Redefining Critical in Critical Dimension Metrology

Farid Askary[a] and Neal T. Sullivan[b]

[a] MetroBoost, 1750 Halford Avenue, Suite 218, Santa Clara, CA 95051
[b] Schlumberger Semiconductor Solutions, 45 Winthrop Street, Concord, MA 01742

ABSTRACT

Critical dimension (CD) metrology as practiced in semiconductor industry displays characteristics not observed in other metrology disciplines. This paper will present some of the unusual aspects of CD metrology and attempt to elucidate the causes for the observed behavior.

Through an examination of the characteristics of measurement accuracy, it is possible to observe these situations where CD metrology departs from the ideal. The typical process for achieving accuracy involves the use of certified standards in a well-defined calibration procedure. However, calibrating CD instruments with linewidth standards will not necessarily guarantee sufficient accuracy of subsequent measurements of production samples. This well-known result follows from lack of physical models to relate the detected signal to sample shape in combination with the many-to-one nature of the mathematical mapping that describes the process of obtaining CD from feature shape. Despite this limitation, monitoring tools such as CD-SEM systems have demonstrated to be useful for process control and are extensively used in semiconductor manufacturing.

The requisites for a well-behaved measurement process will be described in detail. The unusual characteristics of CD metrology will be identified, as will the underlying reasons for the behavior. These results will be examined in the light of common process control techniques to explain how CD-SEM measurements still add value despite the flaws.

In conclusion the role and value of certified standards in feature shape determination will be placed in the context of CD metrology. Reference Measurement Systems in conjunction with calibration standards are recommended to characterize process variations and determine feature shapes across a variety of samples. In order to ensure that the high throughput monitoring metrology tools flag process excursions for not meeting specifications, feature shapes must be quantified with additional metrics besides a single number CD.

Keywords: CD metrology, accuracy, calibration, linewidth standards, process control

1. INTRODUCTION

The behavior of CD metrology in semiconductor manufacturing displays unusual characteristics. Chief among these is that the practice, common in other metrology disciplines, of measurement calibration with certified standards will not necessarily result in achieving the same level of measurement accuracy for the production samples.

Unified advanced CD-SEM specifications as published by SEMATECH metrology group[1] include requirements for measurement accuracy. The characteristics of accuracy in CD metrology were presented by Banke and Archie[2] who discussed the concept of measurement sensitivity. They emphasized the importance of sensitivity in process control for its role in determining the corrected measurement precision. Another paper[3] emphasized the importance of the sensitivity parameter and measurement accuracy itself in process control. It was shown that the effects of accuracy, if ignored, could be far more detrimental to process control capability than the limitations of corrected measurement precision in modern CD-SEM tools.

Several papers also have stated that CD alone is not sufficient for process control[4-7]. This work presented examples of pairs of features with in-spec CD measurements in production environment where one feature met yield and performance requirements while the other did not. The features that failed quality requirements suffered from resist loss, scumming, reentrant profiles, or incomplete etch. In summary, the failing features' shapes impacted the circuit devices to the extent that yield or performance specifications were not met. All authors presented additional metrics that could be considered for process control.

To determine if these two characteristics of CD metrology were related, a fundamental, basic approach to CD metrology, not necessarily as currently practiced, was adopted. The behaviors and techniques common in other metrology disciplines, principally as described by Mandel[8] are considered first. This approach will facilitate several conclusions about critical aspects of CD metrology as related to the question of accuracy.

2. BEHAVIOR OF IDEAL METROLOGY

In this section, the characteristics of ideal measurement processes ("proper" metrology) are summarized by paraphrasing statements from several sections of Mandel's book[8].

Measurement can be defined as a "mapping" of a property into the real numbers. This mapping forms a metric for ranking the sample set based on the order property of the real numbers. The elements in the sample set can be ranked according to the value of the real number representing the measurement outcome. The study of a measurement technique must include its application to all the samples for which it is intended, or at least a representative set of such samples. The role of certified standards pertains to the accuracy of the measurement method. Certified standards at several values are used with any single metrology method to arrive at the calibration curve for that method. Measurement accuracy is related to this calibration curve. However, in the absence of any knowledge of the true values of the samples (i.e. certified standards), two alternative methods of measurement can still be compared. The first step in the comparison of alternative methods of measurement consists in verifying that a functional relationship exists between the quantities representing the two measurements of a sample set. Furthermore, this functional relationship should be monotonic in the region of interest. A consequence of the monotonic functional relationship is that two different measurement methods for measuring a property of the sample set must rank the sample elements in the set in the same order, or by extension, in exactly the opposite order.

It is of critical importance to emphasize that two measurement methods may not even measure the same property if the monotonic relationship between the measurement results cannot be established. Furthermore, certified standards are not required for comparison of alternate methods of measurement such as matching of a pair of tools of the same model or comparison of two different measurement methods.

Examples of sample properties that can be measured with ideal metrology behavior are feature height and pitch. In what follows, we intend to establish that CD metrology as practiced in the semiconductor manufacturing industry does not strictly satisfy the requirements of "proper" metrology. Specifically, most in-line CD metrology tools do not measure a well-defined property of the feature shape. However, such measurements have demonstrated to be useful in process control. The reasons for this behavior will be explained and in this process, additional conclusions will be proposed.

