Application note

New Method for 3D NAND Channel Metrology Using PFIB-SEM DualBeam

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Background

Modern 3D NAND technology is widely used in devices we use in our daily lives, such as solid-state drives and other items. Compared to traditional planar NAND devices, 3D NAND devices provide many advantages, including higher storage capacity, enhanced reliability and durability, and lower latency and cost-per-gigabyte. However, as the aspect ratio of the 3D NAND structure increases with more layers to provide more capacity, manufacturing process challenges and costs are also increasing.

At a high level, the 3D NAND manufacturing process consists of six steps. These are channel hole etch, cell deposition, stacking, staircase and slit etch, slit fill, and staircase contacts.

Of the process modules, channel hole etch is one of the most difficult, generating many metrology challenges as the 3D NAND features within the high-aspect-ratio structure cannot be easily measured by legacy fab metrology tools like traditional optical scatterometry or CD-SEM.

In recent years, new techniques became available to perform channel metrology, such as infrared CD and CD-SAXS [1]. With these techniques, there are two major weaknesses. First, these methods rely on critical modeling processes to provide feedback to the manufacturing process versus direct measurements. The result is a lack of “ground truth” insights that may generate wrong conclusions. Second, these methods provide “big picture” measurements by averaging many channel structures, which obfuscates local channel variations, such as channel-hole-to-channel-hole differences. For process development

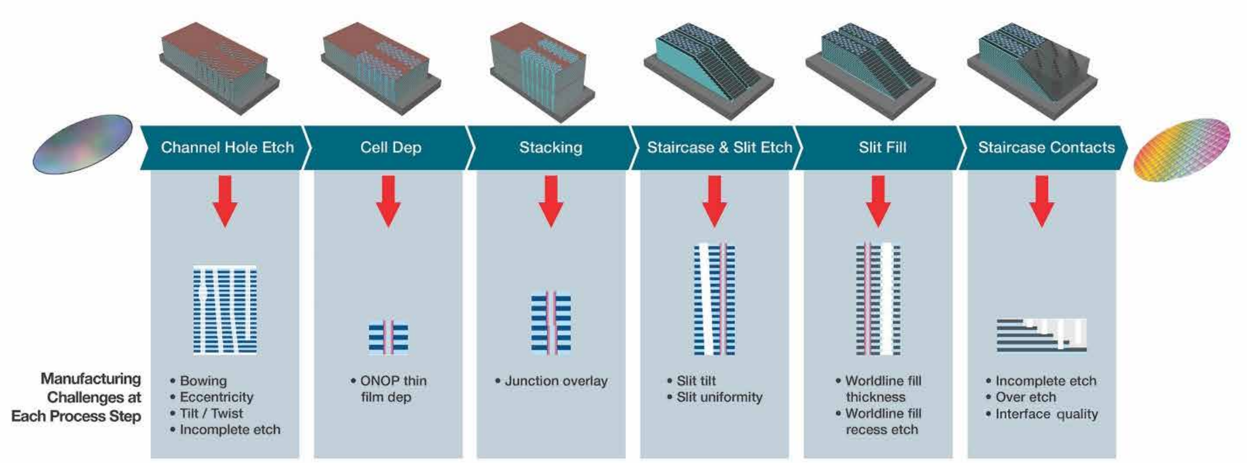

Figure 1. 3D NAND process flow with key challenges at each process module.

and yield improvement, accurate information on local channel variations is important. It is especially critical for process monitoring with potential excursions that occur while processes or device structures are changing.

To overcome the deficiencies of legacy solutions, a solution is needed for fast access to through-stack channel critical dimension (CD) issues, such as tilt and twist, with accurate insights on site-specific local variations across the entire wafer.

