CD-SEM Technologies for 65-nm Process Node

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OVERVIEW: Improved measurement repeatability of new CD-SEM systems for the 65-nm node has increased demand for ways to deal with pattern roughness and other new issues that have emerged as device feature sizes have continued to shrink. Hitachi Group's newest generation CD-SEM developed for the 65-nm node and beyond, is now available. A range of elemental technologies are now under investigation to derive the full performance benefits from the new system and to deal with finer feature size processes.

INTRODUCTION

CD-SEM (critical-dimension scanning electron microscope) is an essential tool for measuring the fine pattern dimensions formed in semiconductor processes that require to fabricate high-quality semiconductor devices. Hitachi has developed a diverse range of elemental technologies to address the needs of ever smaller dimensions[1], and many of these innovations were incorporated in Hitachi's conventional CD-SEM. These technologies can also be applied to the latest CD-SEM developed for the 65-nm node and beyond. Yet at the same time we continue to investigate metrology related technologies to deal with the effects of pattern edge roughness on measurements and other new challenges that have emerged as features sizes continue to shrink. This paper highlights some of the new technologies developed specifically for application to Hitachi's latest CD-SEM (see Fig. 1).

ROUGHNESS AND CD MEASUREMENT FUNCTIONS

Roughness and Transistor Performance

Measurement of pattern edge roughness becomes increasingly important as LSI technology evolves toward smaller features. The need for extremely precise measurement of LER (line-edge roughness) and LWR

- Measurement repeatability: Static 1.0 nm (3 σ)
- Beam energy range: 300 V to 1,600 V
- Resolution: 2.0 nm
- Throughput: 55 wafers per hour
- MAM time: < 5 s
- Visual field positioning accuracy: ±1 µm
- FOUP type mini environment system
- Software: Contains standard version 17
- Safety standard: Complies with SEMI S2-0200

MAM: move, acquire, measure
FOUP: front opening unified pod

Fig.1—Hitachi's New CD-SEM.
Shown is a Hitachi's latest CD-SEM developed for development and mass production of 65-nm design rule process devices of 300-mm wafers.

(line-width roughness) of line patterns (primarily gates) is especially crucial. This is because the gate pattern width, or the gate length, has an enormous influence on the performance of transistors (see Fig. 2). For example, an LWR with shorter frequency than transistor width W_g could cause local short-channel effects that reduce the gate length causing higher device leakage current and reduced threshold voltage. Alternatively, if the LWR has longer frequency than W_g, this could cause variation in gate length across multiple transistors, resulting in variation in transistor performance[(1)]. In LSI processes for the 65-nm node and beyond, the ability to assess LER and LWR becomes critically important in addition to the concerns of earlier metrology management.

Roughness and CD Measurement Specifications

The usual index for LER is the edge point position while the typical index for LWR is the line width distribution as a 3-σ value (σ is the standard deviation).

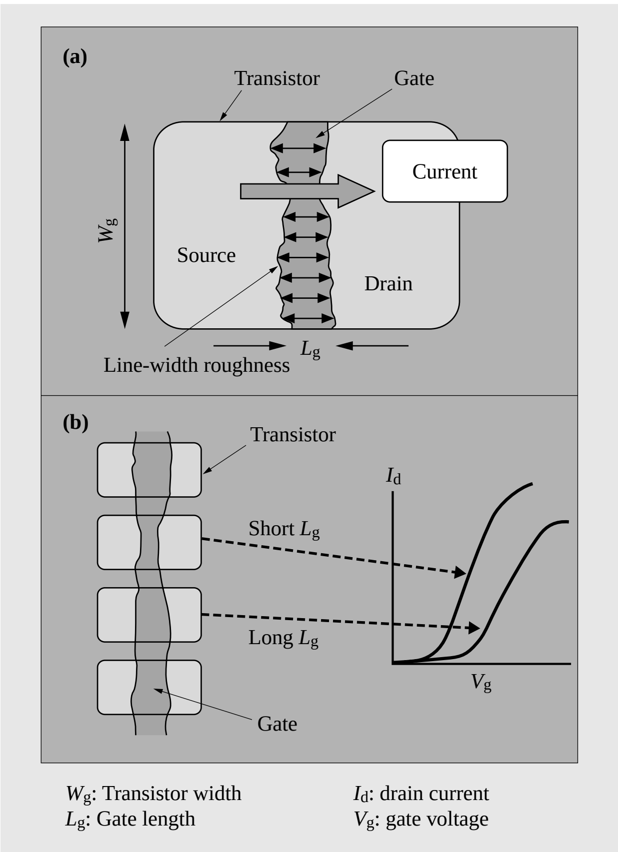

Fig. 2—Effects of Gate Pattern Line Width Roughness (LWR) on Transistor Performance.
(a) Roughness with shorter frequency than transistor width W_g causes local short-channel effects. (b) Roughness with longer frequency than transistor width W_g causes variation in transistor performance.

