Hybrid scatterometry measurement for BEOL process control

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ABSTRACT

Scaling of interconnect design rules in advanced nodes has been accompanied by a reducing metrology budget for BEOL process control. Traditional inline optical metrology measurements of BEOL processes rely on 1-dimensional (1D) film pads to characterize film thickness. Such pads are designed on the assumption that solid copper blocks from previous metallization layers prevent any light from penetrating through the copper, thus simplifying the effective film stack for the 1D optical model. However, the reduction of the copper thickness in each metallization layer and CMP dishing effects within the pad, have introduced undesired noise in the measurement. To resolve this challenge and to measure structures that are more representative of product, scatterometry has been proposed as an alternative measurement. Scatterometry is a diffraction based optical measurement technique using Rigorous Coupled Wave Analysis (RCWA), where light diffracted from a periodic structure is used to characterize the profile.

Scatterometry measurements on 3D structures have been shown to demonstrate strong correlation to electrical resistance parameters for BEOL Etch and CMP processes. However, there is significant modeling complexity in such 3D scatterometry models, in particular due to complexity of front-end-of-line (FEOL) and middle-of-line (MOL) structures. The accompanying measurement noise associated with such structures can contribute significant measurement error. To address the measurement noise of the 3D structures and the impact of incoming process variation, a hybrid scatterometry technique is proposed that utilizes key information from the structure to significantly reduce the measurement uncertainty of the scatterometry measurement. Hybrid metrology combines measurements from two or more metrology techniques to enable or improve the measurement of a critical parameter.

In this work, the hybrid scatterometry technique is evaluated for 7nm and 14nm node BEOL measurements of interlayer dielectric (ILD) thickness, hard mask thickness and dielectric trench etch in complex 3D structures. The data obtained from the hybrid scatterometry technique demonstrates stable measurement precision, improved within wafer and wafer to wafer range, robustness in cases where 3D scatterometry measurements incur undesired shifts in the measurements, accuracy as compared to TEM and correlation to process deposition time. Process capability indicator comparisons also demonstrate improvement as compared to conventional scatterometry measurements. The results validate the suitability of the method for monitoring of production BEOL processes.

Keywords: OCD, scatterometry, hybrid metrology, BEOL, process control, variability, dielectric

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1. INTRODUCTION

Scaling of interconnect design rules in advanced nodes has been accompanied by an increasing demand on inline metrology to enable tight control of back-end-of-line (BEOL) processing. Dielectric hard mask layer thickness control to enable consistent etching of BEOL trenches is one challenge that has emerged with the progressively thinner copper layers of advanced technology nodes. Traditional inline optical metrology measurements of these hard mask layers after their deposition have relied on 1-dimensional (1D) film pads to characterize the dielectric thickness. Such film pads typically have copper blocks underneath that are unpatterned within the measurement target and simplify the optical measurement by minimizing or eliminating any optical signal from below the conductor. However, the reduction of this copper thickness, along with variations of this thickness across the target due to CMP dishing effects, have introduced undesired noise in the acquired measurement spectra due to an increased signal coming from layers below the copper, and variations in the strength of that signal—adding measurement uncertainty. Relying on 1-dimensional film pads that have no copper layers is not preferred due to groundrule concerns. Thus, to avoid these variations, and to measure structures that are more representative of product, measuring structures that have patterned copper gratings underneath is needed. Such structures can be measured using scatterometry, a diffraction based optical measurement technique using Rigorous Coupled Wave Analysis (RCWA), where light diffracted from a periodic structure is used to characterize the details of profile.

Scatterometry measurements on 3D structures have been shown to demonstrate strong correlation to electrical resistance parameters, enabling automated process control for BEOL Etch and CMP processes. However, there is significant modeling complexity in such 3D scatterometry models to take into account contribution from underlying front-end-of-line (FEOL) and middle-of-line (MOL) structures. The accompanying measurement noise associated with such structures can contribute significant measurement error. To address the measurement noise of the 3D structures and impact of incoming process variation, a hybrid scatterometry technique is proposed that utilizes key information from the structure to significantly reduce the measurement uncertainty of the scatterometry measurement. Hybrid metrology combines measurements from two or more metrology techniques to enable or improve the measurement of a critical parameter.

