Complex metrology on 3D structures using multi-channel OCD

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ABSTRACT

Device scaling has not only driven the use of measurements on more complex structures, in terms of geometry, materials, and tighter ground rules, but also the need to move away from non-patterned measurement sites to patterned ones. This is especially of concern for very thin film layers that have a high thickness dependence on structure geometry or wafer pattern factor. Although 2-dimensional (2D) sites are often found to be sufficient for process monitoring and control of very thin films, sometimes 3D sites are required to further simulate structures within the device. The measurement of film thicknesses only a few atoms thick on complex 3D sites, however, are very challenging. Apart from measuring thin films on 3D sites, there is also a critical need to measure parameters on 3D sites, which are weak and less sensitive for OCD (Optical Critical Dimension) metrology, with high accuracy and precision. Thus, state-of-the-art methods are needed to address such metrology challenges. This work introduces the concept of Enhanced OCD which uses various methods to improve the sensitivity and reduce correlations for weak parameters in a complex measurement. This work also describes how more channels of information, when used correctly, can improve the precision and accuracy of weak, non-sensitive or complex parameters of interest.

Keywords: OCD, Scatterometry, Enhanced OCD, XPS, high-K, 3D, Proximity, TMU

1. INTRODUCTION

The transition of thin film thickness measurement from solid sites to more complex multi-dimensional structures is required due to the frequent inability of solid site thicknesses to properly track those of patterned or device sites leading to defectivity issues and yield loss. Thus, the transition away from such non-patterned sites can become more of a necessity than of preference. Although 2-dimensional (2D) sites often are found sufficient for process monitoring and control of very thin film thickness, sometimes 3D sites are needed especially for FinFET processing. The measurement of film thicknesses only a few atoms thick on complex 3D sites, however, is very challenging. Apart from measuring thin films on 3D sites, there is also a critical need for high accuracy and precise measurements of parameters on 3D sites which are weak and less sensitive for OCD (Optical Critical Dimension) metrology.

The OCD metrology, or Scatterometry, is a non-destructive optical technique for measuring detailed profile information on patterned structures[1, 2]. Important device characteristics are controlled by such parameters and confidence in the metrology read-out is of utmost importance. Thus, state-of-the-art, and new methods are needed to address such metrology challenges. This work introduces the concept of Enhanced OCD which uses various methods to improve the sensitivity and reduce correlations for weak parameters in a complex measurement. Three items in a toolbox which could be utilized to generate an Enhanced OCD solution could include but not limited to optical channel weighting/optimization, hybrid metrology, virtual metrology, machine learning, and algorithmic approaches which are utilized to aide in the choosing of items to generate an optimum solution. Improving standard OCD technique to provide improved accuracy and sensitivity for critical measurements of fine details of complex 3D structures by utilizing items in the tool box results in an Enhanced OCD solution. The concept of Enhanced OCD and various tools in a tool box are shown in Figure 1. In this paper we describe the methodology and detail the results that demonstrate the improvement of using the new channels of OCD information on 3D structures.

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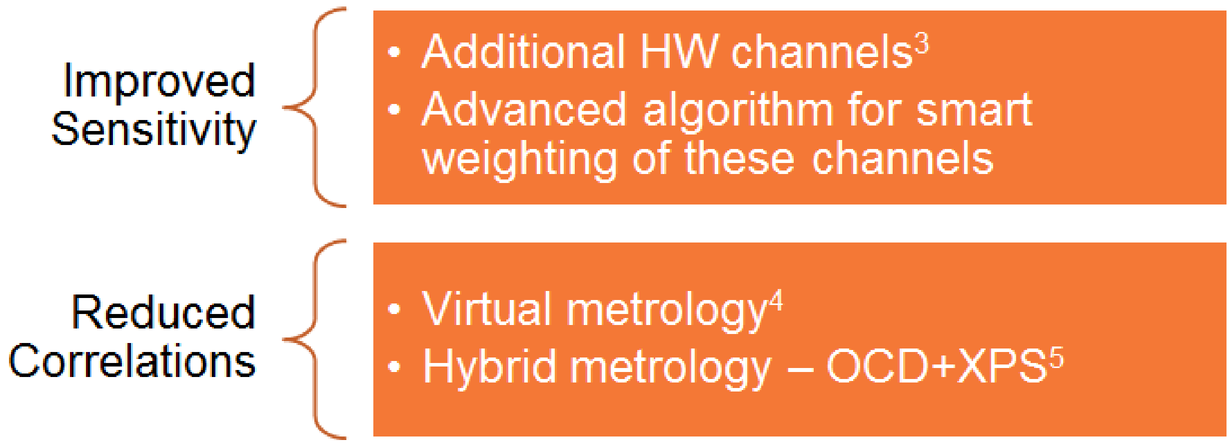


