CONTACT HOLE IMAGING AT THE 0.13 µm NODE USING KrF LITHOGRAPHY

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ABSTRACT

In this paper we discuss possible solutions for the imaging of 0.15 \( \mu \text{m} \) contacts through various pitches by the use of high-NA KrF-lithography. As different pitches have there own critical points, isolated, semi-dense and fully dense contacts are addressed separately.

On the way to a production worthy solution of printing contact layers at this resolution, two main obstacles have to be overcome. These are limited depth of focus for isolated features and high optical proximity effects.

The established enhancement technique to widen the process latitude of isolated contacts is the use of Attenuated Phase Shift Masks (AttPSM). The necessary parameter optimization required for its application is considered. This comprises numerical aperture, phase shift error, aberrations and mask feature bias for a 6\% AttPSM using a partial coherence of 0.4. The boundary conditions to prevent sidelobe printing are addressed as well. Predictions for this optimization, using the PROLITH/2 Lumped Parameter Model was verified by experimental results using ASML’s high-NA PAS 5500/750E Step & Scan system. Encouraging process latitudes of 0.45 \( \mu \text{m} \) DoF@10\%EL were achieved for both fully isolated and semi-dense (1:2) contacts.

For dense (1:1) contacts quadrupole illumination (QUASAR\textsuperscript{TM}) using Binary Intensity Masks (BIM) gave the best results. A full-field CD uniformity of 17 nm or better (3\( \sigma \)) is obtained through an 0.4 \( \mu \text{m} \) focus range. At least 80\% of the observed variation is due to the reticle used and to the measured MEF. Therefore, we studied influences on MEF for 0.15 \( \mu \text{m} \) dense contacts in more detail. This revealed a high impact of non-linearities introduced by the resist process. We also analyzed the issue of closing contacts and formulated boundary conditions for its avoidance.

Finally, the further potential of KrF lithography in terms of resolving “near half wavelength sized” contacts is demonstrated by cross sections of 0.13 \( \mu \text{m} \) contact holes.

1. INTRODUCTION

The printing of contact hole layers will probably be one of the most difficult lithography issues for chip manufacturers moving to the 130 nm node. There might be different solutions for memory and logic devices, as dense and more isolated features have their own weak points in lithographic performance. In both cases, however, the presence of considerable optical proximity effect will need to be addressed. This becomes ever more critical with the further reduction in feature size and, hence, the k1-factor of the optical projection.

General approaches to take these hurdles may be:

1. To relax the chip design in terms of minimum feature size for small contacts or via holes. However, ambitions are present not to enlarge the traditional resolution gap between lines/spaces and contacts (Table 1).

2. To switch to ArF lithography as soon as resist materials have become mature enough. The latter has not been proven yet but of course strong efforts of resist suppliers are ongoing.

3. The further development of imaging enhancement techniques for KrF lithography which will be applicable for 193 nm wavelength as well. The use of attenuated phase shift masks (AttPSM) is already established. Probably it needs to be supported by other techniques, e.g. the use of assisting features.

<table>
<thead>
<tr>
<th>SIA ’99:</th>
<th>Min C/H size [nm]</th>
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<tr>
<td>year</td>
<td>Node [nm]</td>
</tr>
<tr>
<td></td>
<td>(Half pitch L/S)</td>
</tr>
<tr>
<td>1999</td>
<td>180</td>
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<tr>
<td>2000</td>
<td>165</td>
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<td>2002</td>
<td>130</td>
</tr>
<tr>
<td>2003</td>
<td>120</td>
</tr>
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Table 1: Shrink path of contacts vs. lines/spaces according to ITRS Roadmap of 1999

Following the third approach this paper presents expectations from simulations and actual exposure results on a high-NA KrF scanner. For a targeted minimum pitch of 300 nm the maximum NA of 0.70 yields a k1-factor of

1
0.42. The main obstacles and some first promising achievements on the way to a viable full-field CD uniformity performance of 0.15 μm contacts through multiple pitches are described.

2. METHODS AND CONDITIONS

2.1 Simulations

PROLITH/2D v. 6.1.2. was used for the predictions of process windows. The Lumped Parameter Model (LPM) was selected to examine general trends caused by parameter variations related to the mask, the illumination system and the lens.

