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Optimal Z-axis Find Algorithm in Ellipsometry Semiconductor Process based on Local Search using Machine Vision

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Abstract

By the latest method, wafers of semiconductors have been sliced very thin for manufacturing efficiency, and the manufacturing process of stacking various thin films has been used. In order to measure such a thin film during the semiconductor manufacturing process, an Ellipsometer, a non-destructive optical device, is used. Ellipsometer analyzes the thin film by checking the change in the polarization state of the incident light after the light irradiated to the wafer surface is reflected from the incident surface. However, thinly sliced wafers are often bent during the manufacturing process, so in industrial sites Therefore, it was difficult to efficiently measure the thin film by maintaining an accurate optical state. Accordingly, this study analyzed data based on the image of Machine Vision and compared algorithms that efficiently enable precise measurement on vented wafers by using it and changing the Z axis. Thus, we propose a focusing optimizing algorithm based on machine vision image processing and evaluate the data and features to support it, and we open data sets and algorithm codes that can prove this process in GitHub repository\textsuperscript{1}. In addition, the efficiency of these algorithms was interpreted through simulation figures, and through this, an optical system capable of precise measurement applying a method of efficiently moving the Z-axis is proposed.

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1. Introduction

During the semiconductor manufacturing process, thin films are used for various purposes. The oxide film formed on the silicon surface protects silicon from impurities generated during the process, and the photosensitive agent (PR) forms a pattern using a developer after becoming a Global search’s Local search conversion algorithm to find the optimal Z-axis of the Ellipsometer in the surface semiconductor process.

\textsuperscript{1} All data and code available at http://www.github.com/objective0923/MobiSPC_paper_2023

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In order to maximize semiconductor manufacturing and improve quality in the industry, the number of dies in one wafer must be maximized, and the thickness and material of the thin film used must be uniform.

In order to analyze these thin films, an Ellipsometer, an ultra-precision analysis meter that can analyze the surface and thin film structure, physical properties, and mineral properties of materials by measuring changes in the polarization state of light, is used.

Ellipsometer is a non-destructive optical device that can obtain detailed information on the physical properties and structure of the sample in a polarized state of reflected or transmitted light, and the polarized state of light changes sensitively depending on the physical properties and structure of the sample. Therefore, Ellipsometers are widely used in thin film analysis, including measurement of the thickness and density distribution of oxide films in the semiconductor industry.

With an Ellipsometer, a thin film layer, a Roughness layer, an interface layer, and a natural oxide layer corresponding to the film thickness can be measured, and optical constants such as refractive index and absorption coefficient can be measured. In addition, material properties such as composition, microstructure, doping concentration, and uniformity can be measured. The principles of the Ellipsometer are as follows. The polarization change between the incident light and the reflected light occurs due to the phase change and the reflectance difference between the s-polarized light and the p-polarized light. At this time, the measured phase difference between s-polarized light and p-polarized light and the reflection amplitude ratio of s-polarized light and p-polarized light change by wavelength, incident angle, film thickness, and optical integer (composite refractive index, complex dielectric constant), so film thickness, refractive index, and absorption coefficient can be obtained.[1]

However, bending occurs in the process of slicing the wafer thinly. Wafers are manufactured by making silicon columns, or ingots, with high-purity silicon solutions and thinly cutting the bottom of the ingots. At this time, there are two processes for manufacturing ingots: the Czochralski method (CZ method) and the Float-zone method (FZ method). Both processes include the principle that the silicon solution rotates and single crystal silicon (seed) comes into contact with the surface to cool at the interface between the solid single crystal silicon and the liquid silicon solution to form an ingot. As such, wafers are manufactured by rotating and stretching liquid silicon, resulting in stress. Therefore, when the wafer is sliced thin, bending occurs due to this stress.

