Contour metrology for process matching and OPC qualification with machine learning-based site selection

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INTRODUCTION

Matching a manufacturing patterning process is a complex project with multiple components: identification of process critical sampling site locations, metrology at those locations, post metrology data extraction, and finally a decision of whether the processes are sufficiently matched. It is required to have robust process matching to ensure an OPC solution is suitable across tools, fabs, and even mask manufacturers thus providing foundry flexibility to meet customers' supply chain requests while maintaining a streamlined OPC execution procedure.

Metrology plays a key role in the qualification process and yield ramp. Traditional metrology to qualify the litho/etch process for one critical layer focuses on gauge CD matching of selective locations (test-patterns, SRAMs, process hotspots), while the abundant information of the CDSEM images is discarded. With the increase of process and product design complexity, the CD-only method is no longer enough to ensure process matching between the two fabs. Extracted SEM contours together with CD metrology can provide a complete representation of the quality of process matching of one layer. Recent developments in machine learning and image analysis enable the community with new tools to take advantage of increased information available in contour metrology. In this paper, we present a process matching flow. Starting from selection of verification patterns that can best represent production design chip based on machine learning clustering method, followed by accurate SEM contour extraction, contour comparison and scoring with EPE heatmap and histogram, we are able to quantify the process difference, which can significantly improve the efficiency on process technology transfer from one fab to another.

Machine-Learning Based Site Selection

Identifying critical sites in production layouts is essential yet challenging. Traditional methods face constraints due to time and equipment limitations. Our innovative approach integrates intelligent methodologies to identify and categorize unique patterns, reducing redundancy, and enhancing efficiency in comparing tools, processes, and manufacturing sites.

