Monte-Carlo Simulations of Image Analysis for flexible and high-resolution Registration Metrology

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ABSTRACT

The continuous progress of PROVE, the new photomask registration and overlay measurement tool currently under development at Carl Zeiss has been reported at mask related conferences since it's first publication at EMLC 2008. The project has moved in the past year from a final design on paper to functional hardware in the lab. Major tool components such as the climate control unit, the automated mask handling system and the metrology stage have been assembled and successfully tested. The scope of this paper is to report on the current status of PROVE and furthermore present results from simulations utilizing the image analysis routines of the tool. Monte-Carlo simulations were used to analyze the impact of several realistic tool limitations (camera noise, stage position errors and imaging telecentricity) on the image analysis process. The evaluation itself was based on a conventional threshold approach to perform both registration and CD measurement simultaneously. The results show, that the routines can deal with the tool imperfections and limit the contribution to the reproducibility error for standard registration markers to a negligible part. Even single contact holes suffer only from small errors, when camera noise is low and image averaging is increased. Employing a generally used test pattern the CD test results also confirm a sufficiently small error contribution to the CD non-uniformity reproducibility.

Keywords: photomask metrology; registration; pattern placement; Monte-Carlo simulation; image analysis

1. MOTIVATION

Photomask registration measurement has gained importance with the introduction of the 45 nm technology node and the discussion of double patterning schemes for several device applications. Measuring and analyzing pattern placement is not just a qualification task of high-end photomasks for the most advanced nodes, it also enables the continuous improvement of writing tools and the optimization of the overlay performance for the complete lithography process. Last year at EMLC 2008, the authors informed the mask making community about PROVE, the registration and overlay metrology tool which is currently under development at Carl Zeiss. PROVE addresses in-die measurement capability on production features by means of a high-resolution 193 nm optic, as well as optimized illumination for best contrast and pellicle compatibility. Within the last 12 months the project has made steady progress towards functional hardware as described in the following section of this paper. Meanwhile, the image analysis software has also been programmed, and was utilized for a Monte-Carlo simulation to test its functionality and assess its contribution to the overall error budget. In the main part of the paper, we present the effect of unavoidable machine inaccuracies, such as lateral positioning errors, focus errors, camera noise and telecentricity in the imaging path on the image analysis for registration an CD metrology.

2. PROGRESS IN PROVE

The basic working principles of PROVE, focusing on the optical beam path including the new auto focus concept and illumination conditions have already been presented at photomask related conferences in 2008 [1,2,3]. The project has made continuous progress and has developed in the meantime from conceptual ideas, over a design on paper to tangible hardware in the lab. Critical subcomponents such as the metrology stage, the environmental control system and the automated mask handling system have been assembled, tested and shipped to the Carl Zeiss for tool integration. As an example, figure 1 displays the complete environmental control chamber (dubbed PCU for Process Control Unit) after delivery and reassembly in Jena. All subcomponents have met the required specifications and passed their individual acceptance tests. The development team is currently busy with the delivery of the final components for the optical train, the assembly of the entire stage and the integration of all components into the system.

Fig.1: PROVE – Process Control Unit

3. DESIGN OF EXPERIMENT

For a registration tool of the next generation, the relative position of structures on a photomask have to be determined with an error of about 0.5 nm. This sub-nanometer precision translates for the task of image analysis into a sub-pixel position detection capability. The daunting task of analyzing the location of features in a pixelated CCD image requires routines, which can determine positions in an image with errors of less than 1% of a pixel in order to contribute only a negligible part to the overall error budget. The image analysis routines can detect edge locations only with a small uncertainty, since camera noise and shifts of the feature in the pixelated image due to stage inaccuracies inevitably lead to slightly different results. The impact of e.g. camera noise depends on the feature size, and an analytical formula was already presented at BACUS 2008 [3], which properly describes the scaling effects. However, the complete influence of the camera noise, in the presence of ever so slightly shifted images, also depends on the algorithms used to analyze the captured images. Hence, a reliable assessment of the error contribution merely due to the image analysis process can only be obtained by means of a Monte-Carlo approach using the tool routines. The model used in the simulations included three sources of variations depicted in figure 2: the pixel noise inherent in the camera images, a lateral position shift of features in the image due to placement imperfections of the stage, and a defocus uncertainty also due to positional errors in z-direction of the stage. In order to be able to quantify the mere image analysis uncertainty, these stage inaccuracies were included in the simulated images, but the applied shifts were known without error in the routines. This approach emulates a perfect metrology system, which in reality is not true, but is covered in a separate error budget. That way, the obtained results permit a proper test of the capabilities of the analytical routines independent of other tool influences.

