

Enabling Virtual Wafer CD (WCD) Using Inverse Pattern Rendering (IPR) of Mask CD-SEM Images

Thuc Dam*^a, Dongxue Chen^a, Hsien-Min Chang^a, Noel Corcoran^a, Paul Yu^a and Linyong Pang^a
Chia-Wei Chang^b, Rick Lai^b, Peter Chang^b, and Laurent Tuo^b

^aLuminescent Technologies, Inc., 2471 East Bayshore Road, Palo Alto, CA, USA 94303;

^bTaiwan Semiconductor Manufacturing Co. Ltd., 25, Li-Hsin Rd., Hsinchu Science Park, Hsinchu, Taiwan, 300-77, R.O.C.

ABSTRACT

A wafer's printed CD error can be impacted by unaccounted mask making process variation. Unaccounted mask CD and/or corner rounding alters the intended drawn mask pattern contributing to a wafer's printed CD error. During OPC wafer calibration, average mask bias and corner rounding are accounted for in the OPC model, but random local mask making process variations or mask-to-mask variations can be difficult to account in such model calibration. Thus when a wafer's CD has error, it can be difficult to determine if the general root cause was due to mask or wafer or both. An in-line monitoring application has been developed to extract accurate mask CD and rendered mask polygon from collected mask CD-SEM images. Technical information will be presented on the challenges of accurately extracting information from SEM images. In particular, discussions include SEM image calibration, contour extraction, inverse pattern rendering, and general image processing to account for mask SEM aberrations (translation, rotation, & dilation), tool-to-tool variation, vendor-to-vendor variation, run-to-run variation, and dark/bright field pattern-to-pattern variation. After accurate mask SEM contours are obtained, lithographic simulations are performed on extracted polygon contours to determine the impact of mask variation on wafer CD. This paper will present detail information about the Inverse Pattern Rendering (IPR) capabilities developed for a virtual Wafer CD (WCD) application and its results, which is proven to achieved 0.5 nm accuracy across multiple critical layers from 28 nm to 40 nm nodes on multiple CD-SEM tools over multiple mask shop locations.

Keywords: SEM, ILT, image processing, SEM aberration, image calibration, SEM calibration

1. INTRODUCTION

The path towards using mask SEM data to predict wafer CD requires accurate representation of mask that can be simulated with a calibrate wafer models. Many of the options provided for mask representations can be highly inaccurate. One of the most inaccurate mask representation is the ebeam OPC'd or inverse lithography technology (ILT¹) patterns. These lack actual mask process and local CD variation that is accurate to the mask making process. Being a little more accurate, one could use rounded contours extracted from mask SEM images. Although this can account more accurately the mask targeting variation and corner rounding², it still leads to inaccurate simulation results. The reason is that some calibrated models used in simulation already has accounted for corner rounding, and there's no possibility to remove that characteristic from such kernel-based models in production. In essence, simulation results of rounded corner mask has amplified mask corner rounding effects. Another fault with using contours extracted from SEM images is that they generally do not contain post-applied measurement bias performed by some SEM tools or other processing software. Such biasing tables in the post-processed CD SEM data serve the role of nm-anchorage of measurements to standards or other "golden tools", but they are quite difficult to apply to rounded contours. Hence measurements from rounded contours extracted from images may not be equivalent to measurements reported by some SEM tools with post-applied biasing. Simulations of these contours can be inconsistent with the measurements used as inputs into model building process to generate the OPC or ILT masks. So the rendering of accurate straightened edges without rounded mask corner is the main solution needed. Luminescent in collaboration with TSMC has developed and deployed in production a software solution called Inverse Pattern Rendering (IPR).

IPR uses ILT technology to produce accurate mask polygon data with Manhattan pattern edges from mask SEM images. As displayed in Figure 1, IPR masks have straight edges without any corner rounding and can be biased with

measurement biasing table. Having an accurate and model-compatible mask pattern for simulation provides a means to predict wafer CD from mask SEM data. This capability can allow users to isolate mask specific problems that are suspected in wafer printing issues. Also by knowing mask making variations and their potential impact to wafer, it is possible to feed forward such data for dose mapping correction during wafer printing to improve the litho setup efficiency.

For production qualification, IPR software has achieved a ± 0.5 nm (1X) accuracy to actual mask SEM measurements across two technology nodes (N28 & N40) and many layers (Mx/CT/Vx/PO/OD) for two Holon SEM models (EMU250 and EMU270) at two TSMC mask shops. Additionally two Hitachi SEM models (9380M and CG4500) have also been qualified with similar accuracy results for which TSMC has deemed acceptable. This paper focuses on discussing the imaging process technologies that have been used to establish the production accuracy of IPR.

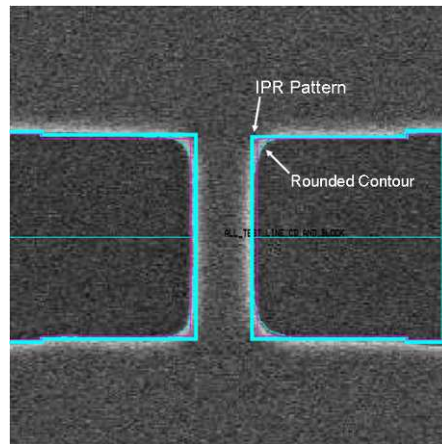


Figure 1. IPR inverts mask SEM image to OPC-like data with Manhattan pattern edges. Relative to extracted rounded contours, IPR provides more accurate wafer simulation results.

2. IPR TECHNOLOGIES

2.1 Inverse Mask SEM Rendering

IPR uses two main inputs to derive accurate Manhattan mask patterns: mask SEM images and OPC mask GDS/OASIS patterns. The IPR process flow occurs as shown in Figure 2, and is composed of two major subprocesses: geometric correction of SEM images and pattern rendering with post-applied biasing. Most SEM tools induce some image aberrations in the form of translation, dilation, and rotation. These geometric aberrations can lead to non-Manhattanizable edges, and so their correction is deemed essential for accurate edge rendering. In order for the ILT engine to de-aberrate an image, an ideal SEM image is generated as a basis for comparison to the actual SEM image. IPR generates the ideal SEM image by iteratively applying various calibrated SEM parameters (corner rounding, bias, white-band profile, etc..) to an OPC mask GDS/OASIS pattern. Both ideal and actual SEM images then undergo binarization or thresholding to simplify them. Iterative calibration of geometrical aberration terms is performed based on differences of the two binarized images. The calibrated geometrical terms are then be used by IPR to correct the geometrical aberrations from actual SEM image without impact to the image's white band where edges are accurately extracted in 2nd part of the flow.

