Improving wafer level CD uniformity for logic applications utilizing mask level metrology & process

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ABSTRACT

Critical Dimension Uniformity (CDU) is one of the key parameters necessary to assure good performance and reliable functionality of any integrated circuit (IC). The extension of 193nm based lithography usage combined with design rule shrinkage makes process control, in particular the wafer level CDU control, an extremely important and challenging task in IC manufacturing.

In this study the WLCD-CDC closed loop solution offered by Carl Zeiss SMS was examined. This solution aims to improve the wafer level intra-field CDU without the need to run wafer prints and extensive wafer CD metrology. It combines two stand-alone tools: The WLCD tool which measures CD based on aerial imaging technology while applying the exact scanner-used illumination conditions to the photomask and the CDC tool which utilizes an ultra-short femto-second laser to write intra-volume shading elements (Shade-In Elements™) inside the photomask bulk material. The CDC process changes the dose going through the photomask down to the wafer, hence the wafer level intra-field CDU improves.

The objective of this study was to evaluate how CDC process is affecting the CD for different type of features and pattern density which are typical for logic and system on chip (SOC) devices. The main findings show that the linearity and proximity behavior is maintained by the CDC process and CDU and CDC Ratio (CDCR) show a linear behavior for the different feature types. Finally, it was demonstrated that the CDU errors of the targeted (critical) feature have been effectively eliminated. In addition, the CDU of all other features have been significantly improved as well.

Keywords: Critical Dimension Uniformity (CDU), WLCD, CDC, wafer CDU, CD linearity, intra-field CDU, logic patterning

1. INTRODUCTION

Unlike DRAM and FLASH memory devices, logic and system on chip (SOC) devices are comprised of a variety of features which have different Critical Dimension (CD), pattern shape and Mask Error Enhancement Factor (MEEF) values which makes CD control very critical. In this work several logic features were evaluated on a production-like photomask which provide a good representation of the variety of features existing in logic application. In a first step the focus was to investigate the CDU behavior as well as the impact of the CDC process on the linearity behavior for the different features. Based on these findings in a second step a CDU correction was performed on a production-like mask where the target was to correct the CDU signature of the main feature and to evaluate the effect on the secondary features.

It was shown that the linearity remains maintained by the CDC process and CDU and CDC ratio (CDCR) show a linear correlation. Additionally, it was demonstrated that CDU of the main feature was significantly improved. The CDU of the secondary features was improved as well. This provides the customer the flexibility to select the most critical feature as an input for CDC correction process.

In this work the CD metrology was performed by ZEISS WLCD system. The WLCD measures the CD based on proven aerial imaging technology while applying the exact scanner-used illumination conditions [1, 2]. The tool performance was demonstrated with excellent dynamic CD repeatability [5] and with high correlation (R^2 >0.95) to wafer CD data [5].
The CDU improvement was done utilizing the ZEISS CDC32 tool located at a leading edge foundry. The CDC process generates small pixels (Shade-In Elements™) inside the photomask bulk material. Those pixels create local morphology change which leads to small change in the refractive index (delta n) of the quartz. This delta n causes a small amount of light scattering outside of the scanner objective pupil and hence causes light attenuation. The applied attenuation controls the dose profile at wafer level and finally the intra-field CDU [3,4,5].

2. LINEARITY TEST

2.1 Set up

For the linearity test an engineering plate was selected. This plate had an array of 11x13 test dies. Each die contains many test patterns. Out of this variety 26 different features were selected varying in CD and pattern density from very dense to isolated. The plate layout and the different level of attenuation (0% - 6%) that was applied by the CDC32 are described in figure 1.

![Figure 1. The test plate 11x13 die array layout and the level of the applied attenuation.](image)

2.2 Results

The CD of the 26 features was measured by the WLCD before (pre) and after (post) the CDC process. Figure 2 shows the mean CD of the 26 features in four dies where attenuation level of 0.7%, 1.4%, 2.2%, 2.8% was applied. One can see that due to the applied attenuation the mean CD of 26 features was shifted by a constant offset (parallel shift of the pink line vs. the blue line). This offset in mean CD increases the higher the applied attenuation is. However, the linearity signature over the 26 features remains unchanged, which is a very important result.

Based on pre and post CD measurement and the applied attenuation the CDC ratio (CDCR) can be computed for each feature. The CDCR is defined by the resulting CD change at wafer level (nm) per 1% attenuation. Figure 3 shows the calculated CDCR for all individual features. Most features have a similar CDC Ratio around 2.7 [nm/%]. Features that have larger MEEF also display larger CDU and have higher CDC Ratio. The CDU and the CDC Ratio follow the same trend. The correlation between the CDCR and CDU is plotted in figure 4, showing a slope of 1.06 and a high correlation with a R² of 0.78. The correlation plot indicates that a CDC job that will be computed based on features having a large MEEF and high CDU will improve the other features that have a lower MEEF and smaller CDU as well and will definitely not deteriorate the CDU of these features. That means we can expect good CDU improvement for all features while we base the correction on the CDU of a single selected feature. This is again a very important result for CDC process capability for logic application. It provides the flexibility to choose the most critical feature as input for the CDC process.
Figure 2. The Linearity test shows a constant CD offset for all 26 tested feature due to the applied attenuation and the linearity signatures is maintained.