The Monte-Carlo approach provides another advantage: since the analysis routines are applied to simulated images, realistic test patterns can be used to obtain a more accurate assessment of the performance. In order to provide features, which can be used for both registration and CD-uniformity testing, three different types of patterns have been selected. Figure 3 illustrates the patterns used for the simulations. The left side depicts single registration crosses of various line width with an arm length of several µm to determine the impact on classical registration jobs. For CD-uniformity assessment, we employed an e-beam PEC (proximity effect correction) structure with two different line widths. This type of structure allows to detect the influence of neighboring features on the obtained CD results. From top to bottom the neighborhood changes from a single line, over symmetric and asymmetric blocks to dense lines on both or only one side. The last pattern investigated is a contact hole array of two diameters, which when analysing single contact holes reveals the noise induced image analysis limit of tiny features.

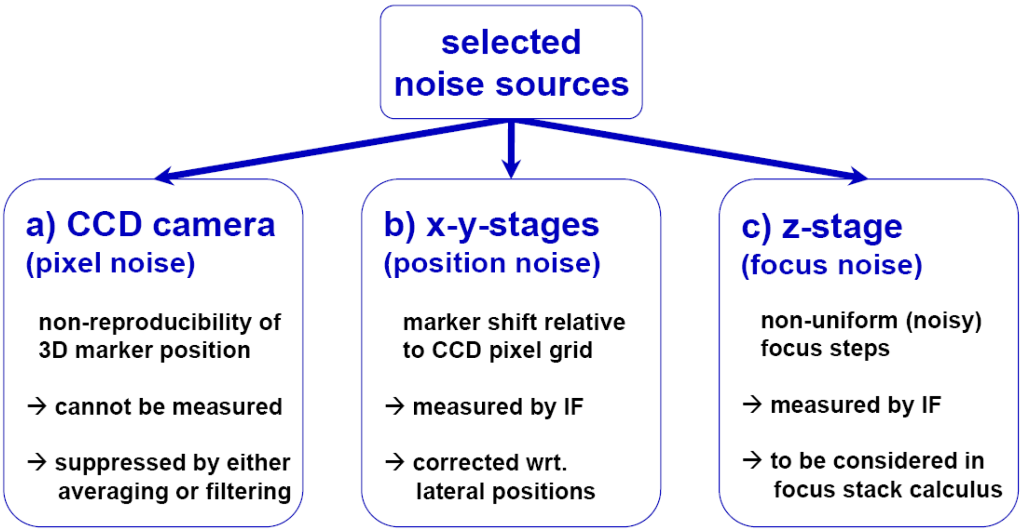

Fig. 2: Important noise sources used as impact for the simulations