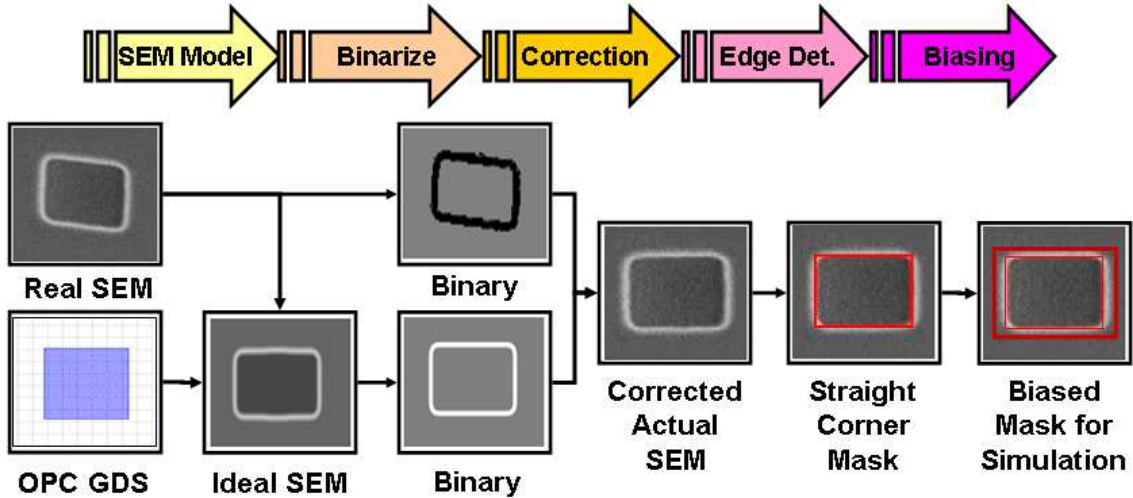


Figure 2. Inverse mask SEM pattern rendering takes input mask SEM image and mask pattern GDS to derive a geometrically corrected SEM image for edge rendering and biasing.

2.2 Normalization of Images for Consistent Image Binarization

For each typical production mask there can be a batch of input SEM images. The intensity variations from image-to-image, mask-to-mask, and SEM-to-SEM can further inject inaccuracies into any image processing software. Figure 3 shows an example of some inherent intensity variations that must be accounted. The first image processing step of IPR, thresholding, is performed with a single value for speed purpose. The use of a single value threshold to binarized all images from within a batch causes some problems. As an example, Figure 4 shows 2 SEM images from one mask acquired at one sitting. The within run variation shows that the L/S SEM image has higher (red) average intensity across the image compared to the 2D SEM image. If a single threshold (green) is applied to both images, all of the edges on the L/S pattern are generated in a binarized image, while only one of the edges on the 2D pattern is generated. Any missing binarized edge will lead to poor geometrical corrections. If the green threshold is lowered to appropriately binarize the edges on the blue intensity profile, it will then also inappropriately capture noise in the red image intensity profile. As a solution for this, IPR has capability to normalize the intensity from a batch of images so that one threshold value could be used during binarization to produce all edges on both images (Figure 4).

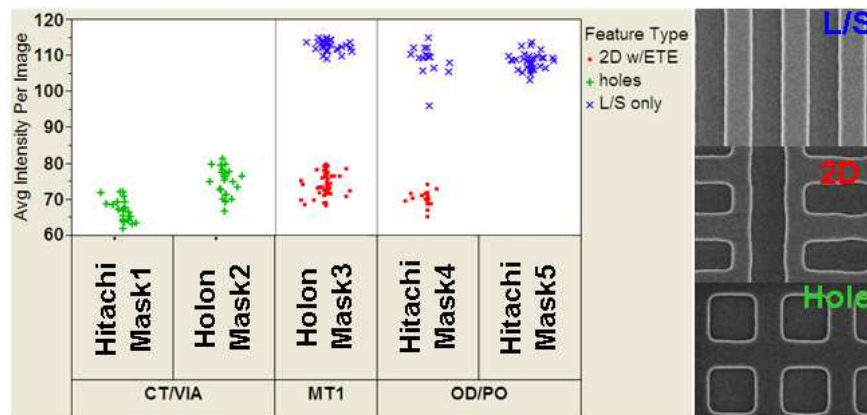


Figure 3. Inherent image intensity variation exist from image-to-image, mask-to-mask, and SEM-to-SEM.

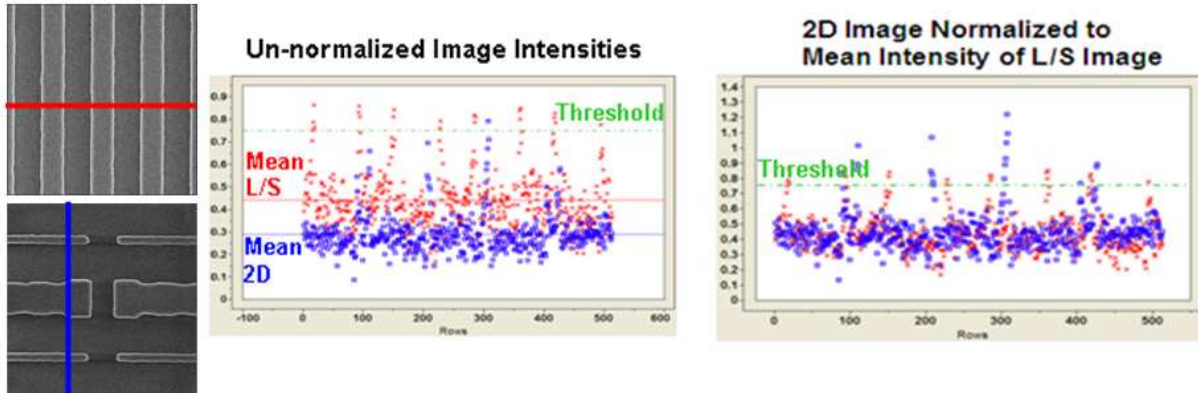


Figure 4. Intensity profile differences exist even between two images taken from a mask at one SEM acquisition. Single thresholding leads to poor edge binarization for one or both images. After image intensity normalization, single threshold is applied to achieve good image binarization for a batch of images within a particular mask SEM acquisition

2.3 Mask SEM Model Calibration

Accurate correction of geometrical aberrations in SEM images also relies on having accurate ideal SEM images to compare against. Such ideal SEM images need to be derived from input mask OPC GDS/OASIS pattern and characteristics of the input SEM image. Mask SEM model calibration is performed iteratively on a set of SEM image parameters (corner rounding, bias, white-band SEM profile, etc..) that are then applied to mask OPC patterns. For each iteration a cost function (CF) is calculated from the difference between ideal and actual SEM images. Then parameter adjustments are searched to minimize the CF. Figure 5 shows the cost function convergence plot for two sample images through the iterative calibration steps. It indicates that over many iterations the differences between actual and calibrated ideal SEM images are reduced leading to model convergence for the set of calibrated terms. Figures 6 and 7 shows first and final iteration of the calibration process for SEM images 5 and 17. In the initial iteration, the set of SEM model parameters applied leads to an ideal SEM image with very narrow white band with sharp corners. The overlay of the two binarized images from the first iteration shows differences in bias, corner rounding, white band, and even some translation errors. As the iterative calibration process converges, the final ideal SEM images show much more appropriate white band width and corner rounding. The overlay of the binarized images from the final iteration shows only speckle of differences which are mostly due to line-edge roughness or SEM background intensity noise.

