The Importance of Measurement Accuracy in Statistical Process Control

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Abstract

Precision is deemed the most important aspect of a measurement for process control. This paper discusses the role of accuracy in process control and product quality. Although the discussion is emphasized for CD SEM metrology systems, the idea can be extended to other metrology areas such as thickness measurement where in addition to thickness, material characteristics also play a role.

In 1999, the characteristics of accuracy were published in a landmark paper[1]. The authors introduced the concept of characteristic slope and offset for the purpose of tool evaluation. Slope and offset were obtained from correlation plots of a measurement tool under test with a reference measurement system. The measurands were features that represent the range of process variations in a line.

This paper builds on the ideas put forth in that reference[1] and discusses the impact of measurement accuracy on process control. First, the issue is considered in an abstract sense, by comparison of the measurement method under test to a standard reference method. Then practical implications are discussed in more detail when tools from different suppliers are used in a fab to manufacture products.

Keywords: Accuracy, Statistical Process Control (SPC), precision, Critical Dimension (CD) measurements

1. Introduction

CD SEM metrology systems are the tools of choice for process monitoring and control in submicron semiconductor fabrication facilities. They are the most precise tools available for measuring submicron features. However, the accuracy of measurements for CD SEM metrology is not well defined. This is due to the fact that physical models that describe the signal do not exist.

2. Accuracy

From Mandel[2] "We have seen that accuracy implies a comparison with a reference value. If we consider a range of values, rather than an isolated point, the determination of accuracy would require the availability of a reference value at each point in the range. In the absence of reference values, the problem of accuracy cannot be discussed. But even if a reference value were available at each point, the problem of accuracy would be trivial: by plotting the measured values versus the reference value, a calibration curve would be obtained."

The implication of the above statement is that the calibration curve solves the problem of accuracy. When applied to CD measurements, the calibration curve can be constructed either from features with different target widths or from features that are all based on the same target width but span the range of process variations. Consider the following example. Fig. 1 depicts the comparison of CD measurements of features on a chrome-on-glass photomask measured on two different systems. The mask was wet etched, and the features measured were dense lines with nominal widths of 0.35, 0.5, 0.7, 1.0, and 1.5 microns. The CD range in this experiment corresponds to the range of drawn feature sizes on the mask. As a result of the method of manufacture and proximity of the test features, all edges on all features, with the same orientation, are expected to have the same profile. In the present experiment the edges were undercut as a result of the wet etch. The reference measurement system was an optical linewidth metrology tool with a

calibration traceable to NIST standards for lines greater than 0.5 micron. The tool under test was a scanning probe microscope (StylusNanoProfilometer, SNP).
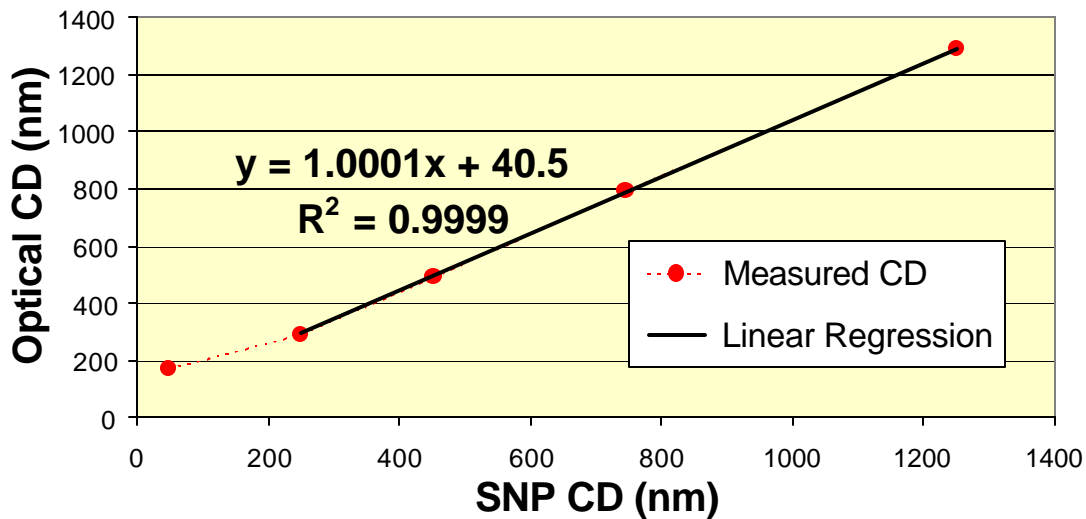

