A HIGH THROUGHPUT DUV WAFER STEPPER WITH FLEXIBLE ILLUMINATION SOURCE

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Abstract

This paper introduces a new high performance 0.25 µm DUV wafer stepper, that has been developed for the mass production of the 256 M DRAM generation of chips. This stepper is the first of a new generation of Deep UV steppers and scanners which use the AERIAL™ illuminator concept, in combination with a double telecentric, variable NA, 4x reduction lens. This system is geared for maximum flexibility, in setting up the optical properties of the lens/illuminator combination, whilst retaining a high throughput and user-friendly operation. This high flexibility makes it possible to tune the system to the maximum imaging performance for different types of features as well as for maximum overlay matching performance, with other DUV and i-line systems. The design of this system is explored in this paper. Experimental results of the most important aspects of system performance are presented.

1. INTRODUCTION

There is a continuing demand for faster, cheaper, and higher capacity memory and logic IC devices.

This trend leads to a continuous reduction of minimum feature sizes and drives the imaging capabilities of the lithographic equipment. Shrinking line sizes will result in faster devices and smaller chips, giving more chips per wafer produced, thus reducing production costs. One of the main process steps in determining the minimum feature size is the photolithographic operation.

After a number of years experience with the first generation1,2,3 of 248 nm systems, the market is now expecting high throughput, high reliability (and thus cost effective), 248 nm production tools. The PAS 5500/300 is ASM L’s third generation 248 nm system, developed in response to this need. DUV lithography becomes the production technology of choice at 0.25 µm and below, due to the inherently better depth of focus (about 50%) achievable at the shorter wavelength. However, the i-line to DUV transition is not abrupt. The type of application will drive the chip manufacturer towards the use of DUV for the most critical layers. For complex and more expensive devices (for example, microprocessors), the transition from i-line towards DUV can be made earlier. This is because the increased cost per layer is acceptable for devices with higher selling prices.

The PAS 5500/300 is optimized towards the highest possible throughput, combined with maximum process latitude, resulting from job level control over lens aperture and pupil illumination settings.

By using the AERIAL™ illuminator concept, the diameter of the source can be varied and the formation of an annular source by optical means is possible. As shown in previous papers7,10 discussing the AERIAL™ illumination concept, the achievable resolution which can be gained with off-axis illumination methods, improves significantly.

This improvement can be described with an adapted version of the Rayleigh equation:

$$R_{limit} = \frac{\lambda}{NA} \left(1 + \frac{\sigma \sin \theta}{NA}\right)^{-1}$$

For: $$(\sigma + \sin \theta/NA) < 1$$

Where:
- $\theta$ is the angle of incidence of the zero order with respect to normal (at wafer level),
- $NA$ is the Numerical Aperture of the optics,
- $\sigma$ the partial coherence of the illumination source,
- $\lambda$ is the exposing wavelength,
- $\alpha$ is a constant related to the resist process.

Off-axis illumination involves shifting the angle of incidence of the zero order by manipulating the illumination source. This type of imaging is generally referred to as “two beam imaging”, in contrast to the three beam imaging which results from on-axis illumination.
The impact of off-axis illumination on the image formation is illustrated in Figure 1.

In recent years, further refinements in optical techniques and resist processing have resulted in pushing the DUV lithography towards feature sizes below the wavelength of the light source. As can be seen from the equation, not only the optical system parameters but also the factor $\alpha$ plays a dominant role in this trend. The transition towards shorter wavelengths (193 nm) will be slow because of the major technology leap required in optical materials (transmission, compaction) and resist processing. For this reason, it is expected that further improvements of 248 nm resists processing and utilization of image enhancement techniques in a production environment will become economic. The use of Optical Proximity Correction (OPC) techniques and high contrast DUV resists will reduce the $\alpha$ factor. Experiences at ASML with the latest high contrast DUV resists have been reported recently.

In this paper, a general description of the PAS 5500/300 is given together with the results from the imaging and overlay performance tests in the <0.25 $\mu$m region.

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**Figure 1**  Depth of focus enhancement by “two beam imaging”\(^\text{12}\)

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In this paper, a general description of the PAS 5500/300 is given together with the results from the imaging and overlay performance tests in the <0.25 $\mu$m region.

