Metrology Standards for Semiconductor Manufacturing

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Abstract

In semiconductor manufacturing, the performance of metrology equipment directly impacts yield. Fabs and equipment suppliers depend on calibration standards to ensure that their metrology results are within tolerances and to maintain their ISO [1] and QS [2] quality certifications. This task becomes more challenging as the device features shrink and tolerances become tighter, to the extent of their physical limits in many cases. As the industry keeps finding ways to meet the demanding metrology requirements, calibration standards have been developed and enhanced for all essential measurements, i.e. critical dimensions, thin films, surface topography, overlay, doping, and defect inspections. This paper provides an overview of such standards and demonstrates how they are certified and tested to be traceable to the International System (SI) unit of length in order to ensure reliable and transferable calibrations for fabs. The latest results on 50 nm Critical Dimension (CD) standards, 2 nm film thickness standards, and 50 nm particle sizing standards, along with their certification strategies, are also presented.

Introduction

Calibration standards have been used for making and maintaining measurement instruments in virtually all industries. Since most instruments do not work on first principles, they must rely on reference artifacts, or standards, in order to be calibrated to provide meaningful data. The accuracy of the measurement result thus directly depends on the accuracy of the calibration standard. For this reason, such a standard must have not only a nominal value close to the quantity to be measured but also a much smaller uncertainty. For semiconductor manufacturing, this means that these standards must have features of dimensions comparable to device dimensions, often in the nanometer scale, with much smaller uncertainties than the tolerances of the devices. To fabricate such standards, one has to utilize state of the art technology and equipment available in the industry and, sometimes, has to resort to novel approaches beyond the current technology generation in the industry, as for the case of the 50 nm CD standard described later.

In addition, in order to obtain accurate measurement results, or even to evaluate accuracy, it is necessary to establish traceability to the SI units. Calibration standards become much more valuable when they are made traceable to SI units because this gives us the guarantee that the results from any metrology instruments in any places that have been calibrated with such standards are matched. For instance, it is desirable that dimensional standards are made traceable to the SI unit of length. Actually, most calibration standards used in semiconductor fabrications (e.g. CD, film thickness, step height, and particle size) are dimensional. It is, however, usually not straightforward to establish traceability for these quantities because the chain of comparison involved can be complex and the equipment required is not commonly available. In order to help the industry obtain and maintain traceable standards, some governmental standard organizations, such as the National Institute of Standards and Technology (NIST) in the US, have made available master standards that are traceable to SI units, known as Standard Reference Materials (SRMs). Unfortunately, the availability of these master standards doesn't always follow the pace of the development of device manufacturing technology. For measurements of CD at about 50nm and film thickness at about 2nm (which are needed at the current technology node), for example, no master standards can be found at this time. To address the demand of the industry, these standards must be certified by traceability to more fundamental quantities of length, such as the Si lattice constant and the wavelength of a He-Ne laser, as discussed below.

Standards for critical dimension

CD metrology involves, among other things, the measurement of the widths of lines and spaces, or the measurement of diameters of holes and posts. Such measurements are primarily performed with critical dimension scanning electron microscopy (CD-SEM) although optical scatterometry CD measurements are emerging [3]. A CD-SEM system has to be calibrated and its accuracy directly depends on the accuracy of the calibration standard near the size to be measured. Pitch standards are most commonly used for this purpose since the common mode errors are cancelled out in pitch measurements (which is not the case for linewidth or diameter measurements). A CD-SEM calibrated with a 100 nm pitch standard (Fig 1) (using single or multiple pitches) [4] can accurately measure features about 100 nm or larger in size. Besides CD-SEM, scanning probe microscopes (SPMs) and optical microscopes can also be calibrated for lateral measurements with this type of standards with suitable pitches.