![Fig. 1: Describe the process of the Ellipsometer of a wafer whose Δh is positive](image)

When measuring the thickness and characteristics of a thin film with an Ellipsometer, artificial intelligence-based data analysis is used because precise measurement is difficult if the thin film is bent.[2] In order to accurately measure the thickness of the thin film reflecting the height of the thin film surface that changes according to the degree of bending of the thin film, the optimal z value is found using the machine vision and the light of the Ellipsometer is irradiated at the corresponding position. Machine vision is a system composed of high-performance cameras, image processors, and software, and provides information that allows image processors and software to perform desired tasks through image processing and analysis according to the purpose of the task. In addition, machine vision has the advantage of being able to process micrometers accurately and quickly.

The optimal z value can be found through a global search as the z value when the machine vision is focused. Global search is a way to check the z value of the entire range with machine vision and the optimal z value, and it has the advantage of increasing accuracy because it checks all ranges, but it has a limitation that it takes relatively much time and money.
Therefore, this study aims to reduce algorithm processing speed and save time and money by finding the optimal z value using a local search that resets and confirms only a certain range after finding the optimal z value through a global search. Local search is a method of using a target function to check neighboring nodes based on the current node and move to a more optimal node.
2. Related Work

Research has been conducted to check the quality of images using machine vision and auto-focusing and to measure thickness using an Ellipsometer.

2.1. Auto-Focusing

Auto-focusing is one of the important technologies to efficiently acquire high-quality images with real-time auto-focus. [3] In order to reduce the focal time, we propose an autofocus algorithm that adjusts the wavelength as a function of focal distance and auto-focuses within 0.9 seconds. As a result of applying it to its own dataset, it was confirmed that the image could be obtained quickly and accurately. In addition, manual focusing is used when the image quality is not optimal in the process of obtaining an image with a biological microscope. At this time, an auto-focusing technique based on Laplace and Fourier algorithms is used to improve the quality of the image. By calculating image-related information, an expression model for the clarity of an image was constructed, and the clarity of a single frame was analyzed and compared to obtain optimal image quality. [4] Cellular logic techniques and new spectral moment autofocus measure were proposed in comparison with these traditional autofocus techniques. [5] [6] In order to improve the image quality of electron microscopes, a single shot auto-focusing technique based on deep learning was proposed. Using a modified MobileNetV3, lightweight network, we predict the distance of Defocus with a single shot microscope image acquired from an arbitrary image plane without auxiliary cameras or additional optics. This not only supports the day-to-day work of pathologists, but also enables real-time and accurate autofocus, which provides potential applications in life sciences, materials research, and industry auto-detection.

[7] We propose neural network-based model predictive control of piezoelectric motion phase for autofocus. This model uses long-term short-term memory units to integrate hysteresis effects and focus measurements into a single learning-based model. To further speed up long-term short-term based model prediction control, an optimized backpropagation algorithm that optimizes the model prediction control cost function is proposed, and experiments demonstrate a reduction of at least 30% for auto-focusing time compared to rule-based auto-focusing techniques and other learning-based methods.

[8] presents a fast out-of-focus detection algorithm for continuously collected electron microscope images and shows that it can be used to provide quality control in near-real-time for neuroscience workflows. The presented multi-scale histological feature detection is based on applying classical computer vision techniques and detecting various fine-grained histological features. We leverage the unique parallelism of the technique to use GPU primitives to accelerate characterization and show that out-of-focus conditions can be detected in just 20 ms. To this end, we demonstrate near real-time use by deploying feature detectors as an on-demand service and showing that they can be used to determine the degree of focus within about 230 ms.

2.2. Machine Vision

Machine learning has been mainly used to analyze fast and accurate optical spectra and images because it can interpret complex data with machine learning. Accordingly, [9] introduced various machine learning algorithms for optical data analysis applied in a wide range of fields and presented the validity of machine learning-based optical data analysis.

