Improving OCD Time to Solution using Signal Response Metrology

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ABSTRACT

In recent technology nodes, advanced process and novel integration scheme have challenged the precision limits of conventional metrology; with critical dimensions (CD) of device reduce to sub-nanometer region. Optical metrology has proved its capability to precisely detect intricate details on the complex structures, however, conventional RCWA-based (rigorous coupled wave analysis) scatterometry has the limitations of long time-to-results and lack of flexibility to adapt to wide process variations. Signal Response Metrology (SRM) is a new metrology technique targeted to alleviate the consumption of engineering and computation resources by eliminating geometric/dispersion modeling and spectral simulation from the workflow. This is achieved by directly correlating the spectra acquired from a set of wafers with known process variations encoded. In SPIE 2015, we presented the results of SRM application in lithography metrology and control [1], accomplished the mission of setting up a new measurement recipe of focus/dose monitoring in hours. This work will demonstrate our recent field exploration of SRM implementation in 20nm technology and beyond, including focus metrology for scanner control; post etch geometric profile measurement, and actual device profile metrology.

Keywords: Modeless optical metrology, in-line metrology, Lithography, Etch, Focus, Dose, CD, Accuracy

1. INTRODUCTION

As critical dimensions (CD) reduce to sub-nanometer region while transistor density on integrated circuits (ICs) increases exponentially, the number of critical patterning process steps with extremely unforgiving tolerances soar sharply and the associated precision limits of metrology techniques were driven down accordingly. Such demand forces the industry to pursue innovative solutions to enable superior accurate and quick turnaround metrology solutions continuously [2-3]. Meanwhile, in-line control requests on unconventional profile details in complex structures prevailed in advanced processes and integration schemes, such as side wall angle (SWA), spacer widths, spacer pull-down, epitaxial proximity, footing/undercut, over-fill/under-fill of 2-dimentional (HKMG), 3-dimentional profile(FinFETs) and line edge roughness (LER) [4-5]. Optical CD metrology has been widely-adopted in 20nm/14nm nodes and beyond, however, conventional RCWA-based (rigorous coupled wave analysis) scatterometry has the limitations of long time-to-results and lack of flexibility to adapt to wide process variations. Furthermore, often times this technique requires special designed targets that are both design rule (DRC) compatible and optimized at the patterning simplicity for computational limitations (RCWA models built for device structures usually come with reduce accuracy and extended turn-around timeline).

Due to all these limitations, there is a need for a new metrology that is fast, accurate, capable to measure DRC targets and operate as in-die metrology to direct measure device profile (such as SRAM cells), which naturally enables better yield correlation of process control by ruling out the discrepancies between test sites on frame and active devices. Conventional imaging metrology (CD-SEM) is used to measure critical dimensions on device structures, but has limited capability to measure complex structure details and introduce additional contamination/damage on photoresist. Optical metrology can provide more profile details and free of morphology or device electrical damage, but as phrased earlier, conventional RCWA-based solution requires sufficient diffraction based volume of repeating arrays and extensive engineering and computational resources, both are challenging for

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compact device design and cost-saving need. Implementation of SRM can be a good candidate to improve the time to solutions, it does not require a geometric model with optimized material dispersion, and it is less sensitive to non-fully periodicity noises than RCWA methodology, therefore it does not require substantial computing resources. The measurement set-up of a device-like structure is the same as design rule test site, in terms of hours. With significantly reduced turnaround time, SRM can provide cost effective solutions to establish correlation of geometric profile to electrical performance of real device, which is of great value to both development and yield ramp-up stages in semiconductor industry.

Last year, we presented detailed working mechanism and business flow of SRM, and demonstrated a field application with results and analysis of how the focus and dose information is captured by the photoresist profile, and how it propagates to the measurement signals using SRM technique [1]. In the past year, we explored a wider range of SRM application in GLOBALFOUNDRIES, at Malta. We will report results of scanner control, post etch profile control, device profile control, measurement size dependency analysis, and discuss its potential application in high volume manufacture environment.

2. EXTRACT PROCESS CONDITION USING SIGNAL RESPONSE METROLOGY

2.1 SRM Process Flow

SRM is a model-less metrology based on statistical analysis and unsupervised machine learning, through sensitivity analysis we select optimized raw signals, and individual profile parameter information will be directly extracted from raw signals using machine learning methodology. In general, we could divide the whole information extraction into two major steps, the first one is to train a process window algorithm, the SRM engine learns from the raw signals through Principal Component Analysis (PCA), extracting the process window and the relations among signals, mostly importantly, it convert the raw spectra data into an equivalent but reduced set of signals, named Principal Components (PCs). In this step, we filter the undesired higher order noises; maintain merely the information relevant to profile variance within the process window.

