# A Sharper Image

## Feed-Forward Spectroscopic Ellipsometry Improves Profile Measurement Accuracy

*Robert M. Peters, Suresh Lakkapragada* – KLA-Tencor Corporation

This article presents a method for improving correlation of advanced gate lithography optical profile measurements to those of a critical dimension atomic force microscope (CD-AFM). By coupling a spectroscopic ellipsometry (SE) film measurement to a subsequent grating measurement, accurate values for underlying films are fed-forward to the grating measurement. This allows for reduction in the degrees-of-freedom during the grating measurement, which reduces parameter cross-correlation.

SE-based optical metrology methods have now gained a strong foothold for measuring the two-dimensional profiles of integrated device features. Optical metrology generally provides superior performance compared to other methods, but there still remain some challenges in terms of precision and accuracy requirements as device geometries continue to shrink at an aggressive rate.

Process engineers use several new techniques to meet device patterning requirements while maintaining manufacturing-worthy process windows. These include thinning the photoresist layers and adding under-layer films to act as hard masks for subsequent pattern transfer steps. Thinning the photoresist layer reduces the aspect ratio of patterned grating targets, which in turn reduces the signal-to-noise ratio (SNR) of the optical profile measurement. The additional films in the process stack below the gratings increase the number of optical interfaces that must be taken into account when building the optical model for the measurement. The increased complexity of the optical model increases the likelihood of cross-correlation between the underlying films and the grating profile parameters, such as CD, height and sidewall angle (SWA). Moreover, the lower SNR and higher cross-correlation negatively impact the precision and overall accuracy of the reported values for these grating profile parameters.

This paper discusses a methodology to overcome these issues. It involves performing a standard SE film thickness measurement on an open pad area in close proximity to the grating target of interest. The thickness values are then fed-forward to a subsequent SE measurement of the grating target. With the under-layer thickness values fixed based on the film thickness measurement, only the grating profile parameters are solved for during the grating measurement. Decoupling the under-layer film measurement from the grating measurement greatly reduces (or even eliminates) cross-correlation between parameters. Both SE measurements are completed within a total move-acquire-measurement (MAM) time of <10 seconds per pair, and the resulting values reported for CD, height and SWA are more accurate compared to reference metrology such as AFM.

Supporting data is presented from measurements taken on a 65nm technology node gate lithography process. Using the feed-forward process, the correlation and slope of profile parameters measured via SE compared to AFM measurements is greatly improved. Furthermore, systematic anti-correlation between resist height and SWA, observed during simultaneous measurement of the film stack and grating, is eliminated when the film measurement is decoupled and fed-forward into the grating measurement.

### SE-based Measurement Technique

The SpectraCD™ measurement based on SE technology is described in detail in previous publications[1,2,3]. For a SpectraCD measurement, a grating target is placed in the path of the SE beam. The grating comprises line/space features of uniform period, with the line width (CD) and period designed to represent the physical device feature under control.

SpectraCD measurements are completed using one of two separate methods: CDExpress™ (regression based) or library mode. Schematic representations of both methods are shown in figure 1. In both cases, the spectra measured by placing the grating target under the SE beam are compared against spectra based on a theoretical model of the grating. Both modes use process information (dispersion properties and nominal thickness of all films in the grating region) and estimation(s)

