Dimensional metrology with sub-nanometer uncertainty: unique role of AFM as the reference

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ABSTRACT

The 2007 edition of ITRS has introduced a new metric for metrology quality assessment – measurement uncertainty (MU). The new metric has precision as one of many uncertainty components. Additional significant components are tool matching, sampling uncertainty and sample-to-sample bias variation. Sample dependent bias variation and, therefore, MU can be measured accurately only if a reference metrology (RM) is employed. RM is a must for achieving and verifying required today sub-nanometer MU of critical dimension (CD) metrology. To insure long-term performance of in-line metrology and reliable process control a simple but efficient way is suggested - employment of in-line RM system. SI-traceable CD AFM with sub-nanometer MU is a proper RM tool for the task.

Keywords: Accuracy, critical dimension, measurement uncertainty, bias variation, reference metrology, AFM.

1. INTRODUCTION

The concept of measurement uncertainty (MU) and guidelines of its implementation have been introduced and developed in the early 1990s [1,2,3]. The ITRS Metrology 2007 edition has adopted the concept and changed metrology performance metric from precision to uncertainty [4]. The new metric, MU, has precision as one of the many uncertainty components. Additional MU components are tool matching and uncertainty related to sampling. The ITRS keeps the list open-ended concluding with the "other" component.

Driven by the industry demand reproducibility of critical dimension (CD) metrology tools has improved dramatically in the last decade. Sub-nanometer precision is common today. With precision below a nanometer other components of MU became noticeable and even dominant. At certain point tool-to-tool matching became a problem [5]. Later component of uncertainty related to sampling attracted our attention [6].

It is important to realize that these three components of MU (distinguished by the ITRS from the "others") can be estimated without knowledge of absolute CD. In other words, no reference or SI-traceable metrology is needed to do the estimates. Precision and tool matching can be estimated by repeatable measurements on the set of technology representative samples [7]. Sampling uncertainty can be estimated using statistics through random measurements of *relative* sample-to-sample CD variation [6].

Importantly, these three components are not the only components contributing to MU. Once CD's reach range of 100 nm and, therefore, required for proper process control CD metrology MU reaches 1-2 nm, sample-to-sample bias variation becomes the dominant component of MU [8]. In this case we are dealing with sample dependent variation of systematic (the mean, time and trial independent) error. For ideal metrology systematic error or bias of the measurement is sample independent. For actual metrology the bias or systematic error is changing from sample-to-sample depending on the secondary properties of the sample (material, geometry, proximity, etc.). One could neglect this a few nanometers large MU component in the past but not anymore. It is a real challenge to keep sample-to-sample bias variation of CD scanning electron microscopy (SEM) and optical scatterometry (OCD) at a nanometer level. Unless special measures are taken MU of CD SEM and OCD could easily exceed 2-4 nm. This fact is well documented [8,9,10]. Clearly, the several nanometers MU of CD metrology is not acceptable today.

The bias variation component of MU can be measured accurately only if reference metrology (RM) insensitive to the secondary properties of the sample is employed. Since the diversity and nature of the secondary effects virtually impossible to predict the only practical way to measure sample-to-sample variation is to employ SI-traceable RM [2]. Since described sample dependent bias variation component is significant and can't be neglected anymore, use of RM becomes a must if true MU to be evaluated.

Choice of RM tools for CD metrology is very limited. CD atomic force microscope (AFM) is a possible choice. Independence of CD AFM bias from proximity effects, sample material, shape, dimensions as well as thorough sampling statistics and SI-traceability make AFM a good candidate for RM in many practical cases. Recent

developments and studies suggest that CD AFM can provide RM with sub-nanometer MU for several key semiconductor applications [9,11].
In this work we look again at components of MU of CD metrology. We suggest further expansion of the "other" component of CD MU and an introduction of the sample dependent measurement bias variation component. We also propose employment of CD AFM as a reference SI-traceable metrology tool for industrial applications. We suggest a simple but efficient and tested [9] way of establishing CD metrology with sub-nanometer MU in industrial environment. The method consists of 3 steps:

- Creating technology representative set of samples calibrated using SI-traceable CD AFM;
- Minimizing MU of in-line metrology using the pre-calibrated samples (tool choice, settings, model tuning);
- Using in-line RM tool for systematic monitoring of bias of in-line "work horse" metrology.