---

**Figure 2** General PAS 5500/300 stepper layout
The main specifications of the PAS 5500/300 are given in Table 1.

### Table 1: Specifications of PAS 5500/300 DUV stepper

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified resolution</td>
<td>0.25 µm</td>
</tr>
<tr>
<td>Lens diameter</td>
<td>31.1 mm</td>
</tr>
<tr>
<td>- Xmax</td>
<td>22.0 mm</td>
</tr>
<tr>
<td>- Ymax</td>
<td>27.4 mm</td>
</tr>
<tr>
<td>NA range (0.63 at 20mm² field)</td>
<td>0.40 - 0.57</td>
</tr>
<tr>
<td>Conventional sigma range at maximum NA*</td>
<td>0.35 - 0.80</td>
</tr>
<tr>
<td>Annular sigma range at maximum NA*</td>
<td></td>
</tr>
<tr>
<td>- sigma inner range (σ\text{inner})</td>
<td>0.10 - 0.45</td>
</tr>
<tr>
<td>- sigma outer range (σ\text{outer})</td>
<td>0.35 - 0.80</td>
</tr>
<tr>
<td>- minimum ring width</td>
<td>0.30</td>
</tr>
<tr>
<td>Distortion**</td>
<td>&lt; 35 nm</td>
</tr>
<tr>
<td>Uniformity**</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>Intensity**</td>
<td>&gt; 220 mW/cm²</td>
</tr>
<tr>
<td>Overlay</td>
<td></td>
</tr>
<tr>
<td>- Single machine</td>
<td>&lt; 45 nm</td>
</tr>
</tbody>
</table>

* Values for sigma are based on the integrated energy definition
** Conventional setting (NA = 0.57; σ₀ = 0.75)

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### 3. SYSTEM DESCRIPTION

The PAS 5500/300 uses a third generation Carl Zeiss DUV lens in combination with an AERIAL™ illuminator. The general lay-out of this system is based on the PAS 5500 generation of steppers from ASML. Figure 3 gives an overview of the light path, from laser to wafer, of the DUV stepper.

#### 3.1. Laser and beam delivery

A 10 W, 1000 Hz, 0.8 pm bandwidth laser is used as a light source. The beam is guided via a sealed beam delivery system into the stepper. The laser can be placed up to 20 meters away from the stepper; for instance in a service area. Routing the beam at the same horizontal level, or to a higher or lower floor in the building, can be custom made to suit (using special beam benders). The laser operation is fully controlled from the stepper workstation.

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![Image of optical light path in the PAS 5500/300](image-url)
The complete beam delivery path is sealed and filled with nitrogen at overpressure. In this way, the airborne based contamination, that is always present in a clean room, cannot enter the system. Therefore, a maximum lifetime and a minimum amount of cleaning actions of the optics is ensured.

3.2. Beam positioning control

In large buildings there will be varying temperature differences between the different areas. These temperature differences in combination with the possible presence of dilation joints between the laser and stepper location may lead to large position and pointing errors of the laser beam at the stepper entrance. Variations will be very low frequency. These variations would be outside the demands on the laser beam position and pointing stability. An automatic beam positioning control unit maintains the position and pointing of the beam, over time. At the illuminator entrance, an optical system continuously measures the laser beam position and pointing with high accuracy. Based on this measurement information, the beam position and pointing are corrected. Since the beam is adjusted automatically, long term stable high uniformity performance and a minimum restart time after laser maintenance is ensured.

3.3. Illuminator

The illuminator is based on the concept of the AERIAL™ illuminator introduced in the PAS 5500/2007.

The diameter of the pupil source can be changed freely in the partial coherence range from 0.35 to 0.80. It is also possible to adjust towards an annulus with independently variable diameter and ring width. Due to the use of special optical elements, the pupil distribution remains very flat over a large range of conventional settings. This is done without significant loss of intensity.

All illuminator settings are controlled by closed loop servo manipulators.

In Figure 4 the pupil distribution for three different types of illumination mode are shown.

Uniform distribution at wafer level is created using the light mixing effect of a quartz rod. The length of the quartz rod has been chosen such that the number of reflections, which result in the integration of the single uniformity distributions, is about one order of magnitude higher than with the fly’s eye integrator as used in previous steppers. This ensures, that even at low \( \sigma \) and annular illumination, there is a good illumination uniformity.

