CD-SEM for 65-nm Process Node

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OVERVIEW: Inspection equipment for 90-nm and subsequent process nodes is required to have not only improved observation ability, but also further improved measurement reproducibility as well. In addition, there has arisen an increasing need for new functions for the ArF resist process, which came into use along with miniaturization, process monitoring, etc. To cope with these processes, the S-9360 CD-SEM (critical-dimension scanning electron microscope) developed by Hitachi Group features (1) superior observation ability due to the use of the same electron-optical system as that of the S-9000 series, (2) improved basic performance such as measurement repeatability and throughput, (3) functions that support new processes including measurement of ArF type resist and measurement of surface charged specimens, (4) complete process variation monitoring functions, and (5) functions that support maintenance management of equipment performance, thus providing a measurement environment that is suitable for semiconductor manufacturing processes in the future generation.

INTRODUCTION

A CD-SEM (critical-dimension scanning electron microscope) measures the dimensions of the fine pattern formed during a semiconductor manufacturing process, thus enabling high quality semiconductor devices to be manufactured.

ITRS (International Technology Roadmap for Semiconductors) provides an outline of the trends in semiconductor manufacturing processes and the market demands for CD-SEM. The needs for CD-SEM are as follows:

(1) Observation of high aspect ratio fine patterns, and the ability to perform precision and stable measurement in a short time

(2) Support for processes based on the 90-nm or subsequent generation

(3) The ability to measure changes in the pattern profile, and detect the manufacturing process

(4) The use of automation for improved productivity and higher efficiency

The basic performance of the new S-9360 CD-SEM, which was developed in order to meet these requirements, together with topics concerning newly developed technology and future prospects are set out below.

BASIC PERFORMANCE OF S-9360

The S-9360 has the basic performance shown in Fig. 1, in order to cope with miniaturization processes.

Features of the type S-9360

- Measurement repeatability: Static 2 nm (3 σ)
- Accelerating voltage range: 300 to 1,600 V
- Resolution: 3 nm
- Throughput: 55 wafers/h
- MAM time: < 6 s
- Visual field positioning accuracy: ±1 μm
- FOUP type mini environment system
- Software: Contains standard Ver.17.
- Safety standard: Complies with SEMI S2-0200.

MAM: move, acquire, measure
FOUP: front opening unified pod
SEMI: Semiconductor Equipment and Materials International

Fig. 1—New S-9360 CD-SEM.
This is the latest model CD-SEM designed to cope with 300-mm wafers. It is intended for process development and mass production using the 90- to 65-nm design rules.

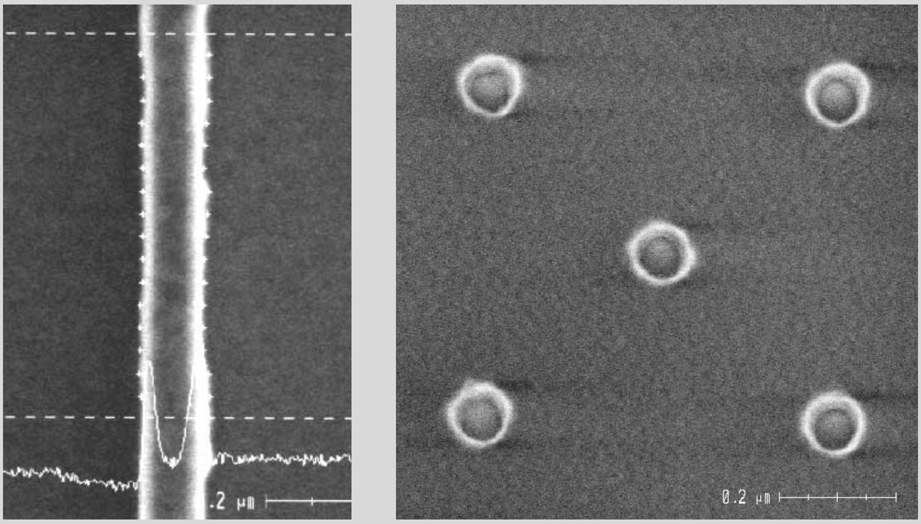

Fig. 2—Examples of Observation of Fine Patterns Using S-9360.
This figure shows an example of observing a line of 69 nm width and a hole of 64-nm diameter (0.5-μm thickness electric conductor resist).

