

# Automated creation of production metrology recipes based on design information

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## ABSTRACT

The volume of measurements and the complexity of metrology recipes in state-of-the-art semiconductor manufacturing have made the conventional manual process of creating the recipes increasingly problematic. To address these challenges, we implemented a system for automatically creating production metrology recipes. We present results from the use of this system for CD-SEM and overlay tools in a high-volume manufacturing environment and show that, in addition to the benefits of reduced engineering time and improved tool utilization, recipes produced by the automated system are in many respects more robust than the equivalent manually created recipes.

**Keywords:** design-based metrology, automatic recipe creation, CD-SEM, overlay

## 1. INTRODUCTION

Creating and maintaining production metrology recipes is an expensive process in modern semiconductor manufacturing. For many types of metrology, a new recipe must be created for each masking layer in a new device. As the number of layers in a device and the number of devices running in a fab increase, the volume of metrology recipes can become quite large, ranging into the hundreds or even thousands of recipes for each metrology type. Creating that many recipes may require significant tool time, lowering the metrology tool capacity available for production metrology. In addition, the process of creating such a large volume of recipes manually is inherently error-prone, as the level of complexity for state-of-the-art metrology tools makes it very easy to overlook an incorrect setting during the recipe creation process. Recipe errors may be subtle and hard to detect, but can have significant consequences on the quality of the measurements they produce. The process of manually creating a recipe on a metrology tool may also introduce errors related to the tool itself (for example, charging effects specific to a particular tool may impact the navigation accuracy). These tool-specific effects reduce the portability of a metrology recipe to other tools of the same type.

For these reasons it is highly desirable to increase the level of automation in the production metrology recipe creation process. The concept of design-based metrology has received significant attention in recent years, primarily for creating very large CD-SEM recipes for OPC model building and verification.<sup>1,2,3</sup> In this work, some of the same ideas have been applied to the automatic creation of production metrology recipes. The principle is to identify production metrology sites during the design phase and tag these sites in the layout. After the design tapeout is complete, the metrology site locations may be extracted from the layout database. We have implemented an automated system to perform the necessary transformations from the design coordinate system to the wafer coordinate system. Relevant information required to make a measurement may also be attached to each site, including pattern recognition templates for alignment and information about the measurement target parameters (line widths, pitch, etc.). Finally, the site and measurement information can be combined to create a metrology recipe for distribution to the tools.

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## 2. REQUIREMENTS FOR PRODUCTION RECIPE CREATION

In general, a metrology recipe consists of the following components:

- **Site list:** a list of  $(x, y)$  coordinates in the exposure field coordinate space where measurements are to be made.
- **Pattern recognition information:** locations of locally unique patterns that are used for aligning the wafer, as well as reference patterns for comparison. Typically pattern recognition is performed using an optical microscope at two to three locations around the wafer for “global” alignment of the wafer. For metrology types with high placement accuracy requirements such as CD-SEM, a second “local” alignment step may be performed using a higher magnification. In some cases a simulated or “synthetic” image may be used as the pattern recognition template, although it is preferable to use clips taken directly from the layout data (*i.e.*, GDS or OASIS format).
- **Measurement parameters:** all information necessary to configure the metrology tool to make the requested measurement, including hardware and algorithm settings.
- **Runtime parameters:** a set of instructions specifying how the recipe should be run (*e.g.*, what to do if a measurement fails or if the pattern recognition target cannot be found).
- **Sampling plan:** a list of fields on the wafer to measure.

The conventional method for creating metrology recipes typically requires an engineer to take a metrology tool offline, load a wafer, manually move the wafer stage to the measurement sites and record their locations, create pattern recognition templates by acquiring optical or SEM images of the desired alignment targets, and adjust all measurement and runtime parameters as needed. To automate this process, all necessary information must be made available in such a way that a software application can access it as needed without user input. It should also be noted that good fleet matching is an absolute necessity for successful deployment of automatically created recipes. Otherwise, the same recipe may behave differently on individual tools, leading to poor measurement quality. Also, some metrology tool types perform an automated recipe optimization step the first time a new recipe is run. In this case, extra care must be taken to ensure that the optimized recipe is synchronized across the tool fleet or to carefully compare the optimized recipes across multiple tools to confirm that no significant differences exist. We discuss considerations specific to some of the common metrology types in the following sections.