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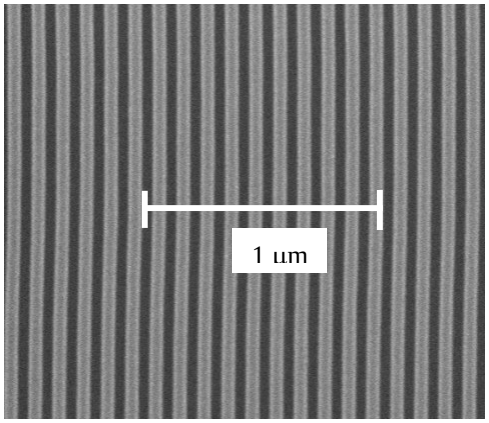

Fig 1. CD-SEM image of a 100 nm pitch standard

The pitch standard shown above was fabricated by etching the pattern into a doped Si substrate for compatibility with common e-beam measurements of Si wafers, i.e. to minimize charging, or e-beam induced damage, as well as being cleanable after normal e-beam measurements. The standard has a large surface area (as compared with the field of view in normal measurements) and the measured result can be stable for thousands of measurements on the same spot (Fig. 2).

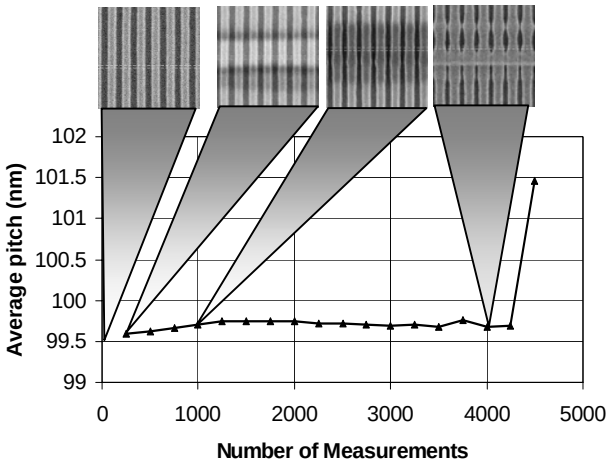

Fig. 2 E-beam induced degradation of the pitch standard and change in measurement result

The standard shown above is traceable to the SI unit of length through a 200 nm pitch standard which was certified by NIST to be traceable to the SI units by calibrated atomic force microscopy (C-AFM) [5][6]. It would be tempting to use the pitch standard for calibration of CD. However this structure is not ideal for that purpose because the sidewalls of these lines are not perfectly vertical. An ideal standard for CD calibration can be fabricated with a different method (Fig. 3).

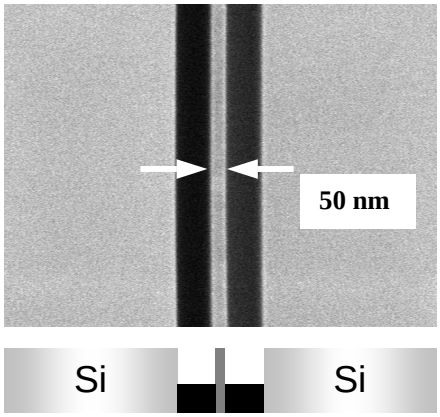

Fig. 3 CD-SEM image and structure illustration of a 50 nm CD standard

In order to obtain vertical sidewalls and precise control of the linewidth of this CD standard, a 50 nm wide line was made out of a layer of 50 nm thick amorphous silicon sandwiched between 2 layers of SiO_2 using thin film depositions. Another layer of Si was then added on top of the film stack. The structure was cut, polished, and the SiO_2 was etched back. Figure 3 shows the sample as seen in a CD-SEM when viewed on edge [7].

Since no SI-traceable master linewidth standards are available near this size, the traceability was established by comparison with the lattice constant of the crystalline Si which was used as the substrate for this structure, as shown in the high resolution transmission electron microscopy (HR-TEM) image below (Fig. 4). With a lattice constant of about 0.5 nm an image of the Si lattice can be used as the dimension reference for the linewidth of these standards because the value of the lattice constant is recognized to be an accurately determined quantity with known uncertainties [8]. It can thus be made traceable to the SI unit of length.