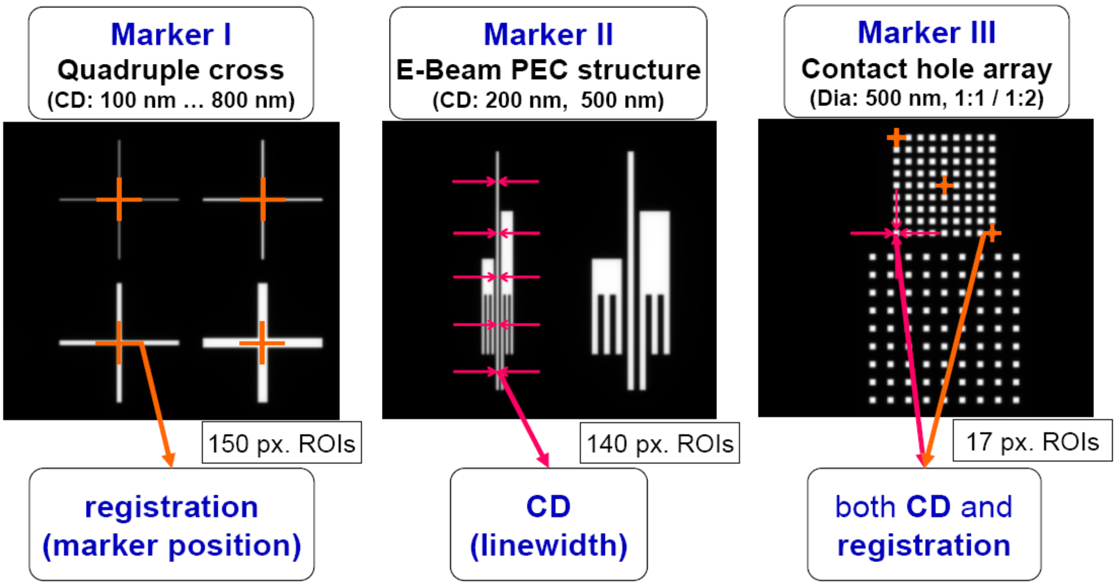

Fig. 3: Registration and CD marker types under investigation

The Monte-Carlo simulations have been perfomed in the scheme illustrated in Fig. 4. First, the type of pattern, the simulation conditions (noise levels) and the image analysis conditions (e.g. number of images) were chosen. Emulating the 193 nm imaging optics, artificial images were calculated including the effects of camera noise and potential mispositioning of the stage during the focus stack. These images were used as input for the image analysis routines, which performed two types of evaluations. The images in the focus stack were used to derive a metric indicating the focal position of the images. With this analysis the best focus position could be determined by interpolation. The images were also utilized in a conventional threshold approach to perform both registration and CD measurements simultaneously. Combining both results led to the desired image properties of registration or CD at best focus. Repeating this procedure multiple times in a Monte-Carlo fashion finally yielded the reproducibility uncertainty for both registration, as well as CD metrology due to the noise induced image analysis errors.

