Spectroscopic CD Offers Higher Precision Metrology for sub-0.18 µm Linewidth Control

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Spectroscopic CD is a rapidly emerging optical metrology technique that can maintain yield in spite of today's shrinking process control windows. Measuring changes in sidewall angle and resist height, as well as detecting subtle phenomena such as line-rounding, t-topping, and resist footing is now as important as the traditional linewidth measurement.

Introduction

Shrinking feature sizes as required by Moore's law produce smaller process control windows that, in turn, drive a need for higher precision metrology to maintain an acceptable precision-to-tolerance ratio. Optical metrology techniques generally referred to as scatterometry offer the potential to meet these requirements.

Current linewidth process control methodologies use a critical dimension (CD) measurement obtained from a top-down SEM. This measurement gives no indication as to the sidewall angle or height of the feature. As transistor gate lengths decrease, non-vertical gate profiles will have an increased effect on transistor performance. The need to detect and quantify sidewall angle changes in addition to CD measurements is becoming critical. In addition, other effects arising from underlying film variations in reflectivity, refractive index, and thickness uniformity must be characterized and understood. Optical metrology techniques generally referred to as scatterometry, offer the potential to meet these requirements.

Fundamentals of scatterometry

The optical metrology measurement technique as applied in a production environment is summarized in Figures 1 and 2. Gratings on the production wafers have polarized light directed onto them and the spectrum of the reflected light is recorded. These gratings are repeating line/space features of uniform period. The line-size and period of the grating are designed to represent the in-die feature that is being controlled.

A model of the grating geometry and underlying film stack is created and incorporates such parameters as the grating height, the linewidth, the sidewall angle, and the film properties. A library is comprised of theoretical spectra constructed by varying the grating parameters. This library is linked to a recipe on the metrology tool.

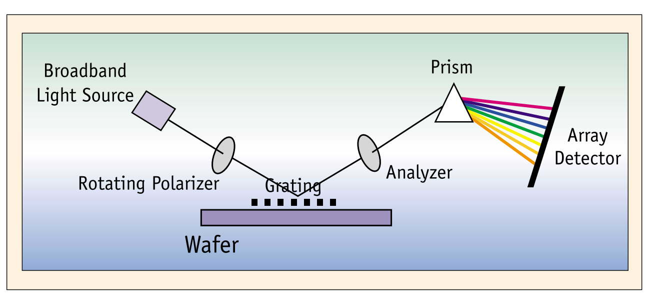

Figure 1. Schematic of SCD measurement on a KLA-Tencor SpectraCD.

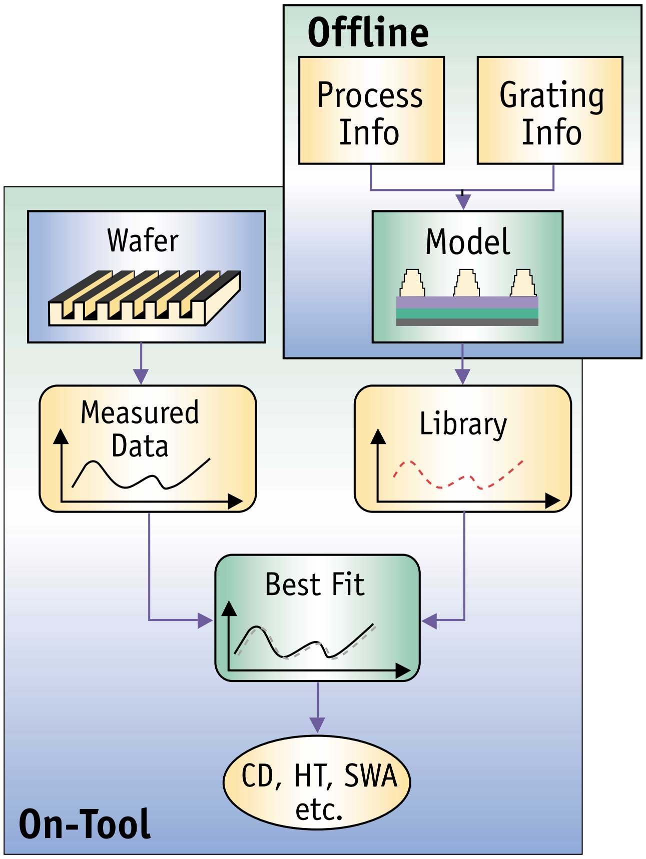

Figure 2. SCD measurement flowchart.

