The Next Generation of SRM Technologies

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Abstract – The demand for accurate measurements of complex 3D structures, on-device or on small targets increases with each technology node. Today Signal Response Metrology (SRM) demonstrates superior performance over the existing technologies in litho application – measuring focus, dose and CD on product and device. In this paper we explore the next generation of SRM technologies applied to areas such as etch applications, on-device measurement, tool matching and computation acceleration. These technologies demonstrate significant differentiation and improvements compared to the existing technologies. We explain the fundamental reasons and demonstrate applications in various areas. The purpose of this paper is to share experimental and simulation results and inspire new innovations in currently unexplored enough areas such as imaging, X-ray, inspection and process control.

I. Introduction to Signal Response Metrology (SRM)

Signal Response Metrology (SRM) transforms the information from the raw metrology signals into parameters (see **Fig. 1**). The signals could be from Spectroscopic Ellipsometer (SE), Reflectometer, images or other sources that contain information about the parameters. Instead of modeling, SRM leans from real spectra collected from real structures on the wafer.

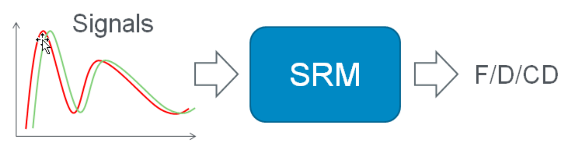

Fig. 1. SRM transforms signals into Focus, Dose and CD parameters.

SRM is based on machine learning, statistical analysis and information theory. SRM models are trained by using raw signals and the corresponding reference data (see **Fig. 2**). The reference data could be CD-SEM, AFM or OCD measurement. For focus/dose recipe (in Litho) the scanner programmed focus and dose values can be used as a reference.

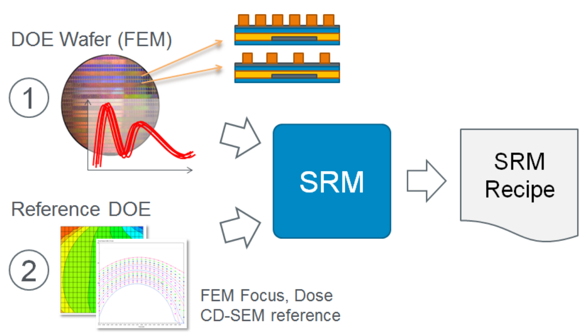

Fig. 2. Raw signals and reference data are used for training SRM recipe.

SRM training (**Fig. 3**) is performed in two steps.

First, a process window model is developed using the raw signals. It learns the process window boundaries and the relationship among signals. We use PCA model for this purpose. In addition, it reduces signal dimensionalities from thousands to few principal components.

Second, a parameter model is created for each parameter of interest. The input and output of the parameter models are the principal components and the reference parameters. They learn the relationship between signals and parameters. The reference data is used in the process of the parameter models training.

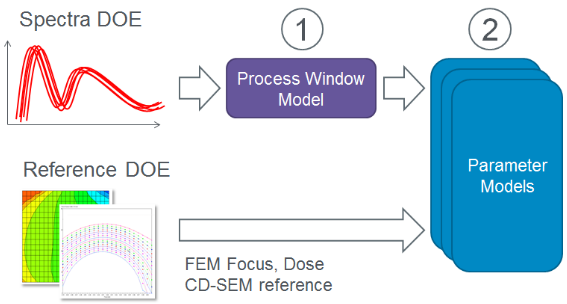

Fig. 3. Training process involves training process window model and parameter models.

These two models represent the SRM recipe that can be used for online monitoring and process control (see **Fig. 4**).

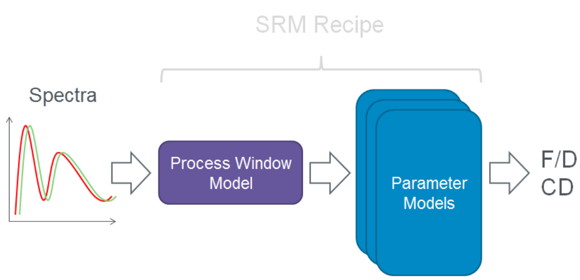

Fig. 4. On-tool SRM measurement.

When the recipe is loaded on tool and new signals are provided as an input they are transformed into principal components and then later into parameters .

II. Unique properties of SRM

The power of the SRM could be described with a number of unique properties which demonstrate various advantages to competing technologies such as Diffraction Based Focus (DBF), CD-SEM and traditional model-based OCD.

A. Precision

SRM uses 5x to 10x more signals compared to the traditional OCD. This improves the precision of the measurements by reducing the random measurement noise. Using all signals also contributes additional information.