The size of the illuminated field is determined by means of the internal reticle masking blades in combination with an optical module that creates an image of these blades in the reticle plane. This enables the size of the chrome border on reticles to be minimized.

To control the illumination dose with sub-percent accuracy, a closed loop pulse intensity control system is used. This device is required with the pulsed laser source, at low doses, where the pulse to pulse fluctuations and discrete pulse errors degrade the applied dose. The pulse intensity is tuned so that every requested dose is optimized for the minimum exposure time in combination with the minimum number of pulses required to correct the laser (pulse to pulse) variations.
3.4. Projection lens

The PAS 5500/300 uses a 0.57 NA, double telecentric (4X reduction) lens. This lens contains the means to make it possible to optimize the imaging performance, independently, for:
- The wafer-to-reticle expansion,
- The field curvature,
- The rotational symmetric distortion.

Using the stepper alignment metrology system, full field (139 points) distortion and focal plane deviation are measured in resist. These results are used to set-up the system and optimize the imaging and stepper to stepper overlay performance.

Online measurements, with use of the reflection image sensor in combination with a pressure and lens temperature sensor, are used to measure and optimize the imaging performance continuously.

As discussed, it is possible to determine the key characteristics of the aerial image such as:
- Optimum focus and tilt,
- Astigmatism,
- Field curvature,
- Image position and rotation,
- Magnification,
- Third order distortion.

Wavelength is used to correct for pressure induced optical aberrations. Changes with respect to a reference pressure are cancelled out completely. This in contrast with previous generation DUV steppers, where wavelength was used to find an optimum between minimum field curvature, astigmatism and rotational symmetric third order distortion. In the PAS 5500/300 this optimization is done using special lens elements in combination with the reticle table height.

Also, magnification is controlled by the special lens elements. Focus, image position and rotation are optimized using the six degrees of freedom of the wafer stage which is controlled by the five axis interferometer in combination with the broadband wafer levelling system.

This flexibility of on-line tuning of the imaging performance in the stepper results in superior distortion and overlay/matching performance.

4. SYSTEM PERFORMANCE

The performance, as presented in this paper, has been evaluated on the first few PAS 5500/300 DUV systems.

The initial evaluation was focused on the capability of the system to image 0.25 μm features. Special attention was paid to the verification of different design parameters such as:
- Imaging behaviour with different lens characteristics,
- Pupil illumination,
- Exposure wavelength.

As mentioned in a previous paper, simulations were done to find the optimal lens/illuminator settings for the
maximum Depth of Focus (DoF) with a 10% exposure latitude. This approach proved to be a more realistic representation of the actual use of the system in production applications. It should be noted however that these settings will not lead to the maximum possible Depth of Focus obtained with smaller exposure latitudes.

During the initial system verification, exposures were made over the complete possible conventional and annular NA/σ range. This to verify the initial choice for the optimal settings.

In addition to the verification of the 0.25 μm performance, exposures were made, to study the system capabilities in the range of 0.18 - 0.25 μm. Some initial results are presented.

4.1. Illumination performance

The measured performance of the main illumination characteristics are presented in Table 2.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity at wafer level</strong></td>
<td></td>
</tr>
<tr>
<td>Conventional illumination: @ NA = 0.57; 10 W laser power</td>
<td></td>
</tr>
<tr>
<td>Annular illumination: @ NA = 0.54; 10 W laser power</td>
<td></td>
</tr>
<tr>
<td>Conventional σ = 0.75</td>
<td>225 mW / cm²</td>
</tr>
<tr>
<td>Conventional σ = 0.35</td>
<td>230 mW / cm²</td>
</tr>
<tr>
<td>Annular σ&lt;sub&gt;inner&lt;/sub&gt; = 0.45; σ&lt;sub&gt;outer&lt;/sub&gt; = 0.75</td>
<td>233 mW / cm²</td>
</tr>
<tr>
<td><strong>Illumination uniformity at wafer level</strong></td>
<td></td>
</tr>
<tr>
<td>Conventional illumination: @ NA = 0.57</td>
<td></td>
</tr>
<tr>
<td>Annular illumination: @ NA = 0.54</td>
<td></td>
</tr>
<tr>
<td>Conventional σ = 0.75</td>
<td>0.9%</td>
</tr>
<tr>
<td>Conventional σ = 0.35</td>
<td>1.3%</td>
</tr>
<tr>
<td>Annular σ&lt;sub&gt;inner&lt;/sub&gt; = 0.45; σ&lt;sub&gt;outer&lt;/sub&gt; = 0.75</td>
<td>1.2%</td>
</tr>
<tr>
<td>Reticle masking penumbra size (σ = 0.80)</td>
<td>420 μm at wafer level</td>
</tr>
</tbody>
</table>