Figure 1 – Accuracy of Scanning Probe Microscope (Data courtesy of Infineon Technologies and Surface/Interface)

Fig. 1 shows that SNP measurements are linear with an offset of 40 nm. The last point is excluded from the analysis due to limitations of the optical tool for small linewidth measurements. The offset is mainly due to the fact that the mask was wet etched, resulting in a re-entrant profile. The CD measurements of SNP were calculated at 50% chrome height while the optical metrology tool is measuring very close to the top of the line due to opacity of the chrome. This difference is constant for all feature sizes in the range of interest, validating the assumption of edge similarity across the drawn CD range, and the slope of regression is unity. It must be mentioned that the scale calibration in neither system was adjusted prior to measurement. That is, the measurements were taken with whatever scale calibration was in place on each tool at the time of measurement. The closeness of regression slope of 1.0 indicates that the scales were well matched.

The above graph shows one aspect of accuracy, the calibration curve that is constructed with standards of different drawn width. The concept here is similar to a linearity test, which is one measure of accuracy. Though the conclusion here is much stronger than linearity alone. Due to traceable measurements from one tool and the slope of unity in the regression, the measurements of the tool under test (SNP) are made accurate by incorporating a simple offset.

The analysis discussed here conforms to the method discussed by Mandel[2]. However necessary, this method of using test structures of different drawn widths is for assessing accuracy, it is not sufficient for process control. For process control, the variations in the process must also be characterized. Thus it is required to construct the calibration curve based on a set of features that span the range of process variations around a targeted dimension.

Let us consider a hypothetical case for comparison of a tool under test with a reference measurement system for two situations. First at different drawn widths, and second for process variations at each drawn width. The factor that influences process control is not the calibration curve that is obtained with reference standards of different drawn width. Rather, it is the curve that is obtained by comparing process variations around the targeted dimension of interest. Each instrument may respond differently to the process variations. A graph similar to Fig. 1, but incorporating the response to process variations at each targeted dimension is shown in Fig. 2 below.
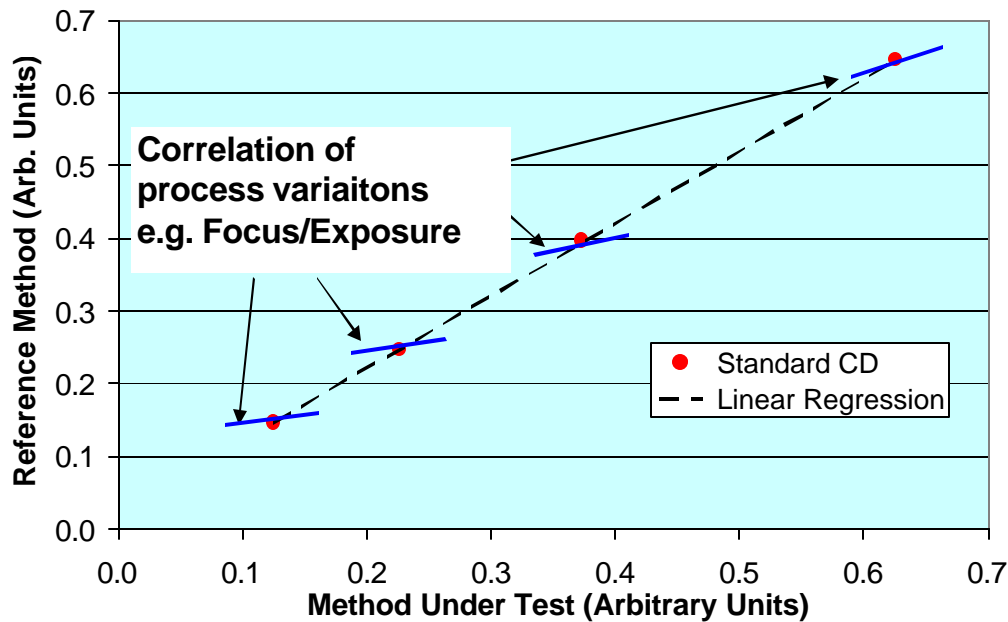
Figure 2 –Relationship of CD measurements between two tools depends on the feature set being measured.