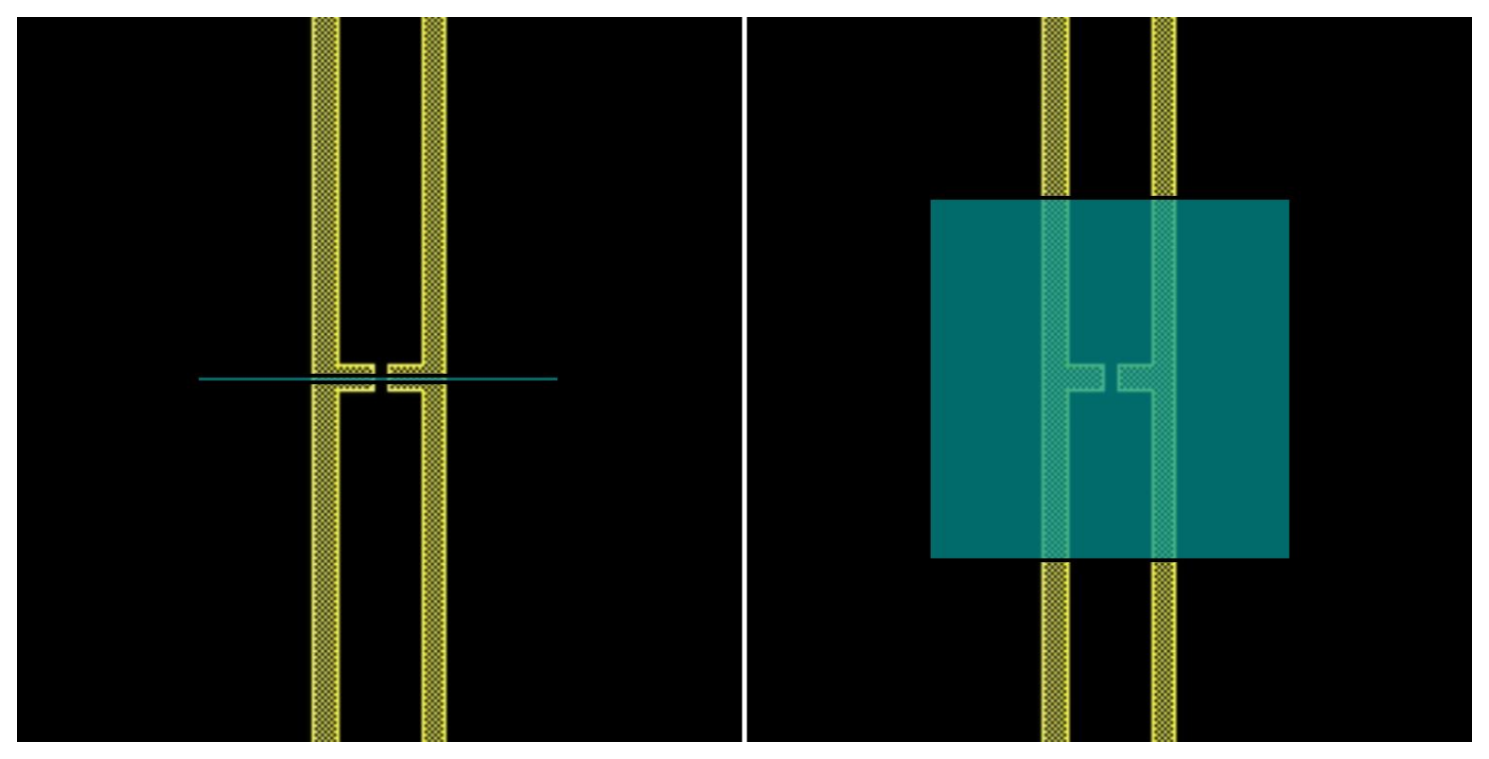
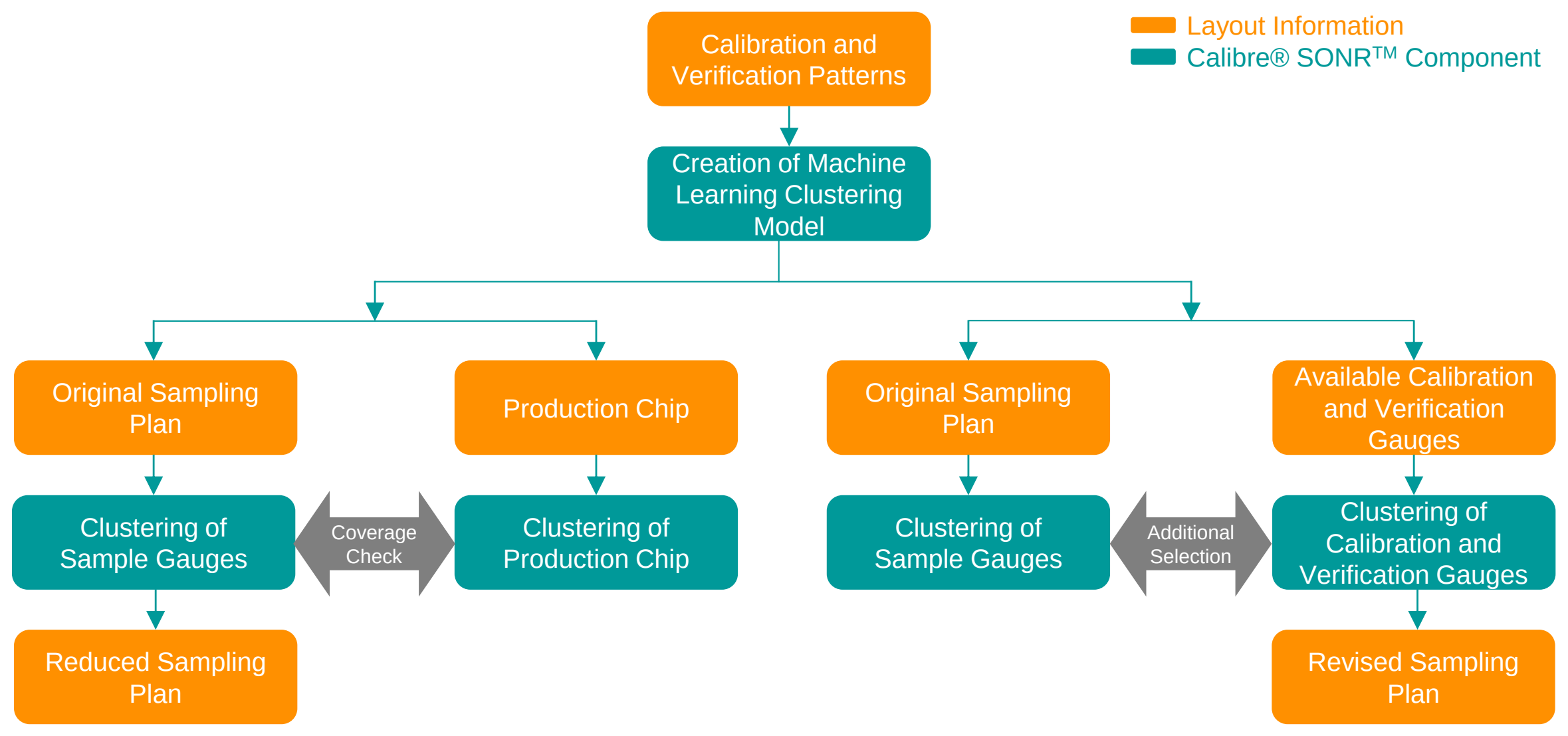


Figure 1: Representative Selection Regions for CD and Contour Analysis

Contour sites, focusing on 2D patterns, provide extensive data from SEM images compared with traditional CD gauges. To augment our production chip's verification set, we aim to identify additional gauge sites.



Layout Information
Calibre® SONR™ Component

Calibration and Verification Patterns
Creation of Machine Learning Clustering Model

Original Sampling Plan
Clustering of Sample Gauges
Coverage Check
Production Chip
Clustering of Production Chip
Reduced Sampling Plan

Original Sampling Plan
Clustering of Sample Gauges
Additional Selection
Available Calibration and Verification Gauges
Clustering of Calibration and Verification Gauges
Revised Sampling Plan

Figure 2: Methodology for Determining Additional Gauge Sites

Clustering model is developed using gauge sites from the test mask, focusing on features like optical properties, resist model properties in addition to geometry features. We then evaluated the coverage of our initial sampling plan against the production chip and existing gauges. SONR clustering can then generate a reduced sampling plan and additional gauge sites that improves the coverage.