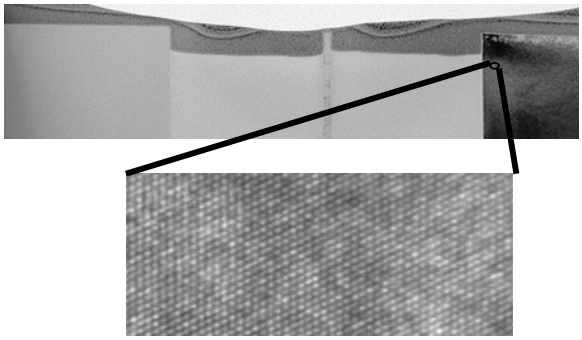

Fig. 4 TEM images showing the cross section of a 25nm polysilicon line and the atomic lattice of the crystalline Si subsrate.

Standards for surface topography

Surface topography is typically measured with scanning probe microscopy (SPM) for determining the surface quality after chemical mechanical planarization (CMP) or the feature heights after other process steps. Since a SPM instrument tracks the vertical movement of its probe (a stylus) to measure surface height variation, an artifact with known height change must be used for its calibration. Such artifacts are generally referred to as step height standards as illustrated in Fig. 5.

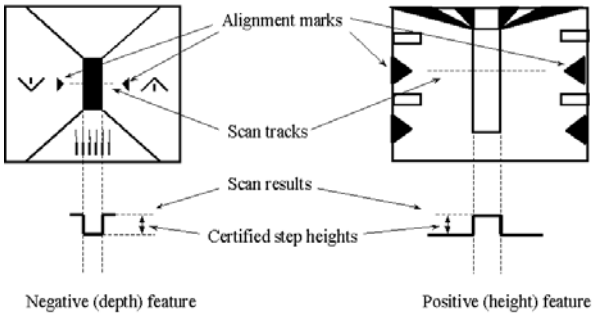

Fig. 5 Step height standards

A step height standard provides a certified surface height variation value with either an elevated or depressed feature, along with some marks for alignment on the instrument and for indicating the certified section of the feature. Step heights in the range of about 8 nm to 100 μm are commercially available. The standard is usually made by etching the features into a quartz plate with extremely flat and parallel surfaces to minimize tilt and background noise in measurements. It can be made traceable to the SI unit of length by comparison with a master standard.

The lateral dimensions of step height standard features are usually not specified. To obtain lateral calibration for an SPM, surface topography standards containing features with certified sizes in all 3 dimensions, as the one illustrated in Fig. 6, are needed. The traceability of lateral dimensions can be obtained using NIST master standards for linewidth and pitch.

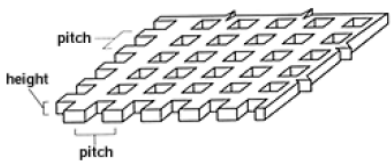

Fig. 6 Three-dimensional surface topography standard

Step height and surface topography standards can also be used for calibrating surface profilers working on optical interferometry [9], in both vertical and lateral directions, as well as the lateral scales of optical and electron microscopes.

Standards for film metrology

It is obvious that the film thickness can be measured with SPM discussed in the previous section, if the film has an accessible boundary with an abrupt step. Otherwise, we have to use instruments designed for measuring uniform films. Optical ellipsometers or reflectometers are the most common ones for dielectric films and they are also much faster then SPMs. In semiconductor manufacturing, they are the dominating equipment for measuring the thickness of gate dielectric and interlayer dielectric films. Although ellipsometers (either single wavelength or spectroscopic) and reflectometers can determine film thickness based on their own mathematical models without relying on calibration standards [10][11], it is not appropriate to use such results directly for manufacturing control purposes because: 1) in the models, the films are considered homogeneous in terms of their dielectric constants (n) and extinction coefficients (k). In reality, the surface of the top layer film and the interfaces between films usually have different n and k from the bulk of the films, resulting in measurement errors, which become more significant for very thin films [12]; 2) in the models, n and k as well as their dependence on wavelength are normally considered to be fixed, but in reality they often have certain variations due to the limitations in process control when the films are made; and 3) manufacturing variation and drifts over time of individual instruments also cause variations in measurement results for the same film stack. Therefore, in order to make the measurement result repeatable to ensure consistent device performance, virtually all major suppliers and users of ellipsometers and reflectometers employ film thickness standards to benchmark their equipment and correct the errors on individual systems. A film thickness standard is usually made of a single layer of SiO_2 or Si_3N_4 on a Si substrate. The reason is that such materials are highly stable and have well-established ellipsometric models. For other less understood materials, e.g. high-k, low-k or porous dielectrics, the measured thicknesses can be converted to an equivalent thickness of SiO_2 [13][14]. This way, although we don't know the exact physical thickness of the films, by comparing with a SiO_2 film thickness standard on an ellipsometer, we can still obtain consistent results by requiring the result of the unknown film stack to be within a certain range of an equivalent SiO_2 thickness. This practice has been widely carried out in the industry also because ellipsometric SiO_2 thickness has been used in the past over many generations of devices and viewed as a baseline to be referred to.