PFIB-SEM 3D Metrology

For analyzing 3D NAND structures and measuring CDs buried within devices, the Thermo Scientific™ Helios 5 PXL Wafer PFIB-SEM (plasma focused ion beam scanning electron microscope) can perform site-specific, large-volume materials removal with high-resolution SEM imaging [2]. Automated metrology can be applied on the obtained SEM images for targeted CD measurements, such as channel area, eccentricity, distances to nearest neighbors, etc.[3] This workflow allows you to obtain through-stack, three-dimensional (3D) metrology of the 3D NAND device with rich information on site-specific local CD variations. For 3D NAND analysis, the data provides “ground truth” insights on local process variations that are difficult to obtain with other non-destructive techniques.[1] Or it can be a high-quality reference for other metrology techniques.

Diagonal mill and delayering

Two major applications for 3D NAND channel metrology are diagonal milling and delayering. With diagonal milling, the PFIB mills into the 3D NAND stacks at a zero-degree stage tilt and creates an angled (>28 degrees) cross section of the device. During milling, the SEM takes high-resolution images of memory cells along the angled cross section from the top to the bottom of the 3D NAND stack, as shown in **Figure 2** [2]. The advantage of diagonal milling is the high-throughput acquisition of through-stack metrology from the series of high-resolution SEM images taken along the angled cut face. This provides you with top-to-bottom data for all of the layers with one angled cross-sectional milling. The disadvantage is that it is difficult to obtain local tilt or twist of channel holes traceable to the top layer, because all the analyzed layers along the cut face are not coming from the same array of channel holes.

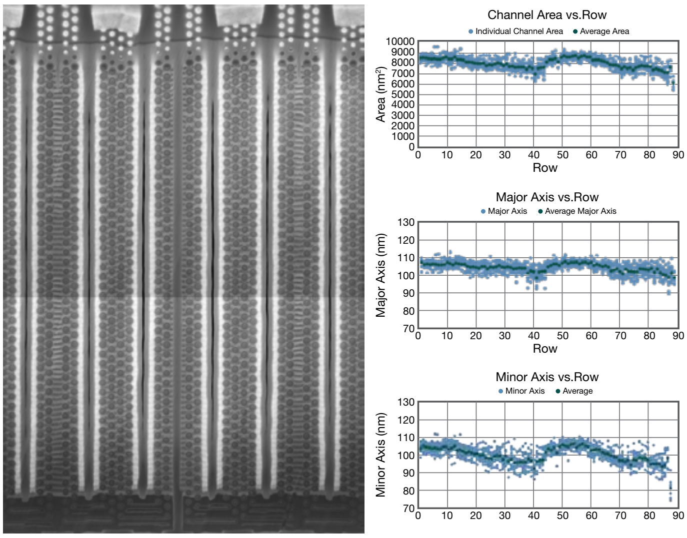

Figure 2. 3D NAND channel metrology using diagonal mill.

To provide traceable measurements of the channel holes to the top layer, delayering can be used. With the delayering application, the PFIB mills through the materials while the stage tilts towards the ion beam with an incident angle of 90 degrees. The Helios 5 PXL DualBeam uses proprietary gas chemistry to assist the milling process so that the delayered surface has a high level of planarity[2]. After the delayering process endpoints to the targeted layer, the stage then tilts towards the SEM for imaging. This application enables a larger number of memory cells to be measured from any single layer in a typical 50x50 µm planarized area, as shown in **Figure 3.**[4] By obtaining SEM images of the top layer and the targeted layer after delayering using a global fiducial marker, local tilt or twist can be measured on the same array of memory cells.[4] The disadvantage of the delayering application is that it can be a relatively slow process to remove all the materials before reaching the targeted layer when the target is buried deep in the 3D NAND stack, and it becomes more challenging to obtain traceable data as layer counts increase.