(1) Resolution

The electron-optical system of the S-9360 has a resolution of 3 nm, and supports line spacing and hole patterns of 100 nm or less. Figs. 2 and 3 show observation examples.

(2) Measurement repeatability

Reduced contamination of the specimen due to cleaning of the vacuum specimen chamber and also higher pattern detection accuracy based on image recognition have resulted in improved measurement repeatability. The repeatability accuracy over 10 repetitive measurements is 2 nm in 3 σ.

(3) Throughput

The time during which the wafer is handled while exposed to atmosphere has been reduced due to the use of a new type conveying robot, the evacuation time has been reduced due to the optimization of the coarse evacuation pump, and the processing time has been reduced due to the adoption of a new image processing unit and stage control method, thus reducing the MAM time. As a result, a throughput of 55 wafers/h (based on 5-point measurement and the use of Hitachi's standard wafers) has been realized. Also, the image storage time in the measurement recipe, which is effective for performing analysis and selecting the conditions at the commencement of the process, has been made lower than that of previous models by the adoption of high-speed image transfer technology.

(4) Visual field positioning accuracy

Because the magnification at which addressing is performed increases along with the degree of pattern miniaturization, the visual field becomes narrow, necessitating improved positioning accuracy. For this reason, the stage positioning correction has been automated, enabling fine correction data to be acquired on the wafer map used for correction. Also, the wafer holder has been improved, resulting in a visual position positioning accuracy of ± 1 μm.

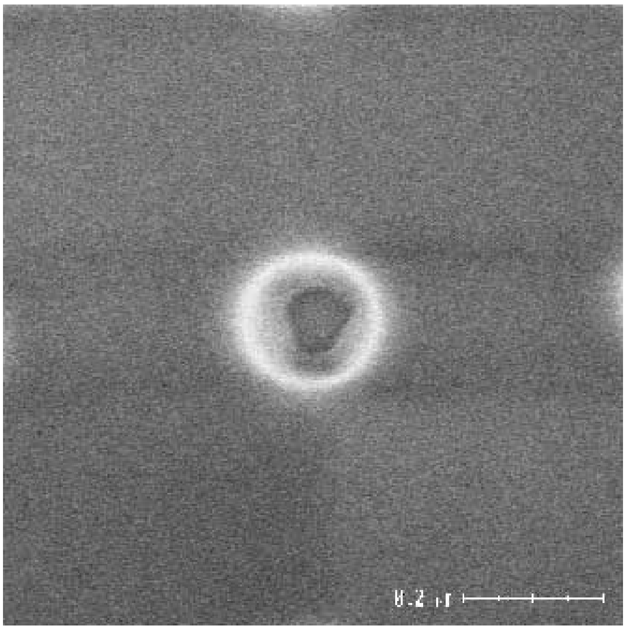

Fig. 3—Example of Observation of High Aspect Ratio Hole Using S-9360.
This figure shows an image of a hole of aspect ratio of up to 20 formed in a 2.0-μm thick film of BPSG (boro phospho silicate glass).

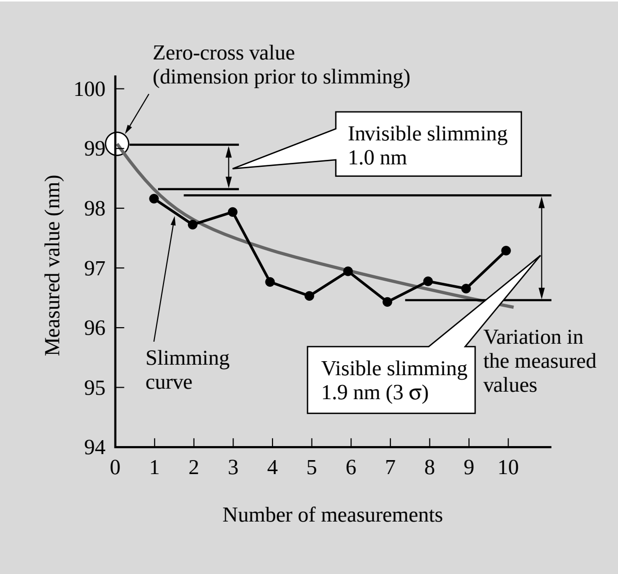

Fig. 4—Reduction of Measured Values Due to Slimming of Resist Pattern.
The first measured value is already a slimmed value. Consequently, it is not possible to determine the pattern dimensions prior to slimming unless both the invisible slimming indicated by the change in the measured value and the invisible slimming indicated by the zero-cross value are evaluated.