For example, consider an LWR measurement performed under the measurement conditions illustrated in Fig. 3. In the figure, the areas enclosed by white frames are the areas where the LWR is measured. Within these areas we first extract the pattern edge points, then derive the LWR value. The white dots are the extracted edge points. If we compare the LWR values of the longer measurement region (b) with the shorter region (a), longer frequency roughness is captured the wider the area measured, so the longer measurement region yields a larger LWR value. It is thus apparent that the LWR value is dependent on the length of the measurement area in the longitudinal direction (i.e. the measurement area length)[(1), (2)]. Thus, the first question we have to address is what length measurement area would be most appropriate.

At the same time, the spacing between sampled edge points is also important. For example, if we compare the measurement approach of region (b) with that of region (c), the larger gap between detected edge points in region (c) makes it impossible to capture a finely detailed frequency roughness. Needless to say, the accuracy of the approach shown in region (c) is far worse than that shown in region (b). So, the second question we have to consider is how finely the pattern edge points should be spaced. Now let us examine

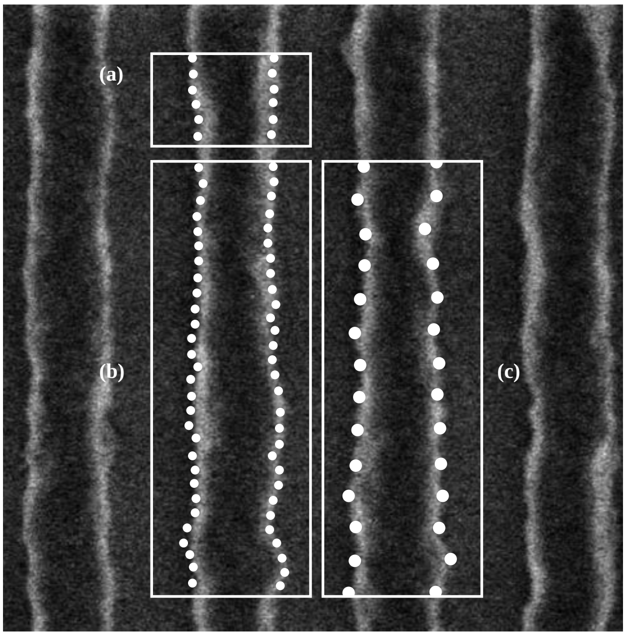

Fig. 3—Effects of Measurement Region Length and Edge Point Spacing on Measured LWR Values.
Region (a) is too short, so long frequency roughness cannot be measured. In region (c) short frequency roughness cannot be measured, so accurate values cannot be obtained. Region (b) represents the best compromise.

these two questions in greater detail.

Optimum length measurement region

To determine the optimum length measurement region (the first question), we measured the dependence of the average LWR value on the measurement region length. The LWR value variation 3-σ values are shown on the vertical axis in Fig. 4. One can see that the 3-σ values increase as the length of the measurement region L increases, but exhibits a tendency toward saturation at $L > 2$ µm. This same pattern of behavior was confirmed for various types of resists[3], where we found that compared to measurement values where L = several tens of micrometers, the 3-σ values reach 95% when $L = 2$ µm. Note that the LWR values shown in the graph are averages which actually represent a number of LWR value variations around the average values. The 3-σ value is large when L is small, but decreases as L increases. While there is some variation in the 3-σ values due to statistical error, we confirmed that the statistical error is less than 10% of the average values when $L = 2$ µm. Based on these findings, we can conclude that 2 µm is a required and sufficient length for the measurement region length.

