

Measurement traceability and quality assurance in a nanomanufacturing environment

Ndubuisi G. Orji
Ronald G. Dixon

National Institute of Standards and Technology
100 Bureau Drive
Gaithersburg, Maryland 20899–8212
E-mail: ndubuisi.orji@nist.gov

Aaron M. Cordes
Benjamin D. Bunday

International SEMATECH Manufacturing Initiative
257 Fuller Road, Suite 2200
Albany, New York 12203

John A. Allgair
GLOBALFOUNDRIES

Wilschdorfer Landstrasse 101
D-01109 Dresden, Germany

Abstract. A key requirement for nanomanufacturing is maintaining acceptable traceability of measurements performed to determine size. Given that properties and functionality at the nanoscale are governed by absolute size, maintaining the traceability of dimensional measurements of nanoscale devices is crucial to the success of nanomanufacturing. There are various strategies for introducing traceability into the nanomanufacturing environment. Some involve first principles, but most entail the use of calibrated artifacts. In an environment where different types of products are manufactured, it is challenging to maintain traceability across different products mix. In this paper, we present some of the work we have done in developing methods to track the traceability of dimensional measurements performed in a wafer fabrication facility. We combine the concepts of reference measurement system, measurement assurance, and metrological timelines to ensure that traceability is maintained through a series of measurements that involve different instruments and product mixes, spanning a four-year period. We show how to use knowledge of process-induced and instrument systematic errors, among others, to ensure that the traceability of the measurements is maintained. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3549736]

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1 Introduction

In a semiconductor development environment where different products are being evaluated, one challenge is maintaining the traceability of the instruments used. Usually the instruments will have different levels of accuracy, resolution, and stability. As such, care must be taken to keep track of the traceability and relative capability of the instruments under different scenarios. When measurements are made at different stages of product development, it is important to make sure that the measurand is the same.

There is, therefore, a need for an unambiguous way to track the accuracy and traceability of the instruments, the long-term stability, and the relationship between the instruments. The reference measurement system (RMS) is not fast enough to meet the throughput requirements of a fabrication facility, and faster instruments that are calibrated by the RMS tool have greater material sensitivity. To meet these challenges, we have developed the strategy presented in this paper.

We use three different but related methods to do this: the RMS methodology,¹ measurement quality assurance,² and metrological timelines.³ The goal is to ensure that the traceability of each measurement can be validated with respect to the measurand and the stability of the instrument. In Sec. 2, we briefly describe the RMS approach, measurement quality assurance as applied in this work, and metrological timeline. The details of how these techniques are implemented are provided in Sec. 3, including a description of the long-term monitoring data that forms the foundation of this work.

1.1 Reference Measurement System

A reference measurement system is an approach using a high performing instrument to characterize, compare, and quantify errors in less costly and faster tools than are used in production. The idea of an RMS for semiconductor manufacturing was first proposed by Lauchlan and coworkers.⁴ The RMS includes not only the instrument, but also calibrated samples and measurement procedures. The idea was later refined by Banke and Archie,⁵ who implemented an RMS using both a critical dimension atomic force microscope and a cross-sectional scanning electron microscope. The goal is to achieve consistency among measurements made by different tools and to reduce the uncertainty of measurements made with the system by using suitable samples with close traceability to the International System of units (SI) meter. Details of an RMS implementation are contained in Refs. 1 and 5–9.

1.2 Measurement Quality Assurance

To ensure the stability of the RMS, we implemented a performance monitoring system. This is similar to the Measurement Assurance Program at NIST.² This system provides a framework for coupling the determination of sources of uncertainty with statistical control of the measurement process.¹⁰ This is accomplished by performing measurements on a traceable calibration sample or check standard and by applying statistical process control to the results of these measurements. Regular performance checks indicate the long-term stability of the instruments. The calibration intervals and the relationship among the different types of samples and

Table 1 Process averages and process standard deviation for width.

