Improving chip performance by photomask tuning: ultimate intra-field CD control as a major part of an overall excursion prevention strategy

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Improving Chip Performance by Photomask Tuning: 
Ultimate intra-field CD control as a major part of an overall excursion prevention strategy

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ABSTRACT

Excursion prevention is one of the key points in the mission of leading edge foundries. In this paper, we concentrate on patterning excursions and how to prevent them. This strategy concentrates pro-actively on the task to minimize the distributions of critical input parameters as much as possible, independently upon a certain pre-defined specification is met or not. In our paper, we will describe this concept by improving intra-field CDU using CD Correction (CDC) by mask tuning. Mask Tuning by the ForTune system uses ultra-short pulse laser technology to locally change the mask transmission, based on the wafer intra-field CDU, and hence improves CDU on wafer (CDC).

To ensure a save patterning with a large enough process window without any negative yield or reliability impact, our concept looks for the tail of the final CD distribution instead of traditional 3-sigma numbers. By using a calibrated 3D resist model, we simulate the wafer CD distribution under all combinations of the Litho input parameter distributions dose, focus and mask CDU. As a result of the simulation, we get thousands of CD-results. The tail of that CD distribution still needs to be larger than the minimum CD needed for a safe etch transfer. Based on our simulation data we can calculate patterning failure probabilities and thus expected yield loss for the different patterning cases, including systematic process deviations (mask, dose, focus).

At the final step, we will show in detail how the pro-active optimization of intra-field CDU by Mask Tuning using the ForTune CDC process will give us more patterning margin and thus will reduce the failure probability dramatically. The calculated yield loss for the worst scenario (focus & dose offset additionally to the mask signature) will be reduced from several percentages close to zero.

Keywords: photomask, CDC, Critical Dimension Uniformity (CDU), weakpoint, excursion prevention, mask tuning, failure probability, yield

1. INTRODUCTION

The reputation of state of the art logic fabs (foundries) highly depend on predictability and credibility. High yields are very important to convince customers of the capability of the fab. However, more important than one or two percentage more yield is the fab’s capability to deliver the committed yield and the numbers of wafers reliably. Any process excursion that reduces the yield significantly is catastrophic and undermines the trust of the customer into the fab’s capability and reliability. Thus, the fab’s trying everything to prevent excursions. Important foundries such as TSMC or GLOBALFOUNDRIES have a “zero excursion” mission as part of their fab strategy [1, 2].

Excursions can have multiple root causes (e.g. non-recognized material, tool, process, mask defect issues). In our work we concentrate on patterning excursions. Such excursion can happen when a parameter shows a deviation from normal that is not recognized quickly enough. However, fab engineers usually know which deviations of their processes they can live with and should have defined the process specifications or control limits accordingly. Things get more complicated for processes that depend on multiple input parameters where complex inter-dependencies between parameters are present. This is the case for patterning at low k1, see figure 1.
Within a life cycle of a technology, it is nearly impossible to ensure that all parameters are within the optimum control all the time. Scanners, tracks and etchers have its own variability and despite of the efforts of the tool vendors and the fab engineers, it can happen that they operate a bit off of its optimum condition for a certain period of time. Mostly that is tolerable and won’t result in a catastrophic patterning failure. However, the situation becomes critical if more than one parameter is out of its optimum control and shows a systematic deviation, even if every single one still meets its specification. In particular it happens that systematic intra-field CDU fingerprints that come from the mask or the scanner are present over quite some time. Figure 2 shows an example of a patterning excursion caused by such a multiple parameter dependency. Here, a little tiny circuit failed (brownish stripes in the on wafer die-topography map) in the left die but was still working in the right die. Thus, although the de-focus due to the topography might have contributed to the fail, it can’t be the only root cause for the fail. As we see from figure 2, we additionally have a large mask CD (brown area) plus a relatively high dose due a non-optimum scanner illumination uniformity at the position of the failing circuit (green curve; optimum = brown curve at the bottom graph). Although each of the three parameters (focus, mask CDU, dose) was in specification, we got a patterning defect due to the interaction of three parameters that all have a systematic shift. At the right die, where just the topography is out of optimum, the patterning is still working.

