Can We Get 3D CD Metrology Right?

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ABSTRACT

Our world is three-dimensional, and so are the integrated circuits (ICs), they have always been. In the past, for a long time, we have been very fortunate, because it was enough to measure a simple critical dimension (CD), the width of the resist line, to keep IC production under acceptable control. This requirement has changed in the last few years to contour and now to three-dimensional measurements. Optical lithography is printing photoresist features that are significantly smaller than the wavelength of the light used, and therefore it is indispensable to use optical proximity correction (OPC) methods. This includes modeling and compensation for various errors in the lithography process down to sub-nanometer, essentially atomic levels. The process has to rely on sophisticated and complex simulations and on accurate and highly repeatable dimensional metrology. The necessary dimensional metrology is beyond the conventional one-dimensional line width measurements, and must include two - and three-dimensional measurements of the contours and shapes of structures. Contour metrology needs accurate and highly repeatable measurements on sets and individual OPC structures, for which the critical dimension measurement scanning electron microscope (CD-SEM) is the key metrology tool. Three-dimensional (3D) metrology is now indispensable for IC technology, but current metrology tools and methods cannot fulfill the requirements. We believe that with the implementation of new methods it is feasible to develop 3D metrology that will well serve IC production, even on structures in the few nanometer-size range.

Keywords: three dimensional, 3D, contour metrology, critical dimension, atomic force, scanning electron microscope, AFM, SEM

1. INTRODUCTION

Our world is three-dimensional, and so are the integrated circuits (ICs), they have always been. In the past, for a long time, we've been very fortunate, because it was enough to measure a simple critical dimension (CD), the width of the resist line, to keep IC production under acceptable control. In reality, we have never really done CD metrology right, i.e., by no means were the dimensional measurements fully optimized. We used much less sophisticated methods for measurements than for crafting of the integrated circuits, which was understandable, but not advantageous. We used and still use mostly arbitrary edge algorithms; therefore we have to deal with unpredictable biases (systematic errors) due to the neglect of the 3rd dimension, i.e., the profile shape of the resist structures. Also there was little regard to the use of the best principles of measurement science (metrology) and sophisticated statistical methods. Dimensional metrology just sort of drifted through time; there was never a concerted effort to use metrology, which is based on, and fully taking advantage of, the best physics and statistics can offer. It is likely that those who -some time ago- addressed metrology, as "it does not add value" have done a great disservice to this industry.[1,3]

Amazingly, things went quite well, even if we kept marking red almost every current and future entry in the International Technology Roadmap for Semiconductors (ITRS) Metrology section.[4] Dimensional metrology of ICs played an indispensable part of the phenomenal success of this industry; it kept up with the advances of IC production, and likely will continue to do so, but now we have to develop much better measurement methods than in

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Metrology, Inspection, and Process Control for Microlithography XXVI, edited by Alexander Starikov,
Proc. of SPIE Vol. 8324, 832402 · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.916537

the past. We have to deal with real 3D structures, which are much smaller than ever before, so, essentially every atomic layer counts (Si atoms sit on (111) crystal planes with approximately 0.3 nm spacing), and we need many more measurements for statistical validity.

Both imaging (e.g., SEM) and non-imaging measurement tools and methods (e.g., scatterometry) are needed for proper characterization of process mean and variation. There is no single method that can deliver all needed information, therefore we must use several methods and take advantage of the most useful information they provide, i.e., combined metrology. We have to take advantage of the high-quality information we can get from a slower, more accurate method when we use a faster, less accurate one. We have to optimize not just each measurement method, but the best combination of those that can provide the needed information. We need physics-based models to optimize data acquisition and for the proper interpretation of the results, and we have to do all this so that we can maximize the confidence in our results using the best statistical methods with the least amount of time and resources.

In short, there is no other way around it: we must develop IC dimensional measurement science, i.e., metrology in 3D. There are metrologists, who for many years, have been talking about accuracy, comprehensive measurement uncertainty assessment and statements, model-based measurements, and about all these done with more than one metrology tool, while using sophisticated physics and statistical methods that give seemingly unpleasant but correct results. They have made everybody to face reality.[5,6] All these understandably bring up a lot of questions. Do those metrology ideas and solutions make concrete sense, and are they practical? Would those methods and ideas yield better results? Provided a lot was spent on them, would the payback be worth it? If yes, are there ways to actually do them, quickly and economically?

Some examples can shed light into these unclear matters. There are physical reasons why line scans of images and scatterometry signals look how they look. Using wrong assumptions and disregarding the underlying physics in interpreting them will lead to wrong results, wasting time and money. The solution is to use sound physics and model-based methods to minimize unpredictable biases.[7] Similarly, scientific edge roughness measurements account for noise that otherwise causes bias.[8,9] Two-dimensional measurements also benefit from doing them in scientifically sound ways. These include highly repeatable, accurate and optimized 2D contour measurement methods, which optimize raw image collection, the beam scanning area and scheme and the image processing methods, and use model-based methods to arrive at the results. These models must be 3D, otherwise, just like in the case of linewidth measurements, unpredictable biases can appear, which leads to loss of control.

2. NEED FOR OPTIMIZED TWO- AND THREE-DIMENSIONAL METROLOGY

To ensure optimized performance in 2D and 3D, metrology has to be done with the firm knowledge that we know that we measure things correctly. These contours allow for better correlation among CAD and SEM and aerial images, and optimized metrology that delivers superior results. Without such methods, one cannot be sure whether the right kind and right amount of information is acquired, so likely it is too much (loss of throughput) or not the right kind, or not sufficient (loss of control due to increased noise). Currently the industry CD-SEMs use less-then-optimal types of beam scanning and image interpretation methods, so throughput, accuracy and repeatability are all far from optimal.