3. CD DEFINITION

The SEMI P19-92 definition[9] of linewidth for CD metrology is chosen at the precise description of the property to be measured. "In semiconductor technology, at a given cross section of the line, the distance between the air-line material boundaries at some specified height above the interface between the patterned layer in which the line is formed and the underlying layer."

As per the drawing in Fig. 1, CD is a property of the feature that is defined as a function of the position of the cross section plane along the feature, i.e. CD = function(x_0). Without loss of generality, we assume that the features have translation symmetry, which implies that the cross section shown in the image is constant and independent of x_0.

Throughout this paper, the term "profile" or "feature profile" will denote the curve in two dimensions that results from the intersection of the feature with the cross section plane at a given location, excluding the line that forms the boundary between the feature and the underlying layer. The feature profile in Fig. 1 is shown as the dotted curve that lies in the cross section plane illustrated by the gray area. Feature CD is defined as the difference in the abscissas of the two points that result from the intersection of the profile with the horizontal line drawn at a height z_0 above the interface in the cross section plane. Hence CD is defined as a function of the height above the interface at any cross section location, i.e. CD = function(z_0). Finally, CD is given by the difference between the abscissas y_2 and y_1, i.e. CD = $(y_2 - y_1)$.

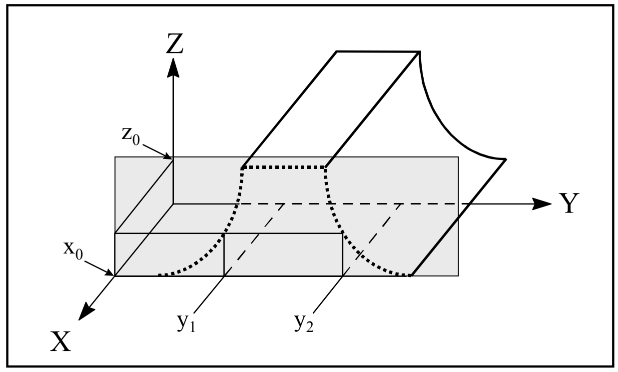

Figure 1. Definition of CD, the property to be measured CD = function(x_0, z_0) = $y_2 - y_1$

Measurement of the property CD as defined above forms a mapping from the set of graphs in two dimensions to the set of real numbers. From known mathematical theorems, this mapping is not one-to-one. Rather, it is a many-to-one mapping. As a consequence of the many-to-one property of the mapping, multiple features can have identical CD measurements. Undesired shapes can have identical CD as acceptable shapes. Therefore, the criteria that measurement of this property, namely CD, fall within specification limits is a necessary but not sufficient condition to ensure features meet quality requirements such as device yield and performance. It is important to note that this behavior is not specific to particular measurement systems, but falls out of the definition of CD, the property to be measured. Equally important is that such a behavior would also persist in the absence of all measurement noise. While it is obvious that CD measurements of nearly identical features would be indistinguishable in the presence of noise, it is most critical to realize that entirely different looking features can produce the same CD.

Fig. 2 depicts three simple shapes: a rectangle and two trapezoids whose sidewall angles differ slightly from the 90-degree sidewall of the rectangle, one slightly reentrant. As illustrated in the figure, the three features have the same value for property defined as CD at 50% of the height above the interface.

At issue is the relevance of these shapes to the features that the measurement method is intended to examine. In semiconductor manufacturing, the shapes we are concerned with are those encountered in the course of production which result from process variations. Such variations are typically induced and examined with a focus exposure matrix (FEM) test. The shapes in Fig. 1 are the simplest geometrical models that are considered for the set of profiles obtained from samples generated by a FEM. The range of sidewall angles for both I-line and deep UV resist features in FEM tests includes the range from 89 to 91 degrees. These shapes also set the stage for further analysis.

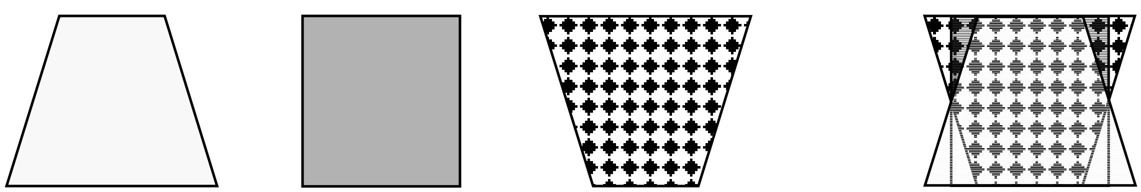

Figure 2. Three shapes with the same value of the property defined as CD at 50% height

4. COMPARISON OF TWO CD METROLOGY METHODS

Consider four different cases whereby two alternative methods of CD measurement will be compared. These cases include: comparison of two identical and well-defined properties, two different but well-defined properties, two properties of which at least one is not well defined, and two identical and ill-defined properties.

Case I:

In this case, assume that the two metrology methods under consideration follow the accepted definition of CD and also assume that both methods measure CD at the same height above the interface. In other words, the property to be measured is well defined and identical between the two measurement methods. In this case comparison of the results of two measurement methods will lead to a “proper” or ideal behavior expected of all well-described measurement processes.