This example illustrates the hypothetical case of comparison of two measurement methods where the response to the set of reference standards (the part represented with dotted line obtained from regression to a range of different sized standards) is different from the response to the process variations (the solid lines centered around each targeted dimension). What matters for process control is the "local" characterization of the response of the measurement tool (and method) to the process variations at a point near the center of a process.

It will be shown that this hypothetical case is experimentally observed in the measurements of CD SEM systems. However, the underlying reason for this behavior is not limited to CD SEM measurements. The reason for such behavior is that CD measurements, by necessity, condense a two dimensional representation (line profile or image) of a three dimensional feature, into a one dimensional result (CD number). The measurement can vary in response to two degrees of freedom. For example, the measurement of the line, there is width (x direction) and sidewall slope. Only one degree is captured by drawn variations of the dimensional standards, assuming that all corresponding sidewalls have the same shape. In the space of allowable process window, the dimensional variations of a feature are not solely along the x direction. Variations in feature dimension that result from the device manufacturing process are often manifest as changes in both the CD and the sidewall (e.g. stepper / scanner focus and exposure variations).

In the case of top-down CD SEM systems the issue is further compounded by the fact that physical models for the signal are not available. Thus, ad hoc algorithms are used for edge pixel assignment. This results in an unpredictable response to process variations than what would be indicated by an accurate Reference Measurement System (RMS). To investigate this effect, reference measurement systems are used that are able to reproduce, with reasonable accuracy, the two dimensional line shapes. Such reference measurement systems include cross sectional SEM or scanning probe microscopes.

Last year in this conference, Banke and Archie[1] presented their landmark contributions in a paper titled "Characteristics of accuracy for CD metrology" and their main perspective was tool evaluation. Their method of characterization starts by building a set of wafer artifacts that represent subtle, but important, process variations. The authors emphasize that quality of this step determines the usefulness of the tool evaluation. Their wafers were 0.25 micron focus/exposure matrices. The resist patterns consisted of