The applied LPM contrast (γ) was set to 20. This ensures the predominance of the calculated aerial images over the resist related contributions. The model was calibrated with exposure results of 0.15 μm isolated contacts using the Binary Intensity Mask. The most suitable effective resist thickness was found to be 200 nm, vs. 500 nm as used for the experiments. This can be explained by high absorption [1]. In addition, a quite large “aerial image diffusion length” of 40 nm was necessary in order to match the results. Table 2 lists all four LPM parameter values used in this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Resist contrast</td>
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<td>Effective Resist Thickness (nm)</td>
<td>200</td>
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<tr>
<td>Effective Resist Absorption Coefficient (1/μm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Aerial Image Diffusion Length (nm)</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 2: Chosen LPM parameter values for the prediction of process windows of 0.15 μm semi-dense and isolated contact holes

The CD measurement method is adjusted to 50% weighted average, minimum required sidewall angle is 80 degrees and maximum resist loss is set at 10%. The “process measurement method” of fitting rectangles was selected.

2.2 Experimental conditions

Test exposures were carried out on ASML PAS5500/750E Step & Scan systems with a maximum NA of 0.70 and the QUASAR v. 6.1.2. illumination option [2]. A commercial resist, tailored for dense C/H performance, was used. In terms of sidelobe resistance it is not performing optimal. The resist was coated at a thickness of 0.5 μm on silicon wafers, on which an organic BARC (SiON) had been deposited. Resist processing was done on a FSI POLARIS 2100 series cluster track, using a puddle development scheme with a standard non-surfactant MIF developer.

Two masks were used:
- A chrome mask consisting of dense (1:1) 0.15 μm contacts repeated in 20 field locations.
- A test mask containing features in chrome on MoSiON (binary absorber) and in 6% transmitting MoSiON only (attenuating phase shift absorber).

The phase shift of the latter is 185 (±0.8) degrees, as measured with a LASERTEC MPM100 tool by the mask shop. This 5 degree average phase shift error represents state-of-the-art mask quality which is in line with the current SIA optical lithography roadmap [3]. The mask design comprises a large range of different feature sizes and pitches. Full-field mask CD measurements were done with an optical measurement tool (LEICA LWM250UV). A subset of those has been compared to respective KLA 8100 CD-SEM measurements (50% threshold). Apart from a 15 nm offset no significant differences were found.

Top-down wafer CD measurements were done on a Hitachi 8C40 and an AMAT VeraSEM 3D, both low-voltage SEMs. Contact diameters are automatically measured in multiple directions and CDs are derived from the arithmetic average. Top-down CD measurements were compared with cross-sectional SEM graphs, using a FEI DualBeam (FIB / SEM). As was verified for 0.15 μm dense contacts, the used CD SEM measurement algorithm approximately registers the hole widths through focus at 50% resist height.

Process windows from experimental data were calculated using PRODATA v. 2.0.

3. SEMI-DENSE AND ISOLATED CONTACTS

For this evaluation we defined the range of sparse contacts to start at a duty cycle of 1:1.5, thus at 375 nm pitch for 0.15 μm sized contacts. Other representative duty cycles are 1:2 and 1:6. The latter contacts were assumed to be fully isolated.

In Figure 1, the optical proximity effect based on aerial image calculations through pitch, is illustrated. Although actual curves are obviously dependent on illumination conditions and mask feature bias, the significance of the chosen duty cycles is evident. It should be noted that resist processing (in particular acid diffusion) effects can change this behavior considerably for pitches smaller than 375 nm [4].

The final objective is not only to optimize individual process latitudes but also to find solutions for an overall process window covering a large pitch range. From Figure 1 it becomes clear that attenuated phase shifting
Relative energy to size: 0.15 μm contacts vs. pitch

Figure 1: Calculated optical proximity effect from aerial image threshold intensities normalized to that of 375 nm pitch (duty cycle 1:1.5). The threshold energies at this duty ratio are between 60% and 67% of the maximum aerial image intensities for the calculated cases. Energy to size was assumed to be inversely proportional to the threshold intensity.

alone will not enable to achieve this goal. After all, an exposure latitude of 22% would be needed just to close the gap between required “energies to size” for 375 nm and 450 nm pitch (NA=0.70; σ=0.4). Thus, optical proximity correction (OPC) will be mandatory when using Attenuated Phase Shift Masks at this resolution.

In order to assess the benefits that can be expected from using AttPSM, process latitudes for fully isolated features are compared first. They represent the bottleneck in terms of depth of focus. Boundary conditions to prevent sidelobe printing were studied afterwards, using the most critical duty cycle of 1:2.

3.1 Predictions

In order to assess the imaging capability using standard chrome masks to print isolated contacts, DoF@5%EL was chosen as a figure of merit. Its variation as a function of NA and σ is shown in Figure 2a. The maximum performance is expected at the highest considered NA of 0.70, while partial coherence has very little impact. Still, DoF@5%EL remains below 0.25 μm.

As stated earlier, the model has been calibrated so that absolute numbers coincide with the experimental results for this case. Figure 2b shows the predicted process window at the optimum illumination setting.

