Non-Destructive Metrology Techniques for Measuring Hole Profile in DRAM Storage Node

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ABSTRACT

DRAM storage node profile measurement during high aspect ratio (HAR) etch has been one of the most challenging metrology steps. DRAM storage node profile affects refresh time and device electric quality. So, controlling this profile is one of the key challenges. Conventional 3D modeling in Optical Critical Dimension (OCD) metrology has typically used multiple cylinder stacks. This method cannot provide an accurate model and computed spectrum through the RCWA engine. This means we need a more accurate model. In this paper, we used hyper-profile to accurately measure a hole profile for better process control. Hyper-profile uses a polynomial to describe the smooth shape of a hole profile, which is much closer to the real product and provides a more accurate computed spectrum. With hyper-profile, a continuous storage node hole profile and managed CD correlation are achieved. It can maintain the same profile complexity with less degree of freedom, reducing the model uncertainty and ensuring more robust regression. On the other hand, as the metrology error budget becomes stricter and the process variation cycle is increasing, the OCD based model-guided machine learning (MGML) approach can provide a faster solution turnaround time with more accurate measurements than either pure OCD or pure ML approaches. It also can better decorrelate profile CDs and achieve more robust profile monitoring. In this paper, we will demonstrate the above benefits of hyper-profile and MGML in the DRAM storage node application.

Keywords: Metrology, Non-destructive, Ellipsometric spectroscopy, 3D profile metrology

1. INTRODUCTION

The etching hole profile in DRAM storage node has been one of the most challenging metrology steps. The hole profile affects refresh time and device electric quality. So, controlling this profile is one of the key challenges. Conventional 3D modeling in Optical Critical Dimension (OCD) metrology has typically used multiple cylinder stacks for a hole having HAR type. This method cannot provide an accurate model and computed spectrum through the RCWA engine. This means we need a more accurate model. In this paper, we used hyper profile to accurately measure a hole profile for better process control. Hyper profile uses a polynomial[1] to describe the smooth shape of a hole profile. Together with hyper profile, we used MGML(Model guided machine learning which is the hybrid method using both physical modeling approach and machine learning approach) which is the innovative analysis feature for OCD metrology. As the metrology error budget becomes stricter and the process variation cycle is increasing, MGML can provide a faster solution turnaround time with more accurate measurements than either pure OCD or pure ML approaches. It also can better decorrelate profile CDs and achieve more robust profile monitoring. In this paper, we will demonstrate the above benefits of hyper profile and MGML in the DRAM storage node application.

2. EXPERIMENTAL PARAMETERS

For data collection, we collected on Onto Atlas® platform and used spectroscopic ellipsometer. Based on the experimental spectrum and the below analytic configurations, we created 3D OCD model which shows process coverage. The measurement angle is set as the angle which is parallel with bit line. On RCWA configurations[2], X & Y harmonic oscillators are used with order truncation factor. Also, bandwidth is used.