isolated and dense lines and isolated spaces. Next the authors measured the artifacts in a reference measurement system (RMS) and with several CD SEM tools under evaluation and compared the measurement results. As an example, to demonstrate the work of Banke and Archie, CD SEM to cross section correlation data obtained from SEMATECH was used (Fig. 3).
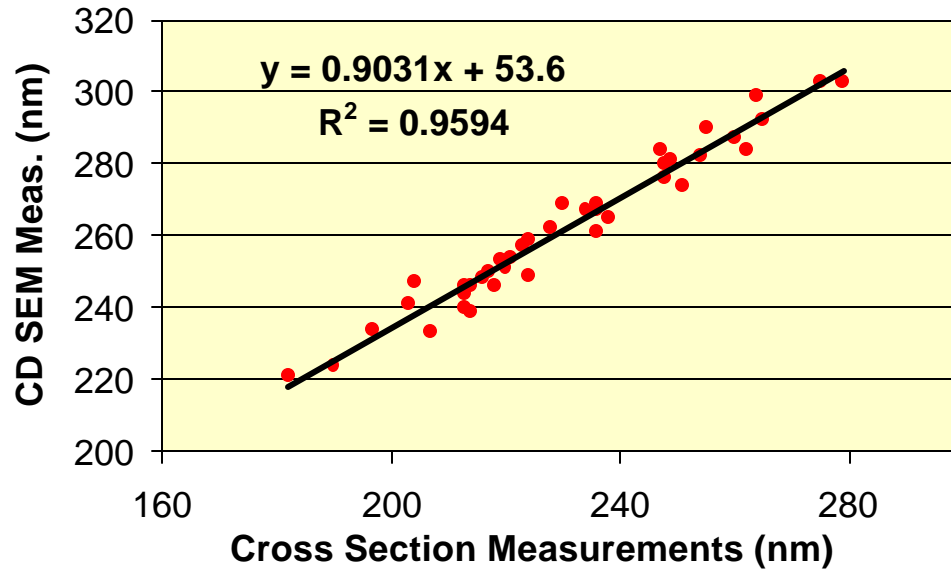

Figure 3 – Experimental results of CD SEM to Cross section correlation. (Data courtesy of Arnie Ford, SEMATECH)

The samples in the above graph were long, 0.25 micron dense lines suitable for cleaving. The lines were drawn with equal line and space on the mask. The features were resist on a 200 mm silicon substrate. The features were measured on the CD SEM, then cleaved and cross-sectioned. Both linewidth and pitch were measured on each system. The measurements of structure pitch are used for calibration of magnification in the cross section tool, so the pitch measurements were identical. But the linewidth measurements behaved differently. The parameters of interest are slope and offset of the linear regression. It can be seen from Fig. 3 that the slope of measurement is not unity.

We mention in passing that the relationship between the measurements of the two tools in Fig. 3 is different than their relationship when measuring different drawn widths. Suffice it to say that all modern CD SEM systems pass the linearity tests with ease. One can presume that the slope of regression obtained with different drawn widths would be very close to unity.

In their study, Banke and Archie measured the wafers on six CD SEM models from various manufacturers. However, they used Mandel's regression analysis method for correlating CD SEM measurements to RMS results. Mandel's regression method provides the ability to account for the error in both RMS and CD SEM tools as part of the calibration process. The authors emphasize that errors in the RMS and CD SEM measurements limit the accuracy assessment. The results can be summarized in the form of a linear relationship:

$$y = sx + b$$

Where y denotes CD SEM Measurements, x denotes the RMS measurements, s is the slope of the linear regression, and b is the offset. Note that this definition of slope is the reciprocal of the definition of the slope in the original reference[1]. Among the results obtained by Banke and Archie were estimates of slope for each CD SEM relative to the RMS. The results for the slopes of 6 CD SEM systems A through E are depicted below:
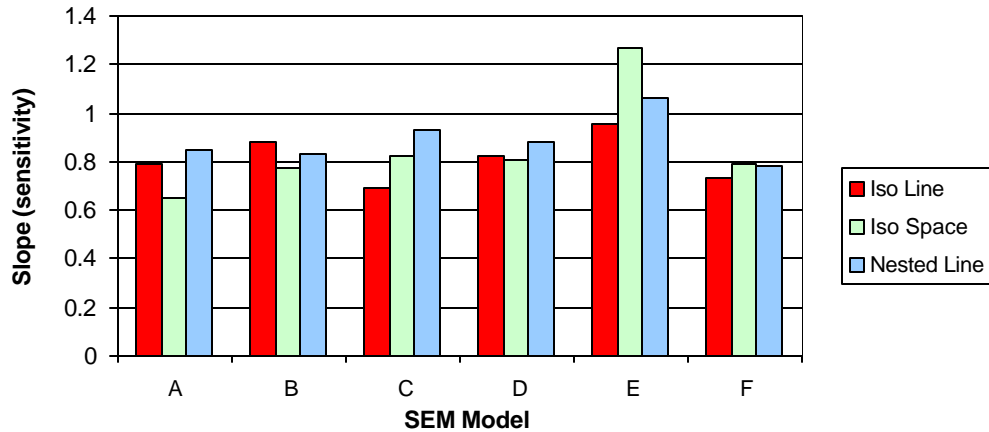
Figure 4 – Slope of CD SEM Measurements
[Modified from the original reference with permission of B. Banke and C. Archie]

