Scatterometry Measurement for Gate ADI and AEI Critical Dimension of 28nm Metal Gate Technology

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ABSTRACT

This paper discusses the scatterometry-based metrology measurement of 28nm high k metal gate after-develop inspection (ADI) and after-etch inspection (AEI) layer structures. For these structures, the critical measurement parameters include side wall angle (SWA) and critical dimension (CD). For production process control of these structures, a metrology tool must utilize a non-destructive measurement technique, and have high sensitivity, precision and throughput. Spectroscopic critical dimension (SCD) metrology tools have been implemented in production for process control of traditional poly gate structures. For today's complex metal gate devices, extended SCD technologies are required. KLA-Tencor's new SpectraShape 8810 uses multi-azimuth angles and multi-channel optics to produce the high sensitivity and precision required for measurement of critical parameters on metal gate structures. Data from process of record (POR), focus-exposure matrix (FEM) and design of experiment (DOE) wafers are presented showing the performance of this new SCD tool on metal gate ADI and AEI process structures. Metal gate AEI scatterometry measurement results are also compared to transmission electron microscopy (TEM) reference measurements. These data suggest that the SpectraShape 8810 has the required sensitivity and precision to serve as a production process monitor for 28nm and beyond complex metal gate structures.

Keywords: scatterometry, metal gate, critical dimension

1. INTRODUCTION

For reduced gate leakage and enhanced device performance, many IC manufacturers utilize novel metal gate technologies instead of traditional poly silicon gate formation technologies. Metal gates require a novel approach for process control because of the new materials utilized and the new parameters that are critical for the optimization of device performance[1]. Scatterometry is an established, non-destructive metrology technique with proven performance for traditional gate process control. The development of additional optical technologies has extended scatterometry's measurement capability to today's more complex device structures. In particular, a new-generation scatterometer with multi-Azimuth (multi-AZ) angles and multi-channel optics has been shown to provide the sensitivity required for process control of complex devices in a high volume manufacturing environment. This paper presents data from metal gate ADI and AEI process layers demonstrating the ability of this new-generation scatterometer to measure critical parameters on 28nm devices.

1.1 Dimensional Metrology

For 90, 65, 45 and 40nm standard poly gate devices, and older-generation spectroscopic critical dimension (SCD) metrology tool has been used to measure critical parameters at the gate ADI and AEI layers. This SCD tool is utilized as the advanced process control (APC) system providing improved sensitivity to process variations compared to a traditional CD-SEM tool. Advanced design node devices, using complex metal gate technology, required improved SCD metrology tool performance. A new-generation SCD tool, KLA-Tencor's SpectraShape 8810, includes several enhanced and new optical technologies that make it a viable candidate for 28nm and beyond process control. The SpectraShape 8810's core technologies include a multi-AZ spectroscopic ellipsometer with broadband light (often down to wavelengths in the deep UV portion of the spectrum[2]) and a polarized, enhanced ultra-violet reflectometer (eUVR). The multi-AZ and multi-channel capabilities of this new SCD metrology tool provide enhanced critical parameter sensitivity

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and reduce the correlation of the parameters.

In multiple-AZ scatterometry, spectra from two or more different AZ angles are collected sequentially from the same structure and analyzed simultaneously. Figure 1a shows a schematic of multi-AZ scatterometry, where blue ray is perpendicular to the grating and green ray is parallel to the grating. The same physical model of the structure is used to analyze both spectra, and a single set of results is the output. This approach significantly increases the amount of information collected from the sample.

In multi-channel scatterometry, spectra from two different optical systems are collected sequentially from the same structure and analyzed simultaneously. Figure 1b shows a schematic of multi-channel scatterometry, where the blue ray represents ellipsometry and the pink ray represents eUVR. The same physical model of the structure is used to analyze all the spectra, and a single set of results is the output[2]. By utilizing a combination of multi-AZ and multi-channel spectra, the SpectraShape 8810 provides significant gains in sensitivity and signal, thereby breaking parameter correlation and producing a better measurement of critical parameters for complex applications.

