SCANNING VOL. 35, 355–361 (2013)
Published by Wiley Periodicals, Inc.

Does Your SEM Really Tell the Truth?—How Would You Know? Part 1

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Summary: The scanning electron microscope (SEM) has gone through a tremendous evolution to become a critical tool for many and diverse scientific and industrial applications. The high resolution of the SEM is especially suited for both qualitative and quantitative applications especially for nanotechnology and nanomanufacturing. Quantitatively, measurement, or metrology is one of the main uses. It is likely that one of the first questions asked before even the first scanning electron micrograph was ever recorded was: "… how big is that?" The quality of that answer has improved a great deal over the past few years especially since today these instruments are being used as a primary measurement tool on semiconductor processing lines to monitor the manufacturing processes. The well-articulated needs of semiconductor production prompted a rapid evolution of the instrument and its capabilities. Over the past 20 years or so, instrument manufacturers, through substantial semiconductor industry investment of research and development (R&D) money, have vastly improved the performance of these instruments. All users have benefited from this investment, especially where quantitative measurements with an SEM are concerned. But, how good are these data? This article discusses some of the most important aspects and larger issues associated with imaging and measurements with the SEM that every user should know, and understand before any critical quantitative work is attempted. SCANNING 35: 355–361, 2013. Published 2013 by Wiley Periodicals, Inc.†

Note: Certain commercial equipment is identified in this work to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.

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Received 18 December 2012; Accepted with revision 2 January 2013

DOI 10.1002/sca.21075
Published online 20 February 2013 in Wiley Online Library (wileyonlinelibrary. com).

Key words: calibration, measurements, metrology, modeling, Monte Carlo, scanning electron microscope, SEM, standards

Introduction

Scanning electron microscopes are used in all phases of scientific, medical, and industrial research, as well as manufacturing. Since its inception in the 1950s and its introduction as a commercial product in the 1960s, the SEM has gone through a tremendous evolution to become an indispensable tool for many and diverse applications. Numerous improvements in capabilities and the operation of the instrument have occurred. Electron sources have evolved from tungsten to lanthanum hexaboride to cold and thermal field emission providing much higher brightness and improved instrument performance. This performance is also enhanced by the incorporation of new electromagnetic and electrostatic lens designs, as well as digital electronics. Today, additional operational improvements such as: automation, autofocusing, and auto-astigmatism correction and digital imaging make the once core microscopy functions nearly transparent to the user. These improvements, in total, have improved the overall SEM performance and have made the instrument easier to operate. But, ease of operation also fosters operator complacency. In addition, the user friendliness has reduced the "apparent" need for more thorough operator training for these instruments. Therefore, this overall attitude has fostered the concept that the SEM is just another expensive digital camera or another peripheral device for a computer. Hence, a person using the instrument may be lulled into thinking that all of the potential pitfalls have been eliminated and they believe everything they see on the micrograph is always correct. But, this may not be the case.

Discussion

The SEM is a valuable scientific instrument, and as such, care must be taken and certain caveats must be remembered, as one must do with any scientific instrument used to generate reliable data. For this particular work, only three major areas will be discussed

(others will be covered in a subsequent paper). The first area of interest is the acquisition of the image, the second is instrument calibration and the third relates to how the first two areas affect metrology (measurements) with the SEM. Clearly, sample preparation, contamination deposition, and charging all remain critical issues, but they are not topics for this particular work. Optimization of the SEM performance is covered in another publication (Damazo et al., 2001).

Acquisition of the Image

The modern SEM displays and records an image that appears to be rapid, and real-time. The electron beam is, in reality, very rapidly traversing the sample in a typically rectangular (or square) "raster" pattern. As the electron beam traverses the area under examination, several different signal types are generated, such as transmitted electrons, secondary electrons, backscattered electrons, characteristic X-rays, etc. (Wells, 1974; Goldstein and Yakowitz, 1975; Postek et al., 1980). If the instrument is equipped with the proper electron detector(s) some or all of those signals can be collected and displayed. In fact, multiple signals can be displayed or recorded simultaneously. Regardless of the signal chosen, it is a point-by-point representation of the signal that results from the interaction of the electron beam with the sample as it scans in the raster pattern. The signal collected and displayed is known as the "secondary" electron signal, forms the typical SEM image. The "secondary" in secondary electron signal is intentionally written in quotes here because it can be the sum of several components (Peters, 1982, 1985), as shown in Figure 1(a). Different final lens designs and detector positioning will vary the number and type of electrons collected. However, this is not the topic of discussion of this work since it has been well covered in several other publications (Peters, 1982, 1985; Vladar and Postek, 2009).