Figure 1. Parameters that have impact on the final patterning result.

Figure 2. Excursion example due to a patterning defect signal across die: patterning failure happens due to interaction of non-perfect wafer planarity (de-focus), mask CDU and scanner dose.
2. SIMULATION OF PATTERNING INTER-DEPENDENCIES

2.1 Simulation conditions

To get a better understanding of patterning parameter interaction and the relationship to excursion probability, we decided to do an excessive simulation run based on a calibrated 3D resist model. We used a 28nm metal application that runs on an ASML NXT1960 or similar. 28nm metal uses a minimum pitch of 90nm that corresponds to a k1 of 0.32 for unconstrained designs. Thus, from a pure imaging perspective this case is aggressive and sometimes even more challenging than the conditions at more advanced nodes. As the patterning breaks first at its weakest point, simulation was done for the most critical weak-point of that technology. It is at minimum pitch and consists of only 3 lines with a very short run-length (see figure 3). That pattern has a very high MEEF (>5) and very low NILS of <1.5 and a high dose sensitivity [3].

![Figure 3. Super-critical weak-point used for simulation](image)

For simulation, we restricted to focus, dose /dose like effects and mask CDU. As a first step, we defined four different cases of input variations:

1. All parameters are controlled well with reasonable tool and wafer control loops. No systematic signatures are present. The mask CDU is totally flat with only random CD-noise of <1nm.
2. We add a strong, systematic mask signature.
3. Sequentially, we add a systematic dose error and
4. a joint dose /focus error.

Figure 4 summarizes these four cases and the numbers for the input parameter variability and shows the principle of simulation: out of Gaussian dose and focus variations and the mask CDU we get a final wafer CD distribution. As we talk about patterning fails, we should not forget the local CD variability. We simulated the local CDU (LWR = 4.5nm) for our weak-point and convoluted the LWR with the CD distribution out of the parametric simulation.

![Figure 4. Input parameter variation for the four simulation cases and the resulting wafer-CD distribution.](image)
In the next step, we want to calculate the fail probability for the 4 cases. For our weak-point with a resist line as the critical pattern, just the lower tail of the CD distribution is of interest, whereas the upper tail might be important for other, pinching sensitive weak-points. By comparing simulation results with AFM scans, cross-sections and corresponding etch experiments we found that a top-CD (resist height 50% of nominal) of the weak-point resist line of 20nm is needed to guarantee a reasonably reliable etch transfer. Thus, a CD of <20nm is our fail criteria. To better understand how big the fail probability for the 4 cases will be, we just need to transfer the CD distribution into the cumulative probability curve. In the cumulative plot (figure 5), the y-axis shows the probability of the CD being smaller than the corresponding CD on the x-axis. The probability at CD of 20nm is then identical with the fail probability for the individual cases. As the weak-point is distributed 1.2x10^4 across the die, we need fail probabilities < 10^-7 to be safe.

![Figure 5](https://example.com/figure5.png)

Figure 5. Transferring the CD distribution into a cumulative CD-plot; CD’s < 20nm are classified as fails.

Figure 6 compares the result of that parametric simulation with the final curve that contains the local CD variation (LWR), which should be closer to reality. Therefore in all following calculations the local variability (LWR) is included. As expected,

- the CD distribution widens heavily
- the failure rate at a certain CD increases significantly

![Figure 6](https://example.com/figure6.png)

Figure 6. Cumulative CD distribution change including the local CD variation (brown curve) versus the CD distribution of the parametric simulation (blue curve).
2.2 Simulation results

2.2.1 Case 1: “Ideal” mask vs. mask with signature

Figure 7 shows the two mask signatures we used for our case study. Whereas the “ideal” mask just includes the local CD-variation <1nm, the right mask has a strong signature with the yellow marked die being most extreme with a CD deviation to mean of -2nm (mask level – X4).