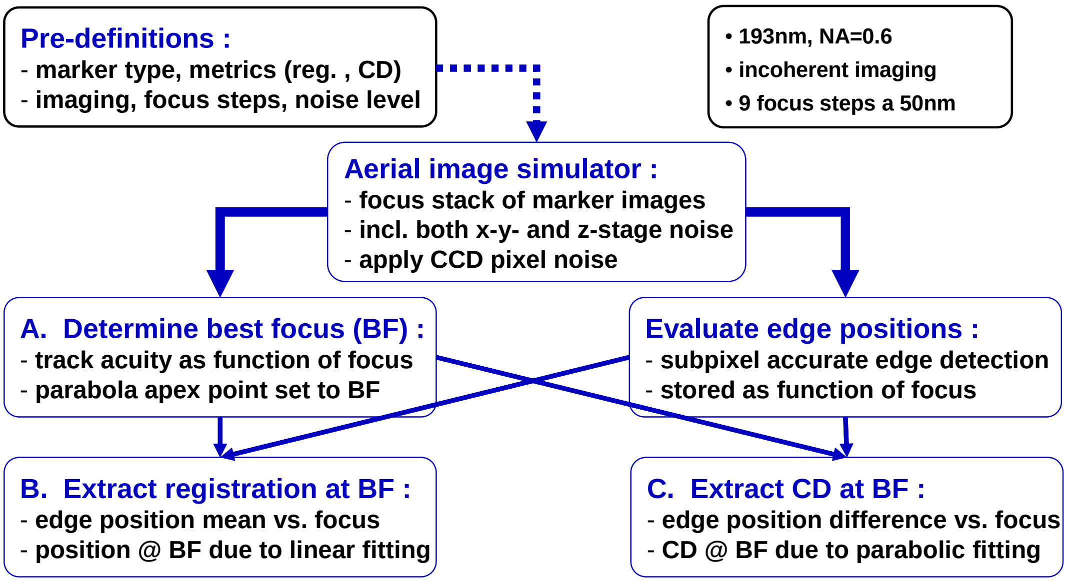

Fig. 4: Monte-Carlo simulation scheme

4. SIMULATION RESULTS

The position of edges has to be evaluated at the best focus, since e.g. telecentricity or coma in the optical path can cause a lateral position shift on defocus. For that reason, registration tools typically capture multiple images while purposly stepping through the focus. Evaluating the complete focus stack of images not only helps in terms of averaging out statistical errors, it furthermore allows to determine the best focus position by analyzing a defocus metric (acuity). Other image properties, e.g. the position of an edge can thus be interpolated to the best focus position. Hence the first question answered by the Monte-Carlo simulation was, what uncertainty in determining the best focus position is caused by the camera noise or the stage inaccuracies.

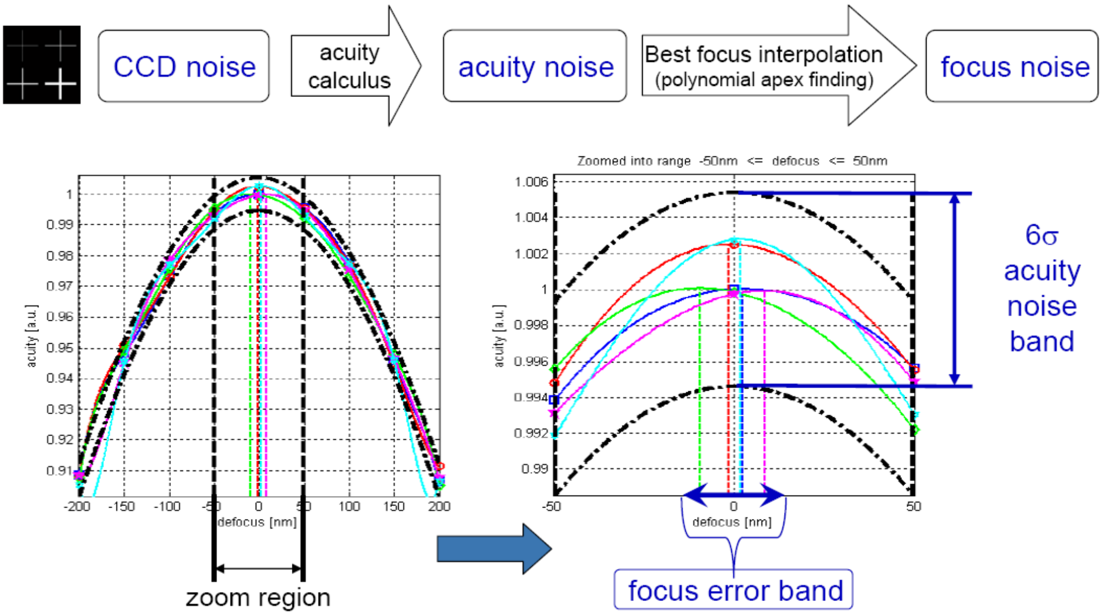

Fig. 5: Impact of CCD noise on best focus.