Contour metrology is about 2D measurements where some of the difficulties of linewidth metrology are greatly exacerbated. Thus they are inherently 3D measurements, even if generally only a contour is extracted from the images. Today, instead of measurements done on the critical areas of the features, whole images are collected, only parts of which are used to generate the needed information. This bogs down contour measurements. Measurements must be carried out as quickly as it is possible, because the throughput, the cost of ownership and the quality of the acquired data depend on the speed of data acquisition. Essentially all SEM measurements take place on a moving target, so the effects of drift and vibration must be minimized.

Today there are methods, which deliver significantly better contour information at a much faster speed without loss of throughput.

One of the problems with current SEM-based contour metrology is in generating accurate two-dimensional measurement results. Unfortunately, today's SEMs are not optimized in their scanning circuitry to make 2D measurements well. Figure 1 illustrates this problem on an L-shape resist pattern. It takes much longer to collect the relevant information on horizontal than on vertical lines, which causes different drift-related errors in X and Y direction measurements that increase the inaccuracies arising from improper scale calibration in X and Y direction and other geometric distortions.

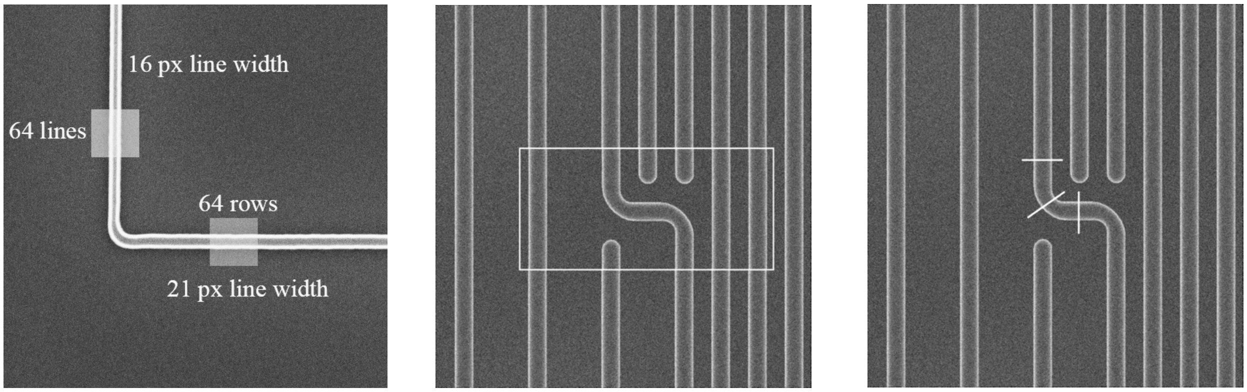

Figure 1. Left: due to the horizontal raster scan, it takes much longer to collect the linewidth information on horizontal than on vertical lines, which causes different drift-related errors. Center: the portion of the image within the marked rectangle contains all information needed for contour measurements. Right: the fastest way to collect width information is perpendicular to the line, so the scan should be optimized to the local shape of the sample as depicted.

Figure 1 left shows conventional linewidth measurements in areas where the line is vertical and horizontal. The width is assigned based on 64 pixel × 64 pixel regions at the measurement sites within the larger 512 pixel × 512 pixel image. If τ is the pixel dwell time, the total time to acquire the data within these measurement windows is in both cases $64 \times 512\tau$ (plus some retrace and sync time at the end of each linescan). Linewidth is the difference between the locations of two edges. For the (16 pixel wide) vertical line, the elapsed time between measuring the left edge and the right one in each linescan is 16τ, so the amount of drift error is the drift rate times 16τ. For the (21 pixel wide) horizontal line, 21 *linescans* are measured before both edges are available. The corresponding drift is the drift rate times $21 \times (512\tau$ + retrace and sync). Both measurements involve much wasted time. In the case of the horizontal line, much of the waste happens within the interval between determining the positions of the two edges. This results in at least two, and perhaps as much as 3, orders of magnitude more drift error.

Obviously, it is better to minimize the time the beam traverses the line to minimize drift-related errors in X and Y direction measurements. Currently the best we can do is make sure that lines are lined up to be vertical, but there is a better solution.

Another problem with current contour measurements and the beam scanning method is that a whole image is acquired instead of only those areas that are actually needed to carry out of the measurements. These actual areas are illustrated also in Figure 1 (center), as a white box, and as the 64 rows wide and 64 lines tall measurements boxes in Figure 1 left. This, i.e., acquiring unnecessary image portions of the sample means significant loss of throughput.

Yet another problem with SEMs is lack of truly excellent repeatability. With an ideal SEM it would be possible to collect two images of any sample that, after subtraction, would result in random noise only. All current SEMs fail this test, because the collected images always contain various amounts of the results of disturbances ranging from sample drift, and vibration, to charging and contamination. The traditional slow-scan image acquisition is the worst method, because it integrates the drift and vibration into a single frame with which very little can be done in compensation of these detrimental effects. Slow-scan imaging is also more prone to sample charging, so for CD-SEM applications it is not used. Instead, multiple faster frames are averaged, which in the generally implemented, traditional way is better, but still not the best method.

Figure 2 illustrates that it is possible to simulate SEM images of contour metrology targets from the computer aided design (CAD) version of the patterns. The image on the left is the simple average of multiple simulated fast (and therefore noisy) image frames shown in the middle. In this case, the NIST analog SEM image modeling method was used.[10] The simulated fast and noisy single-frame SEM images were generated with a small, typical amount of drift, which, after simple averaging, results in a somewhat blurry image, similar to characteristic current CD-SEM imagery.

Figure 2 on the right shows that even closer similarity to real SEM images can be achieved with rigorous Monte Carlo simulation. This method, starting with CAD patterns, can also generate simulated SEM images. The image generation is much slower, but more accurate as it accounts for darkening of the bottom of 3D structures when the closeness of the lines causes a proximity effect. If necessary, these more accurate images can also incorporate imperfections of the SEM imagery. The commonly used simple image averaging, in the presence of drift, inevitably leads to blurry images. NIST has worked out an excellent method to significantly improve the situation and be able to collect images without the detrimental blur arising from adding fast image frames in the traditional way.[11]

This drift-corrected image composition (DCIC) method was implemented as public domain software and is available for free. It has been tested with both simulated and real SEM images. It can yield significantly more accurate images than any of the traditional imaging method. This type of image acquisition is indispensable for nanometer-scale metrology, where the conventional "slow-scan" and "fast-scan" techniques yield images that are often distorted or blurry beyond usefulness. The DCIC works with frames that are taken as quickly as the capabilities of the instrument permit. Physical (electromagnetic and mechanical) drift causes displacement among image frames. This displacement is searched for with cross-correlation in the Fourier domain. Since the quickly acquired frames are usually extensively noisy, a noise reduction is also part of the DCIC technique.