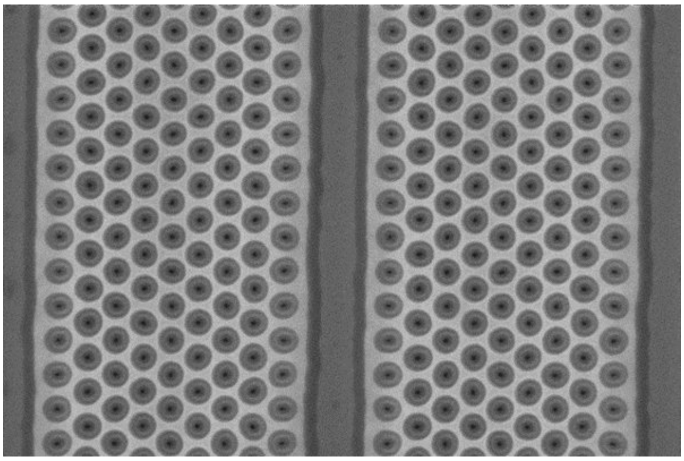

Figure 3. An SEM image showing many 3D NAND memory cells after delayering.

A third method for analyzing the 3D NAND device is using either a diagonal milling or delayering application to take thin slices of the structure and a series of SEM images to reconstruct the entire 3D dataset [4]. This application, although providing the most comprehensive data of the 3D volume, requires SEM images to be taken after each thin slice of material is removed. Therefore, it can be relatively time-consuming compared to the previous two applications.

New Method

We now introduce a new application for channel hole metrology, combining the advantages of diagonal milling and delayering applications, that measures local tilt or twist traceable to the top layer in a timely fashion. We use a commercial 3D NAND device to demonstrate this new application. There are three major steps you can follow for this application to generate channel metrology data.

Step 1: Delayering & SEM Imaging

The first step is to obtain a reference SEM image from the first layer of the 3D NAND device that will be used later for the coordinate traceability. Without this high-resolution SEM image, data obtained from any targeted layers at deeper locations of the device cannot be correlated to the top layer and the local variation is not traceable. The workflow at **Step 1** is as follows:

1. Navigate to the region of interest (ROI) in the 3D NAND memory cell array.
2. Set eucentric height.
3. Tilt the stage to 52 degrees.
4. Insert the GIS / MultiChem for the delivery of the delayering gas chemistry.
5. Load or set the pattern for delayering process.
6. Start the delayering application as shown in **Figure 4**.
7. The stage current monitor can be used as the end-pointing indicator for the process and allows the delayering to stop at the target layer (**Figure 5**).
8. Use low ion beam current to make a global fiducial as the coordinate reference (**Figure 6**).
9. Retract the GIS / MultiChem.
10. Tilt the stage back to 0 degree.
11. Take a high-resolution SEM image of the reference area as shown in **Figure 6**. Recommended imaging conditions: 5 kV, TLD, secondary electron mode.

After **Step 1**, you will have obtained the first high-resolution SEM image of the ROI from the target 3D NAND layer, i.e., the first layer with memory cell arrays. The next step is to obtain the second high-resolution SEM image of the ROI, including all the layers underneath, after diagonal milling.

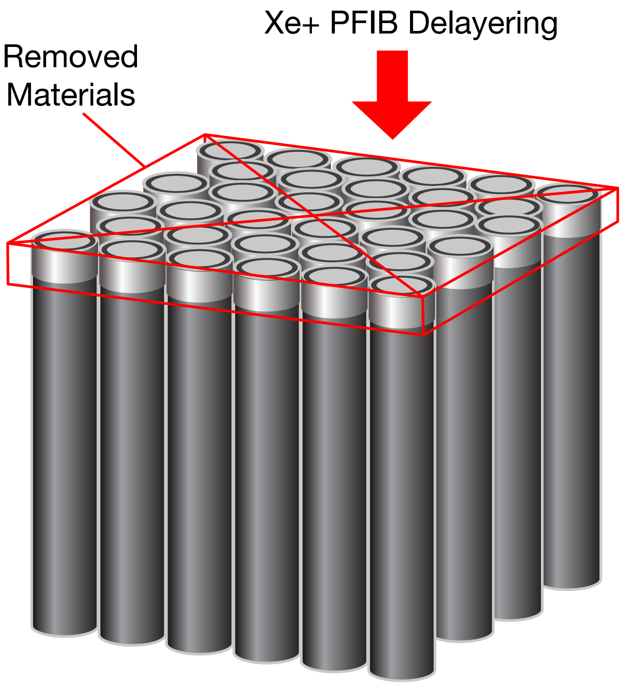

Figure 4. Diagram showing the delayering application using Xe+ PFIB.