It is interesting to note that all six CD SEM systems have slopes less than unity for isolated lines. This means that for a 10 nm change in the linewidth as judged from the cross sections, the commercial CD SEM systems report a smaller change, 8 nm on average. The slopes shown in Fig. 4 define the sensitivity of the CD SEM measurement relative to the RMS. The sensitivity signifies the amount by which the CD SEM measurements change for every unit change in the cross section measurements.

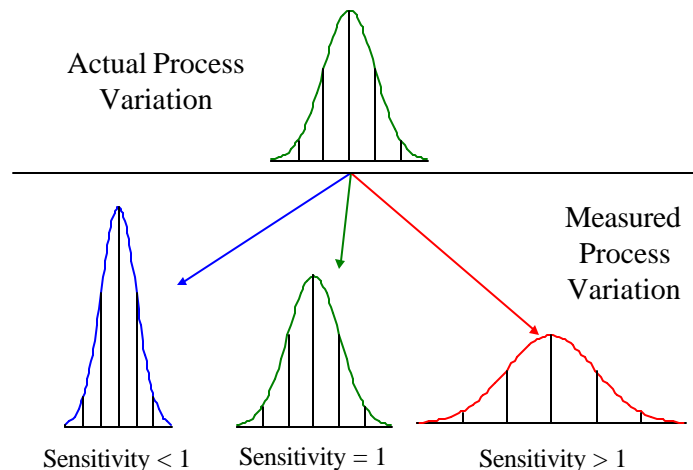## Appearance of Process Variations

Figure 5 – Appearance of process variations based on measurement tool sensitivity

The sensitivity of measurement has a direct impact on the observed process variations. In practice most CD SEM systems have sensitivity less than unity. If sensitivity is ignored, the consequences are much more dramatic than lack of measurement precision. Consider the following example, the significance of which becomes clear when considering two different CD SEM systems in different fabs. Assume that a process is in place that is measured with an accurate tool (such as cross section or scanning probe microscope) and the process is actually within specification limits (as shown in the upper left corner of Fig. 6). Now assume that a CD SEM is placed in the manufacturing line and the proper measurement offset is set up to center the process, but the slope (sensitivity) is ignored, a common practice in manufacturing. With low sensitivity of CD SEM measurements, the process distribution will appear tighter than the specification limits. It is likely, in this scenario that the process will be allowed to drift and will be controlled via the CD SEM measurements. A possible outcome is shown in the upper right corner of