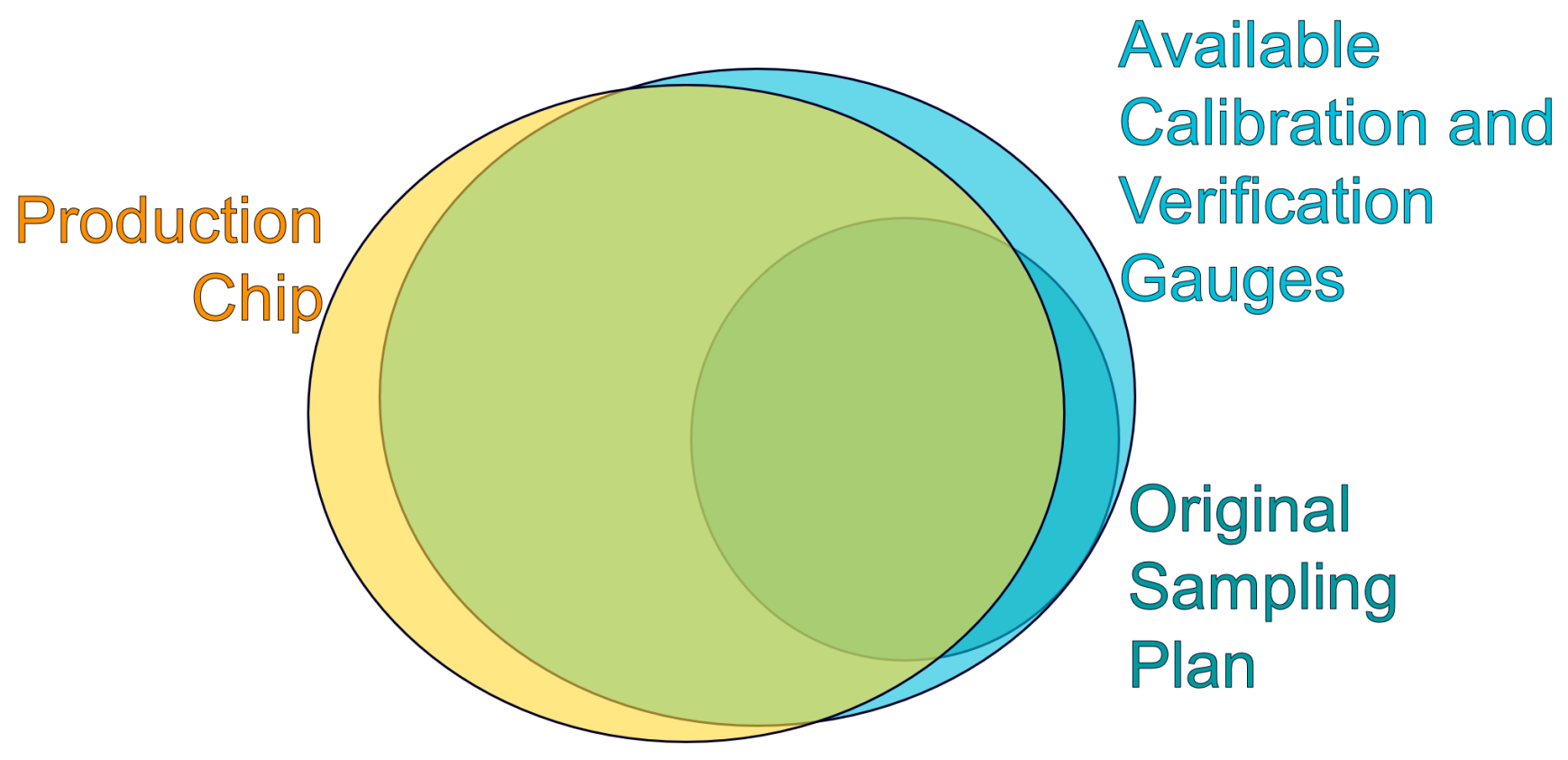


Figure 3: Venn Diagram of Gauge Overlap Among Evaluated Layouts

The logical relationship between the three sets are shown here. The original sampling plan (small circle), as a subset of the available calibration and verification gauges (big light blue circle), covers a limited part of the production chip. To ensure comprehensive and efficient coverage of the design of the production chip, we can append the original sampling plan with CD gauges and contour sites from the pool of other calibration and verification gauges on the test chip (big light blue circle). It is also possible to select sites directly from the production chip (yellow circle) to complement the coverage of original sampling plan. One can also see ways to supplement the full calibration and verification test chip from patterns from the production chip.