We conclude that RM is a must for achieving needed today sub-nanometer MU of CD metrology. To prevent metrology bias excursions and insure reliable process control SI-traceable RM tools should be employed in-line today.

2. COMPONENTS OF CD MEASUREMENT UNCERTAINTY

According to the 2007 edition of the ITRS the measurement uncertainty contains single tool precision, tool-to-tool matching, sampling uncertainty, and "other" components:

$$U_{Combined}^2 = \sigma_S^2 + \sigma_P^2 + \sigma_M^2 + \sigma_{other}^2 \quad (1)$$

As noted by Bunday *et al.* [6] the "other" term includes cross correlations among the time, tool and sample related sources of measurement variation discussed above the σ_P, σ_M and σ_S, respectively. Simple example of such cross correlation uncertainty terms could be the dependence of tool precision on the set of samples used to estimate it. Another example could be a time drift of tool-to-tool matching. To minimize these contributors to the combined uncertainty of the measurement various approaches could be implemented. Use of thorough technology representative set of samples is one way to minimize impact of sample set on precision estimation [9]. Systematic periodic comparison and tuning of fleet of similar metrology tools using in-line production material is another effective way to reduce unaccounted by the σ_P, σ_M and σ_S cross correlations terms [5].
As one can see, no SI-traceability or knowledge of absolute accuracy of CD is needed to estimate terms of MU described so far. The situation is changing qualitatively once one starts to question constancy of measurement bias.
An ideal metrology, of course, has constant measurement bias or offset between the reported and true (absolute) value of the measurand. The bias or, in other words, systematic (the mean, time and trial independent) error of the measurement should be corrected if known [2]. As shown by many studies bias of CD SEM and OCD may vary significantly from one sample to another [8,9,10,12]. Here we present only one example of bias variation for CD SEM measurements of resist lines (Fig. 1). Two brands of CD SEM were used for comparison. CD AFM was used as a reference tool. For SEM_1 bias varies from 6 to 10 nm and for SEM_2 bias varies from 2 to 6 nm. Both tools show similar through pitch trends. Systematic differences were observed for four samples with pitch from 350 nm to 450 nm. For both tools through pitch bias variation is ca. 4 nm. This number is about 4 times larger than σ_P of the SEM's. Therefore, sample dependent bias variation component controls MU in this case.
Bias variation caused by secondary and often uncontrolled sample properties increases combined uncertainty of the measurement (Fig. 2). The sample dependent bias variation is an important term of MU included today in the "other" component of combined uncertainty (Eq. 1). This term is qualitatively different from the previously discussed terms σ_P, σ_M and σ_S since the term can't be estimated without knowledge of the true or accurate CD. We argue that because of this qualitative difference and also because of its large value the term σ_B deserves to be extracted from the "other" term:

$$U_{Combined}^2 = \sigma_S^2 + \sigma_P^2 + \sigma_M^2 + \sigma_B^2 + \sigma_{other}^2 \quad (2)$$

To measure sample dependent bias variation one must use RM, bias of which is independent from the secondary sample properties. At the first sight it looks like there is no need in *absolute* accuracy or SI-traceability to assess MU [10,13,14]. Banke *et al.* [15] uses the *relative* accuracy term or accuracy describing bias variation measurements without knowledge of the bias absolute value. We think that this approach is valid and promises a reduction in uncertainty of the σ_B estimation [16]. However, we also should note that this approach is risky because of wide diversity and sometimes hidden nature of the secondary sample properties which may potentially impact measurement bias. From

this prospective an employment of accurate and SI-traceable RM tool for σ_B estimations seems to be safer and should provide more conservative estimates of σ_B and overall MU.

Bunday *et al.* [6] also discusses bias variation caused by interaction between measurement tool and sample (resist shrinkage, charging, contamination, buildups). In practice, the main portion of this additional time, tool and sample dependent bias variation uncertainty is already included in the discussed above "sample dependent" σ_B [17]. Once again the remaining cross correlation terms will be kept within the "other" component. Thus, in Eq. 2 all known major components of MU are presented in distinguished form and only cross correlation terms are combined in the "other" component. Therefore, we think that Eq. 2 is a clearer way to express combined uncertainty of CD measurements.