As the wafer is measured the data is compared to the library. The best match between the measured spectra and the modeled spectra determines the parameter values that best describe the physical grating. Since the entire wavelength spectrum is used for this measurement, this technique is referred to as a Spectroscopic Critical Dimension (SCD™) measurement.

The physical reason for the variation of the reflectance is that the incident light interacts with the grating, as well as with any layers between the grating and the substrate. These interactions, which are sensitive to angle of incidence and wavelength, cause different amounts of energy either to be reflected or absorbed by the substrate and, when possible, emitted in other diffracted orders. The reflectance is measured as a function of the angle of incidence, θ_{in}, or as a function of the wavelength, λ, as shown in Figure 3.

The effects of varying the linewidth around a nominal value are shown in Figure 4. The added lines depict the reflectivities due to ±4 nm variations from the nominal 0.18 µm linewidth. Observe that the reflectance signature changes due to the line width variation. In this way, using the different signatures for different linewidths, the linewidth for a specific sample target can be identified.

In order to use scatterometry for CD monitoring and control, the one library signature that has the closest

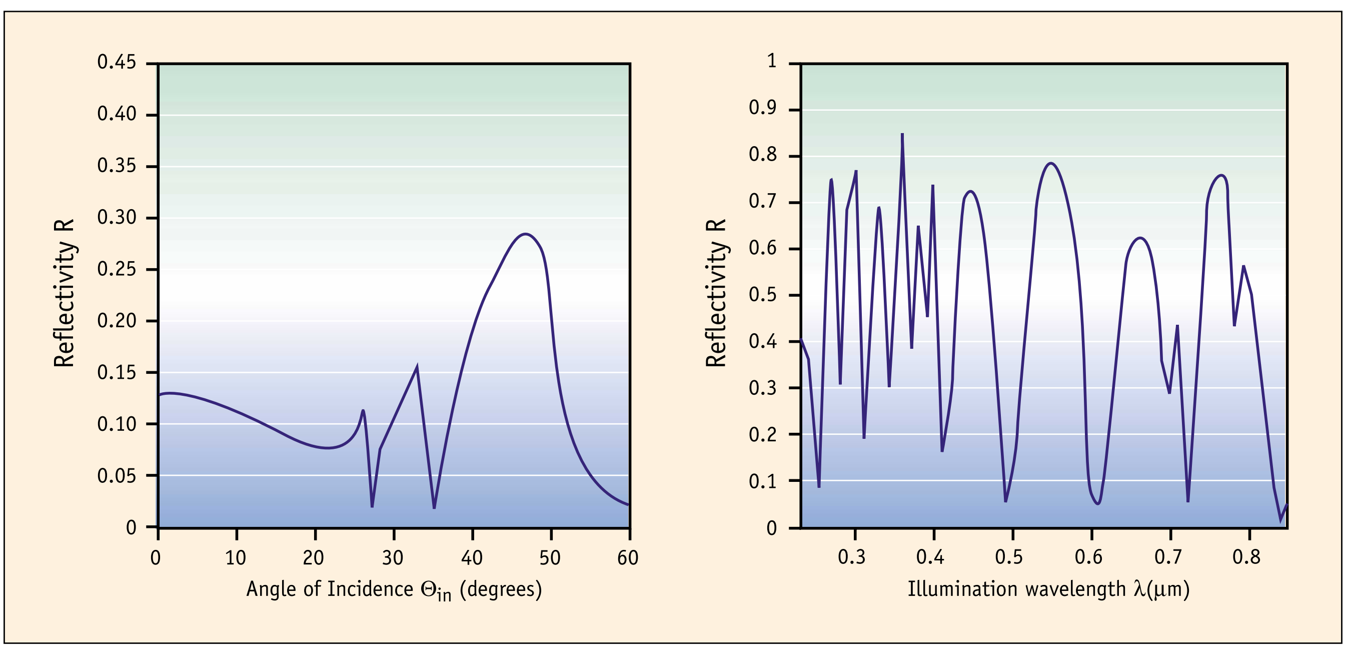

Figure 3. Reflectance, R, versus angle of incidence, θ_{in}, and illumination wavelength, λ (µm), from simulation of 0.18 µm resist lines in a 50% duty cycle grating (1 µm resist thickness, square profile, bare silicon substrate).

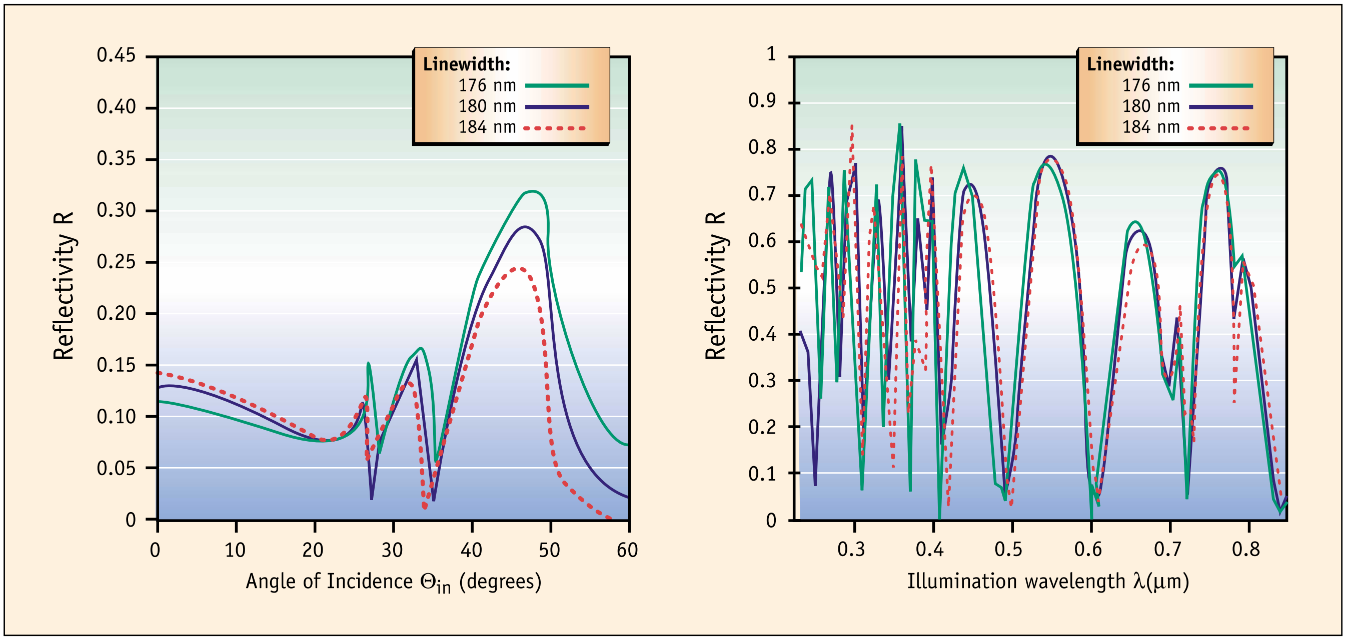

Figure 4. Reflectance, R, versus angle of incidence, θ_{in}, and illumination wavelength, λ (µm), from simulation as in Figure 2 with lines for 0.18 µm ± 4 nm added.

match to the reflectance curve produced by a given sample needs to be determined. Figure 2 illustrates the basic methodology to arrive at a measurement result.