The illuminator is optimized, for a minimal rotational symmetric intensity distribution and for minimal tilts over the field. This optimization is done, using special correction optics, for the conventional NA/σ combination which gives maximum DoF performance with 10% exposure latitude. At all other NA/σ settings, the resulting uniformity performance is shown without further re-adjustments.

The variation of uniformity as a function of σ<sub>inner</sub> and σ<sub>outer</sub> is shown in Figure 5.

![Figure 5](I-07856.ILL) Uniformity for different conventional and annular illumination modes

The relative change in intensity over these settings are shown in Figure 6.

![Figure 6](I-07857.ILL) The relative intensity for different conventional and annular illumination modes

5. IMAGING AND LENS PERFORMANCE

5.1. Experimental

The PAS 5500/300 imaging performance at the specified 0.25 μm resolution, distortion and Focal Plane Deviation (FPD) behaviour, have been evaluated. This was done by exposing at 15 different settings which cover the allowed NA/σ range. Also, the theoretical lens...
behaviour with changing wavelength, reticle table height and manipulator height has been verified.

Imaging performance is evaluated using Apex-E2408 resist at 0.78 \( \mu \text{m} \) thickness. Because this resist is very sensitive to airborne base contamination, like ammonia compounds\(^{10}\), the stepper is purged with activated charcoal filtered air. An additional top coat and careful handling of all wafers ensures minimum image degradation after exposure. For all exposures the time between coating, exposing and developing has been minimized.

SEM analysis have been performed using an OPA L7830i for top down automated CD measurements and a Philips XL-50 for tilted inspection and the photographs of the resist profiles.

FPD and astigmatism are measured in thin OCG895i i-line resist (0.2 \( \mu \text{m} \)) using the automated Focal\(^{10}\) test, at 139 points covering the complete image field. This method is based on the steppers alignment system and measures the displacement of chopped markers with defocus. Minimum marker displacement occurs at optimum focus. For the PAS 5500/300 evaluation those markers have been chopped at 0.25 \( \mu \text{m} \) / s.

Distortion was measured in thin OCG895i i-line resist (0.2 \( \mu \text{m} \)) at 139 points and modelled using the steppers metrology software.

### 5.2. Simulations

During the initial phase of the design of the PAS 5500/300 simulations were done to find:
- The required range for NA/\( \sigma \) to get maximum DoF with at least 10% exposure latitude.
- The optimal setting to optimize the imaging performance of the lens for the lens adjustment at Zeiss.

These simulations were done with Solid C from Sigma C in combination with the Lumped Parameter Model from Prolith. Initial exposures on APEX-E using earlier DUV steppers were made to calibrate the resist parameter set as used in the simulations.

The NA/\( \sigma \), for conventional illumination, was found to be \( NA = 0.54 \) with \( \sigma = 0.75 \) and, for the annular case, an \( NA \) of 0.48 and \( \sigma_{\text{outer}} \) of 0.75 with a \( \sigma_{\text{inner}} \) of 0.45. Both settings resulted in a maximum DoF with 10% exposure latitude for 0.25 \( \mu \text{m} \) dense lines and spaces.

These simulations have also been done for 0.225 \( \mu \text{m} \) dense lines/space. The simulated results for these last features are presented in Figure 7 and 8.

![Figure 7](image1.png) Simulated DoF for 0.225 \( \mu \text{m} \) dense lines at 10% exposure latitude using conventional illumination

![Figure 8](image2.png) Simulated DoF for 0.225 \( \mu \text{m} \) dense lines at 10% exposure latitude using annular illumination (Ring width 0.3)

Optimum DoF for dense lines is, however, not the only criterion. Imaging performance for contacts and CD uniformity are found to improve at higher NA values and processes requiring a higher exposure latitude will drive towards higher NA. As illustrated in Figure 7 and 8, the smaller feature sizes will be optimal at higher NA settings.