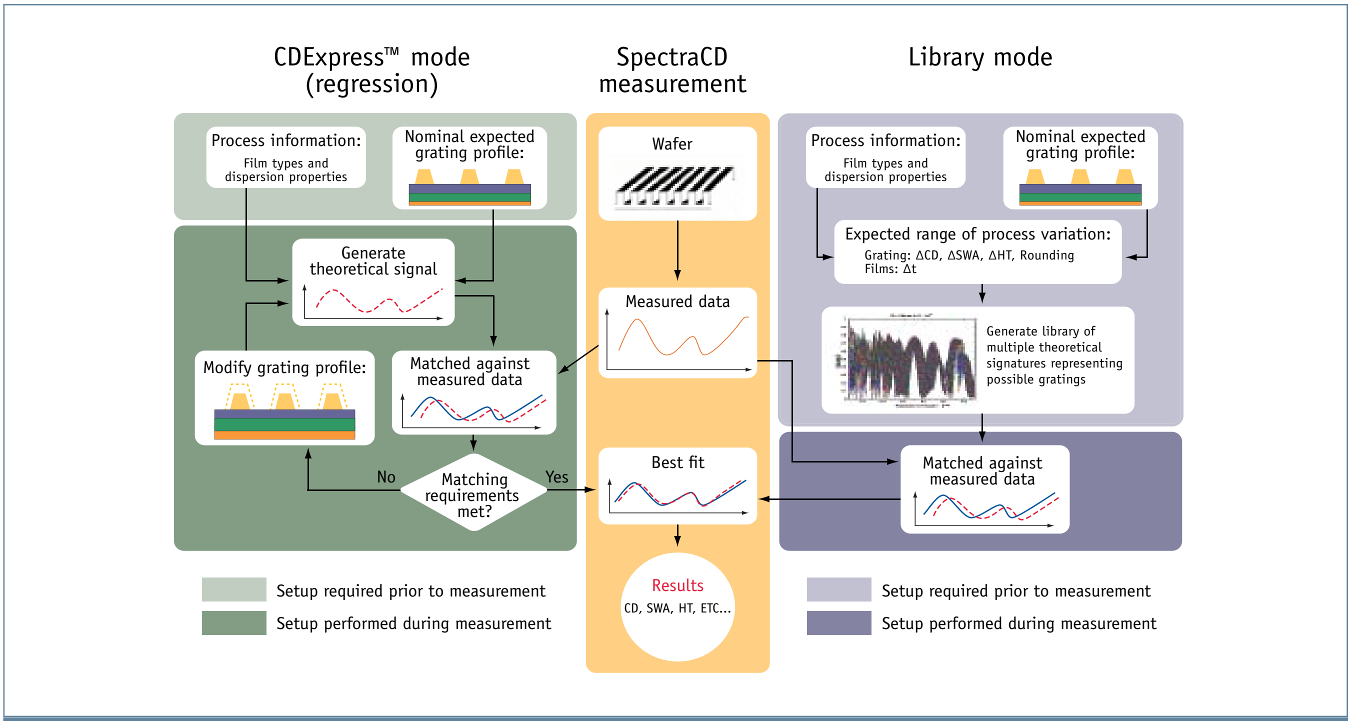


Figure 1: Schematic of SpectraCD measurement modes.

of the grating profile (pitch, nominal CD and height) to generate the theoretical spectra. Benefits and tradeoffs of the two measurement modes are described in previous publications[4].

thickness of these films is on the order of a few hundred angstroms. Using this dual hard mask stack allows for the photoresist to be thinned down to final patterned

**The correlation between the optical profile and the AFM measurements is significantly improved.**

## Advanced Gate Lithography Process

Figure 2 details a typical gate after-develop-inspect (ADI) process stack at the 65nm node. An optimized combination of two separate, yet similar, dielectric films is deposited on top of the polysilicon that is to be etched. This achieves tight CD control while increasing etch selectivity. The combined

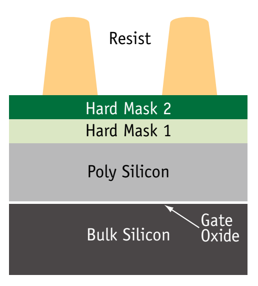


Figure 2: Schematic of advanced gate lithography stack.

heights below 2,000 angstroms. Thinning the photoresist helps expand the exposure and focus process window that provides an acceptable resist profile for pattern transfer.

## Correlation Issues with Single-Pass SE

In a typical SpectraCD measurement, all parameters of interest are simultaneously solved for in a “single-pass”. In the case of the aforementioned gate lithography measurement, the signal response and sensitivity to the underlying films requires that the thickness of both hard mask films be floated in the model, in addition to the CD, SWA and height of the resist grating. This leads to a five degrees-of-freedom (5 DOF) solution.

Here, SpectraCD measurements for the gate litho process are correlated against a CD-AFM that is routinely calibrated to a NIST traceable standard. The correlation results between SpectraCD and the AFM for a single-pass library match are shown (blue lines) in figures 3-5. The correlations are generally good for middle CD and resist height, with $R^2$ values > 0.93. However, the slope of the line for resist height does deviate ~20% from unity (figure 4). In contrast, the correlation for the resist SWA is very poor (figure 5).