CD metrology methods that satisfy the requirements of this case include methods that characterize feature profile prior to CD measurement. Examples include SEM cross section (cleave or FIB) and measurements with the scanning probe microscopes that can remove the tip shape contributions from the raw data.

Comparison of two measurement methods is carried out via a scatter plot of a measured sample set. Each point in the plot corresponds to a sample in the set. The results obtained by the two metrology methods for a feature are used to plot a point. The abscissa and the ordinate of the plotted point correspond to the measurement results of the first and the second metrology method. All the points corresponding to measurement results of all the features in the sample set are plotted. The x and y axes are drawn with the scales in the same units.

For two metrology methods that measure the same well-defined sample property, the points in a scatter plot for ANY sample set will fall on a curve, apart from the dispersion caused by limitations of measurement precision. The principle at work here is that there exists a single curve that describes the relationship between the results of the two measurement methods. If the curve is not known to begin with, measuring a finite number of samples and fitting the resulting data with a curve can estimate its functional representation. This fitting relies on the assumption that such a curve exists in the first place. Such a curve will allow for matching of multiple systems and also for calibration of a single tool via certified standards. When the x axis represents the values of certified standards, the resulting curve is called a calibration curve.

If the two measurement methods are both accurate and precise, the calibration curve will be a 45-degree line passing through the origin. Such a behavior can be verified by comparison of measurements of a few samples covering the range of interest. This is shown in Fig. 3.

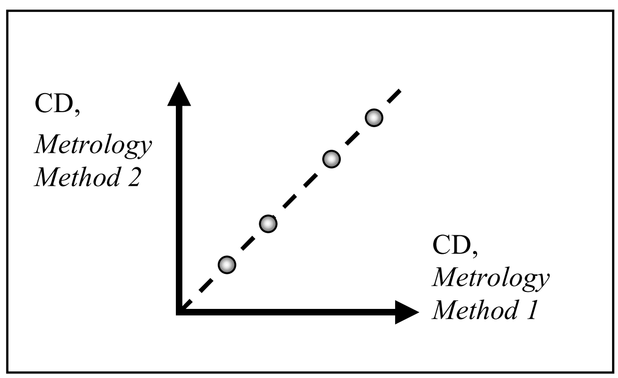

Figure 3. Comparison of two accurate and precise methods of CD measurement

Comparison of metrology methods with scatter plots and linear regression such as shown in Fig. 3 are common. A variation of this type of graph referred to as measurement linearity test is obtained when targeted feature dimensions are used for the x-axis coordinates.

As a final point in this section, there are several other well-defined properties of a feature that can be used as the definition of CD. Measurement of all such properties would result in a similar “proper” behavior for the results. These properties include maximum width of a feature profile, minimum width of a feature profile, width at a percentage of maximum height of the profile, mean profile width based on cross sectional area of the feature, and the distance between the abscissa of the points of maximum slope along each edge of the feature profile.

Case II:

In the second case consider comparison of two metrology methods that measure CD at known but different heights above the interface (e.g. at 50% and at 60% of feature height). This is a comparison of measurements of two well-defined properties of the sample. This case, while not typical, is introduced as a tool to draw insight into the basic problem which stems from the fact that the two methods measure different properties of the sample. The two measurement methods will not necessarily rank the samples in an arbitrary set in the same order. The primary consequence of this characteristic is that the required functional relationship does not exist between the results of the two measurements. The scatter plot for the set of ALL samples that the methods are intended to measure will result in an area that cannot be explained by a single curve.

This can be clarified through two examples in which the three simple shapes introduced earlier are revisited.

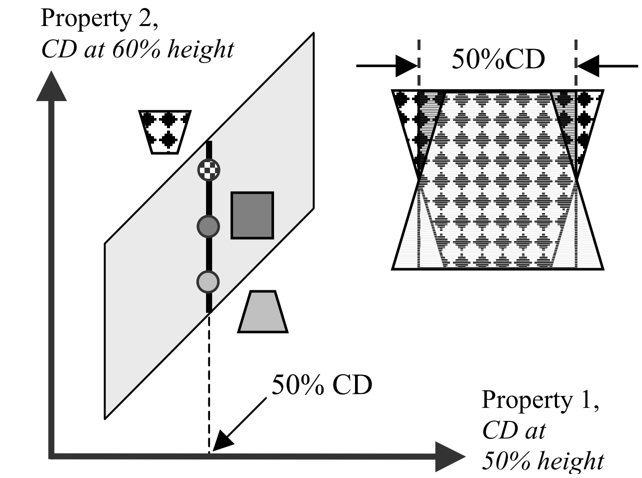

Figure 4. Comparison of two different sample properties: CD at 50% and at 60% height

In the first example consider two different sample properties and compare the values of these properties rather than their measurements. Property 1 is defined as CD at 50% height while property 2 is defined as CD at 60% height above the interface. All three samples have the same CD at 50%, but different CD values at 60% height. Comparing the true values of these properties, the three points in the plot lie on a vertical line as shown in Fig. 4. By extending the sample set to include trapezoids having a range of angles around 90 degrees with the same CD at 50%, a segement of vertical line can be obtained with an abscissa that represents the common property 1 value for all the samples. The vertical line segment covers a range of y-axis values corresponding to the values for property 2. By extending the total sample set to include a number of subsets, each subset having features with identical property 1 (CD at 50%) with varying sidewall angle, yet such that property 1 varies from subset to subset, the plot will fill up an area as shown in Fig. 4.