Edge point spacing

To address the second question as to how finely the pattern edge points should be spaced, we measured the dependence of LWR values on the edge point spacing, that we refer to here as Δy. First we derived the LWR value when dividing up the $L = 2$ µm region into the maximum possible density of edge points, and we assume that this approximates the true LWR. Next, we derived LER values for various edge point spacing values of Δy, and calculated that how far these values diverged from the true LER (see Fig. 5). The disparities exhibited some statistical variation, but we found that the statistical variation could be held below ± 5% if $\Delta y < 20$ nm. Through analysis of various kinds of resist patterns, we also found that among the observed characteristic roughness frequencies, the shortest frequency was about 20 nm[4]. In order to incorporate this roughness component into our measured values, we need to adopt half that value, or 10 nm, as the sample spacing.

We thus found that 10 nm is a suitable value for the edge point spacing Δy. Addressing both questions in sections (1) and (2) we found that measuring LWR should best be done using 200 edge points in a measurement region that is 2 µm in length. We obtained the same results when determining the optimum conditions for measuring LER.

A value of 2 µm is also useful and effective for measuring CDs (critical dimensions)[3]. In Fig. 4 we plotted CD variation measured when using measurement region length L together with LWR. The CD variations are caused by the roughness. Roughness

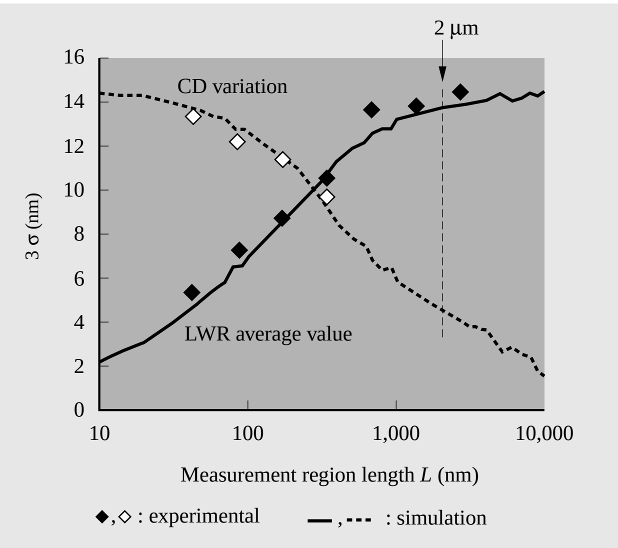

Fig. 4—Dependence of LWR Measurement Value (Average) on Measurement Region Length.
To measure LWR, a measurement region length of L = 2 µm is necessary and sufficient. With a measurement region of this length, the LWR average value is saturated up to 95% and variation is less than 10%.

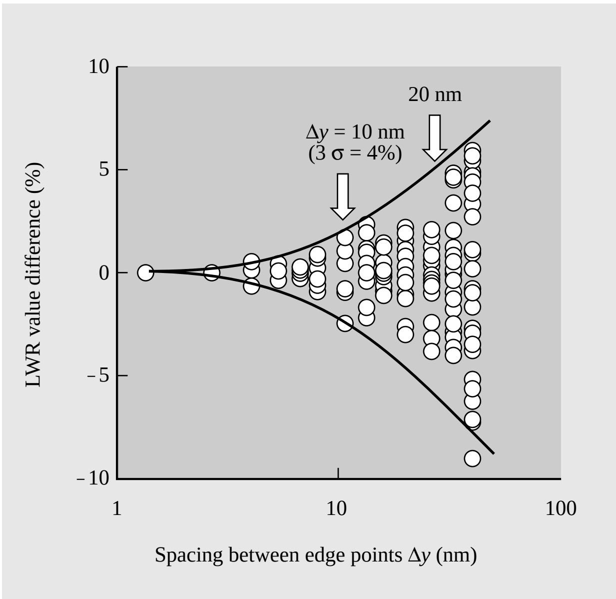

Fig. 5—Difference between LWR Value Measured in the 2-µm Region and True Value.
The difference increases as the spacing between edge points Δy widens.

with a frequency less than L is recognized as LWR, while the component that is greater than L is recognized as CD variation. Consequently, the smaller the L the larger the CD variation tends to become, and this is the CD measurement error. To avoid this effect, CDs must be measured under the condition that LWR is sufficiently saturated ($L \geq 2$ μm). This must be taken into consideration when measuring CD uniformity on a chip, on a wafer, or between wafers, or when evaluating the measurement repeatability of a tool.