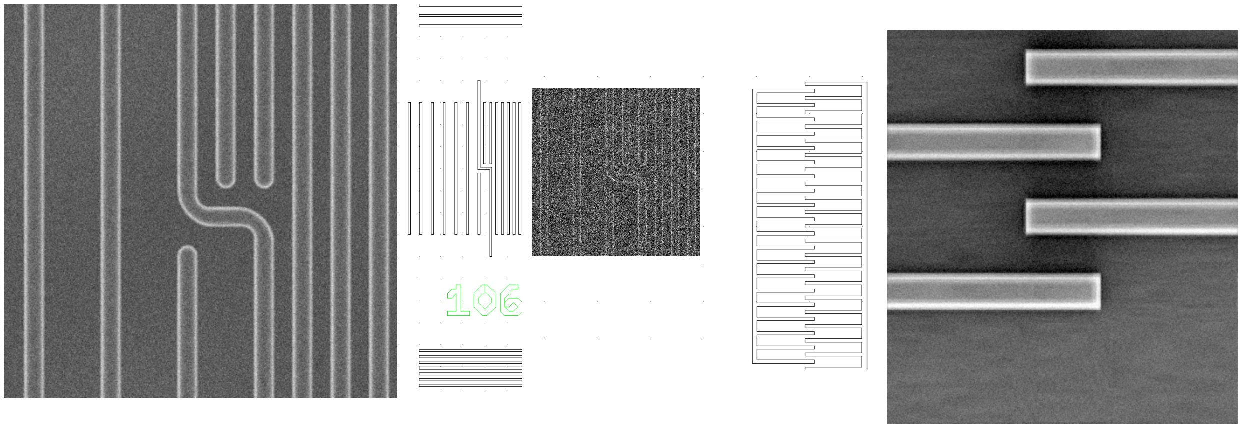

Figure 2. Left: typical fast analog simulated image generated by using CAD, similarly the accurate Monte Carlo modeled image is generated from CAD, but it also accounts for darkening when the closeness of the lines causes a proximity effect (right). 30 nm wide lines.

Figure 3 shows the clear advantage of the DCIC method. Both results are coming from the exact same set of fast image frames, similar to the single frame image on the left. These were acquired in approximately 11 ms frame time (50 ns pixel dwell time). 70 frames averaged using the conventional method result in the image in the middle. The average, with the DCIC, adaptive method, of the same 70 images is shown on the right. The traditional method used in today's SEMs simply adds the images together and calculates an average, which is blurred, and therefore many fine details are lost. The new NIST method uses the same raw images but aligns them 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 raw image data, the result of the traditional averaging is blurred by the compensated unwanted drift and other motions. Compensation for the effect of these at the high magnifications is indispensable for current and future state-of-the-art imaging and dimensional metrology.

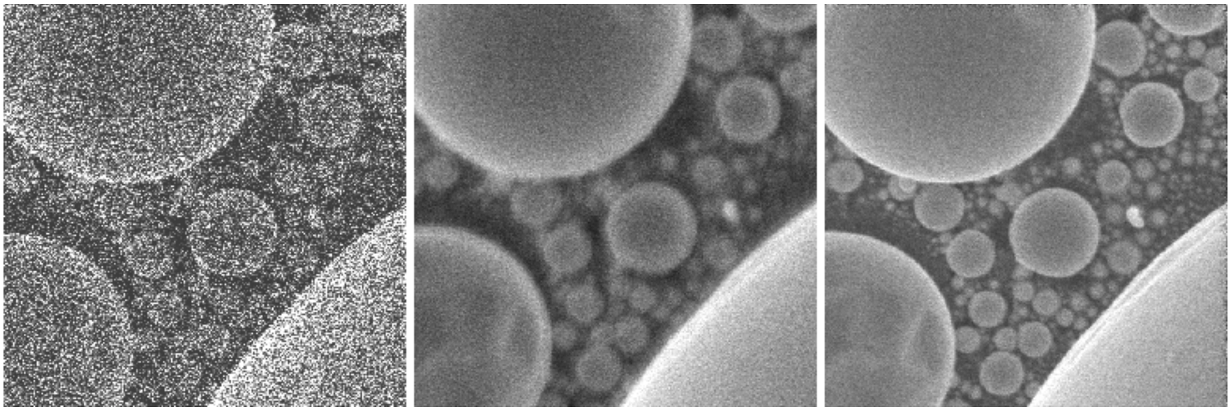

Figure 3. Single image acquired in 11 μs frame time (50 ns pixel dwell time) (left). Traditionally averaged 70 images (middle). The same 70 images averaged with the new, adaptive method (right). The field-of-views are 4.6 μm.

Figure 4 illustrates the performance improvement with modeled SEM images of lines from the image shown above in Figure 2 (left). The result of the traditional, fast SEM imaging of 30 nm wide resist lines is shown on the left through a series of 9 images with progressively more frames averaged, while the better, sharper image is the result of the new method, as shown on the right. This image is a more true representation of the sample, because it is not blurred due to sample drift (which is always present to some extent), and could lead to large measurement errors, especially on the smallest IC and OPC structures. Acquiring images without excessive noise, distortion and blur is especially important for edge roughness measurements and for 3D measurements where the fine details get lost first.