Based on these results, the optimum NA/\( \sigma \) for conventional illumination is specified as \( NA = 0.54 \) with \( \sigma = 0.75 \), while for the annular case it is specified as \( NA = 0.57 \) and \( \sigma_{\text{outer}} = 0.75 \) with \( \sigma_{\text{inner}} = 0.45 \).
5.3. Imaging results

Using the results of the image simulations, a matrix was defined, covering the complete range of possible NA/σ settings and some additional settings at and near the expected optimum settings.

At each setting a Focus Exposure Matrix (FEM) was exposed and measured using the automated top down SEM. Measured Bossung curves were analyzed for DoF at different process latitudes using ‘ED Forest’ software by Linnovations.

An overview of the analyzed measurements on 0.25 μm dense lines and spaces is shown in Table 3a and 3b. The DoF for 10% exposure latitude with conventional illumination, shows a very flat behaviour with NA, indicating an optimum around 0.5 NA.

For annular illumination, also for 10% exposure latitude, there is a clear trend towards lower NA for maximum DoF. Higher exposure latitudes tend towards higher NA.

Table 3a Typical results for DoF@0.25 μm dense lines/spaces as a function of NA (conventional illumination)

<table>
<thead>
<tr>
<th>NA</th>
<th>DoF @2% (μm)</th>
<th>DoF @10% (μm)</th>
<th>DoF @15% (μm)</th>
<th>maximum Exposure latitude (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>2.25</td>
<td>1.05</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>0.48</td>
<td>2.1</td>
<td>1.25</td>
<td>0.5</td>
<td>16</td>
</tr>
<tr>
<td>0.51</td>
<td>2.0</td>
<td>1.2</td>
<td>0.6</td>
<td>17</td>
</tr>
<tr>
<td>0.54</td>
<td>1.8</td>
<td>1.1</td>
<td>0.65</td>
<td>18</td>
</tr>
<tr>
<td>0.57</td>
<td>1.7</td>
<td>1.05</td>
<td>0.7</td>
<td>19</td>
</tr>
</tbody>
</table>

Usable Depth of Focus (UDof), based on a 13 field point measurement, at the specified conventional illumination settings for 0.25 μm dense lines is found to be larger than 1.0 μm.

Table 3b Typical results for DoF@0.25 μm dense lines/spaces as a function of NA (annular illumination)

<table>
<thead>
<tr>
<th>NA</th>
<th>DoF @2% (μm)</th>
<th>DoF @10% (μm)</th>
<th>DoF @15% (μm)</th>
<th>maximum Exposure latitude (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>2.6</td>
<td>1.7</td>
<td>0.25</td>
<td>15</td>
</tr>
<tr>
<td>0.48</td>
<td>2.4</td>
<td>1.5</td>
<td>0.8</td>
<td>17</td>
</tr>
<tr>
<td>0.51</td>
<td>2.45</td>
<td>1.6</td>
<td>0.8</td>
<td>17</td>
</tr>
<tr>
<td>0.54</td>
<td>2.35</td>
<td>1.45</td>
<td>0.85</td>
<td>19</td>
</tr>
<tr>
<td>0.57</td>
<td>1.95</td>
<td>1.15</td>
<td>0.65</td>
<td>18</td>
</tr>
</tbody>
</table>

The Usable Depth of Focus, based on a 13 field point measurement, using annular illumination settings for 0.25 μm dense lines, was found to vary between 1.5 μm at the lower NA and 0.9 μm at the higher NA.

The reason for the relatively high discrepancy between the DoFs at 2% exposure latitude and the UDoF can be found in the fact that making a full lens qualification requires a certain amount of exposure latitude. Variations in the process which contribute to this exposure latitude are:
- Illumination uniformity,
- CD variations across the mask,
- CD measurement errors,
- Resist uniformity.

The estimated value of the required exposure latitude, based on the listed CD error components, is 10%.

Smaller feature sizes will tend to use a higher NA. Based on the measured optical performance, in combination with the high contrast APEX-E resist, it becomes clear that there is still sufficient potential to use the system at even smaller feature sizes.
Figure 9 shows the corresponding SEM results for 0.25 \( \mu m \) dense lines using conventional and annular illumination methods.

