Nanometrology of Critical Dimensions

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Abstract

Metrology and control of critical dimensions (CD) are vital for the nanotechnology success. Modern nanometrology is largely based on knowledge earned during the last 10-20 years of semiconductor technology development. Semiconductor CD metrology entered the nanotechnology age in the late 1990's. Work on 130 nm and 90 nm node technologies led to the conclusion that precision is an insufficient metric for metrology quality assessment. Other components of measurement uncertainty (MU) must be considered. Two of them became particularly noticeable: (i) sample-to-sample measurement bias variation and (ii) sampling uncertainty. The first one (sample dependent systematic error) is significant for commonly used CD metrologies such as top-down and cross-sectional scanning electron microscopy (SEM) and optical scatterometry (OCD). Unless special measures are taken, bias variation of CDSEM and OCD could exceed several nanometers. Variation of bias and, therefore, MU can be assessed only if reference metrology (RM) is employed. The choice of RM tools is very limited. The CD atomic force microscope (AFM) and transmission electron microscopy (TEM) are of a few available RM tools. RM systems must provide sub-nanometer MU for a number of nanometrology applications. Significant challenges of both RM tools TEM and CDAFM still remain.

1. Measurement Uncertainty to Replace Precision as a Metrology Quality Metric

Physical properties of nanoobjects and, hence, quality of nanoproducts strongly depend on their dimensions. Control of these critical dimensions (CD) is vital for the overall nanotechnology success. Metrology is a key to process and quality control. What is nanometrology and how it is different from metrology of macro, mini and micro objects? Modern nanometrology is largely based on knowledge earned during the last 10-20 years of semiconductor technology development. Semiconductor CD metrology entered the nanotechnology age in the late 1990's. Work on 130 nm and 90 nm node technologies led to the conclusion that precision is an insufficient metric for metrology quality assessment. Through research and daily practice it became obvious that other components of measurement uncertainty (MU) must be considered [1,2]. Two components became particularly noticeable: (i) sample-to-sample measurement bias variation [3] and (ii) sampling uncertainty [4]. The first one (sample dependent systematic error) is significant for commonly used CD metrologies such as top-down and cross-sectional scanning electron microscopy (SEM) and optical scatterometry (OCD). Unless special measures are taken, bias variation of CDSEM and OCD could exceed several nanometers [5,6]. Figure 1 illustrates impact of sample-to-sample bias variation on MU [7].

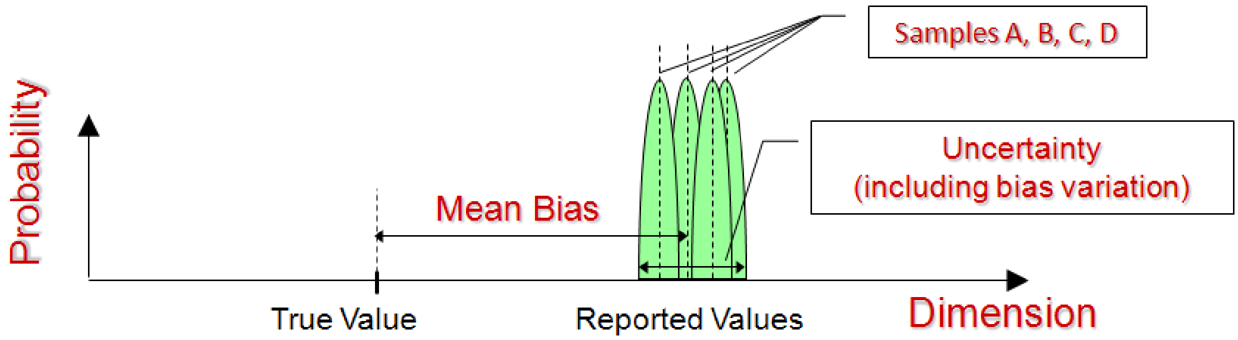

Figure 1. Illustration of impact of sample-to-sample bias variation on uncertainty of the measurement [7].

In a 2009 SPIE paper by Rana, *et al*. [6] shows how MU of CDSEM grows with various degrees of measurand complexity (Fig. 2). The total measurement uncertainty (TMU) of the CDSEM is shown as a function of the feature-shape variation caused by the changes of lithography scanner focus. The degree of out-of-scanner focus is shown in the sketch to the right of the graph in figure. TMU is an IBM-defined metric in units of nanometers which captures additional (beyond precision) components of uncertainty of the measurement system under test, in this case the CDSEM [8]. A reference metrology (RM) system is required to evaluate the TMU of a system under test. In this case the CDAFM was used as the trusted RM.

