Split and Design Guidelines for Double Patterning

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\section*{ABSTRACT}

Double Patterning is investigated at IMEC as a timely solution to meet the 32nm node requirements. It further extends the use of water immersion lithography at its maximum numerical aperture NA=1.35. The aim of DP is to make dense features possible by splitting a design into two more sparse designs and by recombining into the target pattern through a double patterning flow (stitching). Independently of the implementation by the EDA vendors and designers, we discuss some guidelines for split and for DP-compliant design to ensure a robust stitching through process variations. We focus more specifically on the first metal interconnect patterning layer (metal1) for random logic applications. We use both simulations and experiments to study the patterning of 2D split test patterns varied in a systematic way.

\textbf{Keywords:} Double Patterning, Split, Stitching, Metal1, Logic, Process Variations, Guidelines, Restricted Design Rules

\section{1. INTRODUCTION}

Extending the use of immersion lithography to the 32nm node and beyond using the highest numerical aperture (NA) of 1.35 requires the patterning of features at aggressive k1 values. The 45nm half-pitch (hp) (k1=0.315, 32nm node for random logic) still corresponds to a k1 above the physical limit of 0.25. Therefore, a priori, both single patterning (SP) and double patterning (DP) are potential solutions. However, the ease of their implementation depends on the application and more specifically on the compliance of the target design. The single patterning at low-\(k_1\) requires off-axis illumination, along with restricted design rules. Single patterning might be implemented for random logic designs only at the expense of design change. The double patterning in random logic applications requires cutting and splitting of the design polygons. The polygons or parts of them are assigned to two different layers to be patterned separately; this is known as the coloring step. An increased density and increased 2D content results in an increased need for polygons cuts. However, those split polygons need to be recombined through the double patterning flow (stitching). Cutting the polygons is not a suitable solution to coloring conflicts \cite{4} if the polygons cannot recombine in a robust way through double patterning process variations.

We consider the patterning of a 45nm hp first metal interconnect patterning layer (metal 1) in through-pitch random logic application, as a test vehicle for studying the polygon cutting and stitching. The high 2D content and the frequent occurrence of the densest pitch in the metal1 layer increase the need and complexity of polygon cutting and stitching. EDA vendors are addressing the automation of the design split \cite{1}\cite{2}. We are discussing a methodology leading to split and design guidelines to ensure a robust stitching through process variations. The study uses representative 2D test patterns of which the design and the split parameters are varied in a systematic way.
2. TEST DESIGN AND PROCESS

2.1. Test clip selection
Random logic design clips shrunk from a previous node have been used for an early study of design split [3][4], helping to identify the problematic polygon topologies. Representative test patterns have been designed (Figure 1). The design parameters such as the target CD, the pitch and the topology are varied. The split parameters such as the cut position and the stitching overlap are also varied. We need to identify the parameter space in which the stitching is robust through process variations.

![Figure 1 Examples of split test patterns (right) representative for split into random logic metal1 layout (left)](image)

2.2. Metal process
A litho-etch-litho-etch double patterning flow is used [5] [6]. The final 45nm trenches are patterned in a 30nm TiN hard-mask (HM) and subsequently transferred into a 120nm low-k dielectric material deposited on a 35nm SiC etch-stopping layer. The image is developed in 120nm resist on 35nm BARC. In order to improve the lithographic process window of the trenches, the resist target needs to be increased up to 65nm. The BARC-opening and HM etch leads to 45nm trenches after the first patterning. The BARC is used both for planarization and reflection control at the second patterning step. Again trenches are 65nm in resist and shrunk through the BARC opening and the HM etch down to 45nm. After the second patterning, the dense target layout is patterned at 45nm in the HM. The experimental results presented further in this paper are top-down SEM images of the patterns in HM (Figure 2).

![Figure 2 Double Patterning process flow for Metal Trenches applications. Right, a split example and its patterning in HM is shown.](image)
2.3. Imaging

The illumination settings must be optimized through pitch for depth of focus (DOF), mask enhanced error factor (MEEF) and image log slope (ILS) at the trench-ends of small gaps. Optimization takes into account the specifics of the split patterns. Considering $k_1=0.4$ as a typical resolution limit for through pitch metal1 imaging, the pitch splitting is required under 115nm pitch at NA=1.35, or 130nm pitch at NA=1.20. The split pitch may fall in a forbidden pitch range, which should be avoided or minimized by tuning the NA and partial coherence ($\sigma$) settings. NA=1.35 will help to move the forbidden range below 180nm pitch. Increasing the resist target improves the DOF. It is also important to improve the resolution limit for gaps in order to reduce the need for polygon cuts. The ILS at small gaps as well as the MEEF of the trenches will benefit from increasing NA or $\sigma$.