<table>
<thead>
<tr>
<th>Focus (( \mu m ))</th>
<th>Conventional N.A. = 0.57 ( \sigma = 0.75 )</th>
<th>Focus (( \mu m ))</th>
<th>Annular N.A. = 0.54 ( \sigma_{outer} = 0.75 ), ( \sigma_{inner} = 0.45 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.6</td>
<td><img src="image1" alt="SEM photograph" /></td>
<td>-0.8</td>
<td><img src="image2" alt="SEM photograph" /></td>
</tr>
<tr>
<td>-0.5</td>
<td><img src="image3" alt="SEM photograph" /></td>
<td>-0.7</td>
<td><img src="image4" alt="SEM photograph" /></td>
</tr>
<tr>
<td>-0.0</td>
<td><img src="image5" alt="SEM photograph" /></td>
<td>0.0</td>
<td><img src="image6" alt="SEM photograph" /></td>
</tr>
<tr>
<td>0.6</td>
<td><img src="image7" alt="SEM photograph" /></td>
<td>0.8</td>
<td><img src="image8" alt="SEM photograph" /></td>
</tr>
<tr>
<td>0.7</td>
<td><img src="image9" alt="SEM photograph" /></td>
<td>0.9</td>
<td><img src="image10" alt="SEM photograph" /></td>
</tr>
</tbody>
</table>

In Figure 10 the measured CD uniformity over the image field for conventional and annular illumination (as function of defocus) is illustrated. It can be seen that the CD uniformity for 0.25 \( \mu m \) lines and spaces stays well within \( \pm 15 \) nm over a 0.8 \( \mu m \) focus range, and is even as small as \( \pm 10 \) nm with the image in focus. The variations in the reticle CD are not accounted for in these measurements.

Figure 10  CD uniformity over the image field (range) versus focus for 0.25 \( \mu m \) dense lines for conventional and annular illumination

From earlier studies\(^{11}\), it is well known that optical proximity effects become more pronounced when the imaged features are approaching the resolution limit of the exposure tool. Optical Proximity Effects (OPE) can be divided into three categories:

- Line width differences between structures with various densities (various pitches for the same CD on the mask),
- Line-end shortening (or “end-of-line effects”),
- Corner rounding.

In the evaluation of the performance of the PAS 5500/300 we investigated the first effect. For 0.25 \( \mu m \) dense lines and spaces and also for an isolated 0.25 \( \mu m \) line, the CD of the imaged lines was measured.

The resulting ED window was plotted for the dense and isolated lines and is shown in Figure 11. If a 10% exposure latitude criterion is used to find the Overlapping Depth of Focus (O.DoF@10%) for the dense and isolated lines then an O.DoF@10% of 0.9 \( \mu m \) was measured.
The first experimental results at resolutions below 0.25 µm are available. Figure 12 shows the different line sizes for the SEM photographs at best focus and the last positive and negative non failure defocus.

These results, and the results from Tables 3a and 3b, indicate that 0.225 µm and even below is feasible with the PAS 5500/300 DUV stepper.

**Figure 11** ED-windows indicating O DoF region with 10% exposure latitude for 0.25 µm dense and isolated lines

**Figure 12** SEM photographs indicating DoF for different dense line sizes using annular illumination $\sigma_{\text{outer}} = 0.75, \sigma_{\text{inner}} = 0.45$ and 0.64 µm of APEX-E2408 resist
For this reason, the system has been additionally evaluated for 0.225 µm lines and spaces performance. During this evaluation, the standard 0.78 µm resist thickness was used. The SEM photographs are shown in Figure 13. The UDoF was found to be 1.4 µm using annular illumination, with a NA of 0.52, a $\sigma_{inner}$ of 0.45; and a $\sigma_{outer}$ of 0.75.

One of the most critical features to image are contacts. Figure 14 shows the results of imaging 0.25 µm dense contacts, indicating 1.0 µm DoF.