	Process average (nm)	Process standard deviation (nm)	Uncertainty ($k = 1$)
Initial seven weeks monitoring (2005)			
Width -1	117.47	0.31	1.01
Width -2	136.62	0.56	1.11
Width -3	175.30	0.59	1.13
Width -4	208.23	0.40	1.05
Width -5	234.82	0.36	1.04
Width -6	282.91	0.38	1.06
January 2006 to June 2008			
Width -1	117.29	0.36	1.02
Width -2	136.98	0.51	1.09
Width -3	175.25	0.72	1.21
Width -4	208.44	0.15	0.99
Width -5	234.05	0.46	1.08
Width -6	282.90	0.61	1.17

measurands form the foundation for the concept of metrological timelines described below.

1.3 Metrological Timelines

The concept of metrological timelines was developed by Ehrlich and Rasberry.³ It offers formalism to deal with time-dependant changes in instruments and the way they affect the traceability of the measurements. It also provides a way to visualize the relationships among measurements made at different laboratories or instruments at different levels in the traceability chain. The underlying assumption is that instruments experience some change over time and that the rate of change is great enough that the relationship among the traceability statements at each level must be clearly outlined.

The procedures used to establish traceability in the RMS form the core of our measurement process. The RMS instrument used here is a critical dimension atomic force microscope (CD-AFM). It is characterized for both lateral and vertical scales and for width measurements. These form the basis of a broad range of measurements made with the instrument. The details of the instrument implementation as an RMS, the associated sample, and uncertainties are described elsewhere.^{1,6} Here we focus on how the RMS is used together with the concept of metrological timelines. In the concept of metrological timelines as espoused by Ehrlich and Rasberry, the assumption is that instruments on the lower level of the traceability chain drift over time; to ensure that their calibration is valid, the relationship between the two instruments must be carefully maintained. We extend the same concept to instruments in a development or manufacturing environment, where the RMS instrument is at the top of the traceability chain while the rest of the instruments fall at different lev-

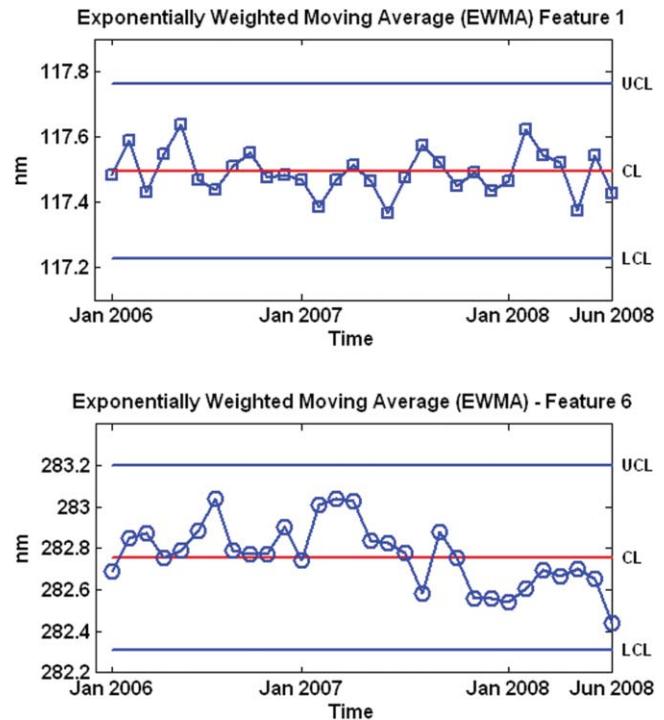


Fig. 1 EWMA charts for feature 1 and feature 6. The data are from January 2006 to October 2008. The process averages are 117.29 nm for width 1 and 282.7 nm for width 7. This is consistent with the data for the initial seven-week monitoring period.

els of this chain, depending on their long-term stability and resolution. In our case, due to the difference in materials, feature size, or geometry, the lower level instruments must be carefully monitored to ensure that each measurement has the correct uncertainty values.

