Nanoelectronics Dimensional Metrology: Understanding the Differences between Secondary and Backscattered Electron Imaging[1]

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INTRODUCTION

In many fields of research and production, a great deal of dimensional metrology, characterization and process control is accomplished using scanning electron microscopes (SEM). The accuracy of these SEM measurements has always been important but is often overshadowed by two other main measurement drivers: throughput and precision. It is slow and often tedious to achieve high degree of accuracy and, so it is often ignored, especially in production where measurements must be made very quickly. However, the accuracy of a measurement is becoming more important as the frontiers of nanoelectronics are being explored, and sub-10 nm semiconductor device structures are routinely produced. Hence, the metrology error budget has shrunk, and has become truly atomic scale. This presentation will discuss new measurement, signal collection and modeling methods applied to sub-10 nm metrology being pursued for all types of semiconductor nanostructures, nanomaterials and nano-enabled materials to ultimately achieve the needed accurate measurements.

SEM MEASUREMENTS

The quality of the SEM measurements depends on how the acquired image is influenced by vibration, drifts, sample contamination and charging. In addition, accounting for specimen-electron beam interactions and their contributions to the acquired image must also be considered. New acquisition methods and successful mitigation of the previously mentioned environmental and instrument-induced effects can alleviate some of the imaging uncertainties. However, another key element is the application of advanced electron beam-solid state interaction modeling such as the NIST JMONSEL model [2] to interpret and account for the physics of the signal generation and help to understand and minimize the various contributions to measurement inaccuracy.

EXPERIMENT

The first part of this work involved a fundamental comparison of secondary (SE), backscattered (BSE) and low-loss (LLE) electron signals acquired on a new instrument that was equipped with SE, high-angle BSE and energy- filtered LLE detectors. Early work indicated that the BSE and LLE signal could be advantageous to help to understand the metrology of semiconductor structures [3]. The LLE image is produced by high-pass energy filtered BSE. These have undergone only minimal inelastic interactions with a sample and therefore, carry high-resolution information, specific to sample geometry [4-7]. LLE imaging is difficult because the collected signal is produced not only by the most energetic, but also a small minority of backscattered electrons. Early work pointed to a potential measurement difference between the SE and the BSE signals [8], it was difficult to obtain the needed information because of the resulting poor signal-to-noise ratio and other instrument-specific geometric limitations. A measurement difference between the

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two signal modes was documented and was as large as 100 nm on the relatively large lines studied. Later, technology improvements facilitated the collection of conventional BSE and SE electron signal with a microchannel-plate electron detector. This approach was shown to be advantageous at low landing energies because of its improved geometry and signal collection capabilities [9]. In that early work, on different samples, collection and comparison of BSE and SE images of line structures again demonstrated that comparative threshold-based width measurements of the BSE images yielded values as much as 10 nm larger for the SE measurements than the BSE measurements on nominal 1.0 µm gold lines. Due to the enhanced emission of low-energy (typically less than 10 eV) electrons at the sides and corners, there are common circumstances in which the SE intensity increases more abruptly at an edge than the BSE intensity. If width assignments are based on an intensity threshold, as is often the case, SE images would then be interpreted as showing a wider, larger feature than the BSE image. It was anticipated that the LLE signal would provide results similar to the BSE results, but with higher edge fidelity. A Hitachi SU 8230 FESEM [10], equipped with an in-lens, high-angle energy-filtered BSE detector, was used to compare the SE, BSE and LLE signals for dimensional measurements of the NIST RM 8820 magnification calibration sample [11]. The design of the field emission SEM incorporating a new in-lens energy filtered detector improves the LLE and BSE signal-to-noise ratio and reduces the geometrical limitations of the early LLE detectors.

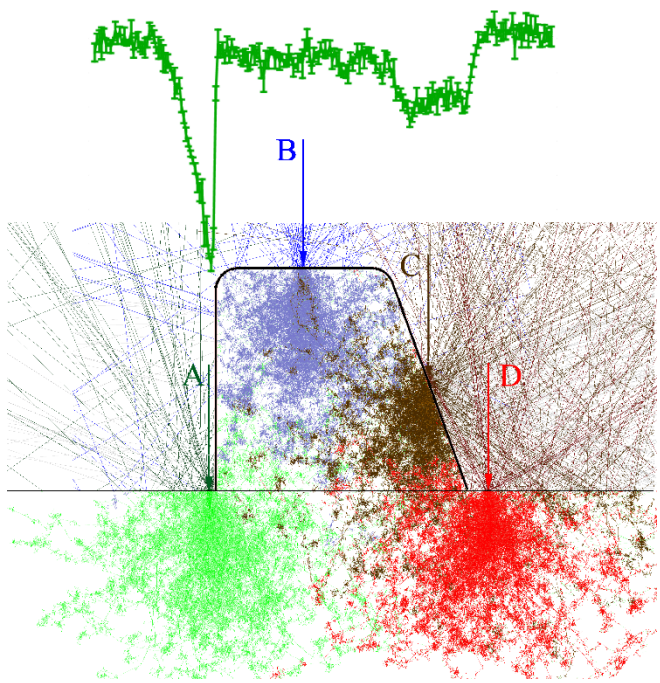

FIGURE 1. Model relationship of LLE signal to sample geometry. The upper (green) curve shows the modeled low-loss signal intensity from the line with near-vertical (left) and sloped wall (right) cross section shown in the lower portion. Electron trajectories at 4 landing positions, labeled A-D are superimposed on the sample geometry.

JMONSEL MODELING

In the second part of the work, we continued the analysis of the dimensional measurements using simulations with JMONSEL (Figure 1), an electron microscope simulator. JMONSEL indicated, as expected, 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 vs. the BSE or LLE signal's characteristic step). But this effect is too small to explain

the 10 nm to 100 nm discrepancies that had been observed in earlier work on the different samples [8, 9]. Additional modeling then indicated that those discrepancies could be explained by considering the much larger sidewall angles of the earlier samples, coupled with the different response of SE vs. BSE/LLE linescans and measurement algorithms to those wall angles. Clearly, serious measurement errors would be encountered in such cases if measurement algorithms were applied blindly without considering the underlying physics provided by applying model-based metrology.

CONCLUSION

In summary, this paper has: (1) demonstrated, for the first time, by simultaneous imaging that the previously observed bias between SE and LLE/BSE images is indeed real, not just an artifact of charging, drift, detector positioning, or some other instrument - or measurement-related 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 for highly accurate measurements, and (4) explained the previously observed mysterious size difference in the measurements with a simple phenomenological model and by a more complete Monte Carlo model.

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KEYWORDS

scanning electron microscope, SEM, JMONSEL, modeling, metrology, secondary, backscattered, low-loss electron