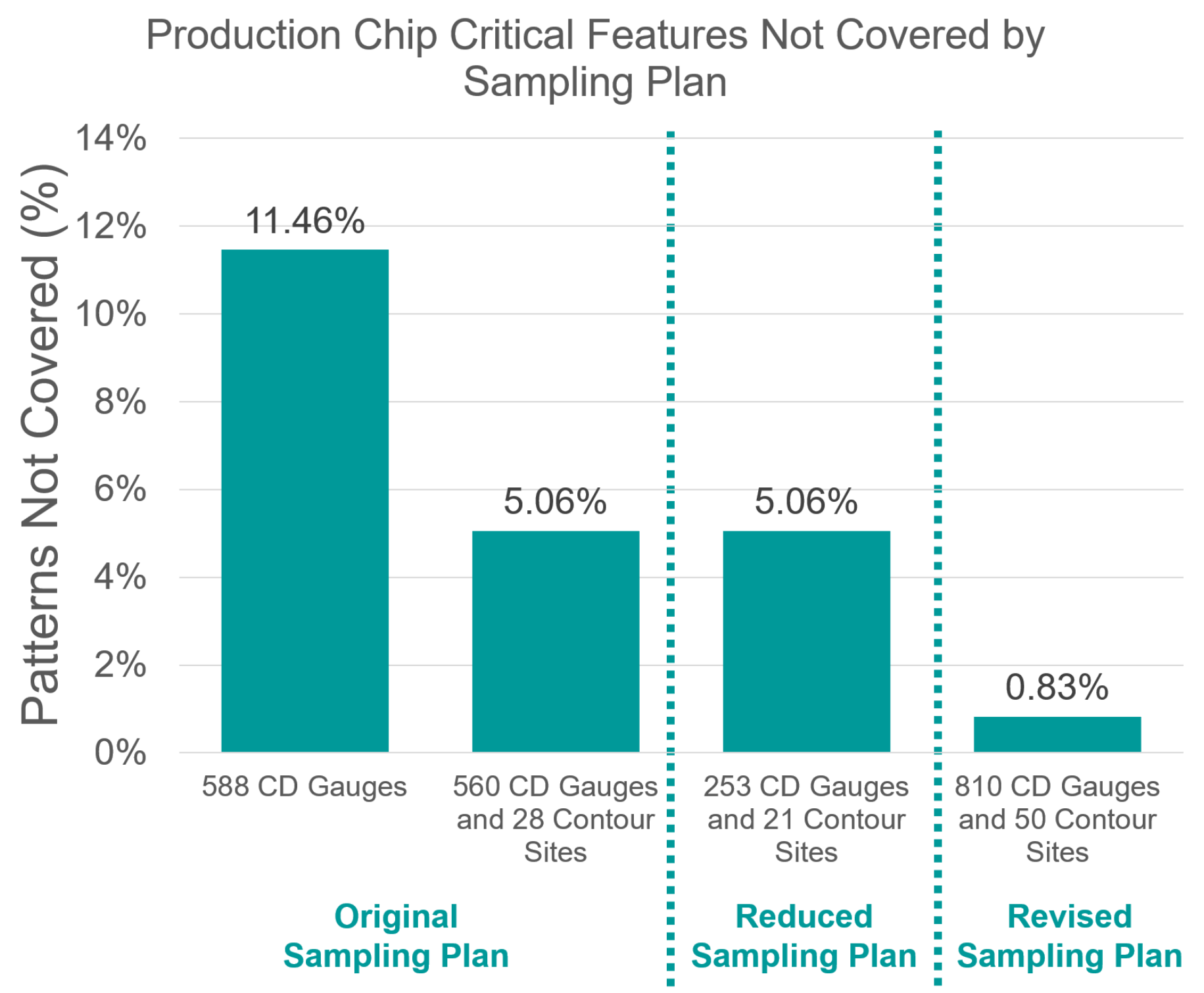


Figure 4: Coverage Comparison Chart

A comparison of different sampling plans shows how much of the critical features in chip production are not covered by these plans. Using a combination of CD measurements and contour analysis significantly lowers the number of uncovered features compared to using only CD measurements. The reduced sampling plan achieves the same coverage as the original plan while using only 45% of the CD measurements and 75% of the contour sites. The updated sampling plan can cover more than 99% of the critical patterns in the production chip.