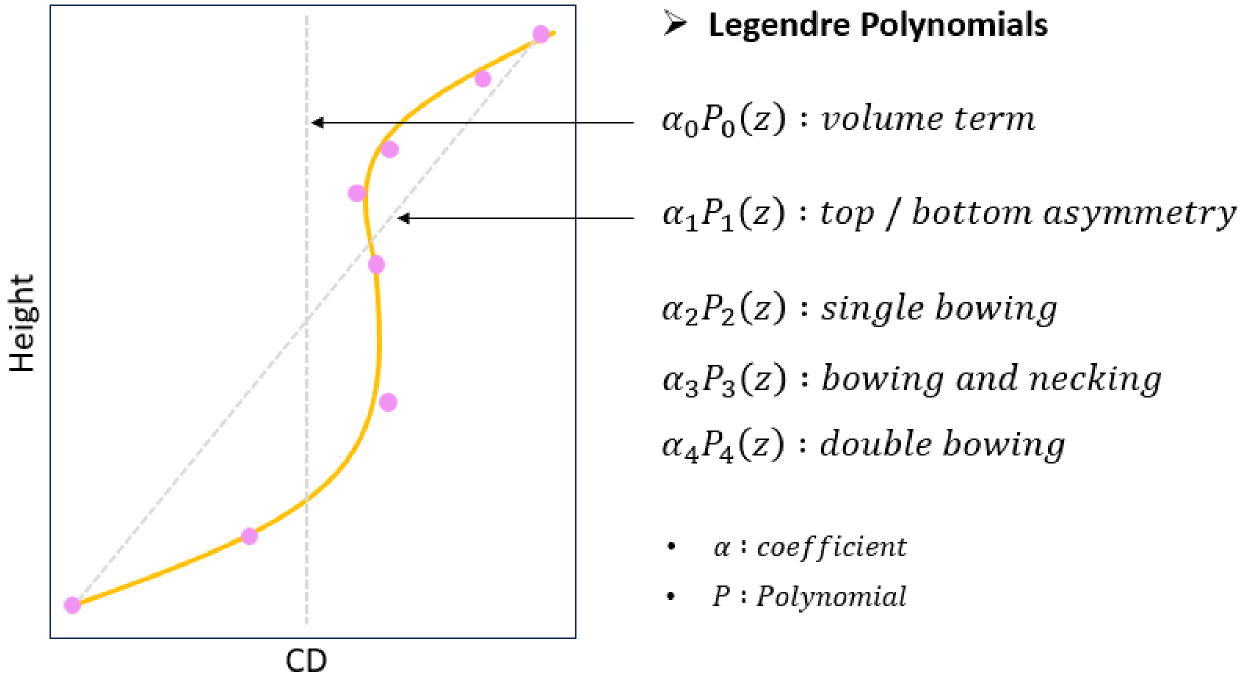

Figure 1. Physical meaning demonstration of hyper profile coefficients

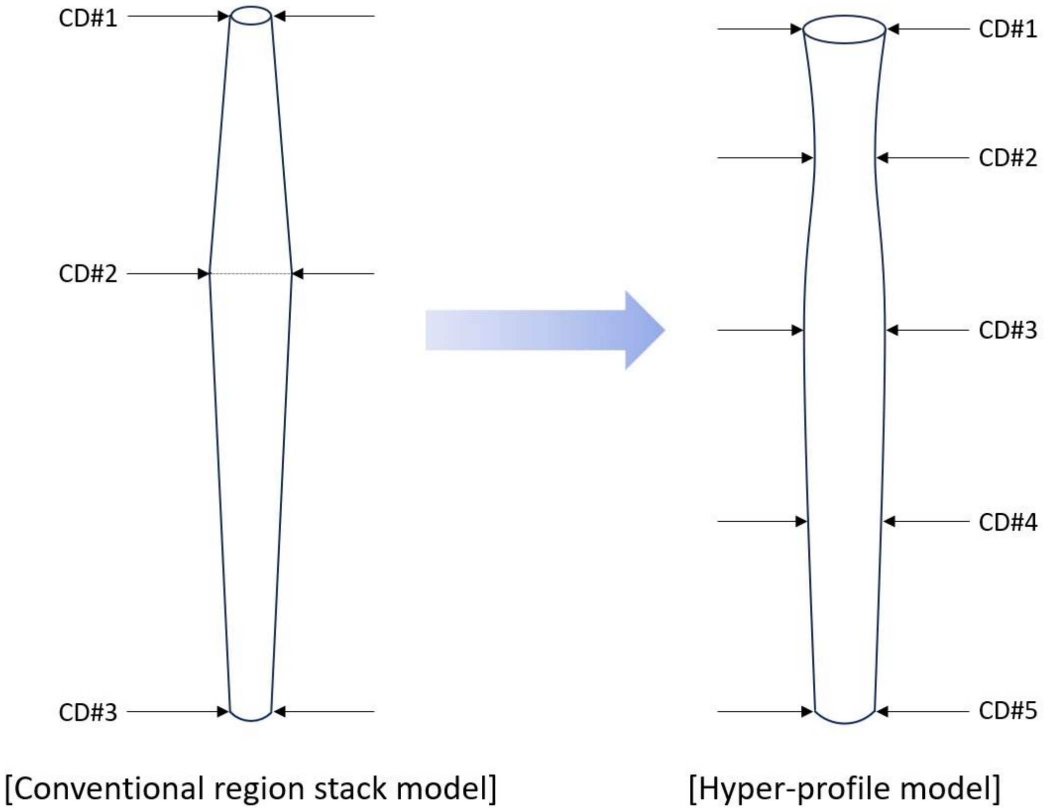

Figure 2. Improved 3D modeling capability in HAR structure by using hyper profile feature.

