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Comparison of Electron Imaging Modes for Dimensional Measurements in the Scanning Electron Microscope†

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Abstract

Dimensional measurements from secondary electron (SE) images were compared with those from backscattered electron (BSE) and low-loss electron (LLE) images. With the commonly used 50% threshold criterion, the lines consistently appeared larger in the SE images. As the images were acquired simultaneously by an instrument with the capability to operate detectors for both signals at the same time, the differences cannot be explained by the assumption that contamination or drift between images affected the SE, BSE, or LLE images differently. Simulations with JMONSEL, an electron microscope simulator, indicate that the nanometer-scale differences observed on this sample can be explained by the different convolution effects of a beam with finite size on signals with different symmetry (the SE signal's characteristic peak versus the BSE or LLE signal's characteristic step). This effect is too small to explain the > 100 nm discrepancies that were observed in earlier work on different samples. Additional modeling indicates that those discrepancies can be explained by the much larger sidewall angles of the earlier samples, coupled with the different response of SE versus BSE/LLE profiles to such wall angles.

Keywords

metrology; backscattered electrons; low loss electrons; secondary electrons; JMONSEL; electron beam modeling

Introduction

Scanning electron microscopes (SEM) are used for a wide variety of applications in both scientific research and manufacturing. Nanoparticle and critical dimension metrology in many production environments currently rely on measurement of the collected secondary electron (SE) data. The accuracy of the sample's geometrical parameters inferred from these measurements has always been important, but is often overshadowed by two other main measurement drivers: throughput and precision. It can be slow and tedious to achieve

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accuracy, so it is often ignored. However, the accuracy of a measurement is becoming more of an abiding concern, in all the applications of the instrument, as sub-10 nm nanoparticles and semiconductor structures are now being routinely produced and SEM instrumentation is pushed to its performance limits. Hence, the metrology error budget has shrunk, and has become only the size of a couple of atoms, that is, virtually nonexistent. Clever new measurement and signal collection methods applied to sub-10 nm metrology must be explored for all types of semiconductor nanostructures, nanomaterials, and nano-enabled materials to ultimately achieve the needed accurate measurements.

Achieving good SEM measurement accuracy depends on accounting for specimen–electron beam interactions and on the quality of the acquired image. This image can be influenced by a whole host of contributors: vibration, drifts, sample contamination, and charging (Postek & Vladár, 2013, 2015; Postek et al., 2014*a*, 2014*b*). New image acquisition methods and successful mitigation of detrimental effects can alleviate some of the imaging problems. However, another key element is the understanding of the electron beam/specimen interactions from which all the measured signals originate (Postek & Vladár, 2011). This can be understood through the application of electron beam–solid-state interaction models, such as those used by National Institute of Standards and Technology (NIST)’s JMONSEL simulator (Villarrubia et al., 2007, 2015) to interpret and account for the physics of the signal generation, and help to understand and minimize the various contributions to measurement inaccuracy.

Typically, imaging and measurements are made on the SE image, as it is the strongest and most convenient signal collected. Backscattered electron (BSE) imaging is typically signal limited and low-loss electron (LLE) imaging is even more difficult because LLEs represent a relatively small and hence inherently noisier subset of all BSEs. LLEs are energy-filtered BSEs that have lost only a small amount of energy and that have therefore undergone only minimal inelastic interactions with a sample. They, therefore, can carry high-resolution, surface-specific information (Wells, 1970, 1971, 1986, 1987). The advantages afforded by LLE and BSE are that they are more readily modeled than the SEs as higher energy scattering processes are better understood than low-energy ones, and higher energy electrons are less influenced by charging.

In this work, we compare SE, BSE, and LLE signals acquired on a new high-resolution field emission SEM (FESEM) that has incorporated high-angle BSE and energy-filtered LLE detectors. Early work indicated that the BSE and the LLE signals could also be advantageous for metrology (Postek et al., 2001). When that early work was first done, both the BSE and the LLE signals were very difficult to obtain because of poor signal-to-noise ratio (SNR) and other instrument-specific geometric limitations. Newer instruments have begun to overcome this limitation by incorporating in-lens electron detectors in field emission electron columns. Consequently, up until now, very few careful comparisons of the three modes of electron collection and the subsequent correlation with measurements have been done. This has been mainly a consequence of the equipment limitations. In the first study of this type (Postek et al., 1988), resolution was limited by the use of a lanthanum hexaboride-equipped, thermionic emission instrument, and incorporated the standard Everhart/Thornley-type SE detector (Everhart & Thornley, 1960), diode BSE detector, and a