This led us to simulate the effects on CD uniformity (CD variation 3-σ values). Fig. 6 shows the relation between true CD uniformity and the observed CD uniformity when the LWR occurring in patterns is 5 nm (measured when L = 2 μm). For the conventional method, we adopted a length of L = 200 nm, which corresponds to a measurement region setting of 150 on a 200,000 × observed image.

In both schemes, the effects of errors caused by LWR tend to increase when CD uniformity is good. In the conventional scheme, when the observed value is 6 nm, the difference from the true value (4.4 nm) is about 40%. However, with the new method, the observed value becomes 4.7 nm, which is sufficiently close to the true value. For future processes that require even higher levels of CD uniformity, there will be growing demand for roughness measurement techniques based on the new method.

To summarize the points made so far, we have found that LER and CDs can be accurately measured by selecting a long edge segment (2 μm) and dense

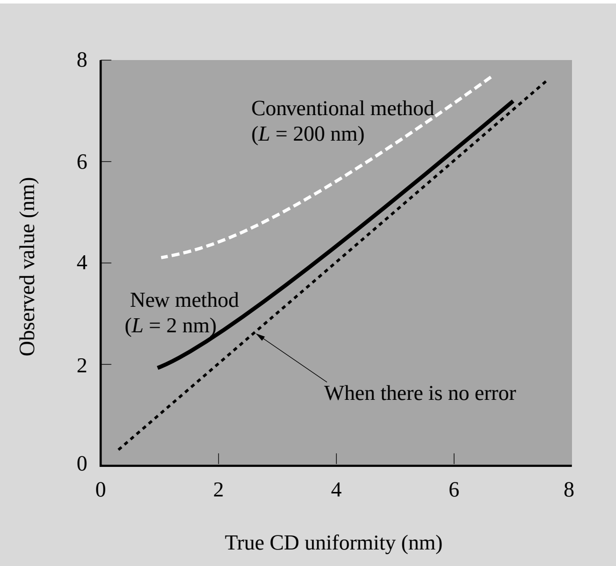

Fig. 6—Measured CD Uniformity for Conventional Method and New Method.
Simulated results of effects on CD uniformity are shown.

concentration of edge points (10-nm spacing).

In order to actually perform measurements using the new approach outlined above, one must observe a single line in a high magnification, and capture 2-μm segments of data while moving the visual field in the vertical direction. However, in actual production processes, there are limitations on throughput. Furthermore, when the visual field is superimposed, exposure to the EB (electron beam) causes ArF (argon fluoride) resist patterns to shrink and other damaging effects. This issue might be addressed by implementing a variable power observation scheme enabling magnification in the vertical direction and in the lateral direction to be set separately. This would permit linewidth measurements in which patterns longer than 2 μm in the length direction could be observed at one time.

HIGH PRECISION MEASUREMENT TECHNOLOGIES

Repeatability Performance Demanded of Measurement Tools

CD-SEM is a tool for measuring the lines and holes and other fine feature patterns formed on semiconductor wafers. As finer device patterns have been made possible by advances in optical lithography, the margin of error in measuring dimensions has become increasingly exacting. The level of precision demanded (measurement repeatability) of measurement tools for the 65-nm node has reached the sub-nanometer order.

Reproducibly in this context means *total repeatability* (3-σ_{total}) encompassing three components:
(1) *short-term repeatability* (3-σ_{short}) meaning CD value variability when the same pattern is measured continuously multiple times,
(2) *long-term stability* (3-σ_{long}) meaning CD value variability when the same place is measured after a time interval (e.g. one week), and
(3) *tool difference* (3-σ_{tool}) meaning CD value variability when the same place is measured by different tools. The relation between these three components is given by

$$\sigma_{total} = \sqrt{(\sigma_{short})^2 + (\sigma_{long})^2 + (\sigma_{tool})^2} \quad \text{.....................} \quad (1)$$

Factors Reducing Short-term Repeatability

Here we will highlight some of our efforts to improve short-term repeatability performance, the most basic constituent factor in total repeatability. The first step toward improved repeatability is to carry out a quantitative analysis to determine what factors are causing repeatability to decline.