Next, consider comparison of two metrology methods for the measurement of the two different properties rather than comparison of the true values of the properties. From the previous analysis, the scatter plot for the measurements of all samples that the methods are intended to measure is also expected to cover an area. It will not be proper to proceed to the next step and consider a linear regression for calibration or system matching since no single curve exists in the first place. Attempts to apply common calibration methods and fit the measurement results of a specific sample set with a line or a curve will generate a line or a curve, but that could be misleading since the resulting fit depends entirely on the sample set considered. Such a curve is not valid for all the sample sets the methods intend to examine.

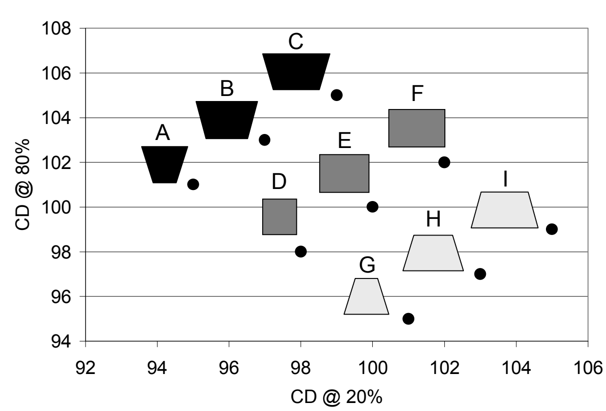

Figure 5. Comparison of values of two properties of a given sample set

In the second example, consider comparison of two metrology methods measuring CD at 20% and 80% of feature height. The sample set consists of nine shapes all of the same height of 300 units. The samples can be further divided into three groups, each group having a 50% CD of 98, 100 and 102 units respectively. Within each group, the sidewall angles are 89, 90 and 91 degrees. Fig. 5 depicts the scatter plot for the values of the two properties for the sample set considered.

A metrology method that accurately measures the first property, CD at 20% height, would rank the samples in the following order: (A,B,D,C,E,G,F,H,I), while a second metrology methods that measures the other property, CD at 80% height, would rank the samples as (G,H,D,I,E,A,F,B,D). The two measurement methods do not rank the samples in the same order. This follows from the fact that the two methods are not measuring the same property of the samples.

Case III:

The third case involves two alternative methods of CD metrology in which at least one of the methods measures CD at an unspecified, unknown height above the interface. All CD metrology tools that do not employ models to relate the detected signal to feature profile fall into this category. Within a set of samples with varying physical edge shape, the height at which such tools measure CD varies depending on the shape of the samples. This constitutes a departure from the definition of the property to be measured. The results of comparison of the two methods in this case on all the samples intended for measurement is even more arbitrary than in the results obtained in case II.

In-line CD metrology tools such as optical microscopes in mask manufacturing and CD-SEM systems in semiconductor manufacturing measure CD from the detected signal, but do not relate the signal to the physical edge shape. Instead, such tools assign to the edge position, a location that is obtained from the detected signal intensity as a result of application of an ad-hoc algorithm. Common edge detection algorithms include threshold, linear regression and maximum slope. The abscissa of the assigned edge location from the signal is considered, and the corresponding point that has the same abscissa on the physical sample is assumed to be the physical edge location. But in practice, such a point might not even be on the physical edge. Consider as an example a vertical step in silicon. None of the points on the optical or SEM signal will correspond to the edge location except one. For reentrant or T-topped profiles, there could be two or more points on the physical sample edge with the same abscissa but at different a heights, so multiple points could qualify as the assigned edge point. In general, the relationship between the position assigned to the edge from the signal waveform and the physical feature profile is usually unknown. If the assigned edge actually corresponds to a single point on the physical edge, the height above the interface is not known and varies within a group of samples of the same material depending on the profile shape (edge shape).

Again, the scatter plot for comparison of measurements of ALL possible samples will generally result in an area not a curve, unless for each and every sample in the set, both measurement systems employ an identical height at which CD of a feature is measured, even if that height varies from sample to sample within the set. We will consider this as a special case separately.

One category of comparisons corresponding to this third case involves comparison of CD measurements between an AFM, which measures CD at a known height, and any top-down CD SEM tool which does not measure at a known height. Specific examples of such comparisons were carried out in an AMAG study[10]. When comparing the results of measurements of all samples, one expects in general, for the scatter plot to cover an area. Attempts to fit the data from a finite sample set with a curve or a linear relationship are of limited use and any relationship obtained in such a manner would only apply to that measured sample set and should not be extended to other samples. This explains the reason why the slope of the linear fit (sensitivity) comparing measurements of each CD SEM model to the AFM measurements are different for the four types of samples (dense and isolated lines, resist and etched features) in the AMAG study.

