Application Note

Grayscale with GenISys 3D-PEC

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INTRODUCTION

Grayscale laser lithography is used to create 3D[1] micro-structures in photoresist. In contrast to traditional, or binary, lithography (photoresist is either completely exposed or unexposed), grayscale lithography creates intensity gradients, which translate into a resist topography. Direct-write laser lithography is a fast, scalable and geometrically flexible approach to grayscale microstructure fabrication. It is suitable for both fast prototyping and large-area production of 3D microstructures for micro-optics – e.g. diffractive optical elements (DOE), micro-lenses, computer-generated holograms (CGH) – MEMS, microfluidics and many other applications.

The resulting topography is strongly influenced by geometry-dependent proximity effects, lateral development and a non-linear dose dependence of the resist. Finding the optimal combination of these factors is a major challenge for grayscale lithography. It is usually addressed by iterative optimization of the gray value distribution (GVD), until remaining deviations from the desired target topography are sufficiently small.

Although the iterative approach fits well for many common patterns, it requires a lot of experience in grayscale lithography from the system operator. Even long-term users have to carry out many time-consuming iterations of exposing, measuring and optimizing before obtaining a satisfactory result. Furthermore, this approach is not suitable for complex patterns such as asymmetric lenses, freeform optics or DOEs. A global solution provided by GVD tuning does not compensate deviations from the designed profile caused by local proximity effects – i.e., effects caused by the local surroundings of any given position in the pattern.

Both limitations of the iterative approach can be avoided by using numerical methods based on process modelling such as those implemented in the 3D-PEC module of GenISys BEAMER software. This module takes into account the resist contrast curve, models the exposure and development and modifies the dose assigned to each pixel based on strength of proximity effects from its surroundings. Here, we present this powerful software solution for rapid and easy optimization of complex 3D microstructures.

> Gray Value Distribution (GVD): Relationship between gray value and exposure dose. On DWL systems, this relationship can be defined by the user. Nonlinear distributions can be used to compensate resist non-linearities and proximity effects.
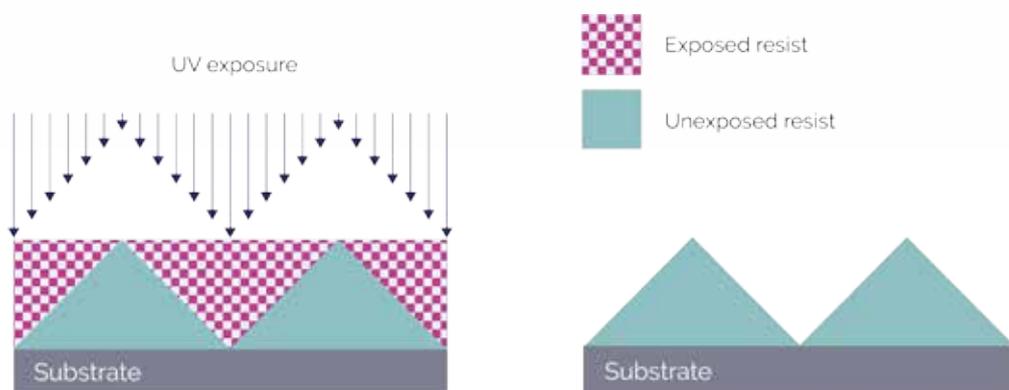

Figure 1: Schematic illustration of grayscale lithography. The photoresist layer is partially exposed by UV-light (left). During development, exposed resist is removed (right), resulting in a 2.5-dimensional topography.

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[1]Depending on conventions, grayscale or 3D microstructures are called 2.5D, as the geometry is limited by patterning the surface.

[2]See the Brochure and an Application Note on Grayscale lithography

SOFTWARE-BASED APPROACH: GenISys BEAMER

GenISys BEAMER is a data preparation software for electron-beam and laser lithography. It is used for preparing a designed layout by using a set of comprehensive layout operations (e.g., Editing, Extraction, Healing, Biasing, Boolean Operation) and correction (PEC, OPC) for the exposure and generating the final exposure data for the e-beam or laser lithography tool.

3D Proximity Effect Correction, or **3D-PEC** – one of the advanced features of this software – provides an alternative to the iterative optimization of the gray value distribution.

