Spectral tunability for accuracy, robustness, and resilience

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Spectral Tunability for Overlay Accuracy, Robustness and Resilience

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ABSTRACT

In overlay (OVL) metrology the quality of measurements and the resulting reported values depend heavily on the measurement setup used. For example, in scatterometry OVL (SCOL) metrology a specific target may be measured with multiple illumination setups, including several apodization options, two possible laser polarizations, and multiple possible laser wavelengths. Not all possible setups are suitable for the metrology method as different setups can yield significantly different performance in terms of the accuracy and robustness of the reported OVL values. Finding an optimal measurement setup requires great flexibility in measurement, to allow for high-resolution landscape mapping (mapping the dependence of OVL, other metrics, and details of pupil images on measurement setup). This can then be followed by a method for analyzing the landscape and selecting an accurate and robust measurement setup. The selection of an optimal measurement setup is complicated by the sensitivity of metrology to variations in the fabrication process (process variations) such as variations in layer thickness or in the properties of target symmetry. The metrology landscape changes with process variations and maintaining optimal performance might require continuous adjustments of the measurement setup. Here we present a method for the selection and adjustment of an optimal measurement setup. First, the landscape is measured and analyzed to calculate theory-based accurate OVL values as well as quality metrics which depend on details of the pupil image. These OVL values and metrics are then used as an internal ruler ("self-reference"), effectively eliminating the need for an external reference such as CD-SEM. Finally, an optimal measurement setup is selected by choosing a setup which yields the same OVL values as the self-reference and is also robust to small changes in the landscape. We present measurements which show how a SCOL landscape changes within wafer, wafer to wafer, and lot to lot with intentionally designed process variations between. In this case the process variations cause large shifts in the SCOL landscape and it is not possible to find a common optimal measurement setup for all wafers. To deal with such process variations we adjust the measurement setup as needed. Initially an optimal setup is chosen based on the first wafer. For subsequent wafers the process stability is continuously monitored. Once large process variations are detected the landscape information is used for selecting a new measurement setup, thereby maintaining optimal accuracy and robustness. Methods described in this work are enabled by the ATL™ (Accurate Tunable Laser) scatterometry-based overlay metrology system.

Keywords: scatterometry, overlay, metrology target, spectral tunability

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1. INTRODUCTION

Scatterometry overlay (SCOL) metrology[1] uses specialized targets which consist of a diffraction grating in each layer of interest on the wafer. To determine the relative placement, or overlay (OVL), between two layers, these targets are illuminated with laser light and diffracted signals are collected at the pupil plane (Figure 1). The collected diffracted signals are a result of interference between light scattered from the top grating and light scattered from the bottom grating. The sensitivity of these signals to OVL depends on the phase difference ($\Delta\varphi$) between light scattered from the top and bottom gratings.

$$Sensitivity \propto sin(\Delta\varphi)$$

The phase difference is the result of the different optical path between light scattered off the different gratings. It depends on both geometrical (layer thicknesses, feature dimensions) and optical (materials n and k) properties of the target. In Figure 1 this optical path difference (OPD) is the difference between E_i-$E_{2,1}$ path and E_i-$E_{1,1}$ path, which is the same OPD as E_i-$E_{2,-1}$ vs. E_i-$E_{1,-1}$.

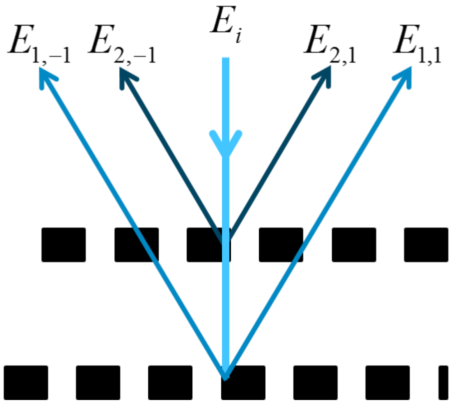

Figure 1. Cross sectional diagram of a SCOL metrology target, including an upper and lower periodic grating (black), incoming light E_i, and diffracted light: plus and minus first order from grating 1 ($E_{1,1}$, $E_{1,-1}$), and plus and minus first order from grating 2 ($E_{2,1}$, $E_{2,-1}$) are shown.

