Traceability: The Key to Nanomanufacturing

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Abstract: *Over the last few years key advances have been made in the area of nanomanufacturing and nanofabrication. Several researchers have produced nanostructures using either top-down or bottom-up techniques, while other groups have functionalized such structures into working devices. In all cases, for the devices to be useful, there has to be a way not only to measure their properties but also to know that the results are valid. The measurements have to be traceable. Some of the properties of these nanostructures are determined by size; this increases the importance of accurate measurements. In this paper, we present work that we have done to introduce traceability to a nanomanufacturing environment, using a concept called reference measurement system. The paper focuses on length traceability.*

Keywords: Traceability, Nanomanufacturing, reference measurement system, critical dimension, Scatterfield microscopy

1. Introduction

As fundamental research has now yielded standalone nanostructures using top-down techniques[1], and bottom-up techniques such as self-assembly[2], nanomanufacturing and nanofabrication are emerging as key industries for the years ahead. The key objective is to make nanoscale devices that perform certain functions. One of the most important parameters of nanostructures is size. This is because functionality at the nanoscale is determined by size. To ensure that the dimensional measurements are valid, there has to be a way to validate the results. This is done through traceability to established standards. In areas such as microlithography, the features being manufactured are increasingly getting smaller. The international technology roadmap for semiconductors (ITRS) 2007 edition[3] forecasts that the half pitch of DRAM features will be around 25 nm by the year 2015. This puts a burden on the resolution of the instruments needed to measure such small features[4, 5]. In addition to instrument resolution, traceability is also important. This ensures that 25 nm is indeed 25 nm.

In this paper we will describe work we have done to introduce traceability to a semiconductor nanomanufacturing environment[6-8]. The focus is on length traceability. The paper is organized as follows: In section two we will give a brief overview of how traceability is realized for most length measurement instruments. This is followed by a description of a reference measurement system in section three. In section four we will outline how *SI* traceability is realized for one of the measurands characterized by the reference instrument, while section 6 describes current work in Scatterfield optical microscopy, and how AFM measurements are used to reduce the uncertainty. The paper will conclude with a discussion and summary.

2. Traceability in Length Metrology

The Vocabulary of Basic and General Terms in Metrology (VIM)[9] defines traceability as "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties."

In length metrology, the primary reference is the *SI* (*Système International d'Unités* or International System of Units) unit of length - the meter. For displacement measurement instruments, one of the ways to achieve traceability is to monitor the motions of a scanning system within a defined coordinate system using displacement interferometry. Usually a laser with a 633 nm wavelength of the I_2-stabilized He-Ne laser (a recommended radiation for the realization of the meter in the visible wavelength) is used[10]. Other ways of introducing traceability include the use of atomic lattice spacing[11-13]. The lattice spacings are

measured using x-ray diffraction[14], and can serve as length standards at the nanoscale. For nanoscale measurements, traceability is important when comparing the performance or consistency of results from different instruments, and when instruments based on different technologies are used. Traceability to a standard is also important when verifying the reliability of models or validating the results of work performed at a different location.

One of the industries (among others) where length traceability is important is the semiconductor industry. Traditionally, the semiconductor industry placed greater emphasis on precision rather than traceability. However, as feature sizes continue to decrease; the performance of devices depends not only on precision, but also on accuracy. Recent results linking parameters such as line edge roughness[15-18] to device performance underscore this[19].

3. Reference Measurement System

To address the issue of lack of traceability in semiconductor length measurements, the National Institute of Standards and Technology and SEMATECH (a semiconductor industry consortium) implemented a Reference Measurement System (RMS). The RMS is a well characterized and traceable instrument that is used to evaluate the performance of tools used in a semiconductor manufacturing facility[20-23]. The ITRS[3] describes an RMS as an instrument that "is well characterized using the best science and technology of dimensional metrology can offer: applied physics, sound statistics, and proper handling of all measurement error contributions."