converted backscattered secondary electron (CBSE) detector (Moll et al., 1978; Moll et al., 1979). That earlier study, on semiconductor production-like samples was also limited by the low sensitivity of the diode BSE detectors to the low landing energy^a electrons and subsequent signal-to-noise (S/N) issues. Geometric differences in the placement of the detectors also presented fundamental issues, which could not be overcome. However, even with these limitations, it was the first study to point out that there were systematic measurement differences between SE and BSE collection. The reproducibility of the measurements also demonstrated the potential robustness of the BSE measurements. Some of these limitations were subsequently minimized in a second study (Postek, 1990) employing a microchannel plate electron detector (Postek et al., 1990). In that study, serial imaging and metrology of the SE and BSE images were done using the same detector and same geometry to the sample. In that work, collection and comparison of the BSE generated images of line structures measured about 10% narrower, compared with the width of measured SE images. These data were consistent with the previous study. Following that initial work, Monahan et al. (1993) using a new design instrument with a microchannel plate electron detector located in the column, also confirmed the previous observations. The Monahan et al. (1993) work presented some theoretical and experimental data characterizing a new low landing energy technology based upon collection of the BSE image. Subsequently, a new instrument was produced by Metrologix using this technology. Unfortunately, it did not last in the market as a result of other limitations, such as contamination deposition and throughput. That work was followed by Sullivan & Newcomb (1994), who also provided data consistent with the earlier results, but found an even greater divergence in size at the lower landing energies they used. These workers also confirmed the higher precision attainable from the BSE measurements. Sullivan & Newcomb (1994) placed a higher emphasis on charging being a negative contributor to the broader SE data.

The study presented here extends the early work by utilizing high-resolution field emission instrumentation coupled with optimized in-column electron detectors. Newer design detectors and multichannel electronics also permits the acquisition of pairs of SE/BSE and SE/low-loss data simultaneously, thus reducing some of the experimental issues revealed in the previous work. JMONSEL, an electron beam–solid-state interaction model, was used to verify and assist in interpreting these data.

Materials and Methods

SEM

A Hitachi SU 8230^b (Hitachi High-Technologies, Hitachi-Naka, Japan) FESEM, equipped with in-chamber (lower), high-angle (upper), and energy-filtered (top) electron detectors, was used to compare the SE, BSE, and LLE signals for the imaging and dimensional

^aLow landing energy is used here as that term has replaced the term low accelerating voltage because in some of the newer instruments the electron source can emit electrons at high accelerating voltage, but they are decelerated to a lower landing energy in the column and/or at the sample stage. This technique allows the electron optical column to operate more optimally (see Postek & Vladár, 2013). In SEM literature, landing energy is usually given in kilo-electron volts. For example, applying a 15 kV accelerating voltage with no deceleration results in a 15 keV energy primary electron beam landing energy.

^bCertain commercial equipment is identified in this report 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.

measurements (Fig. 1). The instrument was typically operated at 2.0 keV landing energy. For this work, 2.0 keV was the highest landing energy possible because of limitations in the electron optical design, including the high-energy electron filter. Within this allowed energy range, the BSE and LLE SNR generally increases as the beam energy increases. This meant that the chosen 2.0 keV maximized the signal. For LLE detection, the energy filter grid was set to only allow BSEs exceeding 1.9 keV (95% of the landing energy) to pass and to be amplified and collected. In other words, the BSEs only lost ~100 eV in the electron beam/specimen interactions that preceded the amplification and collection. Pairs of SE and BSE, and SE and LLE images were taken simultaneously for comparison, measurement, and analysis.

Energy-Filtered Detector

The column design of the instrument used in this work incorporates a high-angle in-lens, energy-filtered detector that greatly improves collection efficiency for both the BSE and the LLE. This is accomplished by having the high-energy BSEs, which are returning up the column; impinge onto a SE conversion plate where the signal is amplified. The total signal generated is then collected by the electron detector in SE mode. The high-pass filter preceding the top detector (shown in the drawing of Fig. 1) can allow all the BSE to enter or can filter the incoming electrons to the range desired for the LLE collection. Once through the filter, the LLEs are now only a small portion of the initial BSE signal. An order of magnitude estimate, based upon the NIST JMONSEL modeling, is about: LLE:BSE:SE (high θ) of 1:15:300, for the instrument conditions used. See the Modeling section below for further explanation and discussion, but SE conversion of the BSEs at the conversion plate provides a significant amplification of this signal much like the CBSE technique described and referenced above. In addition, the placement of this type of electron detector high in the column also reduces the geometrical limitations experienced by the early LLE detectors.