The limited field of view and micron-level detection accuracy requirements in mechanical vision inspection of large-diameter aspherical optical components necessarily require sub-piercing scan imaging. The high-precision scan depends on the alignment of the spin axis of the mechanical system and the optical axis of the component, so the component must be centered before scanning. Considering this problem, [10] proposed a high-precision auto-centering method (HPACM) for rotational symmetric aspherical optical elements based on mechanical vision. This HPACM adjusts the two reference points of the optical axis to the mechanical spin axis and uses the pixel coordinates of the cross-hair center extraction algorithm (PCEA) to obtain a cross-hair center trajectory circle during circular motion.
2.3. Ellipsometer

Ellipsometer has been mainly used to measure thin films. [11] presents how an Ellipsometer was developed to measure the thickness of a thin film. Ellipsometer can identify many materials and structures, but it mainly focuses on oxides and photoresists. This method can be used to evaluate multilayer, nanostructure, and composite media. In addition, [11] presented the development of the Ellipsometer. The proposed ellipsometer is a single wavelength Ellipsometer with a fixed angle and provides non-destructive optical technology for measuring oxide thickness, that is, Photoresist thickness, and refractive index at the measurement wavelength. As usual, the Ellipsometer is specifically accurate under a film of 10 nm thickness, reflects from the incident surface, and uses changes in polarization state in the incident light. At this time, the polarization state of light is evaluated by the relative amplitude of the lifetime component and the vertical component and the phase difference between these two components. Optical spectroscopy is essential for research and development in nanoscience and nanotechnology, microelectronics, energy and advanced manufacturing. Advanced optical spectroscopic tools often require both specially designed advanced instrumentation and complex data analysis techniques. In addition to general analytical tools, deep learning methods are well suited for interpreting high-dimensional and complex spectroscopic data. Deep learning offers a great opportunity to extract fine and deep information about the optical properties of materials with simpler optical settings, otherwise sophisticated instrumentation will be required. Accordingly, [12] proposed a computational Ellipsometer measurement approach based on the existing tabletop optical microscope and a deep learning model called EllipsoNet. Without prior knowledge of multilayer substrates, EllipsoNet can predict the complex refractive index of thin films on these non-critical substrates in an experimentally measured optical reflection spectrum with high accuracy. This was not feasible with conventional reflection measurements or Ellipsometer measurements. This approach enables optical characterization in operands of functional materials within complex photonic structures or optoelectronic devices.

As such, the design of the Ellipsometer has been proposed in various ways, and a Return-path Ellipsometry (RPE) has been proposed in [13], which enables reflection-based measurements of both planes and curved surfaces. Mirror-based RPE is not applicable to surface characterization of free-form samples. Therefore, [13] avoids this constraint by using a microsphere-based retroreflector instead of a mirror. The measurement equation of the retroreflection-based RPE is very similar to that of the mirror-based RPE.

2.4. Search algorithms

Global search algorithms and local search algorithms are used to find the optimal z-axis height. Global search algorithms are enumerated approaches to problem solving that generalize computational paradigms such as binary search, backtracking, branching and boundary, heuristic search, and constraint satisfaction. The common structure of global search algorithms is formulated as a theory that provides the basis for design tactics that define how to construct the correct global search algorithm in the given formal specification of the problem. Global search theory initially uses the concept of conditions necessary for the existence of feasible or optimal solutions to describe well-known programming concepts such as incorporating constraints and pruning branches.[14] These global search algorithms are used in various fields. [15] proposes to find the optimal solution using global search algorithms for the problem of optimizing the performance of stochastic systems for a finite set of alternatives in situations where the performance of the system cannot be evaluated analytically but must be estimated or measured by simulation. The principles of the global search algorithm proposed in [15] are as follows. We generate a sequence that takes values from a set of viable alternatives, where each new element of the sequence is generated by comparing the current element with another candidate alternative and making the next element of the sequence one of the current and candidate alternatives that appears to yield better performance. In both versions of the proposed method, it is shown that the elements of the feasible alternative set that the generated sequence most frequently visits converge almost reliably to the global optimal solution of the underlying optimization problem.