MEASUREMENT OF ArF-RESIST PATTERNS

Uncertainty of Measured Values

A resist that is formed for a lithography process using an ArF laser will slim when illuminated by an EB (electron beam) depending upon its chemical characteristics. Consequently, when measurement is performed, the pattern will slim, causing errors to occur in the measured values.

Fig. 4 shows the reduction in the measured values when one pattern is measured 10 times consecutively. In the conventional method of evaluating the measurement repeatability, the variation in the 10 measured values is evaluated as the 3 σ value, so the measurement accuracy is 1.9 nm. This is due mainly to the reduction of the measurement value caused by slimming.

However, in addition to these variations, there are also variations that exist prior to the commencement of measurement. In other words, the first measurement value is the dimension that exists after slimming has already occurred, so this slimming must also be taken into account. It is clear that the slimming during the initial measurement is due to illumination by the EB as is the case in the second and subsequent measurements. Here, it is considered that the greatest amount of slimming occurs between the 0th and the first measurements. This is because the amount of slimming increases the closer the process is to the initial stage of the EB illumination.

If the amount of slimming between the 0th and first measurements is known, it is possible to estimate the pattern dimension prior to slimming, from the first measurement value. However, the slimming that occurs between the 0th and first measurements is “invisible slimming,” and cannot be quantified by simply observing the variation in the measured data. Also, it is considered that the slimming condition is affected by the material and solvent of the resist, the pattern profile, the size of the pattern, etc., and hence the degree of slimming that occurs between the 0th and first measurements changes when the pattern is changed, even when measurement is performed using the same equipment.

Measurement of Dimensions Prior to Slimming

In order to estimate the “invisible slimming,” the slimming curve that indicates that condition of the slimming was found. This was extrapolated to the zero point in order to determine the CD value (hereafter called the zero-cross value) prior to slimming. The “invisible slimming” was estimated by taking the CD value as the measured value for the 0th measurement, resulting in a value of 1.0 nm. This value corresponds to about one half of the “visible slimming” of 1.9 nm that was obtained from the variations in the measured values. This indicates that this value cannot be ignored in a 65-nm process in which dimension control of the pattern and slimming evaluation must be performed at the nanometer level, and also that measurement control based on the slimming value is important.

The slimming curve used to compute this “invisible slimming” is obtained based on the following way of thinking.

Fig. 5 shows the situation where a pattern without slimming is measured. In this case the measured values are scattered about the average value, and the 3 σ value that indicates the range of variation is the repeatability of the measured value. If the S/N (signal-to-noise) ratio is low, the variation in the measured values increases, however if the number of measurements is increased, the average value of the measured values will approach the dimension of the true pattern without limit, enabling high accuracy measurement to be realized.

Fig. 6 shows the case where a slimmed pattern is measured. The slimming curve indicates the dimension of the pattern that becomes progressively smaller due

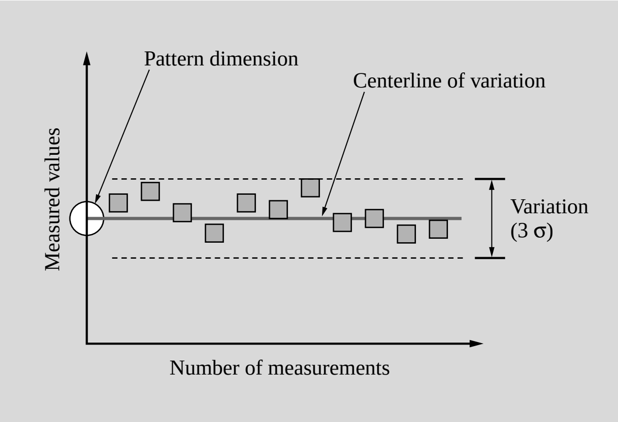

Fig. 5—Example of Measuring Dimension of Pattern without Slimming.
If the number of measurements is increased, the average value of the measured values will approach the dimension of the true pattern without limit, enabling high accuracy measurement to be realized.