2 Measurement Stability

In this section, we focus on how the RMS instrument was initially monitored. This will help establish the validity of the measurements and comparisons of instruments in the cluster of instruments. In establishing a traceable RMS instrument, two main questions arise: (1) For each of the measurands, how does the instrument derive its traceability from the *SI*, and what is the uncertainty? (2) Does the instrument have the long-term stability wherein a single measurement is indicative of the overall performance of the instrument? That is, can we tie a single measurement to a reference base? The first question has been rigorously addressed elsewhere.⁸ The second question is the topic of this section.

What resulted from the initial RMS implementation is a set of samples that derive their traceability to the *SI* from first principles⁸ (lattice constant of silicon). These samples are now used as check standards for long-term monitoring of the RMS instrument. The samples are primarily used for calibrating width, but can also be used for monitoring sidewall angle, height, and scale. The frequency and length of this initial monitoring period depends on the specific requirement of the instrument, such as how often it is used. The information gathered forms the reference base with which future measurements can be compared. In general, the reference base represents realizations of a particular unit of measurement

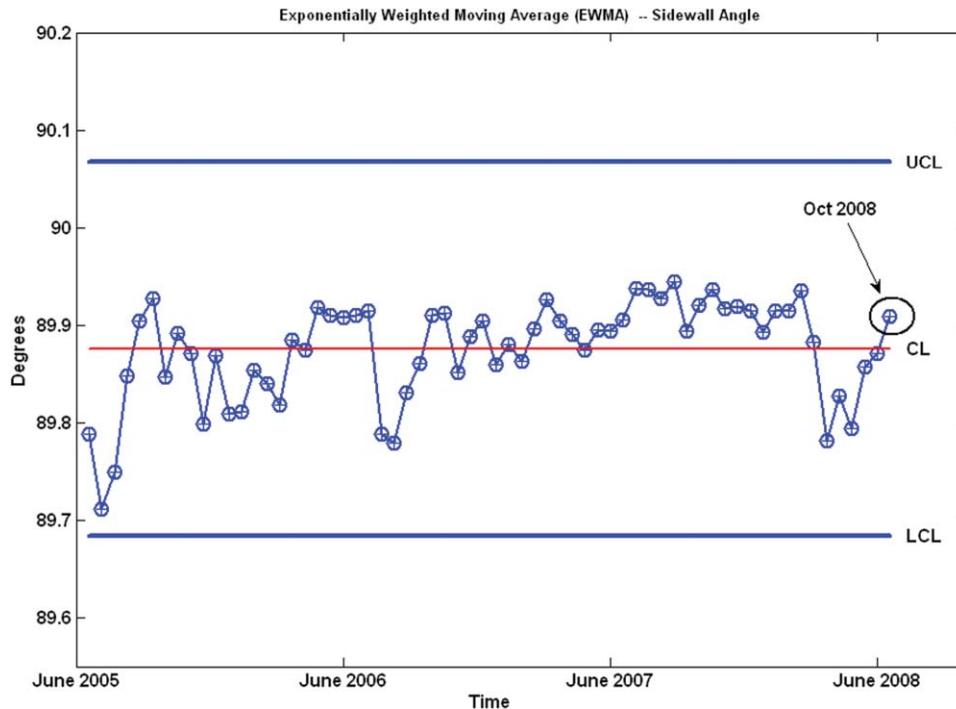


Fig. 2 EWMA plot for sidewall angle. Note: we used values of $\lambda = 0.3$ and $k = 3$ to calculate the EWMA, UCL, and LCL.

from first principles or international standards that represent that unit of measure. In the rest of this paper, reference base will refer to the stated values of our calibrated samples and long-term monitoring data.

The actual monitoring involved taking repeated measurements on the check standards. We monitored the performance of the instrument for seven weeks, four times a week. Each measurement comprised three repeats. Due to the large number of measurements needed to establish a reference base, the monitoring site is different from the primary calibration site, thus reducing the number of measurements and risk of damage. Due to the greater number of measurements, a possible source of uncertainty is tip wear. To minimize this effect, we used nitride-capped critical dimension tips, which have been shown to be less susceptible to wear.¹¹ Due to the controlled environments of the fabrication facility and the limited number of operators, only the time and day of the week that the measurements were collected were randomized.