Secondly, the PCs and reference data are paired to train the parameter algorithm, which is a single hidden layer neural network in terms of machine learning. Each parameter algorithm is trained and optimized separately, in order to set up an individual parameter model for the target parameter as output. SRM uses an automatic optimizer to run cross validation of parameter models on training and testing set of signals, by minimizing the difference between these two sets, the SRM engine determine optimal value of the number of PCs, neurons and levels of over fit penalty, etc. We have a details discussion reported in SPIE 2015 [1], and the schematic of the process flow is shown in Figure 2.1.

2.2 SRM Properties

The statistical analysis and machine learning of SRM engine is the root cause of its superior improvements in time to solution. It is free of the RCWA-based computational complexity, therefore has not limitation of using a large number of raw data, the accumulating computational resource need is negligible and bring the benefit of more encoded profile variations would rather be forced to be left behind. In this work, all data were acquired from the KLA-Tencor Spectra Shape 9010 system, which employed large range of wavelengths, multiple azimuth angles provides a large set of signals that encode the information related to profile variations . The rich information content in the measured signals provides great opportunities for decoupling the correlation between profile components and from underlying structure. With the next generation tool, KLA-Tencor Spectra Shape 10K system equipped with more optical subsystems, it is anticipated that in future our model-less SRM engine will exhibit enhanced spectra response sensitives on smaller profile features. A good illustration is shown in the field application of monitor Focus control, we used signals from different structures of dense and isolated line/space gratings in order to de-correlate the target parameter from the variations of the under layer structures, we have reported some results in SPIE 2015 [1], will present more field cases in the results and analysis section.

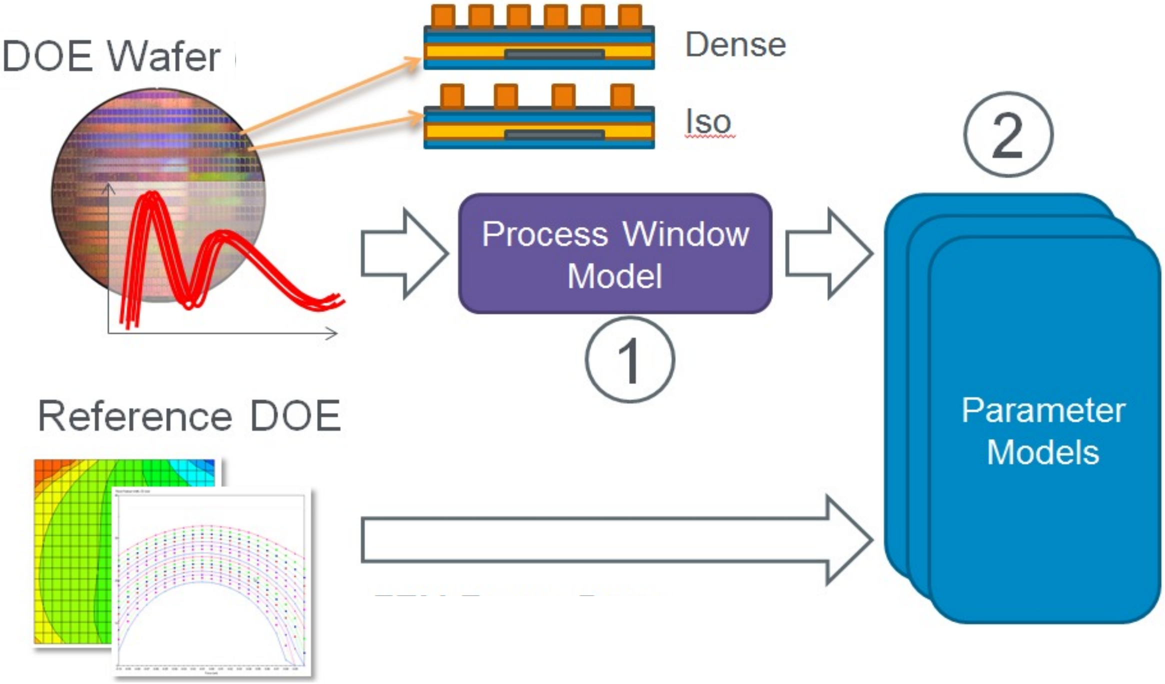


Figure 2.1. SRM Process flow: Process Window Model and multiple Parameter Models

In conventional RCWA-based scatterometry, models are embedded with approximations in geometric and dispersion simulation, which acts as systematic inaccuracies propagating to the final results, and usually the more complicated the geometry profile is targeted, the more approximations will be deployed. But the SRM methodology is free of approximations, and in terms of the data extraction process, there is no difference between raw data from design rule compatible targets and device-alike targets, engineers follow similar machine learning protocol to determine optimal value of the number of PCs, neurons and levels of over fit penalty for a particular parameter model, we have data shown measurements on SRAM structure with good matching across training and test sets. Additionally, since SRM's process training algorithm filters the high order noises by design, it provides high tolerance of surrounding contaminations, boundary interruptions and distortions. We have a field application of running line-scan on regular DRC test site (50x50 µm) with a roughly 25µm box-sized beam spot, same spectra input using conventional scatterometry model-based solution and SRM solution, while model-based solution reports significantly reduced goodness of fit and trailing off critical dimension parameter values beyond a 30µm desirable boundary, SRM solution mitigates the noise from the non-grating areas taken outside the 30µm desirable boundary, and is capable of maintain reasonable readouts. We tested SRM solution in an equivalent measurement using test site sized down to 15x15um and smaller than light source beam spot, the outcome shows good measurement merits matching well with CDSEM reference and will be presented and analyzed in details later in Section 3.

