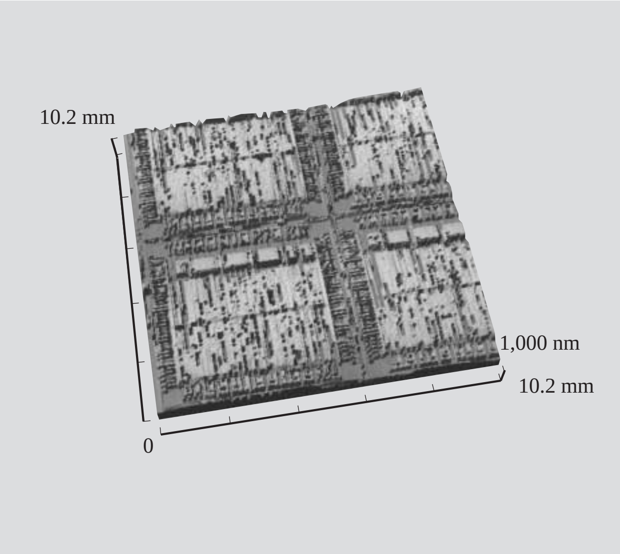


Fig. 5—Chip Flatness (under CMP).
Results of pre-CMP flatness by chip-size flatness measurements that only the WA-AFM can perform (height increased by 500 times for clarity).

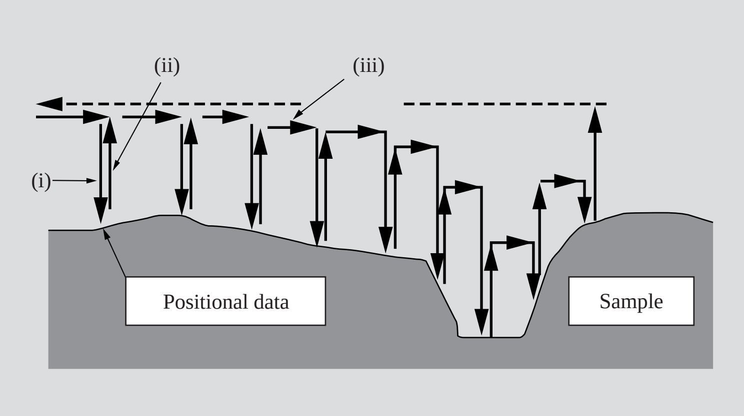
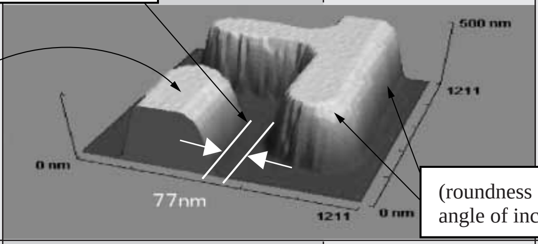


Fig. 6—Operating Principle of Step-in Mode.
*The probe descends in state (*i*) in which scanning has stopped, and retracts in state (*ii*) after detecting the surface. Scanning proceeds by one step in state (*iii*) during which the probe is retracted.*

Process	Change in manufacturing process		Solution by WA-AFM	Observed dimension	Issue in past evaluation method
	Change	New needs			
Exposure	Adoption of high-sensitivity photoresist	Support photoresist weak to electron beams	Observe pattern shapes	–100 nm [X]	Scanning electron microscope Issue: photoresist deformation
	Ultra-high-resolution method (PSM)	Measure phase shift layer	Measure depth (height)	– 500 nm [Z]	Optical method Issue: indirect measurement
Isolation	Change in isolation process (LOCOS → STI)		(Observe embedding shape)  Observe state of oxidation of surface of impurity-diffusion area (Si) (roundness of shoulder section; angle of inclined surface: up to 85º)	– 600 nm [X]	Scanning electron microscope Stylus method Issue: scratching
			Determine shape of deposited film for stress relaxation Observe state of planarization Observe suppression of parasitic transistor by divot on STI	– 20 nm [Z] – 20 nm [Z] Several nm [Z]	Transmission electron microscope Transmission electron microscope Transmission electron microscope Issue: cross-sectional image with cutting sample
Planarization	Change in plug material	Optimize process end points	Observe amount of recess (divot from periphery) Observe protrusions in barrier film	– 20 nm [Z] Several nm [Z]	Scanning electron microscope Issue: indirect measurement
	Change in method for removing pattern step heights	Optimize process conditions	Observe allowed step height on surface Observe local step height Observe micro scratches Determine optimal CMP conditions	– 200 nm [Z] Several tens of nm [Z] Several tens of nm [Z] – 25 mm [XY]	Stylus method Issue: scratching Optical scattering method
Wiring	Change in wiring material (Al → Cu) (etching → CMP)	Shape of trench Estimate resistance value	Observe depth of trench Measure global step height Measure amount of over-polishing Measure amount of dishing Measure amount of erosion Observe grain	– 500 nm [Z] – 100 nm [Z] Several tens of nm [Z] Several tens of nm [Z] Several tens of nm [Z] 1 nm [X]	Scanning electron microscope Stylus method Scanning electron microscope Conventional AFM, stylus method Conventional AFM, stylus method Scanning electron microscope