It uses a three-dimensional physics-based model of photoresist exposure and development to compensate for the proximity effect in grayscale exposures. The input includes tool-specific exposure parameters, the target design data and, most importantly, the resist optical parameters (absorption) and contrast curve – the relation between the exposure dose and the resulting developed resist thickness.

Based on these parameters, BEAMER assigns an individual gray value to each pixel of the pattern according to its local environment.
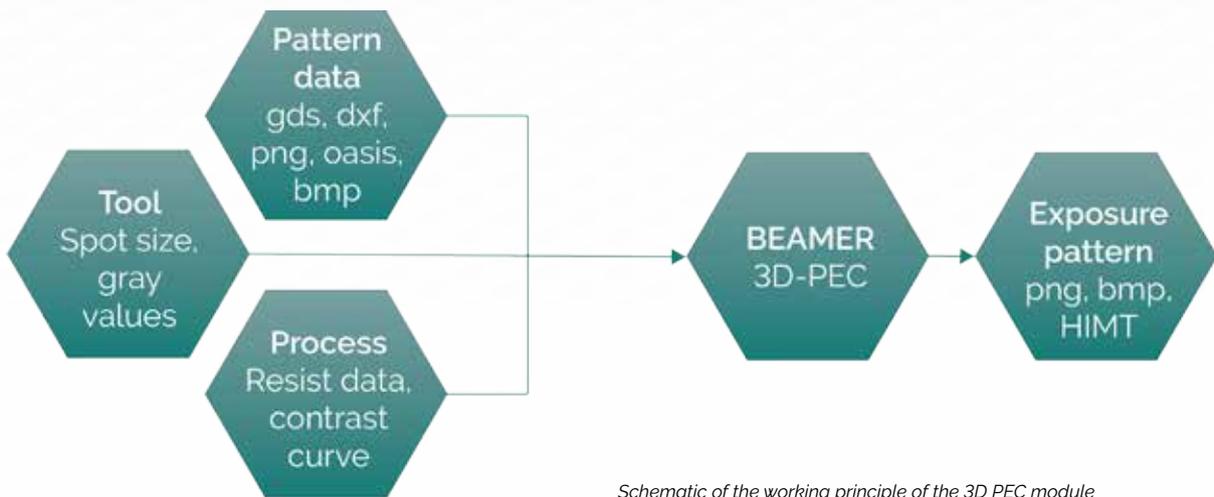
Schematic of the working principle of the 3D PEC module

Iterative approach		BEAMER 3D-PEC	
●	Keeps the design layout fixed.	●	Keeps dose of every gray value fixed.
●	Changes the dose assigned to every gray value based on previous tests.	●	Changes gray value of pixels according to the simulations based on the contrast curve.
+	More precise approach for simple and repetitive structures (e.g. micro-lenses).	+	Fast: Requires only one test exposure for the contrast curve measurement.
+	Fine dose assignments possible for each gray value.	+	Universal: One contrast curve can be applied to any design.
−	Not possible to fully optimize patterns with complex non-repetitive designs.	−	Eventually reduced height resolution because of limited number of gray values.
−	Testing can be very time-consuming.	−	Can be computationally intensive for non-repetitive designs.

EXAMPLE: OPTIMIZING A DIFFRACTIVE OPTICAL ELEMENT WITH BEAMER 3D-PEC

Here we present the grayscale pattern optimization pro-
cess for a diffractive optical element using BEAMER
3D-PEC software and show the resulting microstructure.
Diffractive optical elements (DOEs) consist of square flats
with different heights. The absolute accuracy of the final
topography is paramount to the optical properties and the
quality of the resulting device. To ensure a uniform target
depth and sharp transitions from one flat to the next, the
exposure dose close to edges and corners has to be modi-
fied individually for each flat. This cannot be solved by the
iterative approach, since the same dose assignment would
be applied to all pixels within one flat and to all flats with
the same gray value. In contrast, 3D-PEC changes the gray
value of each pixel individually and thus is the more effec-
tive approach for this application.