In pseudo-OCD model, there are 9 floating parameters, shown in Figure 3. silicon trench’s top and bottom height (■ gray region), bit line CD (■ pink color), contact height (■ carrot color), three critical thickness (P3, P4 and P5) and two hyper profile parameters to describe the hole profile. These parameters are used for covering the incoming process variations. By floating these 9 parameters, the model is stable and can provide good fitting quality, as shown in Figure 4, with MSE from 0.5 to 0.8 across POR wafer.

Before using hyper profile, we have been used cylinder stacks for etching holes. This conventional method shows poor fitting quality because the model is not accurate. This affects process monitoring performance with the low GOF(Good of fitness) which means high MSE between experimental spectrum and RCWA-engine-calculated spectrum. However, when we use hyper profile, we can fit the model to experimental spectrum well with small MSE. This improves confidence interval much smaller than the result using the conventional method we have used. With smaller MSE, we can improve TTTM (Tool to tool matching), too. Every single tool shows slightly different spectrum by HW manufacturing tolerances but if we have a model with good MSE, we can improve TTTM performance with small MSE. So, small MSE is critical item in OCD modeling.

The next stage is to use model guided machine learning method (MGML). MGML helps break parameter correlations among floating parameters. If we use the conventional method, we only see 2 or 3 parameters to be monitored. However, We have 5 CDs to monitor and MGML makes it possible to monitor multiple parameter metrology. In this manuscript, we show the result about monitoring 5 parameters.

Figure 3. Pseudo OCD model[3] and Definition of floating parameters (P1 : Btm STI Height, P2 : Top STI Height, P3 : BL CD, P4 : Contact Height, P5 : Top Ox Thickness, P6 : Btm Mask Thickness, P7 : Top Mask Thickness, P8 : Hyper Profile P0, P9 Hyper Profile P3)