<table>
<thead>
<tr>
<th>focus (µm)</th>
<th>Conventional NA=0.57 $\sigma_{outer}$=0.75</th>
<th>focus (µm)</th>
<th>Annular NA=0.52 $\sigma_{outer}$=0.75 $\sigma_{inner}$=0.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td><img src="image1" alt="SEM photograph" /></td>
<td>-0.8</td>
<td><img src="image2" alt="SEM photograph" /></td>
</tr>
<tr>
<td>-0.4</td>
<td><img src="image3" alt="SEM photograph" /></td>
<td>-0.4</td>
<td><img src="image4" alt="SEM photograph" /></td>
</tr>
<tr>
<td>0.0</td>
<td><img src="image5" alt="SEM photograph" /></td>
<td>0.0</td>
<td><img src="image6" alt="SEM photograph" /></td>
</tr>
<tr>
<td>0.5</td>
<td><img src="image7" alt="SEM photograph" /></td>
<td>0.5</td>
<td><img src="image8" alt="SEM photograph" /></td>
</tr>
<tr>
<td>0.6</td>
<td><img src="image9" alt="SEM photograph" /></td>
<td>0.9</td>
<td><img src="image10" alt="SEM photograph" /></td>
</tr>
</tbody>
</table>

**Figure 13** SEM photographs for 0.225 µm dense lines as a function of focus

<table>
<thead>
<tr>
<th>focus (µm)</th>
<th>Centre NA=0.57 $\sigma_{outer}$=0.75 $\sigma_{inner}$=0.45</th>
<th>Corner NA=0.57 $\sigma_{outer}$=0.75 $\sigma_{inner}$=0.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td><img src="image11" alt="SEM photograph" /></td>
<td><img src="image12" alt="SEM photograph" /></td>
</tr>
<tr>
<td>-0.4</td>
<td><img src="image13" alt="SEM photograph" /></td>
<td><img src="image14" alt="SEM photograph" /></td>
</tr>
<tr>
<td>0.0</td>
<td><img src="image15" alt="SEM photograph" /></td>
<td><img src="image16" alt="SEM photograph" /></td>
</tr>
<tr>
<td>0.5</td>
<td><img src="image17" alt="SEM photograph" /></td>
<td><img src="image18" alt="SEM photograph" /></td>
</tr>
</tbody>
</table>

**Figure 14** SEM photographs for 0.25 µm dense contact performance

### 5.4. Lens Performance results

Using the stepper alignment systems, the distortion and FPD performance for different NA / $\sigma$ combinations have been evaluated.

To be able to measure FPD at the specified lens resolution, the FOCA technique has been extended towards chopped markers with 0.25 µm lines and spaces.
In Figures 15a, 15b and 15c the distortion plots for different illumination settings, as well as the difference vector plot between the conventional and annular setting is given. The maximum distortion measured in both NA and illumination modes was smaller than 24 nm. Measured changes between both settings (defined as the maximum vector change for any point in the field) was less than 9 nm.

In Figures 16a, 16b and 16c the same is done for the field flatness plots. Field flatness is based on the average best focus for horizontal and vertical lines. The field flatness, measured in both NA and illumination modes, is below the 0.17 µm range. The measured change between both settings was less than 50 nm. The Focal Plane Deviation (FPD) (defined as the total focus range for horizontal and vertical features) was found to be smaller than 0.30 µm for both settings. These results are well within the production requirements to allow operations over a wide NA and illumination range.

Figure 15a Conventional illumination (Non correctable distortion vector plot)  
Maximum < 24 nm, NA=0.57, σ=0.75

Figure 15b Annular illumination (Non correctable distortion vector plot)  
Maximum < 22 nm, NA=0.54, σinner=0.45, σouter=0.75

Figure 15c Distortion difference vector plot between conventional and annular settings  
Maximum < 9 nm,
Changes in wavelength, manipulator, and reticle table height and their effect on the lens behaviour, have all been tested against the theoretical lens behaviour. These results are important, they are used as real-time correction factors to optimize the system. These correction factors supply the correct offsets based on information gathered from pressure sensors, temperature sensors and from using the stepper alignment system and image sensor system to monitor the wafer expansion and image performance respectively. All the measured parameters were compared to the theoretical parameters and were found to be well inside the tolerance levels. Therefore, corrections based on the theoretical lens behaviour were proven.

5.5. Overlay performance

The high flexibility in the set-up of the lens and illuminator combination gives some potential for variation in the residual lens distortion.

