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Abstract. For robustness improvement of inline metrology tools, we propose an inline reference metrology system, named verification metrology system (VMS). This system combines inline metrology and nondestructive reference metrology tools. VMS can detect the false alarm error and the nondetectable error caused by measurement robustness decay of inline metrology tools. Grazing-incidence small-angle x-ray scattering (GI-SAXS) was selected as the inline reference metrology tool. GI-SAXS has high robustness capability for under-layer structural changes. VMS with scatterometry and GI-SAXS was evaluated for measurement robustness. The potential to detect metrology system errors was confirmed using VMS. Cost reduction effect of VMS was estimated for the false alarm case. Total cost is obtained as a sum of the false alarm losses and the metrology costs. VMS is effective for total cost reduction with low sampling. Also, it is important that the sampling frequency of reference metrology is optimized based on process qualities. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JMM.13.4.041405]

Keywords: reference metrology; measurement uncertainty; process variation; measurement robustness; grazing-incidence small-angle x-ray scattering.

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1 Introduction

As the pattern size of semiconductor devices is shrinking, a higher level of measurement accuracy of inline metrology is required. Advanced process control (APC) for higher level process capability is needed with inline quality control. Higher accuracy metrology technology for next generation devices is required not only for the pattern size shrinkage, but also for high-level process controls such as APC. In recent years, the concept of measurement uncertainty (MU) has replaced accuracy and precision and is shown in Fig. 1.[1,2] The horizontal axis in Fig. 1 shows the measurement results of a reference metrology tool, for example, transmission electron microscopy or atomic force microscopy. The vertical axis shows the measurement results of an inline metrology tool, for example, critical dimension-scanning electron microscopy or scatterometry. The MU is calculated by its total deviation from linear regression. The quality of total metrology system can be evaluated by using the MU method. Figure 1(a) shows the case of an ideal pattern shape without process variation. In this case, the correlation only shows variation from the linear regression line. This variation is caused by random variation of the inline metrology tool. However, the actual pattern shape is changed by process variation or process changing in production. Figure 1(b) shows a case of actual pattern shape with process variation. These process variations cause offset changes and correlation changes by measurement robustness decay. As a result, MU becomes worse. A new measurement technology with higher accuracy for inline metrology has only been developed recently. For example, combination systems of several metrology tools have been put to practical use, such as double metrology[3] and hybrid metrology.[4] To improve the MU, advances in inline metrology and reference metrology in production are needed. But it is difficult to check MU by using reference metrology with a high frequency in production. A verification system with higher level measurement uncertainty and high frequency sampling is required for inline metrology. The concerns are robustness for unpredictable process variations, measurement frequency of the reference metrology, and cost effectiveness of the reference metrology. So we propose an inline reference metrology system, named verification metrology system (VMS). In this paper, we show a concept of VMS, experimental results, and cost analysis results.

2 Concept of VMS

Figure 2 shows the conceptual diagram of VMS. This system is built using a combination of reference metrology and inline metrology tools. Target wafers are measured by the reference metrology tool with a set sampling rate (α) and the inline metrology tool. The measurement results are sent to the VMS system and calculated. If the calculated VMS result is "out of specification" in accordance with the MU guidelines, then the inline metrology tools are optimized with the calculation from the VMS result. Metrology tools are classified into three groups: inline metrology tools, inline reference metrology tools, and offline reference tools. Inline metrology tools can measure with high throughput and nondestructive observation, but have robustness issues for process variations. Inline reference metrology tools have the advantage of high robustness and nondestructive observation, but have a lower throughput. Offline reference metrology tools can measure with high accuracy by direct observation of cross-section, but are destructive and, therefore,