Since layer properties are wavelength dependent due to the complex index of refraction, the measured sensitivity and OVL results are also wavelength dependent. At wavelengths where $\Delta\varphi$ is a multiple of π, the sensitivity of SCOL metrology is close to zero and there is a high level of instability and inaccuracy in the results.

$$\Delta\varphi \approx n\pi \rightarrow Sensitivity \approx 0$$

Due to such wavelength dependence of the OVL sensitivity, the accuracy and precision of SCOL results can vary significantly between different measurement setups. Before deciding on a measurement setup, we map the SCOL landscape (Figure 2), to identify wavelength ranges which will yield favorable measurement conditions.

In a typical SCOL landscape we identify two types of wavelength ranges, named “resonances” and “flat regions”.[2] The resonances are wavelength ranges where $\Delta\varphi \approx n\pi$ and the OVL sensitivity is close to zero. Here the details of the pupil image show the instability of the signal. Pixels on the left and right side of the pupil have a signal with the same sign within the group and opposite signs between the groups. Between these two groups of pixels there are resonance conditions:

pixels with large positive and negative signal values. At such measurement conditions, SCOL metrology suffers from a high level of inaccuracy. This is evident in the OVL trace, where near resonance the OVL values show a large wavelength dependence.

Far away from resonance, the SCOL results are more stable: the pupil image shows a uniform signal distribution and the OVL has a weak wavelength dependence ("flat region"). These are the measurement conditions which yield the most accurate results and the best metrology tool performance in terms of precision and tool induced shift (TIS).

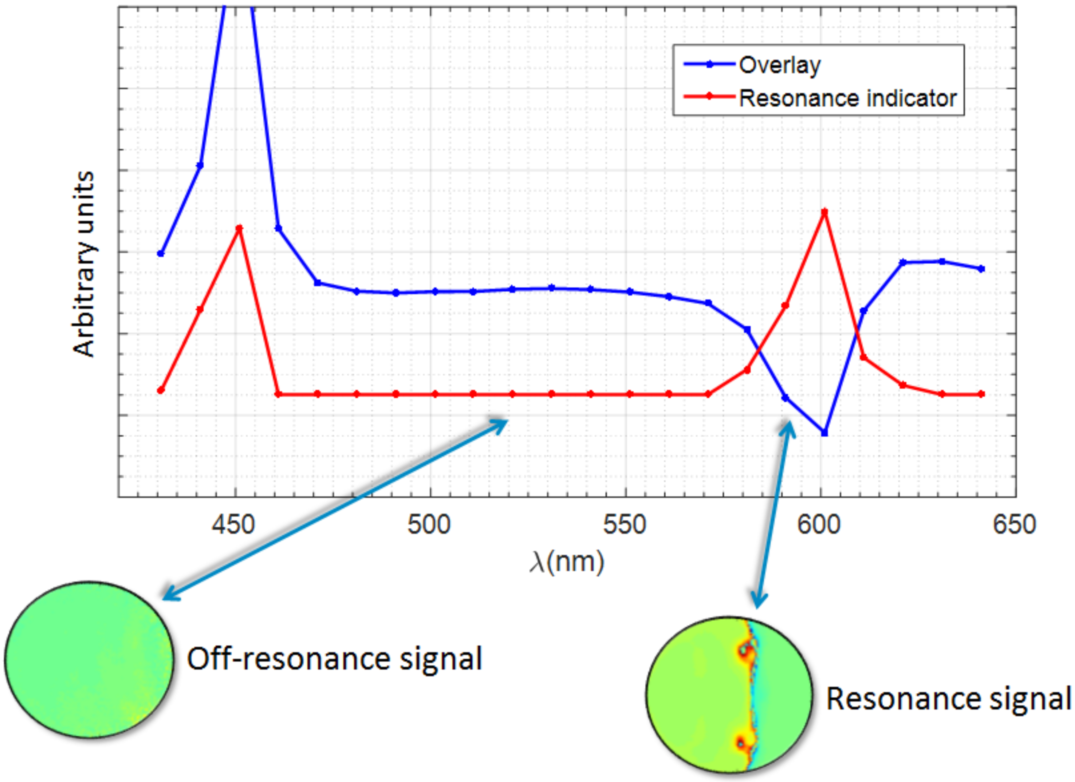

Figure 2. Overlay metrology and a resonance indicator metric as a function of illumination wavelength. Two types of regions are observed in the pupil image: off-resonance signal and resonance signal.