The LLE signal, as described above, is much weaker than the SE signal (~300:1). However, the LLE can be collected simultaneously with the SE. Therefore, the SE image can be used for all the focusing and astigmatism operations and then both images simultaneously recorded, providing the sharpest possible beam for the LLE image, as well. This type of dual signal collection facility was not possible for the previous work and provides an opportunity for sharper images as the higher quality or better S/N image is being used for the focusing and astigmatism correction.

Sample

The NIST RM 8820 (National Institute of Standards and Technology, Gaithersburg, MA, USA) magnification calibration sample^c (Postek et al., 2014c) was used in this study. Its characteristics are well known and hence could be readily modeled. The patterns on the RM samples were fabricated on 200 mm silicon (Si) wafers using 193 nm, extreme ultra-violet light lithography. A dry-etch process formed all the patterns from an amorphous Si layer deposited on the Si substrate, as shown in Figure 2, the lines are very close to vertical in cross-section (shown in a later figure) Apart from minimal edge roughness, the sample

^chttps://www-s.nist.gov/srmors/view_detail.cfm?srm=8820

cross-section is translationally invariant along the y axis. A large number of test patterns are available on the sample, further details of RM 8820 can be found in Postek et al. (2014c).

Models

Results will be discussed below in the light of two different kinds of models: (1) simple general principles or rules of thumb, for example, the secant law that describes the dependence of SE yield on sample surface angle or the mathematical behavior of convolution of a Gaussian with a peak or step function; (2) Monte Carlo simulation using JMONSEL (Villarrubia et al., 2007, 2015). The former is much simplified, retaining a description of only the most important phenomena. It is useful primarily because of the qualitative insight it lends, but it ignores many phenomena (scattering details, proximity effects from neighboring topography, etc.), the importance of which it therefore leaves in doubt. The latter model is considerably more detailed. JMONSEL is a single-scattering Monte Carlo simulator with a choice among a number of physical models. Our simulations were modeled on the RM 8820 sample (sometimes with geometrical changes, such as more gently sloped sidewall angles, to observe their effect), so we assumed the sample was composed of Si. Elastic scattering was modeled with tabulated Mott cross-sections. For SE generation we used dielectric function theory. Electron-phonon interactions and electron diffraction (or total internal reflection) at the vacuum/Si interface were also included. The model did not include charging effects, which we expect to be small as the Si sample was conductive except for the native oxide, which is too thin to sustain a significant potential difference. Details of these models are provided in Villarrubia et al. (2015). In this case, the main benefit of the more detailed model is to provide assurance that the qualitative insight suggested by the simpler model is not, in fact, compromised by the details it omits.

Results

Imaging and Measurements

For the first time in this type of study, point-by-point measurement data were able to be obtained simultaneously on a sample using the pairs of different electron collection modes. Previously, duplicate serial scans were necessary, leading to potential errors due to misalignments, contamination buildup, and drift in the measurement between the recording of the first and second image. The same scan line or average of several scan lines between SE and BSE and SE and LLE modes were analyzed. Figure 3 (top) shows a SE image of the lines at a landing energy of 2.0 keV and Figure 3 (middle) shows the simultaneously taken LLE image. Figure 3 (bottom) is the high-angle BSE image obtained during a second scan without the addition of the energy filter. The SNR of the LLE image is still somewhat poorer than either the SE or the standard BSE image, but is much sharper and has a much better SNR than earlier efforts due to the reasons described above. Additional experimentation and further instrument optimization, as with all new imaging modes, will improve the LLE image even further. In addition, as SEM is an imaging tool, the inherently high noise in the LLE image can be significantly reduced by the application of noise filtration such as the Nik Collection^d plug-in for Adobe Photoshop® (Fig. 4).