B. Accuracy

SRM leans from real signals collected by real systems from real devices. In comparison, the model based OCD relies on accurate models of dispersion, geometry and systems. Many of them are approximations leading to errors.

SRM does not have floating parameters, so it doesn't suffer from fixed parameter errors (FPE) – the biggest contributor of errors in traditional model-based OCD.

SRM is also accurate in representing the process behavior because, it measures design rule (DR) targets and directly on-device. Some competing technologies are limited to special design targets (DBF) that prevents them from measuring on-device or DR targets.

C. Time to results

Setting SRM recipe is straightforward and simple. It does not require modeling or special target design which could take weeks. An SRM recipe can be set up in less than one hour. The competing technologies require much longer time due to complex modeling and time consuming computation (traditional OCD) or special target design and test (DBF).

D. Mixing technologies

Hybrid metrology is natural for SRM. Since SRM doesn't depend on the input signals' types and only depends on the information encoded into the signals, it is easy to mix different signal types (e.g. scatterometry, imaging, X-ray). Scatterometry and CD-SEM are also commonly used together during the recipe development, which is another kind of hybrid metrology.

III. The brave new world of Signal Response Metrology

A. Machine learning, statistical analysis and information theory

SRM is based on machine learning, statistical analysis and information theory. Instead of modeling the whole system of dispersions, geometries, parameters and optical systems (generative model), SRM models only one parameter at a time (discriminative model) andit minimizes the errors of other parameter and process changes or sources of errors.

As the complexity of semiconductor devices increases (see **Fig. 5**), the need for floating (modeling) a large number of parameters (degrees of freedom DOF) in traditional model-based OCD becomes critical.

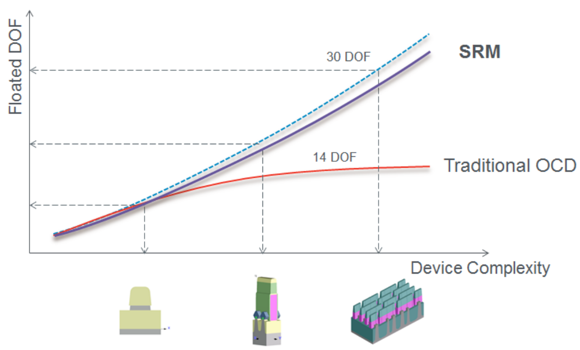

Fig. 5. SRM's capability.

Traditional OCD has limitations of how many DOF it can handle due to correlations and low sensitivities. Usually the floated parameters are less than 15, where the total number of dimensions that change could be over 30. When a parameter is fixed and it changes in the real device then FPE immerses in the rest of the floated parameters. SRM measures one parameter at a time and accounts for the rest of the parameter and process changes. There is no limit for the number of parameters that SRM can measure from a single structure.

B. SRM Etch – how to replace CD-SEM

Scatterometry provides superior precision and higher throughput compared to CD-SEM. The main obstacle for replacing the CD-SEM tools with KT scatterometry tool is the time for setting up a recipe. With CD-SEM a user can set up a recipe in 30min, where the traditional OCD takes days and weeks.

SRM has short recipe development time and all the advantages of the scatterometry signals, which makes it a better alternative for CD-SEM replacement (see **Fig. 6**). It uses the same CD-SEM noisy data as a reference in order to train a recipe that will outperform and eventually replace the CD-SEM as an online metrology.

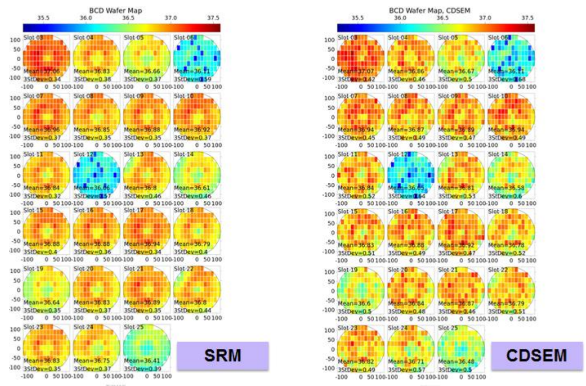

Fig. 6. Comparison between SRM and CD-SEM measurements on same wafers. CD-SEM data is much noisier than SRM.

In general, SRM has the capability to minimize the random errors in the reference data. **Figure 7** shows the errors as a function of reference data errors for focus models.