Figure 1. Concept of Enhanced OCD showing which tools can improve different challenges in a complex OCD measurement.

2. EXPERIMENTAL

For this work, three different applications were selected to show the improvements seen from Enhanced OCD when compared to a standard OCD solution. These applications were selected because the parameters measured at these process steps have a direct impact on critical device parameters, which in turn defines the performance and yield of the device. Each application has parameters which have been historically challenging to be measured due to lack of sensitivity or high correlation with parameters. By using tools like additional hardware channels and an advanced algorithm to down select the correct channels to be used, we have shown that the measurement quality is improved tremendously. In addition, choosing the best combination of channels is important because having too much data can increase the time to solution as well as impact the throughput of the measurement. In some cases, apart from lack of sensitivity for a given parameter, there is also a lot of correlation from other parameters. In this case, more tools are required for Enhanced OCD, to reduce these correlations. For such cases, virtual metrology which leverages machine learning from a reference plays an important role to boost the measurement quality. There was a DOE (Design of Experiment) performed for each application to intentionally vary the parameter of interest. Results from standard and Enhanced OCD were compared with reference and measurement quality was analyzed.

3. RESULTS AND DISCUSSION

In this section we will discuss the results for three separate applications and show that the measurement quality improves drastically when we use various tools for Enhanced OCD.

3.1 Metal Gate Measurement

Planarized metal gate 3D structure is presented in Figure 2. Critical parameters such as gate height and CD (critical dimension) are measured as they impact device performance characteristics such as C_{eff} (effective capacitance) and V_t (transistor threshold voltage). Traditional metrology approaches commonly measure Gate height but often experience challenges with providing a stable measurement of gate CD. In this work, we have evaluated additional channels and utilized an advanced algorithm to select the most sensitive and useful channels for the measurement. By using these tools we can provide improved measurement performance.

A three wafer DOE was performed to artificially vary the gate height parameter. Compiling the optimum analysis channels into an Enhanced OCD analysis technique provided expected DOE trends for gate height as demonstrated in Figure 3. Also, CD measurements were observed to track well with TEM analysis as demonstrated in Figure 4.

Optimization of optical channels and information provided improvement in accuracy, precision, and parameter range over standard OCD for measurements of gate dimensions as demonstrated in Figure 5. The accuracy component measures the improvements seen in slope, R^2 and TMU (Total Measurement Uncertainty) when compared to the reference.

The TMU analysis has been discussed in great detail by Sendelbach et al.[6]. This is an analysis technique that uses Mandel regression to measure accuracy compared to reference. Main component of the analysis is the incorporation of the measurement error coming from the reference itself. This provides a better metric to quantify accuracy of a measurement when compared to the simple R^2 results.

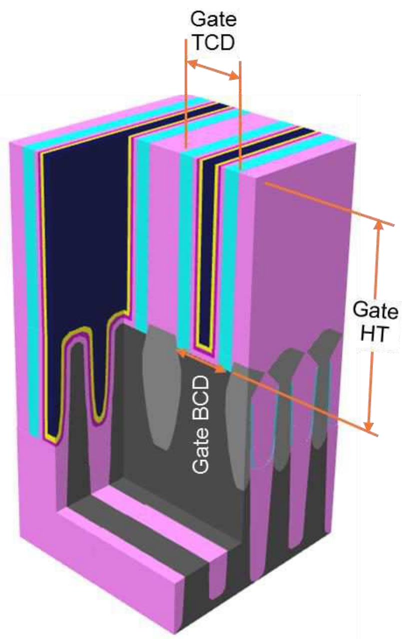


Figure 2. Schematic for 3D structure of planarized metal gate with detail of measurements which impact key device parameters.