In this work, the hybrid scatterometry technique is evaluated for measurement of interlayer dielectric (ILD) film thickness, dielectric hard mask film thickness and dielectric trench etch depth. These three applications were measured on 3D copper line structures. The data obtained from the hybrid scatterometry technique demonstrates the capability for robust characterization of the measurement parameter of interest without excessive measurement noise from the incoming process DoE conditions. The application of this hybrid scatterometry technique to both film thickness monitoring and trench etch depth monitoring demonstrates the flexibility of the technique for monitoring of different BEOL processes.

2. BACKGROUND AND MOTIVATION

Measurement of 1D pads in BEOL are known to have limitations of capturing the exact process performance at the parameter of interest [1]. In figure 1, measurement of remaining dielectric post CMP and measurement of the copper trench area are compared to the electrical resistance. The 1D measurement shown here did not have impact from underneath copper. Previously, the additional complexity induced in modeling of films deposited on top of thin and dished copper pads has been reported [2]. Although the latter work offered some capability to extend the lifetime of such 1D measurements, the measurement precision remains a concern, particularly given the criticality of the copper thickness on the quantity of light penetrating through the copper into previous film deposition layers.

Though the 3D scatterometry data shown above suggests that the measurement technique may be more suitable for BEOL process monitoring and control than the 1D optical measurement approach, there are some challenges in 3D scatterometry model development. As the advanced node integration schemes become increasingly complex, the 3D model development must address more floating parameters while also aiming to condense the time to solution as much as possible. The cost of accuracy has also been documented previously [3], demonstrating that a 2x reduction in targeted metrology error budget translates to a 4x cost increase for TEM. Given these considerations, development of 3D scatterometry models requires optimization of the tradeoff between time to solution, number of floating parameters and availability of reference metrology.

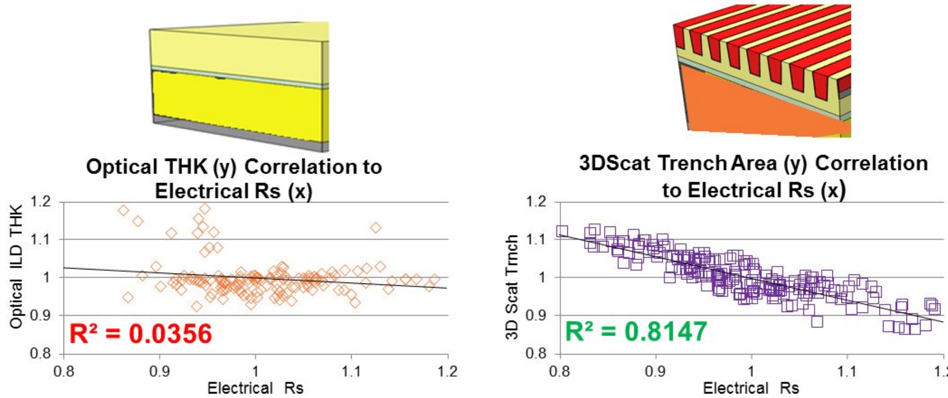

Figure 1: Comparison of correlation of 1D optical measurement and 3D scatterometry measurement to electrical resistance parameter [1]

Evolution of optical metrology tools to meet these challenges may be categorized in terms of both hardware level innovation to increase measurement sensitivity through improved signal quality and reduced noise [4,5] or by innovation in the measurement modeling techniques utilized to extract data from the signal. In hardware level refinements, one available approach is to add more channels of spectral acquisition to try to break down parameter cross correlation [4]. This approach, accompanied with an automated methodology for selecting the channels with most sensitivity for the measurement of interest, enabled significant improvement in measurement accuracy, and precision as compared to measurements using a standard 6-channel spectral reflectometer configuration [4]. Improvement in the laser sustained plasma source used in spectroscopic ellipsometry measurements was found to improve the signal intensity by a factor of 3, resulting in significant reduction in residual measurement error for direct optical measurements of band-gap [5]. To address challenging emerging measurement applications with shorter lead time, innovative methodologies have also been developed to optimize measurements using existing optical metrology tools. In recent years, numerous demonstrations of hybrid metrology have been reported, enabling improved measurement of a key parameter by combining information from two or more sources [6]. Hybrid metrology solutions have been reported combining CDSEM with OCD, OCD with XPS and XRF/XPS with OCD for various applications [7]. Significant measurement precision and accuracy benefits are demonstrated in many applications of hybrid metrology through reducing the measurement uncertainty of the parameter of interest through a complimentary measurement.