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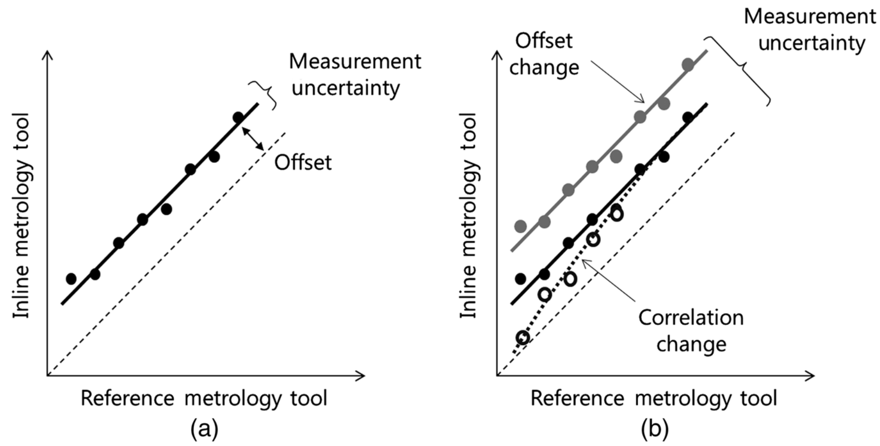

Fig. 1 Measurement uncertainty (MU) for ideal and actual pattern shapes: (a) ideal pattern shape without process variation and (b) actual pattern shape with process variation.

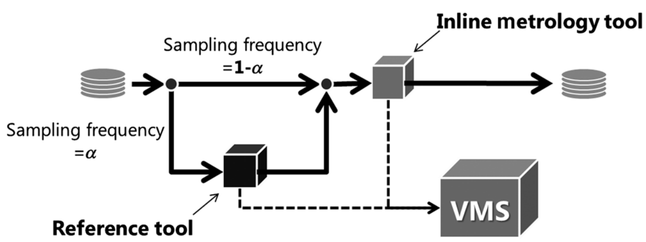

Fig. 2 Conceptual diagram of VMS.

difficult to apply as inline metrology tools. By combining the information from metrology tools, it is possible to make use of the merits of each individual tool type to cover the shortcomings of each tool on its own.

Figure 3 shows the different use cases of the VMS. Upper graphs are the results of the reference metrology tool. Middle graphs are the results of the inline metrology tool. Lower graphs are the delta of results of inline and reference tools. Reference metrology tools can detect pattern shape changes caused by actual process variations. Figure 3(a) shows the case of a stable metrology system. Both inline metrology and inline reference tools show the same measurement trends and the delta maintains a constant value with the offset. Figure 3(b) is the false alarm case, in which this graph shows that only the inline metrology result is changed. The inline metrology result is out of specification, but actual pattern shapes do not change as shown by the reference metrology. As a result, this inline metrology judgment is a false alarm. Figure 3(c) is a nondetectable case, where only the reference metrology result is changed. The inline metrology result is within the specification and this wafer is judged as "pass," but the reference metrology result is out of specification and the actual pattern shapes are changed by process variations. An inline metrology tool does not have enough sensitivity to measure the process variations. The metrology system with only inline metrology tools has the risks of misjudgment, but by using VMS, it is possible to detect the metrology system error due to measurement sensitivity and robustness issues.

3 Experimental Results of VMS by Using GI-SAXS

In this experimental evaluation, grazing-incidence small-angle x-ray scattering (GI-SAXS) was selected as the inline reference metrology tool[5] and scatterometry was selected as the inline metrology tool. Figure 4 shows a schematic diagram of GI-SAXS. X-rays irradiate the sample with a very low incident angle and scattered x-rays from the sample are detected at a two-dimensional (2-D) detector. On the 2-D