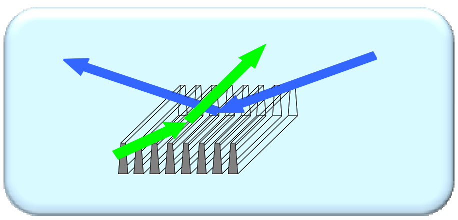

Figure 1a. Schematic of multi-AZ angle scatterometry.

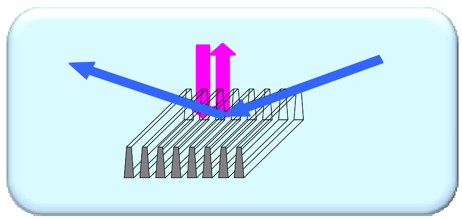

Figure 1b. Schematic of multi-channel scatterometry.

2. METAL GATE PARAMETERS AND MEASUREMENT RESULTS

2.1 High k Metal Gate ADI

In-line control and monitoring of high k metal gate length after lithography is very critical for device performance[3]. Studies were performed to determine the sensitivity and precision of scatterometry measurement for a 28nm high k metal gate ADI layer. Two wafers were used in the study. The first was exposed with a focus-exposure matrix (FEM). The second was exposed with constant and standard (POR) lithography conditions. For the same DOE conditions, there are two targets in one field: one for a NMOS structure and a second for a PMOS structure. A schematic of the detailed layer structure is shown in figure 2.

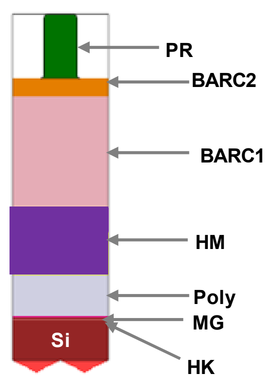

Figure 2. HKMG ADI model and stack information.

The SCD tool used for the measurement was the SpectraShape 8810. This ADI structure is very challenging for scatterometry measurements because the seven different films under resist result in higher correlation among measurement results parameters. For this study, AcuShape 2 advanced modeling software was used to break the parameter correlation. The floating parameters used in the model (the measurement parameters) are shown in Table 1. The critical parameters for this application are the middle CD (MCD) of the resist, the sidewall angle (SWA) of the resist, and the height of the resist (PR_HT). The scatterometry measurement requirements include: (1) dynamic precision <0.1nm or <0.1degree; (2) sensitivity to dose and focus on the FEM wafer; and, (3) baseline wafer verification.

Table 1. Floating parameters for the model and measurement parameters utilized.

Floated Parameters:

1) PR MCD
2) PR Height
3) PR SWA
4) Barc2 Height
5) Barc1 Height
6) HM Height
7) Poly Height

SpectraShape 8810 Technologies Utilized:

1) 240SE
2) Azimuth 0°
3) AcuShape 2 Modeling SW

The MCD measured by scatterometry versus focus and energy exposure for both NMOS and PMOS targets are displayed in figure 3. The Bossung curve is plotted for both the NMOS and PMOS structure indicating that scatterometry has good sensitivity to focus and exposure variations during photolithography.

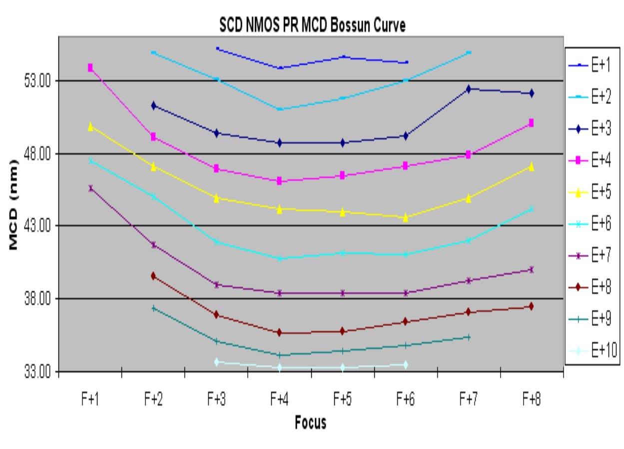

Figure 3a. MCD as function of focus and exposure for NMOS target.