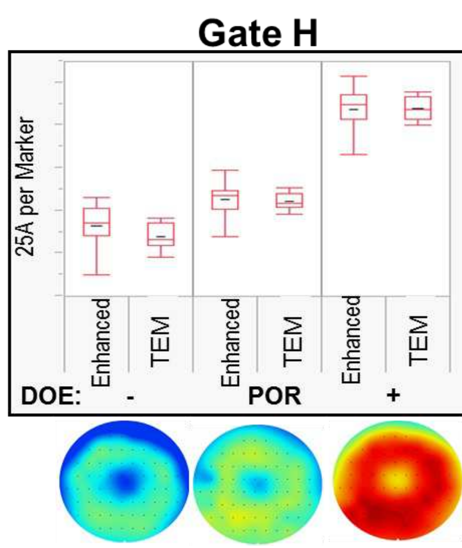


Figure 3. Gate height results from analysis of 3 wafer DOE demonstrating that Enhanced OCD full wafer map analysis matches trends of select sites evaluated by TEM. Wafer maps of Enhanced OCD results provided expected trends.

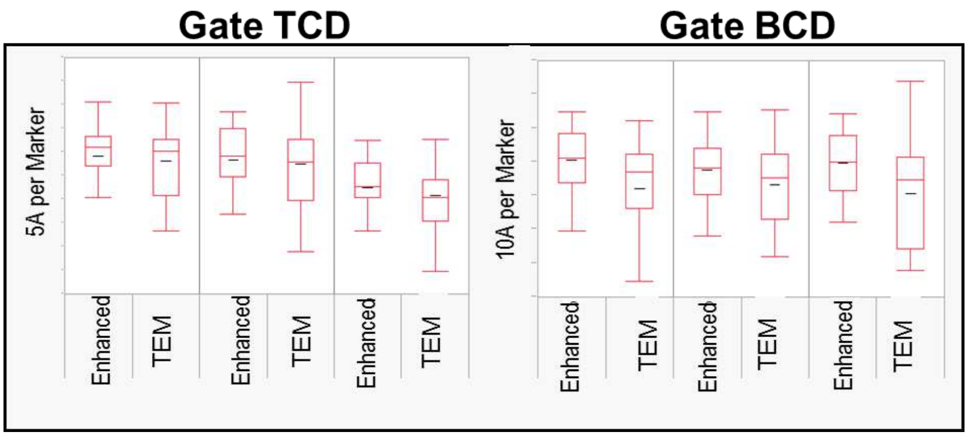
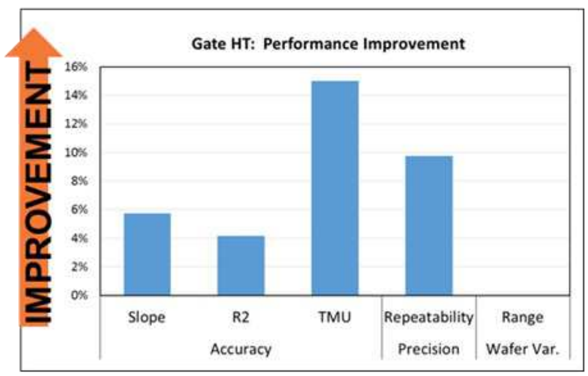
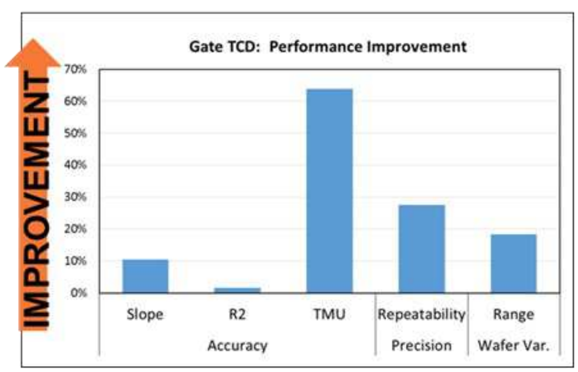


Figure 4. Gate CD results from analysis of 3 wafer DOE demonstrating full wafer map analysis of Enhanced OCD technique matches trends of select sites evaluated by TEM.