Increasingly, machine learning based algorithms leveraging high accuracy reference metrology data or electrical test data have also been proven to optimize measurement sensitivity to real process excursions that correlate to the electrical data [8].

In this work, key information from complex structure is utilized to reduce parameter correlation in optical measurement. Data will be presented from 3 categories of measurement application as shown in figure 2. The schematics show a BEOL measurement location featuring minimum design rule metal trenches above 3D FEOL / MOL structures omitted for simplicity. Above the metal trenches, a nitride layer and an interlayer dielectric (ILD) layer are deposited as shown in the first image, 'ILD Deposition Thickness'. Subsequently, the hard mark material is deposited above the ILD film and through various patterning schemes, the ILD etch eventually forms an array of trenches with some ILD remaining at the bottom of the trench and with some hard mask material often remaining at the top of these trenches. The remaining ILD below the trench and the final CMP trench height directly influence the metal trench resistance. The ILD film also provides insulation from adjacent metal line structures as well as cut lines and vias that are present within chip devices. For the purpose of CMP polish time control to stabilize electrical resistance, large arrays of overlapping trenches from the various metallization layers are probed. Thus, by performing the ILD deposition, hark mark deposition and ILD etch depth measurements on the same structure, the capability for one to one process control, and potentially feed forward feed-back control [1], is provided.

In the following results, 3D scatterometry and hybrid scatterometry measurements from the same structure will be compared for 7nm and 14nm BEOL ILD deposition, hard mask deposition and ILD etch processes.

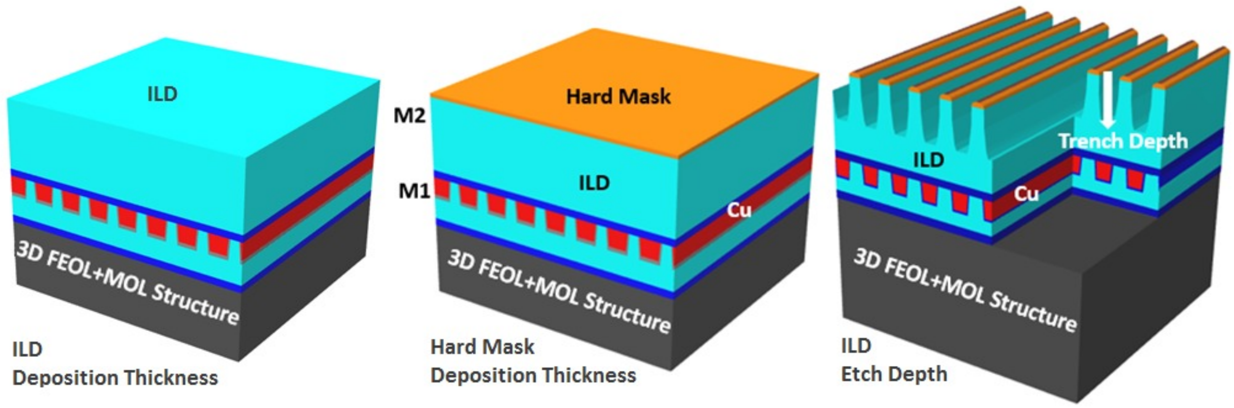

Figure 2: Schematic of measurement structure used for interlayer dielectric (ILD) thickness, hard mask thickness and interlayer dielectric trench depth measurements.