![Figure 2](image)
The limited DoF can be enhanced when using attenuated phase shift masks. However, deviations from the ideal phase shift of 180 degrees cause distortion of the Bossung curves. This leads to asymmetric process windows w.r.t. defocus. Figure 3 illustrates this effect when a phase shift of 185 degrees is present, as it is on the used test mask. The shown impact is comparable to that of spherical aberrations.

**Process window AttPSM 185 deg**

\[
\text{NA} = 0.63; \ \sigma = 0.4; \ \text{fb} = 35 \text{ nm}
\]

**Figure 3:** Bossung curves (a) and predicted process window (b) of isolated 0.15 µm contacts using a 6% AttPSM with 5 degrees phase error; feature bias = 35 nm, NA=0.63, \(\sigma\)=0.4 (LPM model). Best Focus is shifted about –0.25 µm w.r.t. that of Binary Intensity Mask imaging.

**Simulated DoF@5%EL for AttPSM with 185 degrees phase shift**

**Figure 4:** (a) Process latitude vs. mask feature bias and numerical aperture (\(\sigma = 0.4\)); (b): same graph as 3D visualization
Another very sensitive parameter connected with the use of AttPSM is the mask feature bias. This is the offset of the mask dimension compared to the target dimension on the wafer. Throughout this paper we express the mask feature bias on wafer scale (1x). Its variation shifts the isofocal CD and thus influences the process latitude considerably. Depending on the used numerical aperture, there is a small optimum range for feature bias. This is shown in Figure 4 as predicted through simulation with a fixed partial coherence of 0.4. For an NA of 0.70 the feature bias tolerance is ±5 nm only. This leads to a stringent mask CD control requirement of ±20 nm in terms of absolute accuracy! Reducing the NA to 0.60 leads to an increasing optimum feature bias and also allows an increased tolerance, in order to meet the maximum achievable DoF@5%EL (>0.45 µm).

Provided that these conditions can be met, a considerable performance improvement should be obtained using AttPSM instead of conventional masks. In fact the theoretical process window calculated with 180 degrees phase shift and an aberration free lens surpasses the one of a binary mask by a factor of four in terms of maximum DoF. This is shown in Figure 5 which also illustrates, how much of this improvement is maintained when the effect of 5 degrees phase shift error and/or 5 nm (rms) spherical aberrations is considered. Still, a gain of 0.3 to 0.4 µm DoF@5%EL can be expected compared to imaging with a chrome mask. All the curves shown are calculated for optimum conditions of NA and feature bias, respectively. Note that according to simulations, these imperfections reduce the optimum NA and enlarge the optimum feature bias.

A well known issue connected with the application of AttPSM is “sidelobe printing”. According to aerial image calculations of 0.15 µm holes this is most severe at a distance of about 300 nm from any hole center. The exact number depends on the actually chosen NA, partial coherence and mask feature bias.

With a two dimensional layout of equidistant contacts, a pitch of approximately 450 nm gives a worst case condition. This is because the center position of a cell containing four adjacent contacts is located 300 nm away from each designed hole center. At this point, unwanted energy will be at its highest. It is denoted as sidelobe intensity (I\_SL), which is compared to the threshold intensity (I\_Thr) of regular contacts (Figure 6). In this way, the severity for sidelobe printing is expressed by a “sidelobe margin ratio” (SLMR) with: SLMR = I\_Thr / I\_SL. The larger this ratio, the smaller the risk of sidelobes being printed.

**0.15 µm isolated contacts: comparison of simulated process latitude**

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**Figure 5:** Simulated process latitude improvements for perfect 6% AttPSM imaging vs. the presence of 5 degrees mask phase shift error, 5 nm (rms) Z9 spherical aberrations and their combination. Optimum feature bias and NA was chosen for each calculation (AttPSM: 12.5 nm for NA = 0.70; 40 nm for NA = 0.64).

**Aerial image for SLMR calculation SLMR = I\_Thr / I\_SL**

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**Figure 6:** Principle of “sidelobe margin ratio” (SLMR) calculation from aerial image. Threshold energy (I\_Thr) is sampled at the targeted feature edges while sidelobe intensity is read out at position 0. This case yields a SLMR of 1.22. Thus in first approximation sidelobes would start to print at 22% overexposure.
Calculations for varying NA and mask bias show that a minimum feature bias of 30 nm is needed just to achieve an SLMR of 1 at a NA of 0.70. For a given required SLMR, which mainly depends on the resist process, a higher feature bias is needed when the NA is reduced. (see Figure 7a). The simulated process latitude (DoF@5%EL) as a function of feature bias and NA is shown in Figure 7b. When both contour plots are compared, assuming a required SLMR of 1.3, it can be concluded that only a very high NA gives an optimum process window, while preventing sidelobe printing. A combination of 0.70 NA and 45 nm mask feature bias appears optimal.