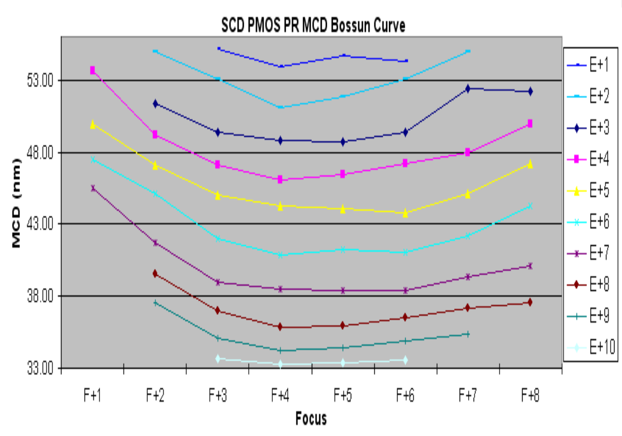

Figure 3b. MCD as function of focus and exposure for PMOS target.

The MCD and SWA of whole wafer map plots for the FEM wafer and the baseline wafer are shown in Figure 4. The wafer maps show that MCD decreases from left to right for both NMOS and PMOS targets and the SWA is increasing from left to right. These results are consistent with the FEM DOE pattern. For the baseline wafer there is no clear pattern observed, as expected.