### 2.1 CD-SEM

As mentioned previously, CD-SEM measurements often have a demanding requirement for high measurement placement accuracy as the target features are often quite small. Therefore, a local pattern recognition step is often employed in addition to the global alignment step. For the purposes of creating a recipe automatically, an algorithm is employed to search the design for an area that is “locally unique” to find a pattern suitable for pattern recognition for both the global and local alignment steps. For measurement of resist layers, it is usually desirable to limit the exposure of the measurement target location to the electron beam to minimize resist shrinkage. Therefore, the local pattern recognition site should be chosen such that it does not expose the measurement location if possible.

In addition, the pattern recognition selection algorithm must be aware of what design layers are visible to the CD-SEM. For many applications, multiple layers may be visible and the software must be aware of this to create a reliable template for pattern recognition and accurately place the measurement box (for example, the user may want to measure a gate only where it overlaps an active area).<sup>4</sup>

Information about what type of measurement to make (linewidth, pitch, contact/via, tip-to-tip, etc.) must also be communicated for each measurement site, along with any algorithm parameters and hardware settings relevant to that measurement type (*e.g.*, beam voltage, number of scans, etc.).

### 2.2 Overlay

Overlay measurements have a less stringent placement accuracy requirement than CD-SEM because the measured features are much larger. Therefore, typically only a single global alignment step is required. However, overlay measurements by definition require that multiple patterned layers are visible, and the algorithm that selects the pattern

recognition target must be aware of this. Furthermore, the measurement algorithm must know to which layers the different features of the overlay target mark correspond so that it can correctly calculate the various overlay model parameters.

Increasing attention is being devoted to in-die placement of small overlay marks for more accurate understanding of the overlay behavior within the functional chip area.<sup>5,6</sup> The small size of these marks combined with the fact that they are surrounded by chip features (as opposed to more easily identifiable test features in the scribe area) typically makes them much more difficult for a human operator to locate during overlay recipe creation. In addition, the number of in-die overlay targets is often much greater than conventional scribe area arrangements, requiring a much longer time to create the recipes manually. Therefore, the capability to create recipes that employ in-die micro-targets automatically is essential to successful deployment of in-die overlay measurements.

Again, information about the measurement target (type, dimensions, layers, etc.), measurement algorithm, and tool settings (*e.g.*, illumination conditions) must be passed to the system for recipe creation.

### **2.3 Scatterometry**

Automatic recipe creation for scatterometry recipes is still relatively immature compared to CD-SEM and overlay. In many respects, the requirements are similar to those of overlay metrology. The measurement locations are typically relatively large grating features that are not difficult to locate for a pattern recognition algorithm. Information about which scatterometry model to use in the measurement and any relevant hardware settings must be available for the system to use in recipe creation.

Of course, this analysis does not include the effort required to develop a robust scatterometry model, which is nearly always a much more intensive effort than the creation of the production recipe. The engineering effort required to build the scatterometry model likely means it will not be possible to fully automate the entire recipe creation process for the foreseeable future. However, once a model for a given process layer is available, it should be possible to automatically create recipes using that model.

### **2.4 AFM**

Automatic recipe creation for AFM tools has seen little development activity to date. The requirements are most similar to those of CD-SEM because AFM is most commonly used to measure very small features. One key difference is that an AFM performs fine alignment using probe scans rather than an electron beam image. Therefore, an automated recipe creation tool would need to automatically identify suitable features for use in this process. The system would also be required to account for underlying layers that might impart topography to the measurement target layer.

### **2.5 Film thickness**

The possibility also exists to automate the recipe creation process for film thickness measurement tools. Currently, such measurements are usually made using optical metrology tools such as ellipsometers or reflectometers, and the thickness measurements may be made on either blanket film layers or on relatively large 'pad' areas on patterned wafers.

Optical film thickness measurements are similar to scatterometry in that the technique is based on a model that must be developed before the recipe can be created. These models are typically much less complex than scatterometry models, and once the model is available it should be straightforward to automate the process of creating recipes that use the model.

