Why Magnification is Irrelevant in Modern Scanning Electron Microscopes

Application Note

Introduction

From its earliest inception, the Scanning Electron Microscope (SEM) has been widely used as an imaging tool. It produces images by raster scanning an electron beam over a region of interest on a sample. The SEM allows for the visualization of features too small to resolve by the unaided human eye. Early SEM images were analog images which were preserved on 4 x 5 Polaroid or Kodak film. The proliferation of high speed digital electronics has revolutionized SEM, whereby everything from digital scan control to digital acquisition, to archival of digital images is not only common but expected by default on modern SEMs. Since this digital revolution, digital images are displayed on everything from desktop computer monitors to large projection screens and printed at various pixel densities on a wide variety of paper sizes.

Once the image is projected or reproduced, the size of the image, and therefore the magnification depends on the scale at which the image is viewed. Hence, the original magnification value when the image was collected is irrelevant at best and very misleading at worst. By comparison, another raster scanning microscope which produces digital images, the Atomic Force Microscope (AFM), addresses the issues of magnification by referencing the scan size opposed to magnification. For any digital image, the scale of the image, i.e. nanometers per pixel for microscopes or kilometers per pixel for satellite images, is a fundamental property not the magnification. In addition to the image scale other contributing factors to what can be visualized and measured are empty magnification and pixel resolution.

With AFM which has been a digital microscope since its introduction, magnification is a non-issue because the images are always referenced to the scan size (the actual area on the sample that was scanned). Scan size is a very useful, display-independent way to view and analyze digital images. Given the many advantages digital images and their widespread use in microscopy, there is a compelling need to standardize on scan size when discussing the scale of features observed in digital images.

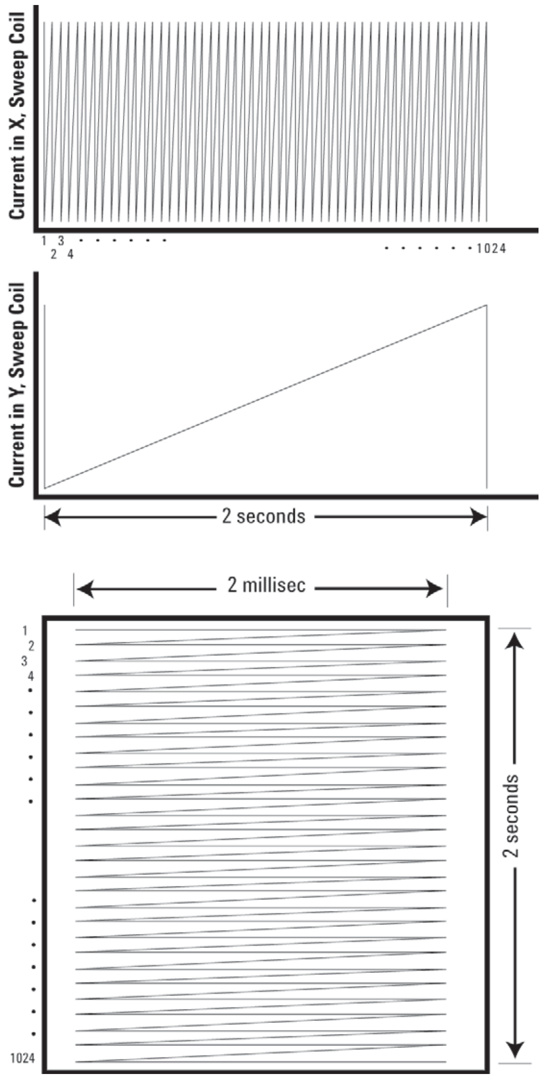

Figure 1. Analog scan generation to create a 1024 x 1024 image.