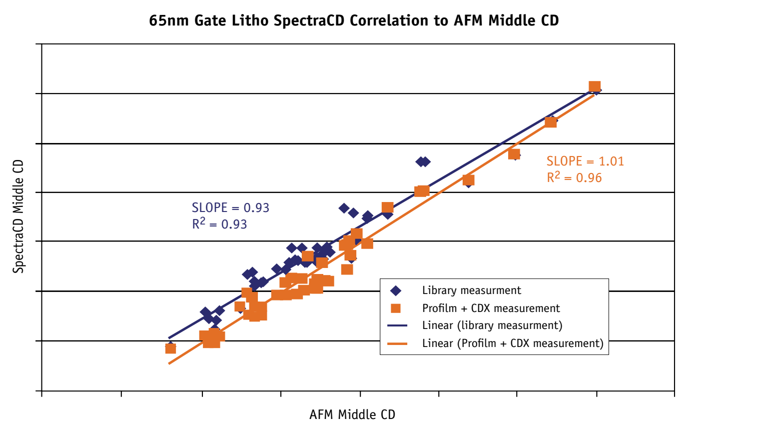


Figure 3: Resist middle CD correlation between SpectraCD and AFM (blue), with correlation improvement using Profilm (orange).

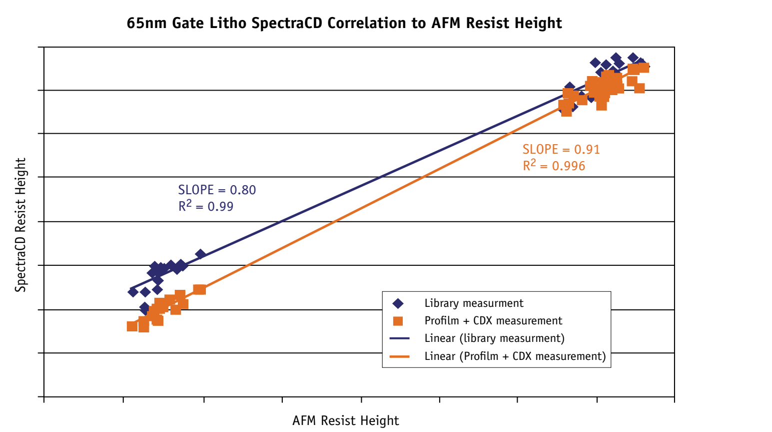


Figure 4: Resist height correlation between SpectraCD and AFM (blue) with correlation improvement via Profilm (shown in orange).

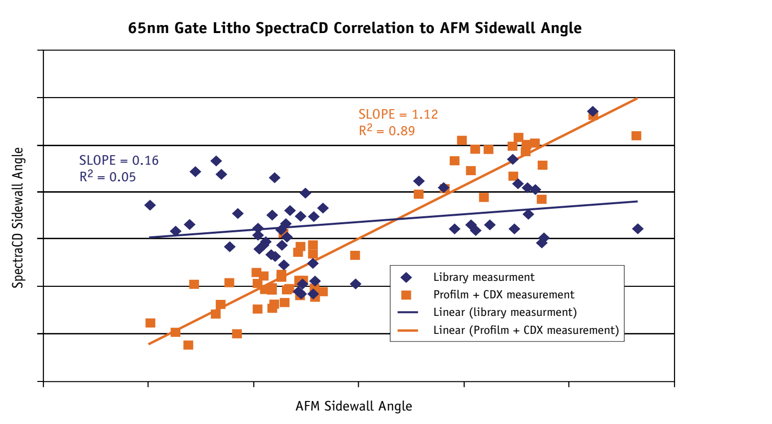


Figure 5: Resist sidewall angle correlation between SpectraCD and AFM (blue), with significantly improved correlation using Profilm (orange).

Furthermore, when the SpectraCD site-by-site results for resist height and SWA are plotted on the same chart, a clear anti-correlation behavior is seen between these two parameters (figure 6, top). SWA decreases as resist height increases, and vice-versa. This is counter-intuitive to typical behavior of the resist profile through the focus/dose process window.

The poor correlation on SWA, slope deviation from unity on height, and the anti-correlation behavior between SWA and resist height suggest cross-correlation between parameters in the model. An effective method is needed to overcome this limitation.

## Feed-forward SE Measurement (Profilm)

One potential method for reducing or eliminating cross-correlation is to minimize the number of parameters in the simultaneous solution. To get accurate solutions for the remaining parameters, however, you need to remove the influence of the excluded parameters from the measured signal or find a way to accurately account for some parameters and fix them during the measurement. It is difficult to remove the influence of any individual parameters from the measured signal, but since the SpectraCD measurement is an extension of a standard SE measurement, it is possible to accurately measure the underlying film thickness values using SE and then feed those values forward to fix them during the SpectraCD grating measurement.

Figure 7 shows a schematic of this technique (known as Profilm). In step 1, a standard SE film thickness measurement is performed in an unpatterned region where the resist has been exposed. From this measurement, accurate values for the underlying polysilicon, hard mask 1, and hard mask 2 films are obtained. Typically, this measurement is performed at a location within a few hundred microns of the location of the grating target of interest.