> As gray value 0 always corres-
> ponds to zero exposure dose, it
> is recommended to not use this
> value in the design layout. This
> way, it is possible to introduce
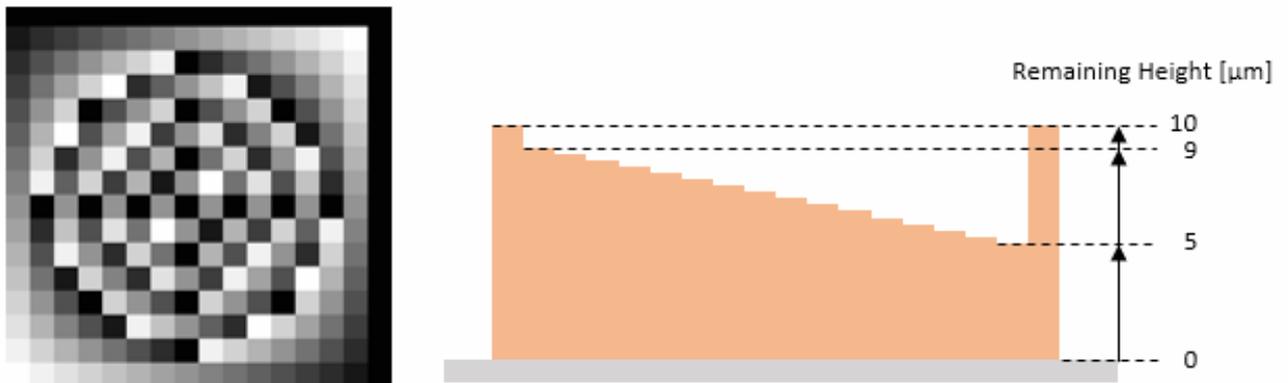> an offset between resist surface
> and final target structures.

Figure 2: .png layout of DOE structure (left) and target resist profile cross section of the top row (right)

The pattern	DOE-like structure, 16x16 square flats The shallow flats (black): 1 µm below the resist surface The deepest flats (white): 5 µm below the resist surface
Size of each flat	6.4 x 6.4 µm²
Grayscale	16 selected levels, 8 bit layout
Exposure	DWL 66⁺ with a 405 nm diode laser, Write Mode I and a 200 nm pixel grid[3]
Resist	10 µm thick layer of AZ4562
Development	AZ 826 MIF, 6 minutes

STEP-BY-STEP PROCESS FLOW

1. Set up the BEAMER flow

The BEAMER graphical user interface has a modular, sequential design. Individual modules are simply dragged and dropped into the flow window and connected in the desired consecutive order.

A basic flow for 3D-PEC correction consists of three modules:

Import: Imports the design bitmap (PNG) layout and converts design gray values into layers. With a slightly more complex flow it is also possible to import true 3D objects in STL file format, where the z-values are translated into layers.

3D-PEC: Corrects the data for three-dimensional process and proximity effects

Export: Exports the corrected data in the desired format, which can vary depending on the exact configuration of the tool.
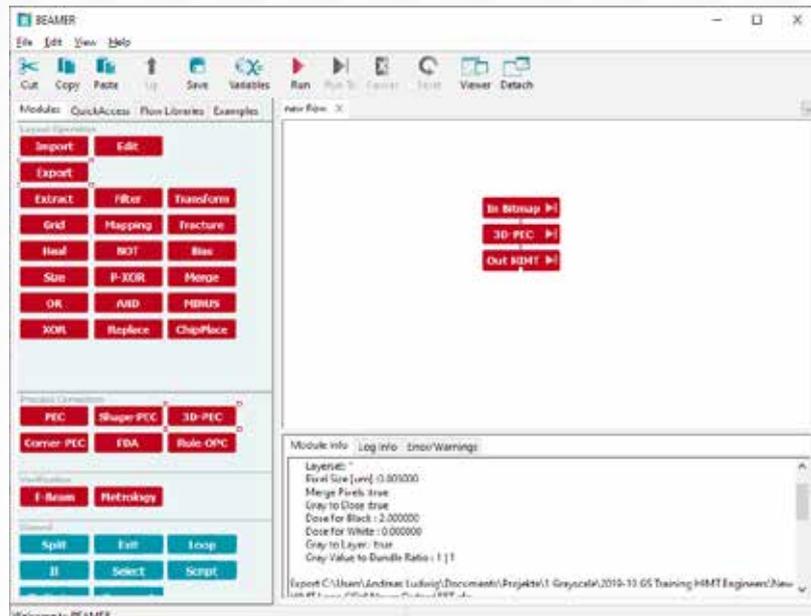