In a factor analysis evaluation of repeatability, short-term repeatability generally means CD variation (3-σ_{short}) observed when continuously and repeatedly measuring the same line patterns throughout the dynamic sequence consisting of wafer loading → imaging → measurement → wafer unloading. The primary combination of factors causing repeatability to decline in CD-SEM measurement processes are summarized as follows (see Fig. 7):

(1) Noise in this context refers to shot noise, an attribute of the principle by which SEM imaging works. Shot noise is cause by secondary electrons given off as a result EB irradiation.

(2) Visual field misalignment affects the potential state on the surface of the sample at the point where the EB impinges on the sample, and occurs with each measurement. When visual field misalignment occurs, a slightly different place is measured and this results in CD value variation.

(3) Auto focus variation refers to CD value variation caused by slight differences in calculated focal points when capturing images. This results from the focal point position detection process for obtaining focused images.

(4) Brightness correction variation is caused by the accuracy of internal automatic adjustments of detected signal amplification factor required for imaging various materials with different secondary electron emission efficiencies at a fixed brightness level. There are slight differences in the signal amplification factor that is set when capturing images due to potential change on sample surfaces and other factors, and it is thought that these differences might reduce the repeatability.

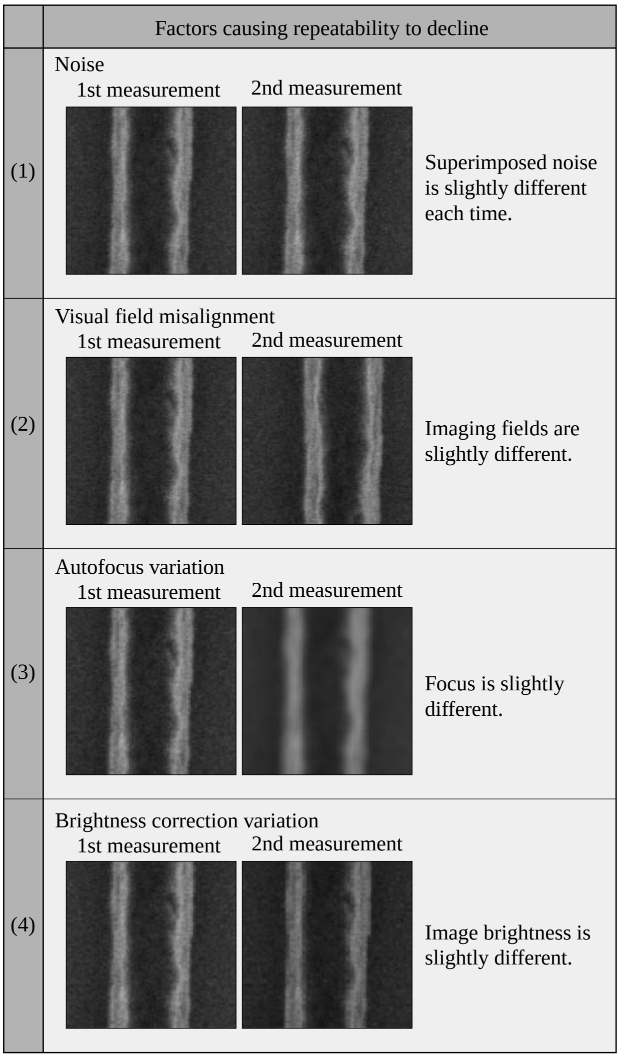

Fig. 7—Factors Reducing Short-term Repeatability.
Shown are the typical examples of the adverse effects of factors reducing repeatability when measurements are performed two times in the same place. Images are exaggerated to illustrate the effects more clearly.

Factor Analysis Results

Fig. 8 shows the results of a quantitative analysis of the various factors outlined in the previous section. In our experiments, the effects of charge were minimal and post-etching polysilicon line patterns were used as evaluation samples.