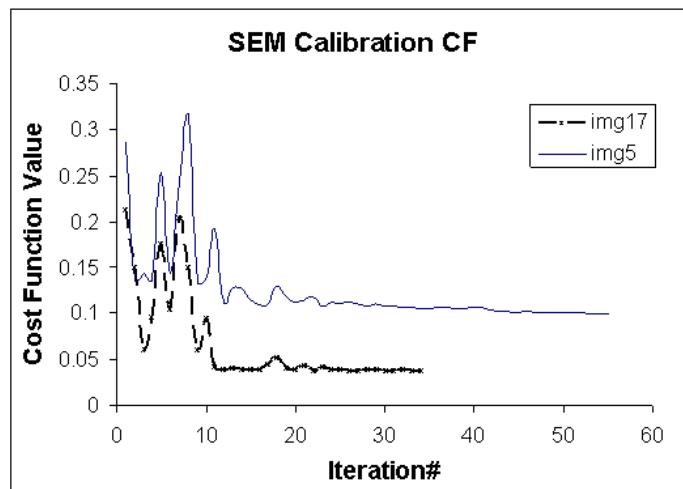


Figure 5. Cost function ($CF \approx [I_{ideal} - I_{actual}]$) convergence for ideal SEM image calibration.

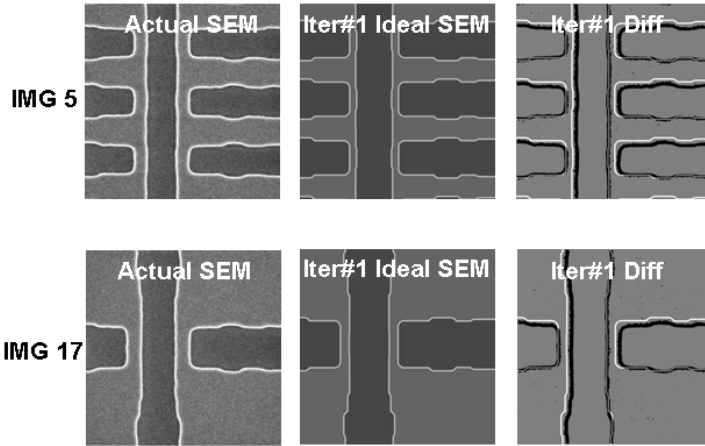


Figure 6. Initial ideal SEM image calibration shows high differences.

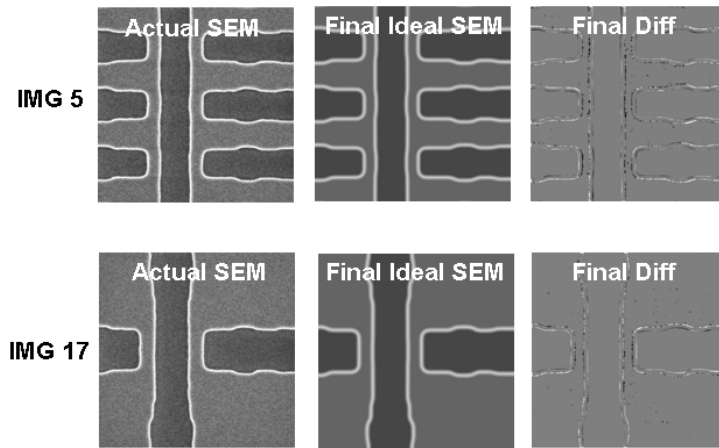


Figure 7. Final ideal SEM image calibration shows low difference and good convergence.

2.4 Mask SEM Edge Rendering

Edge rendering is performed on geometrically corrected SEM images along with some information derived from input mask patterns. Straight edges, jogs, corners, and various other geometrical feature lengths are defined from input mask patterns. Over these respective features on geometrically corrected SEM images, IPR collects intensity profiles, averages them, performs interpolation on averaged profile and then applies a threshold to render an edge (Figure 8). Any rounded corners are straightened lengthwise from the rendered edge based on a factor of corner rounding amount as determined during SEM image calibration.

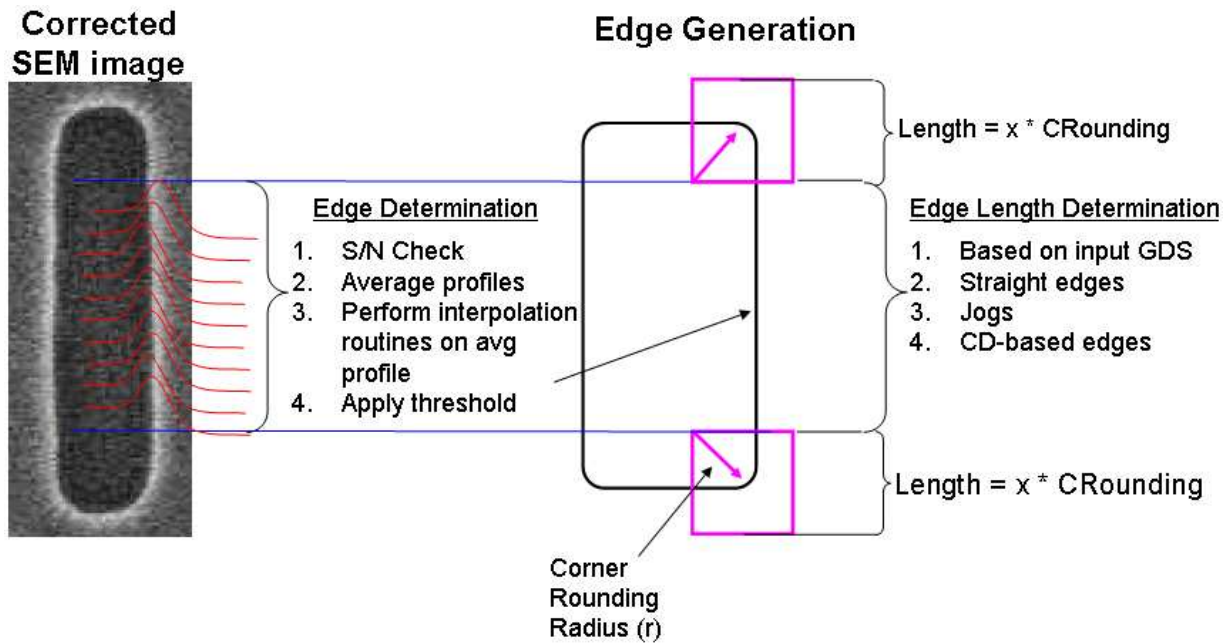


Figure 8. From a correct SEM image, IPR collects intensity profiles, averages them, perform interpolation on average profile, and then apply a threshold to render edges and straighten corners.