A second consideration, where the derivation of the image is concerned, is that depending upon the composition of the material being examined and the landing energy of the primary electron beam, the beam can penetrate into that sample for some measurable distance. The primary energetic charged particles can generate signal as they enter into the sample and as they leave the sample (Fig. 1(b)). Depending upon the topography of the sample under observation, as the beam approaches an edge, it generates more secondary electron signal at these topographical features (e.g. peaks, steps, insect hairs, etc.). All of this signal whether useful or extraneous is summed for that point. This results in apparent enhancement or "blooming" at the edge, which is a characteristic of most secondary electron images as shown in Figure 2 (the edge enhancement is observed as well in subsequent micrographs). The edge enhancement also varies with detector position, the sample and other instrument operating conditions.

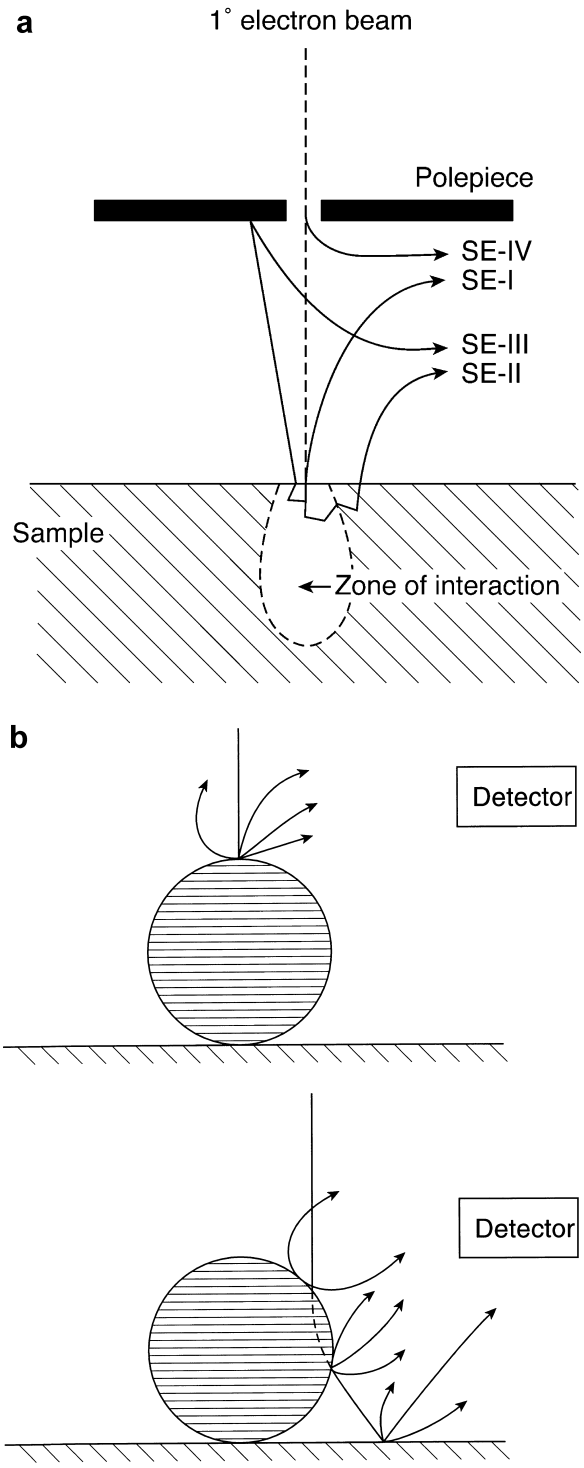

Fig 1. (a) Graphic representation of the derivation of the secondary electron signal and the four possible types of secondary electrons which can potentially contribute to the image. (b) Graphic representation of one possibility for derivation of edge enhancement which provides uncertainty in the physical location of an edge in an SEM.