Figure 3: Basic flow for 3D-PEC data correction

> Please refer to the BEAMER user guide for more detailed information

2. Set up the 3D-PEC Module

The 3D-PEC Module needs definitions of the exposure tool and resist parameters as an input.
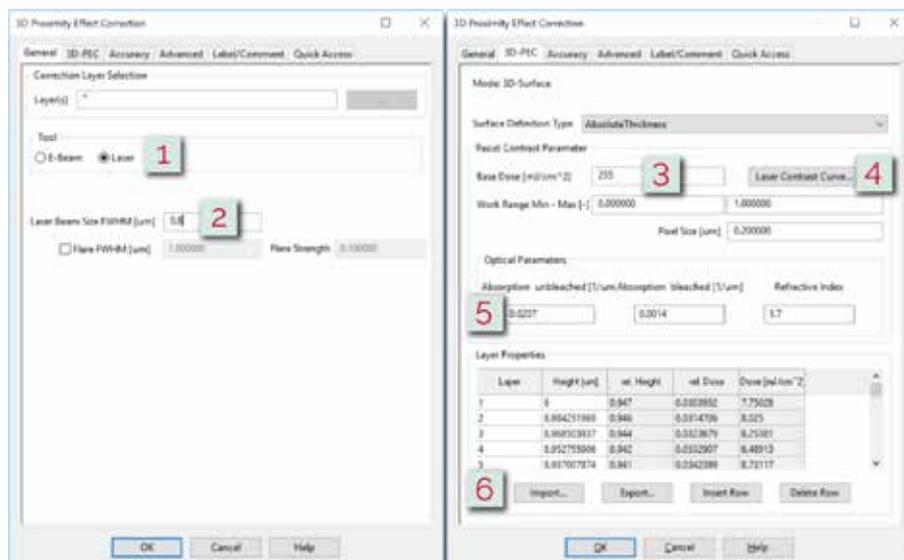

Figure 4: Main tabs of the 3D-PEC module setup. The red figures highlight wherever critical user input is required. As indicated by red numbers, the user first specifies the type of lithography under consideration (1) and the FWHM of the beam size (2). In the second tab, the number of gray values (3) available on the tool are specified together with the measured contrast curve (4) and optical parameters of the photoresist (5). Finally, the layer definition table is imported (6). The dose class definition table is specified in the tab Accuracy (not shown). Refer to the text or the BEAMER manual for more detailed information.

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Apart from basic definitions, like the laser beam size, number of gray values on the system and optical parameters of the photoresist, the following inputs are required:

Resist Contrast Curve

A contrast curve (CC) correlates each exposure gray value to the depth it produces under given process conditions (base exposure dose, photoresist, developer, development time, ...). This relationship can be derived from a simple test exposure with a pattern consisting of a set of squares, each of which is assigned to a different gray value. An example obtained in 10µm of AZ4562 is shown in Fig. 5. The detailed information on how to measure a contrast curve is given in Appendix A.
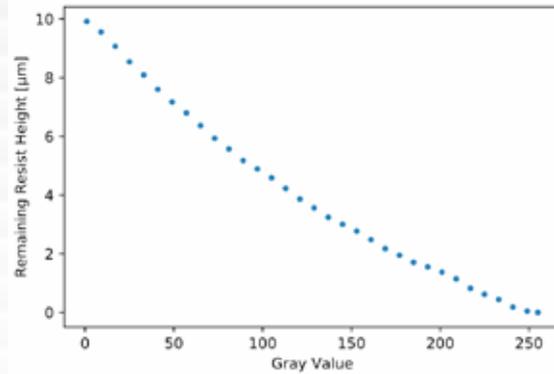

Figure 5: Example contrast curve (CC) 10 µm thick AZ4562

Layer Definition Table

The layer definition table defines the target depth of each layer (= layout gray value) in the photoresist. For convenience, this can be done in a simple text file, which can then be imported to the software. According to the specifications given above, the layer definition table would look like this:

```
# Layer    ,    Remaining Resist Height
1          ,    9
2          ,    8.98425
3          ,    8.96850
           [...]
255        ,    5
```