Total short-term repeatability performance of the

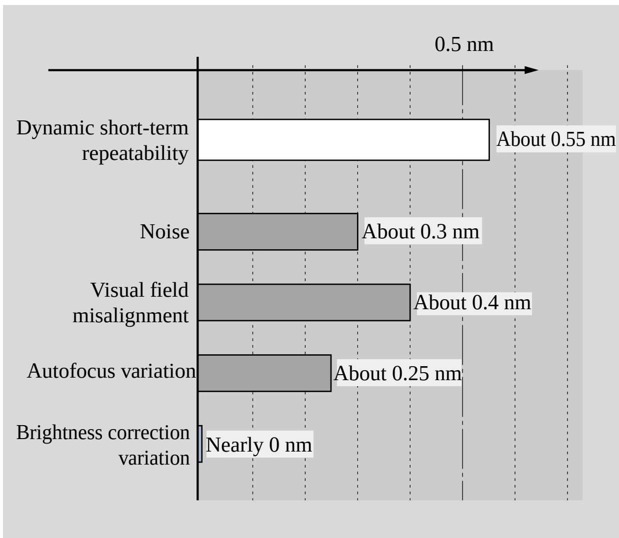

Fig. 8—Analysis of Factors Reducing Repeatability on New CD-SEM.
Quantitative evaluation results of short-term dynamic repeatability and various factors reducing repeatability are shown. The values in the figure are 3-σ values.

polysilicon lines was about 0.55 nm, of which 0.3 nm was contributed by noise, 0.4 nm was contributed by visual field misalignment, 0.25 nm was contributed by the autofocus, and nearly 0 nm was contributed by the brightness correction. Here the short-term repeatability of 0.55 nm and the amount of reduction contributed by each factor were related by the sum of squares, the same as in Eq. (1).

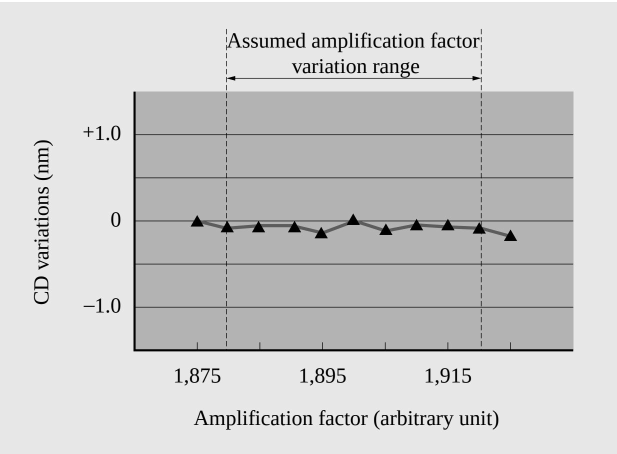

Fig. 9—Evaluation Results of Effects of Brightness Correction Processing.
This shows the relation between the signal amplification factor that is automatically set and the CD value in the brightness correction processing. The device parameter value expressing the amplification factor is shown on the horizontal axis as a function of the amount of relative CD value variation on the vertical axis. One can see that for the range of assumed amplification factor variation in the brightness correction processing, the CD value changes very little compared to the variation in the amplification factor.

Among the four repeatability reducing factors, Fig. 9 shows the analytical results for brightness correction. In the brightness correction process, the amplification factor when detecting signal amplification changes is automatically adjusted inside the tool in order to obtain image data with constant brightness. In the figure, we plotted CD values for imaging the same sample at different amplification factors. One can see that there are no significant variations in CD values despite the changed amplification factors. This confirms that variation in the signal amplification factor during brightness correction processing is not a significant factor in the reduction of repeatability.

Among the factors reducing repeatability, the effects of visual field misalignment depend on the object being measured. In other words, for objects with little edge roughness the contribution of field misalignment to CD value variation is minimal, but for objects with substantial edge roughness the contribution of field misalignment to CD value variation is relatively great. Since this factor