A number of studies have been done on the edge enhancement characteristics of the secondary electron image because it can mask where the true edge of the specimen is located (Postek, 1984, 1994; Postek

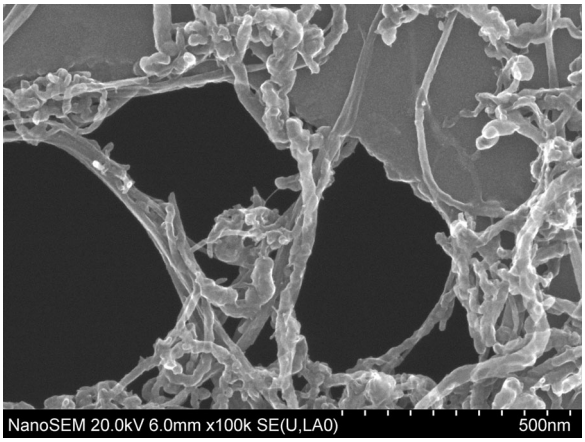

Fig 2. Scanning electron micrographs of a carbon nanotube sample suspended on a coated grid viewed in the secondary electron mode image showing edge enhancement. (Horizontal field width = 1,220 nm).

et al., 1988). Thus, edge blooming can potentially lead to errors in many interpretations and any measurements made from the SEM image. Many adjustments in operating conditions (landing energy, signal choice, tilt, etc.) or signal selection are usually available which can often minimize these effects, if they are recognized by the operator. It is critical that that for accurate measurements, physics-based modeling and interpretation is used, as discussed below.

Calibration of the Instrument

Simplistically, calibration means that the *X* and the *Y* scan circuits of the SEM are adjusted to nominally scan in a 1:1 ratio, and the overall result is that a round object will appear round and a square object appears square. If that is not correct, the images will appear distorted and rectangles and ovals result. In addition, one must also ensure that the "magnification" or horizontal field width (also often called field of view[1] or FOV) is correct. Horizontal field width (HFW) is a convention adopted several years ago to clearly define the image scale on a micrograph for publication or display purposes (Boyde, 1979). HFW is especially useful when an image has been reduced or enlarged through the printing process or is projected onto a screen in sizes different than the size of the original calibrated reference image. In this case, it is common that the displayed magnification on the alphanumerics of the micrograph is incorrect and misleading. However, the value of the HFW remains the same, and is correct. Not all instruments output the HFW in the alphanumerics, but most do display a linescale. The HFW is easily calculated since is the ratio between the length of the entire field in "*X*" to the length of the displayed linescale multiplied by the value shown for that linescale. It should be noted however, that the typical convention is that the microscope stage tilt is moved and displayed in the "*Y*" direction (i.e. in the vertical direction). In this case, the field width becomes problematical because of the potential of any tilt being applied to the sample. So, any similar "*Y*" measurement must be done with zero degrees of tilt and then would be referred to as vertical field width.

Accurate calibration of the scale, i.e. the HFW is very important. SEMs have always come from the factory calibrated to some extent. But, even if their HFW was well calibrated at the factory, scan electronics settings can drift with time. In an Interlaboratory Study (Postek and Gettings, 1995), using a prototype SEM magnification calibration Reference Material (RM), it was demonstrated that accurate scanning electron microscope magnification calibration and error analysis were significant problems affecting imaging and measurements with the SEMs investigated in this study. The work demonstrated that many of the instruments tested were mis-calibrated with an error that varied between 10% and 60%. Additionally, the calibration of the "*X*" scan to the "*Y*" scan was not 1:1 in many of the instruments so a round particle under those circumstances was recorded distorted. In the same study, multiple instruments from the same laboratory were also tested, and gross calibration differences were observed. This means that, besides the inherent error in the data incurred by using one of the instruments, the error was compounded when the other instrument was used in place of the first. These data would be highly inconsistent. This situation could be a common problem in a multiple instrument laboratory where the researcher uses either of the instruments depending upon availability and scheduling.