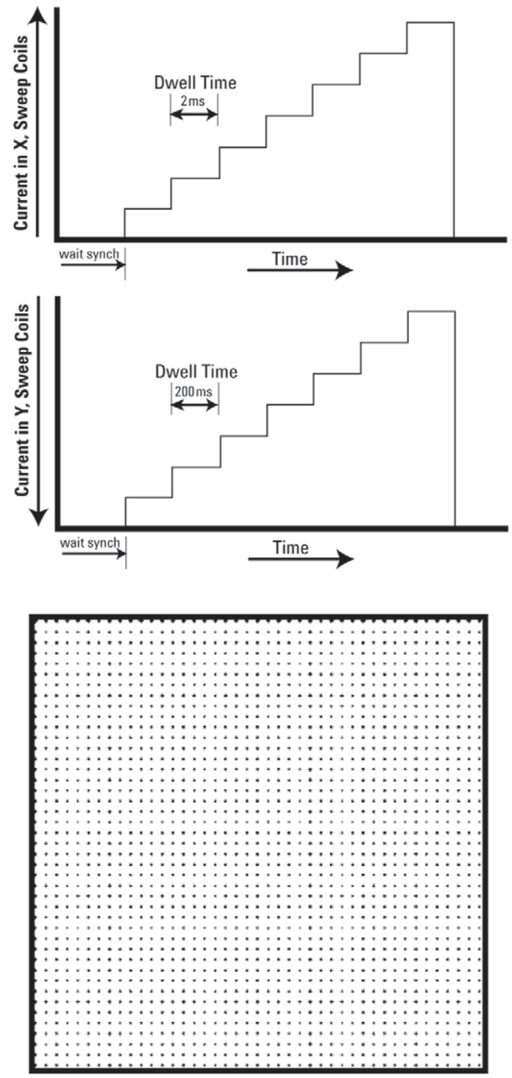

Figure 2. Digital scan generation to create a 1024 x 1024 image.

SEM Imaging the Analog Way

With analog SEMs, imaging usually entailed Polaroid film or several hours in the darkroom developing Kodak film. It also connoted analog electronics that generated scan waveforms and synchronization of the user display with an internal CRT (Cathode Ray Tube monitor) from which the photograph was exposed (Figure 1). The synchronization involved sending the same analog scan generation signal to both the electron beam and the CRT. The intensity signal from the detector was sent to the CRT as the brightness control signal.

The magnification was well controlled because the ratio of film size to internal CRT screen size was fixed. Therefore the original magnification value was directly linked to the photograph. With the advent of digital imaging and the variety of display formats, this link has been broken.

SEM Imaging the Digital Way

With digital SEMs, like the Agilent 8500 FE-SEM, most of the signals are handled digitally with analog to digital converters (ADC), digital to analog converters (DAC), and field programmable gate arrays (FPGA) in conjunction with electrostatic optics. With this arrangement the scan waveform is generated digitally, i.e. pixel by pixel in incremental steps, and the image is collected and displayed digitally in the same pixel by pixel fashion (Figure 2).

An advantage with digital image data is the intensity data can easily be normalized for example, with the typical 8 bit gray scale SEM image, the darkest pixel is set to 0 and the brightest is set to 255. Normalization is sometimes referred to as ABC (auto brightness and contrast) and it allows for convenient storage and

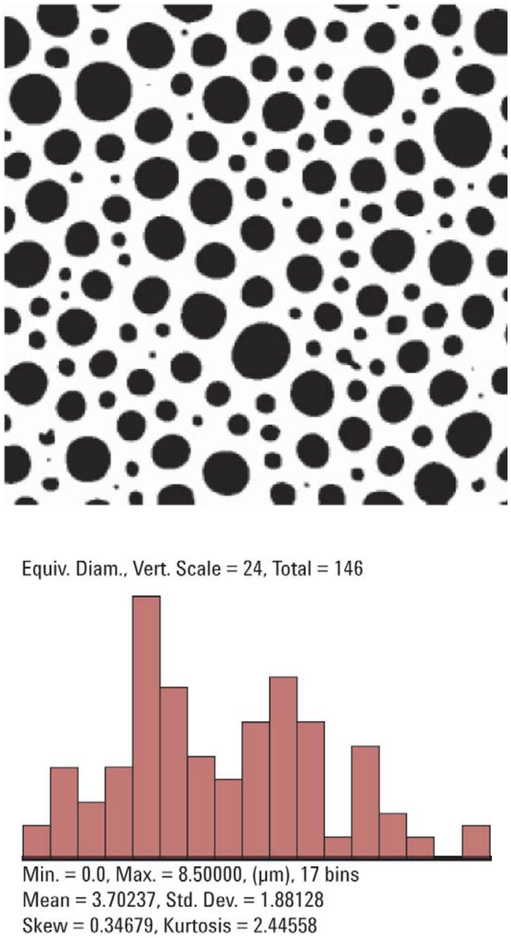

Figure 3. Particle size distribution calculation on threshold image.