Figure 5 illustrates the simulation procedure to obtain the best focus position. The left graph shows the acuity as a focus metric, which reaches a maximum of unity at best focus and drops off with increasing defocus. Every image yields one acuity value, and all data points are subsequently fitted with a parabola, whose apex coincides with the best focus position. Due to the camera pixel noise every acuity value can slightly vary, as indicated by the black ± 3 sigma acuity noise band. The colored lines indicate a few Monte-Carlo realisations. Due to the parabolic fit, the apex of the different acuity curves varies less than the individual data points. This variation finally yields the focus error band, or the uncertainty of determining the best focus position. This analysis was done for all the structures described above, and with focus step sizes of 50 nm or larger the 3 sigma uncertainty of the best focus position was at most 4 nm. This value scales with the pixel noise and decreases for larger step sizes.

The registration simulation for single contact holes in the presence of an imaging telecentricity error is shown in figure 6. This telecentricity error causes the contact hole position to depend linearly on the defocus. The defocus error mentioned above thus translates into an additional registration error. Every individual registration result lies between the marked noise band, however the linear fit used to interpolate the registration position at best focus reduces this error band. The enlarged picture on the right side illustrates the final registration uncertainty including telecentricity effects. Monte-Carlo simulations of the registration analysis of both the conventional crosses and contact holes have been performed. The contribution of the image analysis to the overall registration error was negligible (below 0.1 nm) for all line widths of the crosses. On the other hand, single contact holes, which do not provide sufficient edge information for an accurate position analysis, also contributed only 0.2 nm to the error budget. This small number is encouraging, since it permits the tool to be used even for tiny features in special applications, when further averaging over more images at the cost of throughput is tolerable for most precise measurements.

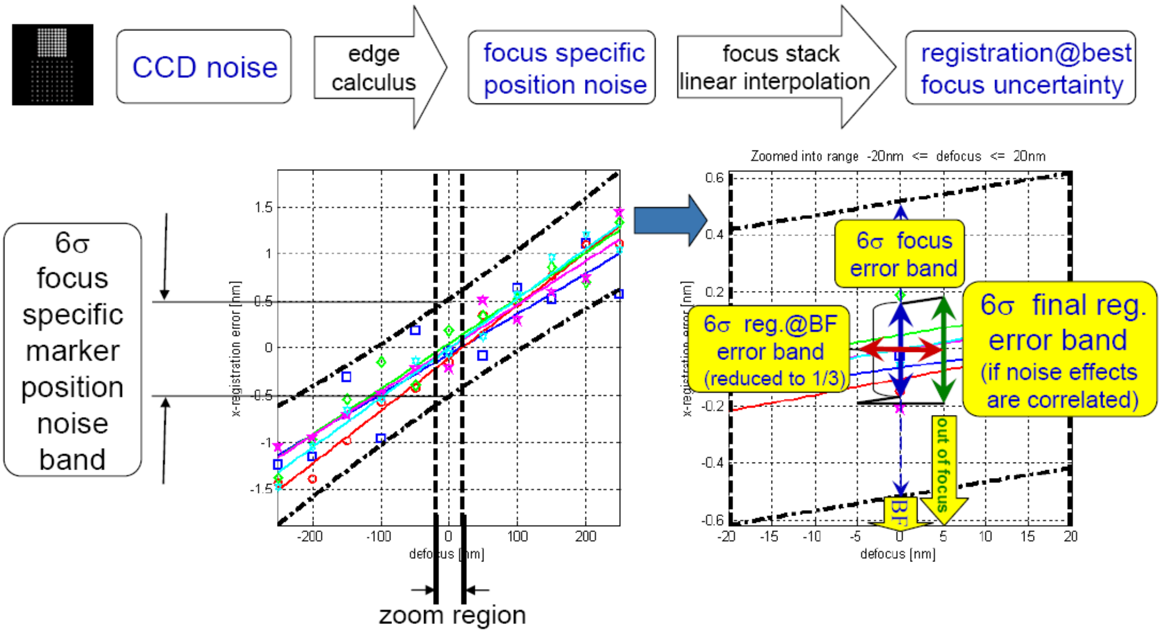

Fig. 6: Registration accuracy assuming an additional imaging telecentricity error