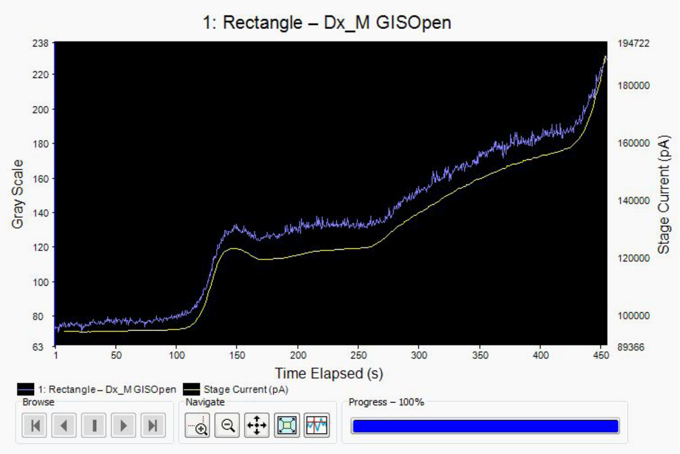

Figure 5. Automated end-pointing process using the Stage Current Monitor.

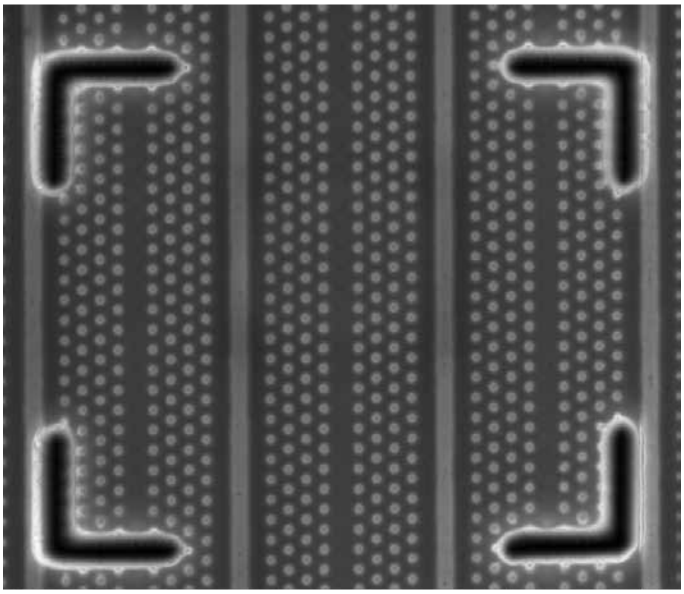

Figure 6. The global fiducial marker used as the coordinate reference.

Step 2: Diagonal Milling & SEM Imaging

This step is to obtain the second SEM image on the angled cut face of diagonal milling. The image contains information of memory cells from all the layers underneath that can be used for metrology on local tilt or twist of the channel holes. The workflow at **Step 2** is as follows:

1. Keep the stage tilt at 0 degree. For more layer exposure, the stage can be tilted to a negative degree with the maximum at negative 10 degrees.
2. Align the field of view of the FIB and make sure it is centered around the ROI.
3. Insert the GIS / MultiChem for the gas chemistry delivery of the protective layer deposition.
4. Deposit a protective layer for the diagonal mill application.
5. Retract the GIS / MultiChem.
6. Load or set the pattern for diagonal mill.
7. Start the diagonal mill as shown in **Figure 7**.
8. Perform low-kV cleaning as needed.
9. Keep the stage tilt at 0 degree.
10. Take the second high-resolution SEM image as shown in **Figure 8**. Recommended imaging conditions: 5 kV, TLD, secondary electron mode.