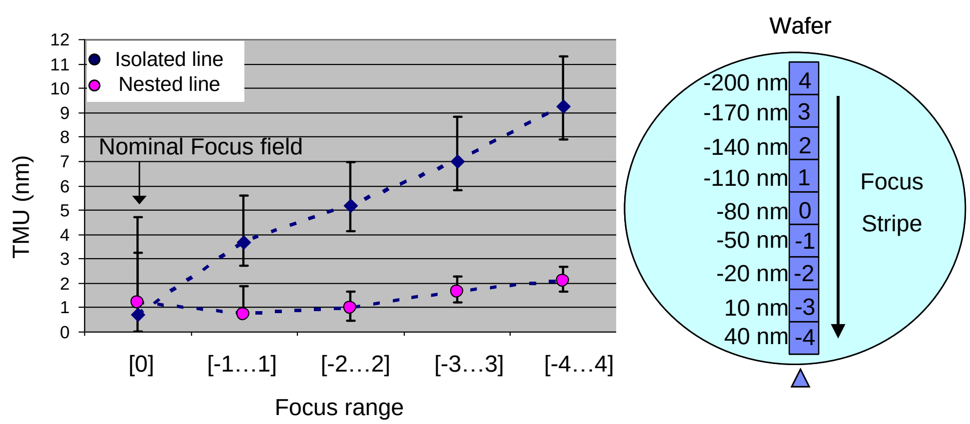

Figure 2. The increased CDSEM measurement uncertainty as a function measurand complexity induced by scanner focus [6].

The following two examples demonstrate another employment of RM for evaluation of TMU of OCD for CD and sidewall angle (SWA) measurements of a nominal 40 nm wide poly-Si line [5]. Figure 4 presents the correlation between OCD and reference data (CDAFM) for bottom CD and SWA of the line (gate). Fleet of 3 OCD tools was evaluated. TMU analysis shows that MU of fleet for bottom CD measurement is about 2% of the nominal CD. For a process tolerance (T) of ± 4 nm, the TMU/T ratio is 0.2. This level of measurement uncertainty is acceptable from process control prospective. As a general rule of thumb, the measurement uncertainty should only consume a maximum of 20% of the process tolerance budget. The data from Figure 3 also shows the OCD fleet TMU for SWA measurements is a nominal ± 0.8 degree. This level of uncertainty (U) is not acceptable since SWA process tolerance for that technology was ±1.6 degrees. This leads to TMU/T ratio of 0.5 which exceeds the required limit of 0.2 for the ratio. Figure 3 shows that OCD single tool precision is ± 0.2 degrees. If this single tool precision (P) was used to evaluate quality of the SWA metrology, a result of P/T = 0.2/1.6 = 0.12 would significantly overestimate the SWA measurement capability of the OCD. There is a danger here. Clearly, this shows the importance of using an uncertainty estimate (TMU) instead of a precision estimate alone for estimating a measurement technology's ability to control a process.

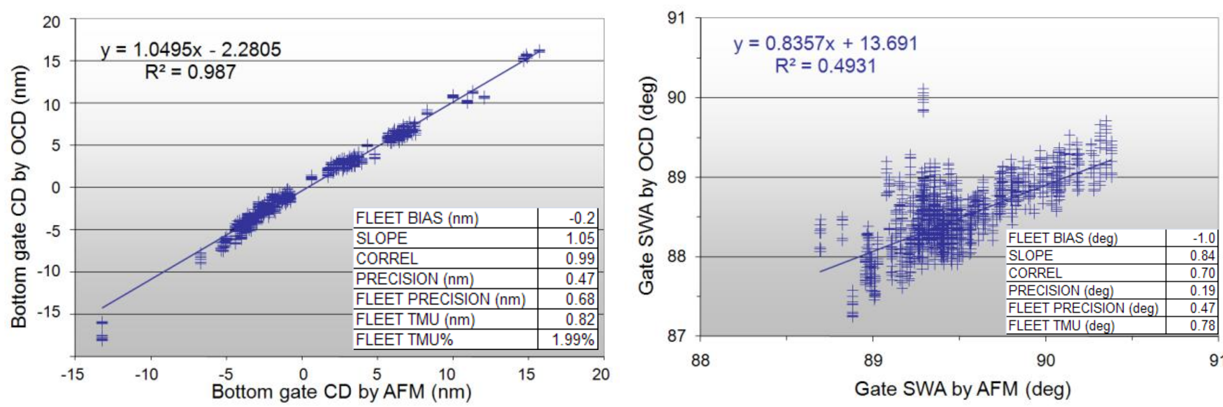

Figure 3. The correlation between OCD and reference data for the gate bottom line CD (left) and SWA (right).