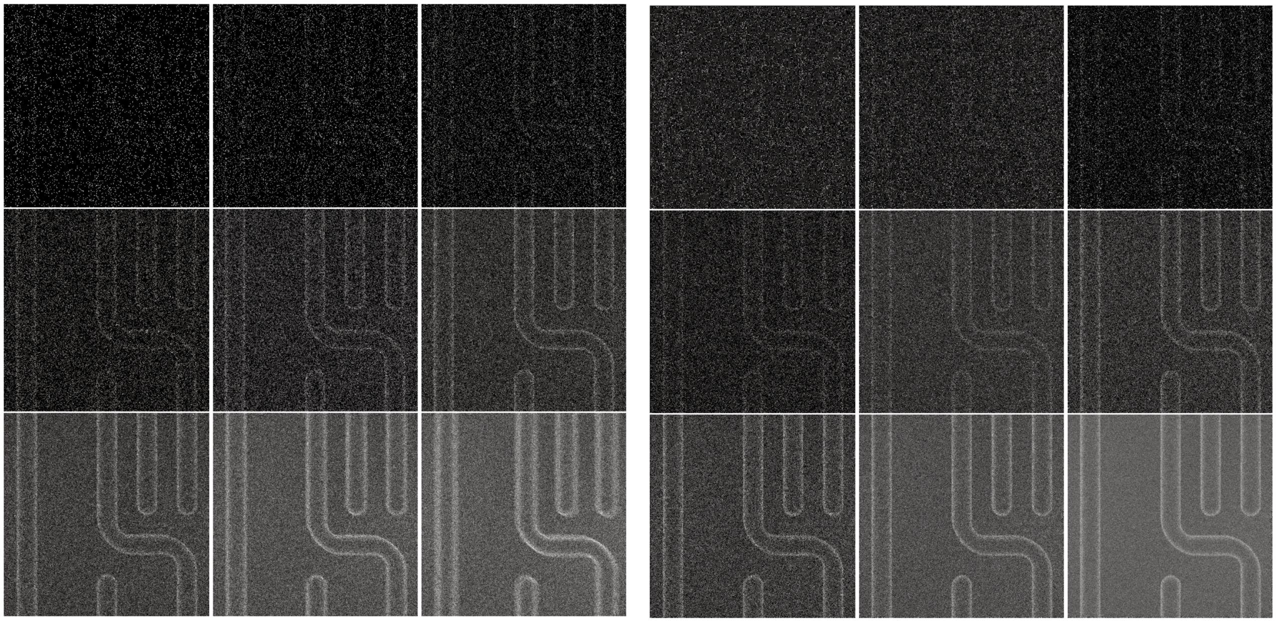

Figure 4. The results of traditional (left) and the drift-corrected (right) methods illustrate with more and more single image frames (generated by the NIST fast analog SEM image generator) are added together. The same raw images were used for both cases. Note the significantly sharper, better final image of the drift-corrected method. Images of 2, 4, 8, 16, 32, 64, 128, 256, and 512 frames. 30 nm wide lines

Modeling and computational scanning electron microscopy through rapid image modeling is gaining importance. NIST has developed an advanced artificial SEM image generator (ARTIMAGEN), which has been released as public-domain software.[5] It is implemented as a library written in C^{++}. This also allows for linking with programs written in other programming languages. The software works in Linux, Mac OSX, and Windows. Hundreds of images can be generated with known critical imaging parameters in a matter of ten minutes on a single, typical personal computer. It is a useful tool for evaluation of imaging and metrology methods, since real SEMs or other charged-particle microscopes do not have optimal repeatability. The artificial image generator is capable of modeling all essential effects in a deterministic way. One can a priori choose parameters such as the drift function, the magnitude and type of the noise, the shape, size and charge distribution of the charged particle beam, etc. The computer-generated artificial images can be used as input to the imaging and metrology techniques and the results compared to the well-known parameters, hence reliably comparing the performance of the various methods. This is impossible with real images, where these effects are present during acquisition but are not systematic (to varying extent), not quantified, and often entirely unknown.

In digital images used for line width and contour metrology, noise causes errors in the measurements and makes it difficult to discern the details of the sample. Noise reduction is also important for another, somewhat distinct reason. It is always a human who first must find the sample feature, some information in the image to look for and measure with quantitative, computer-automated methods. For this, the human eye needs some level of signal over the noise to be able to discern a sample feature. Rose criterion, a biophysical hypothesis based on observations, states that a signal is readily detectable if the signal level is 5 times above the noise level.[12] This essentially is the minimum contrast that can be observed in an image. Due to the small primary beam currents, limitations of the focusing abilities of the electron optical columns, and limited resilience of the samples, only small primary electron beam currents are used, and as a result all SEMs produce very noisy signals. This is especially true for images collected at high speed, where -on average- less than one electron is contained in a pixel. Images that are as noisy as or even a lot noisier than the middle image shown in Figure 2 are common.

The current level of sophistication in improving the signal-to-noise ratio of the SEM images barely goes beyond opting for longer acquisition times. While it is true that four times longer acquisition time improves the signal-to-noise ratio by a factor of 2 (square root function -in theory), there are today further possibilities that take advantage of a priori knowledge of information related to the detector and the signal chain of the SEM. Various noise components can be dealt with in an optimized way at different stages of the signal chain. Some of the highly sophisticated noise reduction methods developed for digital cameras and other applications are directly applicable to SEM imagery. One can hope that SEM manufacturers will heed the call and implement better, more refined methods for achieving optimized digital imaging and measurements.

Once images are collected in an optimized way, evaluation of the results and generation of contour data must take place. There are sophisticated methods already utilized in astronomy, and transmission electron and optical microscopy, which directly, or with modifications, which could be, but have not yet been, successfully implemented in CD-SEMs. NIST has evaluated several of them for usefulness in CD-SEM contour metrology and developed a 2D Fourier transform-based fast image acquisition.[11] Some of the results of this method are shown here in Figure 3 and 4 right. These include methods to improve the signal-to-noise ratio, which is an important part of optimized measurements for both CD and overlay metrology for effective lithography process control. Again, with images and data which are too noisy, losing control is inevitable, but with signal-to-noise ratios that are too high, one loses time, i.e., throughput. Again, artificial SEM images can help the optimization of contour measurements.