Figure 1 shows a schematic diagram of the RMS concept. A RMS starts with calibration standards or first principles realization of the definition of the meter[7, 24, 25]. The standards are used to characterize one of the better performing instruments, which is then used to evaluate a set of reference wafers. The wafers are used to evaluate the performance of an in-line tool. Preferably, there will be reference wafers for each product the fabrication facility measures. This ensures that the measurements made using the RMS instrument are consistent with the final product. The RMS could be one or more instruments[26, 27]. A key requirement is that it should have better performance than the instruments it is evaluating.

The specific instrument described in the rest of the paper is a critical dimension atomic force microscope (CD-AFM)[20-22]. The CD-AFM is a specialized atomic force microscope that actuates and senses in two directions instead of one[28]. For dimensional metrology applications in the semiconductor fab, the CD-AFM works well as a reference instrument because it is relatively insensitive to the different materials being measured. The instrument is calibrated for height, pitch, linewidth, and sidewall angle[29]. These measurements lend *SI* traceability to a wide range of production relevant samples[6, 7, 12]. One of the key measurements in semiconductor dimensional metrology is linewidth (also known as critical dimension). It currently represents the smallest feature that needs to be controlled in the semiconductor lithography process. The rest of the paper shows how we use the CD-AFM to calibrate the linewidth standards[23, 25, 30], and reduce the uncertainty of other instruments.

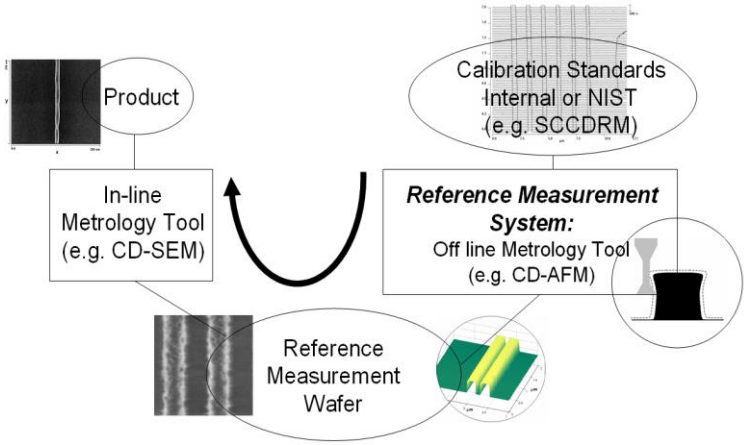

Figure1: Schematic diagram of the Reference Measurement System concept.

4. First Principles CD-AFM Tip Calibration for Linewidth

To measure linewidths with the CD-AFM, the size of the tip should be known. This is because the CD-AFM uses specialized tips known as "boot-shaped" or "flared" tips to access the sidewall[25, 31]. Figure 2(a) shows a schematic diagram of a CD-AFM tip accessing a feature sidewall. The protrusions at the lateral end of the tip are needed to make contact with the feature. By contrast, figure 2(b) shows a conical AFM tip measuring a patterned feature. The profile traced by the conical tip does not faithfully represent the measured feature. However, the profile traced by the boot-shaped tip adequately represents the features, but the width is larger by the size of the tip. Knowing the size of the tip *a priori* allows the user to determine the actual size of the feature. Figure 3 shows the tip width determination sequence. TW stands for Tip Width, CW stands for characterizer width, and AW represents the apparent width. The primes indicate known dimensions. The TW is unknown but the width of the tip calibration structure CW' is known. The apparent width AW' produced by CW' and TW is known. To get TW, CW' is subtracted from AW'. This relatively straight forward approach belies the substantial work required to calibrate CW. For measurements of linewidth, the process is reversed.

The most accurate method used to evaluate the characterizer width is lattice spacings imaged using transmission electron microscope. Descriptions of our previous work using high resolution transmission electron microscope (TEM) are well documented[32]. Here we describe supporting work we are doing with a different mode of TEM to validate the results of the initial measurements[13, 32].