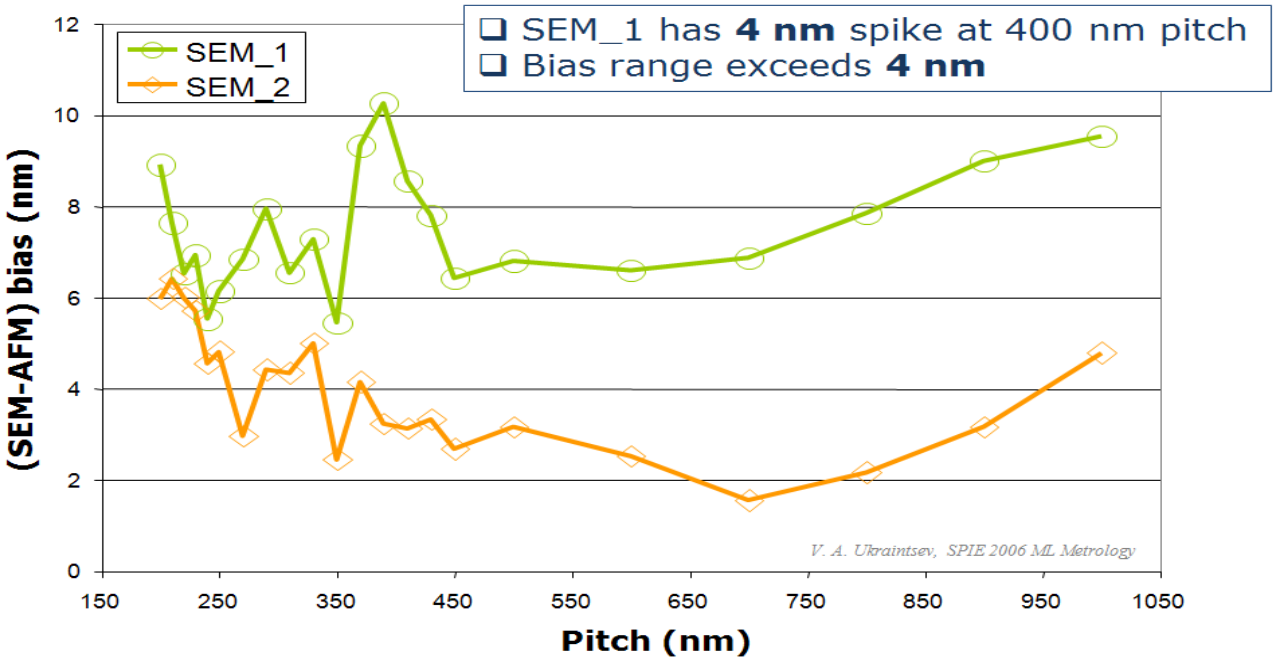

Figure 1. Through pitch CDSEM bias variation for two brands of tools. Photoresist linewidth measurements.

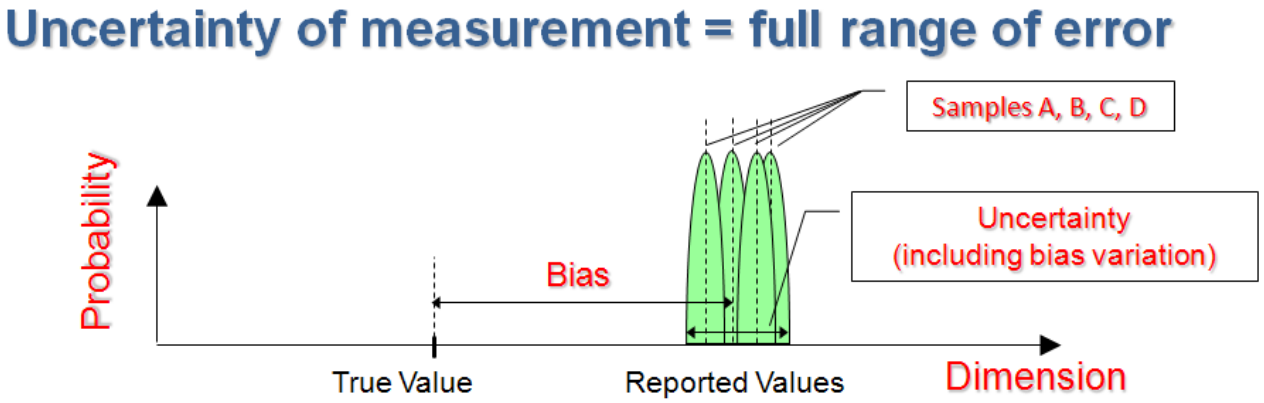

Figure 2. Relations between true and reported values. Impact of sample dependent bias variation on MU.

