WA3300 — High-speed In-line AFM System for 45-nm Node LSIs

Toru Kurenuma
Yukio Kembo
Takafumi Morimoto
Masahiro Watanabe

OVERVIEW: Despite the continuing miniaturization and diversification of LSIs, producing a competitive LSI still requires in-line metrological control of minute structures. Beyond the 45 nm node, LSI fabrication requires atomic-level control. Consequently, an AFM capable of measurements at the atomic level is an essential requirement. However, although conventional AFMs can perform measurements, they have been inadequate for in-line use due to their low throughput, difficulty of operation and lack of precision. To address the measurement requirements beyond the 45 nm node, Hitachi Group has developed the WA3300 in-line AFM which combines high throughput with high measurement precision, and a wear-resistant ultra-fine CNT probe tip for use in this equipment.

INTRODUCTION

AS LSIs (large-scale integrated circuits) become more miniaturized and diverse, it is essential to pursue efficiency throughout the process from design to manufacture. Also, metrological control of ultra-fine structures is essential to realize competitive LSIs in a short period of time. Beyond the 45-nm node, the fabrication of LSIs requires processes to be controlled at the atomic level. Consequently, metrological control systems are increasingly using AFM (atomic force

AFM: atomic force microscope CMP: chemical-mechanical polishing

Fig. 1—The WA3300 High-speed In-line AFM System for 45-nm Node LSIs, and Some of Its Applications.
Hitachi Kenki FineTech Co., Ltd. has developed the new WA3300 AFM system which has sufficient measurement precision and throughput for in-line use in the manufacture of 45 nm devices. It has already gained the top market share in Japan for equipment that is not only capable of flatness measurements over a wide area the size of a CMP stepper field but is also capable of ultra-fine shape measurements. This new system includes further performance enhancements. The range of applications has been extended to include microlens measurements, and Hitachi has made further progress in the implementation of its own measurement methods that allow measurements to be made simply and with few errors.

microscope) technology which is capable of performing measurements at the atomic level. However, although conventional AFMs are capable of performing measurements, they have been unsatisfactory for in-line use due to their low throughput, difficulty of use and inadequate precision.

Hitachi Kenki FineTech Co., Ltd. provides AFM equipment and services to most of Japan's domestic LSI manufacturers. Based on the experience we have accumulated in responding to our customers' needs, we developed the WA3300 next-generation equipment which brings together the technical know-how of the Hitachi Group. The WA3300 not only has substantially higher throughput, but also outperforms conventional equipment in terms of its wide area coverage, ultra-fine measurement capabilities and so on. We have also improved the usability and reliability of this equipment. Furthermore, we have developed a new CNT (carbon nanotube) probe tip with excellent wear resistance which is capable of collecting repeatable data with unprecedented levels of detail and accuracy.

Here we discuss the future prospects of LSI metrology needs, and we describe the WA3300 in-line AFM equipment for 45 nm devices and solutions in which atomic level measurements are realized (see Fig. 1).

NEED FOR THREE-DIMENSIONAL SURFACE STRUCTURE ANALYSIS OF SEMICONDUCTOR DEVICES

In semiconductor processes beyond the 45-nm generation, there is a growing need for AFM equipment that possesses the following characteristics:

(1) The ability to perform high resolution measurements of three-dimensional shapes at the sub-nanometer (sub-nm) level

(2) The ability to make direct observations from any surface material or pattern.

In particular, in measurements of step height and surface flatness, AFM equipment shows considerable potential as a single measurement device that simultaneously satisfies both the requirements of ultra-fine capabilities and wide-area flatness measurements.

Table 1 shows the measurement needs of various semiconductor processes where in-line AFM equipment is used.