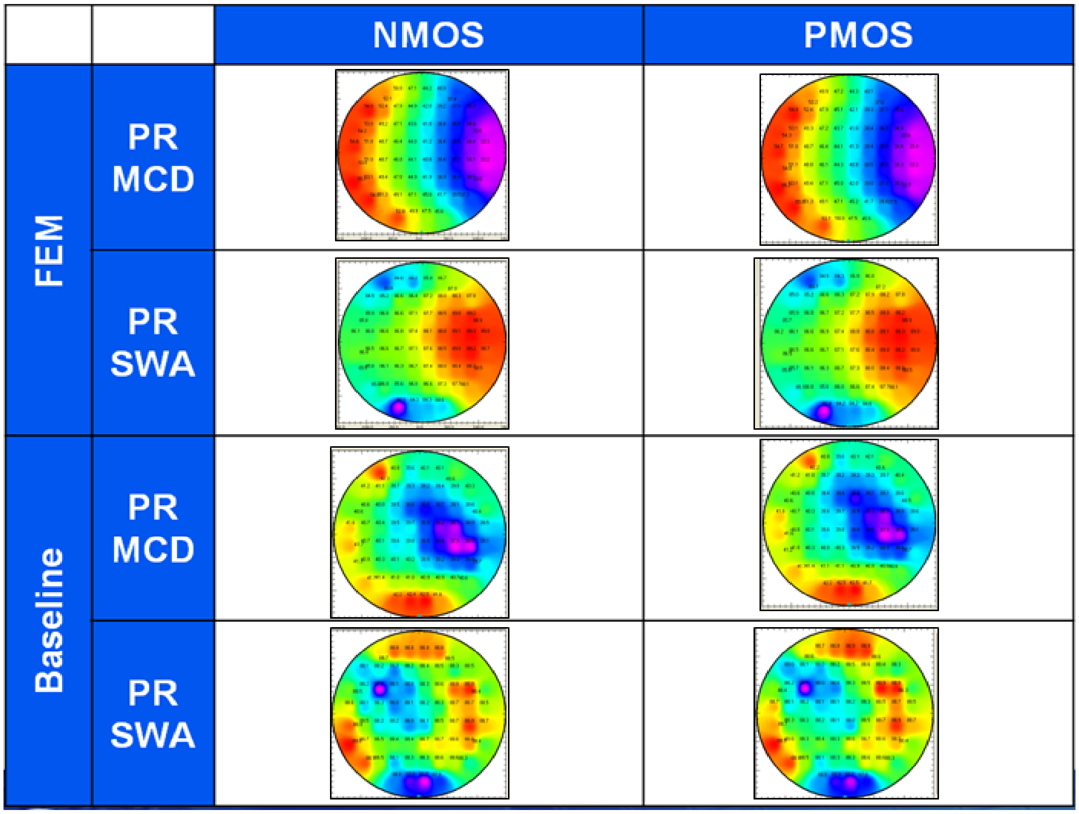

Figure 4. Wafer maps of MCD and SWA for DOE wafer and baseline wafer.

The dynamic precision of MCD, SWA and resist height (PR_HT) was measured on the baseline wafer. Measurements are performed ten times with wafer load and unload for 11 sites. The 3 sigma of pooled precision is listed in table 2. The results show that scatterometry has excellent precision with a demonstrated 3 sigma of less than 0.1nm for MCD and resist height and less than 0.1 degree for SWA.

Table 2. Summary of dynamic precision of MCD, SWA and PR_HT for NMOS and PMOS targets.

	Paramater	NMOS	PMOS
Dynamic Precision (< 0.1)	PR MCD (nm)	0.08	0.07
	PR WA (deg)	0.03	0.04
	PR HT (nm)	0.03	0.02

These results demonstrate that the new-generation SCD tool meets the dynamic precision, dose and focus sensitivity and baseline wafer verification requirements for measurement of the 28nm high k metal gate structure. By meeting these requirements, the new-generation SCD tool can be implemented in production as an in-line ADI process monitor.

2.2 High k Metal Gate AEI

For 28nm node High-K Metal Gate (HKMG) AEI process, the high k and metal gate recess relative to Poly Si width is very critical for device performance[4]. Before these devices can be implemented in production, however, suitable in-line process control metrology must be established. Limiting the field of available metrology techniques to those that are nondestructive, sensitive, and capable of high throughput leaves only scatterometry and top down critical dimension scanning electron microscopy (CD-SEM) as possible choices. However once it is considered that not just *CD* but also *shape* metrology is required, then scatterometry emerges as the only near-term option. The new generation scatterometry tool combines multi-AZ and multi-channels to potentially provide better precision and higher sensitivity to HKMG recess.

In order to demonstrate the SpectraShape 8810's sensitivity and precision for the HKMG AEI profile, seven DOE wafers with varying process conditions were prepared. The DOE wafer had varied metal gate recess (MG_Recess), high k recess (HK_Recess) or poly side wall angle (SWA). The process conditions of the DOE wafers are listed in table 3. The critical parameters for this application are MG_Recess, HK_Recess, SWA, Poly Si CD and hard mask (HM) height. The HKMG AEI model and critical parameters are shown in figure 5. The scatterometry measurement requirements for this HKMG AEI process layer are: (1) dynamic precision <0.1nm or <0.1 degree; (2) metal gate and high K DOE sensitivity; and, (3) correlation to the TEM reference measurement.

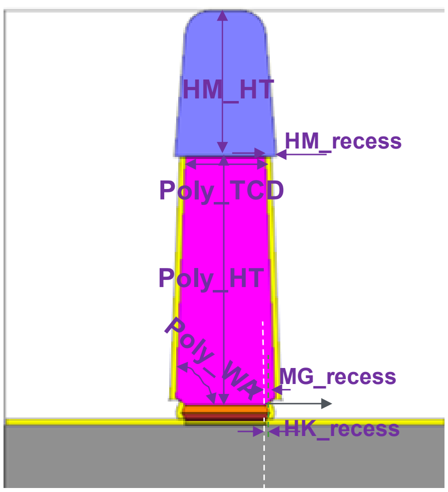

Figure 5. HKMG AEI model.

Table 3. HKMG AEI DOE list.