3. IMPACT OF METROLOGY ON PROCESS CONTROL

As shown in Section 2 sample dependent bias variation σ_B could be a commanding component of MU. SI-traceable RM system should be used to estimate the component. Employment of additional RM equipment and expertise is a significant investment in CD metrology for any semiconductor manufacturer. Is this investment justified?

To illustrate importance of proper metrology on process control and, therefore, on quality and yield of product we will consider an example of MOSFET gate sidewall angle (SWA) measurements using optical scatterometry [9]. The study was conducted at Texas Instruments, Inc. during 65 nm technology development. Uncertainty of gate SWA measurement using OCD tool was evaluated using CD AFM as a reference tool. Results are summarized in Figure 3.

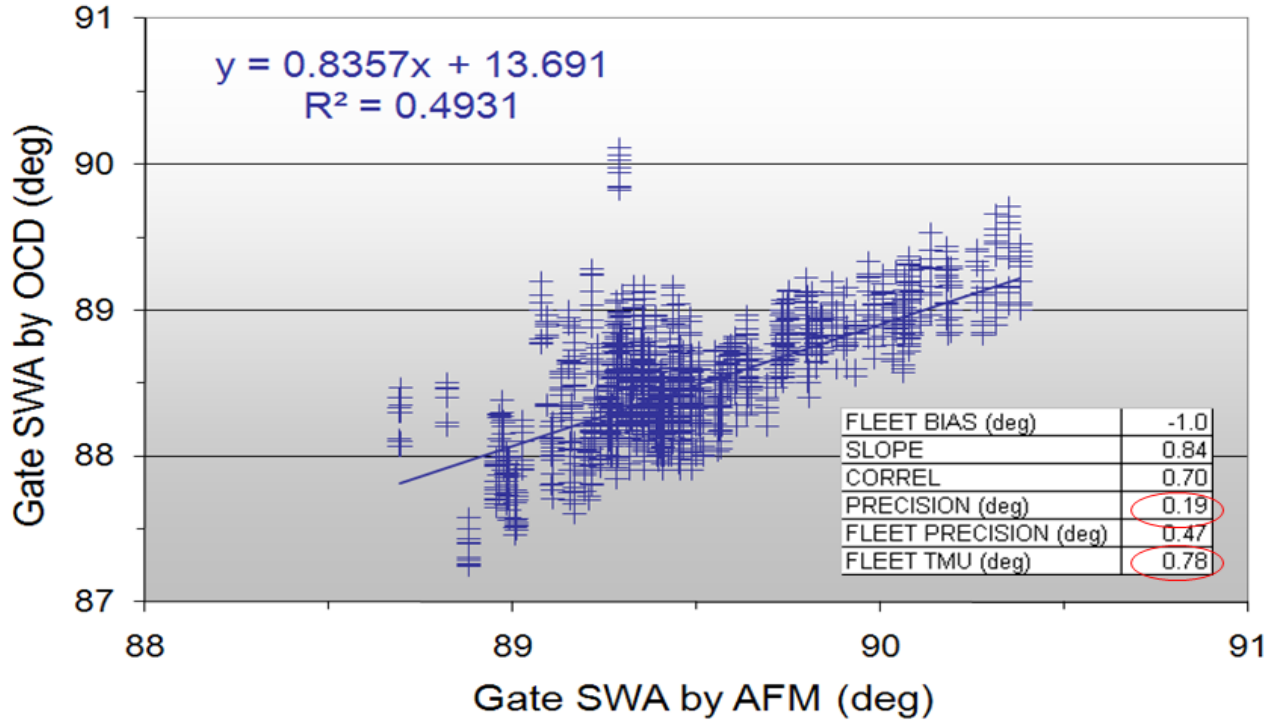

Figure 3. Correlation between OCD and reference CD AFM data for MOSFET gate SWA.