## **3. SYSTEM ARCHITECTURE**

We developed a system for automatically creating production metrology recipes for CD-SEM and overlay tools. The system is highly modular and designed to be generalized to other metrology types as well. We show a schematic diagram of the system in Figure 1 and discuss the key components in more detail below.

Production metrology targets (both in the scribe area and inside the die) are identified with text tags in the layout database (GDS or OASIS). The recipe creation system is then able to search a given layout database for the appropriate metrology features and compile their locations into a site list. Each site location also has supporting information attached, including the required measurement algorithm, orientation, and the tone of the polygons in the layout database.

The system performs the necessary coordinate transformations from the layout coordinate system to the reticle field coordinate system. In addition, wafer map information is available to allow the recipe creation system to determine the wafer coordinates of the measurement target features according to the desired sampling plan.

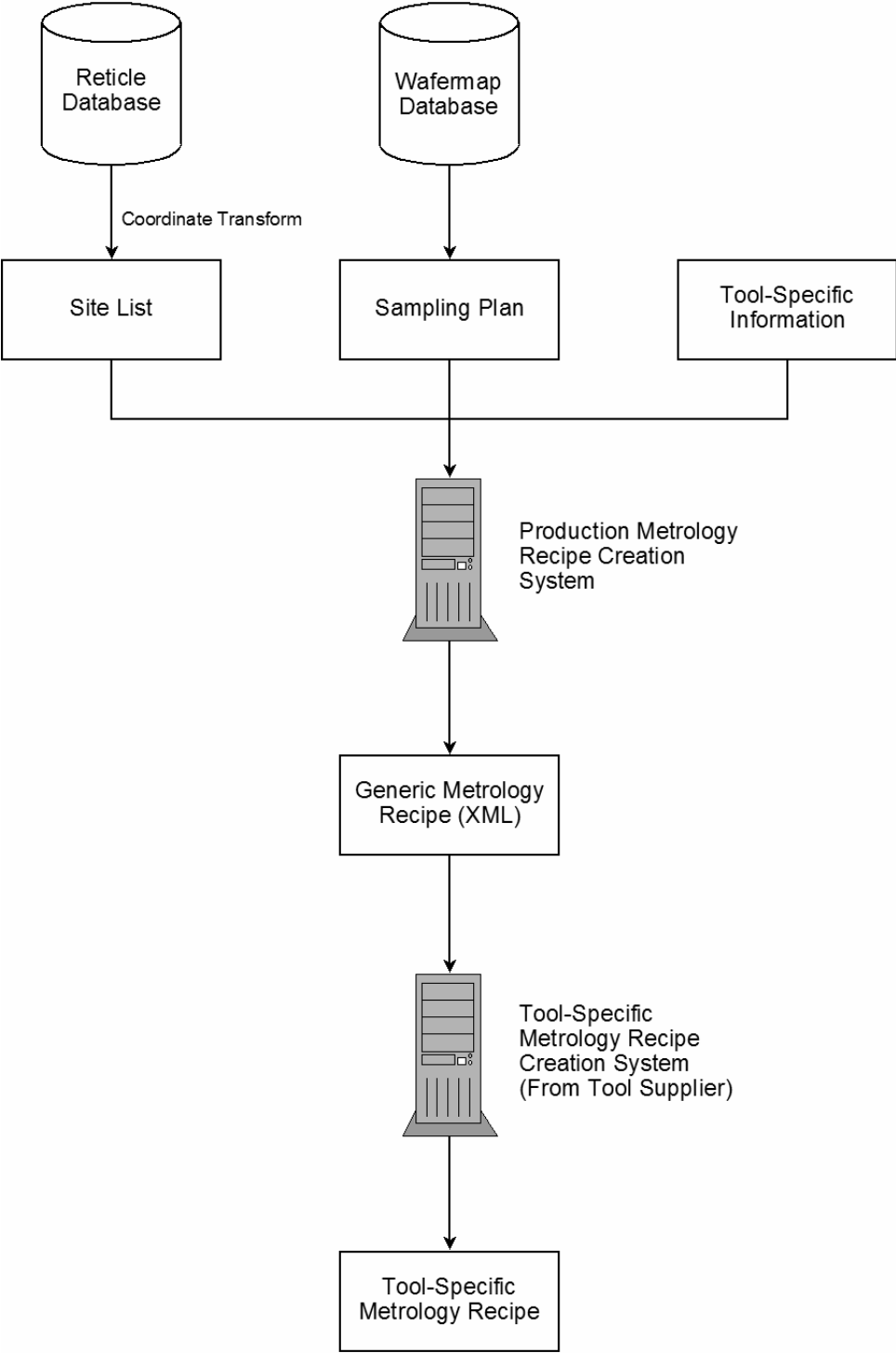


Figure 1. Schematic diagram of an automated production metrology recipe creation system.

A database of value sets grouped by context (target tool type, measurement type, process layer, etc.) makes available tool-specific information (measurement algorithm parameters, hardware settings, runtime parameters, etc.). These values may also be over-ridden as needed.

The site list, sampling plan, and tool-specific information are all passed to the production metrology recipe creation system. This system compiles and formats all of this information into a generic metrology recipe, typically stored as an XML file. Then the generic metrology recipe is passed to a tool-specific metrology recipe creation system. The tool-specific system is normally provided by the metrology tool supplier, and translates the generic metrology recipe into a format that the target metrology tool can understand. The tool-specific software may handle the task of selecting pattern recognition sites and creating the corresponding templates, or this information may be communicated along with the generic metrology recipe. The resulting tool-specific recipe may then be transferred directly to a metrology tool for use or to a recipe database for access by a fleet of tools.