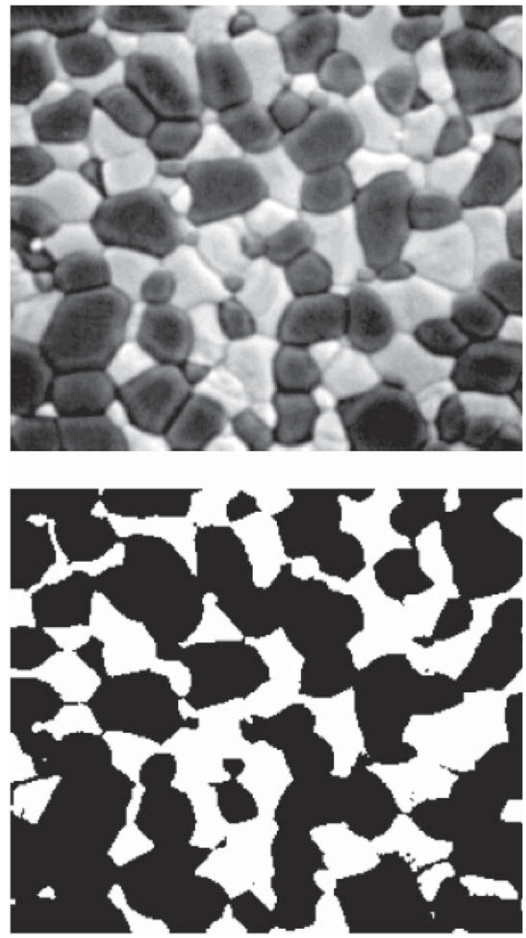

Figure 4. Image analysis showing darker phase comprises 60% of the sample.

display of the data on the computer monitor without the need to worry about film speed as in analog SEM images. However, with normalized digital images it is not appropriate to compare absolute image brightness between images, as was done with controlled exposure photographs.

With the scan size, and therefore the scale of the image known, digital image analysis or processing affords increasing sophistication in what can be analyzed in the collected image data. There are many sophisticated software programs for manipulating and analyzing digital images. With digital images, analyses like particle size distribution (Figure 3), average fiber length, or area ratio of one phase to another in a multicomponent system can be done easily (Figure 4).

Magnification vs. Resolution

SEM manufacturers each have their own samples and methods for determining instrument resolution. There is no internationally accepted standard for determining instrument resolution. Independent of how instrument resolution is determined in practice, the electron beam shape and nominal diameter ultimately define the instrument's true resolution. Measuring the electron beam shape in practice is very difficult and tedious, thus the many different manufacturers' methods for estimating instrument resolution.

Although electron beam diameter is the determining factor of resolution in the ideal case, in practice there are the following subordinate factors, sample preparation and surface roughness, atomic mass and chemical composition of the sample, beam intensity, accelerating voltage, scanning speed, working distance, aberrations and hysteresis in the

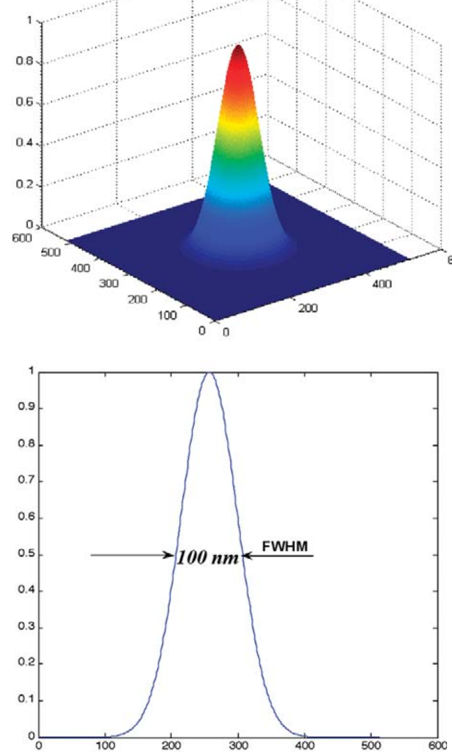

Figure 5. Computer simulation of a 100 nm electron beam.