After **Step 2**, you now have two high-resolution SEM images on the 3D NAND memory cell array that can be used for coordinate correlations. The last step is to correlate the two images using the global fiducial marker and extract key metrology information.

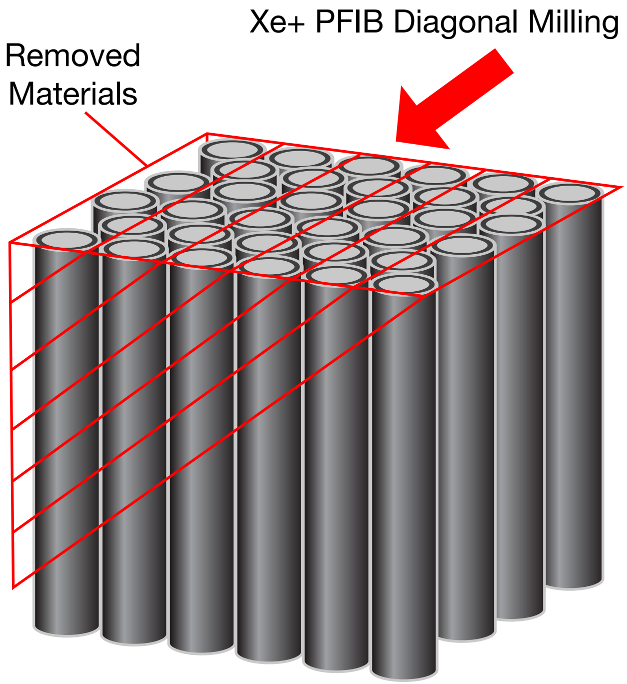

Figure 7. Diagram showing the diagonal milling application using Xe+ PFIB.

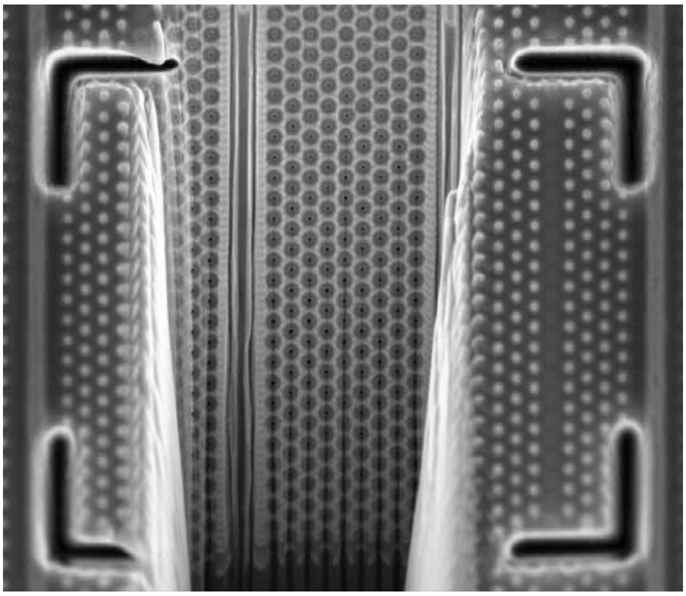

Figure 8. The second high-resolution SEM image of the angled cut face after diagonal milling.