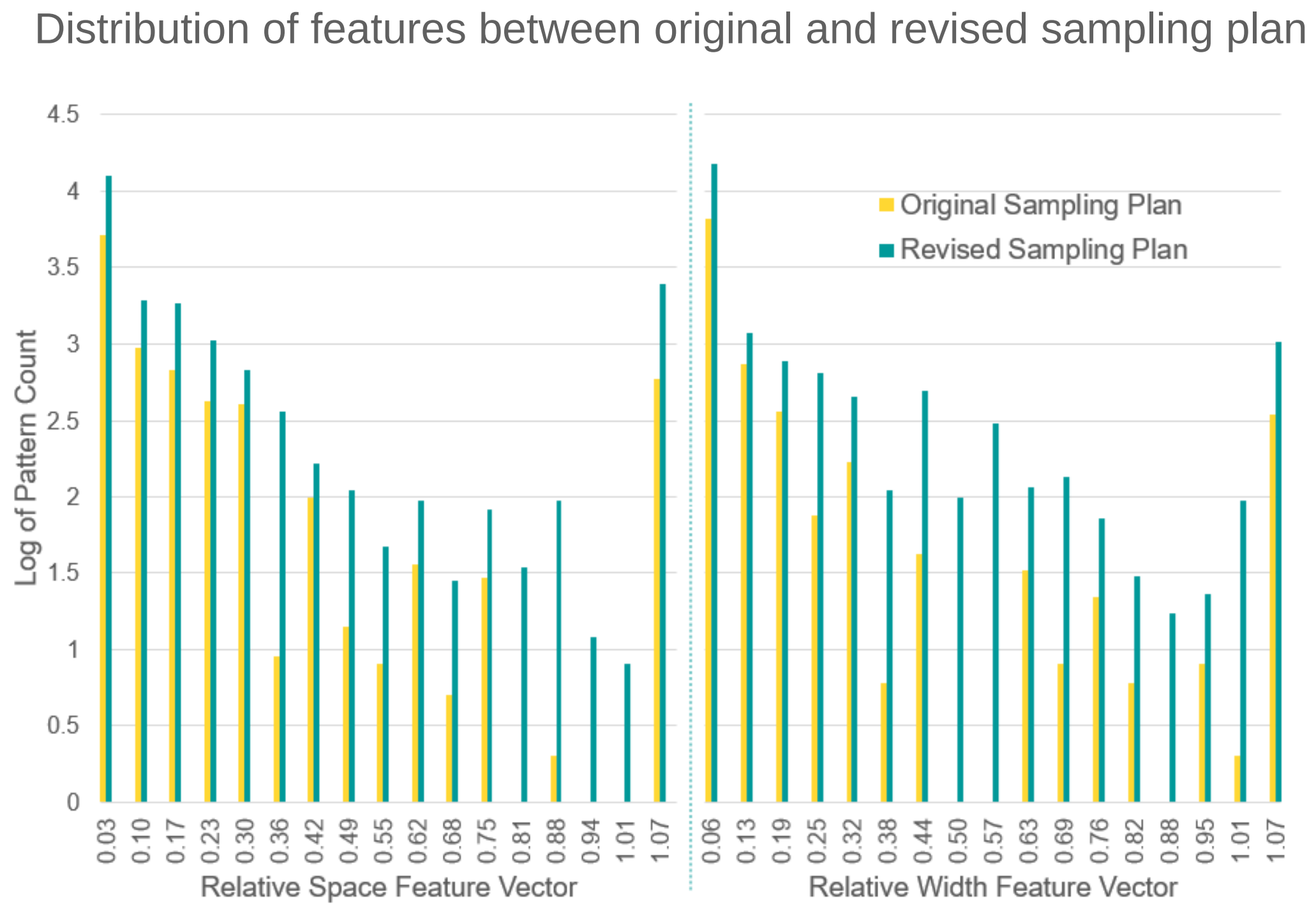


Figure 5: Model Coverage Distribution Differences for Space and Width Features

The revised sampling plan, with the inclusion of additional gauge sites, is analyzed for its impact on model coverage. Take space and width features as example, the revised plan has a more complete distribution in both the space and width space, same for other features that are not explicitly shown here. The enhanced coverage can be observed at the feature level as well.

Contour Metrology for Process Matching

SEM Images
Extracted Contours
Filtered Contours
Average Contours
Final Aligned Contours

Figure 6: Schematic flow of contour extraction and post-processing

Calibre® SEMSuite™ was utilized to extract contours from each individual SEM images with bad extracted contours filtered out. Repeated field contours were overlapped to generate the average contour that are aligned to smooth target layer. Final aligned contours can then be used for process matching comparison.