Fig. 6, where the product, if measured with the accurate tool, will actually follow a wider distribution than is reported by the CD SEM. The economic consequences of ignoring accuracy can be quite significant.
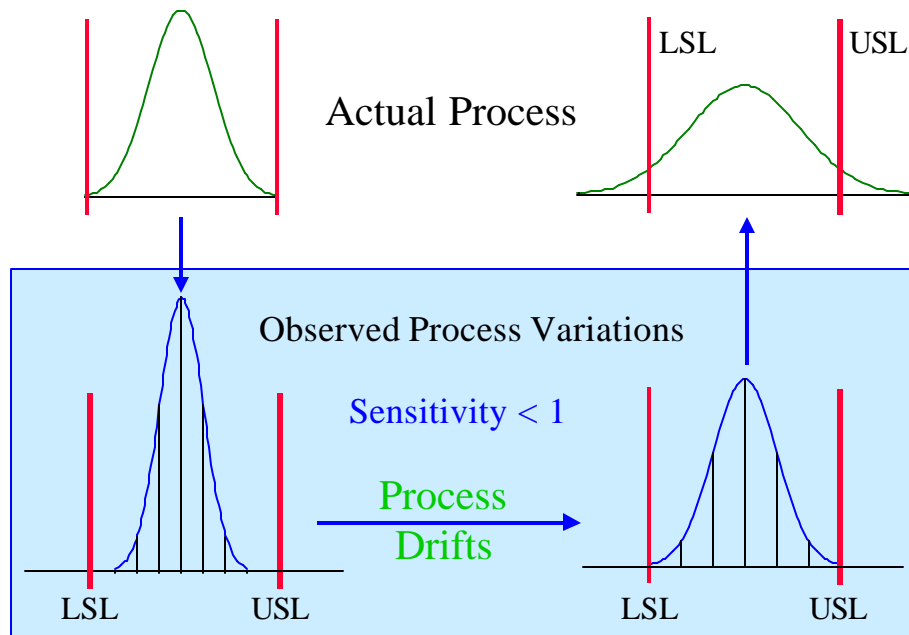

Figure 6 – The consequences of uncorrected low sensitivity. The product will have a wider distribution than reported

The effect of sensitivity can be corrected. Most CD SEM systems provide the capability to modify the results with a slope and offset correction prior to reporting the measurement. If this method is not employed, the effects can still be taken into account post measurement. Following the discussions by Mandel[2], and Banke and Archie[1] where the "corrected precision" of measurement is defined as:

$$\sigma_{m, corrected} = \sigma_{m, uncorrected}/s$$

one can define the "corrected process standard deviation" (since the sensitivity can be thought of as magnifying the variations) as:

$$\sigma_{p, corrected} = \sigma_{p, uncorrected}/s$$

One can also define corrected "observed" process variations, corrected C_p. Since $\sigma_o^2 = \sigma_p^2 + \sigma_m^2$, we get

$$\sigma_{o, corrected} = \sigma_{o, uncorrected}/s$$

$$C_{p, corrected} = C_{p, uncorrected}/s$$

The metric C_{pk} changes differently and is not described by a simple multiplication factor.

$$C_{pk, corrected} = (Min[(USL - \mu_{corrected}, \mu_{corrected} - LSL)]) / 3\sigma_{o, corrected}$$

It should be emphasized that the simple offset correction does not change C_p, the potential process control capability index. This is the reason why accuracy, when interpreted solely as an offset, is often ignored in process control. But measurement sensitivity does affect the process control capability.

3. Practical Considerations for Matching

Typically, matching is evaluated by comparing measurement means of multiple tools. For reasons described in previous section, this can lead to erroneous conclusions about product quality.

We will borrow from and build on Mandel's analysis when comparing two measurement systems. For two measurement systems to be compared according to the above method, each needs to be compared to a reference measurement system, and this requires the knowledge of two characterization curves. But a comparison of the two measurement systems can be achieved directly without a reference measurement system. The comparison will provide a relative sensitivity of the two measurement systems.

To investigate the impact of matching on process control among multiple tools, one does not require traceable standards nor a reference measurement system. Using concepts defined in this paper, the measurement systems can be compared to each other in pairs. The advantage of applying this concept to CD SEM systems is that with their excellent measurement precision, Mandel's regression can be performed with very reliable estimates of the relative sensitivity.

Consider the experimental results of comparison of two commercial CD SEM systems from different suppliers. Engelen and Minnaert-Janssen[3] have described a method for matching CD SEM systems from different manufacturers for the purpose of evaluating focus/exposure analysis in exposure tool characterization. As part of the matching activity, the authors ensure that magnification calibration between the systems agree to better than 1% by measuring pitch of an artifact. After certain other steps, at the very end of the matching process, the authors compute an offset between average of measurements of the two systems. They obtain matching by applying this offset to the results of one of the system.