The data were evaluated using exponentially weighted moving average (EWMA) analysis,¹² which is able to detect small shifts in the data, as the process monitoring tool. A set of data collected during an earlier evaluation is assumed to be the historical dataset for the features. The aim is to see if it deviates from the historical set over the period of use. After this initial monitoring phase, we reduced the monitoring to once every week and finally to once every two weeks. Figure 1 shows the data for two of the width samples from January 2006 to June 2008. We used a weighting factor of 0.3 and multiplicative factor k of 3 to calculate all of the EWMA charts, upper control limits (UCL), and lower control limits (LCL). The process averages are 117.29 nm for width 1 and 282.7 nm for width 6. This is consistent with the data for the initial seven-week monitoring period. The process averages and standard deviations for the initial seven-week

period and for the two and half years are shown in Table 1. In addition to width, we also collected monitoring data for pitch, height, and sidewall angle. Figure 2 shows the control charts for sidewall angle from June 2005 to June 2008.

Overall the monitoring helps to first establish the stability of the system and then ensure that the system is in control over the time it is used. As information in Figs. 1–3 indicate, the system is indeed stable. The process average and the standard deviation data in Table 1 show that the process averages did not significantly shift from January 2006 to October 2008. The process standard deviations are also consistent with the monitoring data taken in the initial seven-week period.

The data from the original calibration sample features (shown in Fig. 2 for features 1 and 2) start in April 2004 and continue to October 2008. For each feature, the data are within the expanded uncertainty and indicate no major calibration shift. This information coupled with the EWMA plots show that the system is under control. A potential cause for concern is the data for feature 6 in Fig. 3. The data display a downward trend in the first eight to nine measurements. The overall data, however, are still within the expanded uncertainty, but will be closely monitored.

3 Application of Metrological Timelines

We now show how the information in Sec. 2 is used to form a metrological timeline. The syntax used here is from Ehrlich and Rasberry³ but adapted for our purposes. The diagram in Fig. 4 shows a metrological timeline with events at three different times. At time t_0 , the measurements are on the calibration sample. In our case, this represents the realization of the calibration values. The event at t_1 represents a calibration transfer to a set of secondary calibration samples and measurements on monitor samples. This establishes an