Dose Class Definition

As HIMT systems work with integer gray values only, it is recommended to specify an explicit list of all available gray values. These are normalized between 0 and 1 corresponding to the power of the laser between off and full power. For a system with 256 gray values, a text file as follows can be imported.

```
# Dose Class Definition
0.003921569
0.007843137
[...]
0.996078431
1
```
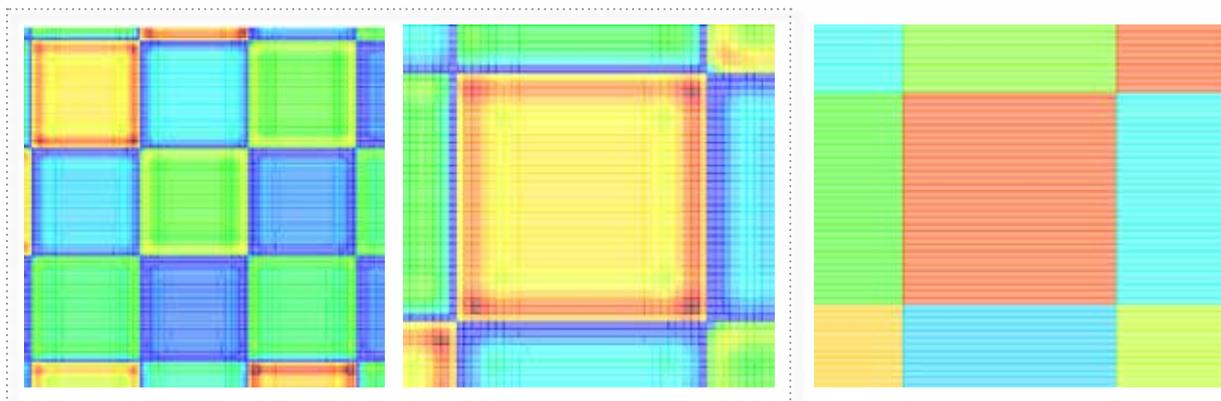
3. Corrected Data Output

Figure 6: Corrected data output as seen from the BEAMER viewer (left and center) and uncorrected data (right). Exposure dose is color-coded, with warmer colors corresponding to higher exposure dose.

After running the 3D-PEC module (a calculation for such small structure takes a few seconds), the corrected dataset is finished and ready for exposure. Selected areas of this optimized dataset are shown in figure 6. The resulting gray values are represented in a color scale from blue (low GV) to red (high GV). The 3D-PEC correction breaks down the individual flats and modulates the gray value within each of them with respect to adjacent structures. In the vicinity of corners and edges, the gray value is either increased or decreased, depending on whether the next adjacent flat is exposed at a higher or lower dose. Individual flats are separated by single-pixel-wide lines of low gray values to ensure the highest possible contrast. The resulting structure matches the specified target very well. Quality of corners, edges and sidewalls is very good with relatively little effort in determining the exposure parameters.

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[3] This configuration does not exist in present DWL 66⁺ systems anymore. The Write Mode I uses the same write lens, but with a 100-nm pixel grid.
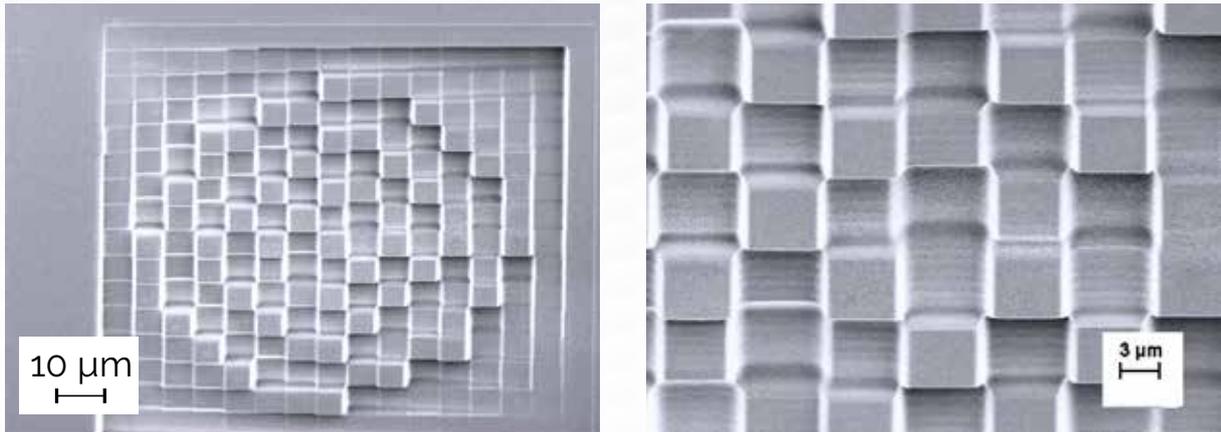
CONCLUSIONS

Figure 7: SEM image of the resulting DOE with a tilt to highlight the resulting topography

The complexity of grayscale patterns is increasing, and the iterative approach is no longer sufficient for 3D micropatterning that meets the specs. The BEAMER 3D-PEC module enables accurate fabrication of complex 3D structures with Heidelberg Instruments lithography systems.