Being evaluated as a new metrology solution, the intrinsic measurement uncertainty of SRM technique is under careful investigation and we have results shown reduced uncertainty from SRM as metrology budget compared to reference metrology. In theory, we could reason such uncertainty superiority is coming from large raw data input from more wafers and test sites, during process window and parameter algorithm training, the SRM engine learns how to reject the errors in the reference data and could finalize a solution with much smaller measurement uncertainty than the reference data set. We have reported reduced residual of SRM compared to reference CDSEM in a Focus and Dose application in SPIE 2015 [1]. Using a simplified theoretical deduction to illustrate sources of variations below, where CDSEM is denoted as the reference data.

$$\sigma^2_{SRM\ measurement} = \sigma^2_{SRM\ intrisic} + \sigma^2_{wafer}$$
$$\sigma^2_{CDSEM\ measurement} = \sigma^2_{CDSEM\ intrisic} + \sigma^2_{wafer}$$
$$\delta_{SRM-CDSEM} = \delta_{SRM\ intrisic} + \delta_{wafer} - \delta_{CDSEM\ intrisic} - \delta_{wafer}$$
$$\sigma^2_{SRM\ measurement\ using\ CDSEM\ reference} = \sigma^2_{SRM\ intrisic} + \sigma^2_{CDSEM\ intrisic}$$

As it shown, we could deduce the contribution of each component to the measurement uncertainty, process variance, intrinsic metrology residual, reference metrology residual, provided the fair assumption that they are free of correlation. In reality, the measurement uncertainty could be dominated by the profile variances from the process, and SRM readouts have big variance as it, but while investigating the intrinsic uncertainty contribution of each component, random errors were averaged across multiple samples, SRM model leans how to eliminate the errors in the reference data and holds substantial smaller uncertainty value compared to the reference metrology and process variances.

3. RESULTS AND ANALYSIS

At GLOBALFOUNDRIES in Malta, NY, we carried series of experiments and analysis, using SRM to develop model-less optical metrology solutions in 20nm patterning and technology beyond. Including gate profile control post etch process, critical dimension measurements on SRAM features, and Focus control for litho process, multiple measurement steps locates throughout the process line.

3.1 Post Etch Profile and Reference Uncertainty

Patterning control post etch process is usually anchored on geometric profile spec, gate height, SWA as well as CD values, model-based scatterometry models is the state-of-art metrology solution but the slow turnaround pace hinder its implementation in early development stage. By using SRM, we could complete the solution delivery in much shorter cycles with good correlations to reference data, shown in Figure 3.1.

SRM parameter models for poly gate height, poly Bottom CD (BCD), poly SWA have good performance tracking profile variance. We have used two different reference sources: CDSEM and model-based scatterometry established different SRM parameter models and both versions have shown good results in Figure 3.1. This set of data is acquired from a group of production wafers fabricated with well-center process, parameter range is limit but the correlation trend is good in terms of tracking the process variances. Through eliminating modeling approximation and fixed-parameter errors, surrounding noise, SRM could provide superior metrology uncertainty compared to CDSEM and model-based OCD. In histogram plot shown in Figure 3.2, under dominating attribute of process variances in measurement uncertainty, SRM shows superior uncertainty control in all profile parameters, with respect to both CDSEM and model-based scatterometry.

