Process Transfer Strategies between ASML Immersion Scanners

Yuan He, Peter Engblom*, Jianming Zhou, Eric Janda*, Anton Devilliers, Bernd Geh**, Erik Byers, Jasper Menger**, Steve Hansen*, Mircea Dusa*

Micron Technology, Inc
*ASML
**Carl Zeiss SMT AG

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Abstract

A top challenge for Photolithographers during a process transfer involving multiple-generation scanners is tool matching. In a more general sense, the task is to ensure that the wafer printing results in the receiving fab will match or even exceed those of the originating fab. In this paper we report on two strategies that we developed to perform a photo process transfer that is tailored to the scanner's capabilities. The first strategy presented describes a method to match the CD performance of the product features on the transferred scanner. A second strategy is then presented which considers also the down-stream process tools and seeks to optimize the process for yield. Results presented include: ASML TWINSCAN™ XT:1700i and XT:1900i scanners 1D printing results from a line-space test reticle, parametric sensitivity calculations for the two scanners on 1D patterns, simulation predictions for a process-optimized scanner-matching procedure, and final wafer results on 2D production patterns. Effectiveness of the optimization strategies was then concluded.

1. Introduction

IC manufacturers transfer processes periodically from R&D to production fabs or from one fab to another. It is usually expected that a reticle set that produces various resist patterns within specification on a certain scanner will have the same performance on another exposure tool. In situations that we see more and more often when entering the sub-50nm era, heavily optical proximity corrected (OPC) reticles are developed and successfully applied on one scanner model, but moving to another scanner model will cause the pattern printing to be out of the process specification. To the scanners of the same model, this result indicates there are mismatches in tool parameters such as illumination or stage, which will require the further tool-tuning to the exact same specifications. For different scanner models the success or failure of minimizing the differences in printed CDs depends on the accuracy of understanding the tool differences and the ability to make the required change on the matching tool. There are a couple of transfer options available for overcoming direct tool-matching difficulties or for producing a more flexible process transfer.

One option is to match the printing performance of the target exposure tool. Since the process output is carefully matched, the additional cost of developing a new OPC model or acquiring a new reticle for each exposure tool[1] is therefore avoided. A scanner is virtually a black box to the customer. However, we know already several tool parameters and have the needed control on them. We can perturb all these parameters and measure the CD changes afterwards. Ideally, after a few wafer tests, we will be able to acquire all the parameter-wafer CD sensitivities, and can choose the sensitive parameters to adjust the wafer CD back to target. In practice however, gauging the process repeatability, metrology accuracy, and possible nonlinear interaction of parameters can easily result in a heavy amount of fab work in exposure and metrology. This results in non-trivial R&D cost and slows the process transfer. In this paper, we propose a highly efficient CD-Optimized Scanner-matching procedure that predicts the parameter sensitivity only through simulations. We guarantee the realistic and robust results from the sensitivity simulations in two ways: accurate scanner and resist modeling, and wafer measurements on 1D-patterns.

A second transfer option carries the process optimization along with the process transfer phase, and is referred to as Process-Optimized Scanner-matching in this paper. Although this may require the transferring and receiving fabs work closer than ever before, it might actually help to reduce the time overhead in the production lifecycle taken by the transferring phase. Simply speaking, a photo process can be tweaked individually for the fleet of a mixed type of scanners in the receiving fab so that every scanner can operate at a stable and optimized condition that is tailored to its capability.

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This approach implies that the tool matching iteration will be relatively quick and painless. Generally, we require the new printing results to meet the minimum requirement for the process integration of the product. This method is based on the general assumption that Photolithography is the process bottleneck of chip manufacturing, and that it is relatively easy to adjust etch or further downstream steps to compensate for the slight variations from Photo. Practically, this “transfer and optimization” approach is most attractive if the receiving fab has newer tools that can breakthrough some printing limitations which will benefit the current process integration flow and ease the downstream process steps.

In this paper, we report the procedures that we developed to perform a photo process transfer with the above two matching strategies for cross-generation/model scanners. Our goals of the project include to (a) demonstrate the capability of matching the latest immersion tools to RMS-error < 4nm for pattern printing at “concerned pitch regions” and at any production layer; (b) investigate the flexible number of process and tool parameters needed at different levels of matching accuracy and implementation complexity; and (c) test practical and high-throughput experiment design, metrology and data post-processing tools. The paper is organized into the following sections. In Section 2, we present the CD-Optimized scanner-matching results. We discuss a multi-pitch line-space tool-matching test reticle design, and present 1D printing results from ASML TWINSCAN™ XT:1700i and XT:1900i scanners 1D printing results Parametric sensitivity calculations for the two scanners on 1D patterns and final wafer results on 2D patterns are also presented. In Section 3, we present the Process-Optimized Scanner-matching results. We propose a simulation based CD optimization procedure that applies directly to the target feature, with simulation and wafer results. The learning from applying the two procedures is concluded at the end of the paper.

2. CD-Optimized Scanner-matching

In order for the CD-Optimized Scanner-matching to be suitable for use during a process transfer the method had two basic requirements: (a) find the optimum scanner knob adjustments to match the CD results as closely as possible, and (b) limit the amount of time-consuming metrology measurements required. Availability of a multi-pitch reticle as described below along with an automated scatterometry recipe were assumed. The general strategy is depicted in Fig. 2.1.