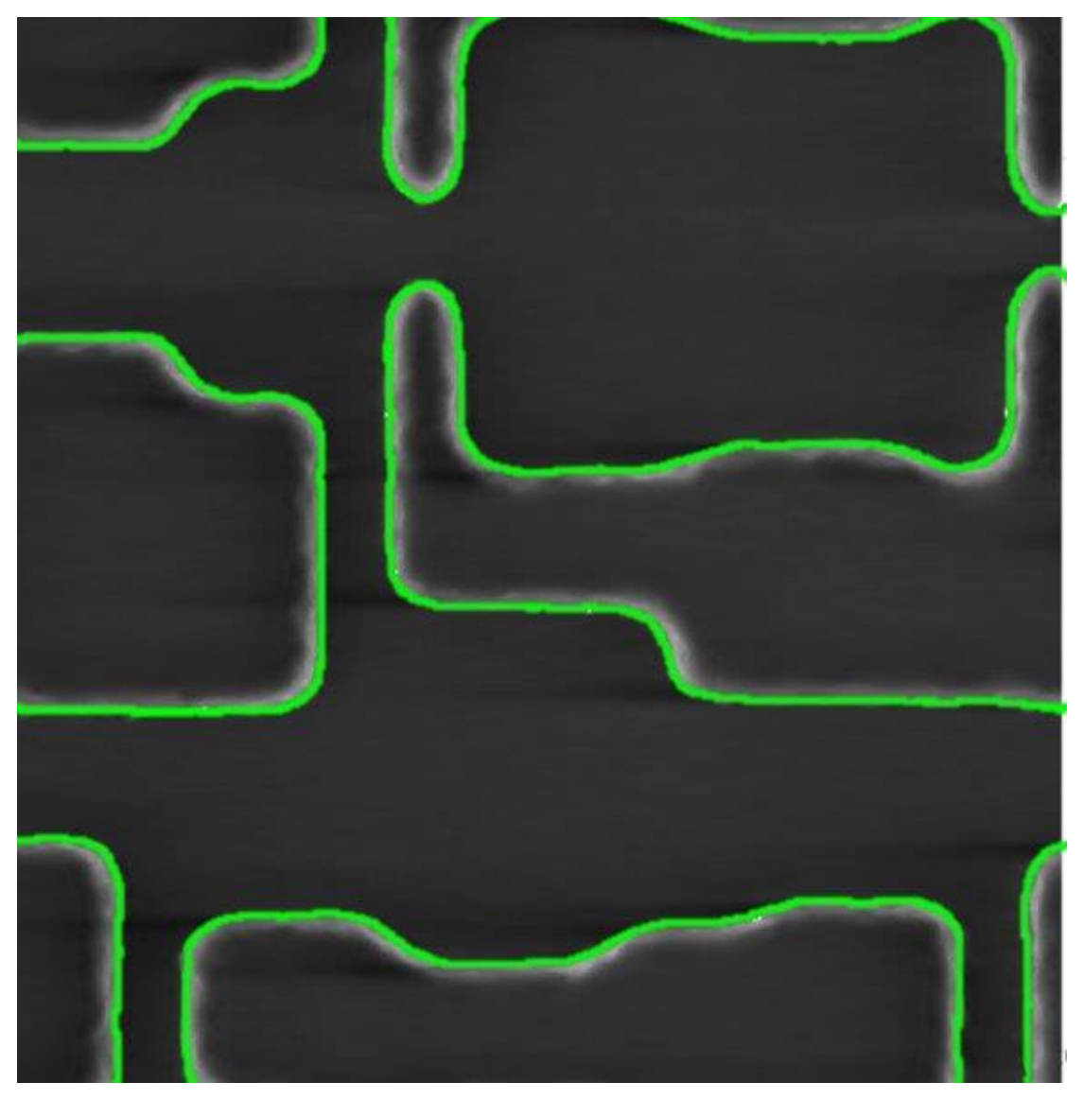


Figure 7: Extracted contour and SEM image overlay

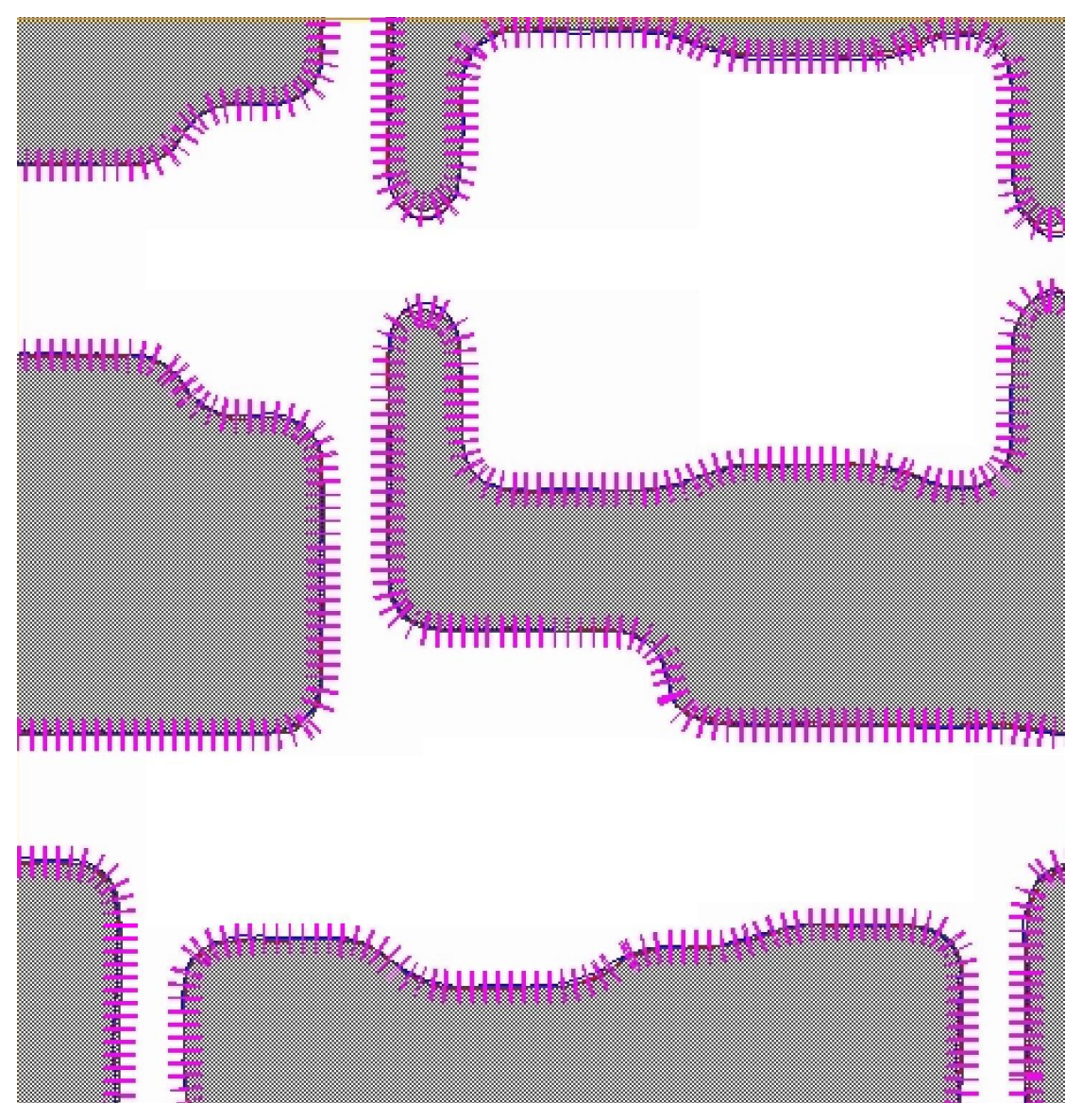


Figure 8: Measurement sites placed at regular interval along reference smooth target layer