Figure 5 shows one example, the result of a new method (developed at NIST) that can eliminate a part of the noise without appreciably altering the fine image details, which is important for high-resolution imaging and measurements.[13]

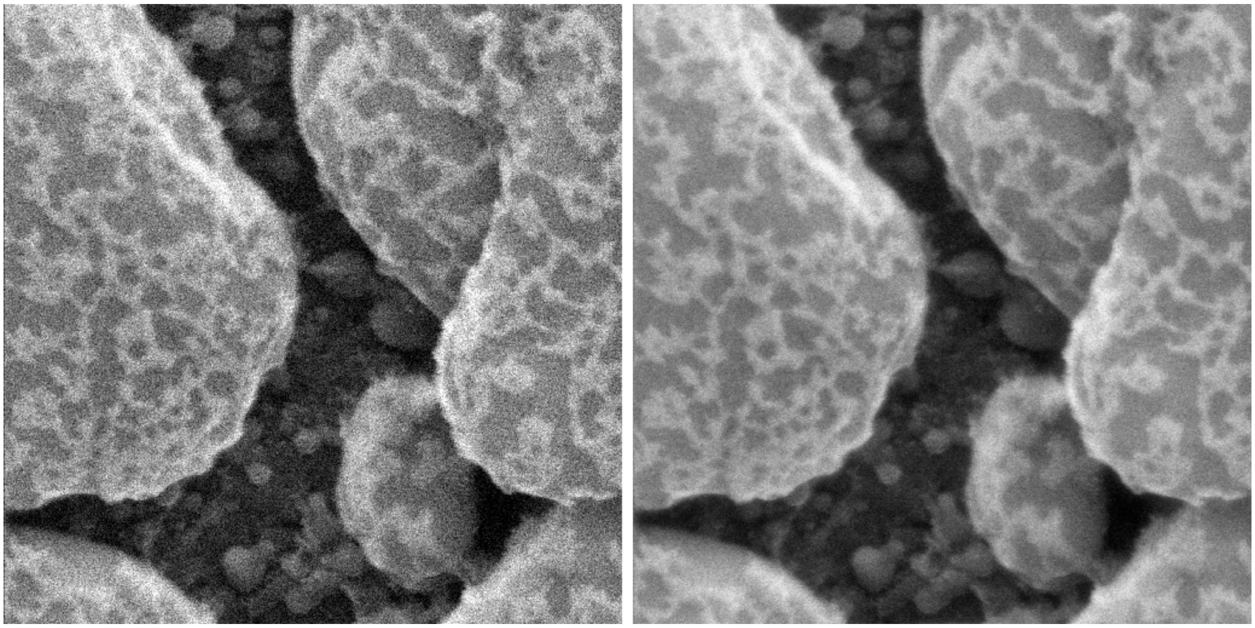

Figure 5. The result of a new NIST image processing method that can eliminate a part of the noise without significantly altering fine image details. Decorated gold on carbon sample,1 μm field-of-view.

3. NEED FOR ACCURATE, MODEL-BASED TWO- AND THREE-DIMENSIONAL METROLOGY

Sophisticated modeling and simulation have helped IC manufacturing in several ways, most notably in crafting ever-shrinking IC features by delivering the needed number of photons in the desired ways into smaller and smaller photoresist volumes, which allowed for the admirable sustained achievements of this industry. While modeling and simulation in making the circuits enjoyed a lot of investment in efforts and resources, the same cannot be said for dimensional metrology, especially for CD-SEM and atomic force microscope (AFM) measurements. Just like IC manufacturing benefited from these computational methods, metrology could as well. Modeling and simulation are useful in correctly designing the acquisition of measured data, as well as in the interpretation of measurement results and in the deduction of the information needed to keep IC development and production running.

In the past, mostly Monte Carlo simulation was used, which was slow, sometime too slow for in-line application. Today, due to improvements to the computation methods and to the fast modern computers, this is not the case. It is possible to generate the needed library in time such that it will not hold back model-based metrology, even in production. The fast analog image simulation from NIST can generate hundreds of SEM images in a matter of hours. The speed and accuracy of modeling can be significantly improved by using exact knowledge in optimization.

One can separate modeling into two categories in another way. One is when modeling is applied to a set of images to generate convincing similarity to real images, which is very useful because actual repeatability can be ensured. The fast NIST image generator falls into this category. The other, called inverse scattering, is useful to find the actual geometry of the measured structure through a pre-computed library.[14] Due to the wealth of information present in the top-down view image, a lot more sample geometry-related information can be extracted from SEM images than a mere line width, including top and bottom CD, and sidewall angle. This method, rigorous Monte Carlo model-based inverse scattering, can also deliver excellent results for 3D metrology. The development and evaluation of this idea are already underway, but it is slow; dedicating the necessary resources would speed up the development and create the possibility of accurately measuring 3D size and shape of IC structures. The generation of aptly tailored modeled libraries can be accomplished within a few hours, and with a larger set of fast computers, in a matter of minutes. The use of pre-computed libraries precludes time penalty in the evaluation of large amounts of 2D and 3D dimensional metrology data, even in state-of-the-art IC production.

The SEM measurement is a highly complex process, which includes electron beam formation and steering, generation and collection of signals, and the proper interpretation of the results. Today most CD-SEMs use algorithms to evaluate the results, and these algorithms do not contain anything that is related to the physical processes that govern the generation of the signal used in the measurements. This, the use of arbitrary algorithms, is the other of the two most severe problems of current SEM contour metrology. Sophisticated, accurate model-based metrology methods are available and can be implemented into the evaluation of the measurement results. These, because they use the whole line scan, instead of a portion of it as the current methods do, provide better repeatability; if the model is correct the results are unbiased, in comparison to the often failing methods of today which are plagued by unpredictable biases.[7,8,9,15]

SEM images used to determine the contours of various mask and IC features exhibit a so-called proximity effect. Similarly to the lithography where lines have different shapes and sizes depending on whether they are isolated or in the proximity of other structures, the SEMs also acquire different images depending on whether they are standing alone or in the proximity of other features. Consequently the features are not just created differently, but they are measured differently as well. In the cases of line edge criteria that disregard physics, the shape and the proximity of the lines bring about an inevitable and unpredictable error in the measurements. Physics-based methods can account for shape and proximity effects and report values much closer to reality.