By examining pupil images and classifying their features we can quickly map the SCOL landscape, to identify the favorable flat regions and the transition regions, or resonances, between them. Accuracy metrics such as the one shown in red in Figure 2 are used to quantify features of pupil images. In the example shown the accuracy metric remains constant at flat regions and has a peak at resonance. Methods described in this work are enabled by the ATL (Accurate Tunable Laser) scatterometry-based overlay metrology system.

2. LANDSCAPE ANALYSIS

For a straightforward SCOL measurement, the most accurate result will be achieved by selecting a measurement setup in a flat region. However, as semiconductor process nodes progress, requiring a considerable improvement in accuracy at the metrology stage, the accuracy of flat region measurements may not be sufficient. Levels of inaccuracy which were previously acceptable may not be good enough for the most advanced nodes. Inaccuracies which now have to be addressed include, for example, inconsistency in OVL values between different flat regions or a weak dependence of OVL as a function of wavelength even within a flat region. Beyond individual measurements, overlay model term dependence and overlay model residual dependence as a function of wavelength can also be analyzed (Figure 3). Similarly, large shifts corresponding to poor metrology performance are seen at the resonances. But even in the flat regions there can be smaller systematic trends which can become important for advanced processing nodes. Additionally, different flat regions can report different overlay values.

To improve the level of accuracy in our SCOL measurements, we use a proprietary algorithm to create an "internal ruler" of accurate OVL values per measurement site. While this approach offers optimal accuracy, it does have a throughput penalty. In practice, the tradeoff between standard SCOL measurements and the internal ruler measurements is considered on a case-by case basis. Additionally, the challenge of process variations needs to be taken into account.

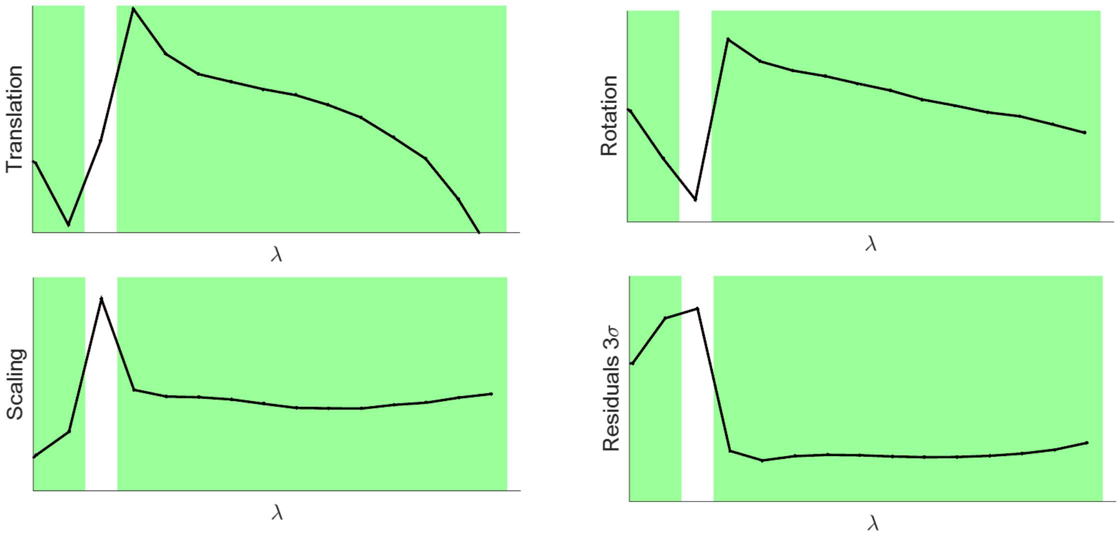

Figure 3. Modeled overlay correctables (translation, rotation, and scaling) as a function of wavelength, as well as modeled overlay residuals as a function of wavelength. Flat regions are indicated as green (shaded), resonances are indicated in white.

Next we consider the impact of process variations. Process variations, can be separated into symmetric and asymmetric process variations.[2] Asymmetric process variations include target asymmetry due to sidewall angle or pad-to-pad variations. Here we focus on symmetric process variations, for example layer thickness or dispersion changes which are constant over the scale of a SCOL metrology mark. The diffracted light from the upper and lower gratings will undergo relative phase shifts (Figure 4), resulting in a sensitivity at the metrology pupil image:

$$Sensitivity \propto \sin\big(\Delta\varphi(\lambda)\big) \rightarrow \sin\big(\Delta\varphi'(\lambda)\big)$$

The impact to the metrology landscape can be seen as a lateral shift in wavelength, both positive and negative as compared to the nominal case, corresponding to positive and negative thickness changes (ΔH) as can be seen in the simulated spectra (Figure 4).