## 4. RESULTS

The implementation of an automated production metrology recipe creation system delivered several tangible benefits, both in terms of cost savings and in metrology tool performance. We describe key results obtained to date below.

### 4.1 Time/Cost Savings

To illustrate the time/cost saving benefits of this system, we conducted an analysis of the time required to create all of the production overlay metrology recipes for a new (hypothetical) product. Table 1 shows the assumptions of this analysis. The software used for the tool-specific recipe creation was Nanometrics SynRG. The setup time applies to the automated system and is defined as the time required to prepare the system to generate the desired recipes. The creation time is the time required to actually create the initial version of the recipe. For manually created recipes, we applied a qualification procedure to fine-tune the various recipe parameters for optimal performance. After we used the new recipe to measure a few lots, we reviewed its performance to ensure that it was operating as desired. Occasionally, we found a recipe performing sub-optimally and used a recipe maintenance procedure to correct the recipe. The maintenance rate is the percentage of all recipes that require maintenance (this rate has been demonstrated to be significantly lower for automatically created recipes than for manually created recipes).

**Table 1.** Assumptions of time savings analysis for overlay metrology production recipes.

	<b>Manual Recipe Creation</b>	<b>Automated Recipe Creation</b>
Setup time	0	15 min.
Creation time per recipe	20 min.	5 sec.
Qualification time per recipe	10 min.	0
Performance review time per recipe	15 min.	5 min.
Recipe maintenance time	30 min.	30 min.
Recipe maintenance rate	30%	10%
Layers per product	50	50

We can calculate the total time savings per product with the following formula:

$$\text{Total time} = \text{Setup time} + \left( \frac{\text{Creation time}}{\text{layer}} + \frac{\text{Qual. time}}{\text{layer}} + \frac{\text{Perf. rev. time}}{\text{layer}} + \frac{\text{Maint. time}}{\text{layer}} \times \text{Maint. rate} \right) \times \frac{\text{layers}}{\text{product}} \quad (1)$$