As a first step, the CD performance differences are measured between scanner types. In our example, a chevron pattern was considered as our critical process feature with CD1 defined as the space between chevrons (X-printing direction) and the dose anchor for the process. CD2 is defined as the space between chevron line-ends (Y-printing direction) and therefore sensitive to the many processing changes that effect line-end pull-back. As expected, CD2 decreases disproportionally to CD1 when a higher contrast scanner is used for imaging and therefore defines the matching objective for this layer. A focus exposure matrix (FEM) was therefore collected to characterize the imaging differences between scanner models as well as for resist model calibration as described in Section 3.1.

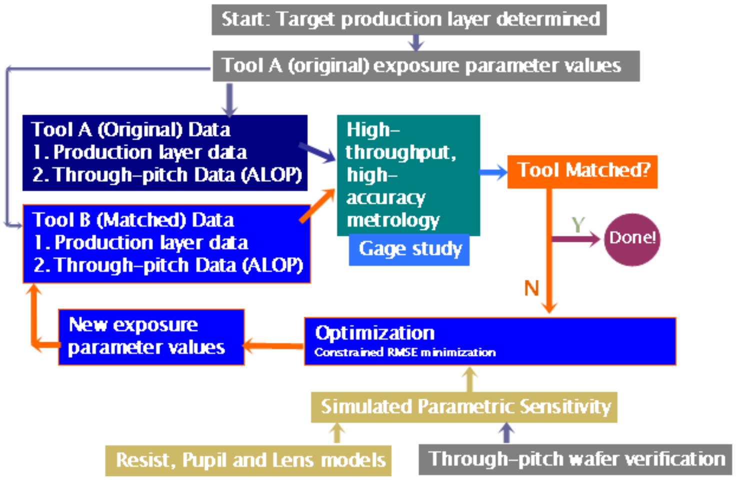


Fig. 2.1: Flow chart of the CD Optimized Scanner-matching methodology. Given accurate simulations the number of expected iterations to reach matched results can be as few as one.

In this work, we evaluated the effectiveness of using through-pitch 1D structures to drive the optimization and preserve the imaging performance of periphery structures of various pitches. A multi-pitch reticle was used to accomplish this and the data collected was limited to best focus and dose. The choice of best dose was of course dependent on the bias/pitch selected as most similar to CD1 of the production chevron feature. Through this exercise we therefore evaluated the effectiveness of using 1D through-pitch features to provide sufficient matching performance for a 2D production structure. The distinct advantage of this methodology is the ease of performing such optimizations for several production layers quickly.

2.1 The Tool-Matching Reticle Design

A test reticle was designed to evaluate the through-pitch imaging performance of the scanners to be matched. The ALOP (A Lot Of Pitches) reticle has both horizontal and vertical features of line/space structure. Fig. 2.2 illustrates the reticle design. The pitches vary from 80 nm to 1000 nm along the horizontal direction. The CD is biased for each pitch along the vertical direction to ensure the desired CD target can be printed.

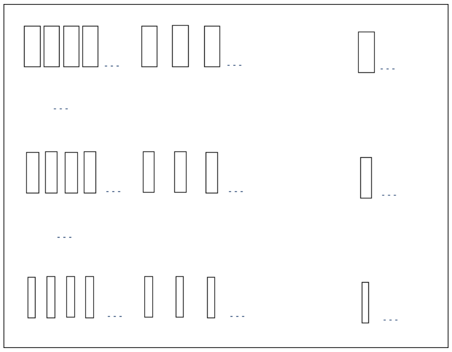


Fig. 2.2 The ALOP reticle. The pitch increases along horizontal direction. Features are biased differently along vertical direction.

2.2 Scatterometry Metrology Setup and Data Analysis

A resist Lumped Parameter Model (LPM) was calibrated based on FEM results from the production chevron pattern as described in section 3.1. Using the LPM resist model, the desired mask bias was calculated for each pitch to obtain CD performance close to the 52 nm target. The through-pitch simulations were performed using a 6%AttnPSM to match the ALOP reticle design. The resist calibration was therefore assumed to be independent of mask attenuation level.

A gauge study of scatterometry vs. CD SEM was performed to determine which metrology should be used. Table 2.1 shows the summary of the result. Three pitches with target CD 52 nm were selected to perform this study. Scatterometry showed much better repeatability over CD SEM and was chosen for ALOP CD measurement. A scatterometry recipe was setup for each pitch with the correct stack information and bias. The CD and 3 sigma of each pattern were collected. Those CDs with high 3 sigma were excluded from the analysis.

Initial exposures were performed with the same illumination condition on both scanners and the results are shown in Fig. 2.3. The plot shows the raw CD data as well as the difference obtained between scanner types. Both horizontal and vertical features were studied. Based on the CD difference and parameter sensitivities, new exposure conditions were generated.