Figure 3. The CDU distribution and the derived CDC ratio (CDCR) for all measured features follow the same trend.

Figure 4. The correlation between the CDU and CDC ratio shows a slope of 1 at high $R^2$. 
3. CDU IMPROVEMENT

The CDU improvement test was done on two production masks of the 2x node. For CDU correction strategies usually line/space pattern are selected as input data set. CD metrology on those features is not as challenging as on 2D features and one can achieve a good signal to noise ratio. Therefore on the first mask the line/space (L/S) feature was selected to be the primary feature. However, the CD uniformity was evaluated on the primary L/S feature (target CD = 44 nm) as well as on the secondary End-to-End features (CD= 116nm).

The L/S and End-to-End features have different MEEF and therefore different CD uniformity and CDC Ratio. Based on the results of the linearity investigation we can anticipate that if we correct the mask based on the L/S features we can expect maximal CDU improvement on the L/S and smaller improvement on the End-to-End. Figure 5 shows the CDU signature for the two features before the CDC process (left side) and the after CDC process (right side). As can be seen the CDU map of the primary feature (L/S) and the secondary End-to-End features are highly correlated with different direction (pick vs. valley) due to the fact that for the primary feature the CD was defined on the opaque line and for the secondary on the space. After CDC process the CD maps are nicely flattened. The absolute numbers are summarized in Table 1.

The CDC process improves the CDU signature of the primary features by more than 80% below 0.25 nm 3Sigma at wafer level and by more than 50% on the End-to-End features. These results confirm our conclusions from the linearity test in Section 2 on a production mask.

For the practical use of the CDC process on logic mask this is an important fact. The user can choose the feature that is most critical for the device performance as input for the correction. This feature will get maximum improvement by CDC correction while the CDU of all other features CDU will be improved as well.

![Figure 5](image-url)

Figure 5. The CDU signature for all features before applying the CDC process (left side) and after CDC process (right side).
Table 1. The CDU statistics (3Sigma & range) for primary and secondary features before and after CDC process

<table>
<thead>
<tr>
<th>Summary</th>
<th>Pre CDC™ CDU [nm]</th>
<th>Post CDC™ CDU [nm]</th>
<th>Improvement [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary feature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS 44 nm Range</td>
<td>2.6</td>
<td>0.51</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>3Sigma</td>
<td>1.4</td>
<td>0.26</td>
</tr>
<tr>
<td>Secondary feature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End-to-End 116 nm Range</td>
<td>10.8</td>
<td>4.9</td>
<td>55%</td>
</tr>
<tr>
<td></td>
<td>3Sigma</td>
<td>5.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

For the second mask of the 2x node we selected the more critical feature as primary feature which is an unique complex 2D feature having a CD of 63nm at wafer level. An important pre-requisite is that the CD metrology systems has to have the capability to provide a reliable CD measurement for such complex 2D features. ZEISS WLCD offers a dedicated CD evaluation function which automatically measures the minimum or maximum CD on complex 2D features. Figure 6 shows exemplarily the Run to Run correlation for two runs of the 2D features measurement representing a slope of 0.98 and a R² of 99%. This demonstrates that WLCD provides a reliable CDU input for the CDC process.

![WLCD Run to Run Correlation: 2D Production Feature](image)

Figure 6: WLCD Run to Run correlation for complex 2D feature measurement

The complex 2D feature has a high MEEF and reveals a 3Sigma CDU of 7.3nm at wafer level. If the 2D feature is taken as input for CDC we achieve an improvement in CD uniformity by 90% and can reduce the value down to 0.7nm 3Sigma at wafer level. This is an excellent result. It confirms that the CDC user can gain maximum benefit from the correction by selecting the most critical feature while improving the other features as well. The pre and post CDU maps are plotted in Figure 7 and the detailed results are summarized in Table 2.
4. CONCLUSION

It was demonstrated that the linearity behavior is being maintained while applying the CDC process. This extremely important result confirms the use and benefits of the CDC correction especially for logic masks having different pitches and features.

Furthermore, it was found that the different features share similar global CDU errors which are mainly differentiated by different MEEF. Intensive investigation showed that the applied attenuation by CDC shows a linear correlation to CD change at wafer level as measured by WLCD. CD uniformity and CDC ratio follow the same trend. This fact provides the IC manufacturer the freedom to choose the most critical feature as the process target in order to finally get the best device performance.

The CDC correction on the 2x node masks shows significant CDU improvement for both, 1D and 2D features. Maximum improvement is achieved for the feature on which the CDC process is based on. This provides the customer the flexibility to select the most critical feature in order to gain maximum benefit from the CDC correction.

Finally, it was demonstrated that WLCD provides reliable CDU input especially for complex 2D features which are a challenge for CD metrology.

Table 2. The CDU statistics (3Sigma & range) for the complex 2D feature before and after CDC process

<table>
<thead>
<tr>
<th>Summary</th>
<th>Pre CDC™ CDU [nm]</th>
<th>Post CDC™ CDU [nm]</th>
<th>Improvement [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complex 2D Feature 63 nm</td>
<td>Range</td>
<td>11.4</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>3Sigma</td>
<td>7.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Figure 7. The CDU signature for the complex 2D before CDC process (left side) and after CDC process (right side).
REFERENCES