IPR has several edge detection algorithms accurate to various SEM models for both Hitachi and Holon vendors. In these algorithms an average profile is first derived from an image feature. Depending on the algorithm, interpolation can be performed on the average image profile prior to thresholding for edge determination. The interpolation methods used vary between linear and quadratic interpolation depending on different parts along the intensity profile (min, max, or at intersection with threshold). Applying such offline image interpolation leads to additional accuracy without significant processing efficiency.

2.5 Signal-to-Noise Requirement Applied to Edge Detection

One of the prerequisite to detecting an edge is to be able to discern an intensity signal among noise at an edge location. Figure 10 shows two SEM images taken for various masks on the same tool at different times. The vertical intensity profile of the left image clearly shows signal intensity peak distinct from the background noise, while the right image shows only top edge intensity signal without the corresponding bottom edge intensity signal. In the normal operation of the SEM tool for these patterns, technicians are measuring the horizontal line-end features which have clear intensity signal, so the lack of intensity signal along the straight line edge could be of little impact to that line-end measurement. IPR, however, needs to accurately render every edge within image field of view, so it is essential that every edge location has a clear signal-to-noise response for the results to be consistent and accurate throughout the image and from image-to-image. Automation was built into IPR to calculate the mean (m) and standard deviation (σ) for background noise. Then for every expected edge location, a minimum intensity (I) peak must adhere to the requirement stated in Figure 10 for IPR to render that edge. Any image failing this criteria produces an error that would alert engineers to potential tool drifts or setup issues.

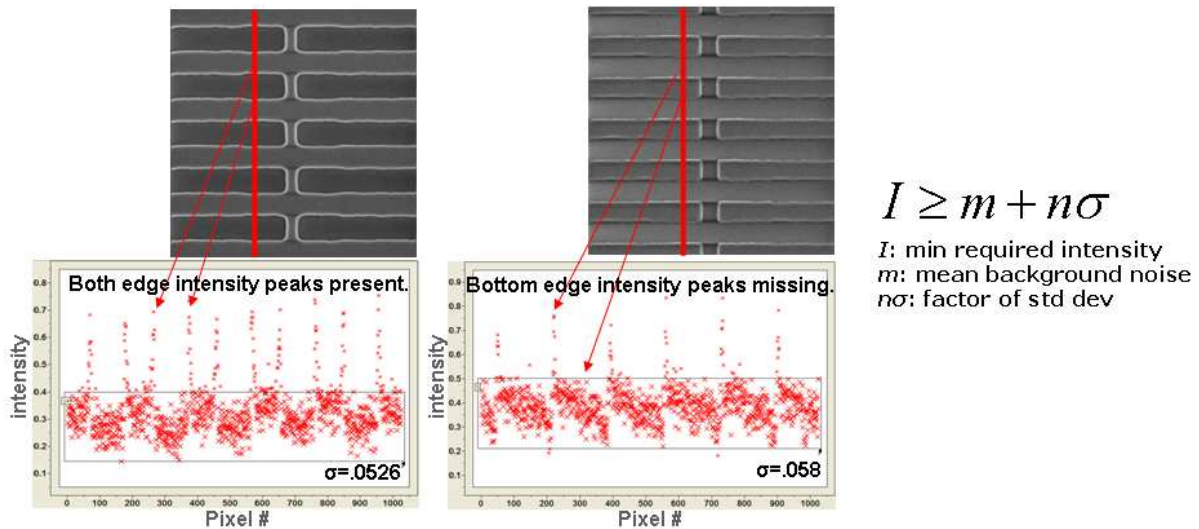


Figure 10. Two SEM images taken of masks at different times can show variation in signal-to-noise. SEM tool imaging variation can impact IPR pattern rendering. Signal-to-noise intensity requirements are enforced in order to assured appropriate signal at expected edge for edge rendering.

3. RESULTS AND DISCUSSION

IPR's production accuracy is established by comparing measurements of IPR patterns versus actual SEM measurements of specific locations and geometries. This accuracy analysis has been performed across two technology nodes for two different mask shops on many different SEM tools for masks of many layers. The introduction discusses the maximum accuracy errors that IPR produced from these many general measurements is within +/-0.5 nm. Figure 11 now shows more detail results for N28 1D pattern set. The varying pitches and sizes for line/space has IPR results with accuracy (bottom right graphs) within ± 0.5 nm. In Figure 12, the results for N28 2D pattern set is shown for IPR detail. The accuracy results for two different SEM tools and vendors have accuracy within ± 0.5 nm across many different features ranging in CD's between 55 & 65 nm. The rendering of corners, jogs, and straight edges on IPR patterns were also well formed.

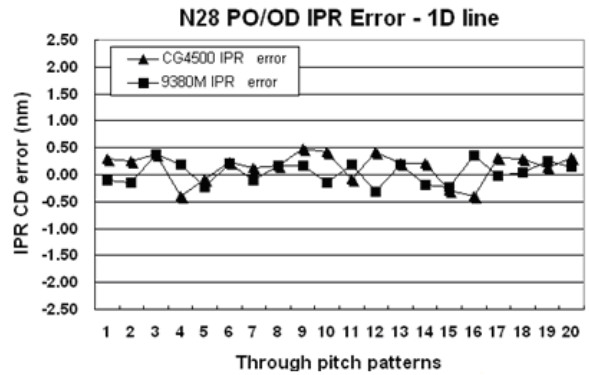
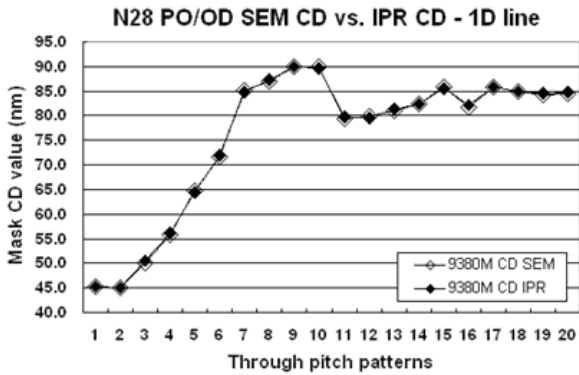
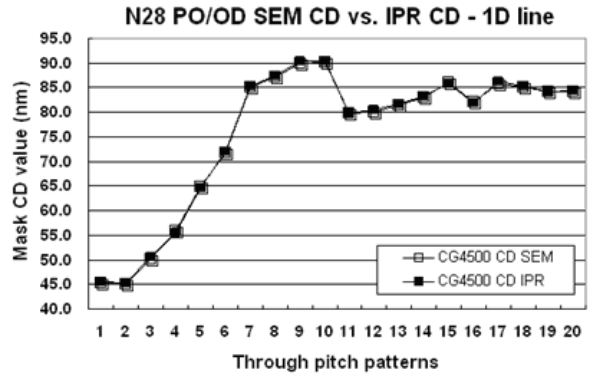
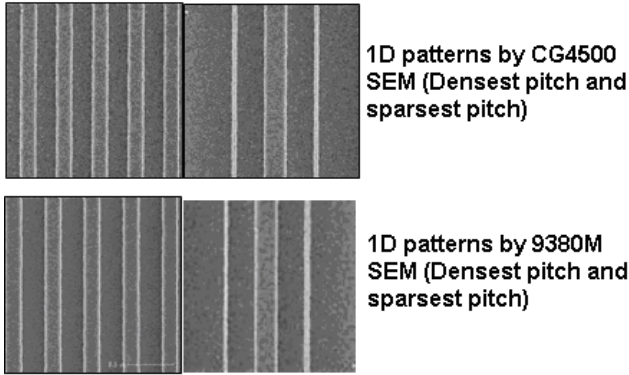