Matching by considering an offset alone will not be sufficient for process control in manufacturing. In Fig. 7, we show the scatter diagram of the focus/exposure matrix measurements on two commercially available CD SEM tools. The data is courtesy of Andre Engelen. The nominal feature size was 0.3 micron and the focus range was 1.0 micron. For reference, the straight line depicts the results of common practice of applying a simple offset to get the tools matched. It is clearly seen that the behavior of the two tools deviates from straight line with unity slope.
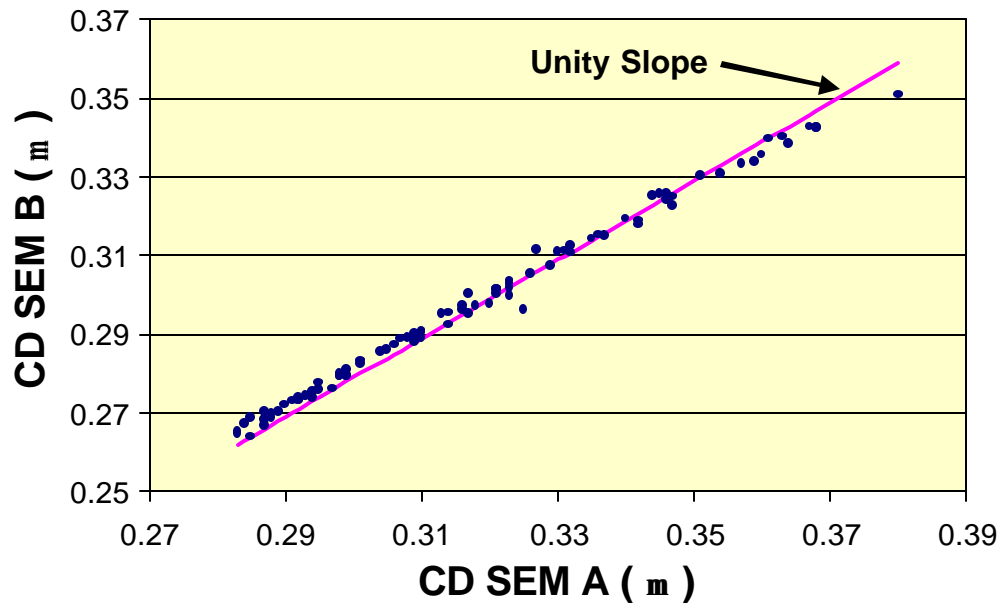

Figure 7 – Comparative characterization of two SEM models. The slope with Mandel's model is 0.926. For comparison, the line with unity slope and offset correction is also shown. (Data courtesy of Andre Engelen, ASML)

To the data we apply the regression method provided by Banke and Archie[1]. However, the method is used to characterize the response of one tool relative to the other. In this case, the slope calculated with Mandel's method was 0.926 assuming equal measurement precision for the two tools. The standard linear regression method yields a slope of 0.924.

The discussion in the previous section regarding comparison of the metrology tool under test to a reference measurement system can be extended to the comparison of two metrology tools with each other. The process variations can be measured with each tool and the correlation plotted in a fashion similar to Fig. 7. The slope of the regression defines relative measurement sensitivity of one tool to the other. The deviation of the relative sensitivity from unity will cause the process variations to appear different when measured with each tool. The conclusions regarding the difference in process control capability when utilizing one tool versus the other remain valid.

Indeed, as can be seen from Fig. 4, existing data indicates that relative sensitivities from tool to tool can vary by more than 20% (for 0.25 micron nominal line). Whenever more than one equipment model is used in fabrication facilities (either in the same facility or different facilities around the world) care must be paid to the relative sensitivity of the different tools to process variations. If the deviation of relative sensitivity from unity goes unnoticed, the product quality for that layer will depend on the tool that is used for measurement. The uncorrected C_p can vary by more than 20%. In the example of Fig. 7, the deviation from unity is 7%. By comparison, a degradation of precision from gage maker rule by a factor of 3 will only degrade C_p by 5%.