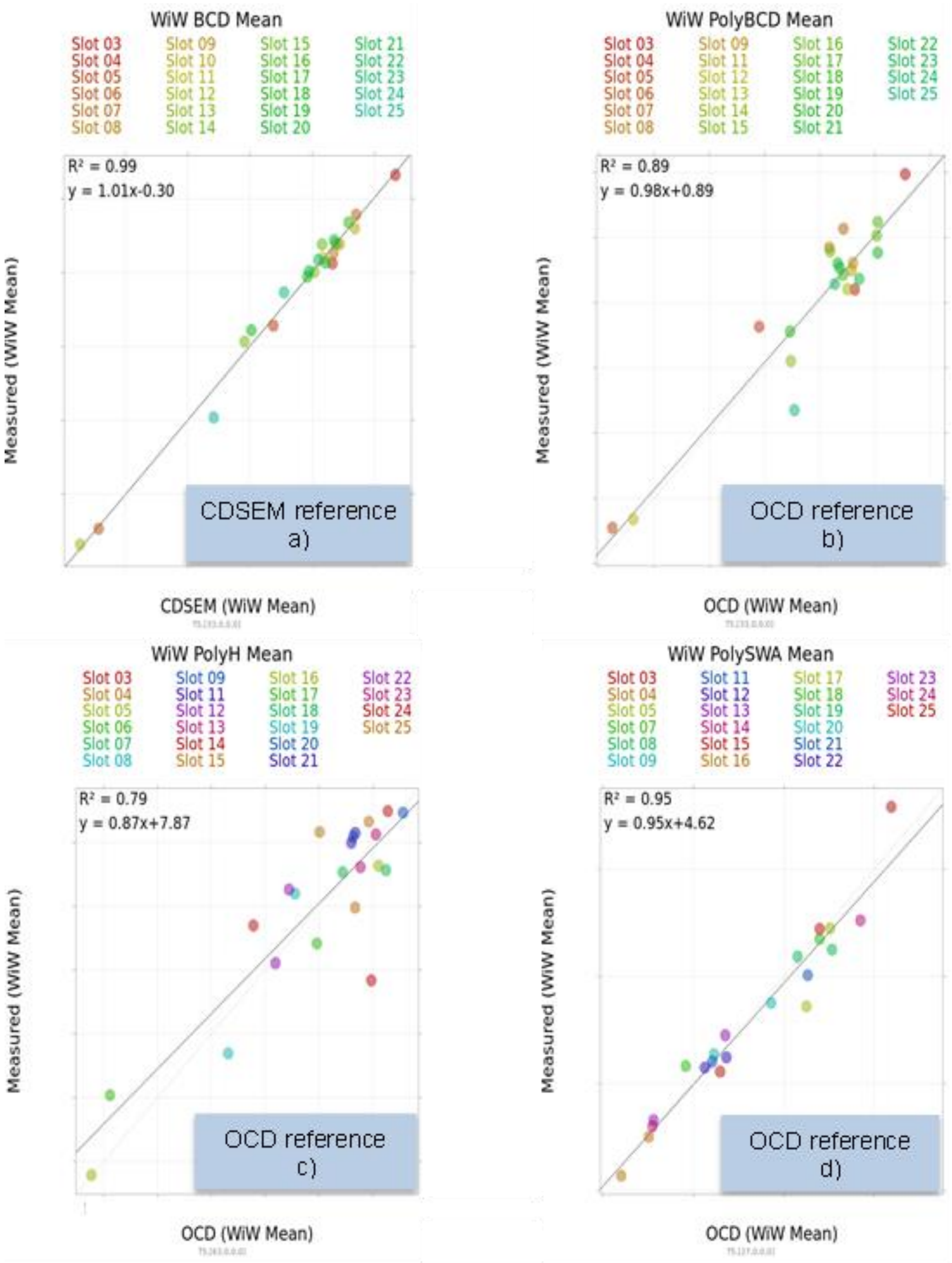
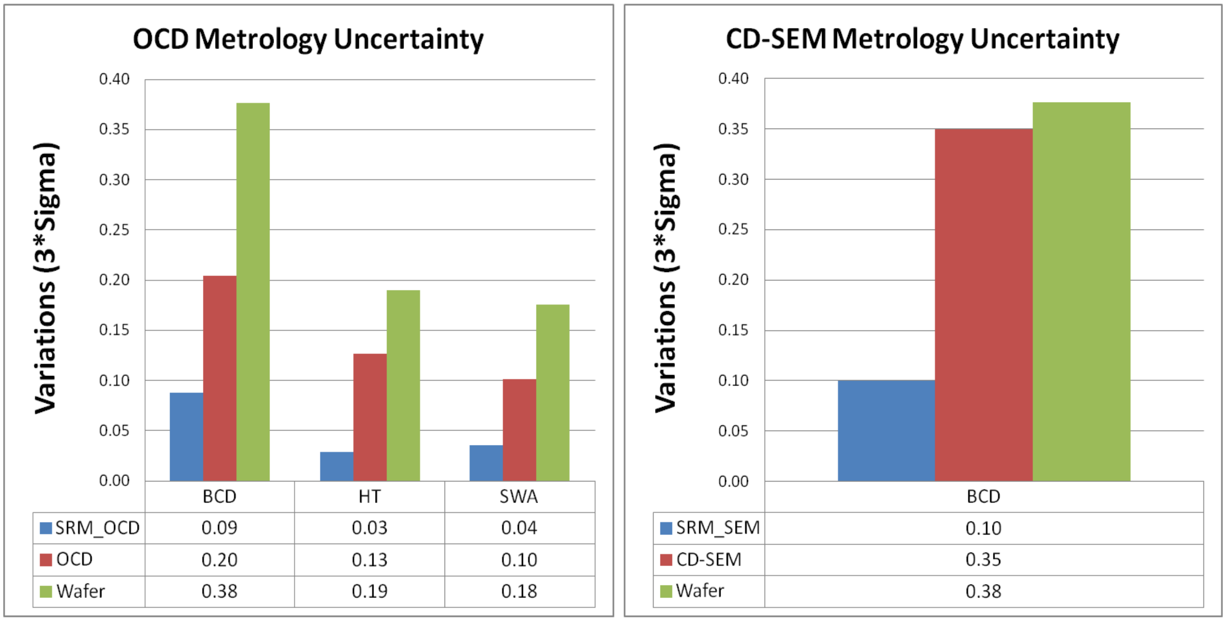