Model-based methods work with a wealth of knowledge of the physics of signal generation and accurately take into account the various characteristics of primary electron shape and electron distribution, the excited volume, the information volume (i.e., that region of the excited volume where the collected electron signal originates), the detector and signal processing, and the feature size, shape and proximity to other features. All these are essential for metrology accurate enough for current and future very small IC structures.

In contour metrology, the CD-SEM is used to find a 2D boundary based on the image of IC features. This is typically accomplished by a simple method based on the intensity of the secondary electron signal, usually by a gray level threshold or gradient, which effectively means that the evaluation of the measured data is not based on physics, and is basically a rudimentary mathematical construct. The problem is that the various IC features have different neighbors, which inevitably leads to erroneous results, due to the so-called proximity effect. Some regions where the contour runs with no close neighbors have different secondary electron intensity than regions where the feature in question is identical except for a neighboring structure nearby. The various contour segments would need different edge criterion, e.g., gray level threshold, to get accurate boundary results. The isolated and dense neighbors will have a varying bias, unpredictable without using physics in the evaluation of acquired SEM or AFM images. The extent of this offset variation has been assessed using SEM images and AFM measurements, and it was found that it can reach more than 1 nm with image-wide threshold, but was smaller when local background and local signal maximum were used. [15] For 3D shape measurements the requirements are more stringent than for contour or line width measurements; the proximity effect variation due to neighboring structures can be even more significant and less predictable in the results unless accurate physics-based evaluation methods are used.

The reason for the secondary electron intensity to exhibit proximity effects due to neighboring sample structures is schematically shown in Figure 6. Some of the electrons that emerge from the 20 nm wide, 40 nm tall SiO_2 line strike the neighboring wall on the right (and other nearby lines as well). Consequently, the number of detectable electrons that emerge from the side of the walls and from the bottom is reduced compared to the top of the lines. These trajectories were calculated for 1 keV landing energy on a 7.5-degree titled sample with the NIST JMONSEL software.[16] This, the greatly varying number of emerging electrons is the reason for difficulties in SEM imaging and measurement of contact holes and trenches. Positive biasing of the sample surface could help to extract secondary electrons even from deep, high-aspect ratio structures, making it possible to see the bottom of the holes and trenches.

Some of the paths away from the sample, and therefore to the detector, are obstructed for electrons that emerge from an edge in close proximity to a neighboring feature. The extent of the obstruction is greater if the neighbor is larger or closer. The effects of such obstruction are easily observable in images.

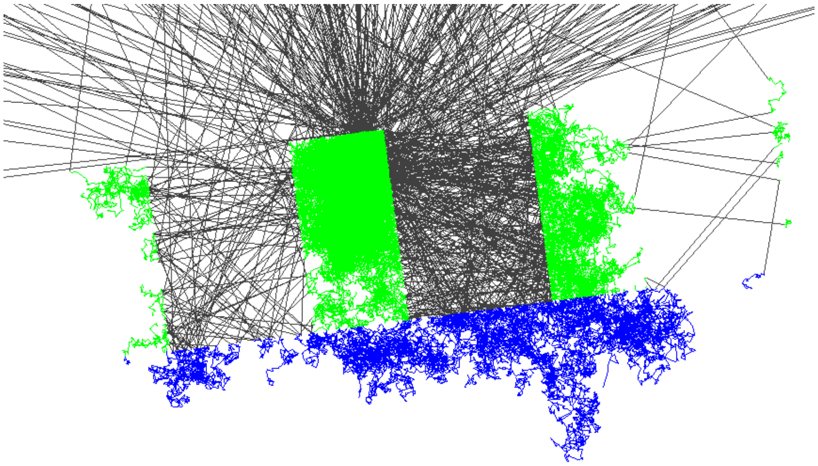

Figure 6. JMONSEL Simulation of 1 keV electron trajectories in a 7.5 degree titled sample with 20 nm wide SiO_2 lines. Note that some of the electrons hit other neighboring lines' walls.

Figure 7 compares a CD-SEM image of an intentional defect structure (the defect is in the area marked 2) with an image simulated with NIST JMONSEL. Regions labeled 3 and 3' are darker than regions that are more open, like the ones labeled 2 and 2' and especially 1 and 1'. These illustrate well that SEM proximity effects can be modeled, and images similar to real ones can be simulated based on these models.