Slot#	Process Condition
2	POR
3	MG Recess _Low
4	MG Recess _High
5	HK Recess _Low
6	HK Recess _High
7	Poly_WA_Low
8	Poly_WA_High

The poly bottom critical dimension (BCD) and SWA sensitivity versus DOE split are shown in figure 6. Poly BCD and SWA data were collected for all wafers on the DOE list (table 3). However, in order to easily interpret the results, the charts in figure 6 only show the data from the POR wafer (wafer 2) and the wafers with altered poly process conditions (wafers 7 and 8). The data from the other DOE wafers (wafers 3 – 6) closely approximated the data from the POR wafer. The results show that the SpectraShape 8810 is able to distinguish Poly BCD and Poly SWA DOE splits.

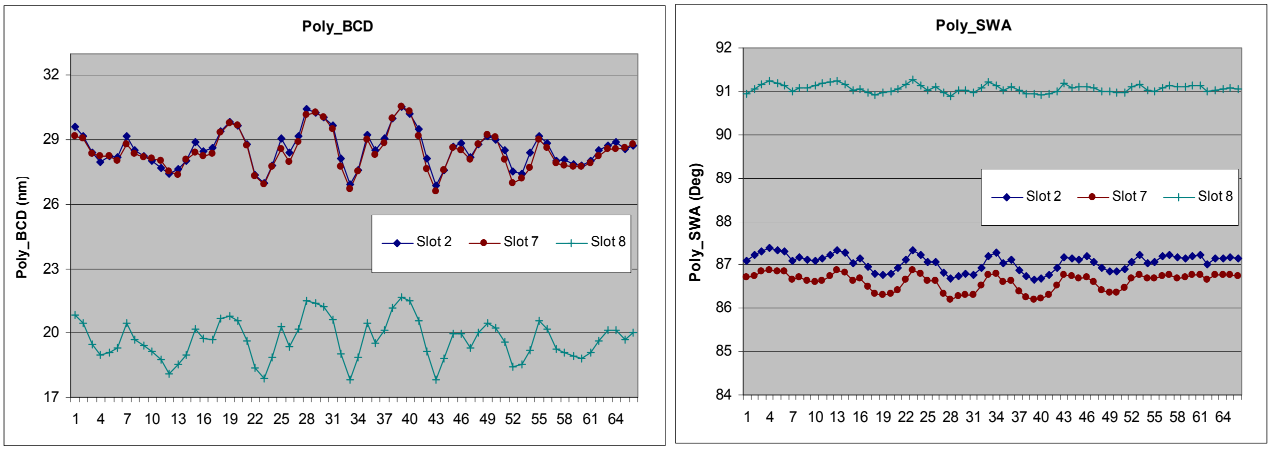

Figure 6. HKMG Poly BCD and SWA versus Poly SWA DOE split.

The high k recess and metal gate recess are the most critical parameters in this application. Since the metal gate and high k layer thickness under poly is very low, the sensitivity of the scatterometer to variations in the MG and HK recess is also very low for the optical signal. In order to improve the scatterometry measurement sensitivity and precision to the HK recess and MG recess, the multi-AZ angle and multi-channels signals were used. The 2D contour maps of MG recess and HK recess for the POR wafer are shown in figure 7. These contour maps reveal that the variations in MG recess and HK recess across the wafer are within 1 nm and have a concentric pattern. The edge of the wafer has a higher MG recess and a lower HK recess.

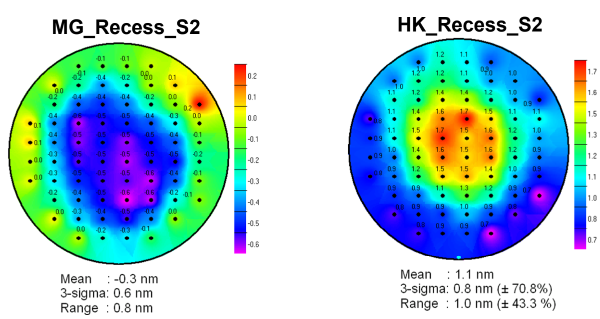

Figure 7. MG recess and HK recess contour maps of the POR wafer.