It is to be expected, therefore, that 1:2 semi-dense contacts of 0.15 μm target CD on the wafer need to be substantially larger on the mask than fully isolated contacts (* 25 nm simulated optimum mask feature bias). This strict predetermination of pitch dependent mask feature bias could complicate optical proximity correction (OPC) to a large extent.

### 3.2 Experimental results

To verify the baseline performance, the focus latitude of isolated contacts using the Binary Intensity Mask was first evaluated. As predicted the maximum available NA of 0.70 performed best. Figure 8 depicts all the CD measurements which could be done at best energy through focus. The achievable focus range is limited to 0.3 μm. Outside of this range, the contacts become unacceptably sloped.

Various exposures were carried out using the Attenuated Phase Shift Mask in order to verify the anticipated improvements. Partial coherence was 0.4 throughout all the experiments. As predicted it is seen that mask feature bias is a crucial parameter which must be tightly controlled.

We found an optimum feature bias of 19 nm when using the 0.70 NA. This value compares well with the simulation outcome described above (Figure 4) suggesting approximately 25 nm. The resulting Bossung curves, shown in Figure 9, also agree with the simulations. Some tilt of the Bossung curves can be recognized. This can be explained by the known phase shift error of the mask, in combination with moderate spherical aberrations. However, the resulting process window is very large when compared to the BIM performance. We verified that the actual resist slopes look satisfactory throughout the expanded focus range. Cross sections are presented in Figure 13. The photos illustrate that sidewall angles remain steep, giving open contact holes through an 0.5 μm focus range. This enables reliable top-down CD measurements down to 115 nm diameter, as shown in positive defocus.

A comparison of the achieved process latitude with that of an 0.66 NA is shown in Figure 10. As expected more exposure latitude can be gained from higher numerical aperture. However, feature bias has not been optimized for the smaller NA, possibly allowing further improvement.

**0.15 μm semi dense contacts (duty 1:2)**

![Figure 7](http://example.com/figure7.png)

**Figure 7:** (a): Calculated sidelobe margin ratio (SLMR) at best focus of 0.15 μm contacts with duty ratio 1:2 as function of NA and feature bias. Partial coherence: 0.4; Phase shift: 185 degrees. For NA < 0.6 data have been extrapolated. (b): Predicted DoF@5%EL
0.15 \text{\,\mu m} isolated contact hole BIM CD vs. defocus

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure8.png}
\caption{Measured Bossung: NA=0.7; \sigma=0.6; Energy = 102 mJ/cm\textsuperscript{2}. The left side SEM micrograph indicates a sloped contact at \text{-0.2} \text{\,\mu m} defocus that is not measured.}
\end{figure}

0.15 \text{\,\mu m} isolated C/H Bossungs AttPSM

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure9.png}
\caption{Measured process window for 0.15 \text{\,\mu m} isolated contacts using AttPSM; field center. Though the predicted Bossung tilt is present a clear improvement w.r.t. the binary mask imaging becomes evident. NA=0.70; \sigma=0.4; feature bias: 19 nm.}
\end{figure}

0.15 \text{\,\mu m} isolated C/H: Measured Process Latitudes using 6\% AttPSM

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure10.png}
\caption{Results of process latitude as derived from Focus Exposure matrices for 0.15 \text{\,\mu m} isolated contacts compared to 0.18 \text{\,\mu m} isolated contacts. Note that the used feature bias was kept constant (19 nm) for both numerical apertures which may be sub-optimal according to the simulations. \sigma=0.4; field center.}
\end{figure}

Although full field CD uniformity has not been measured yet, it is thought that the achieved process windows for 0.15 \text{\,\mu m} isolated contacts form a good basis. However, in order to achieve a satisfactory UDoF throughout the whole exposure field, the focus latitude certainly must be further enhanced.

Approaching the resolution of 0.15 \text{\,\mu m} has an obvious impact on the achievable process windows. In order to quantify this price which has to be paid, 0.18 \text{\,\mu m} isolated contacts were printed at the highest NA as well. The performance offset is also shown in Figure 10. In terms of depth of focus it is approximately 0.3 \text{\,\mu m}.

To verify the simulation results in the feasibility of printing semi-dense contacts of 1:2 duty cycle, a feature bias of 45 nm was selected. Again, partial coherence was kept at 0.4. The measured process windows achieved
with NA of 0.70 and 0.66 are shown in Figure 11. The resultant DoF@5%EL is approximately 0.2 μm less than predicted. This confirms the view that LPM results need to be interpreted qualitatively rather than as absolute estimates.

Furthermore, the large improvement in measured exposure latitude is striking when changing from 0.66 to 0.70 NA. The observed process latitude is very close to that of fully isolated contacts when the 0.70 NA is used. This is not true for the 0.66 NA, where the imaging performance of isolated contacts is superior to that of semi-dense contact holes.