^d<https://www.google.com/nikcollection>

Linescan analysis of the SE and LLE images of Figure 3 are shown in Figure 5 and the measurements are shown in Table 1. The profiles shown in Figure 3 are not of only a single line, but are integrated line profiles averaged in the y axis. These lines demonstrate several nanometers difference between the widths in the SE and LLE images of the nominally 230 nm wide 100 nm tall polysilicon lines at ~50% intensity thresholds. Therefore, these data are consistent with the results of the earlier work, which used nearly the same measurement threshold. However, in the present case, these data were acquired simultaneously instead of serially. These data were also done using the nearly vertical-walled RM 8820 and not samples having the sloped edges that were common on the earlier samples composed of photoresist, silicide, or gold having an inherent edge slope, as shown in Figure 6 and originally used in some of the earlier work.

Figure 7 shows cleaved cross-sections of the SE and the BSE images of RM 8820, which were initially done to confirm the near verticality of the RM 8820 sidewalls. Simultaneous images were taken in both the SE and BSE modes (although no LLE images were taken) and those measurements are also shown in Table 1. The differences between the two measurements are shown in the table. In this case, the SE to BSE shows a difference of ~5%. The difference in the measurements may be due to the fact there is less electron scatter composing the signal from either the substrate or the sidewalls.

Modeling

The advantage afforded by physics-based modeling is that clearly defined experimental parameters can be established within the model and thus, provides far better control and flexibility than the instrument and experiment allows. Thus, by adjusting known parameters in the model, the experimental data can be interpreted much more clearly.

The collection of the BSE/LLE is an adjustable parameter in the model. By definition, the total modeled BSE signal is composed of all the BSEs emitted from the surface of the sample with >50 eV, regardless of angle (i.e., to be emitted in the backward direction, and not transmitted. A BSE needs to have been scattered by $>90^\circ$. “All BSE” then refers to electrons with accumulated scattering angle $90^\circ < \theta < 180^\circ$. Therefore, for this work, high θ BSE, as a defined parameter for the simulation, are those with $165^\circ < \theta < 180^\circ$. That is, those within 15° of being 180° backscattered. For LLEs, the angles are the same. The only difference is that the cutoff, instead of 50 eV, is 95% of the incident energy. In the instrument configuration used for this work, the high θ BSEs are the electrons that go back up the column toward the top and upper electron detectors. As the BSE/LLE are energetic and hard to deflect, any detector which is relatively small and placed in the column or subtending a small solid angle around the exit of the final lens, collects only a fraction of the electrons. On the other hand, if the SEM was equipped with a hemispherical BSE detector such as the work by Reimer & Tollkamp (1980) the total BSE yield could be measured. In addition, by experimentally and sequentially reducing the solid angle of collection, a variety of classes of BSE could also be measured. Today, all of these possibilities can be simulated with modeling. In this application, the goal of this work was to investigate and model the high θ BSE. The modeled ratio of high θ BSE to LLE to high θ BSE to SE was $\sim 1:15:300$. As stated above, the BSE has $15\times$ more signal

than LLE and the SE has 300× more. As the RM 8820 is composed of all Si, there is no atomic number contrast difference. So, all three of the signals vary across the sample topography providing the typical contrast to the image. This means that the ratios depend on where on the image they are measured as well as what energy and angular cutoffs we use to define them. Thus, these ratios are presented as order of magnitude estimates.

As shown in Figure 8, initial modeling using JMONSEL has shown that an ideal Si structure having vertical walls imaged with an infinitely small electron beam would not exhibit as great a measurement discrepancy between the SE and the BSE or LLE images as that observed experimentally. The simulated linescans shown in Figure 8 (top) assume there is no sample vibration or drift and a sharp electron beam. The effect of a broader effective beam due to less than ideal focus, drift, or sample vibration is shown in Figure 8 (bottom).

Discussion

In an attempt to understand what is happening it is necessary to first view the two modeled data curves independently, as shown in Figures 9 (top) and 9 (bottom). For the purpose of this discussion, the SE signal at each edge of Figure 9 (top) can be thought of as fundamentally a peak—ideally a zero-width peak. Alternatively, the BSE/LLE signal (Fig. 9 (bottom)) is thought of as fundamentally a step—ideally, a sharp step—with zero-width transition. In practice, these ideal features get broadened by the defocusing effects.