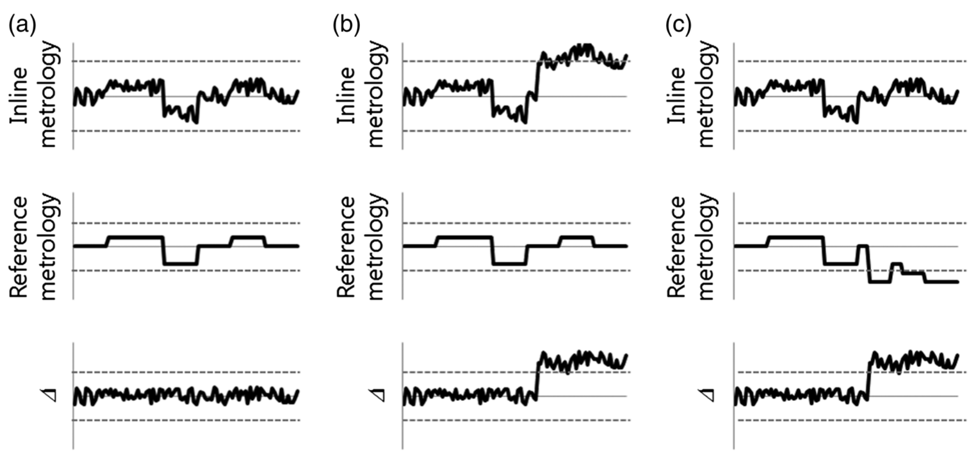

Fig. 3 Case study examples of VMS applications: (a) stable case, (b) false alarm case, and (c) nondetectable case.

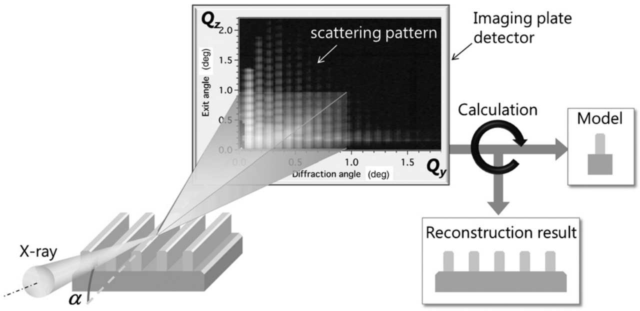

Fig. 4 Schematic diagram of GI-SAXS.

detector, the unique scattering signal caused by the surface structure is detected. A measurement model of GI-SAXS is preset and is calculated to fit the experimental scattering signal. GI-SAXS uses the total external reflection signal with very short wavelength radiation. Therefore, the measurement accuracy of GI-SAXS has a high capability. The measurement robustness of the scatterometry and GI-SAXS applied to manufacturing process variations was evaluated. Figure 5 shows the structural models for scatterometry and GI-SAXS: (a) cross-sectional scanning electron microscopy (SEM) image, (b) scatterometry model, and (c) GI-SAXS model. Line-space patterns are etched into a multilayer stack of Si, SiO_2, and poly-Si films, and the space regions are filled with SiO_2. A second etching process created line-space patterns of the surface layer only. The measurement target is the line height and because of the variation in Si etching conditions 1 and 2, there are small shape variations of the cross-section of the Si line. For line height measuring, the scatterometry and the GI-SAXS models were prepared as shown Figs. 5(b) and 5(c). Scatterometry is an optical metrology system based on spectroscopic ellipsometry measurement with visible wavelengths. Irradiation light can penetrate into surface and internal structures. Therefore, the scatterometry model should be constructed with a complete two- or three-dimensional structure and set a lot of floating parameters. In Fig. 5(b), this model was constructed by using multitrapezoidal parts for Si and poly-Si line patterns. The number of floating parameters is set as eight parameters for line height measurement. The optical constant of each part was a constant value. GI-SAXS, on the other hand, is sensitive to surface structure only as noted above. In Fig. 5(c), this GI-SAXS model was constructed with single trapezoidal parts with top and bottom rounding. The GI-SAXS model is a simpler structure than the scatterometry model, and the number of floating parameters is five parameters. As the incident x-ray irradiates in the total external reflection condition, GI-SAXS detects only surface structure information. Figure 6 shows the comparison with cross-sectional SEM results. The scatterometry results for etch conditions 1 and 2 have 2.3-nm offset when both are compared with the cross-sectional SEM. Scatterometry can detect under-layer information by using visible light and is also sensitive to under-layer shape changes. The height from GI-SAXS for etching conditions 1 and 2 only has a 0.6-nm offset and a very good measurement linearity when compared with cross-sectional SEM measurements in Fig. 6(b). These results indicate that GI-SAXS has a suitable sensitivity to height and has the additional benefit of being a nondestructive inline reference metrology. However, there is a large gap in throughput between the two techniques; the measurement times of scatterometry and GI-SAXS are 3 and 120 s, respectively. Therefore, by combining scatterometry and GI-SAXS, it is possible to improve the metrology capability for robustness and throughput.