3. RESULTS

A. MEASUREMENT PRECISION

Precision measurements from six 14nm wafers were compared between 1D optical, 3D scatterometry and hybrid scatterometry measurements after hard mask deposition. Each wafer was measured in a 10 time repeat cycle. Figure 3 illustrates the normalized hard mask thickness obtained per wafer in these three measurement categories. Table 1 lists the largest measurement precision uncertainty from any the sites measured for each measurement.

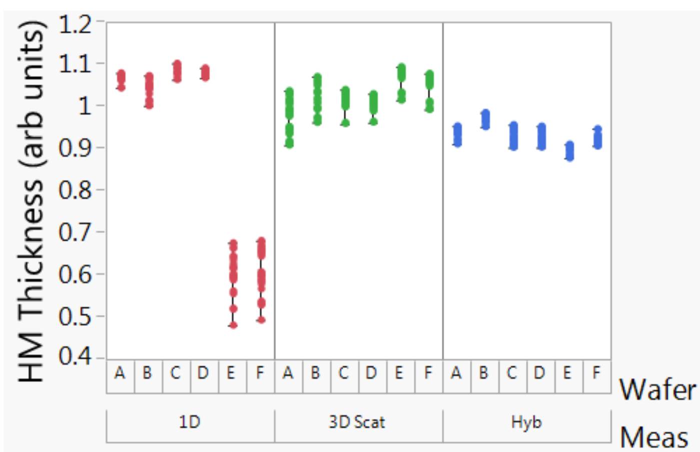

Figure 3: Comparison of 10x precision measurements of hard mask thickness for six 14nm wafers by 1D optical, 3D scatterometry and hybrid scatterometry measurement techniques

The hybrid scatterometry within wafer measurement range is notably similar for all six wafers while the 3D scatterometry results show some variations from wafer to wafer and the 1D measurement shows a significant shift for two wafers. It was found from investigation of these wafers' optical spectra that thin copper at the 1D measurement location contributed to the large shift in the measurement. This also is evident in the large measurement precision uncertainty recorded for these wafers, as shown in table 1.

Max. Site Level 3σ Precision (% of nominal)						
Wafer	A	B	C	D	E	F
1D Optical	0.29%	0.53%	0.19%	0.12%	**7.19%**	**4.29%**
3D Scat	0.51%	0.23%	0.39%	0.31%	**0.48%**	**0.50%**
Hybrid Scat	0.51%	0.33%	0.55%	0.56%	**0.39%**	**0.51%**

Table 1: Max. Site Level 3σ Precision for same wafers as figure 3 measured by 1D optical, 3D scatterometry and hybrid scatterometry measurement techniques

B. MEASUREMENT ROBUSTNESS

Figure 4 compares measurements of hard mask thickness from the same 14nm wafers by 3D scatterometry and hybrid scatterometry.

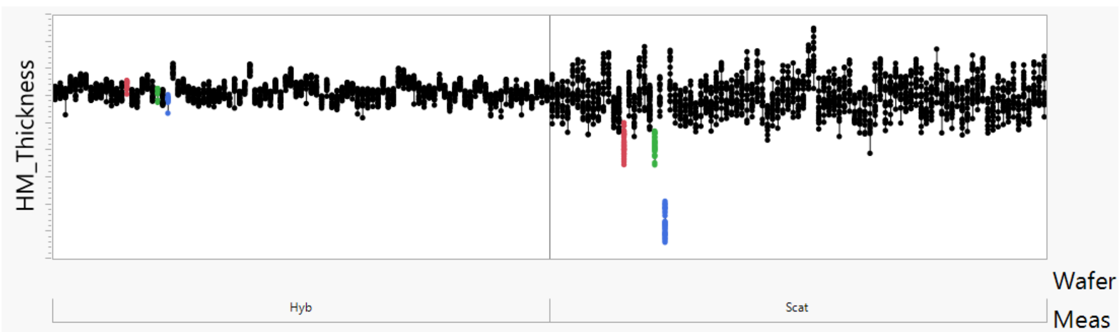

Figure 4: Comparison of hybrid scatterometry and 3D scatterometry hard mask thickness for 14nm wafers.