The edge broadening that takes place is a result of the combination of many factors, for example, the beam's finite size or its spread in the sample. If multiple linescans are averaged together (as is typically done), movement of the sample during the time a pixel is acquired, shift of the beam due to sample charging, and the statistical distribution of edge positions due to line edge roughness (LER), all can affect the average in a way that resembles broadening. All or some of these factors can modify the image, and the better we know these input factors, the better and more accurate will be the modeling.

Therefore, broadening modifies our ideal features. These factors broaden both the SE signal peak and BSE/LLE signal step, *but in different ways*. The effects are different because of their different symmetries. When an ideal step is symmetrically broadened, its center stays in place, whereas its flanks spread out to the right and left as shown by the green curves in Figures 10. This is similar to the effect on the step-like BSE/LLE signal.

Alternatively, when a peak is symmetrically broadened (the blue curves in Figs. 10), the location of its maximum stays in place, whereas its top and bottom move to the right and left, away from the center. This is similar to the effect on the peak-like SE signal. This has significant implications for edge assignments. When edge position is judged by a high threshold (i.e., close to the peak), the BSE/LLE measured value is highly sensitive to broadening, and the SE signal is relatively insensitive because the peak does not move. Alternatively, when the edge position is judged by a 50% threshold, the sensitivity is reversed: BSE/LLE is insensitive and the SE is now sensitive. Hence, the SE and BSE are visualized and measured differently. This also accounts for the improved precision reported when the BSE/LLE image was collected and measured (Monahan et al., 1993; Sullivan and

Newcomb, 1994). However, even today, the choice of measurement algorithm remains arbitrary. In this example, if the SE image is judged at the 90% threshold point and the LLE image by the 50% threshold, then they can give about the same answer in both cases. So the statement that the line is measured narrower in the LLE image is only true for a particular definition of how the width has been extracted, and that definition remains an arbitrary choice. These results lead to further questions about current measurement algorithms and data analysis for comparisons of this type.

This is now especially true as both SE imaging and BSE/LLE collection can be done simultaneously. However, the contrast and the brightness levels are not the same between the two modes of operation and care must be taken to measure the same portions of the linescan. Clearly, as the linescan fidelity is critical, this work points to serious measurement issues encountered by blindly applying measurement algorithms without considering the underlying physics provided by applying model-based metrology (Villarrubia et al., 2005*a*, 2005*b*).

The above explains small differences in the measurement such as those data from this current study using an “ideal” sample and an optimized state-of-the-art instrument. However, some of the prior measurement differences are rather large—as large as 150–200 nm (Postek et al., 1988)—and are not as easily explained only by the above effect. The convolution effect discussed above can account for small differences between BSE/LLE and SE apparent widths. Those differences are comparable with the beam size, vibration amplitude, or LER, depending on which of these contribute to the broadening of the effective beam size. It is unlikely that all of these contribute enough to provide the magnitude of difference between the two modes of electron collection which are on the order of 150 nm or more. However, there is also an effect due to sidewall slope, unimportant in our analysis of results from RM 8820 (as its sidewalls are so steep) but important for the earlier samples. Semiconductor samples of that generation often had sloped sidewalls. Calculation of the wall angle from the best micrograph that could be obtained from that early work (Fig. 6) demonstrated about a 14° wall slope. JMONSEL simulations of structures with sloped sidewalls produce different apparent widths, with SE width greater than that of BSE or LLE, when the sidewall is sloped as shown in Figure 6.

The differences between SE and BSE or LLE images can be qualitatively understood in terms of simple models. A significant part of the contrast in the SE image is due to variation in the orientation of the sample beneath the beam. Other things being equal, according to Reimer (1985), the SE yield, δ , can be approximated as $\delta = \delta_0 \sec(\theta)$ (the “secant law”) with θ the tilt of the sample (0 when the sample is horizontal). This proportionality corresponds to the length of path of the primary electrons within the SE escape depth, a length that increases as the beam’s path becomes more nearly parallel to the local sample surface. For a trapezoidal line this model predicts two yield levels in the image, a high one on the highly sloped sidewall and a more moderate one on the horizontal substrate and line tops. In practice, this simple picture is moderated by other factors: sharp corners are rounded by finite beam size and the interaction volume; electrons emitted near the bottom of the line have lower probability of detection than those emitted near the top, etc. However, it remains largely true (e.g., the blue curve in Figure 11, which is a simulation that included many of

these other factors) that the SE signal shows a marked increase as soon as the beam encounters the highly sloped edge.