As such, global search algorithms have the disadvantage of taking relatively long to execute algorithms because they explore the entire search range. The algorithm used to compensate for these shortcomings is the local search algorithm. Local search algorithms have the advantage of reducing algorithm execution time because they only search a certain range, not global. [16] recently introduced three common heuristics that are widely used. These three heuristics are tutorials on simulation annealing, Tabu search, and genetic algorithms.
3. Main Idea

The technique proposed in this paper aims to efficiently find the location value of the machine vision for Elipsometor by applying a local search interval tracking algorithm based on the optimal value of the machine vision obtained through global search in the early stages. The process is as follows. Contrast analysis is performed on the image data obtained after dividing the video data extracted from the point of the wafer into frame units. Contrast analysis goes through the following process.

3.1. Contrast Analysis Method

The histogram of an image means representing the distribution of pixel values of an image in a graph form. In the case of grayscale images, the histogram can be obtained by obtaining the number of pixels corresponding to each grayscale value and expressing it in the form of a bar graph. Machine vision image analysis conducted in this study is carried out after converting the image to a gray scale, so a graph is drawn only with black and white light, but a histogram can also be obtained by calculating the number of pixels according to the combination of three color components (RGB).

The comparison of image histograms of blurred frames and clear frames from image data extracted from video data is as follows.

![Out of focus image frames and image histograms](Image1)

![Focus image frames and image histograms](Image2)

Considering that the same image file was taken with machine vision through fine-tuning of the Z-axis, it can be seen that the size is the same if the two graphs are actually integrated. (Some errors will occur during the fine adjustment process.) In other words, it is possible to measure the sharpness of the corresponding image according to how many different shades the image represents the same object. In conclusion, by taking different image histograms even when measuring the same object, we find the clearest frame of video data through the dispersion of the graph.
3.2. Local search algorithm

If the optimal Z value was obtained through the above global search technique at the initial wafer point, the optimal Z value can be obtained through local search without global search at the next wafer point.[17]

The pseudocode of the local search algorithm is as follows.

```
Input : Wafer with k points specified
Output : Optimal Z value by point

for each wafer point k do
  if k = 1 :
    do global search algorithm
    Derive optimal Z1 value
    Move to Δ H1 position
    Local search algorithm -> ± Δ H2 prediction
  else :
    for i in range k
      do local search algorithm (t = deltaH ± H1)
      Derive the best each Z1 value
      Move to Z1 position
      Local search algorithm -> ± Δ H1±H1 prediction
  end
end
```

Fig. 5: Local search algorithm

In this way, the local search algorithm works, and the temporal benefits that will be obtained from it are mentioned in the next section.

4. Verification

The total time required by the global search algorithm and the local search algorithm may be expressed as follows.

\[
\int_0^h (t_z + t_{cap} + t_{cont}) \, dh + t_m \times (P - 1) + \int_0^h (t_z + t_{cap} + t_{cont}) \, dh \\
\int_0^h (t_z + t_{cap} + t_{cont}) \, dh + (\int_0^{h'} (t_z + t_{cap} + t_{cont}) \, dh + t_m) \times (P - 1)
\]

Each variable used in the above equation is as follows.

\[
h = \text{Global search z-axis movement height} \\
h' = \text{Local search z-axis movement height} \\
P = \text{Number of points} \\
t_z = \text{One frame travel time} \\
t_{cap} = \text{One frame capture time}
\]
\( t_{\text{cont}} = \text{One frame contrast measurement time} \)
\( t_m = \text{Travel time to next point (x, y axis travel time)} \)

In order to verify the efficiency of conversion with the local search algorithm of the global search algorithm proposed by this study, the total time required for conversion to the local search algorithm was compared. If the total time required when using the global search algorithm is longer than the total time required when using the local search algorithm, the efficiency of the algorithm proposed by this study can be verified.