Figure 3.1: SRM parameter models of post etch profile in FEOL application, plotting poly BCD, Poly height c) and Poly SWA d), good matching between reference metrology of both CDSEM a) and conventional RCWA-based OCD models b). Normalized data used in X, Y-axis, 1.5 nm range for plot a) & b); 0.35nm for plot c); 0.5 degree for plot d)

3.2 Device Test Sites and Environmental Contamination Tolerance

In terms of SRM's machine learning methodology, there is no difference between rigid periodic design rule test sites and complicatedly structured, not-fully periodic devices, the metrology solution can be completed in 1 day in both cases. But it make big impact to process control if we could realize fast in-line measurements on device, e.g.

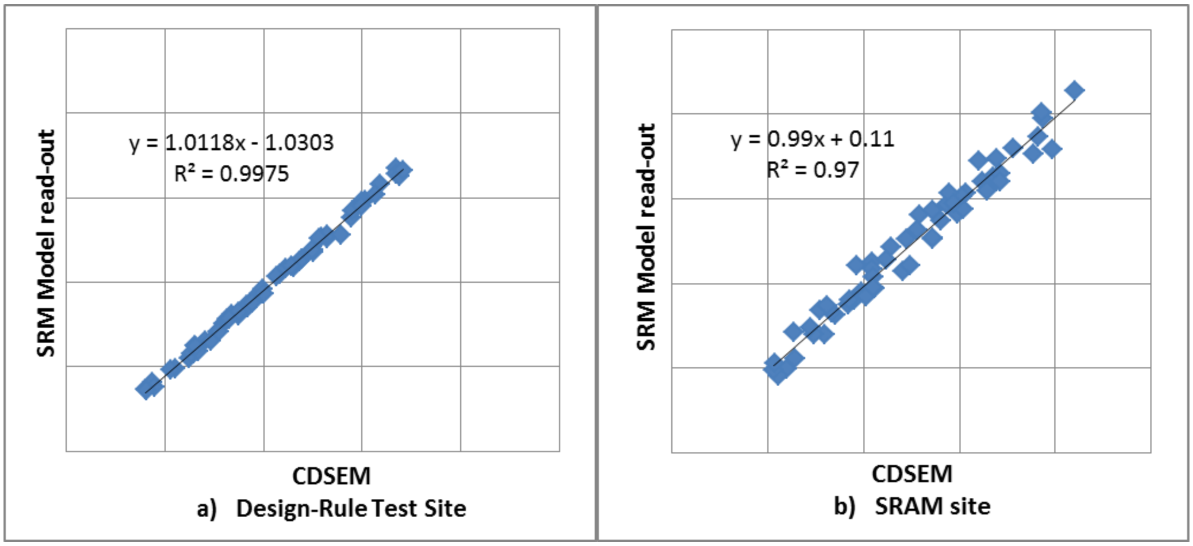
SRAM cells, which potentially enables direct correlation between process knobs and electrical test outcomes. To evaluate SRM capability on device profile, we specially picked two test sites on frame structure, one designed rule test site and one SRAM-alike test site, and two dedicated SRM models were developed for each test site, both of them have demonstrate good performance tracking process variances, and great correlation with reference CDSEM of R^2 close to unity, as shown below in Figure 3.3.



	BCD	HT	SWA
🟦 SRM_OCD	0.09	0.03	0.04
🟥 OCD	0.20	0.13	0.10
🟩 Wafer	0.38	0.19	0.18

	BCD
🟦 SRM_SEM	0.10
🟥 CD-SEM	0.35
🟩 Wafer	0.38

Figure 3.2: Metrology uncertainty comparisons between SRM, and reference metrology: CDSEM and model-based OCD. SRM shows superior performance on measurement uncertainty control in all parameter models, variation value scared in nanometer.



a) Design-Rule Test Site

b) SRAM site

Figure 3.3: Correlation of SRM results to reference metrology of CD-SEM on a 20nm FEOL post etch profile, good matching demonstrated on: a) design-rule OCD structure and b) SRAM-alike test site; measurement data was normalized in a 5nm range for both plots.