Contrast in the BSE or LLE image can likewise be qualitatively understood in terms of a simple but different model (Fig. 12). When the beam hits the top of the line far from an edge (Fig. 12 position B) or the substrate far from an edge (position D), electrons spread within the sample and BSEs emerge with equal facility to the left or right. On the other hand, when the beam hits the substrate near the base of the line (position A), the half on the side with the line emerges from the substrate beneath the line, which further attenuates them. If the line is tall enough to produce significant attenuation, there is a marked difference in yield. The situation is much the same if the beam strikes a sloped sidewall (position C). The beam spreads in all directions. Those that spread beneath the line and are backscattered are attenuated during their escape. Attenuation is largest when the beam strikes the sidewall near the base, where a significant fraction of the line lies above the impact point. When the beam hits the sidewall near the top of the line, attenuation is smaller. The effect is larger for LLEs because the line above the impact point need only be thick enough to remove a small amount of energy before the emerging electron is no longer considered low loss. Thus, in this imaging mode, the signal only becomes significant when the beam is close enough to the top of the line. “Close enough” is closer for LLE than for BSE images.

Thus, qualitatively, BSE and LLE imaging modes produce significant contrast near the top of the line, whereas the SE signal becomes significant near the bottom. Some of the samples used in the prior studies (Postek et al., 1988; Postek et al., 2001) had wall angles $>5^\circ$. However, no definitive cross-sectional data is available on these samples although approximate measurements can be made from Figure 6 that supports that supposition. However, from simple trigonometry, a $1\text{ }\mu\text{m}$ tall line with a 5° average sidewall slope has a bottom width $\sim 175\text{ nm}$ wider than the top. This means that if width assignments are based on an intensity threshold, SE images would be interpreted as showing a wider feature than the BSE or LLE image. Figure 11 shows a structure where the sidewalls are angled at only 5° . The green BSE/LLE profile only increases near the top. The blue SE profile increases near the bottom. The measurement of the SE profile would be larger than the BSE under that situation.

Conclusions

The current work has confirmed the previous observations that intensity–threshold–interpreted SE widths are larger than BSE widths. In addition, for the first time line-by-line simultaneous comparison of SE, BSE, and LLE has been accomplished. Using simple qualitative models, we have explained the differences in terms of the way the different image modes respond to sloped sidewalls and image blur. More comprehensive Monte Carlo modeling with JMONSEL employs fewer simplifications, but continues to show the same effects that were observed. This combined experimental and modeling work demonstrates the growing need to model in order to fully understand the measurement process if accuracy is to be attained for nanoscale measurements. Ideal structures such as the one used in this work provide viable tools for this type of work. Instruments varied, technology levels varied, detector type varied, samples varied, but the constant in this work was that the early

observation that SE measurements are consistently larger than BSE measurements was confirmed, and that mystery has been solved by this work. It should be added that this work is directly relevant to imaging and measurements made in variable pressure instruments where, for charge reduction, many of the images are composed of BSEs as the main imaging mode.

The potential value of BSEs and LLEs has not been fully exploited for dimensional metrology, but has not been forgotten. Some of the early results and further experimental and modeling work coupled with modeling are sufficiently promising that prompt continued exploration into the possibilities that BSEs and LLEs afford to metrology in standards development and to determine the necessary information related to design parameters necessary for its implementation.

In summary, this paper (1) demonstrated, for the first time, by simultaneous imaging that the previously observed bias between SE and LLE/BSE images is real, not just an artifact of charging, drift, detector positioning, or some other measurement error; (2) documented the measurement variation inherent in algorithm choice both on modeled and experimental data; (3) clearly pointed out that modeling of the image formation is necessary if you ultimately want an accurate measurement; and (4) explained the previously observed mysterious difference in the measurements with a simple phenomenological model supported by a more complete Monte Carlo model.

Typically, SEM imaging takes a three-dimensional (3D) world, and flattens and compresses it into a micrograph with only two spatial dimensions; then 3D measurements are inferred from those data. The third dimension information remains embedded in the image for us to use and to further understand the sample being viewed. However, these data are often ignored. Advanced 3D image methodologies coupled with modeling provides the tool to translate this information. Accurate measurement in that third dimension must be explored, for it is the future for particle beam metrology. Modeling provides the tool to translate this information, but the instrumentation must be optimized to obtain it. As instrumentation improves and clever new measurement and signal collection methods are applied, factors discussed in this paper become more important.