The values of commercially available film thickness standards that are traceable to the SI unit of length are in the range of about 5 nm to 1μm. As the gate dielectric layer gets thinner, currently at about 1.5 nm in terms of equivalent oxide thickness (EOT), the demand for thinner film standards will become strong. It is, however, much more difficult to make film thickness standards below 5nm because: 1) the error of the traditional single layer homogeneous film model is significant; 2) the film thickness is much less stable because the measurement error caused by surface airborne molecular contamination (AMC) becomes significant, and 3) no master standards are available for establishing traceability to the SI units.

To meet the demand of the industry, we recently developed a 2 nm film thickness standard using Si wafers with a single layer of SiO_2 grown by rapid thermal process (RTP). It can be seen from the TEM cross section image (Fig. 7) that the boundaries of the SiO_2 layer are not well defined due to the gradual transition from Si to SiO_2 at the interface and the roughness of the interface. Such a variation of the boundaries is significant compared with the thickness of the film. This makes it difficult to utilize the Si lattice in the image to certify the film thickness (as for the case of the CD standard) with a small uncertainty. In addition, there may be variations in n and k values of the film, which cannot be seen in this image.

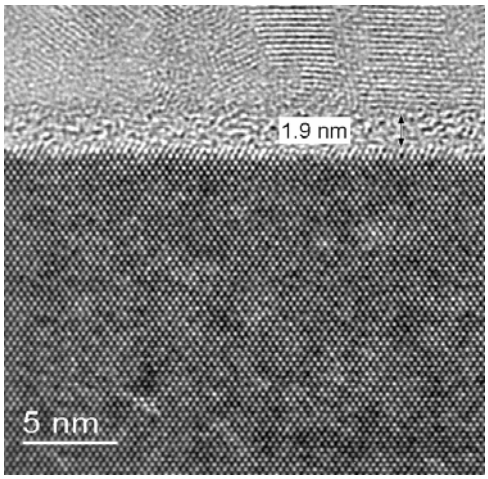

Fig. 7 TEM cross section image of a SiO_2 film thickness standard of about 1.9 nm physical thickness; a poly-Si cap layer was deposited on the sample to obtain a better defined SiO_2 surface for the TEM image.

With all these unknowns, it is also difficult to establish a model for ellipsometry that can accurately describe the real film stack. If we tried to do so, we would find that there are multiple solutions that satisfy the given conditions but generate different film thickness results. It would be hard to justify which result is the most realistic. On the other hand, once a particular structure has been proven to meet the device performance requirements, that performance can be maintained as long as the structure can be precisely reproduced even though its exact physical dimensions are unknown. In this situation, a calibration standard is still required for matching purposes. Therefore, we can use a simplified single layer model for this standard to calculate its equivalent single layer SiO_2 thickness and make it traceable to the SI unit of length under a certain set of conditions.