In the hybrid scatterometry measurement, more than 100% reduction is achieved in process capability indicator, C_p. Three outlier wafers were identified in the 3D scatterometry measurement that did not incur any shift in the hybrid scatterometry measurement. It was found that a change in a parameter that was fixed in the 3D scatterometry model occurred, causing a shift in the hard mask thickness parameter.

In figure 5, hard mask thickness measurements from another 14nm metal level are compared between hybrid scatterometry and 3D scatterometry. Three design of experiment (DOE) conditions were introduced in non critical parameters to try to induce artificial data shift in the hard mask thickness measurement in the 3D scatterometry model. 35% reduction in C_p was demonstrated in the hybrid scatterometry results and no data shift was incurred for any of the DoE wafers. Similar observations were recorded in the ILD etch depth and BCD measurements at the corresponding 14nm metal level as shown in figure 6.

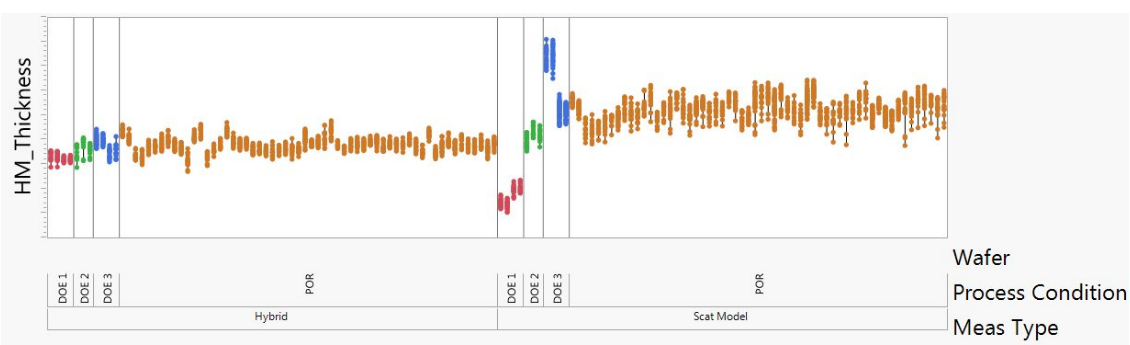

Figure 5: Comparison of hybrid scatterometry and 3D scatterometry hard mask thickness for 14nm wafers including incoming process DoE conditions.

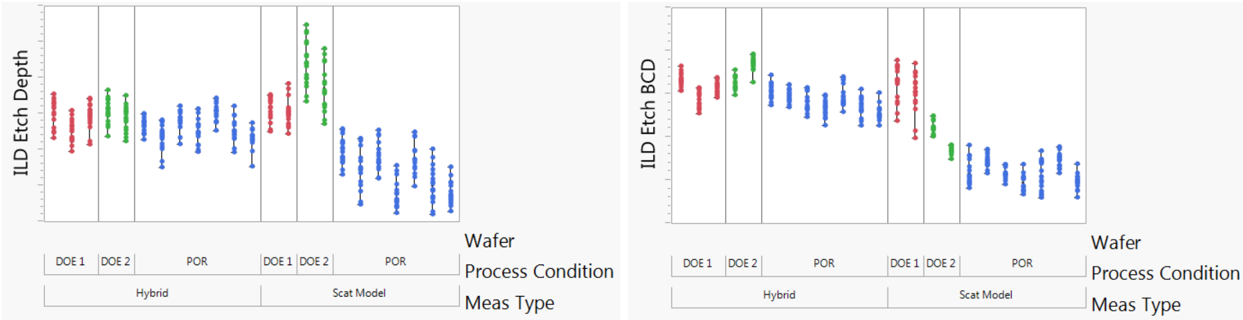

Figure 6: Comparison of hybrid scatterometry and 3D scatterometry ILD etch depth and BCD measurements for 14nm wafers.