It should be emphasized that the presence of different sensitivities (slopes of linear fit) mentioned above is an unusual behavior compared to characteristics of "proper" metrology methods. If CD-SEM systems measured a well defined property of the sample (such as CD at a known height or any of the other well-defined properties of the physical profile mentioned in the analysis of case I) and the AFM measured the same well-defined property, a single calibration curve would exist for each CD-SEM system that would apply to all feature types, including the four feature types considered in the AMAG study.

One very important consequence of this consideration is that the usual practice of "calibrating" measurements of CD metrology systems that do not model the signal, with slope and offset (or a higher order curve) is not valid in general and as we will show later, the applicability of such exercise is limited to a set of features that have identical edge shapes. Thus "calibration" of such tools with CD standards will not guarantee the accuracy of measurement for subsequently measured samples in production. It is an unusual characteristic of CD metrology that it is possible to have a system calibrated in the conventional sense with CD standards, and yet the measurement of subsequent production samples will be inconsistent with their physical dimensions if the production samples have different edge shapes than the standards.

Yet another general example for this third case is comparison of two CD metrology systems where both measure CD at unknown heights and when the two systems are not identical. Specific example involves matching of two CD SEM systems from different suppliers.

Case IV:

A special instance of case III can be considered where the property to be measured is not well defined and varying among a set of samples, but for each and every sample in the set, the two methods measure an identically ill-defined property. This case applies to any two CD-SEM metrology tools of the same model and supplier using the same algorithm for edge detection. The scatter plot for the results of the two measurement methods can collapse from an area to a curve. If the tools are properly setup and matched, the curve becomes a 45-degree line passing through the origin. However, this behavior, while comforting, does not imply that the requirements of measurement accuracy have been addressed. Two identical, matched tools will measure all the samples the same, without even having to satisfy the requirements for “proper” metrology.

5. ROLE OF LINEWIDTH STANDARDS

What are the necessary and sufficient conditions that calibration with certified standards would guarantee accuracy of subsequent measurement on other samples? First, the property of the sample to be measured must be well defined. Secondly the system must be calibrated with standards to report the results that correspond to the prescribed property. The third requirement is that the samples tested subsequent to calibration must also be measured for the same well-defined property.

The accepted definition of CD implies that the metrology tool must measure the CD at a specific height above the interface. The system must be calibrated to report CD at a specific height, and the standard must be certified for CD at the same height. For the standard to be universally useful for all CD metrology tools, its shape must be known. This implies that linewidth standards, in effect, are shape standards.

Since modeling of top-down CD-SEM tools in production is not available, comparison of measurement methods in manufacturing will correspond to cases III or IV. The question arises: What are the appropriate methods to handle CD measurements in semiconductor manufacturing and what is the role of standards? Two areas of applicability are process control and monitoring in production environment and process characterization in development. For characterization, one can use a Reference Measurement System as defined below in conjunction with CD standards. For process control, a different method is proposed to use more information from the data collection than just a single number CD, though RMS can also be used.

In characterization, lithography engineers often wish to determine the shape of the resist features and deduce the allowable process window based on the shapes. Cross-sectional SEM images are often used for this purpose. A Reference Measurement Method (RMS) is any measurement method that can accurately determine feature shape. As a result, RMS can produce CD measurements as a function of height (or any other well-defined property). Possible existing RMS methods include cross section SEM (cleave or FIB) and scanning probe microscopes that are capable of removing tip shape from raw data. Top-down CD-SEM systems are excluded from consideration as RMS tools until signal models become available. Nondestructive methods are preferable. Certified standards can be used to calibrate the RMS when the property to be measured is well defined. The RMS will then be used to characterize shapes that are found in the course of normal variations in production. Features formed in all layers (poly, nitride, etc.) and all shapes of interest (isolated and dense lines, contacts, etc.) need to be studied. Such activity in conjunction with etch characterization will establish the allowable process window at each layer.

Once the process has been characterized and enters manufacturing, process control becomes the main objective of CD metrology. The application of CD-SEM in production is complicated due to the behavior that deviates from “proper” metrology. Users need to be aware of the differences in sensitivity to process variations that will be discussed in the next section. However, even if the requirements of “proper metrology" were satisfied, more information than just CD is required to guarantee quality. This is due to features that do not meet quality standards, but whose CD falls within specification limits.

6. EDGE SHAPE VARIATIONS

From the perspective of edge position detection in CD metrology tools, samples can exhibit two distinct types of edge variation (or a combination). The first is the type of variation in which the shape of the edge does not change, but its position does. The second is the type of variation in which the edge position remains more or less constant, but its shape changes. Examples of the latter are changes in feature shape due to a limited range of focus variations in a focus-exposure matrix test. An example of the former type of variation is seen in the samples prepared for measurement linearity tests. When comparing CD measurements of lines or spaces in a linearity test, features of different nominal size have the same left and right edge shapes, but each sample has a different distance between its left and right edges. For such samples, linearity plots result in a smooth curve, generally linear for most of the range of interest. But the curve will deviate from linear when metrology or lithography limitations manifest. Such tests are common in the industry. An example of this behavior was reported earlier by the authors[3].