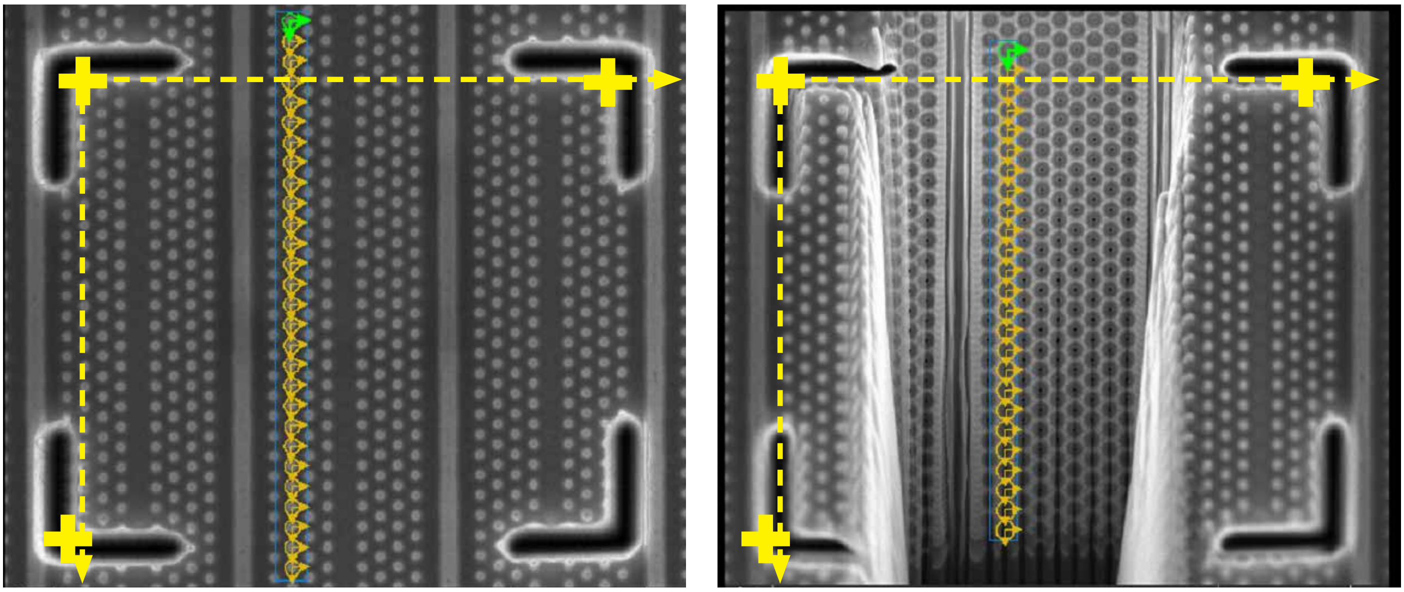

Figure 9. Feature extraction from the two SEM images using iFast or Recipe Editor.

Step 3: Feature Extraction & Metrology

At this step, you can process the two SEM images using *iFast* or *Recipe Editor* on the Helios 5 PXL as shown in Figure 9. The correlated memory cells from the two images are extracted based on the locations of the global fiducial. The global fiducial ensures that the relative coordinates of the extracted features can be compared for metrology purposes.

Figure 10 shows the average tilt of each measured channel hole based on the coordinate comparisons of the extracted features. By comparing the coordinates of correlated channel holes in both X and Y directions, the relative shifts of the feature centers are measured as a function of depth. This method provides two benefits. First, all the channel holes in the ROI can be measured in a highly localized manner, so that channel-hole-to-channel-hole differences can be accurately evaluated. Second, by combining the delayering and diagonal milling applications, local tilt or twist from all the underneath layers can be traced back to the top layer, which provides unique insights to 3D NAND process variations.

This new method combines the advantages of delayering and diagonal milling applications to deliver highly localized and traceable channel metrology as well as faster time to data.

Table 1 (next page) summarizes the comparisons of the new method to existing metrology applications on Helios 5 PXL.