Not all the Interlaboratory Study data were bad. In laboratories where highly trained operators demanded accurate instrument calibration, and the instruments were tested routinely, the reported errors were extremely small and well within the mechanical calibration capabilities of the instrumentation.

Use of a suitable length standard such as Reference Material 8820 (http://www.nist.gov/srm/index.cfm) can facilitate the accurate calibration of the scans of the SEM (Fig. 3). RM 8820 may also be used to calibrate optical microscopes, atomic force microscopes, and other similar instruments in the laboratory all to a common dimensional standard (Postek et al., 2010). There are also numerous additional structures provided on the chip such as those shown in Figure 4(a) and (b). These structures can be used as secondary calibration structures, as well as, for testing instrument stage and scan linearity. RM 8820 can also be used to test for instrument contamination. This topic will be covered in Part 2 of this series.

[1] Although, horizontal field width and field of view are often used interchangeably, HFW has been adopted in this publication since field of view implies a two-dimensional array which is only valid when the beam is normal to the sample (zero degrees of tilt).

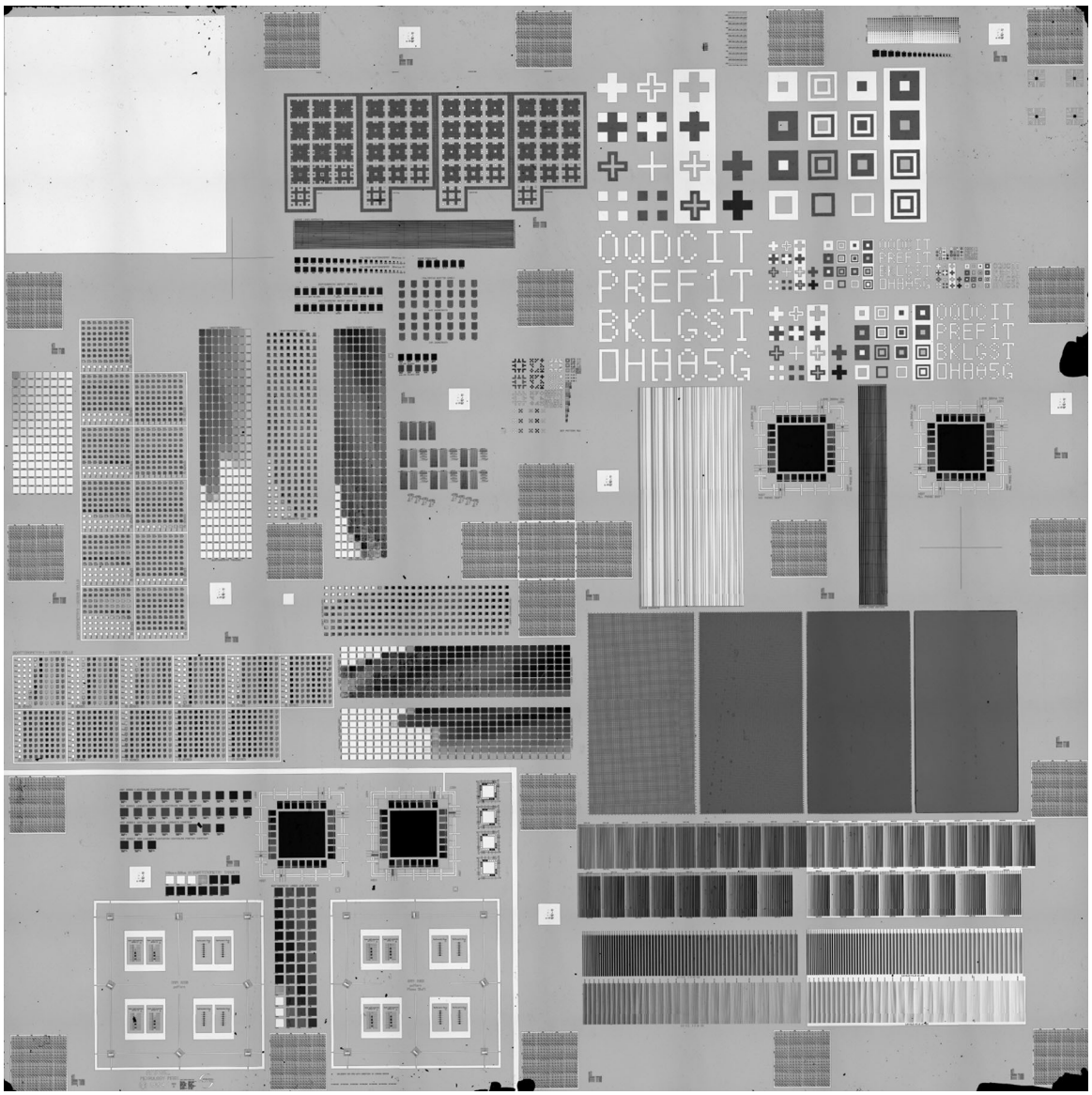

Fig 3. Bright-field optical micrograph of the entire 20 mm × 20 mm RM 8820 sample (micrograph Courtesy of Zeiss, Inc.). A more elaborate description of this sample is found in Postek et al. (2010).

SEM Metrology/Measurements

Someone once said, "If I want the right answer, I give the specimen under test to the scanning electron microscope operator." As stated earlier, the scanning electron microscope is an instrument, which one often takes for granted as being correct and any measured number produced is also correct. It is likely that one of the first questions asked before even the first scanning electron micrograph was ever taken was: "… how big is that?" The quality of that answer has improved tremendously over the past few years, especially since these instruments are being used as one of the primary tools on semiconductor processing lines to monitor the manufacturing processes. But, again the truth can be hidden and one must be careful.

Quantitative measurements with any scientific instrument require more care and understanding than one might first assume. The physical principles that dominate quantitative measurements must be fully understood and accounted for in the measurement. For example, in optics, the effects of diffraction must be overcome; in scanned probe microscopy, the scanned probe tip shape must be considered and in scanning electron microscopy, the generation of the measured signal, beam parameters, sample charging, and the electron beam-specimen interactions all must be considered. If one assumes everything is correct without carefully checking, erroneous data can easily result.

Today, there are essentially three types of measurements made with the SEM especially for semiconductor manufacturing. As shown in Figure 5, the simplest is