Figure 11. 1D IPR Line/Space pattern accuracy of ± 0.5 nm was achieved for through pitch N28 patterns across 2 SEM vendors.

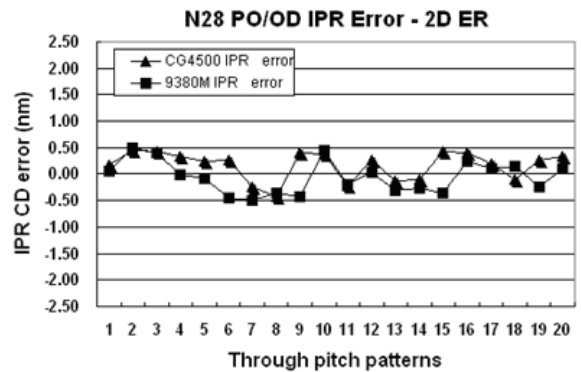
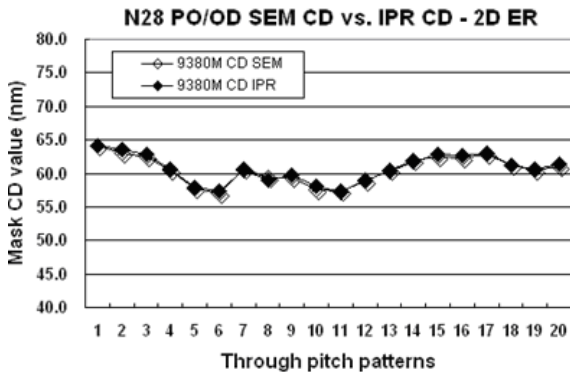
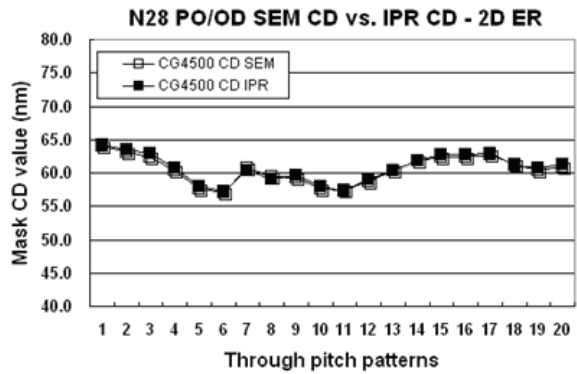
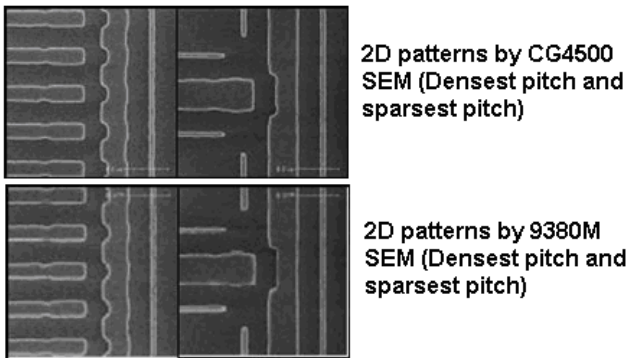


Figure 12. 2D IPR pattern accuracy of ± 0.5 nm was achieved for various N28 patterns across 2 SEM vendors.

IPR collection of N28 M1/Mx 2D patterns has also as shown good accuracy results in Figure 13. The IPR accuracy of features ranging in size from ~20 nm to ~40 nm has been measured to be within specification of ± 0.5 nm.