Then we take a step forward to compare design rule test site on frame with real device in-die, shown in Figure 3.4. This test is done on a set of designed of experiment (DOE) wafers in a 14nm FEOL post etches application. The spread on target parameter are behaving distinctively different across these two test sites, which is very good demonstration explaining why we need to directly measuring what indeed matters to patterning scheme, on real device. Both SRM parameter model developed for these two test sites show good tracking with process variation, provided the metrology solution is accomplished in 1 day turnaround cycle, the overall performance proven indicates SRM can be a good candidate to serve as solution for in-die metrology.

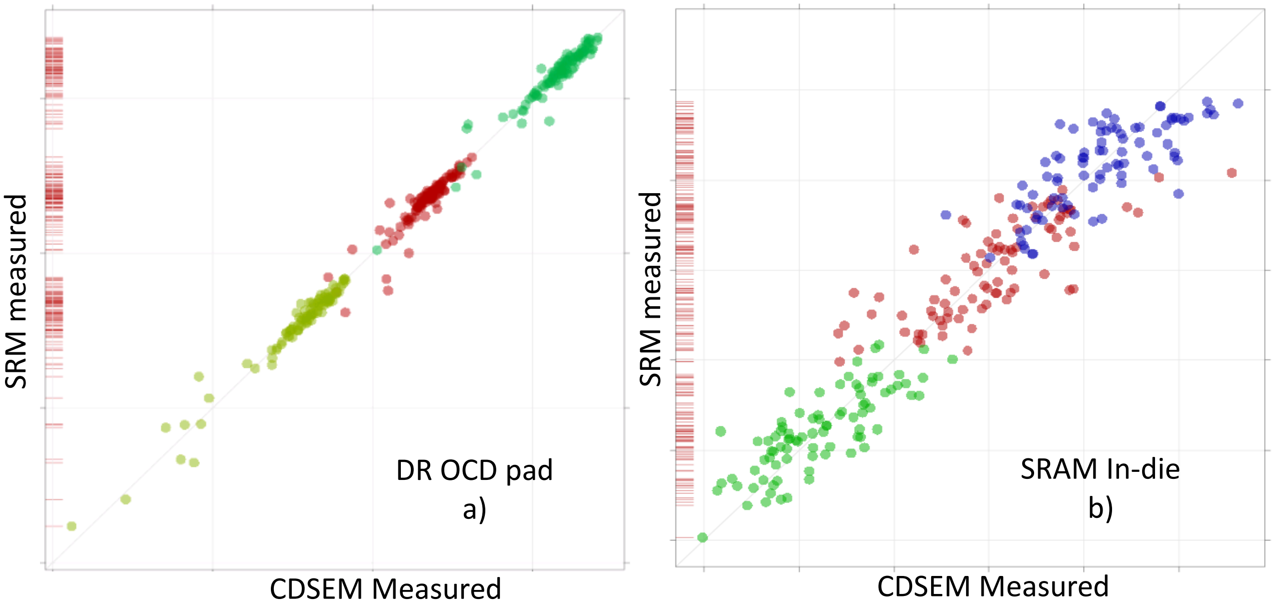


Figure 3.4: Correlation of SRM results to reference metrology of CD-SEM using a 14nm FEOL application, good matching demonstrated on: a) design-rule OCD structure and b) in-die SRAM device; measurement data was normalized in a 18nm range for a) 13nm range for b)

As we exploring the in-die measurement, one challenge occurred frequently is the test site selection; there are not many suitable choices in terms of traditional scatterometry thumb of rule, fully periodic arrays of sufficient size. Factors including but not limited to, comparable area size with respect to beam spot of the metrology instrument light source, periodicity of the array, under-layer infrastructure, could significantly affect the quality of model-based solution and time to establish a solution. However using SRM, we are exempt for these influences to some extent. In a designed experiment, we investigate how pad size of the test site would affect the SRM model compared to model-based scatterometry solution. We selected a test size smaller than the box size of light source, which has a replica of identical patterning scheme on a different location only with bigger size, and we have a model-based scatterometry solution established and verified with good quality on this bigger test site, a schematic is shown in Figure 3.5. When we test the raw data acquired from this smaller test site, the model-based solution failed with severe goodness of fit degradation, but using SRM, we still get decent correlation performance suitable for variation trend tracking. In the metrology uncertainty analysis shown in Figure 3.6, the measurement uncertainty contribution from SRM solution is comparable to the scale of its repeatability precision but significantly smaller than the reference measurement and the process variation, which is well below the control spec requirement for this parameter in this application. In this preliminary study on in-die device measurement feasibility, we have demonstrated promising data showing SRM is capable to tolerate non-fully periodic structures and abrupt boundaries within test area, in form of high-order noise filtering, and we are currently continuing the evaluation on more field applications in advanced technology nodes.
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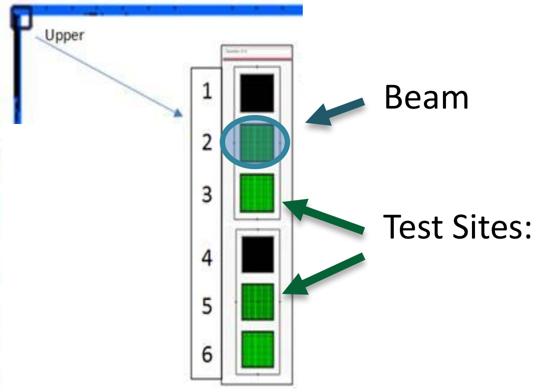