![Figure 7](image-url)

Figure 7. The “ideal” mask showing just noise (left) versus a mask with a strong signature. The yellow marked die has a CD offset to mean of 2nm at mask level.

At a first step, the simulation just is done for that yellow marked die. In figure 8 we see the cumulative probability plots for the ideal case and for the 2nm mask signature case (0.5nm at wafer level).

![Figure 8](image-url)

Figure 8. Wafer CD probability plot for the yellow marked die out of figure 7: ideal mask versus strong mask signature

We clearly can see:

- As expected for the mask signature case, the overall wafer CD distribution is shifted toward lower CD’s
- The wafer CD-shift is roughly 2.5nm and thus bigger than the original mask CD offset of 2nm, indicating a very high MEEF = 5.
- Due to the non-linearity of the process, the tail of the distribution is shifted even stronger (3nm).

Whereas the ideal mask case is far away from any fail, the tail of the CD distribution of the strong mask signature case comes close to the fail CD of 20nm (probability 4x10⁻⁸). Thus, we can already here conclude that masks with a signature like above should be improved.
2.2.2 Results of Case 3 & 4: dose offset and combined dose/focus offset on top of the mask signature

Figure 9 shows the probability plot for all 4 cases. Let’s first concentrate on case 3 (dose offset=green curve). The curve is shifted toward smaller CD’s by 1.6nm resulting in a failure rate of $8 \times 10^{-6}$. This is a significant increase and would result in 8 dies across wafer showing a patterning failure ($1.2 \times 10^5$ weak-points per die, 86 fields per wafer). For the combined dose/focus offset, the fail rate would increase another order of magnitude resulting in a patterning failure across wafer in 83 cases. Keeping in mind that this is for the yellow die only and the neighboring dies have a similar fail probability, we can expect a significant yield loss for case 4. It becomes clear that we need a clear improvement of the wafer CD uniformity.

![Figure 9. Cumulative probability plot for our 4 simulation cases respecting the yellow marked die out of figure 7.](image-url)
2.3 Improvement of the wafer CD distribution by correcting the intra-field CDU using ZEISS CDC

2.3.1 CDC tool concept and improvement potential

Figure 10 shows the working principle of the ZEISS CDC tool [4, 5]. Let’s assume two areas within the image field which have a significantly different CD on wafer. The CDC tool now will introduce shading elements to make the two CD’s on wafer equal. The area with a low trench CD only gets a very sparse distribution of shading elements whereas the area with the high trench CD needs a very dense sampling. During exposure, a big part of the light is scattered out of the lens pupil in the dense shading case whereas the amount light scattered away in the spare sampling case is minor. If calibrated properly, the final CD’s on the wafer are identical.

Figure 10. Working principle of the ZEISS CDC tool: On wafer Intra-field CD will be controlled by locally attenuating the light transmitted through the mask

Figure 11 shows an application case where we see a very strong correlation of the intra-field CDU signature and the stacked patterning defect map [6]. After CDC correction and a corresponding wafer CD reduction of 1nm, the defect signature is completely gone.

Figure 11. Correlation of the process defect map and intrafield CDU (top) & corresponding improvement by CDC (bottom)
2.3.2 Excursion prevention concept using ZEISS CDC

Figure 12, left shows a histogram of intra-field CDU’s as measured in a wafer fab for different products and masks. Although all samples meet the specification, there is a relative wide spread with some product layers being clearly worse than the median. Engineers that are not aware of the excursion prevention concept would except that situation and would release all masks for production. However, the excursion prevention philosophy asks for improvement potential.

As we clearly can see from the strong CDU signature of the red marked sample, there is a lot of improvement potential. Applying CDC, the CDU would improve by roughly 60% (green sample in figure 12, left). Overall, following the excursion prevention concept, all masks/intra-field CDU with a signature larger than a pre-defined value have to go through the intra-field improvement cycle (e.g. by CDC). This ultimate control concept “tighten your parameter distribution – independently of any specification - to whatever is possible at reasonable cost” should be applied to all other important input parameters of patterning. However, there’s an essential difference between the intra-field CDU improvement and other parameters like the scanner focus performance. Whereas the intra-field CDU signature is widely static and the correction is pretty easy, it is sometimes very hard to detect a scanner deviation in “real time” and thus corrections might be late.