Library generation is one of the most critical aspects to achieving successful measurement results. Both empirical and theoretical libraries can be employed. An empirical library is generated from a set of wafers with process parameters varied to cover the process space to be controlled. The generation and characterization of these wafers, however, is non-trivial due to the required level of control over the process parameters. Hence, empirical libraries are not typical.

While requiring significant computational time, theoretical libraries are easier to employ. The theoretical libraries require knowledge of the film stack properties. Film thickness, n and k values and profiles are used to generate the libraries. Figure 5 illustrates how the grating line profile is varied during library generation; this profile lies above a planar film stack (not shown).

The signature library can be computed using rigorous diffraction modeling algorithms. Two of the better-known methods are the Rigorous Coupled Wave Analysis (RCWA)[6-8] and the Classical Modal Method (CMM).[9-11] The results presented here were obtained using the Classical Modal Method due to its superior convergence. Convergence speed is an important consideration when choosing a modeling method. The Rigorous Coupled Wave Analysis method yields slower convergence but RCWA must also be considered since it enables the creation of models for more complex grating profiles. An example of a signature library is shown in Figure 6. Figure 6 shows the reflectance, R, as a function of the illuminating wavelength, λ, with the linewidths varying from 162 nm to 198 nm by 1 nm.

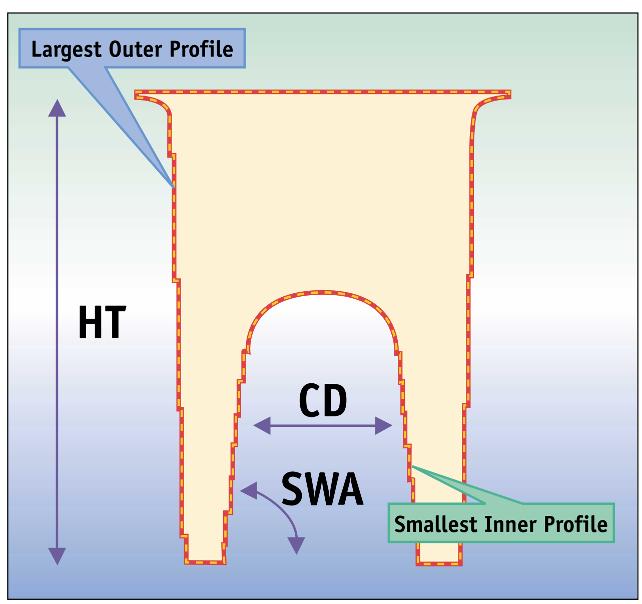

Figure 5. Library profile range with definition of CD, HT, and SWA.

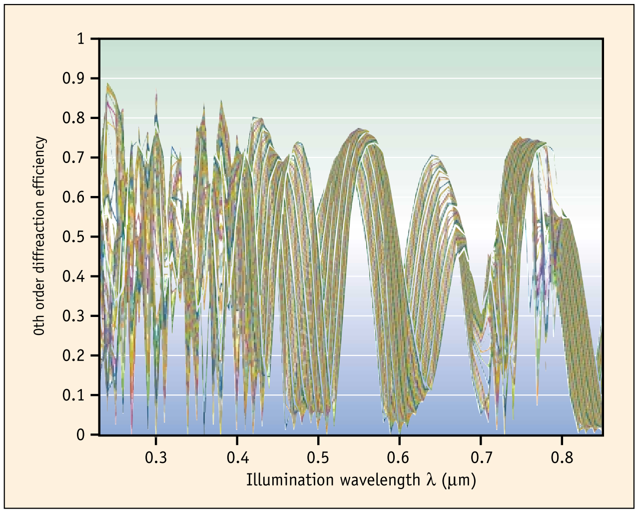

Figure 6. Reflectance, R, as a function of the illuminating wavelength, λ.