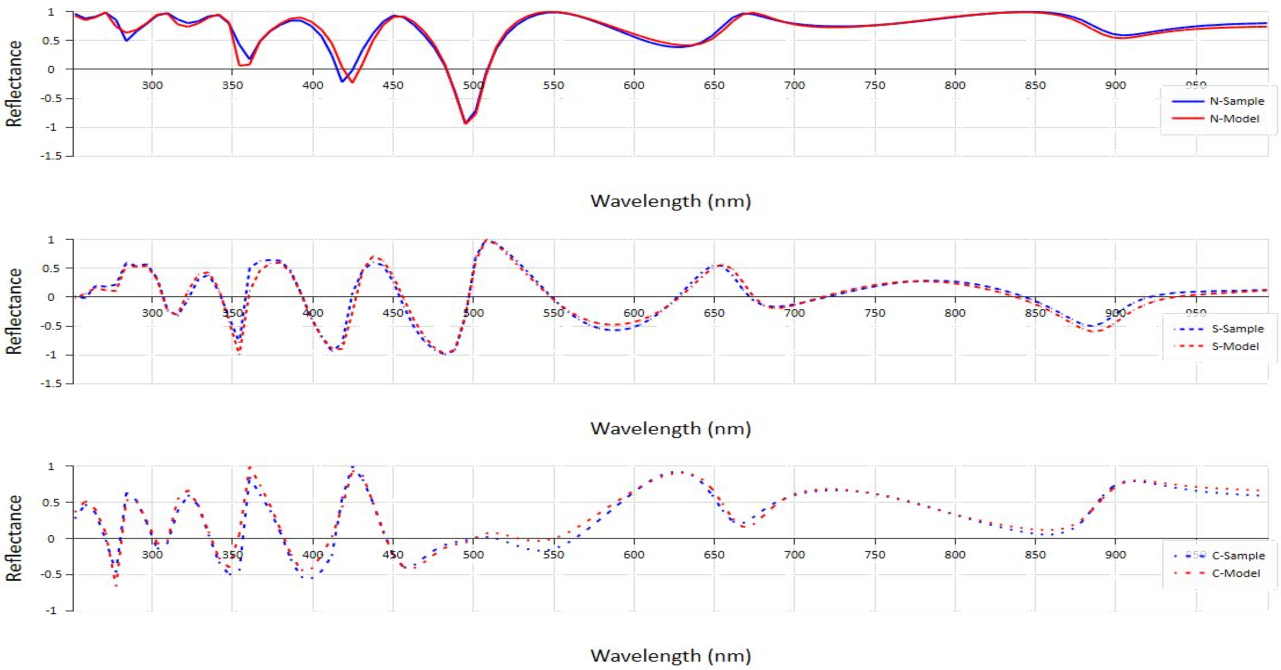

Figure 4.Fitting quality for NCS

3. RESULTS

Here RMSE result for the blind test is presented in Figure 5. Each of the five columns groups represent different CDs. Different colors represent different results: 🟪Pink is for blind test results from competitor's ML solution. 🟦Sky blue is blind test results from OCD model with MGML and hyper profile.

Our OCD model results from recipe setup can reach a typical 0.9 Rsq, 0.9 to 1.1 slope, and minimum level of intercepts. Blind tests is important to prove the recipe performance. Here, ML solution marked as 🟪Pink color from blind test result has large RMSE. This is indicating baseline shift and model disqualify, which is unacceptable for production metrology recipes in high volume manufacturing (HVM). On the other hand, our OCD model results have balanced Rsq, slope, intercept and much smaller RMSE.

Tool to tool matching (TTTM) for our OCD model results for 6 tools are presented in Figure 6 indicating strong robustness of our solution on all CDs. Typically, the level of below 0.2nm is a challenging requirement, and all CDs and all tools are qualified. This implies the dynamic precision 1sigma is around 0.1nm level. Here static/dynamic precision is not characterized, as TTTM is an alternative metric.

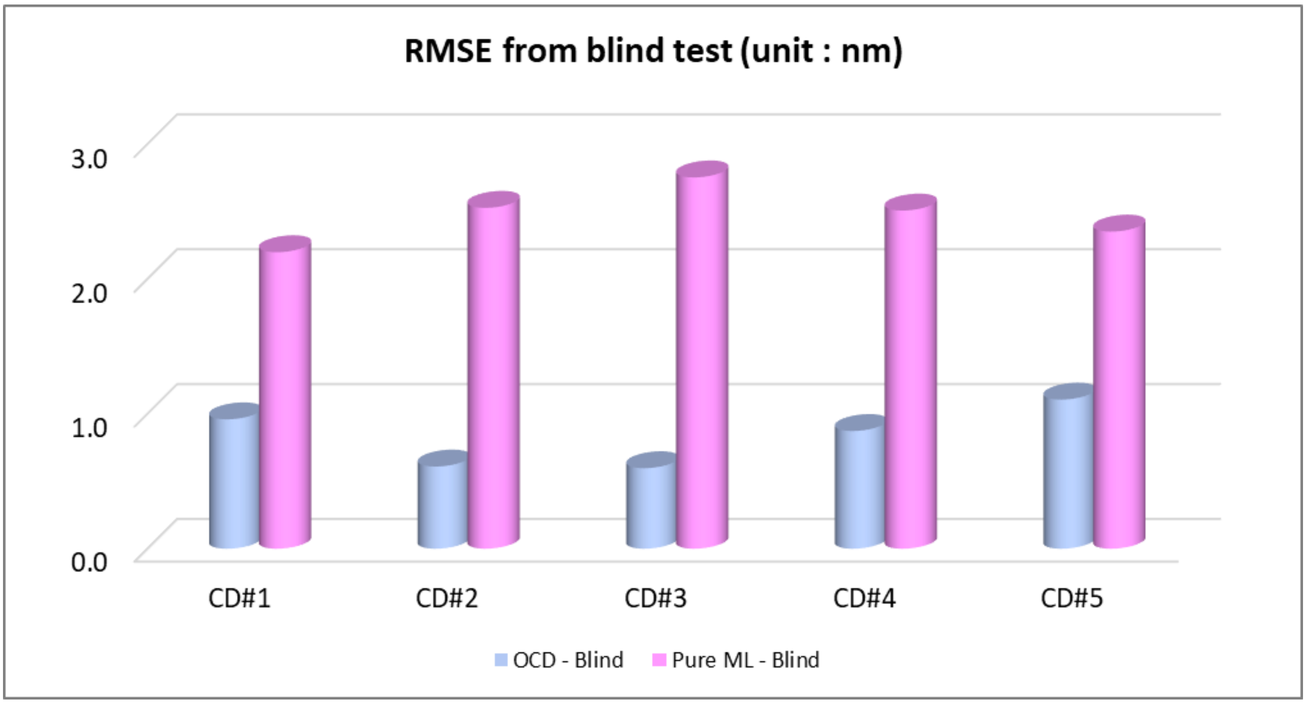

Figure 5. 5CD Blind Test Result based on reference correlation analysis.