Because no traceable master standards are currently available below 5 nm, traceability can be established by resorting to the first principles of film thickness measurements by ellipsometry. The standard was measured on a single wavelength null ellipsometer (Fig. 8) with all manual operations so that all parameters (polarization angles and the angle of incidence) can be accurately determined and made traceable to master angle standards. We used a single layer model (i.e. one layer of SiO_2 on a Si substrate with abrupt and planar surface and interface) and made the assumption that the n and k values of the film and the substrate are known constants (i.e. $n_f = 1.460$, $k_f = 0$, $n_s = 3.875$, and $k_s = -0.016$, at the He-Ne laser wavelength of 632.8 nm). The angle of incidence was set at 70° and accurately measured against angle standards. The thickness was then calculated from the ψ and Δ values obtained through the classic 4-zone measurements using the angles of the polarizer, compensator, and analyzer at nulls [15].

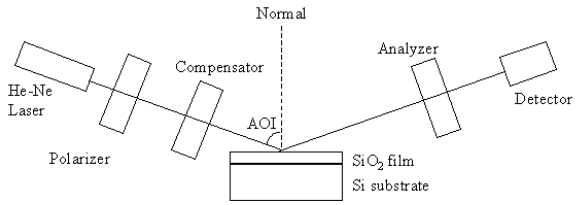

Fig. 8 A single wavelength null ellipsometer

Since the ellipsometer model correlates the resulting film thickness to the He-Ne laser wavelength, the thickness thus obtained is traceable to such wavelength and the thickness uncertainty can be calculated from the uncertainty of the wavelength and the uncertainties of the parameters involved in the model, e.g. angle of incidence and repeatability of the polarization angles. We performed the measurement of these 2nm film

thickness standards in our laboratory and obtained a result of 2.03±0.05nm at the 95% confidence level, traceable to the SI unit of length through the wavelength of the He-Ne laser. The largest contributors of uncertainties in our measurement were found to be the repeatability of polarizer and analyzer angle measurements, the compensator angle measurements, and the stability of the film, which contribute uncertainties of, respectively, 0.030 nm, 0.026 nm, and 0.020 nm, in terms of standard uncertainty.

Note that the certified value is not necessarily the value of the physical thickness of the SiO_2 film but instead, the equivalent SiO_2 thickness as measured on ellipsometers with a single layer film model and the previously described n and k values (for the film and the substrate). Because of the strong correlation between this equivalent SiO_2 thickness and the device performance and the industry's dependence on ellipsometery for film metrology at this thickness (as previously discussed), these standards are expected to be particularly valuable for the fabs.

As mentioned earlier, for films at this thickness level, AMC also becomes a significant error source and it grows with time, making the standards unstable. It has been shown that stability is a major contributor to the overall uncertainty. An acceptable level of stability was obtained when the standards were desorbed (at 230°C for 4 minutes) prior to each measurement. If desorption was not performed, the film thickness had much larger variations over time (Fig. 9).

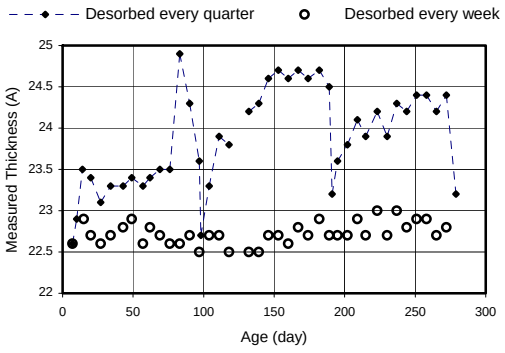

Fig. 9 Film thickness variation over time; quarterly desorption performed on 98th, 191st, and 271st day.

Besides heat desorption, the standards can also be locally (at the measurement spots only) desorbed with laser desorption which has been incorporated into some ellipsometers recently. Laser desorption provides comparable result in removing AMC and also allows desorption to be performed on product wafers in much shorter time (about 2 seconds per spot).