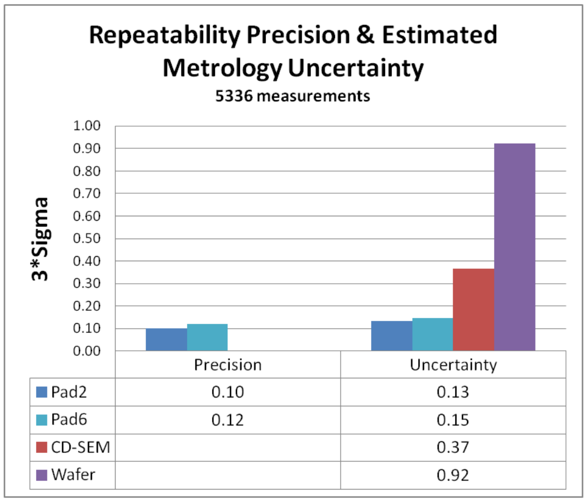

	Precision	Uncertainty
🟦 Pad2	0.10	0.13
🟦 Pad6	0.12	0.15
🟥 CD-SEM		0.37
🟪 Wafer		0.92

Figure 3.5: An illustration sketch of small test size experiment, we picked a set of test sites smaller than the spot size of the metrology instrument light source, plot on the left
Figure 3.6: Repeatability precision and metrology uncertainty analysis of the small test size experiment shown in Figure 3.5

3.3 Focus Control in High Volume Manufactory

In 2015, we reported field application results of Focus and Dose monitoring using SRM, in the past year, we explored Focus and Dose applications in more litho levels across different technology nodes, involving different resist materials and processing conditions, all showing good performance of R^2 and within wafer variance similar to FEM residual error level (systematic error). Figure 3.7 shows SRM training performance of a typical application in 14nm back end of line (BEOL), the offset between measured and programed focus inputs of Focus Exposure Matrix (FEM) wafer has a variance of $3\sigma = 0.15$, which agrees with the expectation of scanner focus error for this layer. Figure 3.8 shows the SRM testing performance on focus split and POR wafers, the reported results demonstrated a Focus tracking performance of $R^2 = 0.99$ and random residual distribution. All Focus values are normalized by the range of each parameter respectively in an artificial range of 0.5 to -0.5.

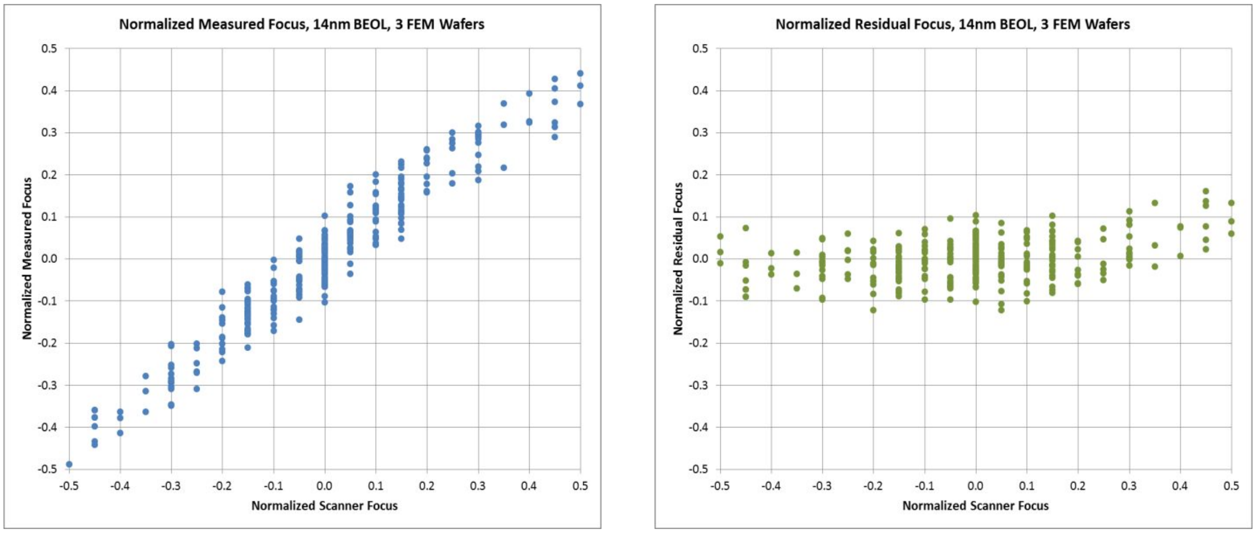

Figure 3.7: SRM measured Focus of the FEM wafer plot against scanner input values (left), SRM measured Focus residual errors with respect to scanner input value (right), and all Focus values are normalized by the range of each parameter respectively in an artificial range of 0.5 to -0.5