On-tool software links the SE film measurement directly to the subsequent grating measurement and feeds the film thickness values into a CDExpress regression-based measurement of the grating. During the CDExpress measurement (step 2) the film thickness values are fixed, thus reducing the CDExpress solution from 5 DOF down to 3 DOF (CD, height, and SWA). The combined measurement of the films and gratings is completed in real time with a total MAM time of ~9 seconds per measurement pair. The underlying assumption is that the uniformity of the film thickness is such that the thickness values do not change significantly over the few hundred microns between the open region and the grating region.

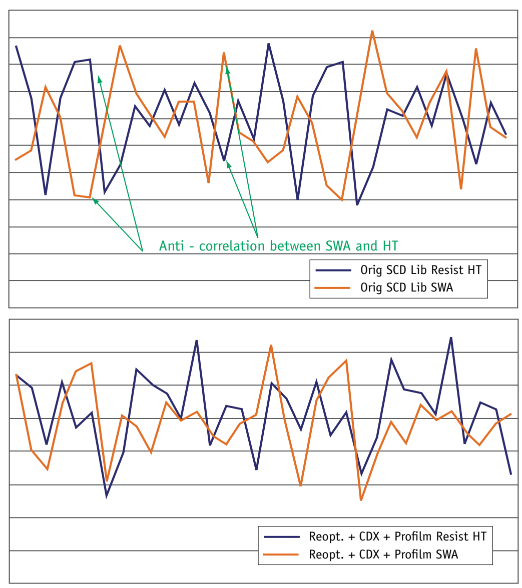


Figure 6: Resist height and SWA anti-correlation between SpectraCD and AFM (top) with dramatically lower anti-correlation exhibited using Profilm (bottom).

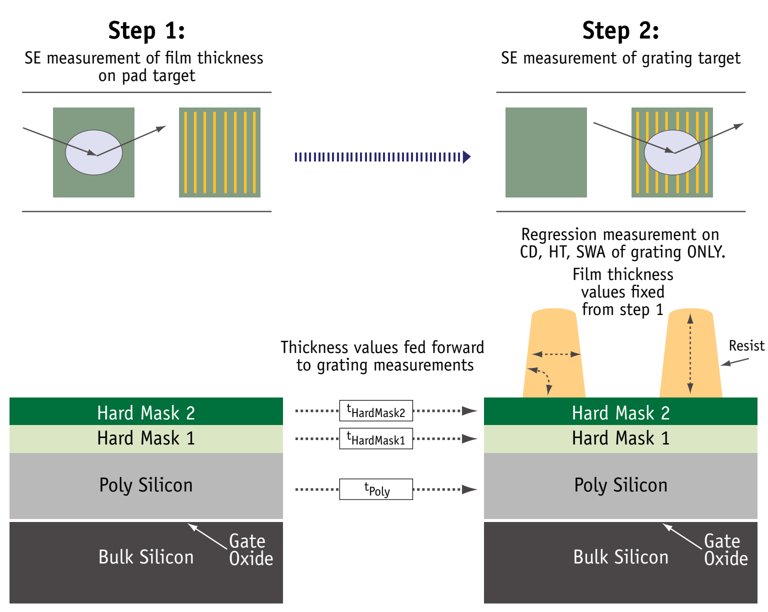


Figure 7: Schematic of Profilm feed-forward measurement.

## Profilm Improves Correlation Results

By reducing the number of degrees of freedom in the SpectraCD measurement, the expectation is that small perturbations in the measured signal are handled more appropriately and assigned to the appropriate parameter of interest. Data in figures 3-5 (shown in orange) demonstrate that this concept works. Comparison of standard single-pass library results against Profilm results are shown for resist middle CD and resist height in figures 3 and 4 respectively. There is some improvement in $R^2$ for both parameters, but, more significantly, there is improvement in slope to values closer to unity. Using Profilm, the correlation between the SpectraCD SWA and the AFM SWA (figure 5) is significantly improved. The slope is much closer to unity, and the $R^2$ value is increased from 0.05 to 0.89. Finally, the site-by-site trend of SWA and resist height shows that the anti-correlation behavior between these two parameters is greatly reduced, if not completely eliminated (figure 6, bottom).

In sum, this article shows a method and supporting data to highlight an effective approach to reduce cross-correlation for a 65nm gate lithography process. Anti-correlation behavior between resist height and SWA is significantly reduced, while correlation of the optical profile measurements to CD-AFM is improved for all parameters of interest. These measurements are completed in real time in a full production environment with a MAM time of ~9 seconds per measurement pair.

## Acknowledgements

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