It is also important to note that the found energies-to-size differ by almost 40% for both numerical apertures. Presumably the higher NA captures significantly more light of the first diffraction orders which also leads to the high gain in exposure latitude. Thus, the numerical aperture also forms an important knob for OPC. This will be crucial if semi-dense and fully isolated contacts are to be imaged at the same time: For the anticipated optimum feature bias (45 nm) and 0.70 NA, best energy (37.5 mJ/cm²) is below 60% of that which was found for fully isolated contacts (65 mJ/cm²) using 19 nm feature bias! This observation underlines that additional techniques (e.g. assisting features) will be necessary.

In order to verify the sidelobe printing energy margin, top-down SEM graphs of semi-dense contacts have been taken through focus. The energy at which contacts start to print was constant through an 0.4 μm focus range. Figure 12 shows micrographs at best focus, exposed with NAs of 0.66 and 0.70. As simulations predicted, the sidelobe margin improves significantly at the higher NA when feature bias is kept constant. In fact, the applied feature bias of 45 nm is not sufficient at 0.66 NA because sidelobe printing already starts at energy-to-size. This means that the measured curve of process latitude for 0.66 NA as shown in Figure 11 does not represent a viable process. In contrast, contacts can be overexposed by as much as 20% (SLMR=1.2) when 0.70 NA is used. Therefore, the full range of calculated exposure latitude (28%, i.e. BE ±14%) can be used without printing sidelobes, leaving a 6% “safety margin”.

When compared to the theoretical considerations shown before, these results match very well. The calculated numbers of SLMR are 1.20 for the experiment vs. 1.3 simulated at 0.70 NA and 0.96 measured vs. 1.1 simulated at the reduced NA. As can be expected, there is a slight offset induced by resist processing. This is approximately 0.1 (10%) for the resist used.

![Measured Process Latitude Semi-Dense](image)

Figure 11: Process latitudes of semi-dense 0.15 μm contacts (pitch: 450 nm). σ: 0.4; Feature Bias: = 45 nm; Energy to size: 52 mJ/cm² at 0.66 NA; 37.5 mJ/cm² at 0.70 NA

![Figure 12](image)

Figure 12: Top-down graphs of semi-dense (1:2) 0.15 μm contacts in best focus indicating the critical energy for starting of sidelobe printing. Feature bias is 45 nm for both cases. The sidelobe margin ratio (E_{crit}/BE) is 0.96 (NA=0.66) vs. 1.20 (NA=0.70)
Figure 13: Cross-sections of 0.15 μm Isolated Contacts (AttPSM; NA=0.7; σ=0.4; feature bias: 19 nm); FIB with FEI Dual Beam™; (top): through 0.6 μm focus range; (bottom): at best focus through 24% exposure range.
To evaluate the potential for higher resolution of isolated contacts, we succeeded in resolving 0.13 \( \mu \text{m} \) feature size. A mask feature bias of 35 nm was selected without further optimization. Figure 14 depicts resulting cross sections. Resist slopes through focus look very promising. The usable DoF of 0.15 \( \mu \text{m} \) is only determined by the printed CD through focus. These results demonstrate the potential of 248 nm resists in resolving near- \( \lambda/2 \) contacts. In contrast, the latest results with 193 nm resists show 0.15 \( \mu \text{m} \) as the current ultimate resolution, approaching a value of \((3/4) \lambda\).

4. DENSE CONTACTS

In this study it was assumed that Binary Intensity Masks will be used for 0.15 \( \mu \text{m} \) dense contacts (duty cycle 1:1). As will be shown later, the achievable process latitude significantly surpasses that of semi-dense contacts. Therefore, it seems not to be necessary to use more complex Attenuated Phase Shift Masks.

Given these preconditions, off-axis illumination at maximum NA and maximum partial coherence settings appears to be the best choice. It will be shown that the use of the ASML quadrupole illumination mode QUASAR\textsuperscript{TM} is an excellent additional enhancement.

For nested contacts there are two important issues that we studied in more detail. It is well known that contact hole printing implies high mask error factors (MEF) when compared to line/space printing. This translates into challenging mask CD uniformity requirements for current mask fabrication technology.

Another obstacle originates from the strong non-linearity of the lithographic process near the resolution limit. This is even more pronounced for contact holes, due to the two-dimensional geometric limitations of the mask openings. As a result, their imaging performance is very sensitive to underexposure and / or undersizing w.r.t. a chosen best energy. The latter is unavoidable if a set of contacts with some CD spread on the mask is to be printed simultaneously. Consequently, contacts partly exhibit severe sidewall sloping or even do not open. The resist process also has an important role.