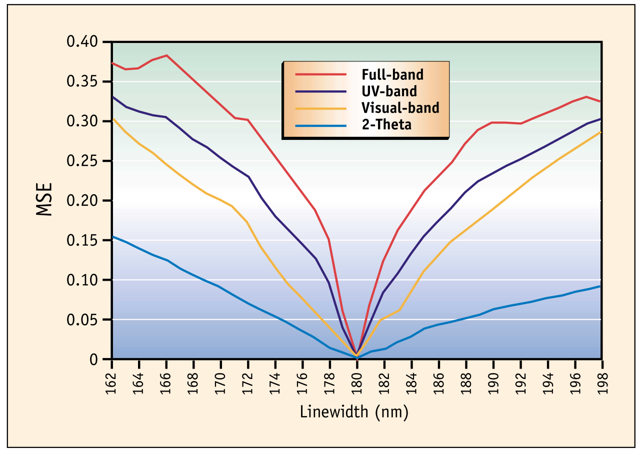

Figure 7. Example of Mean Square Error (MSE) values.

Two essential requirements for the method of comparing a measured reflectance curve to a signature library are sensitivity and uniqueness. If the method must have a resolution of 1 nm, then, within the constraints of the signal-to-noise ratio, the method must be able to differentiate between the fits of two signature curves 1 nm apart in the linewidth space. Also there must be the assurance that within the relevant parameter space there is one unequivocal "best fit," so that two totally different results are not obtained from the same measurement.

A metric for the fit between a measured reflectance curve R_{meas} and a given curve from the signature library R_{calc} can be given by the Mean Square Error (MSE). An example of the MSE-values for angle dependent (ADS) and wavelength dependent (WDS) scatterometry is shown in Figure 7. To generate this figure, the MSE between the simulated reflectance curve for 180 nm and all other curves from 162 nm to 198 nm has been calculated. As expected, the MSE between the 180 nm curve and itself is zero. Note that the full band WDS approach has the greatest change in MSE values with a one nanometer CD change while the ADS approach has the least. This can be interpreted as the full band WDS approach having the greatest sensitivity to one nanometer CD changes while the ADS approach having the least sensitivity.

Table 1 shows the MSE corresponding to 1 nm CD sensitivity for nominal CD values of 100 nm, 180 nm, 250 nm, and 350 nm. The calculations have been performed for the full wavelength band (230 nm…850 nm), UV band (230 nm…450 nm), and visual band (500 nm …750 nm). In addition, the results have been simulated for angle dependent scatterometry (ADS).

The highest MSE, or the most robust measurement, is in all cases obtained using the UV band. The MSE-values in this band are 5 to 12 times those given by the ADS, demonstrating the increased sensitivity of wavelength dependent over angle dependent scatterometry.

Integration of SCD

SCD is a technique that can be integrated onto process tools. Integration is possible because spectroscopic ellipsometry is a well-known, established technique that does not require a vacuum environment and can be scaled down in size for integration. The existing loaders and handlers of the process tools would keep the task of loading and unloading the wafers to and from the cassettes. The integrated SCD module would be another station (similar to a pre-aligner) within the process tools where wafers are measured giving users faster access to film, CD, and profile information. Figure 8 shows the flow of a lot traveling through a process step and illustrates the necessary steps before measurements become useful information.

Traditionally, a user must wait for the entire cassette to finish before the wafers can be measured for overlay, CD, or film uniformity. In some cases, test wafers are used to target or adjust the process just prior to running the lot but these test wafers often do not have the exact

CD(nm)	Full band	UV band	Visual band	ADS
100	0.0780	0.1250	0.0240	0.0100
180	0.0413	0.0614	0.0226	0.0089
250	0.0339	0.0528	0.0142	0.0051
350	0.0166	0.0241	0.0097	0.0048

Table 1. MSE for 1 nm CD sensitivity.