Table 2.1 The standard deviation of Scatterometry vs. CD SEM of 52nm line on three different pitches

Target pitch	Scatterometry (nm)	CD SEM (nm)
105nm	0.08	0.73
199nm	0.14	0.66
411nm	0.11	0.61

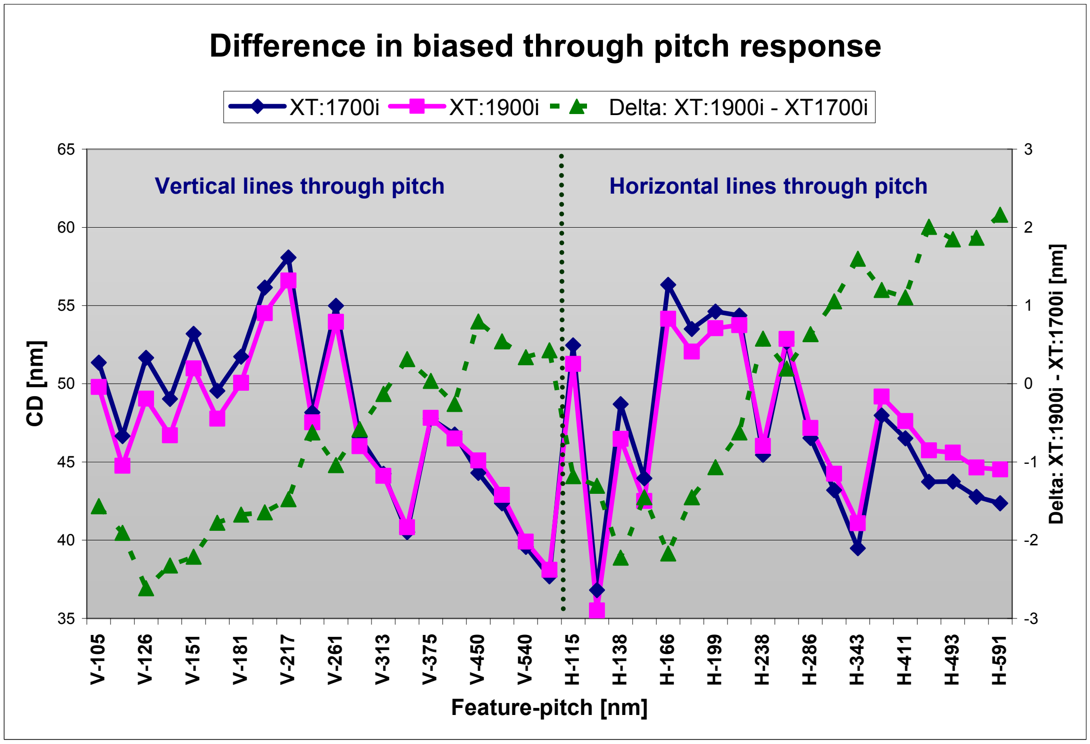


Fig. 2.3. The CD and CD delta obtained from two scanners before the scanner optimization.

2.3 Parameter Sensitivity Calculations

For this matching exercise the use of NA, sigma center, sigma ring width, cA(2) (intensity saddle), focus fading and dose were considered as knobs within predefined ranges easily adjustable on the scanner to be matched. An assumption was made that the scanner knobs were sufficiently independent such that cross terms could be considered negligible. It was also assumed that the response was linear over the range studied except for focus fading which was modeled as quadratic.

For the source parameters: sigma center, sigma ring width, and cA(2), a parametric pupil model was used to create source files as input into the lithography simulator. A measured pupil was used as a starting point which was already collected during the LPM calibration phase. The measured pupil was modeled and then manipulated to represent the source parameter adjustments the scanner is capable of as described in section 3.1. Simulations were then run to calculate the sensitivities. Fig. 2.4 contains the sensitivity results using the previously selected bias for H and V oriented pitches as well as for CD1 and CD2 of the production chevron structure.

These sensitivities, coupled with the measured differences between scanner types, were then input into a global minimization function to determine the optimum process correction. At this phase, one can consider several matching objectives and define the optimum matching prescription based on known CD tolerances and pitch ranges of particular concern. For this case study, the production feature was left out of the optimization and an even weight was assigned to the through-pitch lines. .The optimum process corrections are detailed in Table 2.2. For this optimization the sensitivity curves of NA, sigma ring width and focus range were not well matched to the measured CD differences and therefore not utilized by the optimization function to develop a matching process correction.