Two modes of TEM (among others) that produce crystal lattice-traceable images are high resolution transmission electron microscope (HR-TEM) and high angle annular dark field scanning transmission electron microscope (HAADF-STEM). HR-TEM produces lattice-traceable images by interference patterns of the diffracted and transmitted beams rather than the actual atomic columns, while HAADF-STEM produces direct images of the crystal lattice[33]. To calibrate feature width, the number of lattice spacings from edge to edge has to be determined. One of the key uncertainty sources in this exercise is edge determination. For the purposes of dimensional calibration, the difference in how these two modes of TEM work could cause subtle variations in the way feature edges are defined. We wanted to quantify this variation. A HR-TEM image of a line feature is shown in figure 4, while figure 5 shows a HAADF-STEM image of the same feature. The roll-off at the left edge of the image in figure 5 could be due to aberration in the optics. The images were taken from the middle of the feature.

The cross-sectional size of the sample used was approximately 18 nm, and determined by the HAADF-STEM, which required a field of view of < 25 nm in order to see the atomic lattice. The sample was aligned for the z = [112] of the silicon substrate. The HAADF-STEM image was taken first followed by the HR-TEM. The field of view of the instrument did not allow the whole structure to be measured at high resolution. The spacing in undoped Si (111) is 0.313560137 nm with a standard uncertainty of ± 0.000 000 009 nm, as determined from X-ray diffraction[14].

The TEM images shown here are imaged as lines rather than individual atoms. This makes it easier to count the atomic columns. Also shown in figures 4 and 5 are profiles extracted from the TEM images. These profiles are used to determine the width. The highlighted portions of the profiles indicate the lattice positions that contribute to the uncertainty.

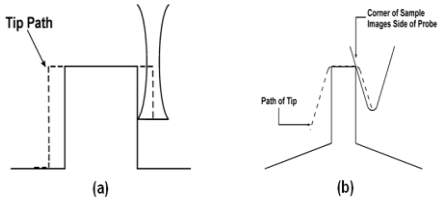

Figure 2: Schematic diagram of (a) CD-AFM tip scanning a feature, (b) conventional AFM tip scanning a feature.

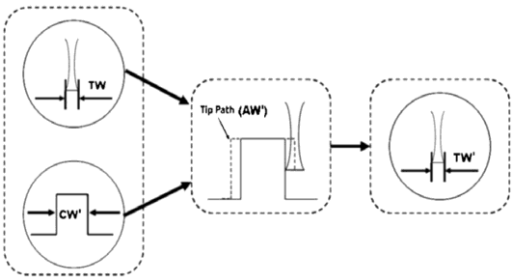

Figure 3: Schematic diagram of the tip-width determination sequence.

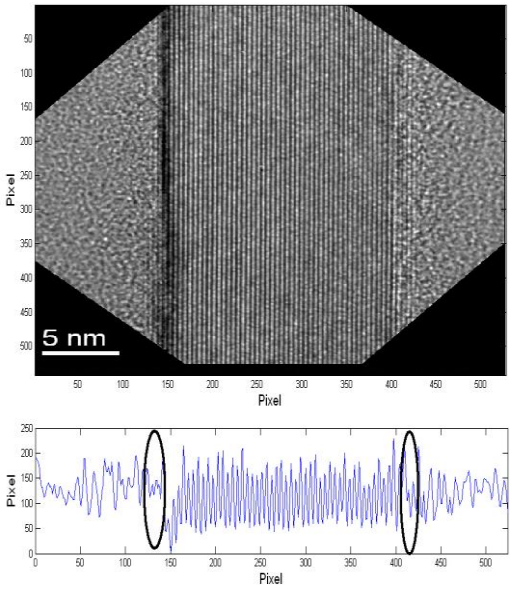

Figure 4: HR-TEM image of a SCCDRM feature. The profile is from the center of the HR-TEM image. The questionable edge locations are highlighted.