In application to these needs, the suitability for ultra-fine measurements is important for etching applications, which calls for an AFM probe with a high aspect ratio that is narrower than the width of trench structures and longer than the depth of these structures, and high-precision control techniques for controlling this probe. Also, as the exposure shot size of lithography processes increases and the depth of focus margin becomes smaller, technology is needed that can evaluate the flatness to within 100 nm over a wide range of 40 mm or so in flatness measurements performed after CMP (chemical-mechanical polishing) of oxide films. The AFM metrology equipment produced by Hitachi Group is well known among semiconductor device manufacturers as being able to cope with these conflicting demands for ultra-fine, high-precision measurements.

TABLE 1. The Needs of AFM Applications in Semiconductor Processing
AFM is mainly applied to step management after etching and flatness management after CMP.

Process		Evaluation needs	Required repeatability	Evaluation dimensions	
				z	*x*, *y*
Substrates, deposition	Si	Roughness	0.1 nm	– 0.1 nm	– 1,000 nm
	Oxide film				
	Various metals			– 10 nm	– 10,000 nm
Etching	STI	Steps, three-dimensional shape	1 nm	– 2,000 nm	45 nm –
	Gate				
	Contacts, vias				
	Damascene processes				
CMP	STI	Micro-steps global flatness	0.5 nm	– 50 nm	– 45 nm
	W-plug		0.5 nm	– 10 nm	– 100 nm
	Oxide film		10 nm	– 100 nm	– 40,000,000 nm
	Cu		0.5 nm	– 100 nm	– 1,000,000 nm
Others	Scratches, defects, particles	Shape evaluation			
	Microlens		1 nm	– 200 nm	– 10,000 nm

STI: shallow trench isolation

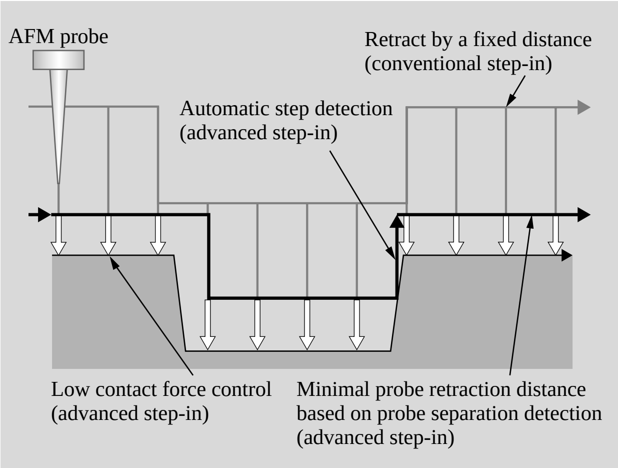


Fig. 2—Advanced Step-in Measurements.
With a measurement reproducibility precision of 0.5 nm (3σ), Hitachi has reduced the measurement time per point to 1/4 (compared with other Hitachi systems).

WA3300 AFM SYSTEM FOR 45-nm NODE

Development of Advanced Step-in Measurement Method

In 45-nm in-line node measurements, not only does the measurement precision have to be increased, but the throughput and ease of use also have to be improved. To meet these needs, we have developed an advanced step-in measurement method.

The advanced step-in measurement method is shown in Fig. 2. In this method, the AFM probe is lifted away from the object being measured until the instant where the contact force is no longer detected. In this method, the lifting distance is greatly reduced compared with conventional step-in measurement method where the AFM probe is lifted by a predetermined fixed distance. When the lifting distance is insufficient, the lifting is repeated by means of automatic step detection. Furthermore, since the method does away with the step of having to set this crucial withdrawal distance parameter before measurements can be made, it is easier to implement and can reduce the time needed for each measurement point by 75% (compared with other Hitachi systems). Hitachi also implemented measurements with contact forces that are more than 10 times lower than in other Hitachi systems by using the proprietary signal processing methods to greatly reduce the contact force detection errors. As a result, in semiconductor devices with a 45-nm processing line width (the mainstream of the next generation of LSIs), Hitachi has achieved a measurement reproducibility of 0.5 nm (3σ) as required by the ITRS (International Technology Roadmap for Semiconductors) (roughly twice that of other Hitachi equipment), and a measurement throughput of 30 wafers per hour.