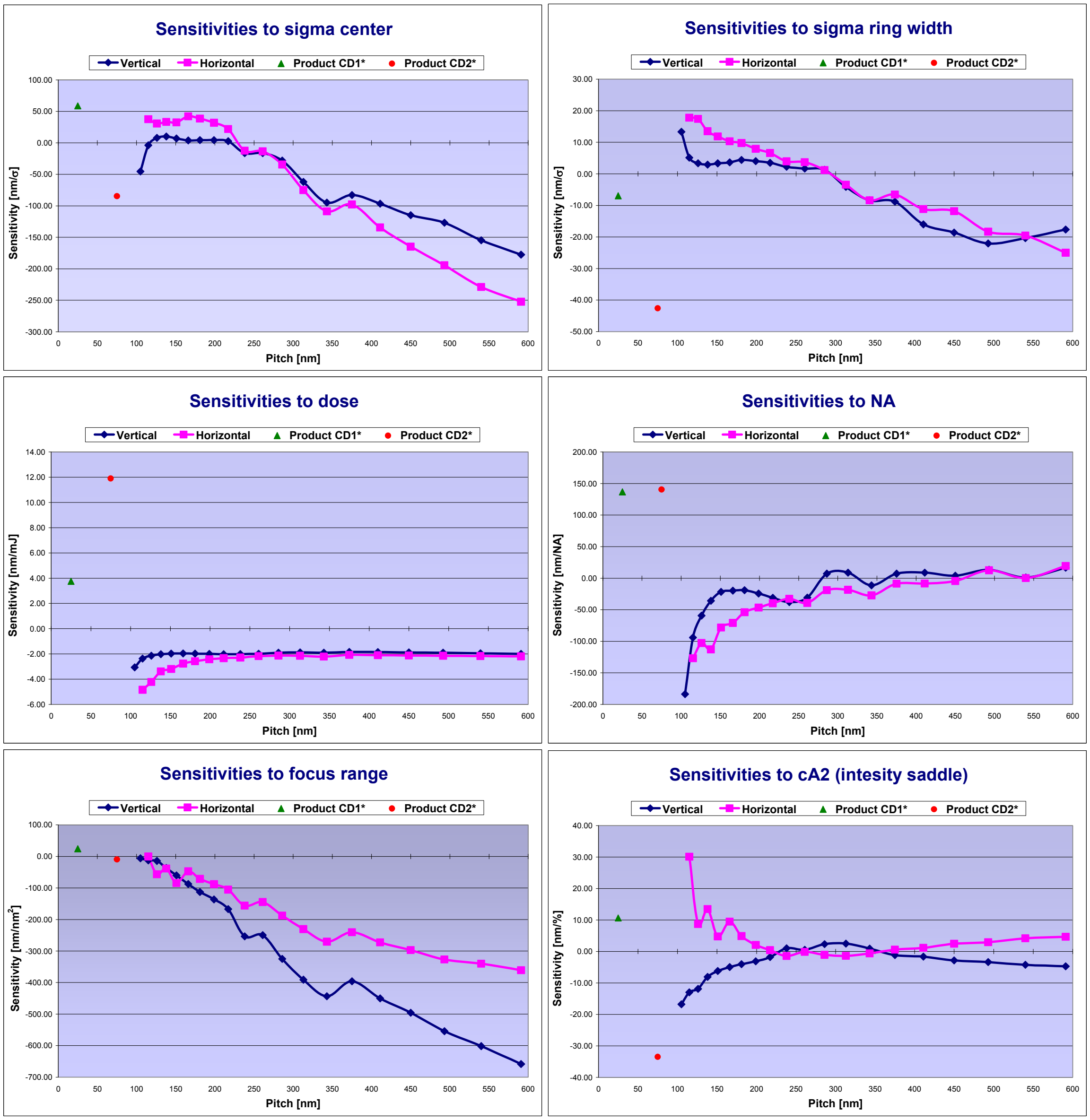


Fig. 2.4: Parameter-CD (through-pitch) sensitivities calculated using calibrated Lumped Parameter Model, illumination source model and the immersion tool lens model. *Pitch location of production features chosen for graphical purposes only and does not approximate the actual pitch of the feature.

Table. 2.2 Prescription from optimization program to achieve matching objectives.

Parameter	Delta	Units
Dose	-0.45	mJ
NA	0	n/a
Sigma Center	+0.013	sigma
Sigma ring width	0	sigma
Focus Range	0	nm
cA(2)	-5	% H/V pole balance

2.4 Matching Results

The optimized process prescription was then verified by measurement in resist for both the through-pitch structures and the production chevron structure. Figure 2.5 shows the results of the through-pitch measurements where a maximum difference in imaging performance between the scanner types was reduced to less than 1.5 nm. The results are also well matched to the predicted performance from the minimization function using linear and orthogonal simulated sensitivities.

The results of the optimization provided sufficient improvement to the through-pitch response to limit any concern over periphery features within the production mask. Figure 2.6 shows the results of the optimization on the production chevron structure. The measurement of CD2 is particularly noisy and causes difficulty in quantifying the improvement. Despite the measurement uncertainty, the performance after the optimization is matched to within 1 nm. The optimization results were evaluated throughout the focus and exposure matrix and the CD2 to CD1 response is compared and fitted using a 2nd order polynomial.