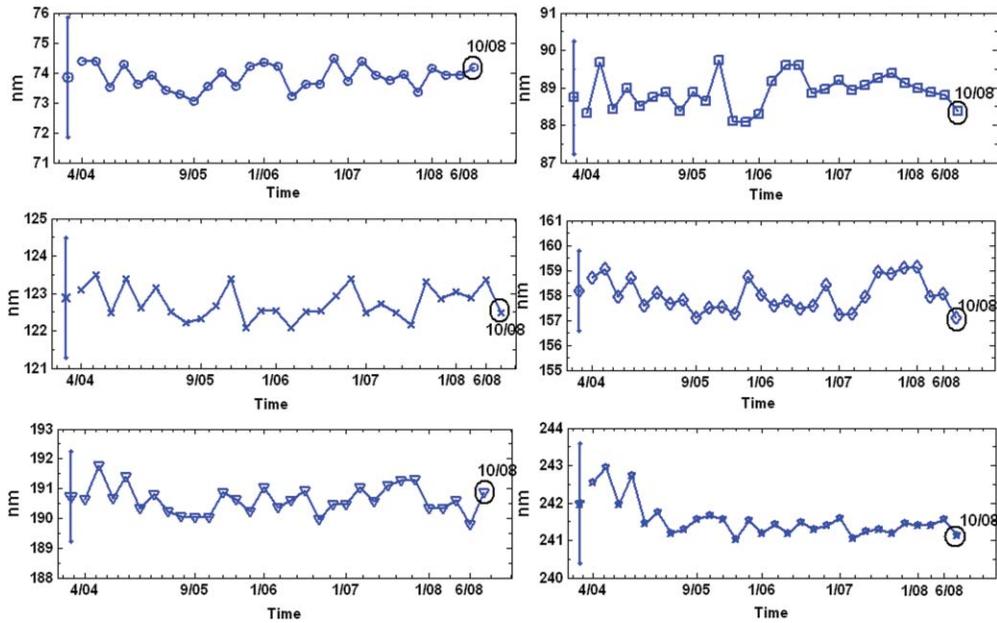


Fig. 3 Monitoring data for the original calibration sample for all six features. The first datum in each plot represents the calibrated value and the expanded uncertainty ($k = 2$). The last datum was taken in October 2008 after monitoring was stopped for four months. Note: the intervals between April 2004 and January 2006 are not uniform.

explicit relation between the process monitoring information and the calibration transfer information embodied in the secondary calibration samples. X_1^C indicates measurement on the calibration sample and U_1^C the uncertainty of that measurement. $X_1^{N_1}$ and $U_1^{N_1}$ represent the measurements and uncertainties of the monitor sample at t_1 . The key information here is that $X_2^{N_1}$ derives its traceability from t_2 rather than t_0 or t_1 . The stability of the process monitoring data links the events at t_0, t_1, t_2 . In the rest of the figures, this link between events at different times is explicitly shown with a thin broken line. N indicates the number of samples used in the monitoring. Figure 5 shows an extended version of Fig. 4 that includes another instrument. In this case, this is a faster “workhorse instrument” that is more suited for a manufacturing environment. At t_1 , measurements are made on a secondary calibration sample that is used to transfer calibration to the workhorse instrument. Usually this instrument will also have its own monitor samples. Unless there are other calibration transfers between the RMS instrument

and the workhorse instrument, traceability to the RMS tool is through events at t_1 .

In our case, the workhorse instrument is used as an evaluation tool for similar instruments in different locations. For such measurements, the benefit is that there is an explicit link to the *SI* through the RMS. In a manufacturing environment where different materials, feature sizes, and product lots are being measured, a system like the one described here becomes very useful. Figure 6 shows a metrology timeline with three levels of traceability hierarchy. Here only one event is shown for the instrument evaluation, but one can easily visualize several instrument evaluations on different materials, size ranges, and lots. Having a clear accounting of which RMS event each measurement is traceable is crucial. ES in Figs. 6, 7, and 8 represents the evaluation sample.

Figure 7 shows results from resist and polysilicon samples made by a workhorse instrument on the same day in January 2006. The polysilicon sample gets its traceability from measurements made in November 2005, while that of the resist comes from measurements made in December 2005. Although the two measurements were made on the same day with the same settings, the workhorse tool has a different interaction with each material. Because of this, there is a 3 nm off-set between the measurements of this particular resist and polysilicon samples. We have seen resist and polysilicon off-sets as high as 15 nm. In addition, the resist sample also has a larger uncertainty, 3.1 nm as opposed to 1.2 nm for the polysilicon. This offset is a systematic error induced by the different interaction of the workhorse instrument with the samples. Without a reference measurement system, this offset would be difficult to determine, and without a strict accounting of the traceability and time of measurements, an incorrect uncertainty value would have been ascribed to the resist results.

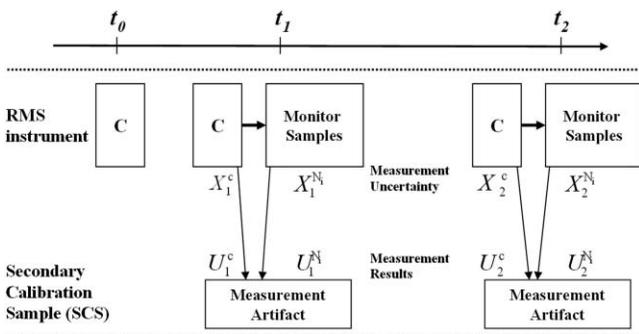


Fig. 4 A metrological timeline showing three metrological events in an RMS.

