Accurate Nanometer-Scale Imaging and Measurements with SEM

Bradley N. Damazo, Bin Ming, Premsagar K. Purushotham, András E. Vladár and Michael T. Postek

Abstract—Scanning electron microscopes (SEMs) are incredibly versatile instruments for millimeter to nanometer scale imaging and measurements of size and shape. New methods to improve repeatability and accuracy have been implemented on the so-called Reference SEMs at the National Institute of Standards and Technology (NIST). These methods include: 1) very fast digital imaging and real-time corrective composition of SEM images, showing superiority over both traditional fast or slow image collection methods; 2) high-precision sample stage with laser interferometry, providing traceability and compensation for stage drift and vibration with sub-nanometer performance; and 3) contamination and charging mitigation through hydrogen and oxygen plasma cleaning. These new methods can be applied in other SEMs as well to realize quantitative scanning electron microscopy.

I. INTRODUCTION

Scanning electron microscopes (SEMs) are incredibly versatile instruments for millimeter to nanometer scale imaging and measurements of size and shape. However, performance shortcomings of today’s SEMs limit the ability to achieve excellent accuracy and repeatability, especially at high magnifications. With an ideal SEM, it would be possible to collect two images of the same sample and after subtraction get only random noise as the result. Current SEMs fail this test, because the collected images always contain various amounts of distortion due to a number of problems ranging from sample drift to charging. There are problems in the acquisition of the raw images as well as in their processing; the evaluation algorithms generally used to arrive at the results disregard the governing physics of the signal generation, and consequently report inaccurate values that are plagued with unpredictable biases.

New and better methods implemented on the so-called Reference SEMs at the National Institute of Standards and Technology (NIST) have now demonstrated excellent repeatability and accuracy. These Reference SEMs are used for the certification of scale calibration and other standards used in integrated circuit and nanotechnology development and production. This paper will discuss these accuracy enhancing methods: 1) very fast digital imaging and real-time corrective composition of SEM images developed for the Reference SEM, which have shown superiority over both traditional fast or slow image collection methods; 2) high-precision sample stage with laser interferometry, providing traceability and compensation for stage drift and vibration with sub-nanometer performance; and 3) contamination and charging mitigation through hydrogen and oxygen plasma cleaning. These new methods can be applied in other SEMs as well to realize quantitative scanning electron microscopy.

II. FAST IMAGING METHOD

The fast imaging method is comprised of compensation techniques to minimize the errors caused by the mechanical drift and vibration of the sample stage and the unwanted motions of the primary electron beam of the SEM [1]. This newly developed method allows for the acquisition of images and data suitable for meaningful comparisons of the results, and for validation of the agreement or pinpointing the reasons for possible disagreements between the designed and printed structures. The results of this comparison can serve as the basis for further developments and improvements both in the SEM instrumentation and in the measuring methods. It is likely that these improvements will lead to smaller measurement uncertainties and faster measurements simultaneously.

Due to the nature of the sample stage, essentially all SEM image collection and measurement is performed on targets that are moving at the nanometer scale. Rarely does an opportunity exist for a measurement to occur without problematic drift or vibrations, which create measurement inaccuracy, especially for the measurements of very small, sub-100-nm structures. Traditional measurement techniques average a number of samples to reduce the effects of noise, but this method is susceptible to pitfalls, including using too many samples which distorts the image and reduces its clarity, as well as arriving at a specific location multiple times from different directions which varies results between samples. These tendencies lead to the inability to obtain two images on the same location multiple times from different directions which varies results between samples. These tendencies lead to the inability to obtain two images on the same location multiple times from different directions which varies results between samples. The new NIST method effectively eliminates problems associated with stage and beam drift, and vibration.
Shown in Fig. 1 is the clear advantage of the new method. Both results are coming from the same raw set of fast image frames. At the top is a single fast image acquired in 11 μs frame time (50 ns pixel dwell time).

![Image](image1.png)

Fig. 1. Single image acquired in 11 μs frame time (50 ns pixel dwell time) (top). Traditionally averaged 70 images (middle). The same 70 images averaged with the new, adaptive method (bottom). The field-of-views are 4.6 μm.

The traditionally-averaged 70 images results in the image in the middle. The same 70 images averaged with the new, adaptive method is shown at the bottom. The traditional method used in today’s SEMs simply adds the images together and calculates an average; this results in a blurred image with many details lost. The new NIST method uses the 70 raw images but aligns them with each other with sub-pixel accuracy before they are added together. The results show a striking difference. Due to the ever-present small-scale vibrations and drifts, all single image frames are collected over a somewhat different location of the sample. Traditional averaging leads to a blurred final image, but the new method results in a much better fidelity final image. It is important to point out while both old and new methods use exactly the same set of images; the result of the traditional averaging is blurred by the amount of the unwanted drift and other motions. At the high magnifications indispensable for imaging present and future state-of-the art, small structures are very visible and can easily be resolved to a 1 nm or so during the short period of time when the set of raw images is collected.