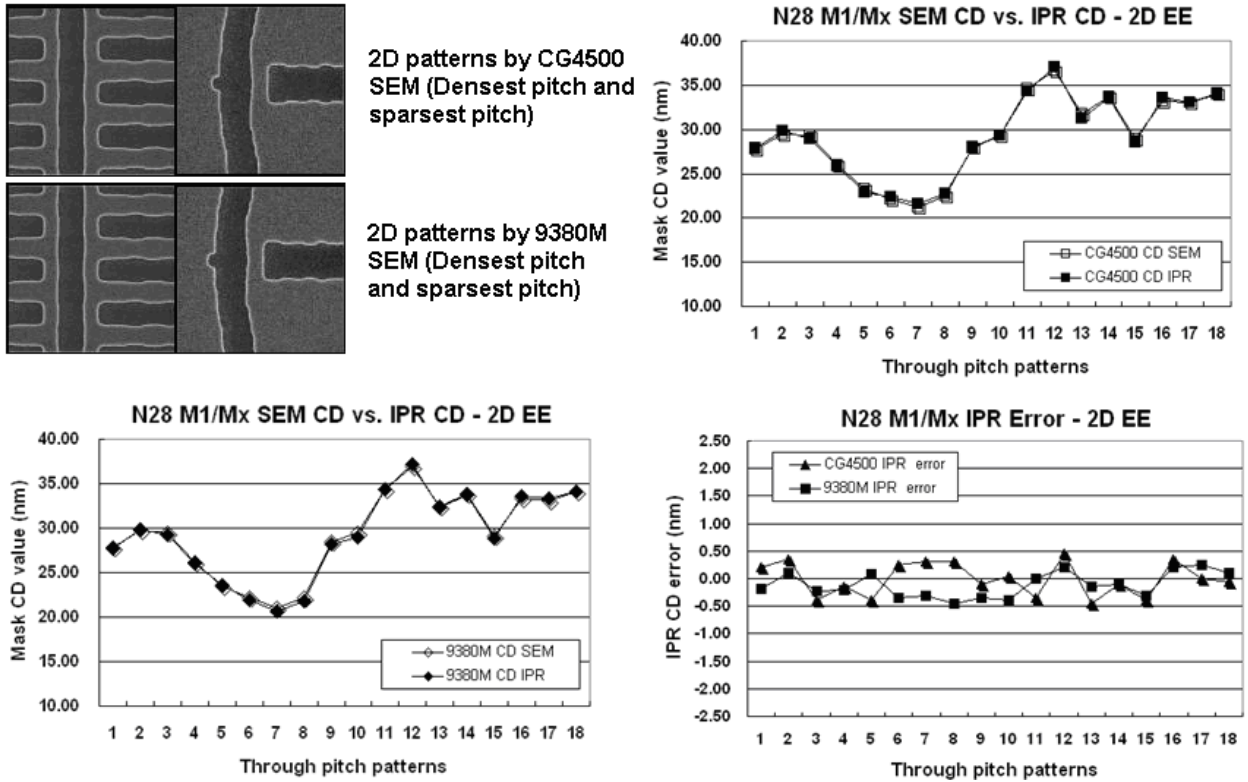


Figure 13. M1/Mx IPR pattern accuracy of ± 0.5 nm was achieved for various N28 patterns across 2 SEM vendors

IPR collection of N28 CT/Vx 2D patterns have been attained as shown in Figure 14. The IPR accuracy of features ranging in size from ~80 nm to ~100 nm has been measured to be within specification of ± 0.5 nm.

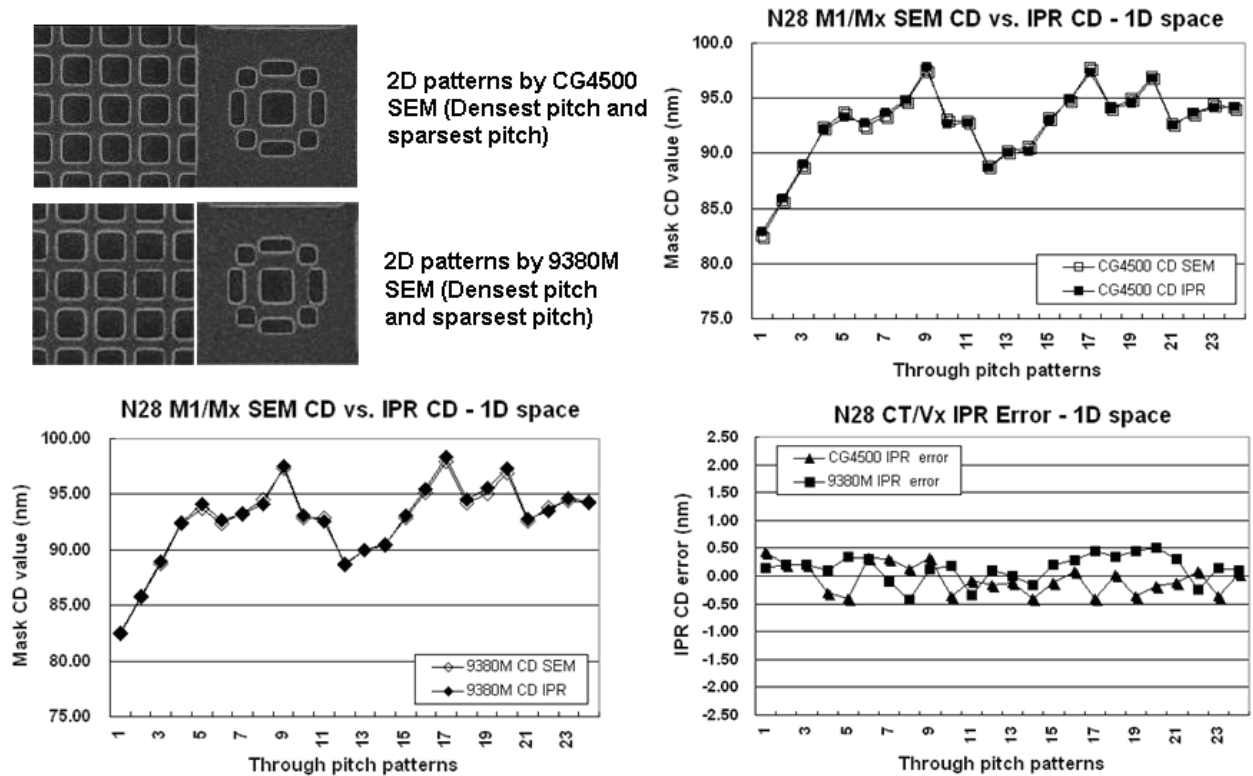


Figure 14. CT/Vx IPR pattern accuracy of ± 0.5 nm was achieved for various N28 patterns across 2 SEM vendors

Results for tool-to-tool variability have been conducted across 4 different SEM tools on 2 different layers. Figure 15 shows that IPR has been able to render accurately within ± 0.5 nm for a set of through pitch hole patterns across 4 different SEM tools. Similar data has also collected for line/space patterns with similar results of ± 0.5 nm accuracy. Figure 16 shows IPR also achieved acceptable accuracy for N40 metal line/space patterns across 4 different SEM tools.

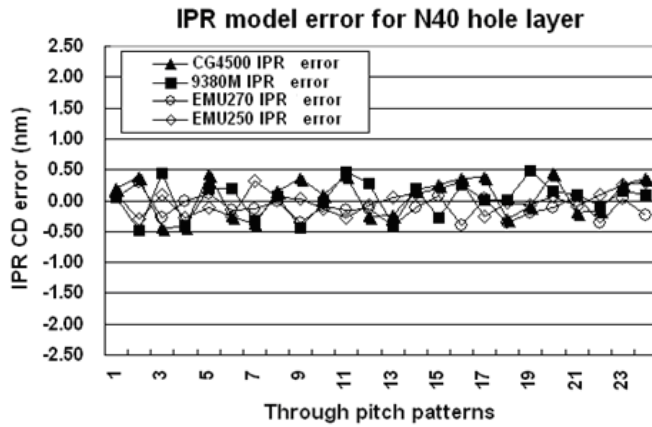
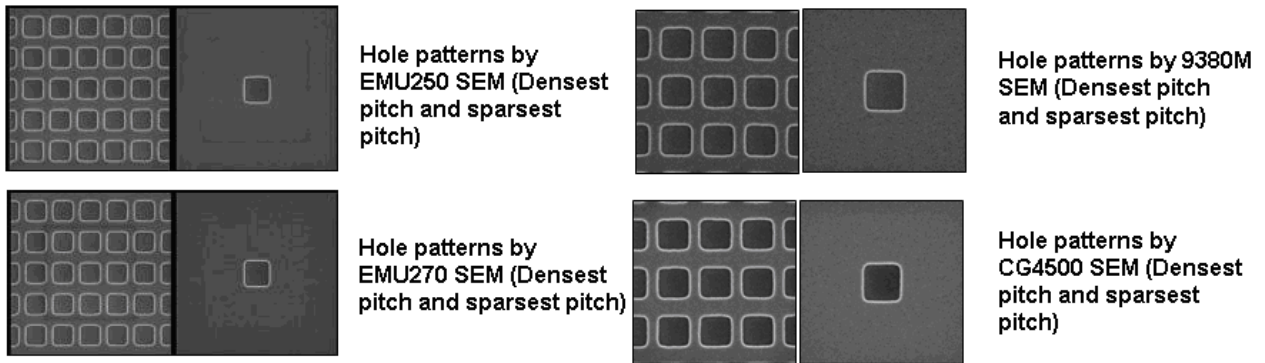


Figure 15. Hole pattern tool-to-tool repeatability shows IPR achieved ± 0.5 nm accuracy for across 4 different SEM tools.