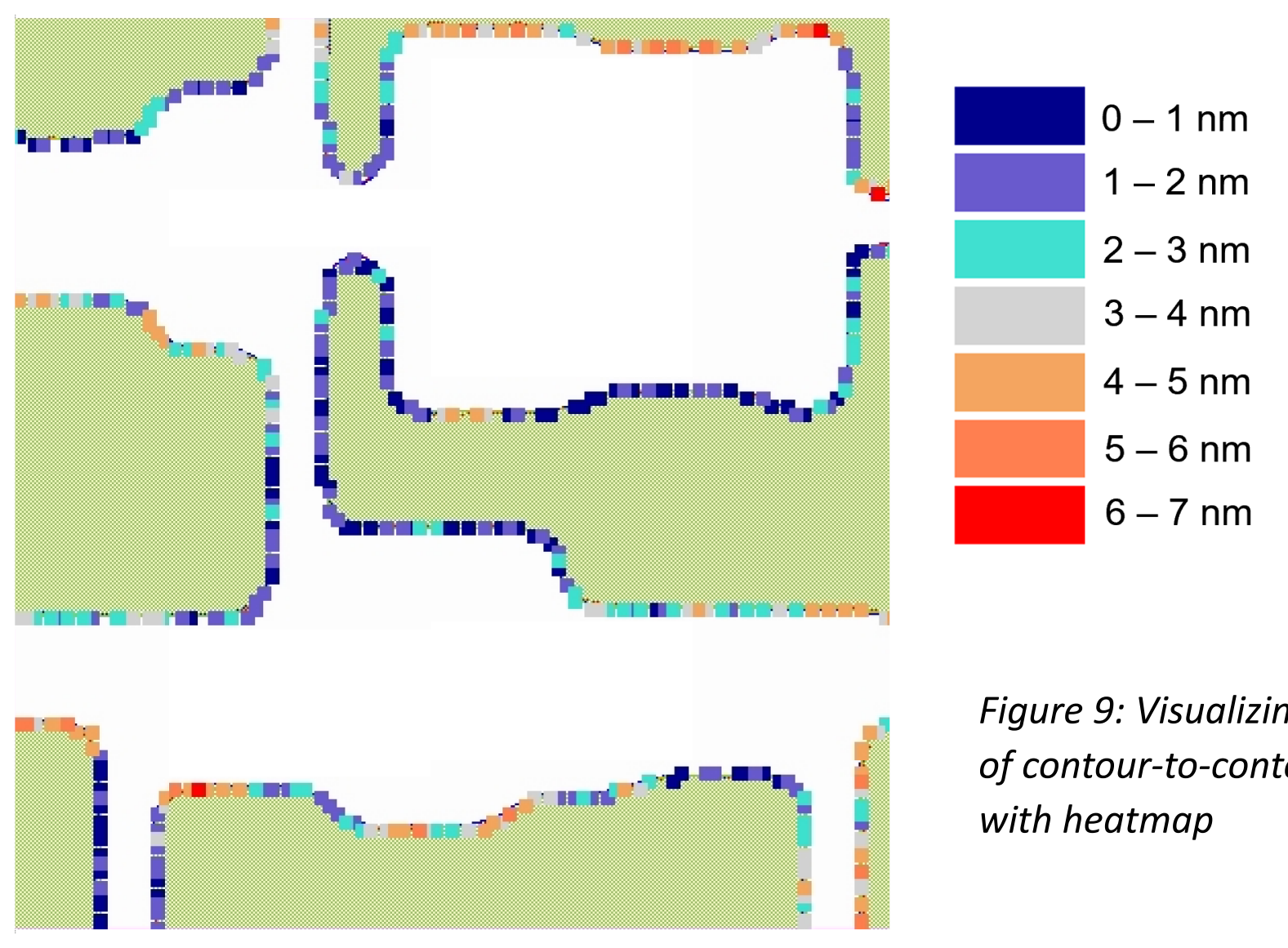


Figure 9: Visualizing magnitude of contour-to-contour difference with heatmap

Process matching with traditional metrology relies on CD matching on single measurement gauge of selected locations. In contrast to traditional CD measurement, contour metrology performs hundreds of measurements for each pattern significantly increases sampling size (Figure 8). Measurement sites are placed at regular interval along smooth target layer. For each measurement site, distance difference between the two extracted SEM image contours for respective fab were measured. In order to understand the contour-to-contour difference distribution across the layout design, a heatmap plot is generated, with each measurement site assigned with the difference data values represented using different colors. The diverging color scheme is used such that darkest blue represents the lowest difference and darkest red represents the highest difference with grey represents the center value. The heatmap plot in Figure 9 enables quick visualization of the magnitude of contour-to-contour difference on various part of layout.