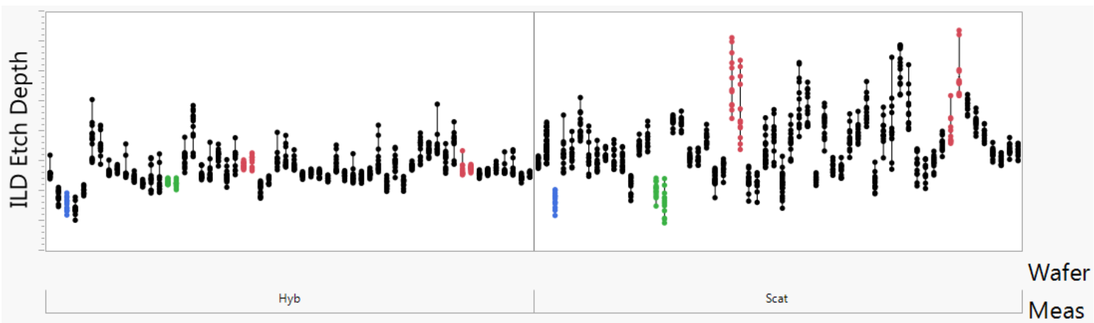

Figure 7: Comparison of hybrid scatterometry and 3D scatterometry ILD etch BCD measurements for 7nm wafers.

From these results, it is clear that the C_p improved for the hybrid scatterometry measurement while also providing better robustness in the situation where a non-critical process parameter had a shift that the 3 D scatterometry model was unable to correctly account for. This is likely due to cross-parameter correlation issue with 3D scatterometry wherein one or more of the under layer parameters had higher variability/shifts for those wafers but due to cross-correlation, undesired impact is observed in the critical parameter being measured. In figure 7, data from 7nm ILD etch demonstrates apparent process variation from wafer to wafer and lot to lot in both hybrid scatterometry and 3D scatterometry results, though with 240% improvement in C_p in the hybrid scatterometry results.

C. MEASUREMENT ACCURACY

Having demonstrated that the measurement precision for the hybrid scatterometry technique is within the metrology budget and that the technique offers improved robustness in both development and production process monitoring, the 3D scatterometry and hybrid scatterometry measurement techniques are now compared to reference metrology measurements. Reference metrology samples were obtained from wafers running the same 7nm ILD etch process shown in figure 7. Figure 8 plots the 3D scatterometry and hybrid scatterometry results on the y-axis, plotted against the corresponding reference metrology values on the x-axis. The slope from the hybrid scatterometry measurements is found to improve significantly compared to the 3D scatterometry result, demonstrating that the measured range in hybrid scatterometry results is closer to the physical within wafer variation of the etch depth.

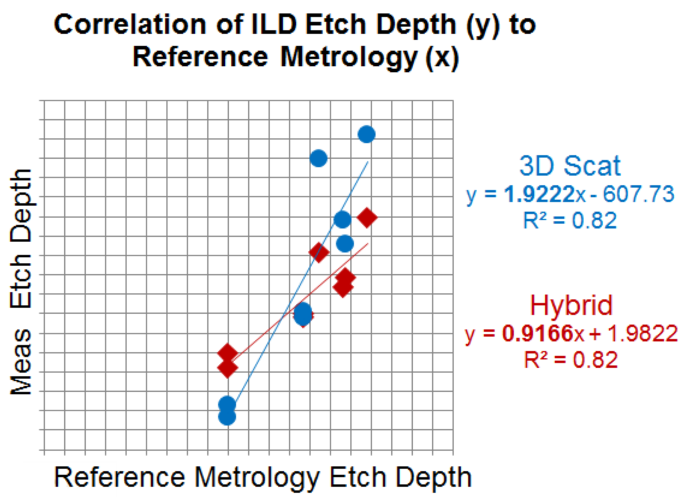

Figure 8: Correlation of hybrid scatterometry and 3D scatterometry ILD etch depth to reference metrology.

D. MEASUREMENT DOE TRACKING

Following demonstration of the measurement precision, robustness in varying incoming process conditions and accuracy vs reference metrology, the hybrid scatterometry measurement was evaluated for a 7nm ILD deposition thickness measurement of wafers with 3 targeted thicknesses values compared to POR wafers processed by the same deposition chamber. Figure 9 shows the measurement result by ILD process grouping and the correlation of the measured thickness by hybrid scatterometry on the y-axis potted against process deposition time on the x-axis. The results demonstrate linear correlation of the measurement to the process deposition time while also demonstrating consistent wafer to wafer and within wafer uniformity. These results were obtained on a measurement structure where no 3D scatterometry model has yet been developed due to the complexity of the measurement structure.