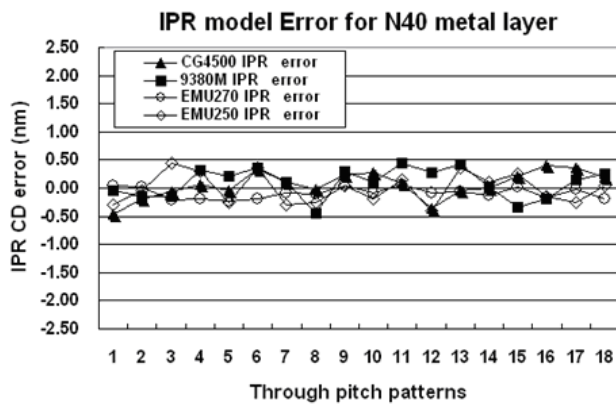
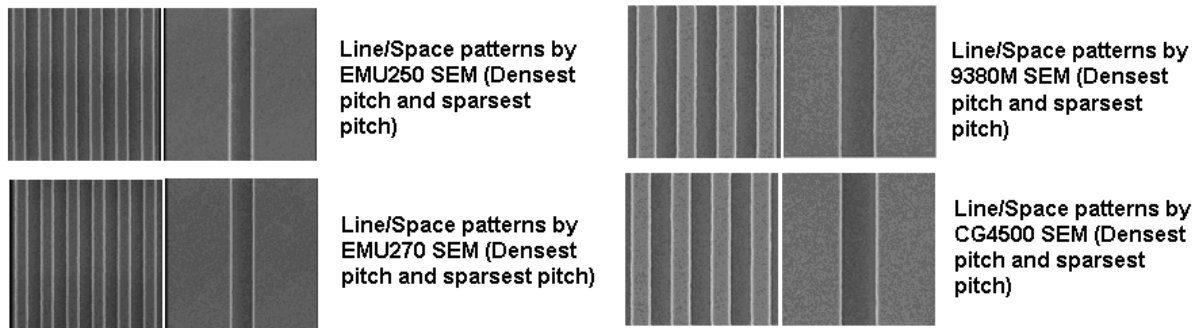


Figure 16. Line/Space pattern tool-to-tool repeatability shows IPR achieved ± 0.5 nm accuracy for across 4 different SEM tools.

Results for IPR repeatability testing of a contact layer on one Holon tool produce static repeatability 3σ of 0.32 nm and dynamic repeatability 3σ of 0.63 nm. These values match well with Holon’s advertised basic specification for that model, and indicates that IPR introduces minimum error to the tool’s inherent repeatability.

IPR accuracy to mask SEM measurements has also been verified on complex SRAM patterns, one of which is shown in Figure 17. All eight different locations with their varying geometries show accuracy within ± 0.5 nm. Figure 18 shows the calculations for dimension-on-mask (DOM) and dimension-on-wafer (DOW) for the IPR mask. DOM represents the differences between post-OPC GDS and IPR mask pattern, while DOW represents the differences in simulation results of post-OPC GDS and IPR. DOW provides the wafer CD difference estimation relative to simulation of post-OPC “perfect mask”. DOW to target measurement is within -0.57 nm and +0.51 nm, and with the proven IPR accuracy to mask CD SEM measurements, there is good confidence in these simulation results. The fact that DOW trend follows DOM is another indicator that simulation of IPR can be accurate.

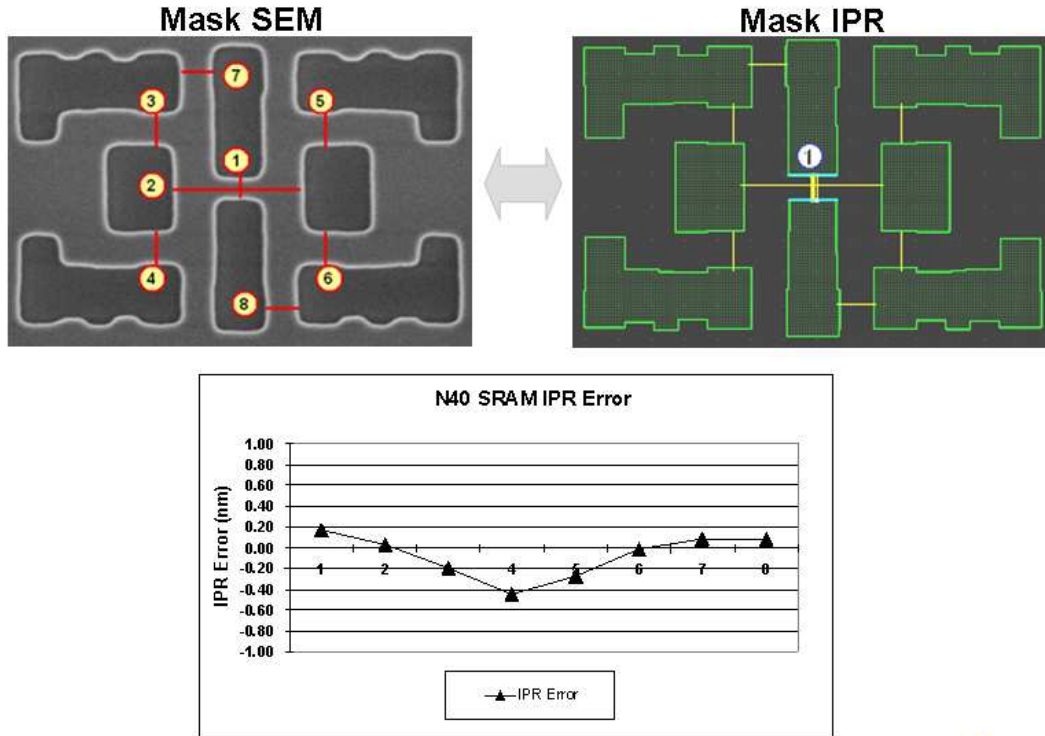


Figure 17. IPR accuracy to mask SEM measurements for an SRAM was between -0.45 nm to +0.16 nm.

