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An intelligent virtual metrology system with adaptive update for semiconductor manufacturing

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ABSTRACT

Virtual metrology involves the estimation of metrology values using a prediction model instead of metrological equipment, thereby providing an efficient means for wafer-to-wafer quality control. Because wafer characteristics change over time according to the influence of several factors in the manufacturing process, the prediction model should be suitably updated in view of recent actual metrology results. This gives rise to a trade-off relationship, as more frequent updates result in a higher accuracy for virtual metrology, while also incurring a heavier cost in actual metrology. In this paper, we propose an intelligent virtual metrology system to achieve a superior metrology performance with lower costs. By employing an ensemble of artificial neural networks as the prediction model, the prediction, reliability estimation, and model update are successfully integrated into the proposed virtual metrology system. In this system, actual metrology is only performed for those wafers where the current prediction model cannot perform reliable predictions. When actual metrology is performed, the prediction model is instantly updated to incorporate the results. Consequently, the actual metrology ratio is automatically adjusted according to the corresponding circumstances. We demonstrate the effectiveness of the method through experimental validation on actual datasets.

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1. Introduction

Owing to rapid technological advances that have occurred in recent years, the semiconductor manufacturing process is becoming increasingly complex and sophisticated. A greater number of inspections of measuring quality factors are being performed at intermediate steps in the process for each wafer in order to control the process effectively, which results in a significant increase in cycle time and production costs [1,2]. Therefore, only a few sampled wafers from each lot are subjected to measurement, while inspecting every wafer would be undesirable in practice. The main concern is that the selected wafers may not comprehensively represent the remaining wafers in the current lot [3]. The wafers excluded from the inspection cannot be monitored thoroughly, giving rise to the possibility that some faulty wafers could proceed to the next step of the process [4]. To facilitate wafer-to-wafer process control within the practical constraints of efficiency, virtual metrology has been widely adopted as a promising solution.

Virtual metrology concerns the estimation of metrology values of wafers based on process data and previous metrology using a prediction model, rather than performing physical measurement actions [5]. As the current state of a wafer is highly influenced by various factors in the previous steps of the process [6], the prediction model predicts metrology values by studying the relationship between the process data and the metrology data of previous wafers. A well-developed virtual metrology system contributes towards advanced process control. A virtual metrology system results in a reduction in cycle time and production costs required for actual measurements [2,7]. It provides an efficient way of assuring wafer-to-wafer quality by obtaining metrology values for all wafers [7]. It also aids in the accumulation of data-driven knowledge that can be used for analysis and decision making concerning manufacturing quality [2,3].

The underlying assumptions for a virtual metrology system are that the prediction model of the system is sufficiently accurate, and that the data characteristics trained from the model can be maintained in the future. However, owing to maintenance events and internal/external disturbances in the semiconductor manufacturing process, such as preventive maintenance, load change, transitions, and environmental regulations, the data characteristics change over time, and hence the prediction model becomes

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unreliable [8–10]. In particular, an unexpected change in data characteristics is a serious obstacle to the actual deployment of a virtual metrology system. Because this results in the prediction model becoming inaccurate, an appropriate updating process is necessary for the prediction model in order to maintain the efficacy of the virtual metrology system.

A common way to incorporate this is to update the prediction model periodically using the actual metrology data for some wafers [11,12], where determining the periods is an important problem. One can consider simply determining the periods according to the known events related to the process, such as preventive maintenance. However, changes in data characteristics do not precisely correspond to known events. That is, not every event influences the data, and changes in data characteristics may occur unexpectedly [13]. Data characteristics often change gradually with time, regardless of the occurrence of any events. An additional issue involves determining how many wafers should be actually measured in order to sufficiently update the model. Frequent updates involving large amounts of actual metrology data results in a prediction model that accurately incorporates changes in data characteristics, but also incurs higher costs. Conversely, the accuracy of the prediction model may be sacrificed if the model is infrequently updated [14]. In order to alleviate this trade-off, it would be desirable for a virtual metrology system to monitor wafer-to-wafer changes in data characteristics, and to update the prediction model instantly when a change is detected.