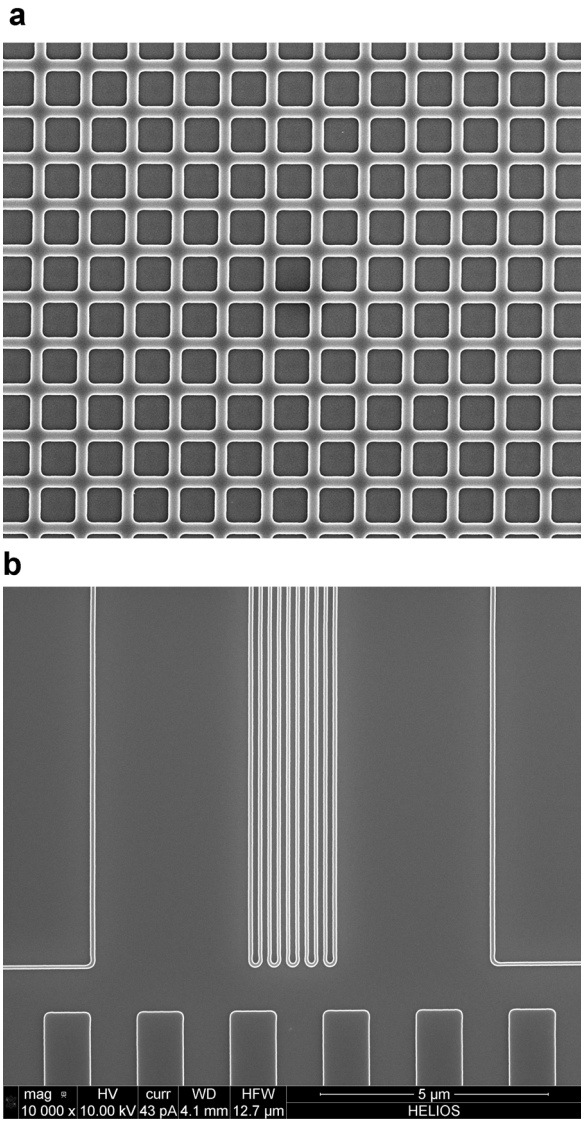

Fig 4. (a and b) SEM micrographs of supplemental pitch structures of RM 8820. These structures can be used to calibrate an SEM, AFM, HIM, or optical microscope all to the same reference material. (Horizontal field width = 12.7 μm).

known as a pitch (or displacement) measurement and the second is a structure width (critical dimension or linewidth measurement). Soon, a third type of measurement will become prevalent which is the contour or three-dimensional (3D) measurement (Orji et al., 2011). But, for the purpose of this particular work, the 3D or contour metrology is arbitrarily ignored, since it is still in the development phase.

Pitch Measurement

If we consider two lines separated by some distance, the measurement of the distance from the leading edge of the first line to the leading edge of the second line defines the pitch or displacement. Several systematic errors (due to vibration, electron beam interaction effects, etc.) in the

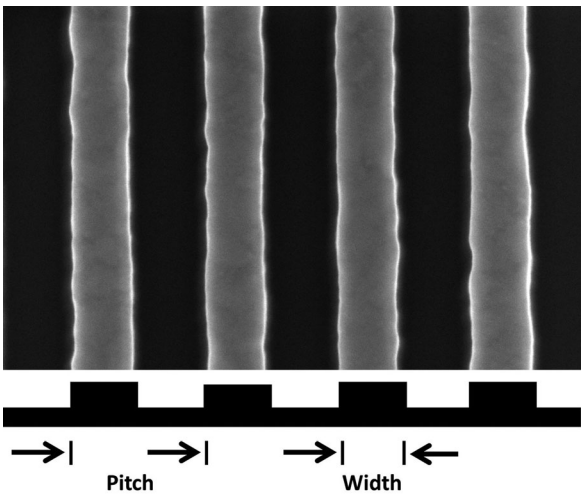

Fig 5. Typical SEM image of the 200 nm pitch patterns of RM 8820 at 100,000 times magnification. (Horizontal field width = 964 nm). The graphic below the image depicts the difference between a pitch measurement and a width measurement.

measurement of the pitch are equal on both of the leading edges; these errors, including the effect of the specimen beam interaction, are then thought to be negligible (Jensen, 1980; Jensen and Swyt, 1980; Larrabee and Postek, 1994). Thus, a rather significant part of the edge-related errors fall out of the equation used to calculate the pitch. The major criterion for this to be a successful measurement is that the two edges measured must be similar in all ways. Averaging many lines can minimize the effects resulting from edge roughness in the calibration sample (Postek et al., 2010). SEM HFW/magnification calibration can be easily accomplished using an accurate pitch standard. RM 8820 has numerous pitch structures available for this procedure; a software program for the calculation of the pitch is available upon request (Postek et al., 2010).

Width Measurement

The measurement of a width of any nanostructure, nanoparticle, or semiconductor line is complicated in that many of the systematic errors, described above, are now additive. Therefore, edge detection errors from both edges are included in the measurement. The SEM magnification should not be calibrated to a width measurement. A width measurement adds these errors together and results in an increased measurement uncertainty. In addition, these errors vary from specimen to specimen because of differing electron beam/sample interaction effects. To complicate this measurement even further, each microscope imparts its own characteristic instrument specific effects due to operating conditions, and electron collection characteristics (as discussed above). Effectively, with this type of measurement we do not know the accurate location of an edge in the image

and more importantly, how it changes with instrument conditions. The Interlaboratory Study cited above, also demonstrated, that the width measurement of a 200 nm nominal linewidth reported by the participants ranged as much as 60% too large (Postek et al., 1993). Many effects contributed to these results especially the type of measurement algorithm used to interpret the acquired image or data. Therefore, calibration based on a width measurement includes many error components and requires the development and use of electron beam–specimen interaction modeling discussed in the next section.