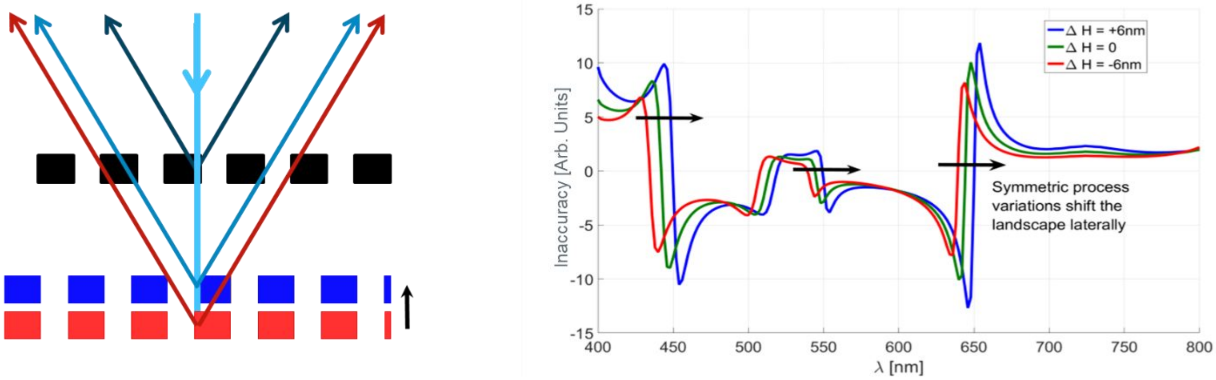

Figure 4. Change in layer thickness causes changes in the landscape. At left, cross sectional diagram of two SCOL metrology targets, including a common upper grating (black) and lower shifted grating (blue and red). The diffracted light from the bottom grating undergoes a relative phase shift from that of the top grating. At right, the corresponding simulated landscape shift due to this type of thickness variation.

3. PROCESS VARIATIONS

In this investigation we studied process variations in an advanced 1Xnm DRAM process and the impact on OVL using SCOL metrology. We look at variations within wafer, wafer to wafer, and lot to lot. Process variations were quantified by analyzing landscape shifts using resonance signal metrics, similar to the one presented in Figure 1. For the case of within wafer variation, we compare results from the X and Y cells, corresponding to the X and Y overlay metrology.[3] Since the X and Y cells of the SCOL target in this layer are very similar it is expected to observe the same process variations in both of them. Figure 5 shows that this expectation was met, and the process signature identified by either cell X or Y is similar. In addition, we compare the landscape of a location with extreme process variation as compared to the landscape of baseline variation on the left of Figure 5. These variations are attributed to anything which causes a phase change between the top and bottom grating, which could include process layer thickness changes, changes in refractive index n and k, or the like.

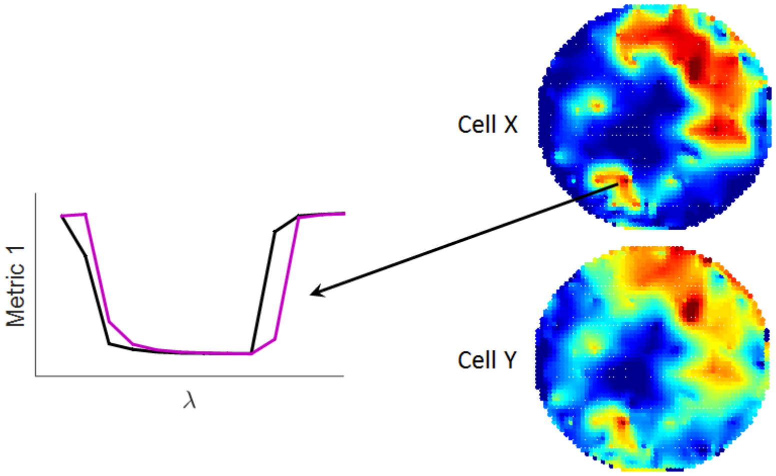

Figure 5. Symmetric process variation within the wafer due to layer thickness for X and Y overlay (right), causes a shift in the SCOL landscape as a function of wavelength as shown on the left.