Based on simulations both at NA=1.2 and NA=1.35, an annular illumination setting has been selected for the imaging of random logic 65nm trenches from $k_1=0.4$ through pitch. $\sigma_{\text{out}}/\sigma_{\text{in}}=0.92-0.72$ and X/Y polarization are chosen to increase the contrast at small gaps and to reduce the trench MEEF.

3. SIMULATION METHODOLOGY

3.1. Process failure detection through process variations

Even if a good stitching is achieved under optimum process conditions, assuming a successful OPC, there is a risk for yield drop through process variations. Therefore, the stitching quality needs to be judged based on relevant metrics defined under various process conditions, i.e. in detuned process conditions.

The contours of the image in resist are simulated. The target in resist is 65nm. An isotropic constant etch bias is assumed to bring trenches down to 45nm in hard-mask. After insertion of the assist features, a dense OPC (using Mentor Graphics Calibre nmOPC) is run using a non-calibrated constant threshold resist model. The default OPC settings are used. At this stage, the two patterning steps are assumed to be independent from each other. Further the image contours are simulated and compared under various process conditions (using Mentor Graphics Calibre OPCVerify).

Let us first consider each patterning step separately. We vary the dose and focus conditions on 9 different positions in the center and along the edge of an elliptical process window (Figure 3). In best focus, the dose is varied by ±3%; in best dose, the focus is varied by ±50nm; the dose and the focus are also varied concurrently by ±2.1% and ±35nm respectively. As MEEF is critical for trenches and certainly at trench-ends, we also induce a ±0.5nm mask bias variation per edge, additionally to the dose variations. When the dose is increased, the OPC’ed mask polygons are upsized by 0.5nm. Similarly, the mask is down-sized when the dose is decreased.

![Figure 3 Scheme of the induced process variations along an elliptical process window varying the exposure dose, the defocus, the sizing of the OPC’ed mask, as well as the relative overlay between the patterning 1 and 2.](image_url)

Process failure criteria are defined (Figure 4). First, an incomplete OPC is defined as an Edge Placement Error (EPE) larger than 3nm at a trench-end in best dose, best focus, and nominal mask. In certain polygon configurations, there is no room to extent the trench-end hammerhead far enough to fully compensate for trench-end pullback. Second, some bridging can happen between neighboring contours in best focus, increased dose, and upsized mask. The bridging is...
flagged as soon as the contours come closer than 15nm to each other. Third, pinching is defined as a trench becoming critically too narrow (namely internal width < 35nm) in defocus, decreased dose, and downsized mask.

The patterns also need to be recombined through the double patterning flow (=stitching). In addition to dose, focus, and mask errors, the stitching can suffer from overlay errors between the two patterning steps. Overlay errors of ±4nm in X and in Y are induced, resulting in a ~6nm overlay error along the diagonal directions (Figure 3). The stitching is checked between contours experiencing overlay shift, with both patterning in defocus, decreased dose, and downsized mask. As a metric for stitching quality, we define the stitching width, which is the smallest internal distance of the merged contours from first and second patterning steps. A stitching failure is flagged if the stitching width is smaller than 25nm. The area of overlap between two contours is not the good metric, as the overlap can be marginal with still a robust stitching.

We have defined a process model and some metrics that constitute our simulation model. The analysis further discussed in this paper is based on non-calibrated simulations and specific failure criteria. It will help to identify the main trends and the critical parameters. Applying the same methodology based on a calibrated simulation model or on experiments would lead to the exact numbers for patterning limits.

4. SIMULATION STUDY

The simulations are run at NA=1.35 with Annular 0.92-0.72 and X/Y polarized light, unless noted otherwise.

4.1. Minimum stitching overlap

A stitching overlap (overlap at mask level between the polygons from patterning 1 and patterning 2) is needed to ensure a stitching without process failure flag. Let us consider the stitching in dense parallel lines (110nm pitch) cut in the middle (Figure 5). At nominal mask overlap of 0nm, the contours from the two patterning steps touch each other without overlapping. In defocus, decreased dose, and downsized mask, the trench-end pullback results in a gap between the two patterns to be compensated by some mask overlap. In “detuned” process, a 48nm overlap is needed to compensate not only for trench-end pull back but also for trench-end rounding, in order to obtain an acceptable stitching width according to the failure-flag defined. If a worst-case 10nm overlay error is induced along the stitching direction, the stitching overlap needs to be increased up to 56nm in order to avoid the stitching failure. We have shown based on this example that the mask stitching overlap is mainly compensating for the variations of trench-end and shape through process variations, more than for overlay (Figure 5). The trench-end process is more critical for stitching than overlay, while overlay remains critical for the pattern placement. It also suggests more specific OPC or resolution enhancement technique (RET) should be used to ensure better trench-end pattern fidelity.
The stitching in parallel trenches is illustrated in Figure 6 by experimental results at NA=1.20 in best dose, best focus, nominal mask. An insufficient stitching width is observed at mask overlap 16nm, showing necking. Further increasing the mask overlap up to 36nm, the difference between patterning 1 and 2 can be barely seen. In addition, 8nm of trench-end pull-back need to be compensated in detuned process. Based on this, we estimate the needed mask overlap around 50nm (36nm plus two times the pullback of 8nm).