As seen from Figure 5, we have improvement in slope and R^2 for all the 3 parameters of interest. The biggest improvements are seen in the TMU results, especially for the gate top and bottom CDs. The measurement accuracy has improved by ~60% when compared to standard OCD. We also see a boost in precision which shows that the Enhanced OCD measurement is more stable when compared to standard OCD.





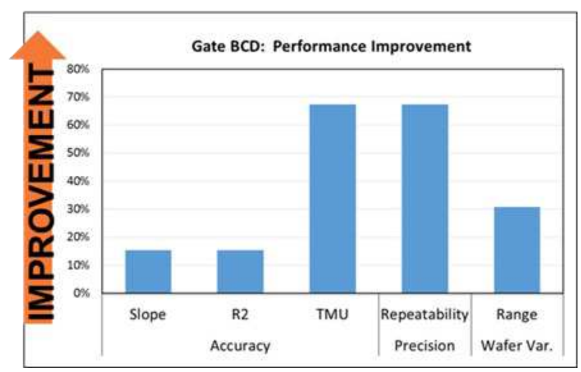


Figure 5. Summary results of DOE demonstrating % improvement of Enhanced OCD compared to standard OCD analysis. Results shown for Gate Height, Gate TCD and Gate BCD.

3.2 HKIL Thickness Measurement

Analysis of solid films are commonly utilized to assess gate dielectric (HKIL) thickness as it is a critical parameter to control threshold voltage (V_t) and leakage current[7]. Due to the direct impact of the gate dielectric thickness on the device performance, the metrology accuracy is very critical at this step. For 7nm technology node and beyond the film thickness is in Angstrom range and the metrology budget is in the sub-Angstrom range. On top of that the measurement is utilized extensively for APC (Advanced Process Control) to ensure quality of the process. Hence accuracy and precision are very important for this measurement. Traditionally metrology techniques have suffered from low sensitivity, parameter correlation, instability, reduced sampling, and analysis of solid films. In addition, solid films are typically not representative of an actual gate or complex shapes within a device where the HKIL films are applied. As a result further advancement of metrology to measure gate dielectric thickness within representative 7nm FinFET two and three dimensional device like structures presented in Figures 6 and 7 are desired.

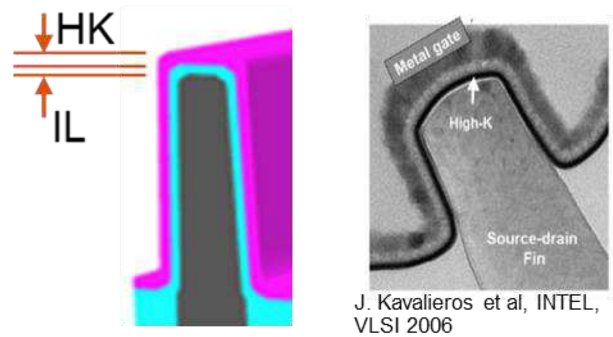


Figure 6. Schematic and TEM image of HKIL on fin.