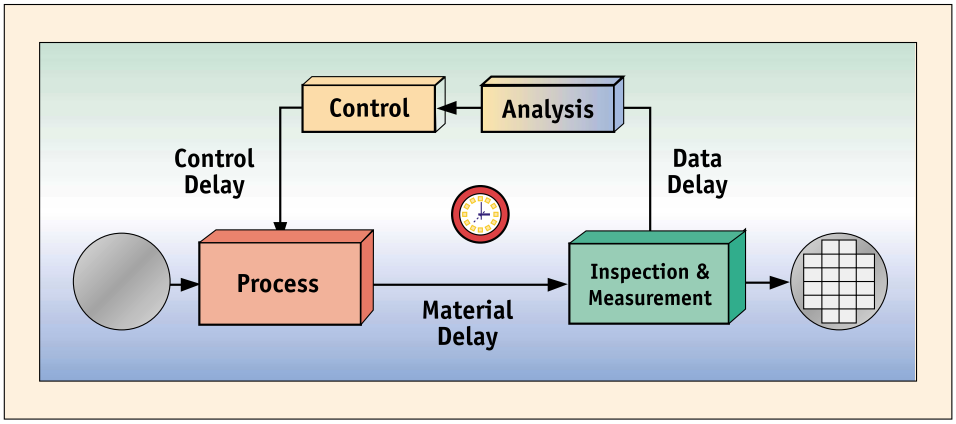

Figure 8. Flow for a process step.

properties (film stack, layer properties, etc.) of the production lot and are therefore not exact predictors. Waiting for the cassette to finish, or running extra test wafers, represents the material delay in processing time. Once the cassette has reached the stand-alone metrology tool, the wafer must be loaded, aligned, and measured. Once the specified number of wafers is measured, the data is fed into a database or SPC chart for analysis, is deemed "in" or "out" of the process window specification (pass/fail/rework), and is used to retarget or modify the process equipment for the following lot(s). The time it takes to acquire and apply this information is shown by the data and control delays in Figure 8. Depending on the speed and efficiency of the manufacturing system, the total delay can range from several minutes to several hours before a necessary adjustment is made to the process. Figure 9 shows the integrated metrology (IM) tool on a stepper/track module. In this case, the ADI CD, the film measurements, and profile information can be fed directly into the database for SPC and APC on a wafer-by-wafer basis instead of waiting for the cassette to visit the stand-alone metrology tools. Out-of-specification conditions can be identified faster which will reduce the amount on scrap or rework and reduce a fabrication facility's costs. The improved precision of SCD will allow for tighter process control and higher yields.

Conclusion

Scatterometry is capable of fully characterizing a target structure by providing CD, sidewall angle, thickness, and optical properties of the film stack. Wavelength dependent scatterometry is more sensitive to small CD changes than angle dependent scatterometry. Tool performance, in terms of accuracy and repeatability, is dependent upon the quality of the modeled library. Finally, the technology is suitable for integration into a photolithography exposure cell for improved process control.

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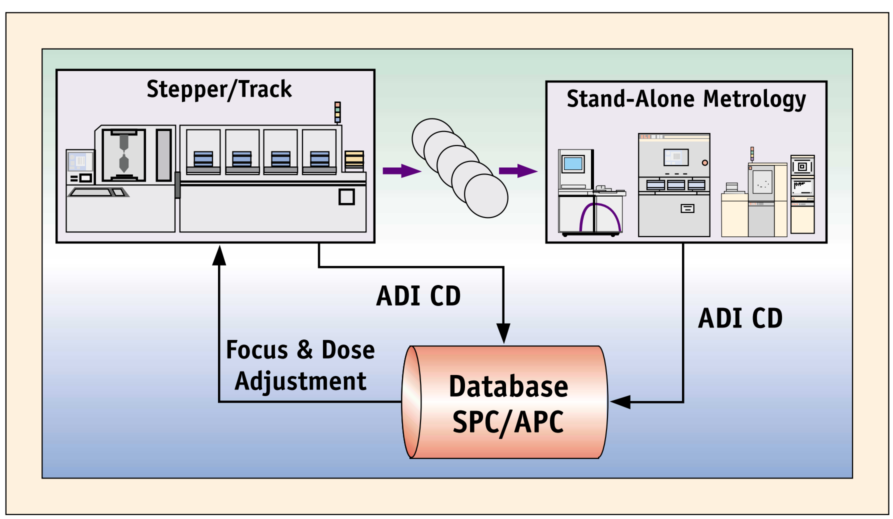

Figure 9. SCD integrated onto a stepper/track module.

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