Flatness Evaluation Function for 40 × 40 mm Areas

In next-generation LSIs, the low depth of focus of the exposure equipment used to print the circuit patterns means that the surface of the wafer has to be made exceedingly flat (within 100 nm). For this reason, AFM is used to evaluate the flatness of wafers. To allow our system to cope with exposure equipment with larger printing regions, we increased the measurement range to 40 mm instead of the conventional 25 mm. We have also greatly reduced the effects of environmental fluctuations during measurements by implementing the advanced step-in mode to shorten the measurement time and a precise local temperature control mechanism to reduce the effects of temperature changes.

Expansion of In-line Compatible Functions

When AFM equipment is operated in-line, it is essential to take steps to reduce the number of times the AFM probe has to be replaced, not only in terms of improving the reproducibility and accuracy of measurements, but also in terms of keeping the production line running as much as possible. In a joint effort between Hitachi Kenki FineTech, Hitachi Kyowa Engineering Co., Ltd., and Hitachi, Ltd., we therefore developed an AFM device with a CNT probe tip. The results obtained with this probe tip are discussed below. The results of actual measurements show that this probe tip is able to withstand being used for at least 1,000 3D images. Together with our existing fully automatic AFM probe replacement facility and host communications facility, this makes our equipment ideal for in-line use.

APPLICATION OF AFM TO SEMICONDUCTOR PROCESS MANAGEMENT

Step Measurements

There is a great demand for the measurement of shapes produced after etching processes such as STI (shallow trench isolation), contact/via and damascene processes. This has hitherto been done using cross-sectional SEM (scanning electron microscope) observations or step measurements with a stylus-type profilometer using a contacting method. Compared with these conventional observation methods, an AFM

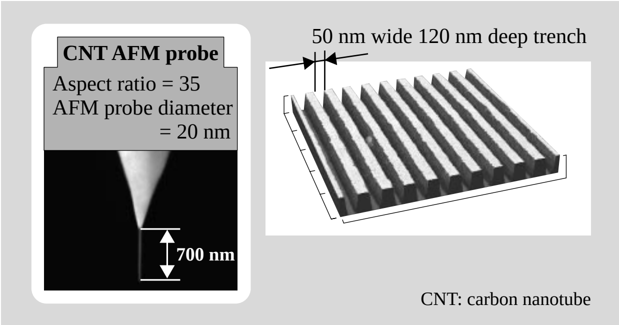
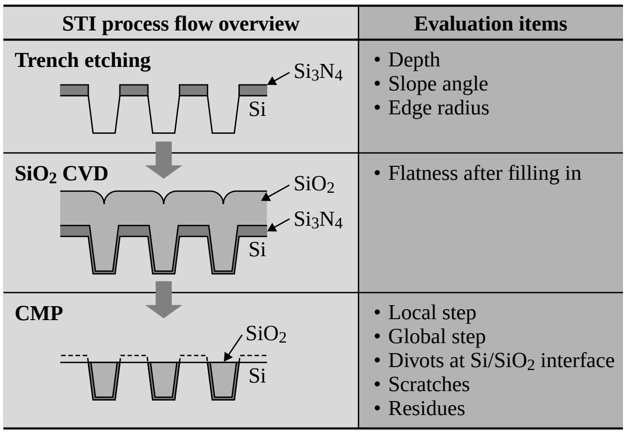


Fig. 3—CNT AFM Probe and AFM Image of 50-nm Trenches.
Using a CNT AFM probe with a diameter of 20 nm, the equipment can be applied not only to 45-nm structures but also to the 32-nm design node. Hitachi has also achieved a substantial improvement in wear resistance.