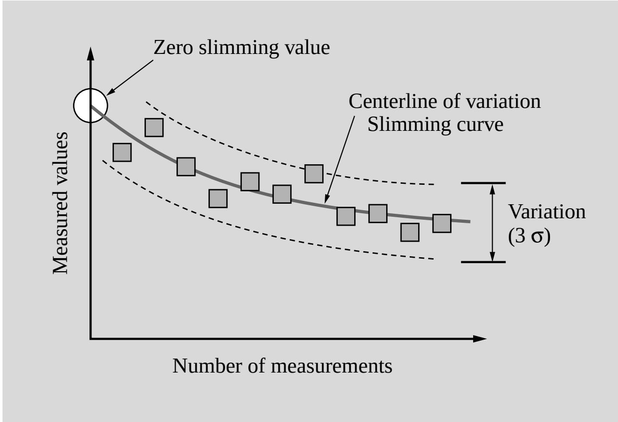

Fig. 6—Example of Measuring Pattern that Slims.
Like the case of a pattern without slimming, the slimming curve approaches the true dimension as the number of measurements increases. As a result, it can be seen that the zero-cross value indicated by the curve approaches the dimension that existed prior to slimming.

to slimming along with each measurement. The variation of the measured values centered about this curve is the same as that for the case of Fig. 5, which shows the case for no slimming. Likewise, if the number of measurements is increased, the slimming curve, which is at the center of the range of variation, will approach the true value. Also, it is considered that the zero-cross value indicated by the slimming curve will progressively approach the true value.

Based on the foregoing, the slimming curve for the resist pattern was determined using the method initially shown in Fig. 6. In the case of normal pattern measurement, two or three measurements are performed, the measured values are placed on the slimming curve, and the zero point indicated by the curve is computed. This value is the dimension immediately prior to slimming, hence it is defined at the measured value of the pattern.

These operations take place automatically in the equipment. Also, the slimming curve is made into a database for each kind of resist pattern, and during measurement it is automatically computed without any awareness on the part of the user. The difference between the amount of slimming and the zero-cross value is automatically quantified, and the optimum measurement conditions are determined.

This method enables the slimming, including “invisible slimming” to be reduced to 1.0 nm in the case of an ArF line pattern of approx. 100-nm width, and also enables the dimensions prior to slimming to be measured to an accuracy of 1 nm.

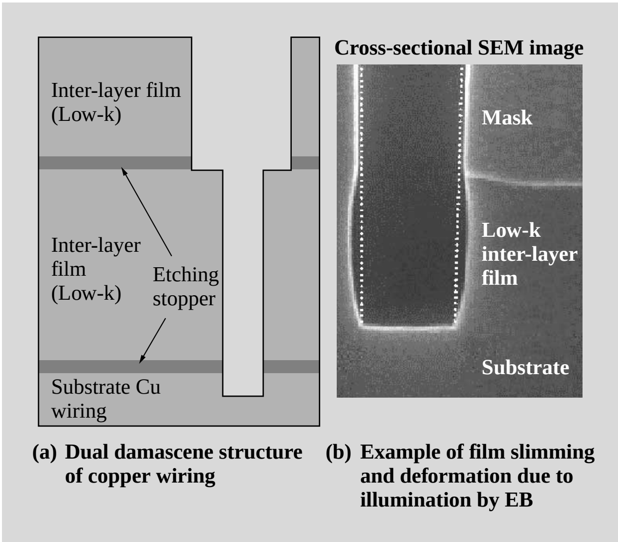

Fig. 7—Example of Cu Wire Dual Damascene Structure and Slimming.
As a result of observing a Low-k inter-layer film using an SEM, it was found that the film shrank, causing barrel-like distortion (the white broken lines indicate the original profile).