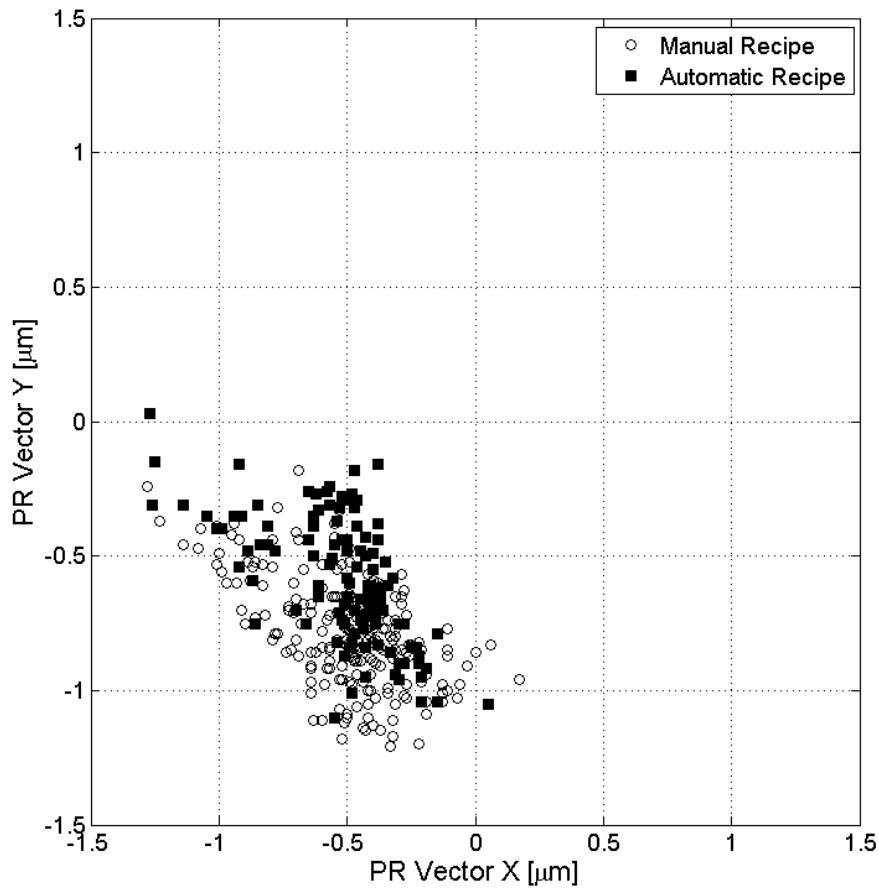
Using the assumptions from Table 1 in this model yields a total time of 45 hours to create all the overlay metrology production recipes for a hypothetical product using the conventional manual recipe creation process. However, the

automated recipe creation system is able to achieve the same result in just less than seven hours. It should be noted that, in both cases, the time required not only occupies a metrology engineer but an overlay tool that is not available for production use during this process.

#### 4.2 Pattern Recognition Arrival Accuracy for CD-SEM Tools

One characteristic of metrology recipe performance is the accuracy of the arrival of the pattern recognition target within the field of view of the optical or electron microscope. For CD-SEM tools, there will typically be some error in the stage movement. This error may have both random and systematic components due, for example, to the fact that coordinates that are “learned” on the tool have an unknown error that is replicated in future stage movements. Also, local charging of the wafer surface can distort the electron beam, leading to an apparent image displacement. In principle, automatically created recipes should not be prone to systematic coordinate errors and therefore should have superior pattern recognition arrival accuracy performance.

To determine if this was the case for CD-SEM tools, we created recipes for the same layer for Applied Materials Verity 2 CD-SEMs using both the manual and automated processes. We recorded the vector between the center of the field of view and the detected pattern recognition target for a series of production wafers. We created automated recipes using the Applied Materials OPC Check software and show representative results in Figure 2 (complete results are reported by Girol-Gunia *et al.*<sup>7</sup>).