The approach presented in this application note enables straightforward grayscale lithography even for complex irregular microstructures.

- Easy-to-use software interface
- Reasonably short computation time
- Required input: a resist contrast curve and target definition
- Output files can be transferred to the HIMT exposure system automatically.

Heidelberg Instruments' processes and applications engineers have accumulated an extensive know-how in optimization and fabrication of grayscale microstructures of various complexity. Advanced exposure systems, established fabrication processes, and 3D-PEC capabilities enable fast prototyping and high-throughput fabrication of high-quality complex irregular microstructures.
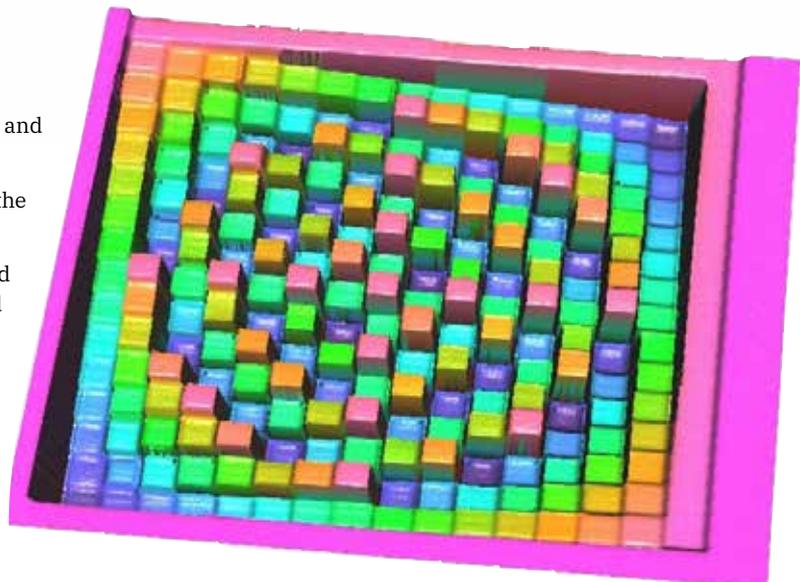

Figure 8: Confocal image of the final exposure

APPENDIX: MEASURING THE CONTRAST CURVE

A contrast curve correlates each exposure gray value to the depth it produces under the given process conditions (base exposure dose, photoresist, developer, development time, an so on). This relationship can be derived from a simple test exposure.

A typical pattern for a contrast curve measurement is a set of squares, each to be exposed with a different gray value. The global exposure dose is chosen such that the curve covers the desired depth range, typically the highest gray value should just barely reach the substrate.

The square size itself affects the resulting contrast curve. It should be large compared to the pixel size, so that the center is not affected by proximity effects from the edge. For 200 nm pixels, for example, a square size of 50 by 50 µm has proven to be optimal.

After development, the depth of each square is measured using confocal microscopy, atomic force microscopy, profilometry or any technique that can quantify the surface topography.
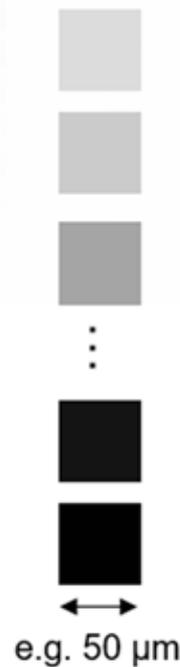

Figure 9: Example layout for contrast curve measurement

Note: Depending on the measurement technique, the measurement time increases drastically with an increasing number of data points. In those cases, it is not necessary to measure every single gray value. For systems with 256 (1024) gray values, for example, it is sufficient to expose and measure only every eighth (sixteenth) gray value and use a polynomial fit for interpolation.

Note: Instead of the achieved depth, 3D-PEC requires the remaining resist height as input for the contrast curve.