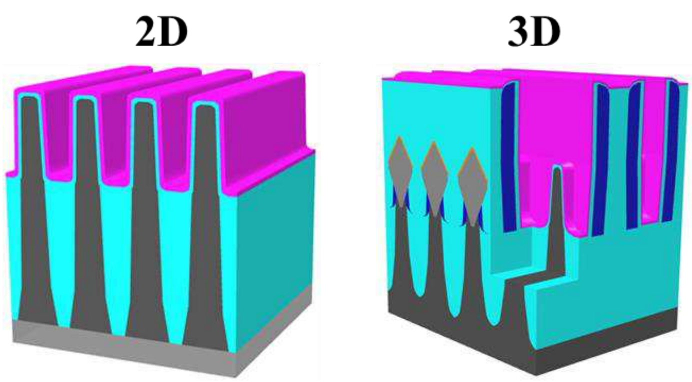


Figure 7. Schematic for 2D and 3D structure of HKIL films over fin.

Wafers were generated following a DOE for both the HK and IL thicknesses. For the DOE, five wafers were processed in which 2 wafers had nominal conditions, 2 wafers had a split in HK thickness and 1 wafer had a split for IL thickness. Reference measurement was done on XPS to measure the individual thickness of HK and IL on solid film pad. XPS can measure these films very accurately on planar film pads, but OCD's higher throughput is more desirable for increased sampling.

The HK and IL layers were analyzed using Enhanced OCD relative to XPS on 2D and 3D structures as presented in Figure 7. In this measurement we employ a virtual reference technique as well as optimize the weighting of additional optical channels as an Enhanced OCD approach for measuring gate dielectric thickness from OCD techniques. In the virtual reference technique the OCD spectra from additional channels and the XPS reference data is used as the training set for a machine learning algorithm to measure IL thickness. The HK thickness is not subjected to machine learning with XPS data as there is ample sensitivity from the standard OCD solution. The HK and IL thickness results from Enhanced OCD are then compared to the XPS reference.

Enhanced OCD provided consistent results with XPS for film thickness of HK and IL as well as improved analysis consistency across the wafer compared to standard OCD techniques as demonstrated in Figure 8. Standard OCD techniques have typically been unable to provide acceptable metrology results for IL thickness. Wafer maps are shown in Figure 9 which demonstrates that the Enhanced OCD results are less noisy and provide the expected uniform wafer maps without any hot spots as compared to standard OCD.