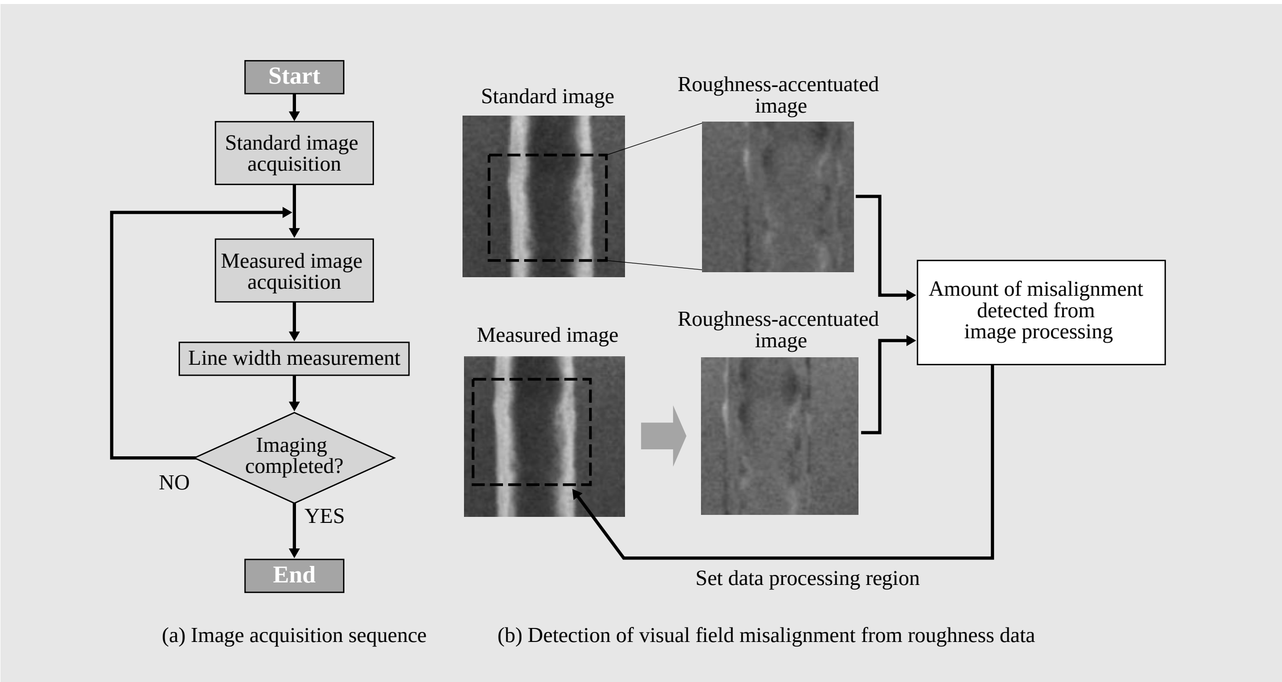

Fig. 10—(a) New CD-SEM Repeatability Evaluation Mode Sequence, and (b) Overview of Visual Field Misalignment Detection Using Roughness Data.
Minute field misalignment amounts between images are detected using roughness-accentuated images. In a strict sense, repeatability performance can be evaluated when measuring the same place multiple times, because the data processing region is set based on the detected results.

contributing to reduced repeatability is caused by the measurement tool, some kind of countermeasure must be implemented in the equipment. One such countermeasure is illustrated in Fig. 10. Here one image among many captured during the dynamic sequence is regarded as the standard, the field misalignment between that image and the others is calculated, and the data processing region is set for each image based on the calculated results. In a strict sense, repeatability performance can thus be evaluated when the same place is measured multiple times.

Detection of the amount of misalignment between images is done using the roughness occurring in imaged line patterns. Specifically, we create images accentuating just the roughness pattern from the SEM images, then use those images to calculate the amount of misalignment through pattern matching. This technique can be used to detect the amount of field misalignment with a high degree of accuracy even for patterns with relatively little roughness. This permits highly accurate assessments of repeatability performance of resist patterns as well as post-etching line patterns. Using repeatability performances of assessment results also eliminates the problem of sample dependent variability.

Based on our analysis of factors reducing repeatability and by adopting techniques that reduce those effects, we were able to improve short-term repeatability in samples under test from 0.55 nm to 0.39 nm. What is more, the prospects are good that we will be able to hold down long-term stability ($3\text{-}\sigma_{long}$) and tool difference ($3\text{-}\sigma_{tool}$) to about 0.4 nm, so we should be able to achieve a total repeatability ($3\text{-}\sigma_{total}$) for the system of about 0.8 nm. We are currently evaluating and testing a wide range of samples for potential application to 65-nm node processes.

CONCLUSIONS

In this paper we highlighted some of the new technologies developed for application to Hitachi's latest CD-SEM. Hitachi Group continues work on a range of elemental technologies to derive the full performance benefits from the new system to meet the needs of semiconductor processing for the 65-nm node and beyond. In addition to the ongoing assessment and testing of wide ranging samples, we are also studying ways to improve metrology technologies to deal with ever-smaller feature sizes in the future including initiatives:

(1) to enhance resolution and measurement repeatability,

(2) to cope with resist shrinkage, charge, and other sources of sample damage, and

(3) to improve 2D (two-dimensional) and 3D measurement techniques.

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