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References

- Everhart TE, Thornley RFM. Wide-band detector for micro-ampere low-energy electron currents. *J Sci Instrum.* 1960; 37:246–248.
- Moll SH, Healy F, Sullivan B, Johnson W. High efficiency, nondirectional BSE detection mode for SEM. *SEM.* 1978; I:303–310.
- Moll SH, Healy F, Sullivan B, Johnson W. Further development of the converted BSE detector. *SEM.* 1979; II:149–154.
- Monahan K, Toro-Lira G, Davidson M. A new low voltage SEM technology for imaging and metrology of submicrometer contact holes and other high-aspect-ratio structures. *Proc SPIE.* 1993; 1926:336–346.

- Postek MT. Low accelerating voltage SEM imaging and metrology using BSEs. *Rev Sci Instrum.* 1990; 61(12):3750–3754.
- Postek MT, Keery WJ, Frederick NV. Low profile high efficiency microchannel plate detector system for scanning electron microscopy applications. *Rev Sci Instrum.* 1990; 61(6):1648–1657.
- Postek MT, Keery WJ, Larrabee RD. The relationship between accelerating voltage and electron detection modes to linewidth measurement in the SEM. *Scanning.* 1988; 10:10–18.
- Postek MT, Vladár A. Modeling for accurate dimensional scanning electron microscope metrology: Then and now. *Scanning.* 2011; 33:111–125. [PubMed: 21630286]
- Postek MT, Vladár AE. Does your SEM really tell the truth? How would you know? Part 1. *Scanning.* 2013; 35:355–361. [PubMed: 23427011]
- Postek MT, Vladár AE. Nanomanufacturing concerns about measurements made in the SEM part IV: Charging and its mitigation. *SPIE.* 2015; 9556:95560Q1–11.
- Postek MT, Vladár AE, Cizmar P. Nanomanufacturing concerns about measurements made in the SEM part III: Vibration and drift. *SPIE.* 2014a; 9173:917306, 1–10.
- Postek MT, Vladár AE, Kavuri PP. Does your SEM really tell the truth? How would you know? Part 2. Specimen contamination. *Scanning.* 2014b; 36:347–355. [PubMed: 24166540]
- Postek, MT.; Vladár, AE.; Ming, B.; Bunday, B. Documentation for reference material (RM) 8820: A versatile, multipurpose dimensional metrology calibration standard for scanned particle beam, scanned probe and optical microscopy. 2014c. NIST Special Publication 1170. Available at http://www.nist.gov/manuscript-publication-search.cfm?pub_id=914808
- Postek MT, Vladár AE, Wells OC, Lowney JL. Application of the low-loss scanning electron microscope (SEM) image to integrated circuit technology. Part 1. Applications to accurate dimension measurements. *Scanning.* 2001; 23(5):298–304. [PubMed: 11587322]
- Reimer, L. *Scanning Electron Microscopy Physics of Image Formation and Microanalysis.* Heidelberg: Springer-Verlag; 1985. p. 457
- Reimer L, Tollkamp C. Measuring the backscattering coefficient and SE yield inside a scanning electron microscope. *Scanning.* 1980; 3:35–39.
- Sullivan N, Newcomb R. Critical dimension measurement in the SEM: Comparison of backscattered vs. SE detection. *Proc SPIE.* 1994; 2196:118–127.
- Villarrubia JS, Ritchie N, Lowney J. Monte Carlo modeling of SE imaging in three dimensions. *SPIE.* 2007; 6518:65180K, 1–14.
- Villarrubia JS, Vladár AE, Ming B, Kline RJ, Sunday DF, Chawla JS, List S. Scanning electron microscope measurement of width and shape of 10 nm patterned lines using a JMONSEL-modeled library. *Ultramicroscopy.* 2015; 154:15–28. [PubMed: 25747180]
- Villarrubia JS, Vladár AE, Postek MT. Scanning electron microscope dimensional metrology using a model-based library. *Surf Interface Anal.* 2005a; 37:951–958.
- Villarrubia JS, Vladár AE, Postek MT. A simulation study of repeatability and bias in the CD-SEM. *J Microlith Microfab Microsyst.* 2005b; 4:033002–1.
- Wells OC. New contrast mechanism for scanning electron microscope. *Appl Phys Lett.* 1970; 16(4): 151–153.
- Wells OC. Low-loss image for surface scanning electron microscope. *Appl Phys Lett.* 1971; 19(7): 232–235.
- Wells OC. Low-loss electron images of uncoated photoresist in the scanning electron microscope. *Appl Phys Lett.* 1986; 49(13):764–766.
- Wells, OC. Low-loss electron images of uncoated non-conducting samples in the scanning electron microscope. In: Geiss, RH., editor. *Microbeam Analysis.* San Francisco, CA: San Francisco Press; 1987. p. 76–78.