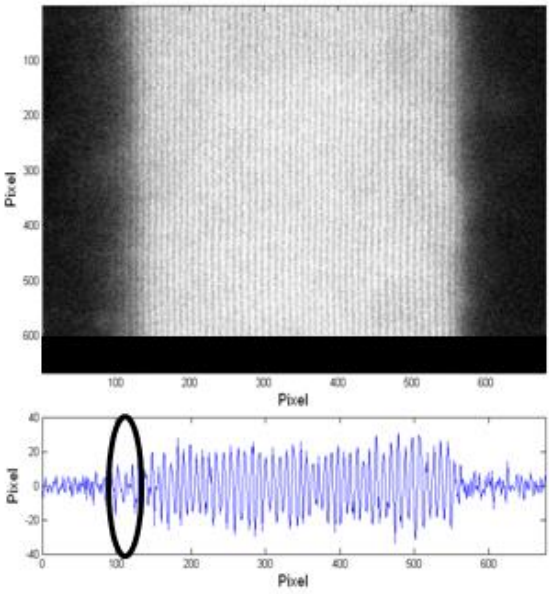

Figure 5: HAADF-STEM image of a SCCDRM feature. The profile is from the center of the HR-TEM image. The questionable edge locations are highlighted.

5. Scatterfield Optical Microscopy

One of the uses of the RMS is to calibrate other instruments used in the semiconductor manufacturing research. One such instrument is the Scatterfield microscope. There has been significant recent research investigating new optical technologies for critical dimension and overlay metrology for manufacturing at and beyond the 32 nm node. Much of this work has focused on scatterometry and, more recently, scatterfield microscopy, a technique combining well-defined angle-resolved illumination with image-forming optics. This has been summarized in Silver *et al.*[34] and in the references contained therein. These optical methods are of particular interest because of their nondestructive, high-throughput characteristics and their potential for excellent sensitivity and accuracy.

The scatterfield-microscopy instrument is based on a Köhler illuminated bright-field microscope, such that each point at the conjugate back focal plane maps nominally to a plane wave of illumination at the sample. Access to a large conjugate back focal plane enables engineered illumination that has resulted in further advances in optical-system characterization and data analysis. As a result, the microscope-illumination and collection-path errors have been mapped to a functional dependence. They can then be used to normalize the experimental data for accurate comparison with electromagnetic simulations. We acquire both microscope images and backgrounds as a function of angle and calculate the mean intensity of the angle-resolved images, which have been corrected using the background scan that was previously normalized by the known silicon reflectance. This is similar to conventional scatterometry, except that measurements were made with high-magnification image-forming optics.

We compared the normalized experimental signatures with electromagnetic scattering simulations using parametric analysis. We assembled a library of curves by simulating a multidimensional parameter space. We completed the comprehensive simulations using a rigorous coupled-waveguide analysis (RCWA) model. Figure 6 shows angle resolved experimental data and fitting results that demonstrate the accuracy that can now be achieved using this method. Good agreement between the simulated library of curves and the experimental data is observed and residuals are acceptable. However, the fitting process produces more uncertainty than desired, 1 to 2nm (1σ).

Measurement uncertainties for optical scatterometry and Scatterfield measurements are fundamentally limited by the underlying cross-correlations between the different fit parameters, *e.g.,* line widths and

heights. To reduce parametric correlation and improve measurement performance and uncertainties, we have developed a Bayesian statistical approach[35, 36] that integrates *a priori* information gleaned from other measurements. This allows us to embed information obtained from reference metrology and complimentary ellipsometry of the optical constants. The Bayesian embedded metrology approach was applied to the silicon target used in Figure 6. Table 1 shows the best-fit values and uncertainties for the regression analysis, with and without embedded atomic-force-microscopy (AFM) reference metrology. The data show a change in the mean values as well as an improvement in the uncertainties.