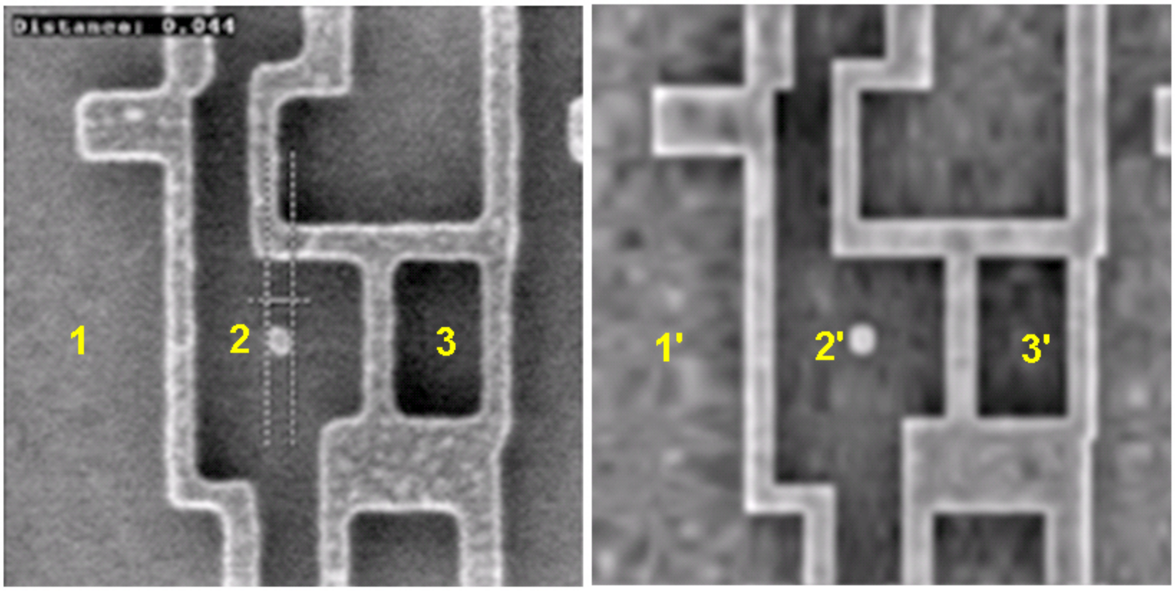

Figure 7. Comparison of measured (left, SEM image, courtesy SEMATECH) and simulated (right) images of an intentional defect array structure. Neighborhoods 1, 2, and 3 (1', 2', and 3' in the simulation) are progressively more confined and also progressively darker. 1 μm fields of view (Figure reproduced from reference 10).

Accuracy is also important in other ways. Measuring the same sample structure with different methods and arriving at results within the uncertainty of the results is a good way to maximize our confidence in the results of the measurements. This comparison is only valid within the uncertainty of the measurements, so understandably it is important to minimize the uncertainty and find ways to take advantage of what the combined measurements offer. Using sound, physics-based modeling for the interpretation of both AFM and SEM results gives the chance of obtaining more correct information than is possible with current industry methods, which disregard the governing physical processes that generate the signal used for measurements and rely on only one type of measurement.

In a short study at NIST to explore such proximity effects, SEM and AFM measurements were carried out.[15] Measurements were done using a Veeco SXM320 critical dimension AFM (CD-AFM) and an FEI Helios SEM installed at NIST laboratory facilities. Using NIST methods and samples, the AFM instrument was turned into a reference measurement system (RMS); it can measure accurately pitch, height, and linewidth.[17,18]

As an example, the edge location results of CD-SEM and CD-AFM are fit using the absolute threshold method, and are shown in Figure 8. The roughness of the edges and the width change at the isolated-to-dense transition help to precisely line up the AFM and SEM edges, because there they are strongly correlated. Differences between the more distant edges (*Δ13* and *Δ24*) are in good agreement between the SEM and AFM. AFM measured the isolated part of the line to be 30.3 nm wider than the line in the dense area. The SEM value was 28.1 nm. The 2.2 nm difference is attributed to proximity effect in the SEM.

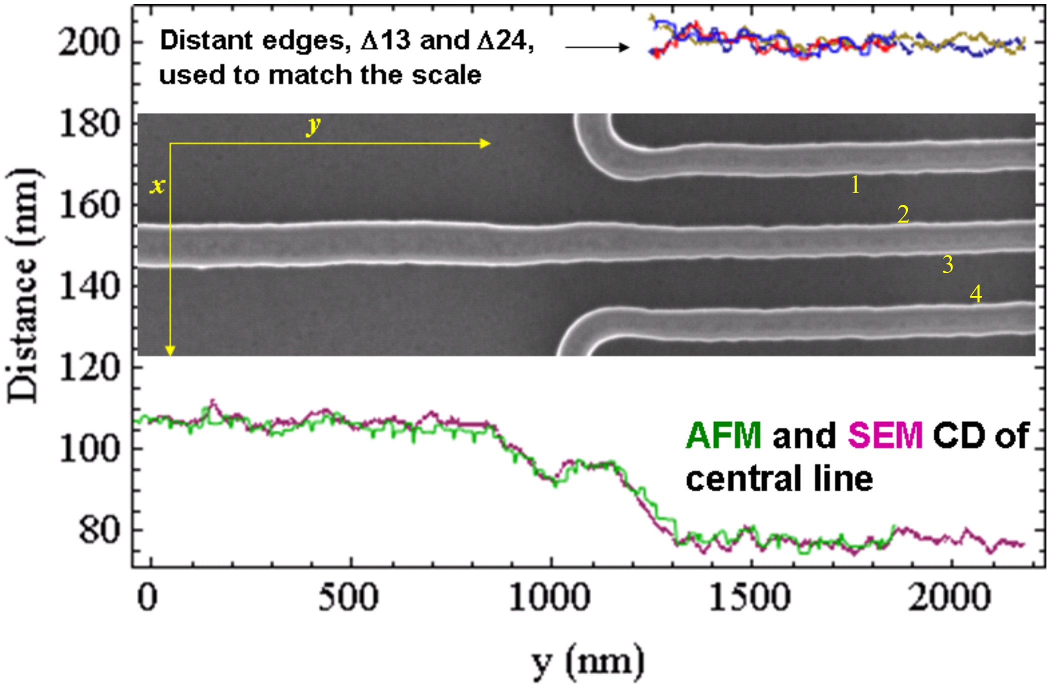

Figure 8. Center: SEM image of the iso/dense transition region, showing the identification of the edges. The AFM and SEM CD values for the line in the center match as shown by the two curves at bottom. Similarly, other edges match as shown by the four curves at upper right. (Figure reproduced from Reference 10.)

The above measurement was repeated with another SEM and three other AFM images. The average value of the proximity-related error was found to be 2.3 nm with a 0.5 nm standard deviation (1 σ). Due to the small number of repetitions, a factor of 3.2 was used to produce an interval of 0.7 nm to 3.9 nm where all the results fall with an estimated 95 % confidence. The Monte Carlo simulation result, 1.2 nm, lies within this interval. On the other hand, in industrial linewidth determinations 0 nm is used, which does not fall into this 0.7 nm to 3.9 nm 95 % confidence interval. The conclusion is both the simulation and measurement agree, yet if the absolute threshold edge method is used, then there is a non-zero proximity-related metrology error of one to a few nanometers. This unpredictable error is large enough to cause problems in the optimization of the lithography process.