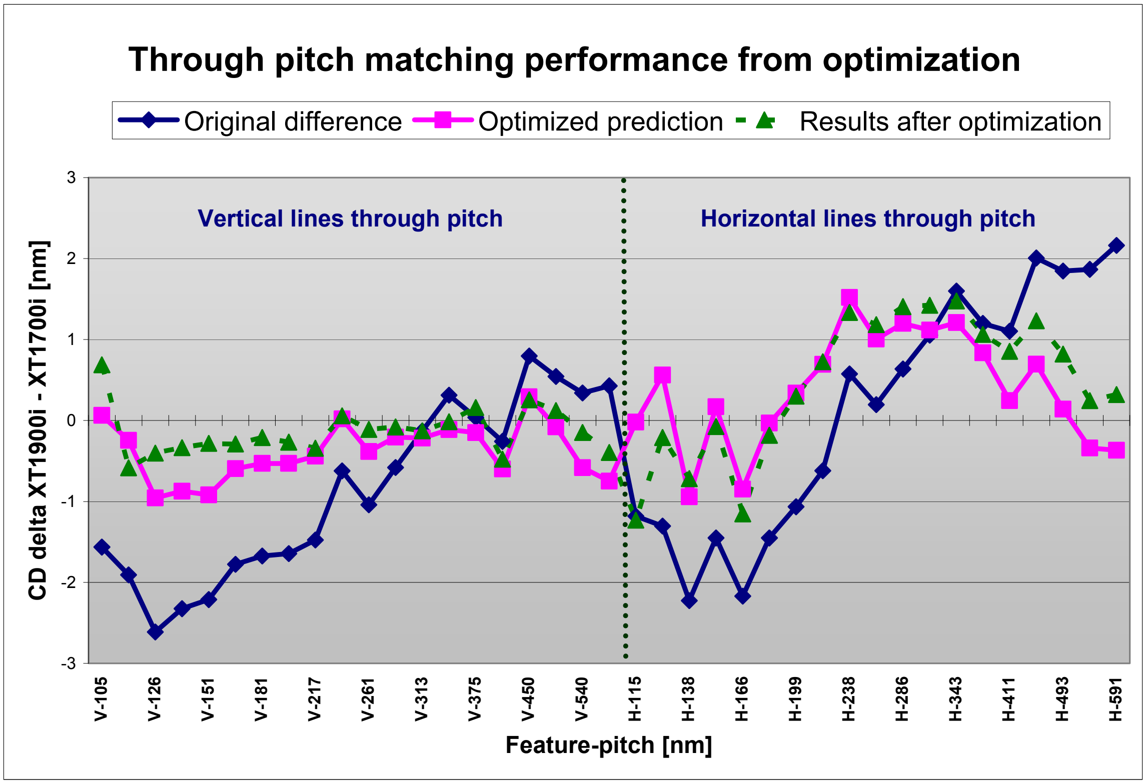


Fig. 2.5: matching results at best focus and dose after using the optimized process corrections. Printing performance before optimization (blue) and after optimization (green) through the entire pitch range studied. Optimized measurement results are also well matched to the predicted difference (pink) using simulated sensitivities.

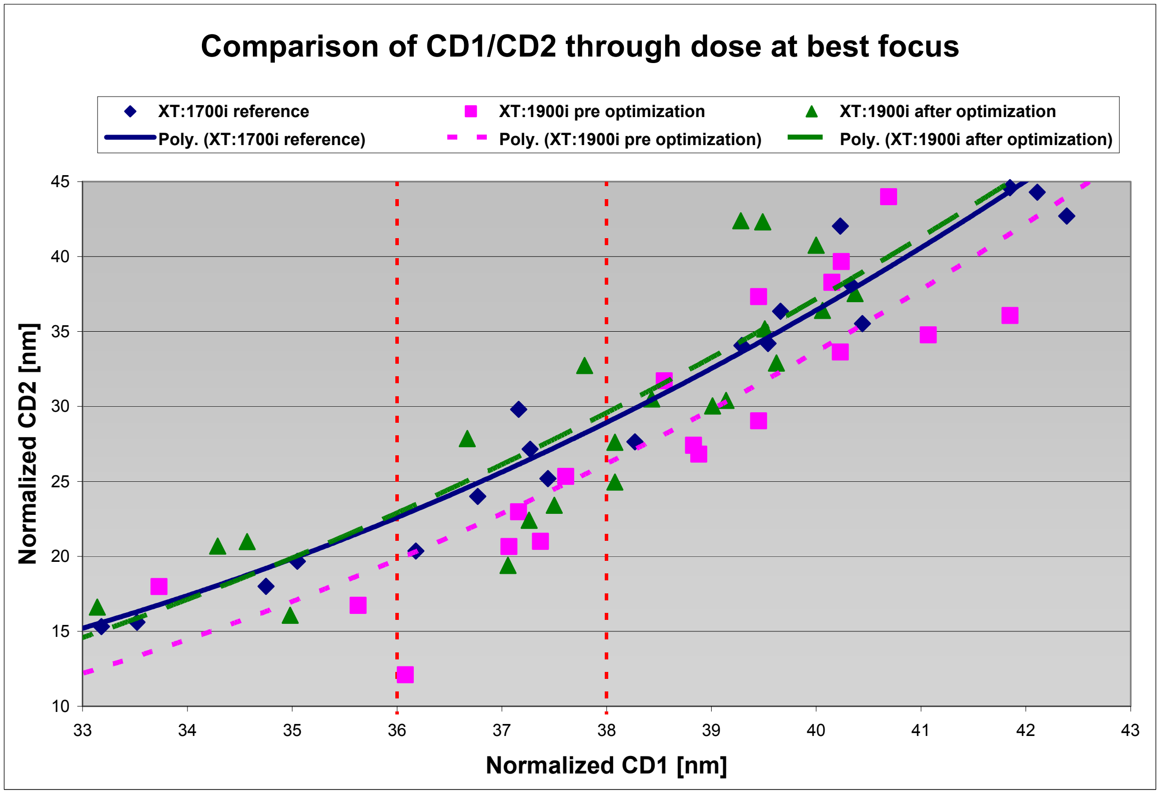


Fig. 2.6: CD2 (Y-direction) as a function of CD1 (X-direction) throughout the focus/exposure matrix. Results are normalized and target region of CD1 denoted by red lines. After optimization (green) the imaging performance is well matched to the reference (blue).