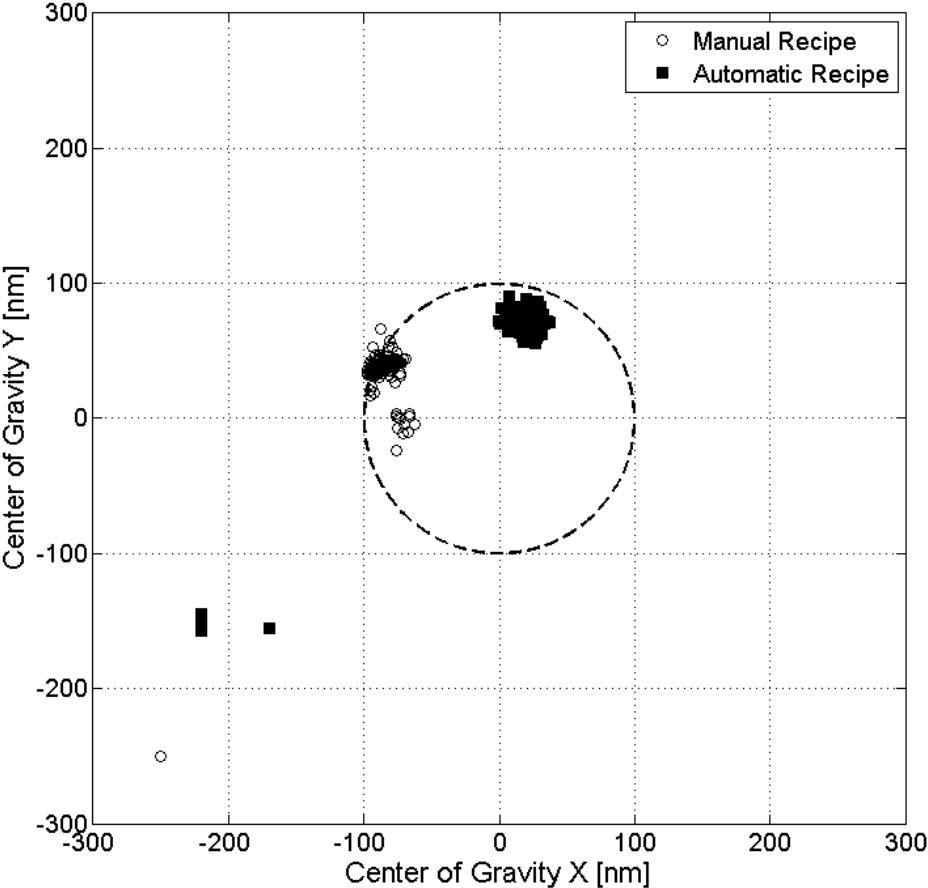


**Figure 2.** Pattern recognition arrival accuracy for a manually created recipe (white circles) and an automatically created recipe (black circles) from the same production layer. Ideal behavior would give a pattern recognition arrival vector of (0,0).

As Figure 2 shows, the automatically created recipe offers a slight improvement in pattern recognition arrival accuracy compared to the manually created recipe. The clustering of the data in the lower-left corner of the figure is a systematic effect of the individual tool on which the data was collected. The mean magnitude of the pattern recognition arrival vector was  $0.97\ \mu\text{m}$  for the manually created recipe and  $0.83\ \mu\text{m}$  for the automatically created recipe.

### 4.3 Measurement Feature Placement Accuracy for CD-SEM Tools

Another key metric for CD-SEM recipe performance is the placement of the target feature within the measurement box (the region of the image that is scanned to acquire measurement data). Ideally, the displacement should be zero; however, for many of the same reasons mentioned for pattern recognition arrival errors, there is always some error associated with the placement of the measurement target feature within the measurement box. Girol-Gunia *et al.* also reported on this topic;<sup>7</sup> Figure 3 shows example results. Again, the hardware platform is the Applied Materials Verity 2 CD-SEM and we used the OPC Check software for automatic recipe creation.



**Figure 3.** Distance from the measurement box center to the measurement target feature “center of gravity” for manually created recipes (white diamonds) and automatically-created recipes (black squares). Ideal behavior would give a displacement vector of (0,0).

This data is for multiple production lots run on the same CD-SEM tool. Again, the performance of the automatically created recipe is superior to the manually created recipe. Aside from a handful of outliers, all of the automatically

created recipes resulted in a feature placement within 100nm of the center of the measurement box, while many of the manually created recipes fall close to or outside this threshold.