Similarly, we look at variations from wafer to wafer. Again, we analyze process variations by comparing OVL landscapes to the baseline landscape. Here two wafers are compared for both the X and Y metrology cells. To the extent that the X and Y cells on a given wafer are similar to one another, we can attribute the variation to phase shifting process variations such as layer thickness or changes in n and k (Figure 6). In addition to improved metrology setup, landscape analysis can also provide important process variation information for monitoring and root-cause analysis.

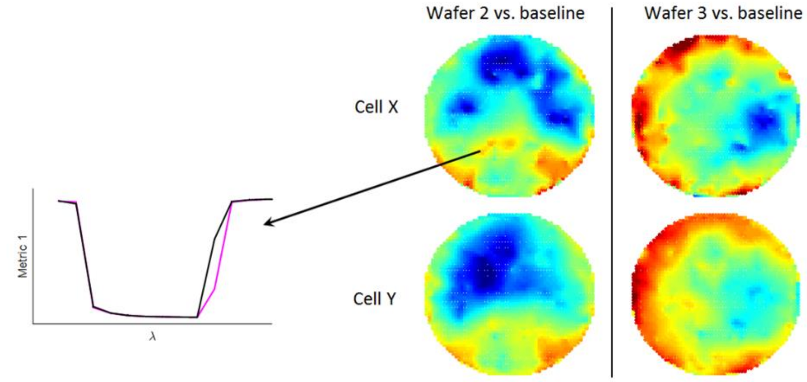

Figure 6. Symmetric process variation wafer to wafer due to layer thickness for X and Y overlay (right), causes a shift in the SCOL landscape as a function of wavelength as shown on the left.

Finally, we consider lot to lot variation. In this case, intentional process variations were induced in the form of a layer thickness change to emulate lot to lot variation. Nine wafers were processed in three groups of three wafers each: wafers 1-3, 4-6, and 7-9. The landscape analysis shows that there is relatively minimal change within each group of wafers, but significant change between groups of wafers as expected (Figure 7). This demonstrates the value of using landscape shifts to quantify and monitor process variations during production. Metrology will have to be adapted to maintain optimal accuracy and performance in the presence of process variations.

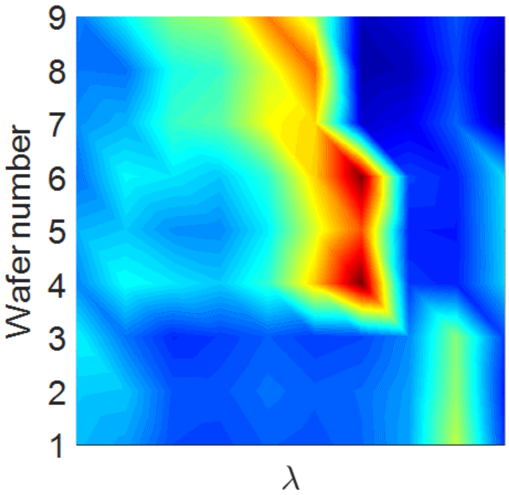

Figure 7. Intentional process variation: change in layer thickness between groups of wafers: 1-3, 4-6, and 7-9 and the corresponding landscape variations as a function of wavelength.

4. CONCLUSIONS

Accuracy and robustness of overlay metrology are critical for successful 1Xnm and below DRAM processing nodes. SCOL landscape analysis, enabled by the ATL (Accurate Tunable Laser) scatterometry-based overlay metrology system, is critical to achieve accuracy. Landscapes are composed of relatively “flat” regions which are best for accuracy and performance of metrology. Resonance regions are poorly suited for metrology and need to be avoided.

An internal ruler of accurate overlay results per site can be used to overcome the challenges of conventional SCOL measurements. The internal ruler, however, comes at a throughput penalty and therefore the tradeoff needs to be considered on a case-by-case basis.

Process variations can be detected and quantified by analyzing landscape shifts. With these techniques, within wafer, wafer to wafer, and lot to lot variability can monitored to provide feedback on process conditions. For best accuracy, metrology should be adapted to take into account process variations. Future reports will include the incorporation of 5D Analyzer® with ATL for optimized process control.

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