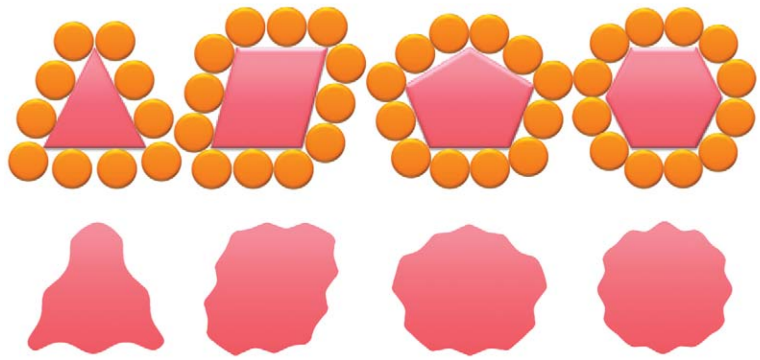

Figure 6. Computer simulation of a 100 nm electron beam scanning various geometric shapes and their resulting image profiles.

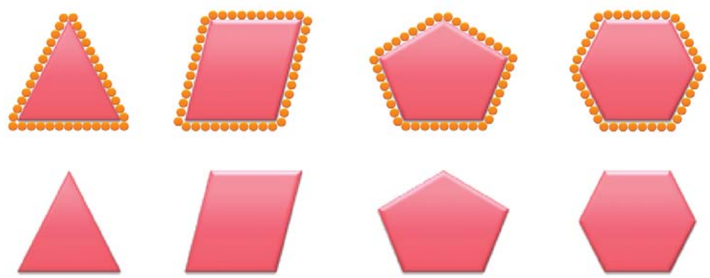

Figure 7. Computer simulation of a 10 nm electron beam scanning various geometric shapes and their resulting image profiles.

electron optics, and interaction volume of the electron beam with the sample. Because the electron beam diameter is the dominant factor, for the examples below the contribution of the subordinate factors were assumed to be negligible.

Illustration of how electron beam shape influences resolution can be facilitated by computer simulation. Figure 5 illustrates an ideal Gaussian beam profile, while Figure 6, Figure 7 show how the electron beam size influence resolution. In reality the electron beam generated in an SEM is rarely Gaussian, however to facilitate the demonstration of the effects of spot size a Gaussian approximation is used.

In Figure 6 we see how a 100 nm electron beam interacts with a triangle, parallelogram, pentagon, and a hexagon and the representation of how the shapes would nominally be represented on the computer monitor. With a much smaller, 10 nm electron beam interacting with the same geometric shapes we see in Figure 7 that the resulting images give a much more accurate representation of the original shape.

Pixel Resolution

For the analog SEM the images were recorded on film, so the exposure and grain size of the film determined the smallest features which could be imaged. For the digital SEM pixel resolution determines the smallest features which could be imaged. Each pixel in a digital image contains just one element of information, i.e. a gray level from 0 (black) to 255 (white). The smallest feature which can be resolved is therefore linked to the pixel size, as seen in Figures 8–13**.**

In Figure 8 it is difficult to discern any sample features. As the pixel resolution, pixel density per area scanned on the sample, is increased to even a modest number, 84 x 84 pixels in Figure 10, the gold islands on carbon test sample can now be recognized, but not sufficiently for making accurate measurements. Ultimately the best image, especially for making dimensional measurements, is seen in Figure 13 where the pixel density is 2048 x 2048.

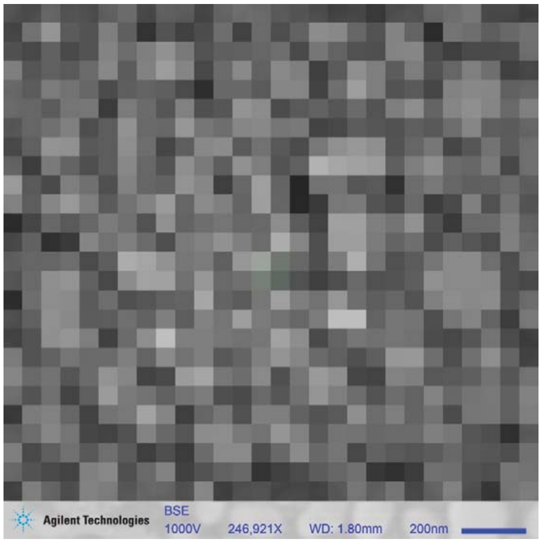

Figure 8. SEM image defined by 28 x 28 pixels.