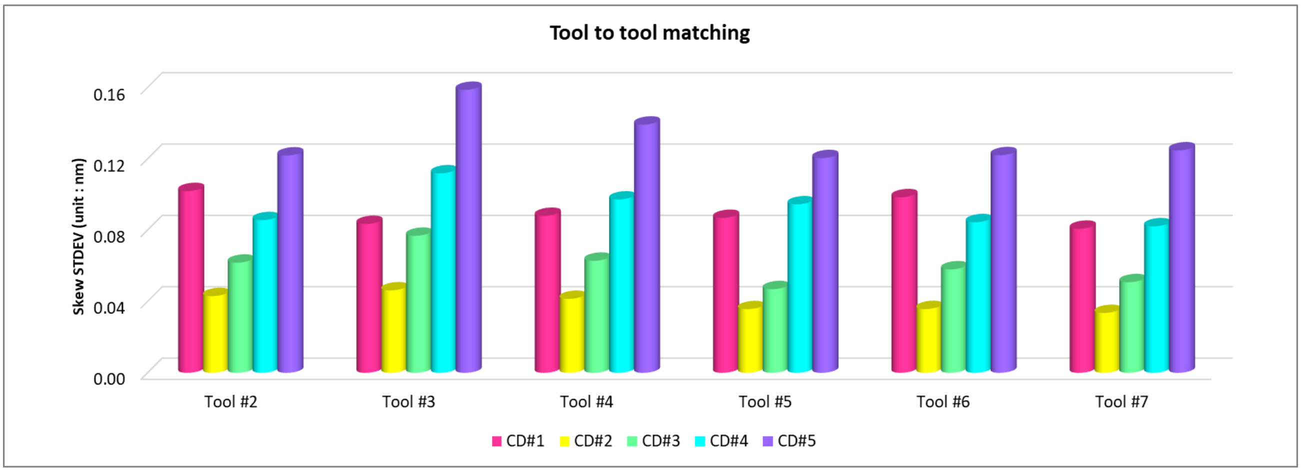

Figure 6. Tool to tool matching result

4. ANALYSIS

4.1 Hyper profile:

For OCD models with HAR profile, hyper profile is an elegant mathematical constrain. Compared to ordinary stacking region model approach, it can provide smooth profiles with high fidelity, leading to more accurate computed spectra, which is closer to experiment. Therefore, it can achieve much better fitting quality across full wafers, leading to more stable models. Meanwhile, the time to solution is greatly improved because of the design and ease of use of hyper profile. Also, it can monitor more CDs, extract more process related information from spectra. In comparison, the conventional region stack OCD model can hardly float more than 2 CDs. When complicated recipe coupling schemes were applied, (e.g. sequential fitting, super recipes, scripting, and etc) developing and sustaining becomes extremely ineffective.

4.2 MGML:

Model Guided Machine Learning can help break correlation between CDs. Out of our expectation, inline stability and recipe survival time is better than the conventional OCD model alone with hyper profile. The time to solution advantage also makes recipe development as well as maintenance smooth. MGML, coupled with hyper profile, also shows high quality of tool to tool matching as we have seen in the data through reducing MSE and parameter correlations.

5. CONCLUSION

The storage node module in the DRAM manufacturing process has HAR dielectric etching process that has been challenging layer because making an accurate model and breaking parameter correlations have been difficult. So, there was no durable robust in-line non-destructive process control solution. This process step to control etching hole profile is challenging for current metrology solutions because the structures are HAR structure and show low contrast between oxide and air. A novel approach with hyper profile and model guided machine learning is presented that can be used by Onto Atlas® platform to improve recipe accuracy, process coverage and robustness to the key parameters. Using this method, we have proven the stability with durable accuracy with small TTTM budget.

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