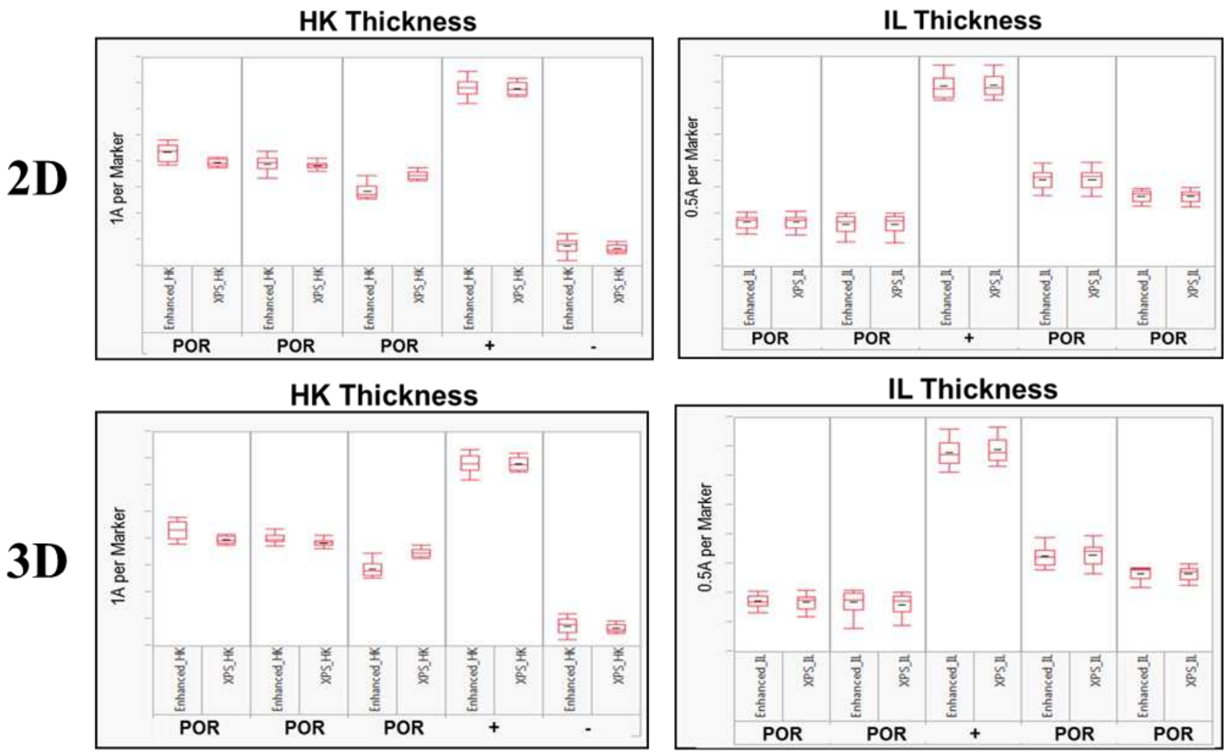


Figure 8. 2D and 3D HKIL DOE results from XPS and Enhanced OCD approach demonstrating similar trends and results between the two methods.

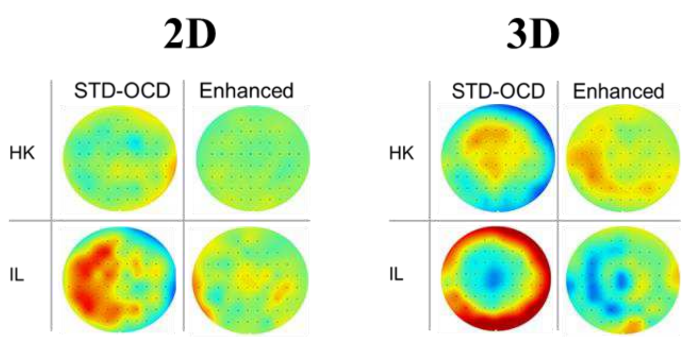


Figure 9. 2D and 3D HKIL wafer maps of Enhanced OCD compared to standard OCD analysis for both HK and IL. Enhanced OCD wafer maps provided expected trends.

The summary of improvements observed by using Enhanced OCD compared to standard OCD is shown in Figure 10. We see that there is a slight degrade in the slope for HK measurement, but there is a significant improvement in R^2 and TMU results. We see these improvements in the HK measurement on 2D and 3D targets. Another improvement we see is in the precision of the measurement. When the structure being measured is very complex (3D) we observe that Enhanced OCD boosts the stability of the measurement by 80% for the HK measurement.

The biggest benefit we see from the Enhanced OCD measurement is the ability to measure the IL thickness individually and with high accuracy and precision. Enhanced OCD dramatically improves the slope, R^2, TMU and precision of the measurement for both 2D and 3D targets. This has enabled an application that was historically not possible to measure using standard OCD.