It is also interesting to notice that an overlay error perpendicular to the stitching direction could be beneficial to the stitching width (Figure 7). Having stitching both in X and Y direction, it means that X and Y overlay specs should be minimized, but not the diagonal specs: the overlay process window is a square instead of a circle when considering stitching.
4.2. Parallel and Perpendicular trenches

Let us further discuss the cut in parallel trenches, as well as the cut in perpendicular trenches as depicted in Figure 8. In both cases, a polygon cut occurs next to a small space (small pitch) or next to a small gap, both removed by design split. However the overlap needed for a robust stitching reintroduces locally the small pitch or small gap. Consequently, such cuts limit the benefits of double patterning. We investigate the different reasons for failures.

For the parallel trenches at NA=1.35, the simulations show that a minimum mask overlap of 56nm is required. Due to the cut in the parallel trenches, the 104nm pitch is the last one without process failure (Figure 9). A stitching failure is found for pitch 102nm and below, which is explained by a lack of process at the trench-end intended for stitching overlap. Increasing the overlap to 64nm moves the pitch limit down to 98nm, but further increasing it does not help. A bridging problem also occurs from pitch 94nm onwards when trench-ends come too close to each other with insufficient exposure latitude.
Analyzing the same parallel trenches with cut at a reduced NA=1.20, requiring the same mask overlap of 56nm, the 102nm pitch is the last one without process failures. The stitching issues begin at 100nm pitch. This marginal improvement compared to NA=1.35 is explained by the increase in DOF. Moreover, the bridging problems occur at larger pitch, i.e. 98nm pitch, indicating an increased lack of exposure latitude at the trench-end intended for overlap. An additional issue occurs at 96nm pitch when the OPC cannot be fully completed resulting in an EPE > 3nm. The stitching overlap makes the trench-end sub-resolution at pitches below 96nm.

Figure 10 Again, at NA1.20, the large overlap re-introduces the dense pitch, resulting in stitching, bridging and OPC failures. The sources of failure appear at different pitch, but there is no real change in terms of minimum pitch for a robust stitching compared to simulations at NA1.35.
In conclusion, to take full advantage of the double patterning to drastically improve the pitch resolution in parallel trenches, any stitching should be avoided. If stitching is needed, then the pitch needs to be relaxed to allow a robust stitching though process variations.

A similar analysis is run on the perpendicular trenches configuration, called “double T-shape”. Pitch, gap and stitching overlap are varied, referred as parameters a, b, and c in Figure 11. Based on the analysis of the parameter space for no process failure at NA=1.35, we show that the gap needs to be relaxed to make the minimum overlap for stitching possible. In case of a gap larger or equal to 58nm, the pitch 88nm can be achieved by double patterning with a 60nm minimum overlap in the horizontal line. If the gap further increases to 62nm, the minimum overlap can be reduced down to 50nm.

![Figure 11 Relaxing the gap is needed to avoid bridging and ensure a robust stitching (NA=1.35).](image)

### 4.3. Combined aggressive pitch and gap

The pattern displayed in Figure 12 is typical for a metal1 layer and it combines both the pitch and the gap at their minimum target of 90nm and 46nm respectively. The test design is such that pitch, gap, cut position and stitching overlap are varied. We identify the densest pitch and gap combinations free of failure flags compared for single patterning, double patterning at NA=1.35 and double patterning at NA=1.20, using the same failure criteria in the three cases. Each litho step of the double patterning flow targets at 65nm trenches at a minimum pitch of 115nm to 130nm, using assist features and assuming an etch bias down to 45nm. The single patterning targets at 45nm trenches at 90nm minimum pitch, while the trenches can be retargeted as the pitch is relaxed, it does not use any assist features. Using single patterning at NA=1.35, the minimum pitch of 110nm and minimum gap of 66nm are such that no process failure are observed using our simulation model. Denser pitch or gap would lead to failures. Using the double patterning at NA=1.35, two cut positions are possible. The aggressive gap target can be achieved by double patterning, resulting in a need for cutting the two central parallel trenches. However the pitch should be relaxed above 100nm to ensure a robust stitching. This constrains on the pitch concerns the trenches around the stitching area. However, if no cut of the parallel trenches is allowed, the target pitch of 90nm is achievable with double patterning of the complete trenches. As a result the small gaps have to be printed at the same litho step, limiting the minimum gaps to 66nm. A similar analysis at NA=1.20 leads to similar conclusions. If a cut is used into the parallel lines, a minimum pitch of 104nm ensures a robust stitching. On the contrary if the gap needs to print in one imaging step, then it should be relaxed to 74nm. Decreasing the NA results in a worse gap resolution; increasing the need for cuts. As a conclusion, a significant resolution improvement using double patterning is only possible if the stitching does not occur next to a small space (dense pitch) or to a small gap (Figure 13).
Figure 12 Comparison of pitch-gap minimum without process failure, for single patterning, and double patterning at 1.20 and 1.35 NA. There are two possible split solution leading to different resolution limits.