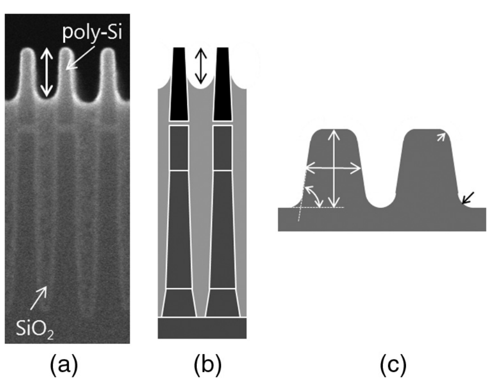

Fig. 5 Structural models for scatterometry and GI-SAXS: (a) cross-sectional SEM image, (b) scatterometry model, and (c) GI-SAXS model.

In this experiment, scatterometry was used as the inline metrology tool and GI-SAXS was used as the inline reference metrology system. The measured height difference (Δh) between scatterometry and GI-SAXS was calculated by VMS. Figure 7 is the long-term evaluation results for VMS. The evaluated wafers were processed by etching condition 2 in Fig. 6. Figure 7(a) shows each measurement result for a month in the R&D pilot line under various types of process conditions. The baseline of these results is the average of the GI-SAXS results. The upper graph is the measurement results of scatterometry, the middle graph is the measurement results of GI-SAXS, and the lower graph is the difference between scatterometry and GI-SAXS. GI-SAXS has an offset close to zero and scatterometry has an offset of −10 nm. This offset is calculated by long-term analysis between GI-SAXS and scatterometry. From this result, we can assume that the metrology system with scatterometry is stable. On the other hand, this result includes two characteristics changes in regions 1 and 2. Figures 7(b) and 7(c) show the detailed data of regions 1 and 2. In the region 1 results of Fig. 7(b), height measurement results were changed by approximately 40 nm, but delta height is constant at −10 nm. The line height of these wafers was changed by different process conditions. This result shows that the scatterometry has a higher sensitivity for line height change. As shown in Fig. 7(c), a false alarm occurs in region 2, where only the height measurement from scatterometry changes. These wafers were processed with different conditions of impurity concentration in poly-Si. The optical constants changes due to variation in impurity concentration are very difficult to predict as floating parameters in the early device development phase, therefore, limiting the measurement robustness of scatterometry. By applying the VMS protocol, the potential for early detection of inline metrology error due to unpredictable parameters such as impurity concentration has been confirmed. VMS has the potential to detect metrology errors by unpredictable variation; however, it is difficult to predict all floating parameters of the sample at this early phase.

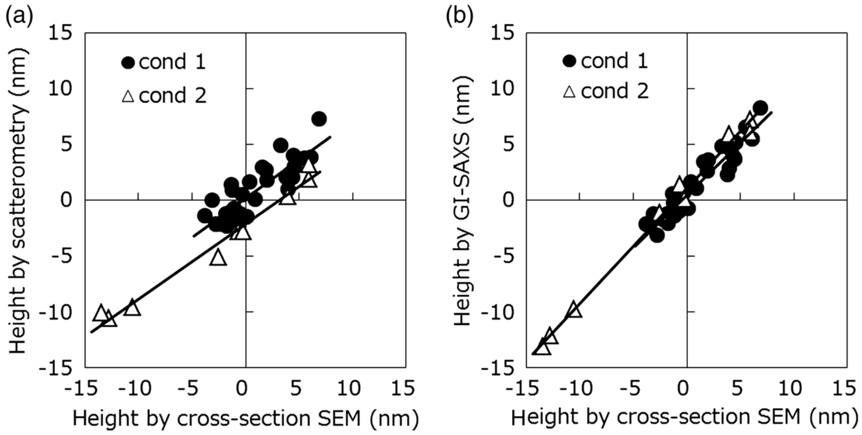

Fig. 6 Measurement robustness of scatterometry and GI-SAXS: (a) scatterometry result and (b) GI-SAXS result.