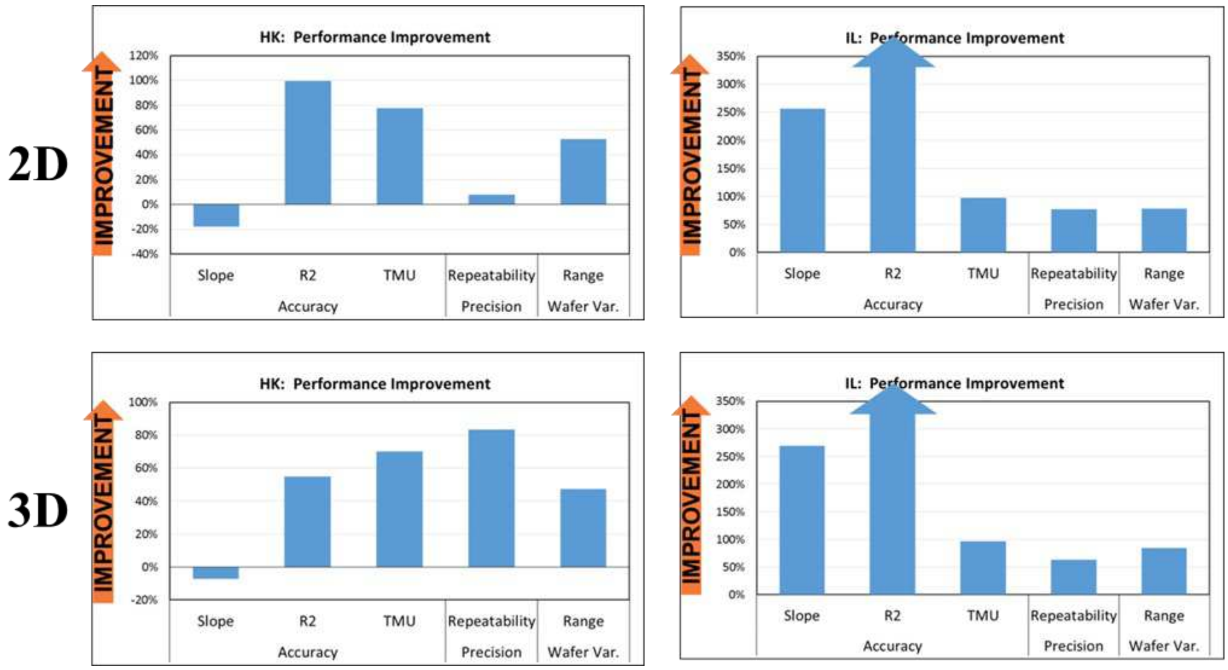


Figure 10. Summary results of 2D and 3D HKIL DOE demonstrating % improvement of Enhanced OCD compared to standard OCD analysis for both HK and IL thickness.

3.3 Cavity Etch Proximity Measurement

Cavity etch is executed on the exposed fin between the gates in the FinFET 3D structure as presented in Figure 11. The cavity size and its location in relation to the gate bottom CD affects key device parameters such as R_{on} (Resistance of transistor when device is ON) and DIBL (Drain Induced Barrier Lowering). This parameter is known as Proximity. Standard approaches typically have low sensitivity to the cavity dimensions particularly proximity and have been observed to provide instability or parameter correlation. In this work we employed additional optical channels and an advanced algorithm for selecting the most appropriate optical channels to further improve and optimize the OCD solution.

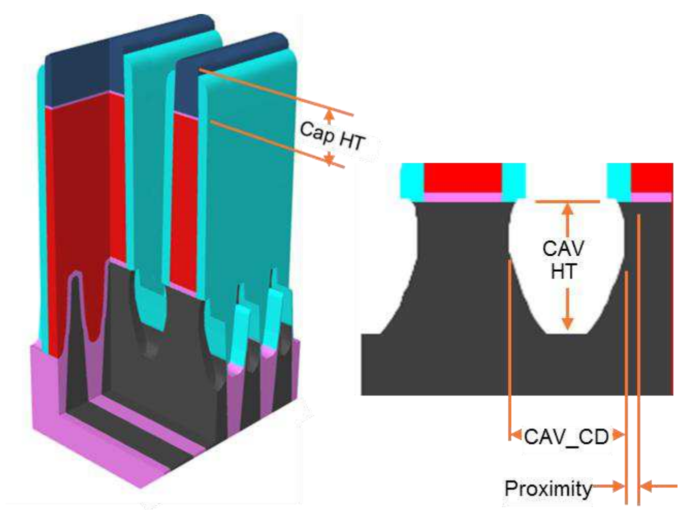


Figure 11. Schematic for 3D structure of cavity etch with detail of measurements which impact key device parameters R_{on}, DIBL, etc.

Wafers were generated following a DOE for proximity and Cavity CD. A 5 wafer DOE was generated in which the proximity was varied from low to high. These wafers were analyzed using Enhanced OCD relative to TEM. Enhanced

OCD provided consistent results with TEM and expected DOE trends as demonstrated in Figure 12. Wafer maps showing proximity variation as per DOE split is shown in Figure 13.