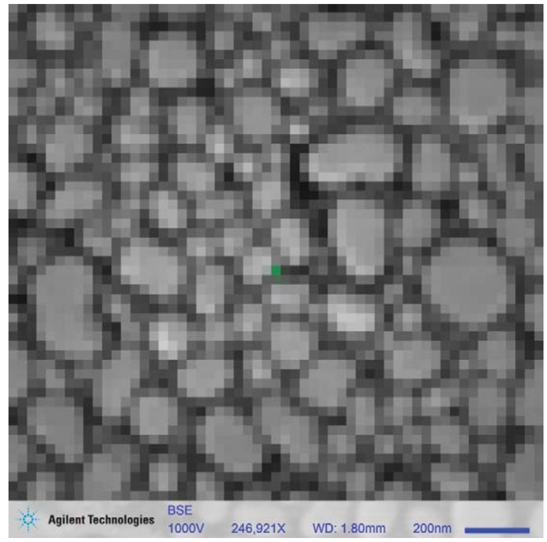

Figure 9. SEM image defined by 56 x 56 pixels.

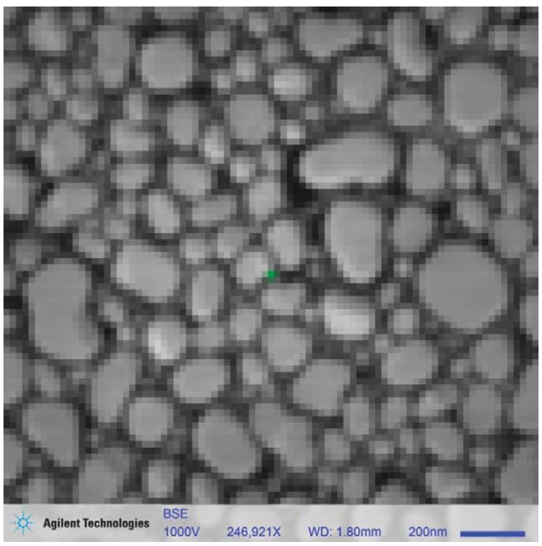

Figure 10. SEM image defined by 84 x 84 pixels.

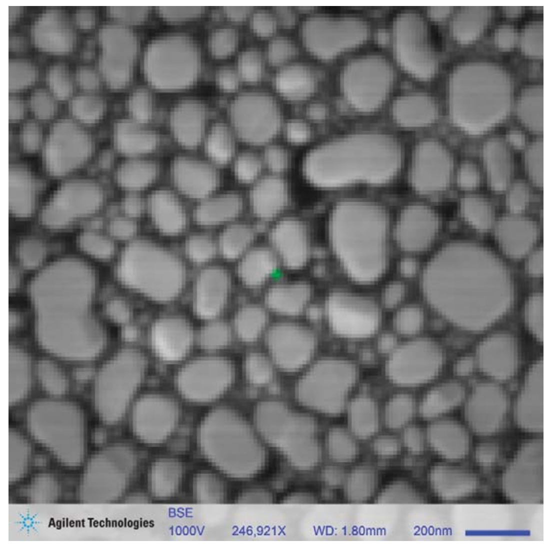

Figure 11. SEM image defined by 112 x 112 pixels.

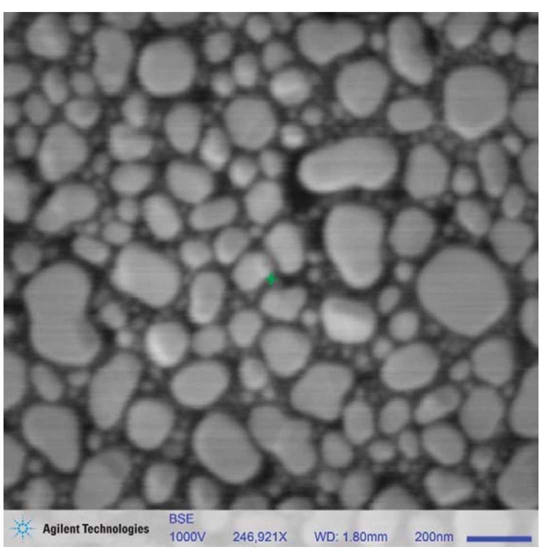

Figure 12. SEM image defined by 140 x 140 pixels.