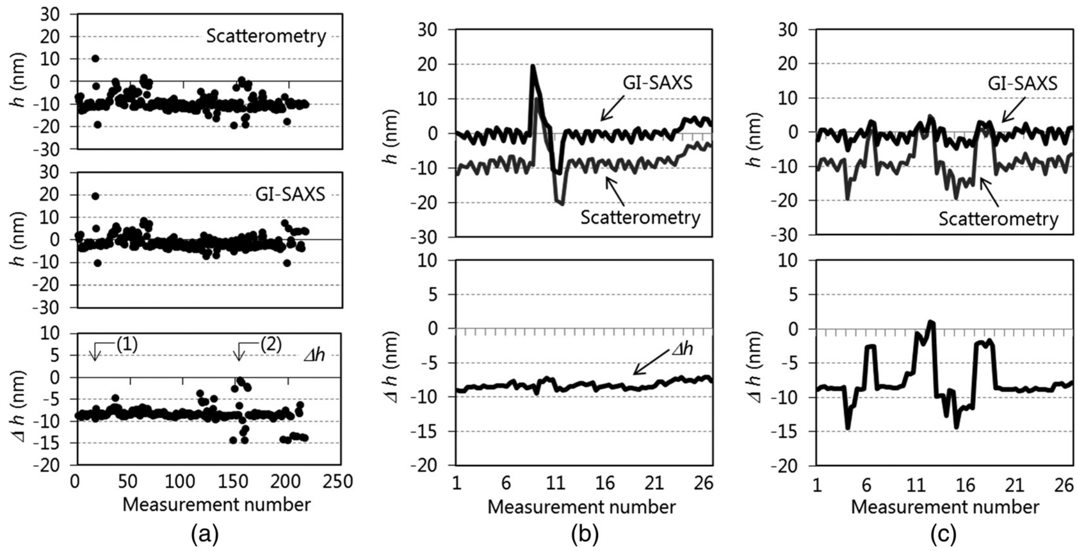

Fig. 7 Long-term evaluation results for VMS: (a) long-term evaluation results for three tools, (b) detail data at region 1, and (c) detail data at region 2.

4 Cost Analysis of VMS

The measurement time of inline reference tools is significantly longer than inline metrology tools, and if only reference tools are implemented, it would result in higher metrology costs. Using a combination of reference and inline tools, the VMS can improve the measurement robustness for inline metrology tools by detecting false alarms. Therefore, the cost of VMS for the false alarm case was analyzed, as shown in Fig. 8. Upper graphs are the results of the reference metrology tool, middle graphs are the results of the inline metrology tool, and lower graphs are the results using VMS. There is not a large variation in reference metrology results; however, inline metrology results detect a large jump. This jump causes unpredictable process variations and continues at the recovery point in inline metrology results. The area over the upper specification limit (USL) shows the false alarm loss. The interval from jump to recovery point is set as a shift period. By monitoring VMS results, the robustness decay of inline metrology can be detected earlier compared with metrology system without VMS. As the result, the false alarm loss can be reduced by using VMS.

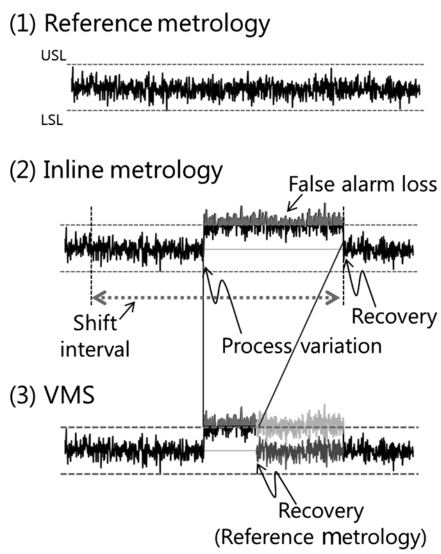

Fig. 8 Cost model for false alarm case.