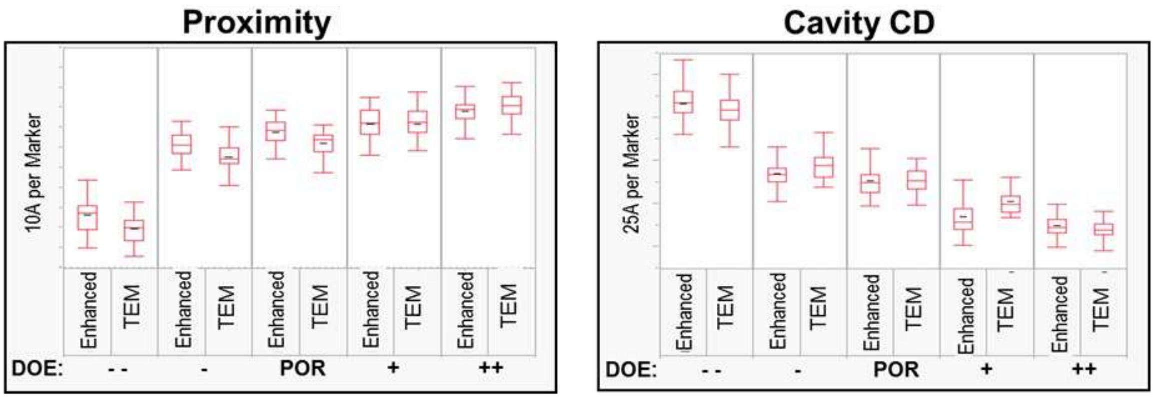


Figure 12. Cavity Etch DOE results from TEM and Enhanced OCD approach demonstrating similar trends and results between the two methods.

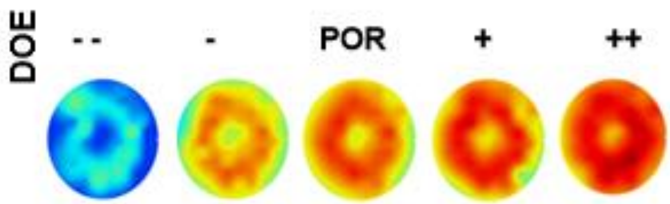


Figure 13. Cavity Etch wafer maps of Enhanced OCD demonstrating DOE trends for proximity.

Figure 14. Summary results of cavity etch demonstrating % improvement of Enhanced OCD compared to standard OCD analysis for Proximity, Cavity HT, Cavity CD, and Cap HT.

Compared to standard OCD, the Enhanced OCD technique provided superior performance as demonstrated in Figure 14 for accuracy and precision. We observed a tremendous improvement in the accuracy components such as slope, R^2, and TMU for all the parameters of interest, A greater than 50% improvement in TMU is of great relevance for a weak parameter like proximity. We also observed an overall improvement in the precision for all parameters. We can see that there is degradation in the wafer range for Cavity CD parameter compared to standard OCD. But since there is improvement in accuracy components, it is believed that this worsening of the range reflects a false positive that standard OCD solution was providing. With Enhanced OCD, we get an improved performance to measure weak and difficult parameters.

4. CONCLUSION

Measurement strategies need to adapt and incorporate new technologies. Measuring on structures which do not replicate the actual device provide no value. We need to measure what matters. Measuring on complex 3D structures has become a necessity for 7nm and beyond technology nodes. There is a need for a tool box which contains tools to improve the sensitivity and reduce the correlation for weak and difficult parameters in a complex 3D measurement. Expansions of the tools in the available toolbox are needed to further enhance OCD and standard metrology techniques in general. In this paper we have demonstrated that additional optical HW channels and smart weighting of these channels can help boost the sensitivity of a weak parameter in an OCD model. This in turn will help improve the accuracy and precision of the parameter. With additional enhancement tools such as hybrid and virtual reference metrology, we can reduce the correlations from other parameters and help improve the measurement performance. Improving precision does not only help in the stability of the measurement. It also enables better fleet matching and thus is very attractive for high volume manufacturing. Utilizing these enhancements we can further improve on challenges faced by several complicated 3D applications in the fab.

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