Single tool precision is ca. 0.2 deg (3σ). Fleet of 3 similar OCD tools has precision of ca. 0.5 deg (3σ). Fleet MU which includes all uncertainty components including σ_B is ca. 0.8 deg (3σ). Assuming for the sake of this illustration that process tolerance is 1 degree one gets uncertainty over tolerance (U/T) ratio of 0.2 if single tool precision is considered as the only source of measurement uncertainty. U/T ratio of 0.2 is widely accepted for process control. Indeed, metrology in this case adds just a bit of scatter to the overall process control (Fig. 4). As the figure shows, process with actual (true) process control index C_P = 1.3 will be reported as process with C_P = 1.27 [18]. This is a minor and acceptable loss. However, if all components of MU are taken into account metrology U/T ratio will be degraded from 0.2 to 0.8. U/T of 0.8 is dangerously high. As the same Fig. 4 shows, in this case process control will be degraded significantly from actual process control of C_P = 1.3 to the affected by the metrology control of C_P = 0.9. C_P below 1 is unacceptable because of expected in this case poor process yield.

Therefore, in this example, the same "good" process (C_P=1.3) will be reported in case of "good" metrology as acceptable process and in case of "bad" metrology as unacceptable process. In reality the process is fine in both cases and no more process development is needed. The poor metrology obscures the situation forcing technology developing company to continue process development, upgrade expensive process equipment, and spend significant additional resources. The metrology under test is "bad." Actual U/T ratio is 0.8 and not 0.2 as the precision test may suggest. However, one would never know that unless full MU evaluation (including σ_B) of the measurement fleet is done.

The simple but often forgotten truth is that quality of metrology and quality of process are *equally* important for the process control. Reported by metrology tool process variance consists of two *evenly* important components:

$$\sigma^2_{control} = \sigma^2_{process} + \sigma^2_{metrology} \quad (3)$$

Similarly both components of the variance are *equally* important for process control:

$$C_P = \frac{T}{6 \times \sqrt{\sigma^2_{process} + \sigma^2_{metrology}}} \quad (4)$$

Profit losses caused by the technology development delay, the poor product quality and the future yield excursions sometimes exceed cost of proper metrology by hundreds times. The losses can and must be avoided.

P/T=0.2
but
U/T=0.8

$$C_P = \frac{T}{6\sigma_{process}}$$

$$C_P \geq 1$$

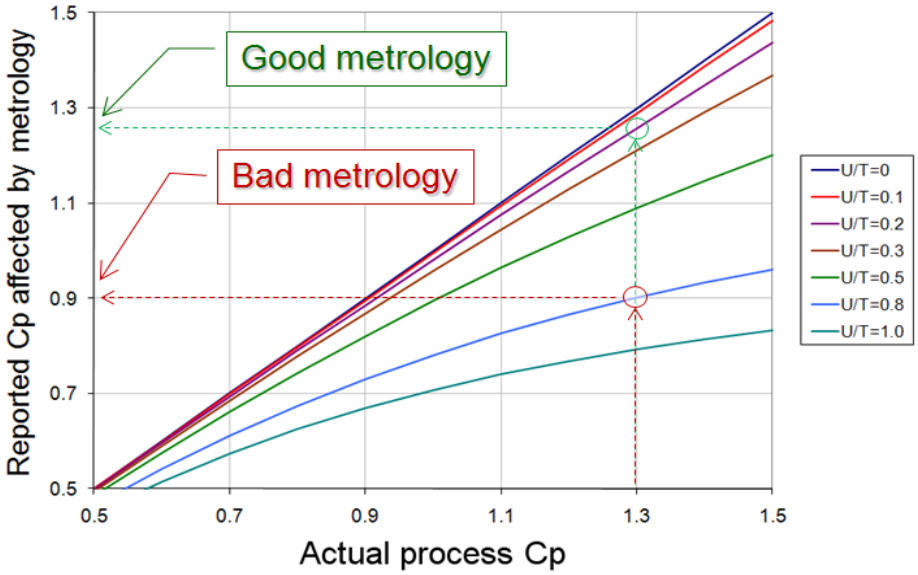

Figure 4. Impact of quality of metrology on process control. Process and metrology qualities are *equally* important.