MEASUREMENT OF LOW-K FILM

Along with the increasingly high speed of LSI (large-scale integration), the various semiconductor manufacturers are employing Cu wiring processes that are compatible with high-speed devices. As shown in Fig. 7 (a), in the Cu wiring process, Low-k material is employed in the inter-layer film in order to reduce the capacitance between the wires. Recently, porous inter-layer film material is being developed with a view to

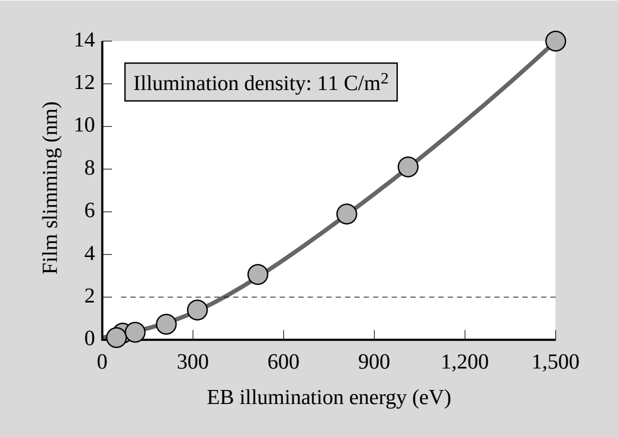

Fig. 8—Example of Slimming Evaluation in Case Where Low-k Film is Illuminated by the EB.
This figure shows the relationship between the illumination energy and the degree of slimming. By reducing the illumination energy to 300 eV or less, the slimming can be reduced to 1.4 nm.

further reducing the dielectric constant of Low-k material.

However, as in the case of the ArF resist mentioned in the previous section, the bonding strength of the film using this porous Low-k material is weak, so slimming occurs due to illumination by the EB. An example of this is shown in Fig. 7(b). When the inter-layer film slims, not only does the measurement accuracy fall, but also problems, such as the reduction of adhesion between layers when the wires are subsequently formed, occur. For this reason, the authors studied methods of EB illumination that would minimize slimming and degeneration of the film.

As an example, Fig. 8 shows the relationship between the illumination energy and the degree of slimming when the EB illuminates porous Low-k material. It can be seen that if the illumination energy of the EB is reduced, the degree of slimming is also reduced, and that when the illumination energy is set to 300 eV, the degree of slimming can be reduced to a value of no more than 2 nm.

In addition, the mechanism of slimming and deterioration was elucidated by analyzing the composition of the area illuminated by the EB and computing the heat generated by EB illumination, using a model. Also, an evaluation of the relationship between the parameters of EB illumination other than those shown here and both slimming and deterioration was performed.

It is thus predicted that it will become increasingly important to study the interaction between the film and the EB, evaluate film damage, and elucidate the mechanism of film damage, for various new materials and structures.

PROCESSING MONITORING FUNCTIONS

Along with the miniaturization of design rules, the needs for CD-SEM are becoming increasingly diverse. Particularly, there is a great need for a function that measures process changes in 3Ds.

CD-SEM manufactured by the Hitachi Group offer the following new process monitoring functions in order to meet these needs.

(1) Photo process monitoring function

In photo process control, it is important to optimize the dosage and focusing values of the exposure unit. An error in the dosage can be controlled by conventional pattern dimension control. However an error in the focusing is manifest as a change in the cross-sectional area of the pattern, so it cannot be monitored by simple dimension control. However, the secondary electron profile of an SEM image contains data indicating the features of the cross-sectional profile (top part and bottom part) in addition to the pattern dimensions, so by extracting this data it is possible to detect changes in the focusing (see Fig. 9).

(2) Etching process monitoring function

It is important to measure the cross-sectional profile of the pattern for the etching process as well. Conventionally, the cross-sectional profile of the pattern is measured using an SEM. However cross-sectional observation is a destructive inspection, and also involves time and money, so it is not suitable for a mass production process. But, as mentioned previously, the secondary electron profile of an SEM image contains various kinds of data concerning the cross-sectional profile of the pattern. For example, by obtaining the first order derivative of the secondary electron profile of an SEM image of a gate pattern, it is possible to extract the feature quantity of the side wall angle of the cross-sectional profile (angle index), and also the feature quantity of the bottom profile (footing index). By using these index values, it is possible to non-destructively monitor changes in the cross-sectional profile of the gate pattern (see Fig. 10).