LOCOS: local oxidation of silicon
STI: shallow trench isolation
TEG: test element group
PSM: phase-shift mask
[X]: lateral dimension
[Z]: height (depth) dimension

Fig. 7—Major Changes in Semiconductor Manufacturing Processes and Solutions by WA-AFM.
As conventional inspection techniques could damage device surfaces and require longer scanning time to improve accuracy, AFM functions are being used to solve these problems.

words, the wide-area measurement function of the WA-AFM contradicts common sense that is associated with conventional AFM equipment. It expands the measurement field and represents a major breakthrough that is just beginning to be applied to semiconductor process management.

Step-in Mode2)

Fig. 6 shows the operating principle of the step-in mode, a new measurement technique. In the figure, items (i) to (iii) represent key features of cantilever motion.

This technique prevents the occurrence of stress in the lateral direction, a problem associated with the contact method, as well as the occurrence of probe jumping (torsional phenomenon) and probe damage even in the case of a sample featuring high step heights. Images can therefore be acquired in a stable fashion and the data so obtained are that of a linear sensor.

APPLICATIONS TO SEMICONDUCTOR PROCESSES

The following describes major changes in semiconductor manufacturing processes and corresponding solutions by WA-AFM (see Fig. 7).

The background behind the introduction of this equipment is the adoption of CMP (chemical-mechanical polishing), i.e., planarization. This process involves tungsten-plug formation, adjusting of the focus depth related to exposure processes, and formation of wiring patterns. It is therefore necessary to evaluate results in a range from the area covered by one shot of a stepper to areas on the order of sub micron.

So far, in the case of wide area scanning to perform roughness measurement including steps using the diamond stylus method, sample scratching could occur. Also, when checking a sample's one small area at a time, cross sectional images of a breaking wafer were taken by a scanning electron microscope. This approach, however, suffered from poor accuracy and excessively long measurement times. The WA-AFM, however, incorporates all functions in a single piece of equipment, and is consequently gathering attention as a novel means of measurement.

Next, in light of the need for measuring high aspect samples after applying CMP technique to the advanced LSI (large-scale integration) process, which is a difficult task for the conventional method, the step-in mode was developed. At present, this technique is finding wide application from observation of photoresists to that of ultra-high-resolution masks in addition to observing etching shapes on silicon.

MAIN FEATURES AND SPECIFICATIONS

The main features of this WA-AFM equipment are listed below. Table 1 summarizes its main specifications.

(1) Wide-area data acquisition up to 25.6×25.6 mm^2 in one operation
(2) Resolution in 0.1-nm units
(3) Wide range magnification from 4 to about 1 million

Measurement mode	Contact mode Step-in mode			
Measurement area	X/Y direction	Contact mode	Wide	$25 \times 25\ \mu$m^2 to 25.6×25.6 mm^2
		Step-in mode	Fine	100×100 nm^2 to $10 \times 10\ \mu$m^2
	Z direction			6 μm
No. of measurement points	Image mode			X and Y: max. 512 points
	Long profile (option)			X: max. 250,000 points (at 0.1μm intervals) Y=1
Resolution	X, Y			≥ 0.2 nm
	Z	Fine		0.1 nm
		Wide Step-in mode		1.0 nm
Operability	Manual mode Automatic measurement mode			
Automatic transport system	Sample radius: 200/300 mm Sample types: LSI wafers, quartz class Open cassette, SMIF, FOUP			
Communications software	GEM300 and others			

TABLE 1. WA-AFM's Main Specifications
The WA-AFM supports two measurement modes: contact mode capable of measurements over a wide range, and a step-in mode that demonstrates special features in standard observation range.

SMIF: standard mechanical interface
FOUP: front open unified pod

times
(4) Parallel-plate XY scanner with good linearity without position error
(5) Observation up to a wafer diameter of 300 mm
(6) Anti-vibration function and high-rigidity mechanism applicable to critical environments such as clean rooms.
(7) WA-AFM can get accurate images of micro structures such as STI, by newly developed step-in mode.

CONCLUSIONS

This paper has described an in-line AFM for evaluating semiconductor processes.

The WA-AFM developed by Hitachi solves the problems associated with conventional AFM equipment as described in this paper, and therefore has the potential of measuring even critical (very small) dimensions as an automatic measurement device. Timely grasping a changing share of a probe is indispensable to the development of future applications.

The solution of conventional problems with this WA-AFM has served to strengthen the integrated semiconductor evaluation system of Hitachi. Future plans call for further development of this equipment and the addition of EES (equipment engineering system) functions with the aim of constructing highly adaptive AFM equipment that can be applied to a wide variety of needs.

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