3. Process-Optimized Scanner-matching

The Process-Optimized Scanner-matching approach takes advantage of the fundamental capability differences between scanner models during a process transfer. With a guide line in mind during the R&D to target the less-capable scanner in the fab for a given process, we are able to transfer the process smoothly using the CD-Optimized Scanner-matching approach explained in Section 2. On the other hand, just because of that restriction the process might have been compromised from the process integration point of view. Here is a simple example: assume we have a 2D pattern that requires 2 critical dimensions to be on target. CD1 must be dosed to size, while CD2 needs to be maximized using a fixed custom illumination type, which is predetermined by both dense-array and periphery features. Within a given process window, an ASML XT:1700i prints CD2 4 nm smaller than an XT:1900i. To target the less-capable scanner, we set our process target for CD2 based on the XT:1700i printing result. The XT:1900i is therefore 4 nm above target and needs to be addressed using other methods such as re-biasing an XT:1900i-specific mask. The smaller the CD2, however, the less margin the dry-etch process will have which will cause higher defects and affect yield noticeably. If now we have Fab A that is equipped with all XT:1700i scanners and Fab B equipped with all XT:1900i scanners, adopting the Process-Optimized Scanner-matching approach, we simply set the CD2 target for Fab B 4 nm higher and relax the fab's etch process. Fab B will therefore achieve a higher yield because of its better tool-set. Simply speaking, a photo process can be tweaked individually for the mixed type of scanners in the receiving fab so that every scanner can operate at a stable and optimized condition that is tailored to its capability for some features, while the printing result for the rest of the features are still within the specification. Major benefits are (a) the transfer process is relatively quick and painless; and (b) the transfer is flexable and can benefit or be compensated by other process areas for slight variations so that the initial process integration requirements are met. In this section, we will present the Process-Optimized Scanner-matching that applies directly to the target feature (fig 3.1); and the final wafer results.

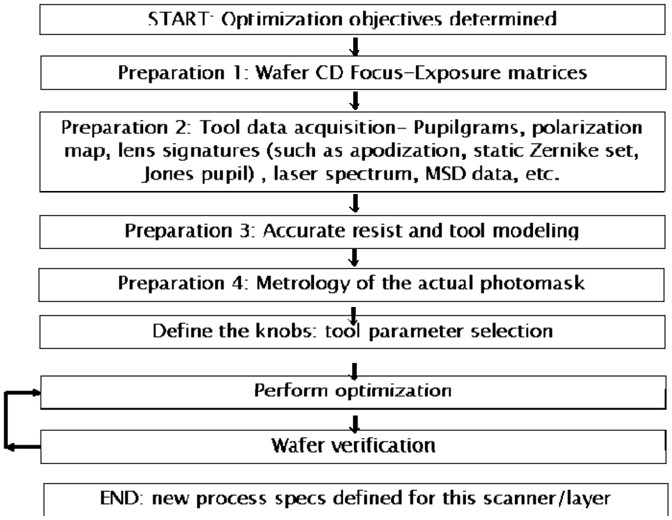
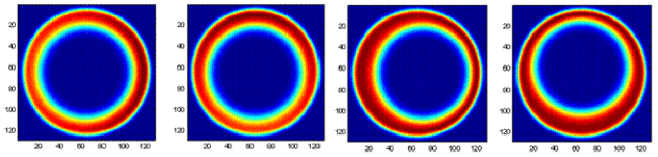


Fig 3.1 Process-Optimized Scanner-matching procedure

3.1 Pupil and Resist modeling

The proposed Process-Optimized Scanner-matching procedure relies on resist simulations. Having an accurate scanner model, as well as a good resist model for the optimization is therefore critical. Most of the scanner parameters, including polarization map, full field aberration set, lens descriptors, laser spectrum and MSD values can be measured off the tool directly. The illumination pupil of any illumination setting can also be measured. Illumination, however, has the most direct impact on resist printing and is not limited to the source's effective inner and outer sigma values. Also important is the 2D light intensity distribution across the pupil as well as the degree of non-idealities. Using an ideal (top-hat shaped) source set at the effective inner/outer sigma numbers would likely lead to non-negligible mismatches between the simulation and the wafer data. To avoid such errors, we used a parametric pupil model[2] in this work, which enables lithography simulations to manipulate illumination parameters freely while keeping the tool-specific source fidelity even at higher order terms (Fig 3.2).


Intensity tilt x Intensity tilt y Inner sigma shift x Inner sigma shift y

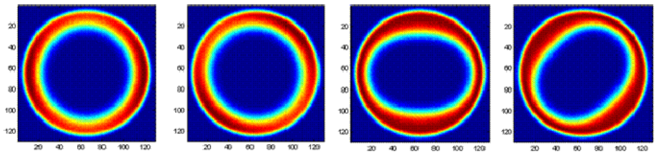

Intensity saddle x,y Intensity saddle 45/135 Inner sigma ellipticity x,yx Inner sigma ellipticity 45/135

Fig 3.2. Various pupil parameter manipulations on a modeled ASML TWINSCAN™ scanner annular illumination

Through many of our numerical experiments on production layers we found that a Lumped Parameter Model (LPM) is able to describe the resist CD performance most closely to reality for both 1D and 2D features once calibrated to the FEM of the CDs in the interested process range.[3] To calibrate a LPM model in a consistent and automatic fashion for any particular production pattern under concern, we have developed in-house multi-CD LPM calibration software. It performs optimization of a lithography simulator LPM to match a given process input set. The software is based on the Simplex and Levenberg Marquardt global optimization algorithm, and can calibrate up to 30 CD locations simultaneously (≦ 5 simultaneous CDs suggested in practice).