(3) Combination with beam tilt function

Both of the monitoring functions for the photo process and etching process mentioned here feature the use of the secondary electron profile of the top-down CD-SEM image. This is extremely useful from the viewpoints of the adding functions to existing equipment, and maintenance of the throughput of the

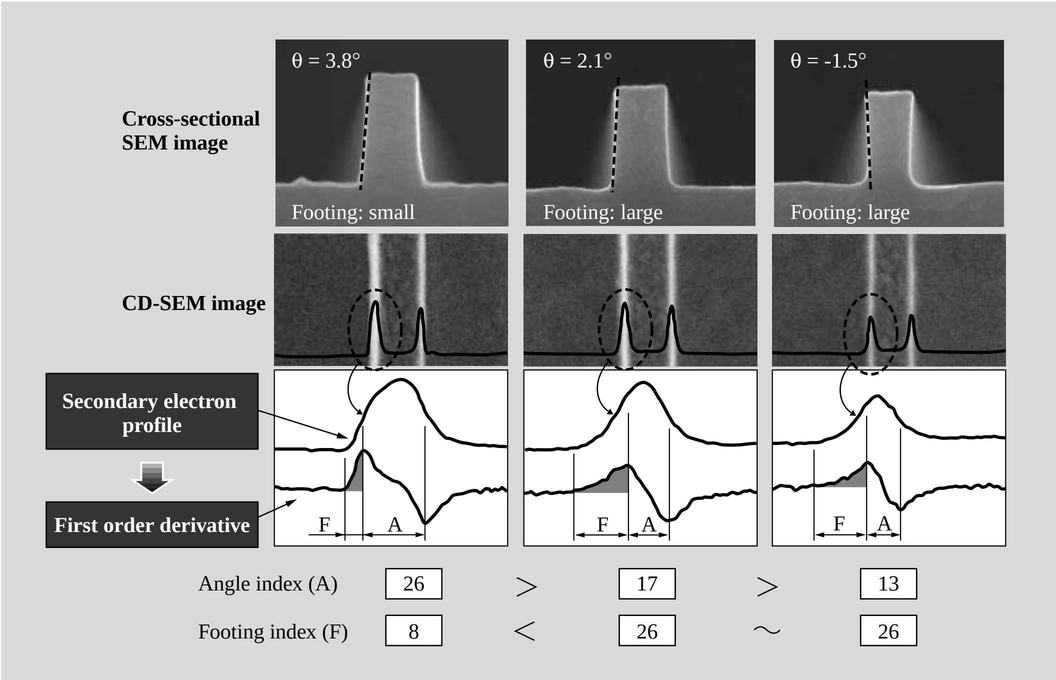

Fig. 9—Examples of Evaluation of Cross-sectional Profile of Gate Pattern Using Etching Process Monitor.
The feature quantity of the pattern side wall angle (angle index) and the feature quantity of the bottom part (footing index) can be extracted from the first order derivative of the secondary electron profile.