![Figure 14: X-sections of 0.13 \( \mu \text{m} \) Isolated Contacts through 0.25 \( \mu \text{m} \) focus range (AttPSM; NA=0.7; \( \sigma=0.4 \); mask feature bias: 35 nm)](image)
This effect imposes strict mask CD uniformity requirements as well. In the following paragraphs, we refer to these mask CD deviations as “CD offsets”. In contrast to the designed mask feature bias described in the previous section, we express mask CD offsets on mask scale (4x). This reflects its relationship to unintended mask CD variations.

4.1 Predictions

Using PROLITH/2D, the MEF of the aerial image was determined. To achieve this, CD deviations from a target CD of 0.16 \( \mu \text{m} \) were calculated by varying the mask CD. The MEF was derived from the ratio of the aerial image CD deviation and the mask CD offset divided by 4 (1x). The contact hole aerial image CD reduces non-linearly with decreasing mask CD offsets, when the latter becomes negative. Therefore, aerial image MEF gradually increases up to a point where in practice contacts get too sloped and are finally closed. It must be taken into account that the non-linearity causing this effect and thus the differences in MEF are further amplified by the resist process.

The annular illumination performance was compared to that achieved with the QUASAR\textsuperscript{TM} (30 degree) setting. A maximum defocus of 0.3 \( \mu \text{m} \) was considered. Figure 15 shows the simulation results. In accordance with what was reported earlier [5] the MEF is rather high at this small \( k_1 \) of 0.42 and it also significantly depends on defocus. As stated above we also found that negative mask CD offsets considerably increase the MEF in defocus. The simulation predicts a strong reduction of mask error factor when using the QUASAR\textsuperscript{TM} illumination mode. This alleviates the described effects on MEF.

The critical negative mask CD offset at which contacts start to close is mainly determined by resist properties and is difficult to predict from aerial image profiles.

**Figure 15:** Simulated Aerial Image MEF for 0.15 \( \mu \text{m} \) dense contact holes.

(a): annular illumination  
(b): 30 degree QUASAR\textsuperscript{TM} illumination; NA = 0.70; \( \sigma_{\text{outer}} = 0.85 \), \( \sigma_{\text{inner}} = 0.55 \). MEF was calculated from a constant aerial image threshold while varying the mask CD and defocus setting using PROLITH/2.
4.2 Experimental results

4.2.1 E-D windows

Dense contact holes with a dimension of 0.15 µm were exposed on several ASML PAS5500/750E Step & Scan systems using a Binary Intensity Mask. The experimental boundary conditions are equal to those used for isolated contact holes. The NA - σ setting used were 0.70 NA with 0.85 σouter and 0.55 σinner for both annular and 30 degree QUASAR™ illumination. Figure 16 shows the CD as a function of defocus and Figure 17 the cross section photos of the contacts at BE (52mJ/cm²) when plotted over a focus range of –0.4 to 0.4 µm. The cross section photos show clearly that the contacts are fully opened at the bottom over a wide focus range. The slope of the contacts increases slightly in negative defocus. Figure 18 shows the resulting process latitude for annular and QUASAR™ illumination. It can be seen that the latter gives a higher EL and a larger DoF. These are 27% compared to 20% maximum EL and 0.78 µm compared to 0.65 µm DoF at 10% EL. Thus, QUASAR™ illumination is the preferred illumination mode for printing 0.15 µm dense contact holes.

![Figure 16: Bossungs of 0.15 µm dense C/Hs in field center using NA=0.7, σouter = 0.85, σinner = 0.55 and QUASAR™ illumination. The numbers below the graph indicate the dose in mJ/cm².](image)

![Figure 17: Cross section photos of 0.15 µm dense C/Hs at BE through focus. The cross section is made with a Focused Ion Beam (FIB). The corresponding Bossung curve is shown in the middle.](image)
4.2.2 MEF

The achievable CD uniformity (CDU) is very much dependent on the CD range of the reticle used and the MEF. The latter determines how deviations from the mean CD on reticle level are transferred to wafer level [6]. This section will focus on the MEF as function of ask CD offset for annular and QUASAR™ illumination.

The MEF largely depends on aerial image contrast. Defocus or illumination settings yielding a lower contrast will increase the MEF significantly, thereby causing the CD uniformity to deteriorate. The earlier simulations confirm that the aerial image MEF is clearly higher for annular than for QUASAR™ illumination. This result was verified by experimental data described in the paragraphs that follow.