CVD: chemical vapor deposition

Fig. 4—Overview of STI Process Flow and Measurement Requirements.
STI processes require step management precision at the nm level.

that can measure ultra-fine three-dimensional shapes in a non-destructive manner is suitable for use as an in-line measuring tool, and will become more and more important once 45-nm processes on 300-mm wafers become commonplace. It can also be used for global flatness evaluation and the measurement of micro steps after CMP stages.

Fig. 3 shows the results of using a CNT AFM probe to observe a line and space pattern of width 50 nm and depth 120 nm. The CNT AFM probe used in these measurements was 20-nm in diameter. As this example shows, we confirmed that the use of such a probe makes it possible to measure trenches produced with a 45-nm process.

Also, as an example of the needs of step measurement, Fig. 4 shows an overview of the STI process flow which is an element separation process,

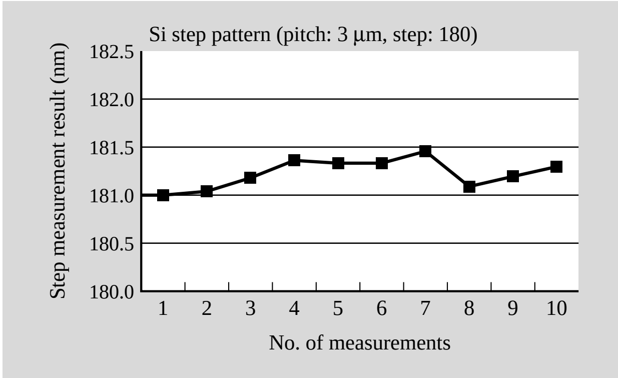


Fig. 5—Reproducibility of Step Measurement after STI Flattening.
The equipment has a static reproducibility of 0.45 nm (3σ), which makes it accurate enough for use in STI process management.

and the measurement needs for AFM. The purpose of the STI process is to ensure favorable electrical properties by relaxing stresses in devices, and thus it is a severe process requiring step management precision at the nm level. Fig. 5 shows the results of evaluating the step reproducibility of the equipment using standard step samples made by VLSI Standards Incorporated (U.S.A.). The static reproducibility is 0.45 nm (3σ), showing that it has sufficient precision for application to STI process management.

Wide-area Flatness Measurements of Oxide Films after CMP

As lithography exposure is performed at shorter wavelengths and with lenses having a larger NA (numerical aperture), the lithography equipment is left with almost no DOF (depth of focus) margin. Also, although ultra-fine processing is used in SoC (system on chip) devices which have appeared in a form that can respond to requests for advanced high-performance LSIs for applications such as consumer electronics, the complexity of their layouts which include on-chip memory and the like means that the flatness of the entire exposed surface after CMP of the ILD (inter-layer dielectric) is a major technical issue. Hitachi Group's AFM can acquire AFM images non-destructively over an area of up to 40×40 mm, and is used by many device manufacturers as a key piece of equipment for setting the conditions of flattening processes. In particular, in SoC devices where the process conditions need to be frequently changed to produce a wide range of products in low quantities, this makes a large contribution to achieving a vertical ramp-up of new processes. Fig. 6 shows an