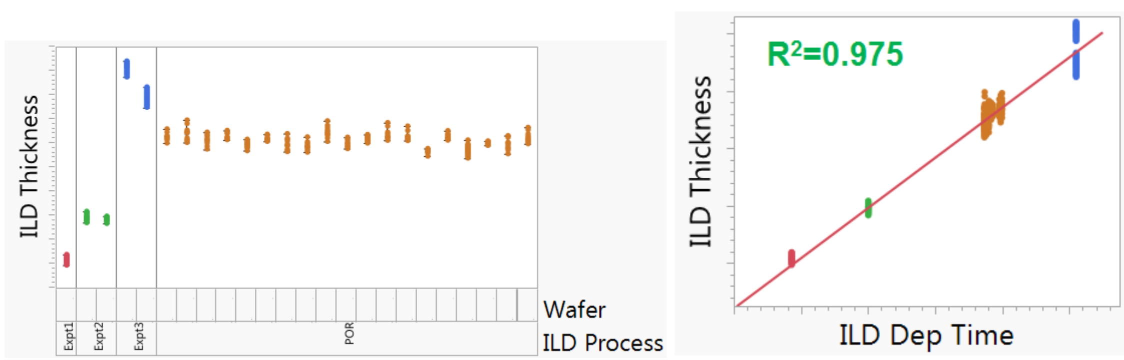

Figure 9: Measurement of ILD thickness by ILD process grouping and correlation of ILD thickness to ILD dep time

4. CONCLUSIONS

In this work, the challenge of meeting metrology budget requirements for inline BEOL optical metrology is introduced, together with the limitations of 1D optical measurements in advanced nodes. In addition to the known previously published issue that 1D optical measurements do not correlate well to electrical parameters, increasing metrology noise due to copper thinning and dishing in the large 1D measurement pad is also reported.

A new hybrid scatterometry measurement technique is introduced as a potential solution to address these challenges. Measurement precision of 6 14nm wafers measured after hard mask thickness is compared for 1D optical, 3 D scatterometry and hybrid scatterometry measurement techniques. The precision of all 6 wafers is well within the 1% metrology budget for both 3D scatterometry and hybrid scatterometry measurements but significantly exceeded 1% for 2

wafers using the 1D optical measurement due to thin copper in the underlying layer at the measurement structure. The scatterometry techniques overcome this limitation by measuring the dielectric and hard mask films directly above copper gratings in a complex device-like 3D structure. The within wafer and wafer to wafer uniformity from the hybrid scatterometry measurements is noted to be significantly tighter than the corresponding 3D scatterometry measurements.
Improved measurement robustness of hybrid scatterometry was demonstrated for sample 14nm and 7nm hard mask deposition and interlayer dielelectric (ILD) etch applications as compared to corresponding 3D scatterometry results. In addition to significant improvements in process capability indicator, C_p, the hybrid scatterometry measurements were also found not to inadvertently shift in cases where incoming process changes occurred. There were large data shifts observed in the 3D scatterometry data, owing to the limitation of the 3D scatterometry models to account for all the possible sources of variation in the complex structure. Improved correlation of the hybrid scatterometry measurements to reference metrology was also demonstrated as compared to corresponding 3D scatterometry results, demonstrating the improved capability of the measurement to accurately characterize the process of interest without significant impact from incoming process variability. Linear correlation of hybrid scatterometry measurements to ILD deposition time was also shown for post ILD deposition measurements, verifying that together with measurement precision, robustness and accuracy, the measurement is sensitive to changes in process targeting that impact the parameter of interest. The hybrid scatterometry measurements have been implemented for various 7nm and 14nm inline measurements with continuing exploration of other potential applications to enable improved BEOL process control in advanced nodes.

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