On the reticle so-called picked CD modules were designed, which means that every module consists of 9 arrays of contacts with increasing CD [7]. The average increment was about 20 nm at reticle level. In 6 exposure fields, the wafer CD of the 9 different contacts corresponding to one module on the reticle was measured. The average wafer CD was then plotted as function of the applicable mask CD offset. The CDU of this experimental curve was defined as \( \Delta CD_{\text{wafer}} / \Delta CD_{\text{reticle}} \), with \( \Delta CD \) equal to the deviation of the CD from the mean CD. The MEF is determined for every mask CD offset and related change in the wafer CD.

In best focus standard off-axis illumination (annular) gives a MEF around 3.0 while QUASAR™ gives a MEF of 1.9. The curves in Figure 19 show that the MEF is not only a function of illumination mode and defocus, but also of mask CD offset. For a positive mask CD offset the MEF is found to coincide with the simulated results and is almost constant. For a negative mask CD offset, however, the experimental MEF is shown to increase quickly whereas the simulations predict a gradual increase. At \(-40 \text{ nm (4x)}\) mask CD offset the MEF is more than twice that of the simulated result. This discrepancy can be expected since the simulations are based on aerial image calculations and do not allow for the non-linear behavior of the resist near the resolution limit.

4.2.3 Full-field CD uniformity

A full-field CD uniformity test is a standard ASML test that determines the intrafield CD variation, which is used for machine qualification. The 20 modules on the reticle are exposed in one field, and there are 6 fields distributed over the wafer in order to reduce the effects of measurement noise. A 3σ-value is calculated from the CD variation of the 20 field points. This is a measure of the CD uniformity.

Several full-field CD uniformity tests were exposed on 5 different Step & Scan systems using the QUASAR™ illumination setting. The limitation of closed contacts to small values is regarded as a necessary condition for a good CD uniformity. The combined results of various CDU exposures using the same reticle show that the presence of closed contacts is very sensitive to focus offset, underexposure and reticle CD distribution. A limited CD range on the reticle is crucial with respect to closing contacts. This becomes evident by the observation that the smallest contacts in the picked set...
on the mask are closed more frequently in defocus. The correlation between the presence of closed contacts and the individual reticle CDs is clearly shown in Figure 20. In this figure all closed contacts detected in defocus are shown as a function of the corresponding reticle CD, which is presented as offset from the mean mask CD. The two smallest features on the reticle that are taken into account are responsible for more than 50% of the detected closed contacts. This is a combined effect of defocus and negative mask CD offset because all closed contacts are measured around a defocus of -0.3 \( \mu m \). From the figure can be concluded that a negative mask CD offset of less than 15 nm will reduce significantly the number of closed contacts.

The largest mask CD offset of -20 nm tightens the requirements on maximum defocus, dose accuracy and resist process repeatability. The CDU results from five Step & Scan systems were examined. It was found that best focus can be displaced by 0.1 \( \mu m \) to have more than 98% open contacts over the 0.4 \( \mu m \) focus range. Dose-to-size can be approximately 3% off-value to avoid closing contacts in defocus. These numbers are, of course, dependent on the mask CD range. In Figure 21 the CDU results of these five machines are plotted. The 3\( \sigma \)-value of the measured CDs is shown for every machine in BF and through focus. For the latter a 3\( \sigma \)-value of 17 nm is achieved with a reticle CD variation of 30 nm (3\( \sigma \)). This means that at least 80% (13.5 nm) of the wafer CD variation is caused by the mask, if the lowest observed MEF of 1.8 in BF is considered. This reticle contribution to the CDU results has been partially removed by applying a so-called reticle error correction (REC). This method corrects for the measured spread in CDs on the reticle by calculating the offset in CD on the wafer caused by an offset in CD on the mask. The current correction algorithm assumes that this mask CD offset is transferred to the wafer with a constant MEF. This, however, is only valid for a constant defocus level and over a limited mask CD range. As a compromise, a constant MEF of 2.3 is used. This improves the calculated 3\( \sigma \)-value through focus slightly by a reduction from 17 nm to 14 nm.

Using this simplification it is thus not possible to reveal the pure machine contribution which would be desirable for an ideal system qualification. There is still a rather large reticle contribution left, together with a small CD SEM and processing contribution.

**Closed contacts in defocus (approximately -0.3) vs. Mask CD offset**

![Figure 20: The number of closed contacts relative to the total number of closed contacts for all 20 mask features. The relative fraction of occurrence is plotted at the corresponding mask CD offset. All data are taken from exposures in -0.3 \( \mu m \) defocus. There is strong correlation between the mask CD offset and the frequency of detecting closed contacts. A steep rise in the number of closed contacts is seen below -15 nm mask CD offset.](image)

**CD uniformity results of 0.15 \( \mu m \) dense contacts**

![Figure 21: The 3\( \sigma \) value of intrafield CD distributions on the wafer is measured in BF and through 0.4 \( \mu m \) focus range, with and without applying reticle error correction (REC) for 5 different PAS 5500/750E Step & Scan systems.](image)
4.2.4 Summary dense contact holes