4. Conclusions

Accuracy, if ignored, will have a significant impact on the manufacturer's ability to control the process. By considering the sensitivity of the measurement system's response to process variations, we have shown that there exists a linear relationship between measurement sensitivity, s, and the apparent potential process control capability index C_p. This compares to measurement precision which impacts C_p based on a root-mean-square relationship with process standard deviation. Thus accuracy can have a much larger effect for an equivalent deviation.

A method to minimize the impact of inaccuracy on process control has also been described. This method relies on a reference measurement system[1], used to provide the best possible characterization of the artifacts. Such a characterization should be performed by using sample artifacts that reflect the range of acceptable process variations (e.g. for lithography this would require a focus and exposure matrix). The RMS must be known to be, from basic physics, more accurate and more precise than tools used in the manufacturing line. However, such a system need only be significantly better than the in-line system to be of value. The RMS should be used to pick out the aspect of the feature on which the final product performance depends.

An extension of the accuracy argument has been made to the case of system-to-system matching of different equipment models. Here again, it has been demonstrated that the impact of the existing relative sensitivity (relative for the case of matching) of a CD measurement system on the process control capability is more significant than the precision. Traceable linewidth standards are not required for such a determination since relative measurement matching is being characterized.

5. Acknowledgements

with Robert Lipari of Surface/Interface. His insistence on clear and simple explanations led us to the last conclusion of this paper.

6. References

1. Bill Banke and Chas Archie, SPIE Vol. 3667, p.291 (1999)
2. John Mandel, "The Statistical Analysis of Experimental Data", Dover, 1984
3. Andre Engelen and Ingrid Minnaert-Janssen, SPIE Vol. 3667, p.280 (1999)

Appendix 1: Statistics after Linear Transformation

For a measurement of a quality x, we define mean μ_x and standard deviation σ_x of the quality as follows:

$$\mu_x = E(x)$$
$$\sigma_x^2 = E ((x- \mu_x)^2)$$

The notation $E(x)$ represents the expectation value of x. These quantities refer to the population parameters for the hypothetical set, not the estimates.

Given a linear transformation:
$$y = sx + b$$
We have in a similar fashion:
$$\mu_y = E(y)$$
$$\sigma_y^2 = E ((y- \mu_y)^2)$$
It can be shown that:
$$\mu_y = s\mu_x + b$$
$$\sigma_y = s\sigma_x$$

In particular, if x has a normal probability distribution given by $N(\mu_x, \sigma_x)$, then probability distribution of y is also normal and is given by $N(\mu_y, \sigma_y)$. In this notation, $N(\mu, \sigma)$ is the normal probability distribution described by a Gaussian as:

$$f(z)dz = \frac{1}{s\sqrt{2p}}e^{-\frac{(z-m)^2}{2s^2}} dz$$

Appendix 2: Process Control Capability Ratios

There are two metrics that describe the capabilities for statistical control of process variability. Both metrics compare the process variability to the specification limits. The quality characteristic is assumed to have a normal distribution with mean μ and standard deviation σ. A measure of process variation is the 6σ spread in the distribution of the measured characteristic. The potential process control capability C_p is defined by:

$$C_p = (USL - LSL) / 6\sigma$$

Note that σ represents the estimate of process variation standard deviation σ_p) and in practice is confounded by measurement imprecision (σ_m).

$$\sigma^2 = \sigma_p^2 + \sigma_m^2$$

The index C_p defines the maximum capability and is independent of the actual mean μ. In practice the mean μ may be closer to one of the two limits. Then the one-sided process capability ratio is defined relative to the limit near the process average to reflect the actual process control capability.

$$C_{pk} = (Min[(USL - \mu , \mu - LSL)]) / 3\sigma$$