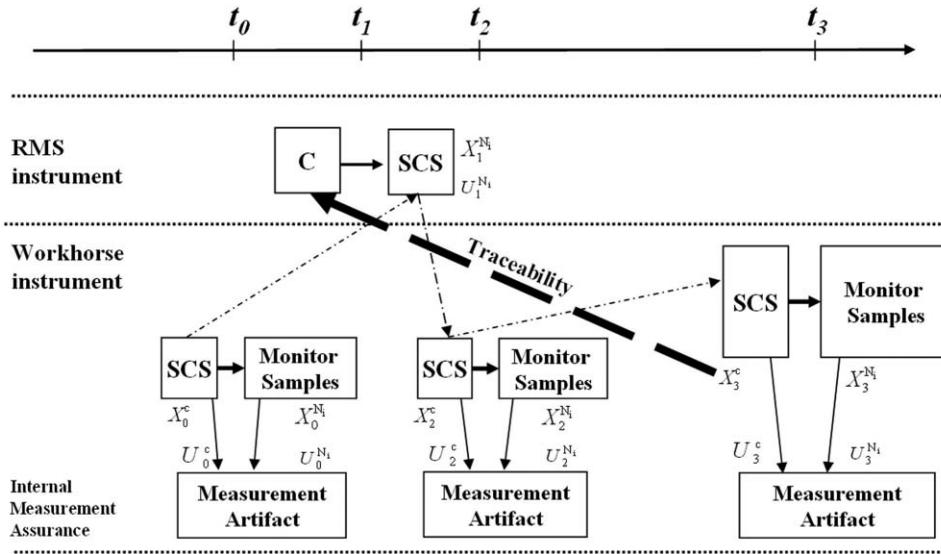


Fig. 5 A metrological timeline showing the traceability of measurement by a workhorse instrument to the RMS.

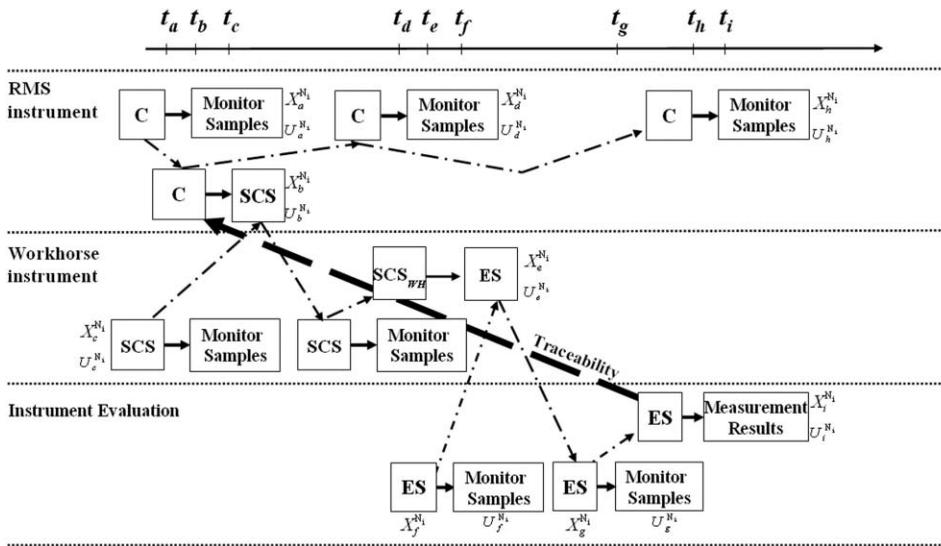


Fig. 6 An expanded metrological timeline showing three levels of measurement.