Summarizing the results it can be stated that the following points have to be taken into account for the exposure of 0.15 µm dense contact holes:

- QUASAR™ is the most suitable illumination mode for full-field CD uniformity of 0.15 µm dense contact holes. Compared to annular illumination a significantly larger process window can be obtained. This is due to the enhanced contrast, which also gives a lower MEF.
- MEF has a significant influence on the CD uniformity result. The MEF is found to be dependent on illumination mode, defocus and mask CD offset. For a large negative mask CD offset imaged in defocus, the MEF rises considerably.
- The presence of closed contacts is a very critical parameter for printing 0.15 µm dense contact holes. The same factors that give the increase in the MEF also enhance the probability of finding closed contacts. This imposes severe restrictions on the acceptable mask CD range.

5. CONCLUSIONS

Main challenges connected with printing 0.15 µm contacts have been addressed. Parameter dependencies for optimum performance have been analyzed and could be confirmed by experiments.

In the semi-dense to isolated duty ratio regime the optical proximity effect becomes a big hurdle when Attenuated Phase Shift Masks and small partial coherence illumination are used. This, however, appears necessary in order to enhance process latitudes. OPC will be more complex than applying pitch dependent feature biases only. This can be concluded from our results showing that mask feature bias is an important and sensitive optimization parameter for the process latitude of any individual pitch.

For fully isolated contacts, LPM simulations show the high potential gain in terms of DoF compared to using Binary Intensity Masks. Taking typical imperfections of 5 degrees phase shift error and 5 nm (rms) spherical aberrations (Z9) into account, still significant improvements are predicted. Experimental results yield 0.45 µm DoF@10%EL. Cross sections photos demonstrate the ultimate potential of resolving 0.13 µm isolated contacts in 0.5 µm thick resist through an 0.2 µm focus range.

Restrictions imposed by sidelobe printing were studied at the most sensitive duty cycle of 1:2. According to our aerial image analysis and LPM simulations a minimum NA close to 0.70 is needed to combine maximum DoF@5%EL with a safe sidelobe printing margin. This result could be verified by demonstrating that an NA of 0.66 does not prevent sidelobe printing at energy-to-size. In contrast, an NA of 0.70 allows to utilize the whole measured energy latitude.

For imaging of dense 0.15 µm contacts the use of a Binary Intensity Mask was considered. Large process latitude was shown to be achievable with off-axis illumination at 0.70 NA. This can be further improved by use of quadrupole (QUASAR™) illumination, yielding about 0.8 µm DoF@10EL. Even more importantly, the associated MEF at best focus can be significantly reduced from about 3.0 to 1.9 for contacts having a positive mask CD offset. It was shown that contacts being undersized (negative mask CD offset) have a higher MEF. Only a fraction of this increase in MEF can be found in the simulated aerial images. Thus, the main cause is attributed to the non-linear behavior of the resist process. For the used resist process, the associated MEF at a CD offset of −40 nm is doubled.

Imaging in defocus aggravates the situation caused by the discussed non-linearities. Contact holes partly do not open during resist development if they are undersized on the mask. Analyzing data of our CD uniformity system qualification test revealed that the probability of this failure mechanism almost triples as soon as the negative CD offset reaches −15 nm on mask level. For machine qualification purposes we are able to use a “picked CD concept”. This allows to select fitting mask CDs and thus to reduce mask contributions. However, if contact layer production masks are considered, this would translate into a reticle CD range requirement of less than 30 nm. As stated above, the resist properties also have a decisive influence.

The ASML PAS5500/750E is capable of routinely achieving a full-field CD-uniformity as small as 17 nm (3σ, 20 field points) through 0.4 µm DoF. Given the measured MEF value of approximately 2, the wafer CD variation is mainly caused by reticle CD variations (30 nm, 3σ). As discussed, the MEF itself depends on contact hole size but also on other factors as defocus. Therefore, it is impossible to accurately calculate the contribution of the scanning system. In order to partly remove mask CD variations with a simple method, a constant MEF of 2.3 was used for “reticle error correction” (REC). This allows slightly improved CD uniformity results to a 3σ-level of 14 nm and better.
We think that main topics associated with printing 0.15 µm contacts for multiple pitches have been covered with this work. The actual capability has been shown and possible solutions to overcome difficulties have been identified. Certainly more effort needs to be put in their elaboration in order to realize a customized and production worthy process. One of the main challenges remains optical proximity correction.

In this paper, a maximum NA of 0.70 was considered. It was shown that a high NA performs best for all discussed duty ratios. KrF scanning systems featuring a numerical aperture above 0.70 will allow further improvement in imaging resolution and process latitude for contact holes.

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