4. CD AFM AS SI-TRACEABLE REFERENCE METROLOGY

Recent studies [9,10,11] show that CD AFM can be successfully employed as SI-traceable RM system for some important semiconductor applications. The methodology has been described in several articles [19,20]. In this paper we present just brief overview of the approach. The methodology consists of XYZ scale calibration using SI-traceable NanoLatice™ (XY) and step height standards (Z) followed by tip width (TW) calibration using SI-traceable NanoCD™ standard(s) by the VLSI Standards, Inc. [21,22,23]. Results of CD AFM MU assessment using three NanoCD™ standards are shown in Figure 5 [24]. Certified SI-traceable CD values for the standards are: (a) (25.4 ± 0.5) nm, (b) (45.7 ± 0.6) nm and (c) (70.3 ± 0.6) nm. Mandel's linear regression has been used to calculate CD AFM's "total measurement uncertainty" (TMU) [14]. CD AFM measurement results were used as "tool under test" data and certified CD's and their uncertainties were used as "reference metrology system" data. Demonstrated TMU of 0.7 nm (3σ) for the poly-Si linewidth measurements is an important result considering independence of CD AFM measurement bias from proximity effects, line profile and, arguably, sample's material. One should expect similar sub-nanometer MU CD AFM capability for other poly-Si measurements. Physical model of CD AFM measurements is relatively simple. Once XYZ scales are calibrated CD AFM measurement can be viewed as direct comparison of SI-traceable certified linewidth standard with unknown linewidth sample. MU of such measurements was assessed in experiment described above (Fig. 5).

CD AFM scale inaccuracy contributes to MU of the measurements should sample dimensions be outside of the tested 25 to 70 nm range of line CD's. Linearity and long-term stability of CD AFM scale are remarkable [25]. Figure 6 shows results of comparison of CD AFM and high-resolution transmission electron microscopy (TEM) linewidth measurements. In this experiment a detailed attention has been paid to insure that the AFM and TEM measurements are done on exactly the same segment of the line. This detailed sample matching was necessary to reduce potentially significant component of measurement uncertainty related to uncertainty of (local) sampling. As this study (Fig. 6) and also years of CD AFM practicing demonstrate accuracy of CD AFM scale is commonly in the range from 0.1 to 0.5% [11,19,20]. Therefore, we conclude that CD AFM is a unique reference metrology instrument capable of sub-nanometer

MU of linewidth measurements in practical range of dimensions from nanometers to a few hundred of nanometers. This capability of CD AFM has been successfully used to create the NIST version of SI-traceable linewidth standard [11].

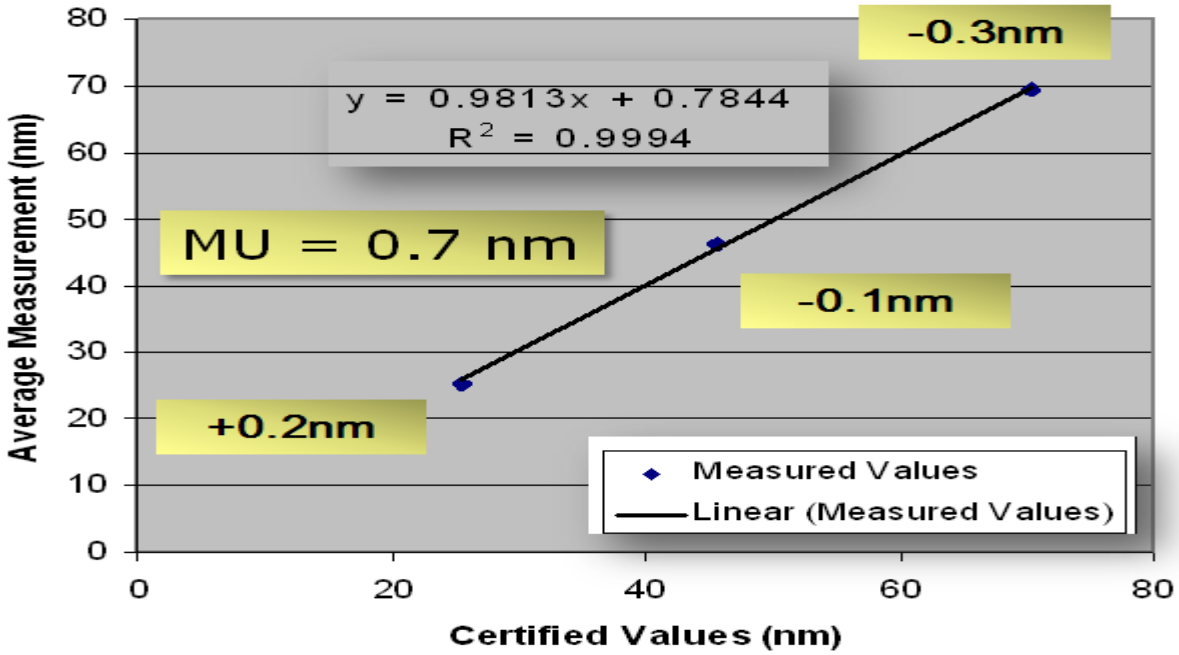

Figure 5. Results of CD AFM MU assessment using 3 SI-traceable NanoCD™ standards [24].