The HK and MG recess sensitivity versus DOE splits are displayed in figure 8. Again, HK recess and MG recess data were collected from all DOE wafers (table 3). In order to easily interpret the results, the MG recess chart in figure 8 only shows the data from the POR wafer and the wafers with altered MG process conditions (wafers 3 and 4). Similarly, the HK recess chart in figure 8 only shows data from the POR wafer and the wafers with altered HK process conditions (wafer 5 and 6). The results show that the SpectraShape 8810 is able to recognize the MG recess and HK recess DOE splits.

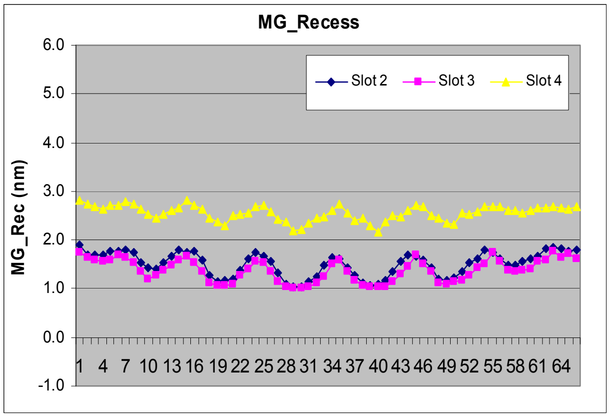

Figure 8a. MG recess versus MG DOE split.

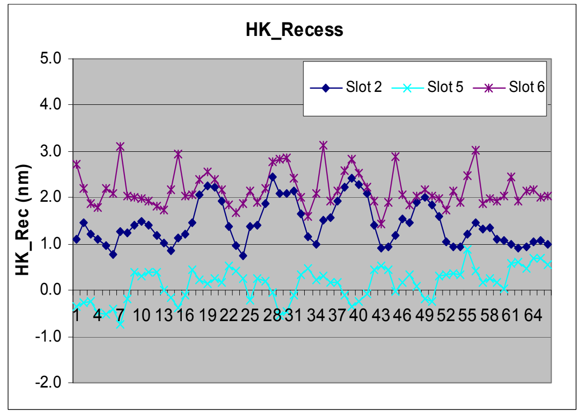

Figure 8b. HK recess versus HK DOE split.

The dynamic precision of critical parameters for HKMG AEI was measured on the POR wafer. The measurement was performed ten times with wafer load and unload for 11 sites. The average of 3 sigma precision is shown in figure 9. The results show that the SpectraShape 8810 has excellent precision for the critical parameters. The average of 3 sigma dynamic precision is less than 0.05nm for MG recess, 0.07nm for HK recess and less than 0.03 degree for SWA.

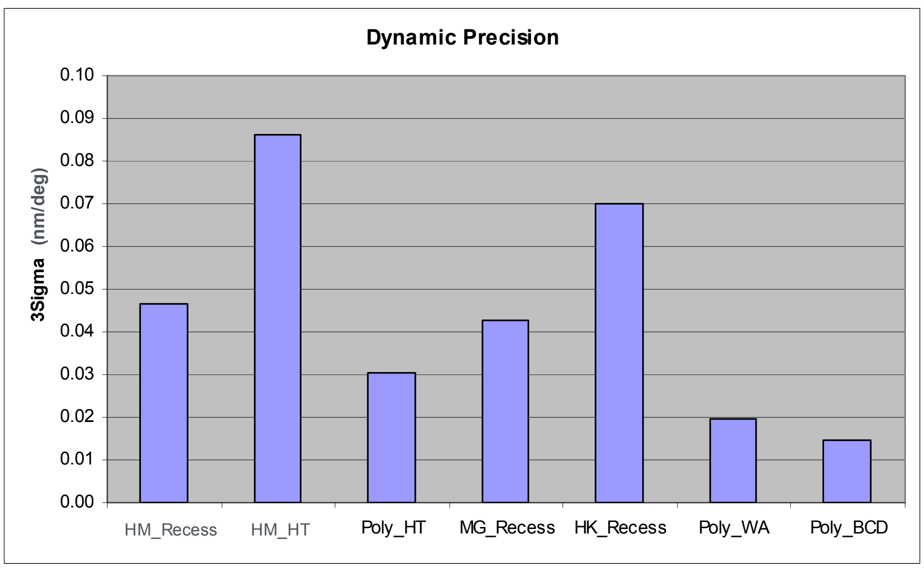

Figure 9. Dynamic precision of HKMG AEI.