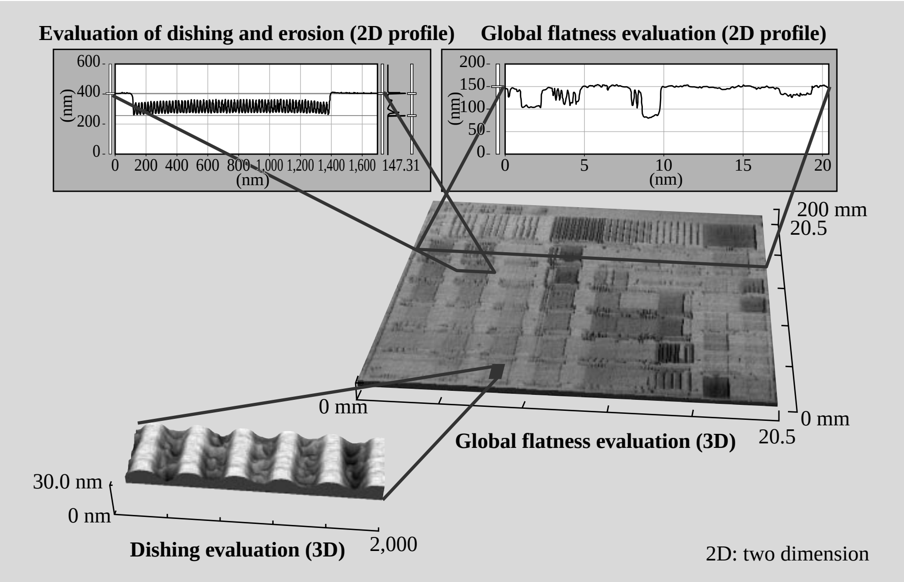


Fig. 6—Wide-area Flatness and Micro-step Evaluation Example.
According to the results of wide-area AFM measurements, it is possible to perform flattening process evaluation on a scale of the order of nm over wide areas and in finely detailed regions.

example of the global flatness evaluation and micro-step evaluation of the entire surface of a chip.

CONCLUSIONS

We have described our new WA3300 AFM system, and we have discussed solutions to process bottlenecks such as ultra-precise flatness measurements over the entire surface of a chip in any process and examples of the application of a new CNT probe tip to bring about a dramatic improvement in wear resistance.

Beyond 45 nm, it is difficult to perform measurements on LSIs using conventional methods. LSI technology is currently reaching the limit of miniaturization in the lateral direction, and one of the ways in which further development can take place is to extend their structures in the vertical direction. In the past, it has been very difficult to perform measurements in this direction. By providing the measurement technology that forms the basis of LSI manufacturing by the new WA3300 AFM equipment, we at Hitachi Kenki FineTech Co., Ltd. hope to contribute to the future progress of LSI technology.

REFERENCES

(1) S. Hosaka et al., “New AFM Imaging for Observing a High Aspect Structure,” Appl. Surf. Sci. (2002).
(2) M. Watanabe et al., “An Advanced AFM Sensor for High-Aspect Ratio Pattern Profile In-line Measurement,” Proc. of SPIE: Metrology, Inspection, and Process Control for Microlithography, Mar. 24 (2006).
(3) S. Baba et al., “An In-line AFM for Semiconductor Inspection,” Proc. LSI Testing Symposium/2006, pp. 35–40 (Nov. 2006).

ABOUT THE AUTHORS


Toru Kurenuma
Joined Hitachi Construction Machinery Co., Ltd. in 1982, and now works at the Design Department 2, the Development and Production Division, Hitachi Kenki FineTech Co., Ltd. He is currently engaged in the development and design of AFM. Mr. Kurenuma is a member of the Japan Society of Mechanical Engineers (JSME) and the Robotics Society of Japan.


Yukio Kembo
Joined Hitachi, Ltd. in 1975, and now works at Hitachi Kenki FineTech Co., Ltd. He is currently engaged in the development of AFM. Mr. Kembo is a member of the Japan Society for Precision Engineering (JSPE), JSME, SPIE, and IEEE Computer Society.


Takafumi Morimoto
Joined Hitachi Construction Machinery Co., Ltd. in 1989, and now works at the Design Department 2, the Development and Production Division, Hitachi Kenki FineTech Co., Ltd. He is currently engaged in the development and design of AFM. He is a member of the Japan Society of Applied Physics.


Masahiro Watanabe
Joined Hitachi, Ltd. in 1988, and now works at the Production Engineering Research Laboratory. He is currently engaged in the development and research of nano-device metrology and inspection systems. Mr. Watanabe is a member of JSPE, SPIE, and IEEE Computer Society.