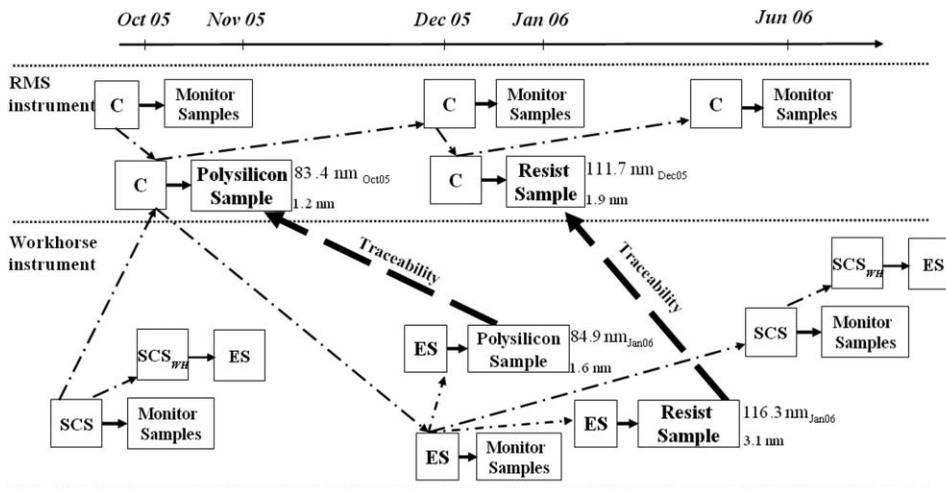


Fig. 7 An expanded metrological timeline showing different traceability paths for measurements made on the same day with the same settings. In addition to having a greater uncertainty, the resist measurements have a real off-set of approximately 3 nm from the polysilicon measurements.

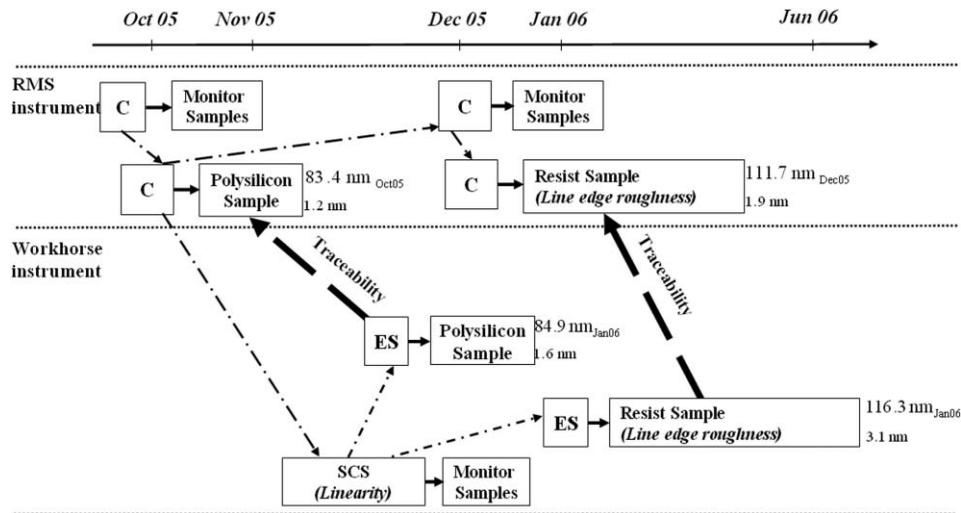


Fig. 8 A simplified version of Fig. 7 showing only the events that are related to resist and polysilicon measurements. The diagram also includes systematic and process-induced error sources.

4 Discussion and Summary

Other information that we add to the metrology timeline is knowledge of process-induced errors and instrument systematic errors. This is not part of the syntax used by Ehrlich and Rasberry; however we find it useful to include additional information that could provide the user with insight about the measurements. So far the metrology diagrams shown above have tried to capture the system as a whole. Figure 8 shows a simplified metrology timeline of the resist and polysilicon samples in Fig. 7. It includes information about the greatest source of process-induced errors and systematic error. The process-induced errors are sample-related; they are noted in the same box as the sample. The systematic errors, on the other hand, are usually instrument-related; they are listed in the same box as the calibration sample. The information as presented in Fig. 8 allows the user to get a clear picture of the traceability, uncertainty values, and key error sources. The idea is not to replace the uncertainty statement but to give the user a way to quickly determine where the key sources of errors are and whether the samples are good enough for the evaluation.