2.3 Metal Gate AEI: Correlation to TEM

To verify in-line scatterometry measurement accuracy, a transmission electron microscope (TEM) is used as a reference. The correlation between scatterometry parameters versus TEM measurement has been studied. In this case, the TEM measured two sites, at the center and at the edge, for each wafer. This resulted in 14 total TEM data points in the DOE wafer set. The scatterometry measurement value at the same coordinate is compared with the TEM value. The MG/HK CD and MG/HK recess correlations between SCD and TEM are shown in figure 10. The R^2 correlation of metal gate CD and high k CD is about 0.97 and the slope is around 1.05. MG recess and HK recess are the most critical and challenging parameters. The SCD correlation with TEM shows a R^2 greater than 0.96 for MG recess and 0.95 for HK recess, and a slope around 1.0 +/- 0.03.

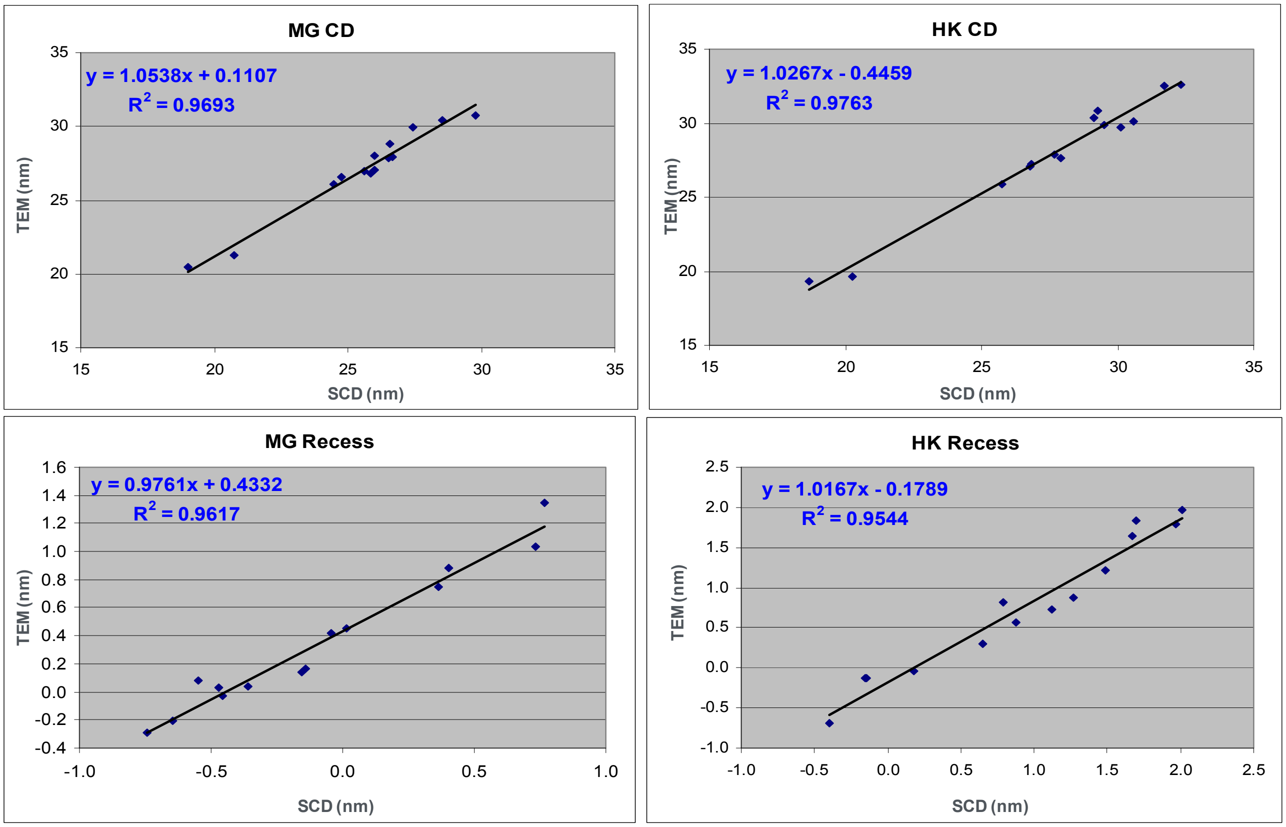

Figure 10. MG/HK CD and MG/HK recess correlation between SCD tool and TEM reference.

The summary of SCD to TEM correlation for all critical parameters is listed in table 4. These data show that for all critical parameters the R^2 correlation is greater than 0.95 and the slope is 1.0 +/- 0.05. These TEM correlation results confirm that the new generation SCD tool, SpectraShape 8810, can be used as an in-line monitor for the 28 nm high k metal gate etch process in production.

Table 4. Summary of TEM correlation.

Parameter	R^2	Slope
Poly WA	0.98	1.05
Poly BCD	0.97	1.03
MG CD	0.97	1.05
HK CD	0.98	1.03
MG_Recess	0.96	0.98
HK_Recess	0.95	1.02

3. SUMMARY