Electron Beam–Sample Interaction Modeling

The SEM image is not a perfect representation of the sample, but rather approximately the convolution of the sample, electron beam, and the excited volume. In addition, the signal which is collected is then "shaped" by the detector and electronics of the microscope. Similar effects have been well documented for energy dispersive X-ray microanalysis (Newbury and Myklebust, 2005). Without properly accounting for these contributions, it is impossible to obtain accurate dimensional results. Some of the effects are negligible and others can result in significant misinterpretation of these data. The size of the excited volume is typically much larger than the desired image and measurement resolution and it depends directly on the sample, which is the measurand, and the instrument parameters. Hence, modeling that accurately accounts for the physics for the signal generation, acquisition, and processing must be used. An early example of the power of modeling and its ability to reveal hidden information was the metrology of the transmitted electron (TE) signal of X-ray masks (Postek et al., 1989). In the TE modeled image, the presence of a small detail, a notch directly relating to the edge slope on the linescan was revealed by the modeling, but experimentally, this notch was not initially noticed because of limited resolution and signal-to-noise problems associated with early SEM instrumentation. However, optimizing the instrument operating parameters revealed the presence of the notch in the experimental data, as well. A number of excellent transmitted, backscattered, and secondary electron imaging models have been proposed and the reader is directed to the review of these models by Postek and Vladar (2011).

In the beginning, scanning electron microscopists believed that irradiating a sample with an electron beam in an electron microscope rather than viewing it with an optical microscope provided an accurate depiction of the sample simply because the "resolution" or sharpness of the image was much better. Unfortunately, that is not the case, and many of the reasons for the importance of modeling have been discussed above and reviewed by Postek and Vladar (2011). Modeling permits a clearer understanding of the numerous factors that comprise and contribute to imaging and measurement uncertainty in an SEM. Modeling is essential, and true dimensional accuracy can only be achieved through the modeling of the entire measurement process. This process may be too involved or unnecessary for some applications, but to claim accuracy in an SEM-based dimensional measurement, modeling is essential.

Conclusion

A well-calibrated, modern SEM instrument is capable of extremely high resolution and highly precise measurements. But, these measurements may be precisely wrong. Due to many instrument improvements, the magnification (or scale) can be accurately calibrated with a high level of confidence using the appropriate calibration samples. The precision of the measurements can generally be at, or better than, 0.2 nm (1σ), and for many applications, such as semiconductor production, this degree of high precision is adequate.

Clearly, just doing imaging is less demanding than making accurate measurements but the potential problems exist in either case. In this article, we have attempted to make the reader aware of potential pitfalls a microscopist can encounter and to dispel a number of fallacies that can result in obtaining erroneous data from an SEM. Some of these are:

Fallacy 1: The SEM image is formed like a standard optical microscope where there is an entire field viewed and recorded at the same time.

Truth 1: The SEM image is formed in a point-to-point manner, which is recorded as a modulation of the collected signal generated as the sample is scanned across the sample.

Fallacy 2: The SEM image is a true representation of the sample being viewed.

Truth 2: Electron beam interaction, atomic number differences, topography and edge enhancement characteristic of secondary electron imaging can complicate image interpretation and mask the true edge of a sample hence increasing measurement uncertainty.

Fallacy 3: The magnification and linescale displayed on a micrograph is a true measure of the length dimension.

Truth 3: Not necessarily, calibration of the scan is imperative to accurate data but the user must also check any other calibration used in the imaging or display such as alphanumeric calibration to the displayed image—often these are calibrated independently of each other.