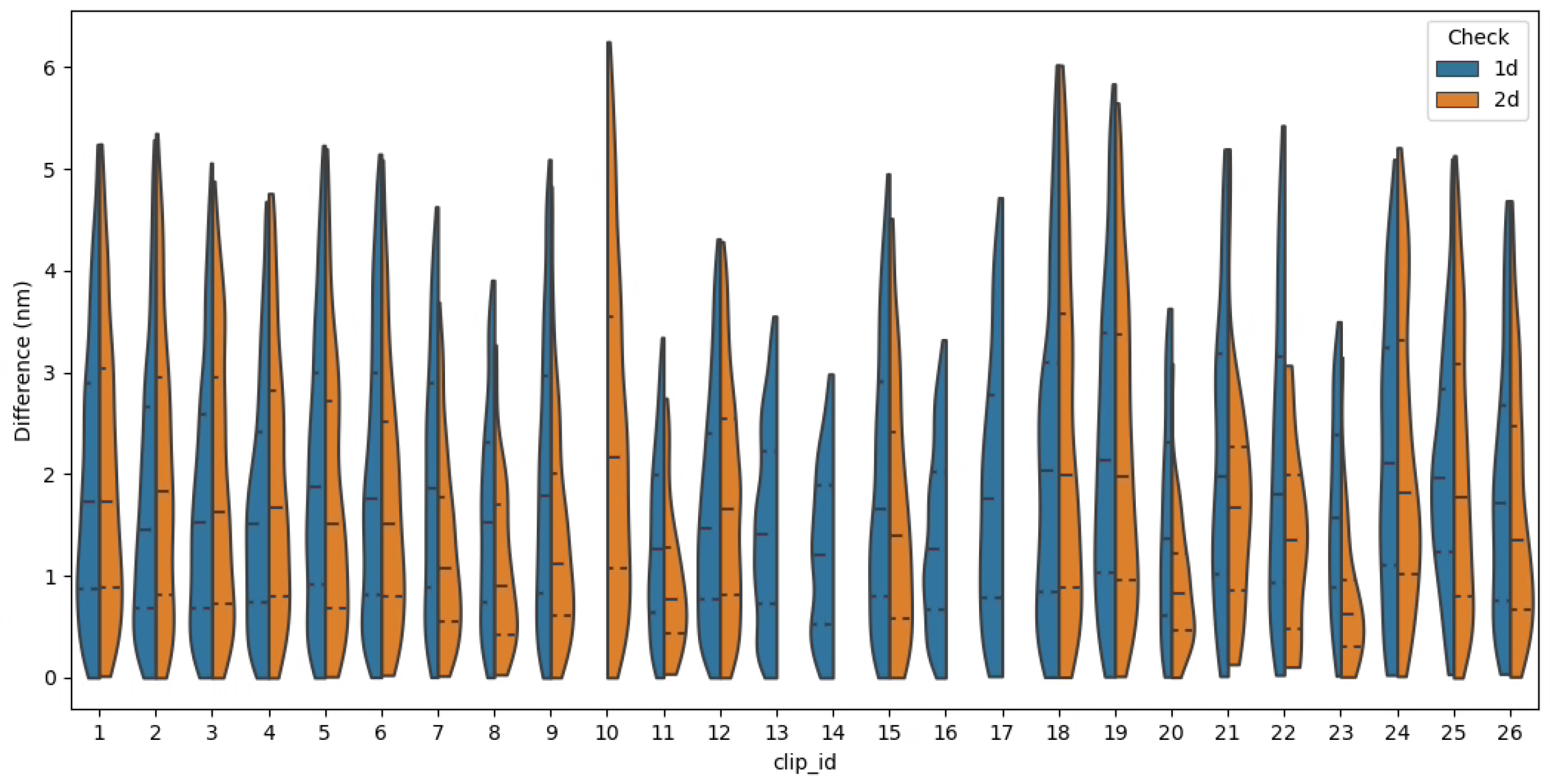


Figure 10: Split violin plots of contour-to-contour difference across all the compared patterns

The contour-to-contour difference across all the compared patterns is summarized as split violin plots for process matching comparison. Left side of split violin plots in blue shows distribution of 1D measurements group and right side of split violin plots in orange shows distribution of 2D measurements group with dashed line representing quartiles for each group. We use the interquartile range method to identify the lower and upper limits of the data set. The upper limit is defined as Q3 + 1.5 (Q3-Q1) and the lower limit is defined as Q1 – 1.5 (Q3-Q1). Any data point outside of the upper and lower limits are identified as outliers and filtered out from the summary plots.

CONCLUSIONS

We present a contour metrology-based process matching flow with machine learning based site selection for best coverage and contour comparison and scoring to quantify the process difference. This method can significantly improve the efficiency on process technology transfer from one fab to another. The key technology includes: 1) High-performance ML clustering on full chip product with hundreds of millions anchoring points 2) process-matching oriented custom feature engineering that drives quantitative understanding of each SEM image 3) Stable and reliable contour extraction of large amount of CD-SEM images.

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