We have presented information on how to use measurement uncertainty, process control monitoring, and metrology timelines to explicitly show the traceability of measurements made in a nanomanufacturing environment. The strategy described above could be applied to any manufacturing environment where there is a need to ensure that each measurement result is reported with the correct uncertainty values. We showed how the uncertainty information, process monitoring data, and metrology timeline could be used to graphically show the traceability of measurements at different levels. Information about the sources of both process-induced and instrument systematic errors is added to further enhance the usefulness of the chart. The result is that a measurement result can be easily traced to the underlying RMS data, the time they were taken, and the main error sources without looking at the uncertainty statement.

The metrology timeline allows us to explicitly link the traceability of any measurement made by any instrument within a cluster of tools to the RMS instrument. Including

information on the most important error sources increases the usefulness of this particular representation. For the procedure above to be useful, we evaluate the in-lot variation and lot-to-lot variation for each product. Hence, when samples from a lot are measured, there is a link between the measurements and the traceability of the instrument. We are currently exploring the possibility of developing software that will automate the synthesis of the uncertainty values, monitoring data, and metrology timelines. Users of the system will be able to pull up information by lot or sample number and get a full history of the traceability and any uncertainty of that measurement.

Acknowledgments

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Ndubuisi G. Orji is a mechanical engineer in the Physical Measurement Laboratory of the National Institute of Standards and Technology (NIST). His research interests are in atomic force microscopy, surface metrology, nano-scale dimensional metrology, and optical metrology. He holds a PhD in mechanical engineering from the University of North Carolina at Charlotte. He is a member of SPIE and the American Society for Precision Engineering.



Ronald G. Dixon is a staff scientist in the Physical Measurement Laboratory of the National Institute of Standards and Technology (NIST) – where he has worked for the past 16 years. His research is primarily on atomic force microscope (AFM) dimensional metrology and standards development at NIST – including the NIST calibrated atomic force microscope (C-AFM) project. Beginning in late 2001, he spent three years as the first NIST Guest Scientist at SEMATECH where he developed a CD-AFM based Reference Measurement System (RMS) and utilized this system for the 2004 release of single crystal critical dimension reference materials (SCCDRM) to SEMATECH member companies. His current research interests are calibration methods, traceability, and uncertainty analysis in AFM dimensional metrology. He holds a PhD in Physics from Yale University.

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Aaron M. Cordes is a project engineer in the Metrology group of SEMATECH. His research interests are in 3D atomic force microscopy, nano-scale dimensional metrology, and electron spectroscopy. He holds a master's degree in applied physics from the University of Texas at Austin. He is a member of SPIE.



Benjamin D. Bunday is the Project Manager of CD Metrology and a Senior Member Technical Staff at ISMI/SEMATECH (Albany, NY, USA). For ten years he has led ISMIs CD-SEM and OCD benchmarking, evaluation, and technology development efforts, and ISMIs well-known Advanced CD Metrology Advisory Group (AMAG). Bunday has been the chief author of the AMAG unified CD-SEM and scatterometry specifications and is actively involved with the metrology chapter of the ITRS. He has 15 years of semiconductor processing industry experience in the areas of CD metrology, lithography, and etch, and received his MS/ABD in Materials Science and Engineering from Cornell University in Ithaca, NY. He is a member of SPIE and the author or coauthor of approximately 75 papers.

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John A. Allgair is with GLOBAL-FOUNDRIES, Inc. He was an assignee to SEMATECH, where he coordinated metrology programs to meet the requirements of the ITRS. He has worked in the semiconductor industry for over 15 years in a variety of areas, including design, etch, films, lithography, and metrology. Previously he was responsible for parametric and defect metrology technology development and manufacturing implementation at Freescale.

He is on the SPIE program committee for metrology and has published papers in several industry journals. He received a PhD in electrical engineering with an emphasis in semiconductor physics and processing from Arizona State University in Tempe.