Such variation should, however, be as small as possible. Large variations will negatively influence the overlay performance between different steppers and also between different layers exposed with different lens and illuminator combinations on the same machine.

At Carl Zeiss, special attention is paid to fine tune the lenses so that the variations are considerably reduced. Any residual aberrations, due to material imperfections, will always lead to some change in distortion. With the use of the metrology software, the overlay errors are minimized by correcting on-line for systematic differences as are translation, rotation, magnification and other software correctable errors.

To investigate the variations with NA/\(\sigma\), ten wafers were exposed using conventional illumination. The NA was varied between 0.4 and 0.57 and \(\sigma\) between 0.35 and 0.8. Seven additional wafers were exposed using annular illumination. In this case, the NA was varied between 0.48 and 0.57 and \((\sigma_{\text{inner}} + \sigma_{\text{outer}})/2\) between 0.5 and 0.7 while keeping the ring diameter constant at 0.3.
The wafers were measured with the stepper alignment system. Correctable errors were removed. The resulting vector distribution, is shown in Figure 17.

The 99.7% values for X and Y overlay errors were 14 nm and 19 nm respectively.

The lens matching for two machines has been determined. The lens distortion difference plot is shown in Figure 18. The maximum overlay error, due to lens distortion differences, was 33 nm.

Because the PAS 5500/300 will be used in a mix and match mode with other steppers, the machine to machine overlay is very important. Different critical layers can be exposed on different PAS 5500/300 steppers while the non-critical layers can be exposed on any i-line steppers.

The results of the overlay measurements between two different machines are summarized in Table 4.

**Table 4** Experimental machine to machine overlay performance results

<table>
<thead>
<tr>
<th>Reference Machine</th>
<th>PAS 5500/300 XY (99.7% value)</th>
<th>PAS 5500/200 XY (99.7% value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAS 5500/300</td>
<td>44, 45 (nm)</td>
<td>80, 61 (nm)</td>
</tr>
</tbody>
</table>

The experimental results on the illuminator and lens induced overlay and the machine to machine overlay performance, indicate that the PAS 5500/300 is capable of performing well within the expected manufacturers’ requirements.

**5.6. Throughput performance**

The high intensities achieved, with the combination of a 10W laser source and a high efficiency AERIAL™ illuminator, allows minimal exposure time at actual exposure energies.

Combining these features with the high performance wafer stage and fast alignment and levelling systems of the PAS 5500 series makes for a machine with a very high (and sustained) throughput of wafers per hour.

Table 5 summarizes the measured throughput performance for a number of different wafer sizes in combination with different illumination settings. Because of the low etendue of the laser, in combination with the novel design of the partial coherence creating optics, it is possible to maintain, even at the low partial coherence and annular illumination, the high output intensities.

**Table 5** Summary of measured PAS 5500/300 throughput performance data

<table>
<thead>
<tr>
<th>NA and σ settings</th>
<th>150 mm wafers (40 exposures @ 30 mJ/cm²)</th>
<th>200 mm wafers (70 exposures @ 30 mJ/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA = 0.57 σ = 0.75</td>
<td>108</td>
<td>80</td>
</tr>
<tr>
<td>NA = 0.57 σ = 0.35</td>
<td>111</td>
<td>81</td>
</tr>
<tr>
<td>NA = 0.54 σ inner = 0.45 σ outer = 0.75</td>
<td>112</td>
<td>81</td>
</tr>
</tbody>
</table>
Deep UV lithography is now beginning to enter mass production at the 0.25 µm level in Dynamic Random Access Memories (DRAMs), and at higher resolutions in logic circuits and microprocessors.

In this paper, results have been presented which demonstrate the performance of a new high NA DUV stepper.

With this stepper, it is possible to optimize the lens NA and partial coherence or annular lens pupil filling for optimal imaging performance, for the different features at every individual layer whilst retaining a high throughput.

It was demonstrated that this stepper provides sufficient Depth of Focus at 0.25 µm feature sizes, with a significant exposure latitude, to allow low cost mass volume manufacturing at 0.25 µm design rules and better.

Flexibility in the system set-up, by the use of the special lens elements, allows good matching performance between other PAS5500/300 steppers and also other i-line systems. This means that mix and match strategies are fully supported.

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REFERENCES