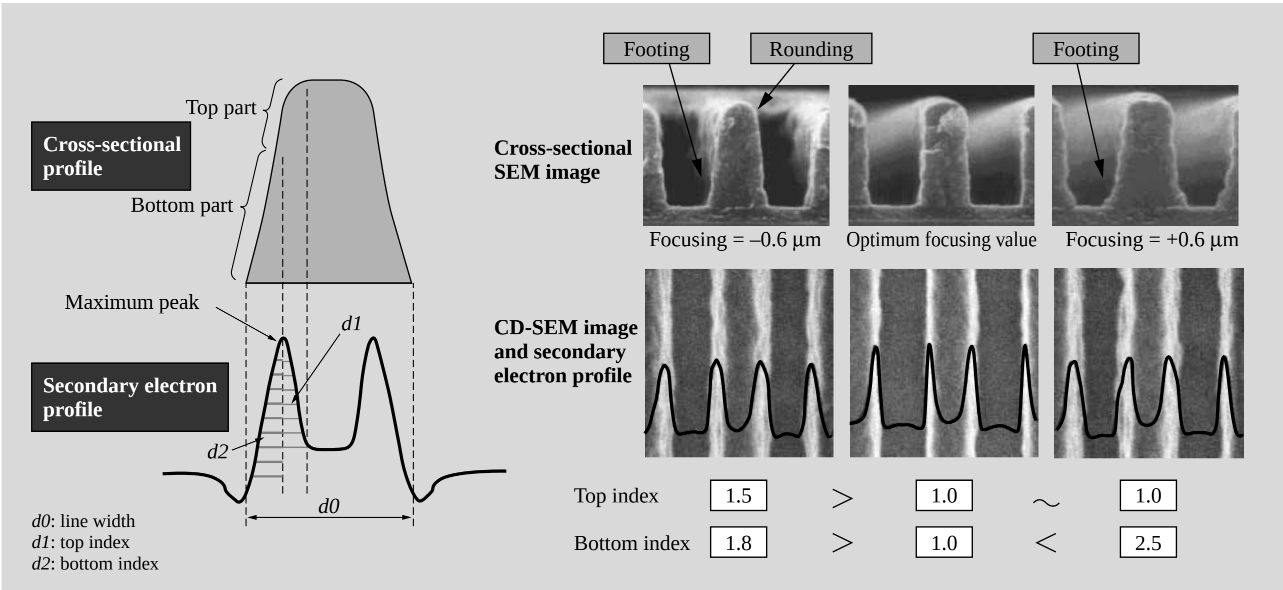

Fig. 10—Focusing Monitor that Uses Top Index and Bottom Index.
By monitoring the rounding and the footing using the top and bottom indexes of the secondary electron profile, it is possible to estimate the error in the focusing value of the photo process (exposure conditions) from the top-down SEM image acquired from the CD-SEM.

CD-SEM. However, if the pattern is near-perpendicular or has a reverse taper (refer to θ = –1.5° in Fig. 9), variations in the process cannot be adequately detected. For this reason, the beam tilt function of a CD-SEM (a function that tilts the EB to enable the specimen to be observed from an oblique direction) is used to improve the ability to monitor vertical patterns and patterns with a reverse taper.

MEETING THE DEMANDS FOR AUTOMATION AND HIGH EFFICIENCY

(1) Optical system performance monitoring functions

The equipment has a function that performs overall monitoring of drift in axis adjustment, astigmatism, etc. The standard specimens used for monitoring are the Hitachi Group's own dimensional calibration specimens. A micro-scale is a device that constitutes a line space pattern of accurate pitch (240 nm). It utilizes laser interference fringe exposure and Si mono-crystal anisotropical etching. An "X, Y" 2D (two-directional) micro-scale image is Fourier-transformed, and the image quality evaluation rating computed. The evaluation rating is displayed as a ratio with respect to a "standard image," and control of secular change can be performed by means of a time series graph. As a result, the status of the optical system can be monitored, and the timing of axis adjustment can be judged.

(2) Electron-optical system automatic axis adjustment function

Previously, the user manually performed axis adjustment of the electron-optical system, either periodically or whenever the image quality deteriorated. The S-9360 has an automatic axis adjustment function that employs image processing, enabling appropriate axis adjustment to be performed in a short time without any need for an operator.

(3) Meeting the demands for 300-mm line automation

The S-9360, which comes with an automatic material conveying system, process job object, etc., complies with the 300 mm series SEMI standard, and has the necessary functions for automating a 300-mm line.

In the future, Hitachi intends to develop an equipment operation status monitoring function, equipment performance tracking function and remote diagnostic function.

CONCLUSIONS

The foregoing is a description of the new S-9360 CD-SEM, which contributes to technical innovation in semiconductor manufacture.

The features of the S-9360 enable it to meet the market needs for semiconductor manufacturing processes of 90-nm and subsequent process nodes. It satisfies the needs of the 65-nm node era.

In order to cope with fine processes, the Hitachi Group intends to tackle the following tasks:

(1) improved resolution and measurement repeatability,
(2) additional countermeasures against resist slimming,
(3) brush-up of 2D and 3D measurement, and
(4) adoption of APC technology (technology that uses a measuring instrument such as a CD-SEM to detect process changes and provides feedback and feed-forward to the process). The Group also intends to develop a user-friendly system aimed at further improved CoO (cost of ownership).

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