Figure 13 Pitch and Gap resolution limits for the pattern shown in Figure 12. Double patterning improves the resolution limit for the pitch or for the gap but not for both at the same time, as they are neighboring constraints in the design.

Figure 14 shows the patterning of the test pattern at NA=1.20 using double patterning in best dose, best focus, nominal mask. At pitch 90nm / gap 46nm, the stitching width in the middle of the parallel lines is too narrow, being already an indication for failure in detuned process. Stitching is improved when relaxing the pitch up to 100nm, where very aggressive gaps ~45nm are patterned with double patterning. If the gap is relaxed to ~60nm, the stitching occurs in the middle of the turns, and the 90nm pitch is patterned using double patterning.
5. CONCLUSIONS

The design split problem is more than just polygon cutting and coloring. The polygons need to recombine through the
double patterning process flow (=stitching). Whereas OPC can ensure some overlap under optimum process conditions,
the yield might decrease under a detuned process due to failing stitching. We have developed a methodology to study
the double patterning stitching robustness through process variations. Design and split parameters of representative test
patterns are varied in a systematic way. Process failures due to variations in dose, focus, mask CD and overlay are
defined and flagged. Based on simulations, the parameters space free of process failure flags is identified. The
parameter space for success is used to indicate best split practice or design guidelines to ensure a robust stitching for
maintaining yield with double patterning.

The trench-end process (pattern fidelity and position) is critical to stitching, more than overlay is. Sufficient attention
must be paid to the line- and trench-end process, using adequate RET (including OPC) to increase pattern fidelity and
process latitude. Of course, the overlay remains critical for the pattern placement, rather than for stitching.

A global scaling from the previous node will not allow taking full advantage of the double patterning. The pattern split
is required due to dense pitch (=small space) or small gap. If cutting and stitching are required next to a split space or
gap, the overlap required for robust stitching will re-introduce locally the initial minimum target space or gap. In
consequence the benefit of the split is partially canceled. The stitching robustness can only be ensured by adequately
relaxing the minimum local gap or space target. Note that reducing the amount of stitching overlap will limit the need
for design relaxation. Basically, it is the imaging resolution at stitching that limits the benefit of double patterning. For
example, according to our simulation model, the cutting and stitching limits the pitch at 100nm/104nm at NA=1.35/1.20
or the gap at 66nm/74nm at NA=1.35/1.20. However, compared to the single patterning limits, i.e. under our simulation
model 110nm pitch / 66nm gap at NA1.35, the double patterning affords significant benefits in terms of resolution,
based on proper design restrictions assuming a partial design shrink where the densest pitch and densest gap are not
combined at the same location in the target design.

We have discussed the patterning of 45nm hp metal1 random logic patterns at NA=1.35 (Figure 15). A typical limit for
through pitch single patterning of a metal1 layer is k1~0.4. Using restricted design rules the single patterning limit can
typically be pushed down to k1~0.3. Under the assumptions of our simulation model, we have shown that unrestricted
design would limit the benefit of double patterning to k1~0.35. However, if some compliant design rule restriction are

Figure 14 Double Patterning in HM of trenches at NA1.2, Annular σ0.92-0.72 X/Y polarized.
followed, the 45nm hp resolution limit at k1~0.30 can be reached using double patterning, with the potential to reach more aggressive pitch or gaps.

As both single and double patterning require restricted design rules to ensure a robust imaging at k1~0.30, the ease of their respective implementation will depend on the compliance of the 45nm hp target design and on the process itself. However, moving down to the 32nm hp applications, the only solution with 1.35 NA ArF water immersion lithography (i.e. k1=0.224) appears to be double patterning with compliant designs to maintain the yield.

![Figure 15 Typical k1 values, comparing single and double patterning limits for 45nm and 32nm metal1 random logic applications with and without restricted design rules (RDR) or design rules (DR) for DP compliance.](image)

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7. REFERENCES