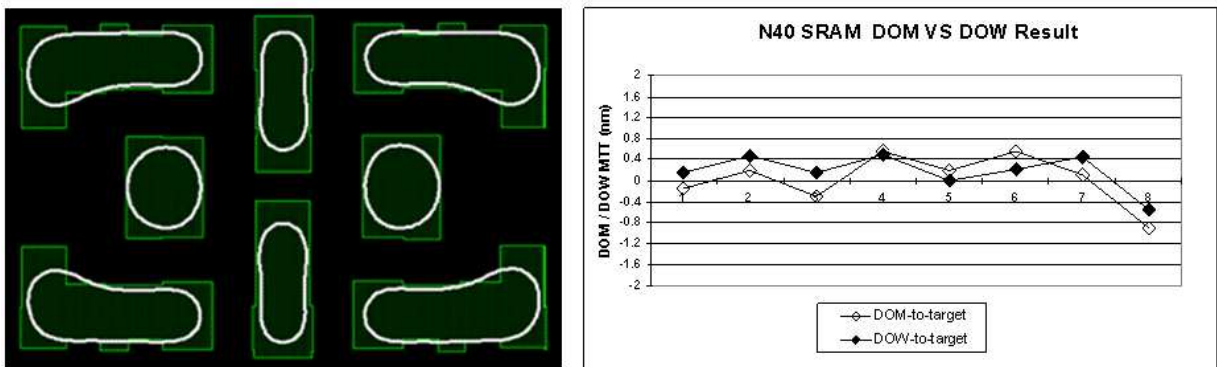


Figure 18. Simulation of IPR shows DOW error between -0.57 nm to +0.51 nm from target, while DOM error for IPR to post-OPC mask pattern is -0.9 nm to +0.55 nm from target. Trends between two are well correlated.

On a set of N28 logic line/space patterns, simulations of IPR mask patterns are compared to simulations of their extracted rounded mask contours. Both IPR masks and extracted rounded mask contours have +/-0.5 nm accuracy to mask SEM measurements, but their simulation results show significant differences as depicted in Figure 23. The measurement of simulation at the horizontal width close to line end tip is a critical measurements. However, due to the application of corner rounding in OPC model plus the rounded mask contour, the line end rounding in the simulation of the rounded mask contour is effectively amplified causing that line end to be pulled back more than compared to simulation of the IPR mask. This effect can be seen in the offset between IPR DOW and Round Mask DOW as it becomes larger from site 1 to site 2. The simulated line width has progressively larger measurements towards the tip. From the graph in Figure 23, simulated measurements at four repeat mask images for IPR DOW show +/-1 nm MTT, while simulated measurements for rounded mask DOW varies from +1 to +3 nm.

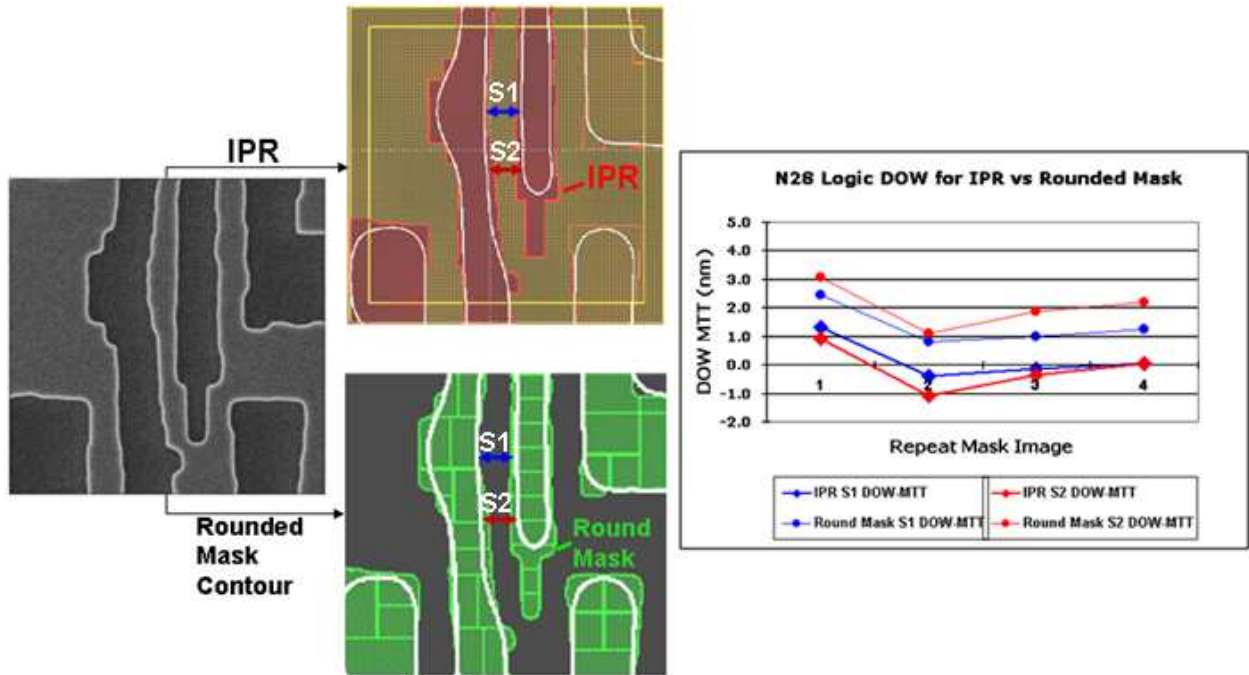


Figure 23. For N28 line space logic pattern, simulation of IPR shows DOW error between ~ +/-1 nm from target, while simulated rounded mask DOW contour is ~+1 nm to ~+3 nm from target. The offset between IPR DOW and Round Mask DOW becomes larger from site 1 to site 2 as the measurements are made closer to tip region where corner rounding plays a significant role.

CONCLUSION

Luminescent's IPR has demonstrated required production accuracy of ± 0.5 nm at TSMC mask shops. The results showed accurate mask rendering of line/space, contact, clear field, and dark field masks for two technology generations (N28 and N40). It has further been demonstrated that these accurate mask rendering can be use for wafer simulations for the purpose of virtual wafer CD metrology. IPR's accuracy enablements are due to 1) accurate SEM image modeling, 2) automated normalization of image intensity variations, 3) detection of signal-to-noise at expected edge locations, and 4) accurate edge rendering with varying algorithms suited for multiple SEM tools models from Holon and Hitachi vendors. Besides the ability to render accurate mask from SEM images, IPR has two other key benefits. IPR's provision of full field mask rendering enables full field mask CD measurement automation without addition SEM time, while the ability to model SEM characteristics enables tool-2-tool matching...even for tools that do not offer measurement biasing capabilities.

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