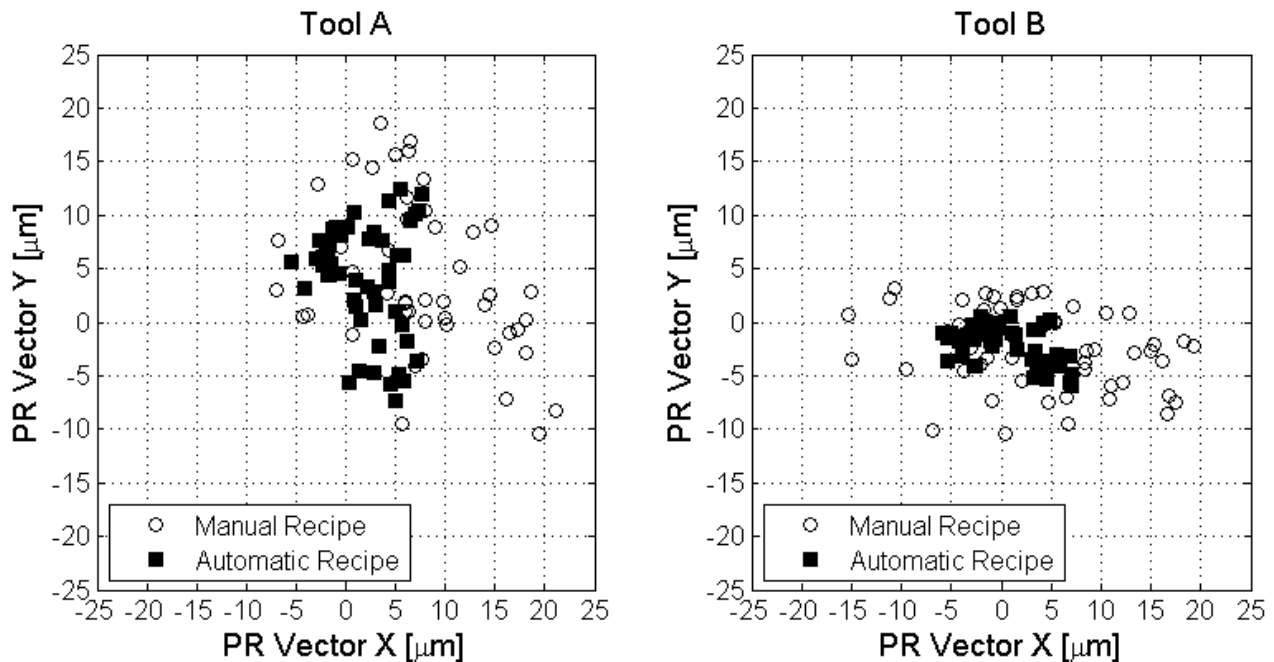
#### 4.4 Pattern Recognition and Measurement Success Rates for CD-SEM Tools

Given the improvements demonstrated in the pattern recognition arrival accuracy and measurement feature placement accuracy, we expected pattern recognition and overall measurement success rates would also improve. We show this is, indeed, the case.<sup>7</sup> For the example application shown in Figure 2 and Figure 3, the pattern recognition success rate was 98.3% for the manually created recipe and 99.0% for the automatically created recipe. The overall measurement success rate was 89.3% for the manually created recipe and 96.4% for the automatically created recipe. Clearly, the automatically created CD-SEM recipe offers superior performance.

#### 4.5 Navigation Precision for Overlay Tools

We can conduct a similar analysis for other metrology types, including overlay metrology. We used the automatic recipe creation system to create overlay recipes for several production layers, and compared these recipes with the existing manually created recipes in terms of navigation precision. Navigation precision is the offset from the center of the field of view to the center of the overlay target located within the image.

We show the results in Figure 4, comparing the manually and automatically created recipes on two different Nanometrics Caliper élan overlay metrology tools to gauge the portability of each recipe.