When the relative threshold method of edge assignment was used, where the local background and signal height is used, the measured mean proximity-related metrology error was -0.4 nm with about 1 nm standard deviation. The corresponding 95 % confidence interval is -1.3 nm to 0.6 nm. Here also, the simulated value lies within the measurement uncertainty window, but this time id 0 (i.e., no proximity-related effect, the method used by the industry today) also lies within the window, so some of the industrial measurements are consistent and can be error free, while other cases might exhibit these errors.[15] These couple of nanometer errors are very important today and especially for future dimensional metrology, and minimizing them is indispensable for 3D metrology of close-to-ten nm size structures of the near future. Clearly, beyond this cautionary case, further, more detailed, accurate, model-based investigation could help to clear this issue and give a more reliable way for process development and control.

4. CAN WE GET 3D CD METROLOGY RIGHT?

The authors are convinced that the answer is: yes, we can get 3D CD metrology right, especially if the IC industry requires it and puts enough resources into the development. As long as we can see them in the SEM, we can measure 3D CD on fins and other structures and reconstruct true 3D shapes with profiles. Figure 9 is a top-down view of a resist sample of intentional defect arrays (courtesy of SEMATECH). The image illustrates that even top-down images reveal a lot of 3D information. In this case, due to delamination, a sort of two-step structure is formed, i.e., the top layer is partially peeled away from the underlying one. Some residue on the substrate surface is also clearly visible.

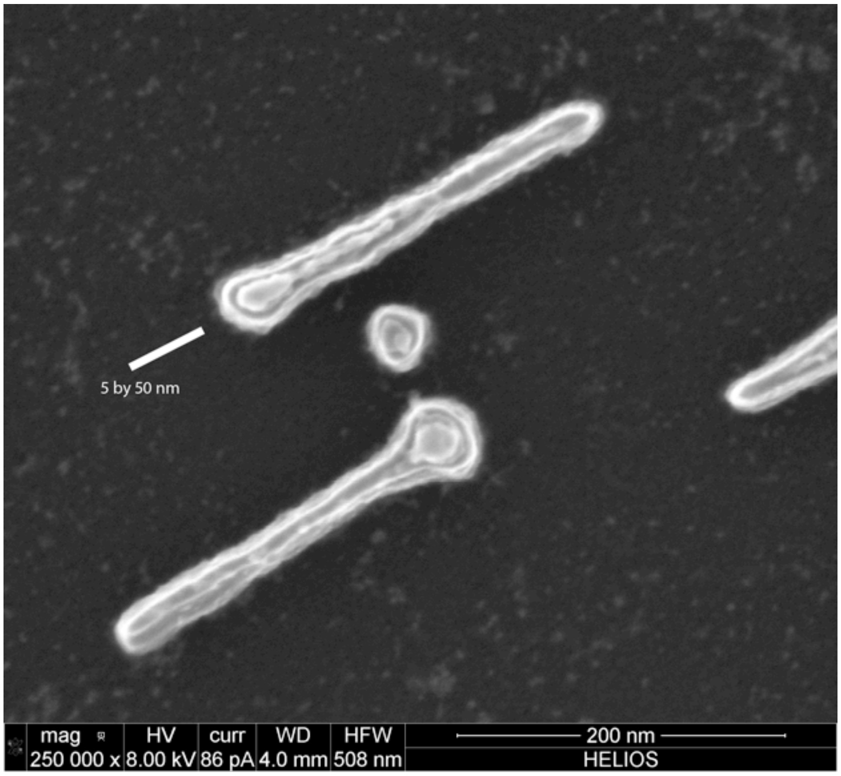

Figure 9. A top-down view of a resist sample of intentional defect arrays. 508 nm field of view.

The 5 nm by 50 nm size bar helps to assess the size of the various sample features, some of the smallest ones are less than 5 nm is size, meaning even details of sub-ten nm size features can be imaged, hence measured. New SEMs can achieve a best resolution of a few 100 pm and produce superbly detailed images, which will allow for precise, high-resolution measurements on sample features down to a few nanometers.

There are excellent examples for the rewards of sound metrology: substantial improvements, solutions for almost all of the shortcomings of current CD-SEMs in acquisition, processing and contour determination and for other methods. Nevertheless, the SEM is no exception to the fact there is no single dimensional method that can deliver all needed information, so we must use several methods and take advantage of the most useful information each technique provides. Ideally we would have all dimensional metrology measurement methods fully optimized, with known measurement uncertainties, and we would combine them in a way that minimizes the overall uncertainty, i.e, maximizes the confidence in the results. We cannot do this today to the extent the industry needs it. Industry-wide consensus, cooperation and standardization would be very helpful, because none can do this work alone. Today there are some in the IC industry who are not even convinced yet that this is the way to go. Still, the work to get to correct 3D dimensional metrology is significant, but will be very rewarding, and a whole set of powerful methods are already worked out and are ready for evaluation and implementation. So, the answer is again: yes, for sure, even for all those structures at the end of the ITRS Roadmap. But will we?

The future of 3D CD metrology is bright and it depends on us to make it as good as it can and needs to be.

5. CONCLUSIONS AND FUTURE ACTIVITY

Hopefully soon, these and other 2D and 3D metrology methods and ideas will be implemented and used for a radically better SEM, and also for other dimensional metrology techniques for the semiconductor industry. NIST will help this effort and will keep working for even better metrology, especially for improved accuracy. Some of the solutions outlined here can be implemented on current CD-SEMs; others can be implemented on future SEMs that will be designed to take advantage of these novel ideas. The results and improvements are substantial and essentially address all key aspects SEM-based contour measurements and offer solutions for almost all of the shortcomings of current CD-SEMs in acquisition, processing, contour and 3D shape determination.

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