Under proper interrogation, the SEM can tell the truth. For imaging and measurement, understanding the components contributing to potential errors is essential. Precision is a necessary but not sufficient requirement for accuracy. For accuracy today, and more so in the future, image and instrument modeling is essential. Modeling is imperative to determine the actual structure from the collected image. In addition, there is a great deal of additional unseen information within these data that the modeling can reveal. Accomplishing that requires employing a tested and verified physics-based electron beam–sample interaction and signal-generation model. The overall model must also account for instrument electronics, pertinent characteristics, and potential sample charging. The images simulated by the model can be compared with the actual images from the SEM. Such a process will then reveal far more structural and dimensional information about the sample under test than is currently being obtained, and ultimately can provide an accurate measurement at a calculated level of uncertainty.

References

Boyde A. 1979. Why horizontal field width? Scanning 2:126–128.

Damazo BN, Vladar AE, Ling AV, Donmenz M, Postek MT, Jayewardene EC. 2001. SEM sentinel—SEM performance measurement system. Proc SPIE 4344:773–782.

Goldstein JI, Yakowitz H. 1975. Practical scanning electron microscopy; electron and ion microprobe analysis. New York: Plenum Press. 582pp.

Jensen S. 1980. Planar micrometrology in the SEM. microbeam analysis. San Francisco, CA: San Francisco Press. p 77–84.

Jensen S, Swyt D. 1980. Sub-micrometer length metrology: problems, techniques and solutions. Scan Electron Microsc 1: 393–406.

Larrabee RD, Postek MT. 1994. Parameters characterizing the measurement of a critical dimension. SPIE Crit Rev CR52: 2–25.

Newbury DE, Myklebust RL. 2005. Simulation of electron-excited x-ray spectrum with NIST-NIH desktop spectrum analyser. Surf Interface Anal 37:1045–1053.

Orji NG, Dixson R, Vladar A, Postek MT. 2011. Strategies for nanoscale contour metrology using critical dimension atomic force microscope. Proc SPIE 8105, 810505-1–810505-10.

Peters K-R. 1982. Conditions required for high quality high magnification images in secondary electron scanning electron microscopy. SEM/1982/IV, SEM, Inc., pp. 1359–1372.

Peters K-R. 1985. Working at higher magnifications in scanning electron microscopy with secondary and backscattered electrons on metal coated biological specimens and imaging macromolecular cell membrane structures. Scanning Electron Microscopy/1985/IV, SEM, Inc., pp. 1519–1544.

Postek, MT. 1984. Low accelerating voltage inspection and linewidth measurement in the scanning electron microscope. SEM/1984/III, SEM, Inc., pp. 1065–1074.

Postek MT. 1994. Critical issues in scanning electron microscope metrology. NIST J Res 99:641–671.

Postek MT, Gettings R. 1995. Report of investigation: Reference Material 8090 - SEM Magnification Calibration Reference Material. Gaithersburg, MD: Office of Standard Reference Materials, NIST. 6 pp.

Postek MT, Vladar A. 2011. Modelling for accurate dimensional scanning electron microscope metrology: then and now. Scanning 33:111–125.

Postek MT, Howard KS, Johnson AJ, McMichael K. 1980. Scanning electron microscopy a student handbook. Williston, VT: Ladd Research Industries. 305 pp.

Postek MT, Keery WJ, Larrabee RD. 1988. The relationship between accelerating voltage and electron detection modes to linewidth measurement in an SEM. Scanning 10: 10–18.

Postek MT, Larrabee RD, Keery WJ. 1989. A new approach to accurate X-ray mask measurements in a scanning electron microscope. IEEE Trans Electron Dev 36:2452–2457.

Postek MT, Vladar AE, Jones S, Keery WJ. 1993. Inter-laboratory study on the lithographically produced scanning electron microscope magnification standard prototype. NIST J Res 98:447–467.

Postek MT, Vladar AE, Keery W, Bishop M, Bunday B, Allgair J. 2010. Reference material (RM) 8820: a versatile new standard for Nanometrology. SPIE Proc 7638:1–11.

Vladar A, Postek MT. 2009. The scanning electron microscope. In: Orloff J, editor. Handbook of charged particle optics. New York: CRC Press, Inc. p 437–496.

Wells OC. 1974. Scanning electron microscopy. New York: McGraw-Hill Book Co. p 421.