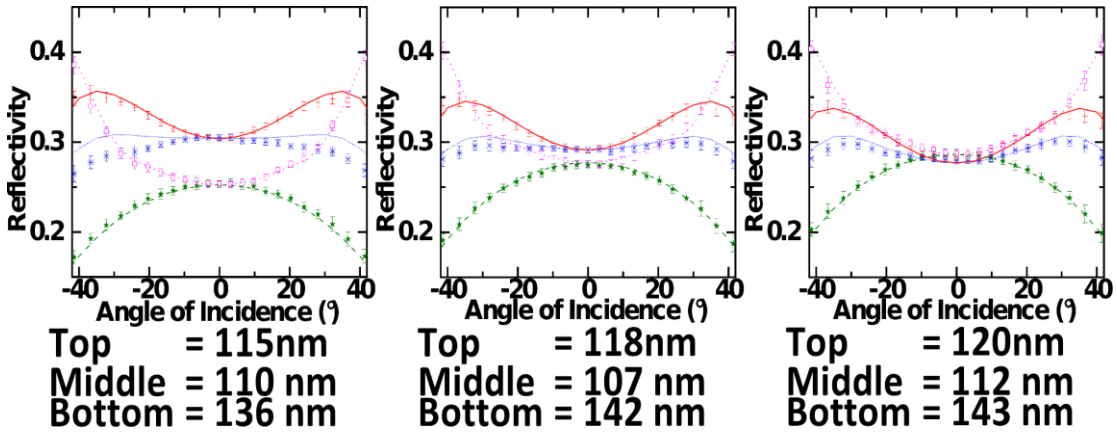

Figure 6: Experimental data and library data fits for three measurements. Top and middle critical dimensions (CDs) show good agreement with reference values.

Table 1: Optical CD (OCD) measurement results with and without embedded atomic-force microscopy (AFM) reference metrology.

	OCD Fitting	AFM	OCD with AFM
CD_{Top}	120	119.2	121
CD_{Middle}	112	117.3	115
CD_{Bottom}	143	132.8	141

	OCD Fitting	AFM	OCD with 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

6. Discussion

The above example highlights a way to introduce traceability through the Si lattice spacing. The number of lattice positions close to the edge that we could not conclusively resolve in figure 6 is three. The error associated with the edge definition can be substantially reduced by using the average of several measurements rather than one[37]. An uncertainty of three lattice positions translates into ≈ 0.94 nm for edge determination component. To put this in the larger context, the ITRS forecast a CD uncertainty of 0.28 nm (3σ) for the year 2010 and 0.22 nm (3σ) for 2012. This is the type of improvement needed to continue to make functional devices that adhere to Moore's law. Currently there are no known methods to meet these requirements. One of the approaches we are pursuing is the use of aberration corrected TEM. This will substantially reduce the uncertainty due to aberration of the electron optics. The uncertainty of determining the feature width for CD-AFM calibration is currently less than 1 nm[32, 38]. In addition to determining the sample width, other uncertainty sources include those associated with the CD-AFM instrument[20, 38].

The Scatterfield microscopy example shows how results from the reference instrument are used to reduce the uncertainty of other tools. In this case the Scatterfield microscope is faster, and better suited for inline use. Incorporating the AFM results has the benefit of decoupling terms that are correlated in the optical measurement, and thereby reducing the uncertainty[34].

The above examples highlight the type of calibration exercise needed to ensure traceability at the nanoscale. Overall the gap between what is required by the ITRS, and what is possible is large. Nanomanufacturing as a whole will benefit greatly from incorporating traceability. This will facilitate replication of results and identification of problems when they occur. Some of the strategies used to introduce *SI* traceability in semiconductor dimensional metrology are directly applicable to the burgeoning nanomanufacturing industry.

7. ACKNOWLEDGMENTS

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