As semiconductor structures become increasingly complex, they require ever more sophisticated metrology for characterization and process control. A new generation SCD tool, the SpectraShape 8810, combines multi-AZ and multi-channel optical signals, providing the metrology performance required for advanced structures in metrics such as precision and accuracy. Data presented in this paper has demonstrated that this new generation SCD tool has good sensitivity and measurement repeatability for the 28nm HKMG ADI process. For AEI, this SCD tool has the sensitivity to track DOE conditions and the measurement results correlate very well with the reference TEM measurements. With its high sensitivity, high throughput, and nondestructive measurement capabilities, scatterometry CD metrology has proven to be suitable as a 28 nm High K Metal Gate ADI and AEI process monitor.

REFERENCES

[1] Matthew Sendelbach, Alok Vaid, Pedro Herrera, Ted Dziura, Xiafang Zhang, Arun Srivatsa, " Use of multiple azimuthal angles to enable advanced scatterometry applications", *Proc. SPIE* Vol. 7638, (2010).

[2] Thaddeus G. Dziura, Benjamin Bunday, Casey Smith, Muhammad M. Hussain, Rusty Harris, Xiafang Zhang, Jimmy M. Price, "Measurement of high-k and metal film thickness on FinFET sidewalls using Scatterometry", *Proc. SPIE* Vol. 6922, (2008).

[3] Sendelbach, M., Natzle, W., Archie, C. N., Banke, B., Prager, D., Engelhard, D., Ferns, J., Yamashita, A., Funk, M., Higuchi, F., Tomoyasu, M., "Feedforward of mask open measurements on an integrated scatterometer to improve gate linewidth control" in *Metrology, Inspection, and Process Control for Microlithography XVIII*, edited by Richard M. Silver, Proceedings of SPIE Vol. 5375 (SPIE, Bellingham, WA 2004) pp. 686-702.

[4] N. Collaert, M. Demand, I. Ferain, J. Lisoni, R. Singanamalla, P. Zimmerman, Y.S. Yim, T. Schram, G. Mannaert, M. Goodwin, J.C. Hooker, F. Neuilly, M.C. Kim, K. De Meyer, S. De Gendt, W. Boullart, M. Jurczak, S. Biesemans, "Tall Triple-Gate Devices with TiN/HfO2 Gate Stack," *2005 Symp. VLSI Tech. Dig. of Papers*, paper 7A-2.