Standards for particle sizing

In fabs, the dominating metrology equipment for detecting and measuring particles on wafers is a scanning surface inspection system (SSIS). On such a system, the sizes of the particles are determined from the intensity of light scattered by them. Therefore, an SSIS must be calibrated with particles of known sizes over its range of operation. Since real world particles found on wafers can be of any materials and shapes, it is an industry practice to use polystyrene latex (PSL) spheres that are highly spherical and stable as calibration standards. A particle sizing standard for SSIS is usually a wafer with PSL spheres deposited on it. When the wafer is scanned on the SSIS, the sphere sizes are shown in histograms, and the peaks (modes) of the histograms are used as the calibration points (Fig. 10)

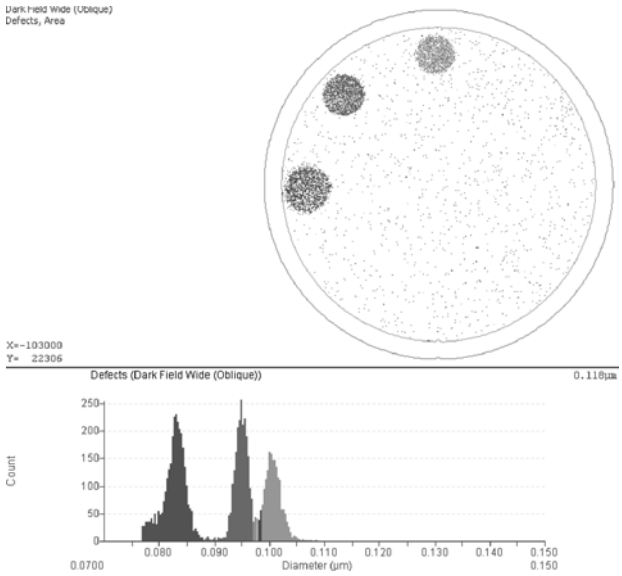

Fig. 10 SSIS scan result of a particle sizing standard

It can be seen that the accuracy of the calibration directly depends on the accuracy of the peak sizes of the spheres on the standards. PSL spheres with modal sizes pre-certified to be traceable to the SI unit of length (e.g. through TEM measurements [16], a Differential Mobility Analyzer (DMA) [17], or an electro-gravitational microbalance [18]) can be obtained commercially. These spheres, however, usually have relatively large size distributions and, when deposited on wafers and scanned by an SSIS, generate a wide peak in histogram (Fig. 11). A wide peak makes it difficult to determine the modal size accurately. Therefore the PSL

spheres to be deposited on the standard are commonly filtered through a DMA, which can be used as a size selection device to provide a narrow size distribution (Fig. 11). With the help of certified PSL spheres and the DMA, SI traceable particle sizing standards down to 50 nm have been made available.

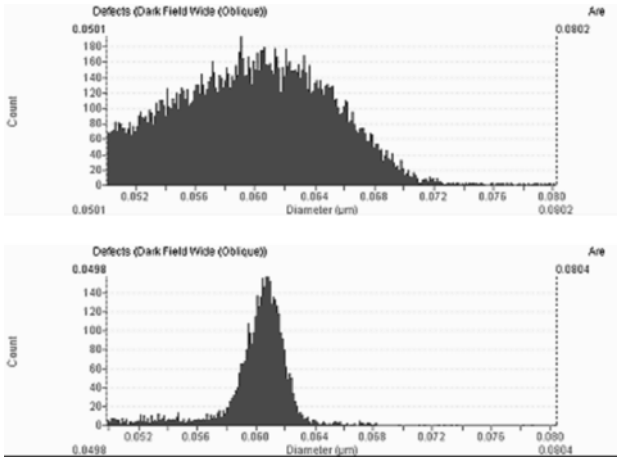

Fig. 11 SSIS histograms of original (top) and DMA-selected (bottom) 60 nm PSL sphere depositions

Because particles found on wafers are contaminants, the standards described in this section are also known as contamination standards. Besides SSISs, optical inspection equipment for patterned wafers and reticles, including dark field and bright field types, also depend on particle sizing standards for calibrations in order to properly determine the sizes of the defects that they find.

Conclusions

We have reviewed the major calibration standards used in metrologies for semiconductor manufacturing as well as their latest development in several key areas. Standards have also been broadly employed for calibrating doping level analysis instruments and are being developed for overlay metrology [19]. As the industry matures and accuracy and traceability become more critical, the development of the standards must keep pace with or stay ahead of the prevailing technology of the industry. This presents a significant challenge and opportunity for both the suppliers and the users of the standards.

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