2. The Role and Choice of Reference Metrology

Variation of measurement bias and, therefore, MU can be assessed only if a reference metrology is employed. What is reference metrology? An ideal RM system provides SI-traceable measurements with known (and low) uncertainty. A nanometer level MU of CD metrology tools is needed to control manufacturing of products with CD's below 100 nm [2]. Required MU of nanometrology RM systems is in sub-nanometer range. The choice of RM tools of such high quality is very limited. To search for the best RM technique one could try to estimate MU of various CD metrology techniques [9]. Table 1 shows MU estimates for 5 most common metrology techniques. The most significant components of measurement uncertainty such as: an accuracy of scale calibration, repeatability, sample-to-sample bias variation and sampling uncertainty [4] were added together. The combined uncertainty for a single site measurement (column 6) and uncertainty of the mean for typical sample size (column 8) are shown. In brief, low sample-to-sample bias variation (intrinsic relative accuracy) and high sampling efficiency make CDAFM a good candidate for linewidth reference metrology.

Table 1. Estimated uncertainty of line CD measurement using 5 conventional metrology techniques [9].

	6S Scale Accuracy (%)	6S CD Repeatability (nm)	Bias Variation (nm)	6S LWR (nm)	Single Site 6S TMU (nm)	Typical Sample Size	Wafer Average TMU/T
TEM	4	2.8	0	9	**9.5**	5	**4.4**
DualBeam	4	2.8	2	9	**9.7**	5	**4.8**
AFM	1	2.0	0.5	1.8	**2.8**	9	**1.1**
OCD	0	0.6	2	0	**2.1**	27	**2.0**
SEM	1	1.0	2	1.8	**2.9**	9	**2.1**
Gate CD		**32**		***LWR***		**1.5**	
				Number of scans		**24**	

Transmission electron microscopy (TEM) has presumably the lowest sample-to-sample bias variation of all considered techniques. Scale accuracy of TEM can be also significantly improved if a crystalline sample with known lattice parameters is used. However, sampling uncertainty of TEM measurements related to local linewidth variation [4] is very high and can be suppressed to a nanometer level only with an extraordinary effort (by averaging tens of TEM measurements each done using independent sample representing the same measurand). Therefore, TEM can be used as a RM tool but this approach is extremely costly and time consuming.

Widely used in nanotechnology (top-down and cross-sectional) SEM and OCD tools do not meet strict MU requirements of nanometrology unless they are properly calibrated and their bias is corrected. Bias correction procedure may be very convoluted [10].

3. The Future of Nanometrology

Various techniques could be considered as a RM tool. Each of them would have strengths and weaknesses. Some time ago an idea of hybrid metrology has surfaced [11]. The idea behind a hybrid metrology is to improve the accuracy of a high throughput in-line or a reference metrology by combining its measurement with that of another measurement. It doesn't have to be, but the complementary metrology could be another measurement technology. The hybrid metrology uses strengths of two or more techniques with a goal to minimize uncertainty of the particular measurement. A recent example of this is from Silver *et al.* [12], where they supplement the OCD measurement with that of a CDAFM and significantly improve the OCD measurement uncertainty, while still able to maintain its high throughput. Table 2 taken from Silver's work shows the benefit of using the CDAFM in concert with the OCD measurement. The table shows the top, middle, and bottom linewidth measurement averages and MU values from the OCD both with and without the supplemental CDAFM measurements. It is noteworthy that the top linewidth OCD average shown in the left matrix assisted by the CDAFM did not position itself *between* the separate OCD and CDAFM averages. It is also important to note that the uncertainties of all OCD measurements were significantly improved with the aid of the CDAFM, and surpassed the uncertainties of the CDAFM, itself! This is a convincing example of the benefit of combining metrology in new forms of a hybrid metrology.

Table 2. Results from Silver *et al.*[12] showing OCD accuracy improvement when assisted by CDAFM measurements.

	OCD fitting	AFM	OCD w/ AFM
Top	120	119.2	121
Middle	112	117.3	115
Bottom	143	132.8	141

	OCD fitting	AFM	OCD w/ AFM
σ_{Top}	1.05	0.75	0.35
σ_{Middle}	1.58	0.75	0.60
σ_{Bottom}	0.78	0.75	0.42

4. Summary

Semiconductor high volume manufacturing entered nanotechnology age in late 90-s. Critical dimension metrology with sub-nanometer measurement uncertainty is required to support modern production. There is a need and urgency to address metrology accuracy deficiencies in nanoscale manufacturing. Specifically, the bias variation of high throughput in-line measurement systems is a major component of the measurement uncertainty. Reference metrology is the only way to assess bias variation of CD metrology tools. This paper points out the virtues of the CDAFM measurement technology as a good start. Significant improvements in reference metrology and in-line CD metrology are needed to support nanotechnology research, development and manufacturing. The future nanometrology will benefit from synergy of optical and various scanning probe techniques.

5. References

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