Figure 7 illustrates the simulation procedure for CD uniformity measurements. The CD metric is sensitive to defocus, typically in a curved fashion close to the best focus position. Hence the individual CD data for the images in the focus stack are fitted by a parabola to interpolate the CD value at best focus position. This analysis was performed for both the PEC structure, as well as for the contact hole array. The CD results for the PEC structure showed a 3 sigma uncertainty below 0.2 nm independent of the neighborhood of the line evaluated. In addition no systematic CD changes could be detected. The contact holes with much less edge information consequently suffer from a larger CD reproproducibility uncertainty of 0.6 nm due to the camera noise. These results are still encouraging, since for both features the contribution due to the pixel noise is still below the overall specification of about 1 nm. While standard size features do not suffer significantly from analysis errors, tiny features would again benefit from averaging over more images at the expense of throughput in special applications where precision is most important.

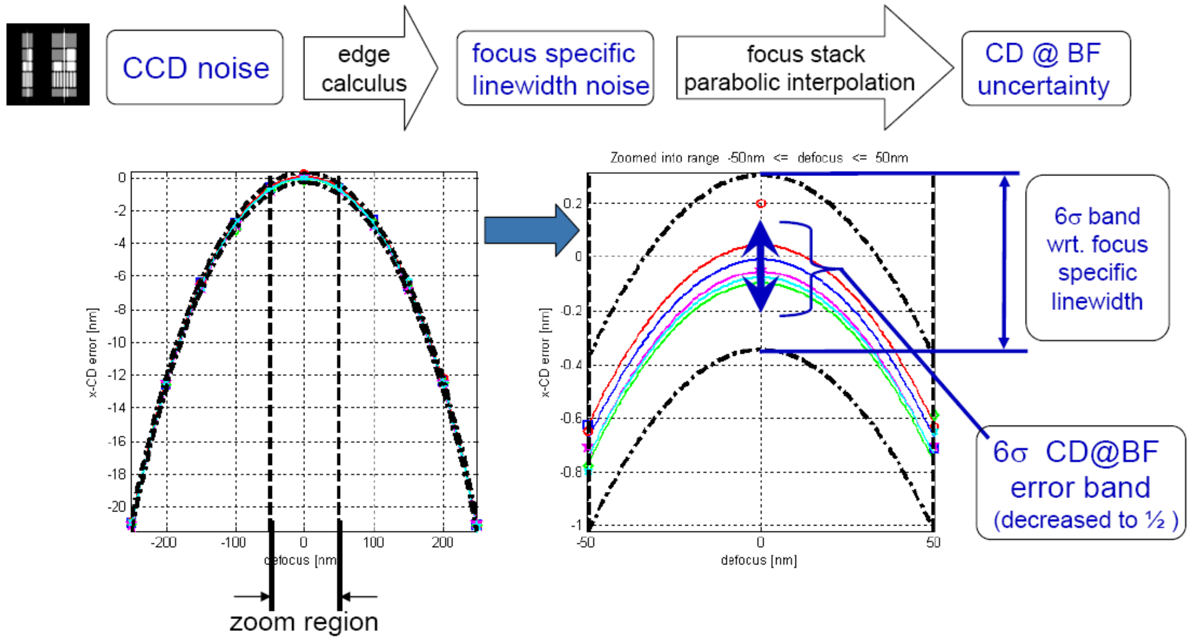

Fig. 7: Impact of CCD noise on CD error at best focus. The noise band is reduced by parabolic fitting.

All the obtained results of the Monte-Carlo simulation for the various structures and both registration and CD analysis are summarized in figure 8. The best focus uncertainty due to pixel noise and stage inaccuracies is limited to at most 4 nm. This uncertainty scales with camera noise, but can be reduced by increasing the focus step size. The registration analysis results in the center illustrate the negligible error contribution for standard registration markers, while single contact holes with only little edge information suffer more from the pixel noise. Further averaging helps to some degree in certain applications, where the throughput can be sacrificed. A similar result was obtained for the CD error analysis shown on the right side. Standard features like the PEC structure get an acceptable uncertainty of only about 0.2 nm due to the pixel noise. For single contact holes this error contribution is much larger and illustrates the limits for tiny features, unless the pixel noise can be further reduced and more image averaging is possible.