When sample edge variations are restricted in this way, the behavior of CD measurements lends itself to calibration with slope and offset. In fact, one can show using simple arguments that despite lack of model for the detected signal, two different tool models (CD-SEM or optical) even when using different edge detection algorithms will have the same sensitivity when measuring edge displacement variations such as those encountered in a linearity test. The reasoning is outlined as follows. Consider two physical features, two lines A and B which have identical heights and physical left edge shapes and identical physical right edge shapes but such that feature B has a slightly wider distance between its left and right edges than feature A. First examine values of the well-defined property, namely CD at a given height, and denote the two values of the property for features A and B as $P_1(A)$ and $P_1(B)$, respectively. Then consider the difference in the two values of the property, $P_1(B) – P_1(A)$. In the cross section plane, we align the profiles of the two features by translating one of the profiles such that the two physical left edges overlap. After alignment, the difference in the two properties, $P_1(B) – P_1(A)$ is equivalent to the displacement between the two right edges. The distance between the two right edges is equivalent to a pitch whose value is independent of the height above the interface. If a second different property P_2 of the two samples, such as CD at a different height, is considered, one can obtain:

$$P_1(B) - P_1(A) = P_2(B) - P_2(A)$$

By extending the sample set (A, B) to a sample set with several elements (A, B, C, …) where all the samples have identical heights, left edge shapes and right edge shapes, the set of resulting equations similar to the above would imply that the scatter plot for the values of the two properties P_1 and P_2 falls on a 45-degree line, though not normally passing through the origin. This is evident in Fig. 5 for any of the three groups of samples meeting our assumptions about edge shapes. The conclusion is that for a sample set whose elements have identical heights, left edge shapes and right edge shapes, the scatter plot for the values of any two well defined properties used for CD will be a 45 degree line.

Next consider top-down CD measurements of the above sample set and denote the linewidths of features A and B measured with a particular metrology method as $CD_1(A)$ and $CD_1(B)$, respectively. We assume that the metrology system collects images or line scan data from both features under the same experimental run conditions, including image brightness and contrast and image magnification, so the pixel size and gray scale depth are the same in the data sets acquired from the two features. Furthermore, we assume that there are no image proximity effects, that is, the presence of any nearby feature does not alter the shape of the detected signal. Then the two left edges appear identical in the images or in the line scan waveforms and can be described by the same function. Similarly, a different single functional form can explain the detected signal for the pair of right edges, but the locations of the two peaks or transitions in the signal corresponding to the physical right edges in the two images or waveforms would be displaced relative to the location of the peaks or transitions in the signal describing the two left edges. It can be shown that the difference of the two CD measurements, $CD_1(A)$ - $CD_1(B)$ is equivalent to a pitch measurement whose value signifies the relative displacement of the two right edges in the images or waveforms when the portion of the waveforms representing the two left edges are lined up. We know that pitch measurement result is in independent of the model required to interpret the signal and is accurate in that sense.

$$CD_1(B) - CD_1(A) = \text{A number independent of signal model}$$

Let $CD_2(A)$ and $CD_2(B)$ denote the measurements of the pair of features with a second top-down metrology tool. Then in the absence of edge signal distortion by any image proximity effects for the second metrology method, one can conclude:

$$CD_1(B) - CD_1(A) = CD_2(B) - CD_2(A)$$

And the above relationship holds despite lack of models for the detected signal in both tools.

By extending the sample set as before, we conclude that the scatter plot for measurements of the two metrology methods on the restricted sample set will be linear with a 45-degree line. The only necessary condition required for CD measurement results of two different metrology tools to be linearly related on a restricted sample set whose elements have identical edge shapes is that each metrology tool not suffer from image proximity effects for the sample set under test.

In addition, the above equation explains why all modern CD-SEM systems pass the linearity tests easily. Such performance does not require measuring a well-defined property of the sample. Rather, linearity tests can gauge the fidelity of imaging in a metrology tool. If the imaging does not distort the signal for each edge, then the systematic error of any single measurement system when measuring a restricted sample set remains the same for every sample in the set if the edge shapes do not vary. To simplify, passing of a linearity test is not evidence of measurement accuracy, only of good imaging. If the metrology method fails linearity test then it does not meet accuracy requirements because the imaging is not acceptable and the method will not produce accurate measurements in that region.

This analysis also helps explain the success of optical microscopes for measuring features on wet etched binary chrome on glass photomasks that until recently dominated the production volume in the reticle manufacturing. Within a given mask manufacturing facility, the height of the chrome layer and the feature edge profiles vary only slightly. So the features on such masks satisfy the assumptions made about the collection of samples in a restricted set. Under these conditions, photomask CD measurements behave properly and the measurement process lends itself to a simple calibration with a single offset. With the advent of dry etched chrome photomasks and etched phase shift masks, other edge profiles of different heights and shapes have been introduced into mask manufacturing and the industry is experiencing the same CD calibration issues as in semiconductor manufacturing.