Global Search Algorithm Total Time ≥ Local Search Algorithm Total Time

\[
\begin{align*}
\int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh + t_m \times (P - 1) + \int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh > \\
\int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh + (\int_0^{h'} (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh + t_m \times (P - 1)) \\
= (\int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh) \times (P - 1) > \int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh \times (P - 1) \\
= (\int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh \times (P - 1) - \int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh \times (P - 1) > 0 \\
= (\int_0^h (t_z + t_{\text{cap}} + t_{\text{cont}}) \, dh \times (P - 1) - (t_z + t_{\text{cap}} + t_{\text{cont}})(h - 0) - (t_z + t_{\text{cap}} + t_{\text{cont}})(h - 0') > 0 \\
= (P - 1)(t_z + t_{\text{cap}} + t_{\text{cont}}) (h - h') > 0 \Rightarrow P - 1 > 0, \; t_z + t_{\text{cap}} + t_{\text{cont}} > 0, \; h > h' \\
\end{align*}
\]

As a result of verifying through the above formula, the sum of \( P \) (number of points)-1, one frame travel time, capture time, and contrast measurement time is always positive, and the total time of the global search algorithm is longer than the total time of the local search algorithm.

At this time, I would like to express the temporal benefits obtained by using the local search algorithm as a formula. The time difference in two cases can be obtained by subtracting the total time required for the local search algorithm from the total time required for the global search algorithm, and the value is the time benefit.

In other words, the time gain from using the local search algorithm is obtained by \( t_z \), which is the total time required for the global algorithm - the total for the local search algorithm.

For verification, set each variable \( t_z = 2s, t_{\text{cap}} = 0.1s, t_{\text{cont}} = 0.05s \), and \( t_m = 2s \). Assuming that the image provided as a dataset has \( h = 615 \) images per measurement point \( P = 11 \) and that \( dh = 100 \) are made using the local search algorithm after the first measurement point, the time required when using the existing global search algorithm and the local search algorithm when using , the time required improves performance as follows.

\[
\begin{align*}
\frac{(t_z + t_{\text{cap}} + t_{\text{cont}}) hP + t_m (P - 1) - (t_z + t_{\text{cap}} + t_{\text{cont}}) h + (t_z + t_{\text{cap}} + t_{\text{cont}}) \int_0^{10} h'dh'}{(t_z + t_{\text{cap}} + t_{\text{cont}}) hP + t_m (P - 1)} \times 100 \\
\frac{2.15 \times 11 \times 615 - 2.15 \times 615 - 2.15 \times (100 \times 10)}{23.65 \times 615 + 20} \times 100 = 76.02 \\
\end{align*}
\]

The time reduction rate when using the local search algorithm compared to when using the global search algorithm calculated through the above process is 76.02%, indicating that a significant time gain can be obtained.
5. Conclusion

This paper improved the previously implemented global search algorithm for the difference in height between the bending of wafers and the resulting height. The temporal gains that will be obtained through the local search algorithm proposed in this paper are as follows.

\[ t_s = (P - 1) \left( t_z + t_{cap} + t_{cont} \right) (h - h') \]

Therefore, measuring the thickness of a wafer thin film bent with an Ellipsometer using a local search algorithm can maintain a precise optical state and at the same time gain time than using a global search algorithm. Since we have verified the existence of temporal gains, the efficiency of the semiconductor manufacturing process can be increased by using the converted local search algorithm for wafer thin film thickness measurement in future industrial sites.

Through this study, we proved that using the local search algorithm to find the optimal z-axis of the ellipsometer for measuring the bent wafer can obtain a time advantage over using the global search algorithm. In the future, we plan to continue research on finding the z-axis of the ellipsometer to measure the vented wafer through optimizing the z-axis using deep learning for optimizing the local search algorithm.

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