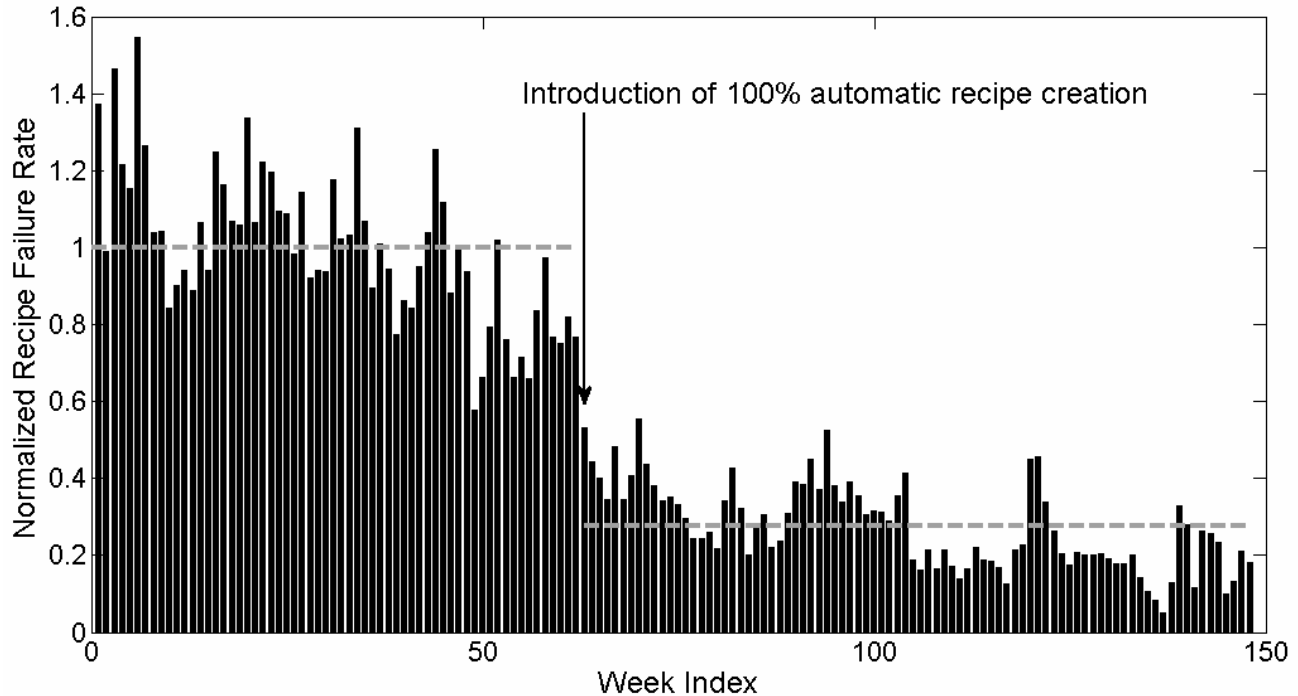


**Figure 4.** Navigation precision for a manually created recipe and an automatically created recipe running on two different overlay metrology tools of the same model.

Once again, the automatically created recipe offers superior performance. In this case, the automatically created recipe delivers better navigation accuracy for overlay measurements than the manually created recipe.

#### 4.6 Recipe Success Rates for Overlay Tools

We studied the impact of automatic recipe creation on overlay metrology performance by monitoring the recipe failure rates before and after a conversion from manual to automatic recipes and show the results in Figure 5. The introduction of automatically created recipes shows a reduction in recipe failure rates by approximately a factor of four.



**Figure 5.** Normalized overlay recipe failure rates before and after a switch from manually created recipes to automatically created recipes. The failure rates are normalized to the mean failure rate before the introduction of 100% automatic recipe creation. Each bar represents the aggregate weekly failure rate for all production lots.

### 5. CONCLUSIONS AND FUTURE WORK

The cost of manually creating and maintaining metrology recipes to meet the demands of advanced semiconductor manufacturing has become prohibitive. To address this problem, we developed a system for automatically creating production metrology recipes. We employ this system in high-volume manufacturing for CD-SEM and overlay production metrology recipes.

We demonstrate the automatic production metrology recipe creation system saves engineering time and improves tool utilization. In addition, we show that the recipes created through this system are more robust than manually created recipes with respect to navigation accuracy and measurement success.

Future work will include the extension of the current system to support other metrology types common in production manufacturing, including scatterometry, atomic force microscopy, and film thickness tools. Support from metrology tool suppliers to enable automatic recipe creation capability on their tools will be critical, and a greater degree of standardization of the data formats and interfaces for design-based metrology would facilitate this process. The ability to automatically create metrology recipes also offers many exciting possibilities for more flexible and dynamic sampling in the fab to change recipes on the fly in response to process conditions or requirements.

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