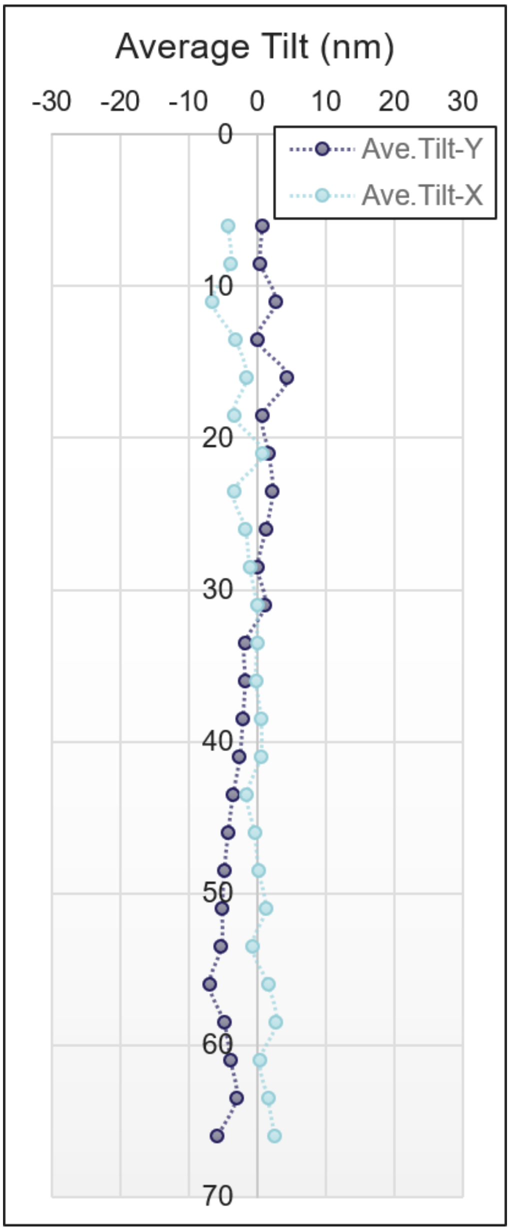

Figure 10.Average tilt from each measured channel hole relative to the top layer.

Method	Delayering (specific layers)	Diagonal Milling	Delayering / Diagonal Milling +3D Reconstruction	Diagonal Milling / Diagonal Milling (new method)
Data volume	Small	Medium	Large	Medium
Time to data	Slow	Fast	Slow	Fast
Traceability of local channel variations (tilt, twist, etc.)	Medium	Low	High	High
Suitable manufacturing stage	Process development, Yield enhancement	Process development, Yield enhancement	Process development	Process development, Yield enhancement, Process monitoring

Table 1.New method and existing metrology applications on Helios 5 PXL

Summary

Manufacturing 3D NAND can be challenging, especially as legacy analysis solutions are not able to accurately measure the critical dimensions of features buried within the device. To overcome the deficiencies of legacy methods, a new solution is needed.

In this paper, we present the Thermo Scientific Helios 5 PXL and four methods to acquire ground truth metrology data to advance process development and yield improvements. The three methods discussed are diagonal mill, delayering, 3D reconstruction and a new method that combines the first two.

While each of these methods provide CD data, the first three have some limitations. To overcome these, a new method combines diagonal mill and delayering. This new method delivers a balanced benefits of data volume, time to data, and traceability of local channel variations. The balanced benefits make this new method suitable for different manufacturing stages, including process development, yield enhancement, and process monitoring.

References

1. Peters, Laura. (2023) "How Metrology Tools Stack Up in 3D NAND Devices" *Semiconductor Engineering* 15 March 2023 (**link**)
2. Thermo Fisher Scientific 3D NAND Whitepaper (2023) "3D Metrology of Advanced 3D NAND Architectures" (**link**)
3. Najarian, Mark (2022) "Helios 5 PXL In-line 3D Metrology Solutions" *M&I Forum,* Semicon Korea 2022
4. Tien, David (2022) "3D Profiling of Individual Memory Holes by Delayering" *International Conference on Frontiers of Characterization and Metrology for Nanoelectronics (FCMN) 2022*

Learn more about Thermo Scientific memory metrology solutions:

Learn more about the Thermo Scientific Helios 5 PXL Wafer PFIB-SEM: