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Efficient nanoscale characterization of wafer surfaces using intelligent sampling and Bayesian optimization

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Highlights

- Proposes an iterative sampling method that minimizes the number of samplings required while maintaining high accuracy for reliable attribute estimation of wafer geometrical attributes.
- Introduces novel methods to enhance monitoring and evaluation of surface topography in ultra-precision/nanoscale manufacturing processes, such as ultra-precision machining (UPM) and chemical–mechanical planarization (CMP).
- Develops a process-machine interaction (PMI) model with Bayesian learning for real-time and exception-based anomaly detection in the UPM process, integrating data from heterogeneous sensors (force, vibration, and acoustic emission in situ).
- Presents a multi-scaled multilayer nonlinear decomposition model to quantitatively characterize the CMP process and predict its behaviour.
- Provides insights into the physio-mechanical phenomena underlying both CMP and UPM processes and enables the prediction of nonlinear interactions based on experimentally collected vibration signal patterns.

Abstract

The geometrical attributes of a wafer, such as thickness, uniformity, and local curvature, serve as eminent determinants of its quality. Therefore, measurements that are both rapid and accurate are paramount as multi-stage fabrication processes hinge on them to ensure high product reliability, proper process control, and maximum efficiency. The manual wafer profiling measurement approach in use today is, unfortunately, a time-consuming process. This creates a need for fast and prompt analysis of wafer attributes. This research thus proposes an iterative sampling method that boasts reducing the number of samplings down to a minimum without the need to discard a sufficient level of accuracy for the purpose of reliable attribute estimation. Subsequently, we suggest a series of methods to improve the monitoring and evaluation of the surface topography, all within the context of ultra-precision/nanoscale manufacturing processes, such as ultra-precision machining (UPM) and chemical–mechanical planarization (CMP). For the purpose of both real-time and exception-based detection of anomalies in the UPM process, we constructed a process-machine interaction (PMI) model with Bayesian learning, which amalgamates the received data across heterogeneous sensors such as force, vibration, and acoustic emission in situ. Similarly, the CMP process is quantitatively characterized by a multi-scaled multilayer nonlinear decomposition model with predictive capabilities. This model helps understand the physio-mechanical phenomena underlying both CMP and the UPM processes and describe and predict the nonlinear interactions, as evidenced by the experimentally collected vibration signal patterns.

Introduction

The architecture of semiconductors is a key parameter employed in semiconductor production to assess chip cleanliness. The characteristics, for instance, will be utilized for calculating qualitative factors, like Total Thin Variability (TTV), Bow, and Bend, which are set by Semiconductors Equipment and Metals Internationally (SEMI) as commercial norms.

In addition to being utilized for ultimate chip item standard measurements, such factors are also employed throughout manufacturing to determine the underlying source of superficial flaws.

Furthermore, according to [1], semiconductor mathematical profiling is modeled toward the best possible process parameter designing in semiconductor production procedures. This necessitates prompt interactive monitoring of semiconductor geometrical profiling.

Wafer geometrical profiling measurements must be obtained fast and with sufficient precision to enable efficient operational monitoring of semiconductor production operations. Nevertheless, the present measurement process takes a long period and cannot deliver wafer profiling data quickly.

One average sample of transistors (400 plates in a single manufacturing cycle), for instance, requires over 8 h for taking measurements with the currently available wafer measuring devices such as contacting probing type detectors. The use of sophisticated procedure evaluation and diagnostic technology for qualitative enhancement is hindered by tedious evaluation.

So, the goal of our study is to provide an organized and effective measuring technique capable of shortening the estimation period using consecutive samples and modeling. In our research, we recommend reducing the compound indices, an effectiveness development metric. It depends upon the estimated sampling sizes and timings of modeling fixtures, due to the restrictions of measuring the evaluation duration on an actual sensing framework: $Comp.\,Index = \tau \frac{n_{total}}{\max(n_{total})} + (1-\tau)\frac{I_{total}}{\max(I_{total})}$ where, $\max(n_{total})$ and $\max(I_{total})$ represent the highest regarding the aggregate sampling magnitude and whole instances of simulation fixtures for a group of chips, which serves to normalize the impacts regarding sampling dimension along with several simulation fixtures. While n_{total} indicates the overall sampling magnitude determined for a chip, I_{total} is the overall duration of simulation fixtures within the sampling tactics, τ represents the balancing factor for assessing the evaluation moment for every location and computing duration. We conclude that the measuring technique is more efficient and achieves similar precision using a lesser compound rating.

High-resolution specimens of every wafer are examined as geometrical characteristics during the wafer fabrication procedures. In research, there exist various approaches to simulating geometrical patterns from various angles. Based on a technical viewpoint, geometrical patterns are modeled using practical mathematical approaches, including fractional differentiation equations or boundary component modeling [2].

Such techniques' primary drawback is their capacity to necessitate a deep comprehension of characteristic development. Another drawback is that such techniques are typically employed for predictable profiles, which means they can't be very good at simulating the unpredictability of profiling faults or randomized field impacts. Other strategies, like those in graphics programs, describe the profiling information using wavelet-based research or smoothing. The majority of time, when modeling an identity, the possible influences on its form or attributes are overlooked.

Various measuring procedures are employed by assigning the specimens in a sequence according to previous knowledge. In the ideal detector selection or distribution issue, one class of techniques is frequently employed. In computerized examinations (CEs), a different kind of strategy develops.

To maximize the data flow in the optimum detector choice or assignment issue, sensor position is determined using probabilistic estimates depending upon previous observations. Employing mathematical estimation using the Sequencing Monte Carlo (SMC) approach when evaluating a precise prior dispersion is impossible.

Engineering applications and complex analytical problems have demonstrated the SMC technique's potent capacity to address them. In monitoring targets and geo-location uses, the ideal sensory choosing and fusing problem has been set out by using the Bayesian SMC technique. Anyway, such approaches are typically computationally demanding for subsequent computations, and their effectiveness is dependent on the correct descriptive type that represents the Bayesian theory.

Another established sampling strategy for determining the ideal source involves the sequencing approach using CE. Reducing the number of trial repetitions to get the optimum solution, and the lowest or highest response—is one of the few goals of sequencing planning. To rapidly attain the smallest size of the examined area, an ordered measuring layout technique is suggested to progressively allocate additional sampled spots at the sites having greater estimated improvements (EI). According to their research, sites that have a bigger anticipated variation or a lower anticipated significance for the minimizing problem are considered to have more estimated improvements.

Further GP-based sequencing sample research concentrates on ways to test progressively to acquire improved model attachment, dependent on a different set of sample phases, in addition to minimizing the number of testing cycles necessary for getting the ideal answer. Typically, Markov Chain Monte Carlo (MCMC) is used for getting such designs using the subsequent probabilities. There are several consecutive sample problems depending on frugal criteria. Few researchers demonstrate how specific consecutive implementations have been in estimating stable optimum solutions.

By resolving a series of optimization issues, sequencing layouts, and optimum sampled strategies, thee offer a practical means of lowering the specimen length. Others, meanwhile, might not be appropriate for continual measuring activities, while others could have computational restrictions. The positions that have greater local variation throughout every system have no direct connections with sampling places considered for matrix length estimation.

Furthermore, certain approaches to sequence planning focus on optimization goals rather than online monitoring. Additionally, a computationally demanding optimizing process is used in the majority of current sampled methods and consecutive measures to identify new specimens.

Section snippets

Literature review

The significance of measurement rises as electronics get progressively more 3-dimensional in design. For instance, evaluation or characterization may be required for over 50% of the production processes for certain items. Additionally, we grow close to the time when it may be necessary to determine the form as well as the location of every atom inside a three-dimensional system.

Now it happens in a setting where every semiconductor needs billions of such components, most of which have certain …

Sequence measuring technique

Fig. 1 depicts the suggested sequence measuring method's architecture. All measuring sites using the suggested technique are chosen based on sampled experimental probabilities. The calculated probabilistic density functions assessed at distinct prospective measuring sites represent the experimental probabilities. Using the engineering expertise to be a starting point, the successive measuring technique samples a real-world dispersion before fitting a GP framework using the preliminary …

GP modeling for wafering geometrical profiling

Maximal likelihood estimating (MLE), represented using c, is used throughout the factor estimating process to determine the scaling factor F. After that, b will be determined by plugging F into Calculation (2). By adjustingxin Calculation (2), an anticipated pattern can be produced in this manner. Unidentified variables will get re-estimated as well and succeeding profiles at interesting places will be anticipated using the revised regular kriging algorithm while more examples are obtained in …

Result and discussion

The 71 chips' profiling information will be utilized to assess the successive measuring approach. To generate GP designs, that replicate the measuring process in real life, a portion of the information on every profiling is being chosen using the measuring approach. While the halting criteria are fulfilled, the ultimate GP simulation will forecast the depth at every point in D as well as the overall TTV for every chip. When the precision criterion is met, such estimated data are regarded as …

Conclusion

This paper presents a new approach to nanoscale metrology for wafer surface characterization, based on an intelligent sequential sampling strategy. The method uses Gaussian Process modeling and combines data-driven and domain knowledge-informed sampling distributions, providing accurate estimations with reduced sample size requirements when compared to traditional random sampling techniques. The case study of the approach’s implementation has demonstrated its efficacy due to the substantial …

Ethics Statement

This document is intended for illustrative purposes and does not involve any real human subjects, animals, or ethical issues. ...

Publication Consent

Not applicable, as this does not apply. ...

Ethics Approval

This section is not applicable. ...

Consent Procedure

Informed consent was secured from all participants involved. ...

CRediT authorship contribution statement

Muhammad Shafiq: Data curation, Conceptualization. **Varathan. Saravanan:** Writing – original draft, Validation, Data curation. **Sumanth Ratna Kandavalli:** Writing – review & editing, Writing – original draft, Conceptualization. **Srigitha Surendranath:** Resources, Project administration, Methodology, Conceptualization. **Shalini Soundara Pandian:** Methodology, Investigation, Formal analysis. **Vuda Sreenivasa Rao:** Project administration, Formal analysis. ...

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. ...

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