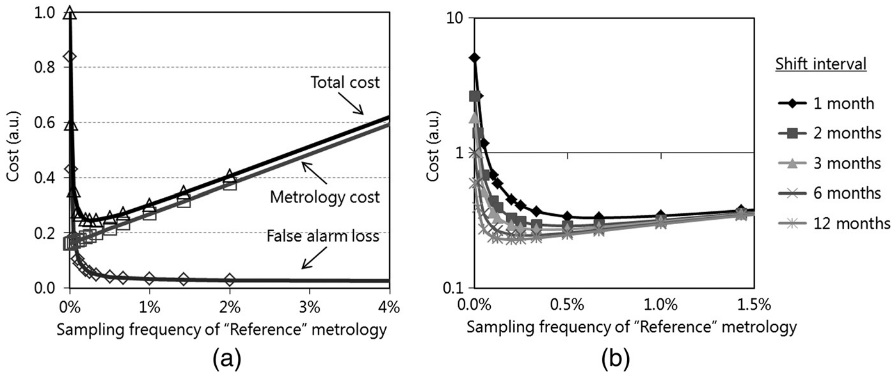

Fig. 9 Cost analysis results for false alarm case: (a) total cost for 6-month shift interval and (b) shift interval dependence on total cost.

The production volume is 10,000 per month and the total period for this estimation is 6 months. The shift period, which is the time period of the false alarm loss, is set as 2 weeks, and the shift interval, which is interval between jumps, is 6 months. Process variation is 2 nm (1σ), USL is 9 nm, and shift value of the measurement jump is 3 nm. The sampling frequency of inline metrology is 100% and the number of target layers is 1. The price ratio between the reference tool and the inline tool is 1.6 and the move-acquire-measure time ratio is 1/40. Figure 9 shows the cost analysis results of the false alarm case. The vertical axis is cost and horizontal axis is the sampling frequency of the reference metrology. The baseline cost is set as the total cost without reference metrology. Figure 9(a) is the cost analysis estimation for a 6-month shift interval including the cost of false alarms, metrology costs, and the total cost.

With the increasing sampling frequency of reference metrology, the cost of false alarms decreases rapidly, but the metrology cost increases gradually. The total cost is obtained as a sum of the false alarm losses and the metrology costs. The total cost reduction is at a minimum at 25% with 0.3% sampling. VMS is effective for total cost reduction with low sampling. However, the total cost is dependent on the shift interval. Figure 9(b) is the shift interval dependence on the total cost. The baseline of the shift interval is 6 months. The shift interval changes from 1 month to 1 year. As the shift interval becomes shorter, the total cost shift is larger, but by setting the optimum sampling frequency of the reference metrology, the total cost can be effectively reduced. Focusing on a 1-month shift interval, the total cost is 500% without reference metrology, when compared with total cost of 6 months. However, the total cost decreases to 33% at a 0.7% sampling frequency of the reference metrology. Therefore, the sampling frequency of the reference metrology must be optimized based on process qualities for the metrology system with VMS to become more effective in reducing the cost of inline metrology.

5 Summary

For robustness improvement of inline metrology tools, we propose an inline reference metrology system, named VMS. This system is a combination of inline metrology tools and nondestructive reference metrology tools. VMS can detect the false alarm error and the nondetectable error caused by measurement robustness decay of inline metrology tools. GI-SAXS was selected as the inline reference metrology tool. GI-SAXS has high robustness capability for under-layer structural changes. VMS with scatterometry and GI-SAXS was evaluated for measurement robustness. VMS with scatterometry and GI-SAXS has a potential to detect metrology system errors caused by unpredictable processes. The cost reduction effect of VMS was estimated for the false alarm case. The total cost is obtained as a sum of the false alarm losses and the metrology costs. VMS is effective for total cost reduction with low sampling. Also, it is important that the sampling frequency of the reference metrology is optimized based on process qualities.

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Hideaki Abe received his ME degrees in mechanical system engineering from Tokyo University of Agriculture and Technology and joined Toshiba Corporation in 1996. He was engaged in the development of CD measurement technologies of ULSI patterns using electron beam equipment. He works in the development of metrology and inspection technologies for semiconductor devices.

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