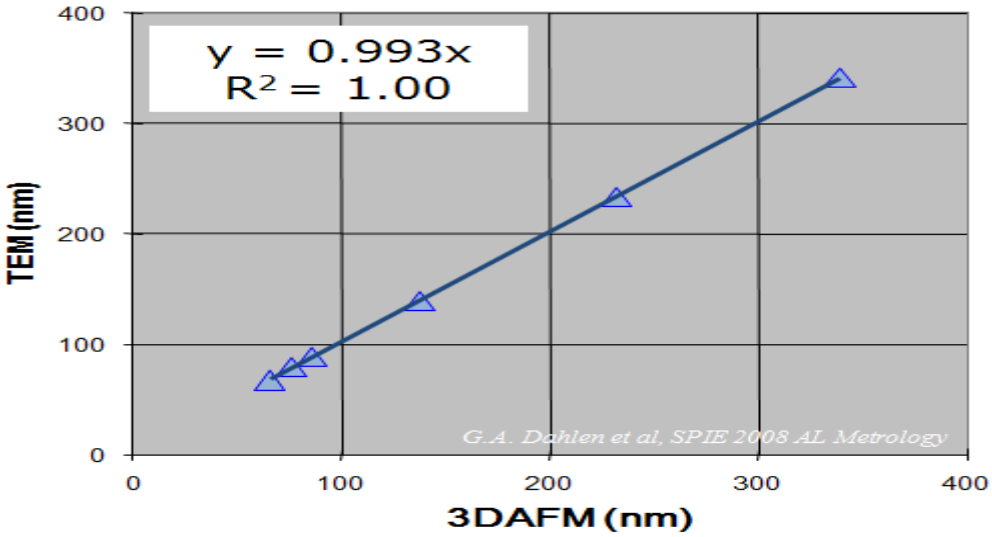

Figure 6. Results of CD AFM and high-resolution transmission electron microscopy comparison [25].

5. IMPLEMENTATION OF REFERENCE METROLOGY

Described in the paper RM concept is not something abstract or theoretical. This concept has been successfully implemented in 2005 and 2006 at Texas Instruments, Inc. during 65 nm technology node development and ramp up [9]. In this paper we would like to outline 3 main steps of the concept. The first step in implementation of accurate CD metrology should be generation of technology representative reference material [9,13]. Since bias of every CD metrology is sample dependent, evaluation of MU of the future "work horse" metrology must be done on set of samples representing specific technology, process flow and even equipment set. Simple calibration of CD metrology tools using external SI-traceable standards would not guarantee low uncertainty of measurements done on internal samples. The set

of reference samples must cover entire technology design and process space as fully as possible. These samples should be measured using SI-traceable RM system. Carefully calibrated CD AFM can be used for the task [9,11].
The next step in accurate CD metrology implementation is evaluation, selection and final tuning of "work horse" in-line CD metrology technique (tool's brand, model and settings). The technology representative set of reference samples should be used during this step. The study should provide full MU evaluation of fleet of similar metrology tools including tool-to-tool matching σ_M and sample dependent bias variation σ_B estimations [9]. After this step one would have in-line metrology with MU minimized for the fleet of tools.
It is virtually impossible to predict all potential material, process, equipment and, therefore, metrology bias excursions. This is why the third step of accurate CD metrology implementation is critical. As the last step we recommend employment of in-line RM system for systematic and periodic checks and corrections of the metrology bias. Frequency of such checks should be relatively high during technology development and the initial period of the technology lifetime. Once the technology matures and higher confidence in the metrology is earned the frequency can go down. The periodic in-line metrology excursion monitoring should be also used to re-evaluate and improve MU of the fleet of the tools using information collected on real production material truly representing the technology.
Figure 7 presents an example of in-line monitoring of CD SEM bias using RM CD AFM tool. The bias of gate CD measurement using SEM has changed from 10.8 nm to 13.7 nm over the period of 2 months of monitoring. Based on incorrect CD metrology information (obscured by the bias drift) in-line gate CD control system adjusted the process and reduced actual gate CD (monitored by CD AFM) from ca. 76 nm to ca. 72 nm. Considering 3 nm bias up drift gate CD reported by SEM was still within control limits. At the same time actual gate CD became dangerously low. Presence of in-line RM system (CD AFM) helped to detect CD SEM bias drift and maintain targeted by device designers gate CD.