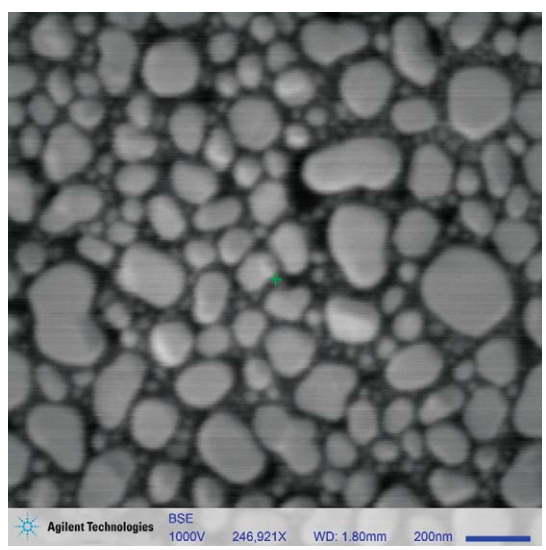

Figure 13. SEM image defined by 2048 x 2048 pixels.

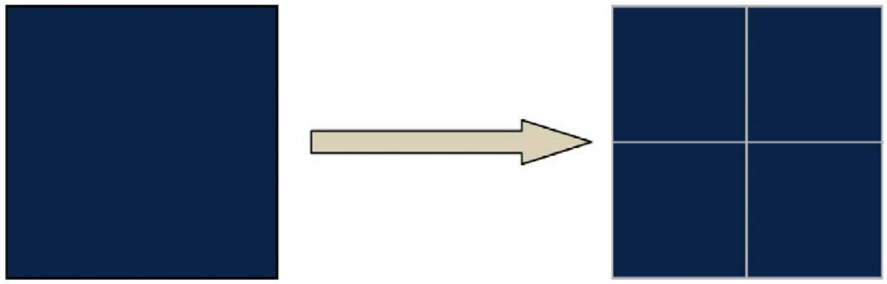

Figure 14. Sketch of Empty Magnification. If an object is "magnified" beyond the resolution based on the electron beam shape it results in the equivalent to digital zoom, i.e. 1 pixel of significant data is divided into 4 identical pixels.

Empty Magnification

The artifact of empty magnification is present in both analog and digital SEMs. The reasoning behind the term empty magnification is that the magnification can be increased such that it exceeds the resolution based on the electron beam size; therefore the image is empty of significant information. With the digital SEM, although the increase in pixel resolution improves the image, it should be noted that the ultimate resolution is defined by the shape of the electron beam, not the number of pixels. If we add a meaningful size scale to the geometric shapes in Figure 6, Figure 7, we see that no matter what instrument magnification or pixel density we use, the images generated with the 100 nm electron beam will not accurately reproduce the original shapes.

Another way of demonstrating empty magnification is shown in Figure 14, where the simulated object on the left is the smallest feature that can be resolved and then either the instrument magnification is increased or the pixel density is increased. The result on the right side of Figure 14, no new information is generated 1 unit of significant data is divided into 4 identical units. The result is the information content is the same, there are just more pixels. The same principal is true for increasing the instrument magnification such that the electron beam becomes large compared to the pixel or feature size.

Therefore just because a SEM can be set to 1,000,000x magnification does not mean the resulting image scale of 0.2 nm per pixel translates into usable magnification. As seen in Figure 6, with a 100 nm electron beam size it does not matter how many pixels are used or how small a scan size is used the resulting image does not accurately represent the original sample. However, if the electron beam is small, as seen in Figure 7, increasing the pixel resolution can be helpful in visualizing small features, i.e. the corners of the triangle shape. This is similar to digital zoom on a digital camera.

What is Relevant: Scan Size and Probe Size

With another common microscope, the AFM, magnification is a non-issue because the images are always referenced to the scan size. Because the AFM is a physical contact, or intermittent contact, the probe size or more specifically the probe tip radius of curvature determines the practical resolution and therefore the smallest relevant scan size. This analogy of scan size and probe size is well suited to SEM inasmuch as the electron beam's size and scan size, or image scale, determine the smallest relevant scan size. The link to the original instrument magnification is now severed because it has no practical meaning for digital images. Using the image scan size is the most relevant way to compare digital images from these microscopes.