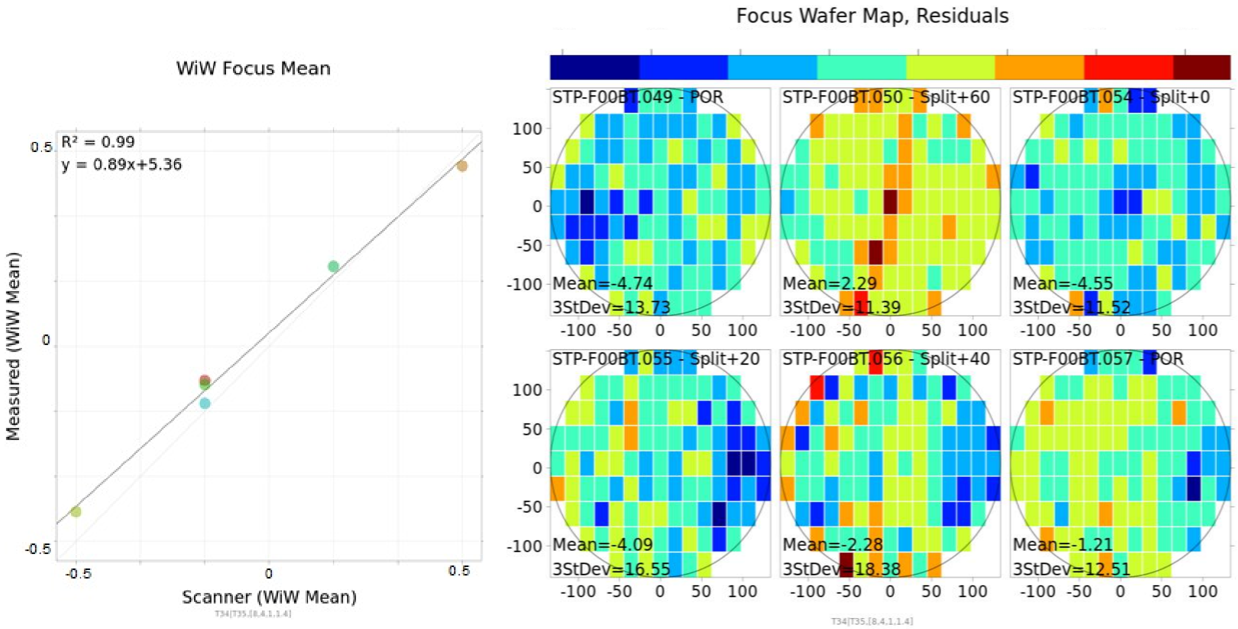

Figure 3.8: Wafer mean of SRM measured Focus is plotted against Scanner input values (left) for 4 Focus split and 2 POR wafers and wafer map plot of the residual errors of the 6 wafers (right), this error value includes the wafer variances and shows no systematic changes across the wafer

We have substantial data showing SRM can perform robust measurement control on Focus, and we are working closely with supplier, KLA-Tencor on the implementation of SRM-based Focus control on product wafers in high volume manufactory.

4. CONCLUSIONS

In this paper we presented a new approach for model-less optical metrology: Signal Response Metrology (SRM). We summarized the mechanism and process flow of how SRM extract process variances from raw signals. Based on experimental data we demonstrated SRM's capabilities for measuring geometric profile post etch process, through investigating source of metrology uncertainty, we performed in-depth analysis of residual errors from process, reference metrology and SRM solutions, the results from multiple applications all suggested SRM solutions have the superior low residual error contributions compared to CDSEM and traditional RCWA model-based metrology. In addition, we continued to test SRM measurements on DRC and device-alike/SRAM test sites, both solutions accomplished within a short turn-around time frame, while SRAM test site's solution provide comparable performance with noisy reference data. Furthermore, the study on test site smaller than optical beam source was carried out to test surrounding contamination effect, our findings proved SRM can be a very promising solution to tolerate the non-fully periodicity and filter out the high order boundary noise. Thus, we conclude that SRM is a suitable alternative for optical metrology in advanced tech nodes, capable of producing robust, fast turn-around solutions for both DSC and device test sites. We are currently working on stress test the SRM's capabilities on more challenging applications on device profile as well as the enablement of SRM's Focus control applications in high volume production environments. We are also interested in evaluating the hybrid options to integrate SRM with other metrology methodologies as well data mining system.

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