With this consideration, this paper proposes an intelligent virtual metrology system based on adaptive updates. We aim to obtain a superior metrology performance, while reducing the actual metrology cost for the practical deployment of virtual metrology. The proposed system performs actual metrology for those wafers that do not fit in to the current prediction model in the system, and updates the model instantly in order to incorporate the actual metrology results. Our proposed virtual metrology system consists of two main modules: the reliability estimation and the prediction model update. The first module estimates how reliable the virtual metrology result of the current prediction model is for a given wafer, and determines whether the model should be updated. When it is determined that the current prediction model should be updated, the second module is activated to incrementally update the model with actual measurements of the wafer. An ensemble of artificial neural networks (ANNs) is employed as the prediction model, while the variance of the predictions of individual ANNs in the ensemble is used in the first module to estimate reliability. In this manner, actual metrology for a wafer is performed selectively only when it is necessary to update the prediction model, improving the efficiency of the virtual metrology system. We demonstrate the effectiveness of the proposed system through experiments on real-world datasets collected from a semiconductor manufacturing company.

The remainder of this paper is organized as follows. In Section 2, we review related work. In Section 3, we introduce the proposed virtual metrology system. In Section 4, we present the experimental results. The conclusions and directions for future work are discussed in Section 5.

2. Related work

Virtual metrology is an important research topic, which has been actively studied. Many researchers have demonstrated the effectiveness of virtual metrology in several intermediate steps of the semiconductor fabrication, such as photolithography, plasma etching, and chemical vapor deposition [5,11,2,7,3,15]. Despite the attention afforded to virtual metrology, the majority of existing work has been limited to taking account of changes in data characteristics. For more advanced virtual metrology, it is important for a virtual metrology system to involve the evaluation of the reliability of virtual metrology for each wafer, and to update the prediction model instantly.

Reliability estimation has mainly been studied with the aim of adjusting the sampling rate of actual metrology by monitoring the process [16]. Regarding virtual metrology, there have been considerable research efforts to evaluate the prediction reliability for wafers. Only virtual metrology results with a high reliability can be used for inspection. Kurz et al. [17] evaluated the reliability for each wafer based on statistical process control. Su et al. [18] and Cheng et al. [19] used a Mahalanobis distance and the overlap of the distribution between current wafer patterns and some reference data to evaluate the reliance level, respectively. Some researchers have adopted a machine learning approach to reliability estimation. Kang et al. [20] employed various one-class classification algorithms to identify new wafer patterns from the prediction model. Wan et al. [21] used the prediction variance of Gaussian process regression as the prediction reliability for each wafer.

More recent work has addressed the updating of the prediction model by incorporating additional data to prevent the degradation of the virtual metrology performance. In Khan et al.'s study [12], a partial least squares model, which requires relatively less training time, was built from scratch as the prediction model, using a moving window of recent data when new metrology data are appended. In Baek et al.'s study [22], the distribution shift of the process variables over time was compensated based on a recursive data normalization process. Hirai and Kano [9] employed an instance-based learning approach based on locally weighted partial least squares to predict metrology values without considering model updating. Despite being effective, such methods are disadvantageous in practice, because they cannot deal with non-linearity effectively or they result in an increase in prediction times.

While the two aforementioned issues, reliability estimation and model updating, have been addressed separately in existing work, combining them into a virtual metrology system would provide a more effective way to improve virtual metrology performance. In this respect, we address these two issues simultaneously in our proposed virtual metrology system, with the aim that the wafer-to-wafer estimation of prediction reliability should be immediately followed by the selective actual metrology for wafers with low reliability, and a subsequent instant model update.

3. Proposed virtual metrology system

3.1. System overview

In this section, we introduce an intelligent virtual metrology system based on adaptive updates, which seeks to minimize the rate of actual metrology while maintaining a high metrology performance. The proposed virtual metrology system consists of two main functions: a *reliability* function and an *update* function. The *reliability* function estimates the reliability of virtual metrology for a wafer. In other words, this function examines whether the current prediction model in the system can predict the target metrology values with a sufficient reliability. A high reliability indicates that the prediction model can reasonably explain such wafers, whereas the prediction model judged to be inadequate for low reliability wafers. Thus, actual metrology is only performed for those wafers that have low reliability. The *update* function adopts the actual metrology data for these low reliability wafers into the prediction model. Through this function, the prediction model is instantly updated when actual metrology is performed. This allows the virtual metrology system to incorporate changes in data characteristics adaptively, thereby

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