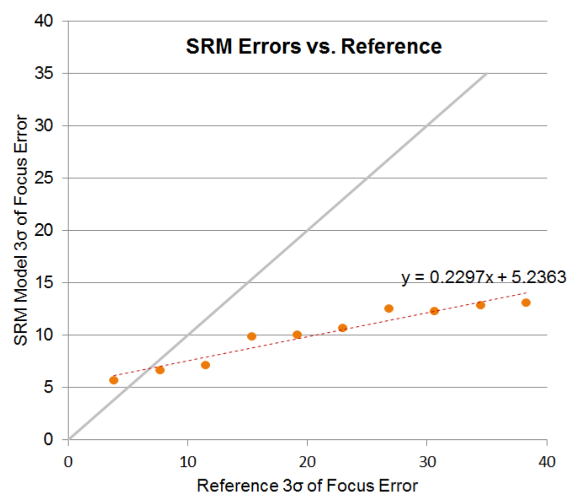

Fig. 7. Large reference errors have a small effect of the SRM measurement errors.

C. Small targets measurements – reducing the box size to the extreme

The continuous shrinking of devices makes the real estate allocated for metrology targets expensive. For traditional OCD technology, the metrology target needs to be larger than the illumination spot. Illuminating smaller targets produces distortions to the measurement signals. The traditional model-based OCD compares the measured signal to the modeled computed signals. If the measured signals are contaminated due to overfill, then the signals don't match and it fails. SRM does not require physical modeling of the signals. As long as the signals contain information about the parameters, SRM can extract it even if the signal is contaminated by the target surroundings. The smallest effective box size we tested with SRM analogous methods successfully was 7x7µm by using 15µm spot size.

Figure 8 shows SRM CD measurements from small targets with overfill. SRM has a good correlation to CD-SEM.

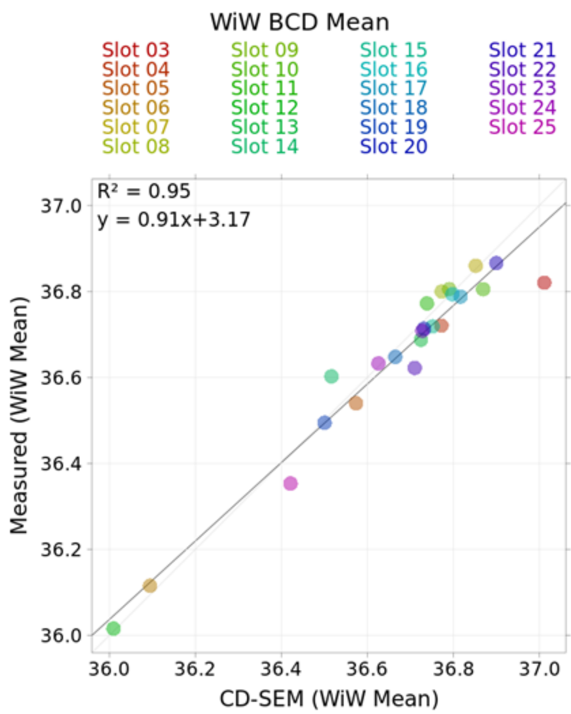

Fig. 8. Good wafer mean correlation between SRM CD measurement and CD-SEM

D. On-Device measurements – more accurate metrology for fraction of the time needed for traditional OCD recipe

Customers prefer on-device measurement instead of measurement on metrology targets because of better correlation to process behavior (better process control) and saving real estate in-die.

Devices are usually complex 3D structures that require complex modeling and parameterization. It takes significant (sometimes impractical) amount of time and resources to compute the simulated signals.

SRM doesn't require modeling or large computational resources, and can perform accurate measurements directly on device. **Figure 9** shows SRM litho CD measurements on SRAM device structure.

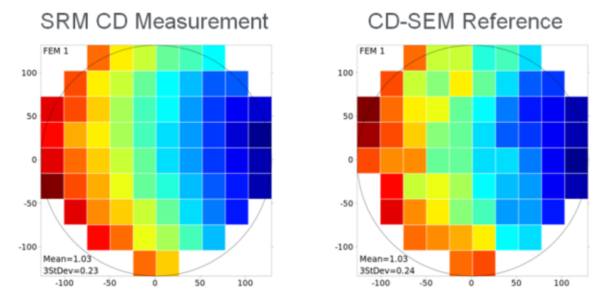

Fig. 9. SRM CD measurement directly on SRAM device

Conclusion

In this paper, we briefly introduced Signal Response Metrology. We described its unique properties and the differentiations with other competing technologies. We explored the new opportunities that the next generation SRM technologies create. We believe that the machine learning, statistical analysis and information theory will significantly change the metrology world. We see significant benefits of applying the next generation of SRM technologies in areas such as etch metrology, small targets measurement, on-device metrology.

The diversity of applications of the next generation of SRM technologies indicates that we can gain same level of benefits and differentiation applying it to areas such as inspection, imaging, X-ray and process control.

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