7. RESULTS AND DISCUSSIONS

Two concepts have been developed to explain the behavior of CD metrology in semiconductor manufacturing. The first is the nature of the property to be measured. If the metrology method does not employ models to relate the detected signal to feature shape, such a property is not well defined. The second notion is the range of samples the method is intended to measure. In a fabrication process, samples of different material, edge shape, and nominal size are encountered. Therefore the relationship between the samples and the property to be measured corresponds to a many-to-one mapping. Whenever both conditions are present in CD metrology, that is, when the signal is not modeled and variations in both shape and size are present in the sample set, the behavior of CD metrology departs from the ideal and one cannot expect the customary calibration procedures to work. However, when either of the two conditions is removed, that is, if either the property to be measured is well defined, or the sample variations are restricted to exclude changes in edge shape, then the behavior of CD metrology becomes ideal and the customary calibration procedures work.

CD-SEM systems, currently the tools of choice for process monitoring and control, are susceptible to feature shape variations which are encountered in the course of production. This susceptibility must be accounted for when setting up a CD-SEM tool for process monitoring. Most important to recognize is that CD measurement alone is not sufficient to guarantee quality. Features that do not meet quality standards can yield CD measurements that fall within specification limits. This behavior is not unique to CD-SEM measurements, though lack of accuracy in terms of absence of signal models adds to the complexity of the issue. This behavior is due to the fact that the complex process of extracting a CD from the feature shape is a mathematical transformation that is not a one-to-one mapping, but a many-to-one mapping. For any given metrology method, there are many shapes that can result in the same CD. A single number CD is not sufficient to guarantee quality. At least one additional metric is needed.

A simple solution is to implement a second metric obtained by comparison of the sample under test with a "golden" sample, that is, a known good sample with CD near the center of specification range. In a CD-SEM, the entire signal waveform or even the sample image can be used as a fingerprint for the feature under test. Such waveforms are routinely obtained during the normal course of measurement so there is no additional data collection required. The waveform of the "golden" sample can be stored during measurement setup. This stored waveform can be used as a template for subsequent measurements: the entire representation of the golden feature can be used to correlate to the feature under test. If the correlation score is unity, the two waveforms are identical. Deviations of the metric from unity are associated with differences in feature shape and size. Some effort is required to determine a threshold for the minimum acceptable value of this correlation. We mention in passing that the correlation metric is mathematically a different construct than CD measurement. While CD measurement maps the set of graphs in two dimensions into the set of real numbers, the correlation score maps into real numbers a pair of graphs in two dimensions that are represented by functions. Thus the value of the metric depends on the "golden" waveform. Several authors have discussed the application of the maximum correlation score in pilot line manufacturing to detect features that did not meet quality standards[6, 7]. Other solutions include Apparent Beam Width [ABW] metric and two CD measurements at different heights. The latter requires more effort than the correlation metric and the method may not necessarily be consistent with precision requirements in production.

The second concern with CD-SEM measurements is that the tool response to the two types of edge variations is not consistent among different tools or in the same tool if two different edge detection algorithms are used. Fig. 6 shows graphs of the difference between the measurements of two CD-SEM tools from different suppliers on the same focus-exposure wafer[11]. The measurements of all focus values for each exposure does are averaged in the graph on the left, while the measurements of all exposure variations are averaged for each focus setting in the graph on the right. The two tools respond differently to focus variations while their response to dose variations track.

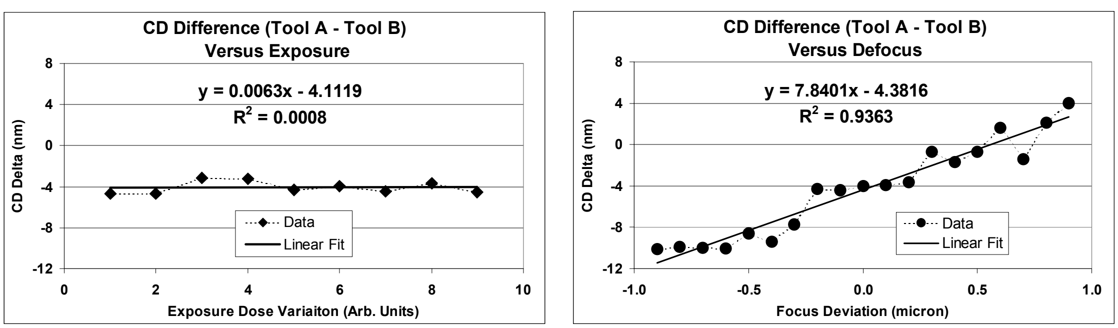

Figure 6. Differences of two CD-SEM tools versus variations in I-line resist FEM

This example is further analyzed in the two charts in Fig. 7. The scatter plots for the numbers representing the average of CD measurements of each tool over exposure variations is displayed on the left, while the scatter plot for the average measurement of each tool over focus variations is displayed on the right. It can be seen that the two CD-SEM systems have identical sensitivity to edge displacement (as caused by dose changes) and yet different sensitivity to shape variation (as caused by lithography tool defocus). The conclusion is that process variations in defocus will not be detected in the same way by CD measurements of the two tools.