The multi-CD LPM calibration software user interface is divided into two pages. The Main page contains: all the user inputs, FEM data for each CD, LPM fitting parameters, the path to the lithography process simulation file, and the current merit function fitting progress. The Fitting Monitor page then dynamically graphs the differences between experimental data point and simulation. All fitting history and temporary data are stored for later evaluation.

3.2 Tool-specific Parameter Optimization

The core part of the Process-Optimized Scanner-matching procedure is a tool-specific parameter optimization. A photo process will be adjusted individually for each type of scanner in the receiving fab so that a scanner can operate at a stable and optimized condition. This condition is tailored to the scanner's capability while meeting the process integration requirement as well as possibly even benefiting the process tolerance of the downstream areas. The optimization has steps including optimization objective(s), data preparation, parameter selection, optimization and verification simulations, and result evaluation. The workflow is easily understandable with the following example:

a. Optimization objectives

A production pattern in a dense array is monitored using two CDs: CD1 (X-printing direction) and CD2 (Y-printing direction). It was found that when CD1 is dosed to size, CD2 is printed smaller on an XT:1900i (Fab B) than on a XT:1700i (Fab A). It was also observed that the XT:1900i provides a larger Depth of Focus (DOF) at the same Exposure Latitude (EL) as the XT:1700i. The process owner's objective was to adjust the XT:1900i to print CD2 6 nm smaller than the XT:1700i using the same reticle while maintaining the XT:1700i process window. This would effectively resolve a Fab B etch process issue related to large CD2.

b. Data and model preparations

Details are described in Section 3.1.

c. Mask metrology

Mask information, such as printing bias, line-ends shape, corner rounding, etc are all important for either model calibrations or accurate photo process simulations.

d. Tool parameter selection

We started with 3 illumination variables: NA, sigma inner, and sigma outer. All these parameters are easy to adjust on an XT:1900i. Later in the work, we also considered the illumination Horizontal-Vertical (HV) intensity balance (cA(2) adjustment).

e. Optimization and verification simulations

An XT:1900i lithography simulation was put together using the best-known tool parameters. Both pupil and LPM resist models were created and calibrated for the stack. The simulation was verified with the base-line data from production first for its accuracy. Next, we set up linked simulations that scan the simulation matrix of NA, sigma inner, sigma outer, and HV intensity balance. It was important to use the linked simultion approach since the source file from the pupil model needed to be generated and CD1 was dosed to size for each simulation. The simulations would usually produce a few possible options for optimizing the process. Verification simulations were critical to ensure criteria such as process windows and printing quality (e.g. 2D shape variations, line-edge roughness, etc) were satisfactory for any other features not included in the optimization.

f. Result evaluation

Fig 3.3 shows the CD2 values predicted at different sigma outer/inner combinations at a certain NA setting. The combinations that meet the optimization objective are: 0.94/0.82, 0.95/0.81, 0.96/0.8, and 0.97/0.79 (the dotted circled region). The right plot of Fig 3.3 is a verification that CD1 (the most important CD of the process) meets the required imaging performance. Sigma 0.96/0.8 was chosen since it gives the highest CD1 NILS. The second set of verifications include checking a few periphery CD locations (not shown here), and checking the affects on the CD1 and CD2 process windows under the new sigma setting (Fig 3.4). We also checked the possible NA changes and found significant sensitivity to isolated and dense features; however low sensitivity to the CD1/CD2 ratio. Changes in NA would therefore be an effective knob for certain CD biasing applications but not suitable for this work. Finally, HV intensity balance turned out to be an effective controlling parameter for the CD1/CD2 ratio, which was also verified through silicon tests. This process optimization, however, could also be achieved through simple sigma adjustments. Intensity saddle adjustments were therefore not selected because of the simpler implementation of sigma adjustments during the transfer phase.

3.3 Wafer data verification

Most simulation based optimizations will require a few fine-tunings based on wafer data feedback. For this example, utilizing an accurate LPM and realistic pupil/lens models, the simulated to measured error for the CD1/CD2 ratio was only -3.5%. Using the new setting of NA=0.93 and sigma 0.96/0.69, Table 3.1 shows both the difference of simulated CD minus the SEM measurments as well as the difference of the new wafer CD to the old (before transfer) target. We can see that both CD1/2 ratio and Edge CD2 were optimized to favor the current integration needs while the printing of the other patterns were still acceptable for the process integration. The process owner concluded that we were able to hit the optimization target with the new sigma settings without further iterations. The required process window was then verified through Real-time Defect Analysis for the conversion to be finally accepted.