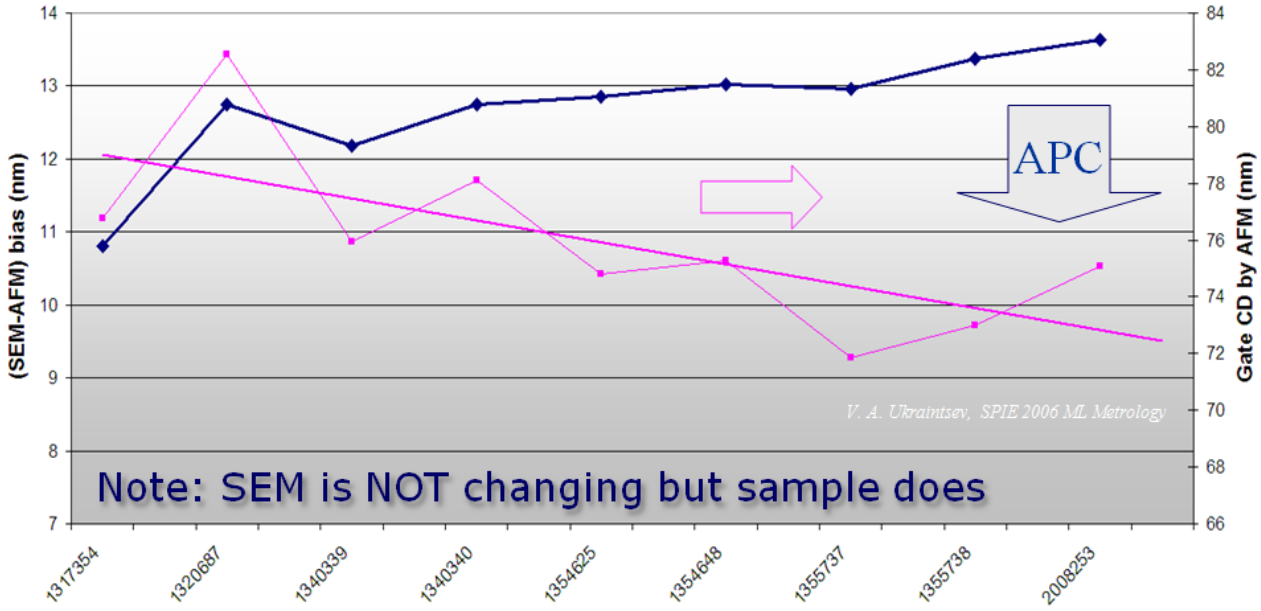

Figure 7. Drift of CD SEM bias occurred over 2 months of development and detected using in-line RM CD AFM.

6. CONCLUSION

Acceptance of MU concept by the ITRS attracts attention of metrology tool users and providers to additional components of MU which were often neglected in the past. Precision (σ_P), tool matching (σ_M) and sampling uncertainty (σ_S) components were discussed in length elsewhere [5,6,7]. In this paper we propose a splitting of the sample dependent bias variation (σ_B) from the cumulative "other" component of combined MU (Eq. 2). The σ_B component is presumably the last significant independent component of combined uncertainty of CD measurement beside cross correlation terms. The component is hard to detect and estimate since measurement bias can be characterized only if RM is employed. Measurements of sample dependent bias variation can't be ignored if the true value of MU to be estimated. The σ_B component often reaches several nanometers [8,9,10]. Adding RM to in-line CD metrology evaluation is expensive. Why one should invest in σ_B measurements? We argue that metrology uncertainty and process

variation are *equally* important for process control (Eq. 4). Underestimation of MU may cause (unknowingly) losses of process yield and product quality. Choice of RM tools is limited. CD AFM is a promising RM instrument. Recent studies suggest that sub-nanometer MU of CD AFM is achievable for some key semiconductor applications [11,24]. Employment of RM for full MU evaluation of in-line CD metrology tools is possible and has been successfully demonstrated in the past [9,10]. We argue that to achieve sub-nanometer uncertainty of in-line CD metrology one must use RM not only to set CD metrology but also to maintain its quality and avoid metrology excursions in a long term.

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[17] Here we assume that factors impacting probe-sample interaction and the corresponding bias remain largely controlled and unchanged during the measurements.

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