Figure 1.

Schematic drawing of the electron column of the instrument used in this work. Shown is the detector configuration. The upper detector was used to collect both secondary electrons (SEs) and backscattered electrons (BSEs); and the top detector was used to collect the SEs generated following collision and amplification with the conversion plate by the energy-filtered, or unfiltered BSEs coming back up the column through the high-pass filter. Not shown is an additional secondary lower detector in the sample chamber which was not used in this study.

Figure 2.
Scanning electron (SE) micrograph of RM 8820. SE Image at 0° tilt (horizontal field width = 1,224 nm).

Figure 3. Imaging of RM 8820. (Top) Secondary electron, (middle) low loss, and (bottom) unfiltered backscattered electron images of the same area (horizontal field width = 1,247 nm). Please note the top two figures were taken simultaneously with the same scan and the lower figure was taken afterward.

Figure 4. Low-loss electron image improvement with noise filtration. (Top) The original low-loss image and (bottom) the same but filtered image showing the de-noising capabilities of the Nik Collection noise filter applied (horizontal field width = 1,224 nm).

Figure 5. Integrated linescans of the data obtained from Figure 3. The blue line is the secondary electron (SE) image and the green line represents the low-loss electron (LLE) data.

Figure 6. Secondary electron image of the sample originally studied in Postek *et al.* (2014c). Note the wall angle is calculated to be about 14° (horizontal field width = $2.95 \mu\text{m}$).

Figure 7. Cross-section of RM 8820 cleaved polysilicon lines. (Top) Secondary electron image, (bottom) backscattered electron image (horizontal field width = 1,224 nm).

Figure 8.

JMONSEL modeled data. (Top) Modeling of a vertical-walled silicon structure mimicking the structure of RM 8820, imaged with a sharp beam. (Bottom) Modeling of the same structure, but with a 5 nm (1 SD) Gaussian beam. SE, secondary electron

Figure 9. JMONSEL “ideal” modeled silicon line: (top) secondary electron and (bottom) backscattered electron/low-loss electron plots with the two plots separated for clarity.

Figure 10.

Illustration of how broadening modifies ideal features of an ideal peak: (top) the green step is idealized backscattered electron/low-loss electron (BSE/LLE), the blue peak idealized secondary electron (SE); (middle and bottom). Ideal lines have been symmetrically broadened by convolution with a Gaussian. Note that the center stays in place, whereas its flanks spread to the right and left.

Figure 11.

JMONSEL simulations of a structure with 5° sloped sidewalls supporting the broadening of the measurements due to wall slope. The line cross-section is shown in red, the simulated secondary electron (SE) and low-loss electron images in blue and green, respectively.

Figure 12.

Model relationship of low-loss electron signal to sample geometry. The upper (green) curve shows the modeled low-loss yield from the line with near-vertical (left) and sloped wall (right) cross-section shown in the lower portion. Electron trajectories at four landing positions, labeled (A–D) are super-imposed on the sample geometry.

Table 1

SE/BSE/LLE Measurement Comparison.

	Pitch (nm)	Average Edge Roughness (nm)	Width (nm)	Average Edge Roughness (nm)	% Difference
Top down					
SE (upper detector)	432.81	1.2 ^a	238.57	1.19 ^a	
Low-loss (top detector) filter 95%	432.28		229.84		3.66
BSE (upper detector)	430.57		234.51		1.69
BSE (top detector) no filter	430.59		234.32		1.77
Cleaved XS					
SE (upper detector)	433.26	0.43	246.16	0.41	
BSE (top detector) no filter	432.68		233.83		5.01

^a Average edge roughness root mean square sigma in nanometres.
XS, cross section; SE, secondary electron; BSE, backscattered electron; LLE, low-loss electron.