Agilent 8500 FE-SEM

For the Agilent 8500 FE-SEM the electron beam is nominally 10 nm and the pixel size on a standard computer monitor is 200 µm with 1920 x 1080 pixels yielding a 3 µm scan size for a 1024 x 1024 image. The resolution limit for the unaided human eye is approximately 200 µm. However the instrument can collect images at pixel densities up to 2048 x 2048. So in terms of magnification a 512 x 512 pixel image of a 3 µm scan size would be 32,500x instrument magnification, the corresponding magnification for a 1024 x 1024 pixel image would

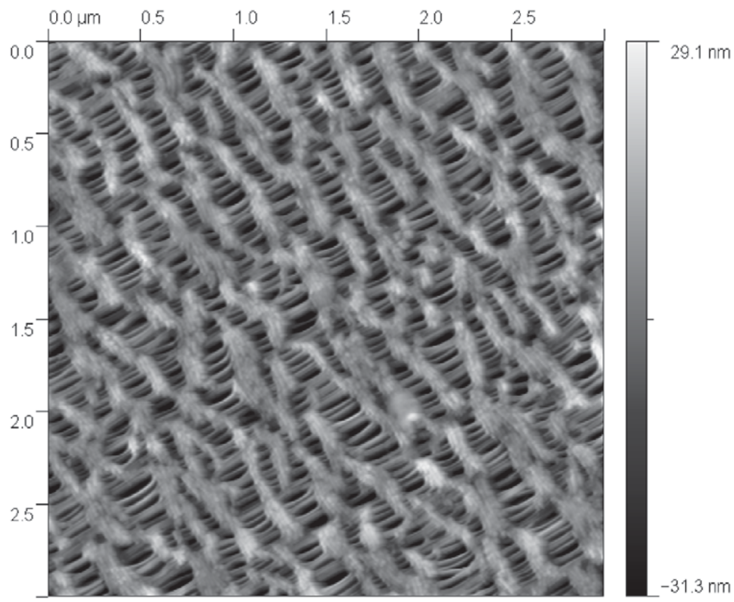

Figure 15. AC mode AFM image of Celgard polymer 3 µm x 3 µm scan size. Imaged on Agilent 5500 AFM.

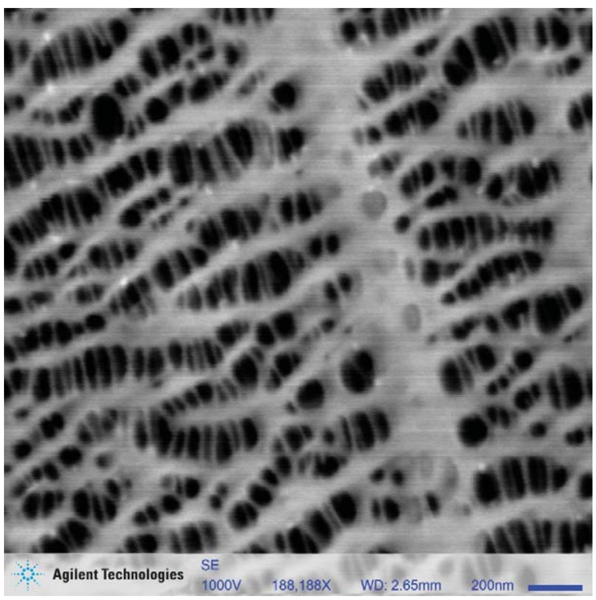

Figure 16. SEM image of Celgard polymer 2.5 µm x 2.5 µm scan size. Imaged on Agilent 8500 FE-SEM.

be 65,000x, and the corresponding magnification for a 2048 x 2048 pixel image would be 130,000x. If the 3 µm scan size is used to describe the digital image it does not matter how the image is viewed or printed dimensionally; it represents the 3 µm x 3 µm area of the sample surface that was scanned by the electron beam. By using scan size in Figure 15 and Figure 16 the image collected on the AFM can be compared to the image collected on the SEM as well as any other digital image of Celgard of similar scan size. However, if instrument magnification was used it would be difficult to make direct comparisons.

Conclusions

In modern SEMs most of the signals are handled digitally and for digital images, the scale of the image is the fundamental property not the magnification. Therefore, the original "magnification" value when the image was collected is irrelevant at best and very misleading at worst. With commercial SEM instruments, if scan size as opposed to magnification was used it would readily allow side by side comparison of images from different instruments as well as easier comparison to AFM images. With the scan size, and therefore the scale of the image known, digital image processing delivers increasing sophistication in what can be analyzed in the collected image data.

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