The graph in the left of Fig. 7 explains how CD SEM tools have been able to provide value for in-line process control. The tools provide useful information when investigating exposure does settings despite the lack of accuracy. Even though the property that is measured is not well defined, measurement of such property reflects correctly the displacement in the edge position. However, shape changes are not tracked accurately. When investigating stepper focus variations, the conclusions could be misleading despite the precise nature of CD measurement.

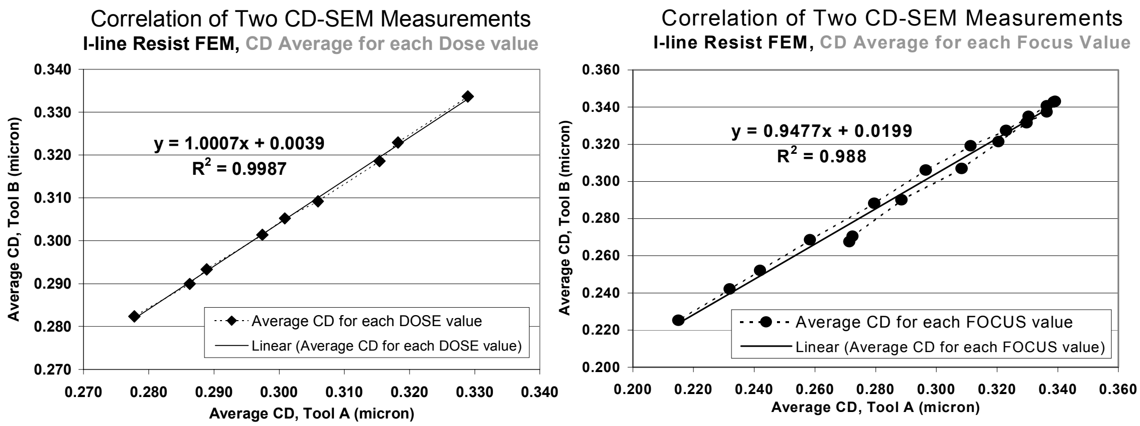

Figure 7. Correlation of two CD-SEM measurements

The potential difference in the response of two CD-SEM measurements to focus variations while having identical response to dose variations is another unusual characteristic of in-line CD metrology that is not consistent with behavior of “proper” metrology. This behavior originates from not measuring a well-defined property of the sample such as CD at a specific height above the interface. Since neither tool implements models for the detected signal, both suffer from lack of accuracy and the response of both tools to focus variations is suspect. Unless comparison studies are undertaken between tools of different types or different generations, this behavior will remain undetected in production environment. However, users should be aware that the level of any single tool’s response (i.e. sensitivity) to process variations can have a much larger impact on process control than the typical limitations of precision[3]. Consider a manufacturing facility using CD alone for process control. Furthermore, assume that the facility uses both types of CD SEM tools discussed here. Then within the set of wafer lots that have met CD specification criteria, the wafers processed through the facility will reflect different levels of focus variations, though identical levels of exposure dose variations depending on the CD-SEM tool used for quality control. It is not possible to fully compensate for such effects by adjusting specification limits for measurements from each tool accordingly because there exist differences in response of the two tools to exposure variations versus their response to focus variations and the fact that both sets of variations are present in the features in production. This example also applies to products from two different facilities using two different types of CD-SEM tools.

Note that it may be possible to match the measurements of two CD-SEM tools by modification of existing edge detection algorithms. In their present form, algorithms on CD-SEM tools are open to user modifications that do have an effect on the measurement outcome. If the two CD-SEM tools provide the same information content in collected images or line scan waveforms, it may be possible to match the measurement response to both focus and exposure variations in FEM tests. This situation corresponds to a trivial extension of case IV. Unless measurements can be related to a well-defined property of the sample, both sets of matched measurements remain suspect in their response to focus variations.

As an aside, inferred conclusions from CD measurements that are obtained without the use of models to relate the detected signal to the feature profile also lose their validity to some extent. Examples include process window analysis and depth of focus versus exposure latitude determination.

8. CONCLUSIONS

Users of CD measurement data (managers, design and CAD layout engineers, device and yield engineers, lithography and metrology engineers) should be aware of the limitations of CD metrology presented here.

The role of CD standards is deduced to be shape standards if such standards are to be useful for calibrating CD at any specified height above the interface.

The behavior of CD metrology is "proper" if the methods measure a well-defined property of the sample such as CD at a known height above the interface. Adhering to this definition is sufficient for proper behavior of the results of CD measurement including comparison of measurement methods and response to process variations in semiconductor manufacturing.

CD SEM tools used in production today lack signal modeling. This implies that the property that is measured is not well defined and varies based on sample edge shape. However, such tools are still capable of tracking exposure variations.

Lack of CD measurement accuracy in terms of tracking edge shape variations can consume part of the allowable process window. This cannot be recovered by simply changing the specification limits.

RMS is essential to process characterization as conducted today.

Finally, CD measurement alone is not sufficient to ensure that a feature meets quality standards. Unacceptable shapes can result in CD measurements that fall within specification limits. This is not limited to CD-SEM tools nor is it due to limitations of measurement accuracy. At least one additional metrics is required to ensure feature integrity. One such metric is the maximum correlation score between the signal from the feature under test and that of a golden sample.

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