Table. 3.1 Wafer measurement validation after Process-Optimized Scanner-matching

	CD1	CD2	CD1/CD2	Periphery1	Periphery2	Edge CD1	Edge CD2
(Simulation-Measurement) Error %	0.0%	3.5%	-3.5%	-4.8%	2.2%	-3.0%	2.8%
(Measurement-Old Target) Delta %	0.0%	7.5%	-7.5%	5.3%	4.1%	2.9%	11.5%
Comments	Dosed-to-Target	Optimized	Optimized	Acceptable	Acceptable	Acceptable	Optimized

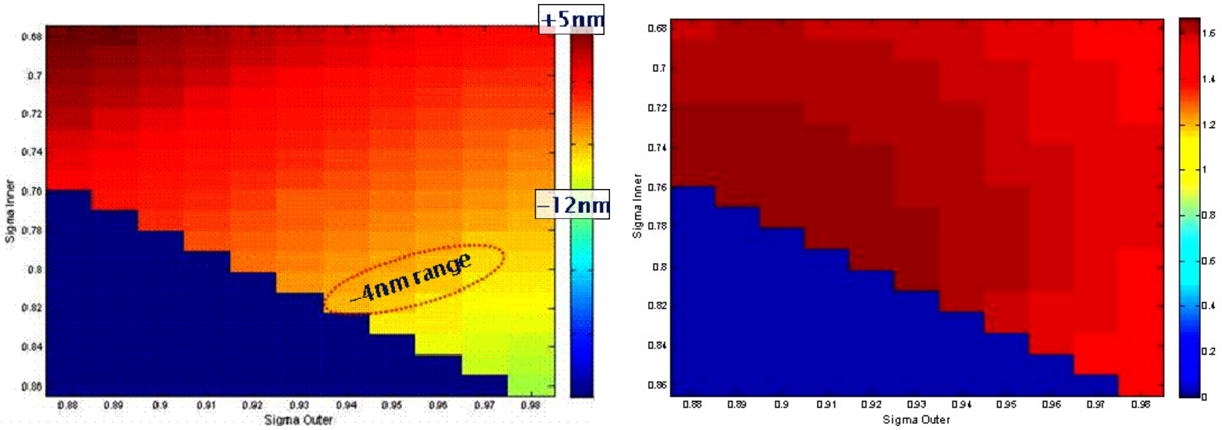


Fig 3.3. Left: CD2 delta (new-original) values simulated at different sigma inner/outer combinations at a certain NA setting. CD1 was dosed to size. Right: CD1 NILS values are calculated for the same sigma settings to check if the imaging conditions are acceptable.

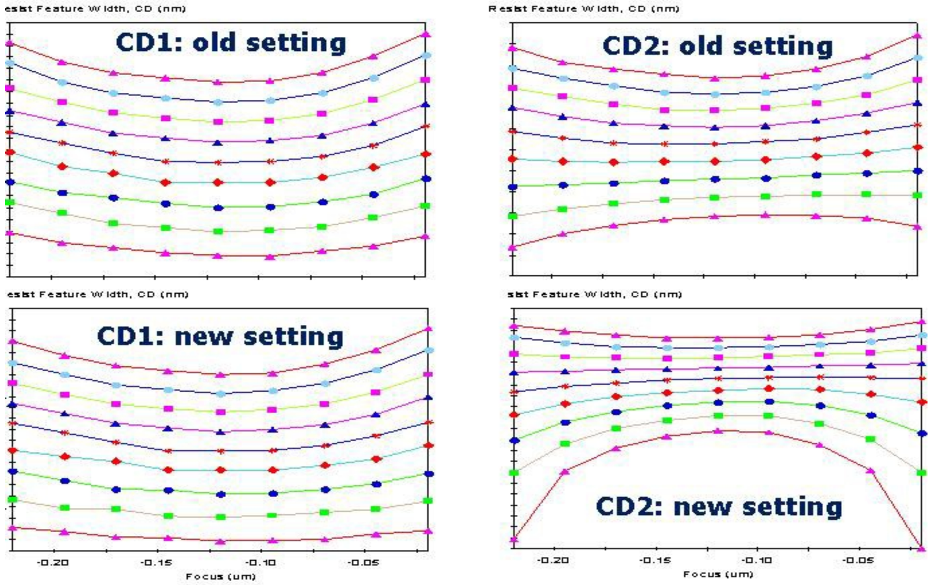


Fig 3.5. CD1 and CD2 process window comparison between the old and new illumination sigma settings (CD values are not shown on purpose). The simulation indicated that the new setting still meets the process window requirement.

4. Conclusions

This work has shown that the CD to scanner parameter sensitivities can be accurately predicted given calibrated resist models and accurate scanner metrology. The assumption that the scanner knobs are sufficiently independent such that cross terms could be considered negligible was proven valid in our case. It was found that a desired photo process change is commonly sensitive to more than just one tool parameter. The final choice of which parameter combination to use can be decided by wafer data verification against the overall process reliability requirements and their relative complexities in implementation.

Our CD-optimized-scanner-matching exercise has shown that it was a success to match 2D pattern printing indirectly using a 1D-through-pitch optimization. This suggests that for our case the imaging differences were well characterized across the entire imaging pupil by the through-pitch horizontal and vertical lines. The standardization of a tool-matching procedure using a dedicated 1D tool-matching mask and its simulation package is therefore possible. Our results from the process-optimized-scanner-matching exercise have also proven that a time efficient and highly effective photo process transfer is achievable with the proposed simulation-central process optimization. The accurate simulations were the consequence of the accurate resist modeling and detailed tool modeling during the project preparation.

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