![Figure 12](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 12. Intra-field CD statistics on wafer for different products / metal layers and CDU signature for the red case pre and post CDC treatment of the mask.

2.4 Impact of the mask CDU improvement by CDC on the wafer CD distribution and the fail rate

As a next step, we calculated the wafer CD distribution and the corresponding fail probability after we have improved the CDU for our yellow marked die with the 2nm CD offset at mask level. Though CDC could take out any signature, we just put a 75% correction efficiency into the calculation, which is a reasonable number based on the CDC correction history. Let’s first have a look onto case 3 (dose offset 1.2%, dark green curve in figure 13, left). As we can see, we are able to shift the CD distribution by roughly 2nm toward larger CD’s resulting in a dramatically reduced fail probability from 9x10^{-7} toward 4x10^{-8}. Considering the 1.2x10^{4} weak-points in the design, this is an uncritical failure rate. For the extreme case with an additionally 15nm focus offset (figure13, right), the failure probability is improved by more than an order of magnitude as well (2x10^{6}) resulting in a reduction of the number of fails across wafer from 83 toward 2 which would be an acceptable rate.

![Figure 13](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Figure 13. Patterning failure rate decrease due to intra-field CDU improvement by CDC (75% correction efficiency).
3. ESTIMATION OF YIELD LOSS DUE TO THE SYSTEMATIC SIGNATURES AND IMPROVEMENT BY CDC

To get an estimate of the yield loss due to the systematic offsets of mask CDU, dose and focus, we need to do the same failure rate calculation that was done for the yellow die for the whole reticle. At a first step, we separated the mask signature into four segments per die getting 64 squares where we do the failure rate calculation. Figure 14 shows that more granular mask CDU signature pre- and post CDC. In the second step, we calculate the failure probability for each of the 64 segments and average across every die. Out of the failure probability per die we easily can calculate the number of fails across wafer: (# wafer fails = probability * # of weak-points * number of fields (86)).

Having the number of fails across wafer it’s just one step to get the yield loss per die. Assuming a purely random yield loss across wafer, the yield loss \( \Delta Y \) equals to: \( \Delta Y = \# \text{ of fails (wafer)} / \# \text{ of dies} \times (1 - p^2) \) where \( p^2 \) is the probability of a die gets hit twice or more. For the most extreme case (marked die) \( p^2 \) equals to 0.23. Figure 15 shows the patterning yield loss distribution pre and post CDU improvement by CDC across reticle, together with the average yield loss for the two cases. As expected, the yield loss for the marked die and the two neighboring dies is heavy (between 17% and 52%) but will be <1% even for the worst die after CDU improvement by CDC. Overall, the average yield loss for the whole reticle due to the 3 systematic offsets mask CDU, dose and focus reduces from 6.9% toward 0.2% post CDC. Thus, the CDU signature compensation really pays back in yield.

Figure 14. CDU signature of the mask pre- and post CDC; 75% correction efficiency.

Figure 15. Calculated yield loss per die and reticle pre- and post CDC for case 4 (combined dose and focus offset on top of the mask signature)
4. CONCLUSIONS

Patterning failures and thus yield loss can happen even if all incoming parameters are within specification. This is the case if more than one parameter is not in optimum condition and shows a systematic offset over a certain time, although every parameter itself is still within specification. In particular, wafer intra-field CDU signatures need to be removed using mask tuning to prevent patterning excursions. The ZEISS CDC concept is an effective, low cost and low effort technology to improve the intra-field CDU massively. Our simulation shows that the failure probability will be reduced by 1.5 orders of magnitude. The corresponding yield loss reduces from roughly 7% to <<0.5 %, even if other systematic offsets (dose, focus) are still present. Out of the data we can conclude the improvement of the intra-field CDU by CDC is a major part of an overall patterning excursion prevention strategy.

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