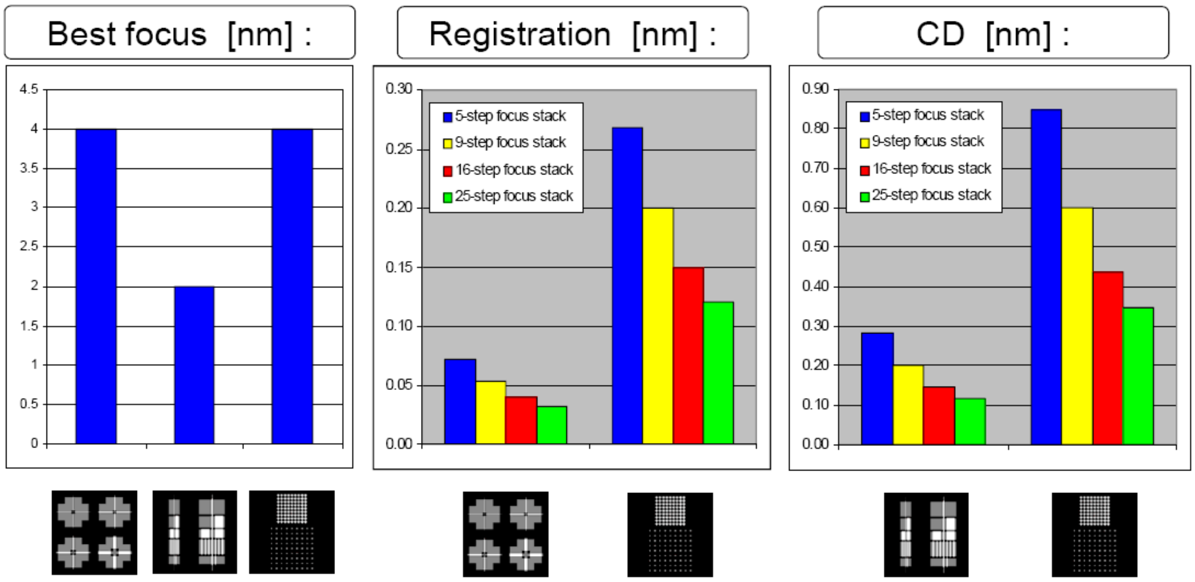

Fig. 8: Theoretical best focus, registration and CD error for the investigated marker types.

5. SUMMARY

The PROVE – Project, targeting first customer deliveries in 2009, is on track and has made continuous progress since its first introduction at EMLC08 just one year ago. All major components such as the metrology stage, the environmental control system and the photomask handling system have been individually tested and were shipped to Jena for final integration into a fully functional system. The individual acceptance tests for these subsystems fulfilled the required specifications and did confirm the feasibility of our initial concepts.

By utilizing the newly developed image analysis routines of the tool, a Monte-Carlo simulation could determine the contribution of the image analysis uncertainties to the overall reproducibility error of the tool. Different metrology marker types were investigated by simulating the corresponding images, applying realistic camera noise and analyzing the data assuming additional stage position errors and non-telecentricity in the imaging path. The simulation results demonstrate that both the registration and the CD measurement only have a small error contribution due to the image analysis in the presence of pixel noise and stage inaccuracies. Only when using tiny features with very little edge information such as a single contact hole, the error contribution due to the image analysis rises and would benefit from further image averaging or lower pixel noise. The simulations furthermore confirmed that the routines implemented in the tool for image analysis are generally up to the task.

ACKNOWLEDGEMENT

The authors appreciate the valuable contributions of Matthias Manger and Dirk Seidel. This work has been partially funded by SEMATECH under the contract no. LITG325.

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