This new imaging method has further advantages also: it works better for edge roughness measurements where the high frequency image components are critical, exactly those that are washed out in the traditional fast-imaging averaging method. It can improve the resolution of the SEM when blurring due the sample stage drift is the limiting factor to the resolution.

### III. Contamination Mitigation

Contamination, the bane of electron microscopy and microanalysis [2], has been with us since the infancy of electron microscopy. It manifests itself as a gradual buildup of material on the surface of the sample and concentrates itself in the immediate vicinity of the electron probe. This deposit not only obscures the area of the specimen, but also adversely affects the entire range of micro-analytical experiments which can be conducted on that sample. An investigation into using a new hydrogen plasma cleaning method as a way to rid samples of contamination shows that contamination is prevented and/or at least reduced to an acceptable level.

There are two basic sources of contamination: the instrument environment itself and material transported by the sample (or operator) into the instrument. In the past, the principle source of contamination could be attributed to the relatively poor and dirty vacuum. This is no longer true in the modern instruments. Careful redesign of the equipment has minimized or even eliminated the vacuum system as the primary source of contamination [2]. Various attempts to cure the problems due to contamination may be found in reviews by Hren [3] and Postek [4]. While the contamination due to the instrument environment can be successfully dealt with using plasma cleaning [5-7], the sample borne contamination still presents a challenge. Also, the development of high brightness electron sources such as LaB₆ and field emission has elevated the problem of specimen borne contamination [2].

Contamination mitigation in SEMs is a daily practice in our laboratories. The SEM chambers are routinely cleaned using oxygen (room air) plasma from an automatic plasma
cleaning and vacuum monitoring system. The plasma cleaner has a built-in power supply to drive the plasma-generation head. The head is mounted in the SEM chamber in an available port on the side wall of the chamber.

The controller can be configured to automatically control the entire cleaning process. Cleaning is carried out at much higher pressures than the normal operating pressures of the SEM. Depending on the type of SEM, the cleaning cycle starts by separating the sample chamber from the turbo-molecular pump, or by using gas flush mode. The plasma gas (in our case room air) is leaked into the sample chamber and the pressure stabilized at its optimal value of 80 Pa. At this stage, the plasma cleaner applies a high frequency alternating current potential to generate gentle plasma for cleaning. The cleaning time depends on the degree of contamination. To ensure complete cleaning, we typically use 14 to 18 hours of plasma cleaning time [5,6].

This same cleaning method is often applied to the samples as well, however, there is not one single general solution to clean all types of samples. Each cleaning technique is sample specific and each sample being cleaned can react differently to the cleaning process. For example, some commercial plasma cleaners are harsh on silicon wafers and gold-on-carbon samples. Although chemical solutions are successful in cleaning silicon wafers, they cannot be used for samples such as gold on carbon and tin balls [6].

Sample borne contamination remains a challenge. A highly contaminated photomask sample, as shown in Fig. 2 and Fig. 3, was loaded into the SEM and cleaned in hydrogen plasma at 10 watts for 25 hours. After cleaning, the sample was tested for contamination. Images before and after the contamination test are shown in Fig. 4 and Fig. 5 respectively. As shown, the hydrogen plasma is very effective in cleaning the sample. Further tests show that at 50 watts for a period of 2.5 hour, contamination has been eliminated. It was found that hydrogen plasma is very effective in cleaning most samples, including sensitive samples such as reflective surfaces, and that by increasing the plasma power the time for cleaning can be reduced drastically.

IV. LASER INTERFEROMETRY

Incorporated into the NIST Reference SEMs are two-axis, high-precision sample stages with laser interferometry, providing measurement traceability to the definition of the meter and compensation for stage drift and vibration with sub-nanometer performance. This setup, shown in Fig. 6 and Fig. 7, allows for large (300 mm) sample capability, an optimized 4 mm working distance, and a 100 mm by 100 mm travel range. Large wafers and photomasks samples fit within the SEM chamber. Fiber-optics deliver the laser light directly to the measurement axes; no beam splitters, benders and adjustable mounts are needed, which reduces the optical path complexity, thermal drift and footprint.

Fig. 2. Photomask sample before plasma cleaning and prior to beam exposure.

Fig. 3. Photomask sample after 10 minutes of beam exposure in central area.

Fig. 4. Photomask sample after 25 hour hydrogen plasma cleaning prior to beam exposure.
The interferometer system provides sub-nanometer non-linearity and a resolution of 38 pm at velocities up to 1 m/s. This enables high band-width, real-time sample stage position measurement with accuracy levels of 1 ppm. The stage has extremely smooth motion with a 1.24 nm stepping increment. The hardware and software is capable of collecting position data at rates at 100 MHz and with a position resolution of 38 pm. A pixel sorting algorithm developed takes advantage of the high throughput data collection of stage position to sort image data based on actual position to minimize the errors caused by the mechanical drift and vibration of the sample stage.

V. CONCLUSION

This paper discusses new methods for enhancing the performance and accuracy of SEMs. These new methods can be used to realize quantitative scanning electron microscopy and range from simple and economical to complex and costly to implement. Future work will focus on improving these methods to lower the measurement uncertainty needed for nanometer scale metrology.

REFERENCES