Incorporating DSA in multipatterning semiconductor manufacturing technologies

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ABSTRACT

Multi-patterning (MP) is the process of record for many sub-10nm process technologies. The drive to higher densities has required the use of double and triple patterning for several layers; but this increases the cost of the new processes especially for low volume products in which the mask set is a large percentage of the total cost. For that reason there has been a strong incentive to develop technologies like Directed Self Assembly (DSA), EUV or E-beam direct write to reduce the total number of masks needed in a new technology node.

Because of the nature of the technology, DSA cylinder graphoepitaxy only allows single-size holes in a single patterning approach. However, by integrating DSA and MP into a hybrid DSA-MP process, it is possible to come up with decomposition approaches that increase the design flexibility, allowing different size holes or bar structures by independently changing the process for every patterning step.

A simple approach to integrate multi-patterning with DSA is to perform DSA grouping and MP decomposition in sequence whether it is: grouping-then-decomposition or decomposition-then-grouping; and each of the two sequences has its pros and cons. However, this paper describes why these intuitive approaches do not produce results of acceptable quality from the point of view of design compliance and we highlight the need for custom DSA-aware MP algorithms.

Keywords: Directed Self Assembly (DSA), DFM, Lithography checks, layout verification.

1.Introduction.

1.1. Introduction to Directed Self-Assembly (DSA)

Self-Assembly is the phenomenon that occurs when block co-polymers composed of immiscible blocks phase-separate into organized structures [1]. For example, a diblock co-polymer can self-assemble into periodic structures of one type of block into a matrix of the other. Lithographically-printed patterns (in a scheme called Graphoepitaxy) or chemically-treated surfaces (in a scheme called Chemoepitaxy) are used to *direct* the self-assembly process [2].

The realizable assembled pitch depends on the characteristics of the used block co-polymer. The graphoepitaxy process for contact holes is shown in Figure 1, where trenches are lithographically printed first, and then the surface is spin-coated with the block co-polymer (BCP). Upon thermal annealing, the phase separation occurs, and with a particular BCP and surface treatment of substrate [3], cylinders are obtained within the guiding pattern.

Figure 1. An example directed self- assembly process of a diblock co-polymer using Graphoepitaxy

In Graphoepitaxy, there are two styles of guiding templates: trenches [4] and posts [5]. Currently, the former option is more mature and understood, and more attractive to the industry since the posts templates need to be manufactured by e-beam in turn limiting the throughput of the process.

DSA has been successfully demonstrated for contact holes [4] and lamellae [6]. Since DSA is capable of printing dense nano-features of roughly uniform dimensions [7], it is a very good fit for contact and via layers. For that reason, this work is concerned with graphoepitaxy for contact/via hole structures.

1.2. Implications of DSA on Contact/Via holes

The natural multiplicative nature of DSA makes it very attractive as a low-cost resolution enhancement technology. However, it imposes some restrictions on the design. The manufacturable pitches depend on the natural pitch L_0 of the BCP, creating polygons of uniform width. Only a certain range of pitches greater than L_0 is manufacturable in DSA. Moreover, the BCP cannot be locally modified on a per guiding-pattern basis. Thus, if the process uses DSA along with a single mask to print the templates, only single-size contact/via holes can be manufactured. In addition, some layout configurations are forbidden because they require guiding templates that cannot be manufactured by optical lithography.

In the contact/via holes DSA scheme where the templates are manufactured using 193nm wavelength, the easiest configurations are one-dimensional arrays of contacts, with pitch equal to L_0, with higher reliability achieved if smaller number of holes are to be assembled per guiding template [8].

1.3. DSA in Hybrid Lithography Schemes with Multiple Patterning

In order to achieve the sub-5nm nodes, DSA will need to be complemented with other technologies in hybrid lithography schemes like DSA with Multiple Patterning (MP), DSA with EUVL or DSA with E-beam [5].

By using DSA along with MP, earlier research [8] advocated that it is possible to reduce the number of exposures used in the process, for example a Triple Patterning (TP) process coupled with DSA, could replace a traditional Quadruple Patterning Process (QP), in order to have a less costly technology.

In a hybrid process, where DSA is applied altogether with MP, it is required to perform the DSA-grouping of the polygons as well as the mask assignment. DSA-grouping is the process of selecting which contacts are to be formed together by one template while mask assignment is the process of determining the mask that is to print each polygon.

There are a couple of different options for such a hybrid DSA-MP process. The substrate can be spin-coated with the BCP only after all the exposures have been done, thus self assembly takes place after all the guiding templates have already been printed. In this approach, all contact holes are defined through the self-assembly process and none is directly printed by the lithography process.

Alternatively, one can apply self assembly on each mask separately. In this latter approach, self-assembly can be bypassed for a subset of the masks making it possible to use conventional lithography to print some of the contact holes directly, which gives some flexibility in the size of the printed holes allowing contact/via bar shapes which cannot be printed with a pure DSA process. In this work however, we are assuming none of the masks can bypass the self-assembly, and hence the lithography step only creates the guiding templates, and does not create contact/via holes directly.

There are several important parameters in this problem:

a) **Minimum Grouping distance** (*min_dsa*): Minimum distance that can exist between two contacts in a DSA group. This distance is usually derived from the natural pitch (L_0) of the block copolymer as follows: $min\_dsa = L_0 - contact\_width$.

b) **Maximum grouping distance** (*max_dsa*): Maximum distance that can exist between two neighboring contacts in one DSA group. This is derived from the properties of the block copolymer, because its self-assembly pitch cannot be stretched beyond a certain threshold.

c) **Minimum Lithography Distance** (*litho_dist*): Minimum space that can occur on a single mask.

d) **Maximum DSA Group Size** (*max_g*): Maximum number of contacts that can be grouped together.

e) **Number of masks** (N): number of exposures in the process.

The DSA groups are determined by constraints from the self assembly process itself as well as the constraints of the photolithography which is used to print the guiding templates. While stronger confinement can lead to less placement error for the holes [8], some templates are not optically manufacturable especially in the case of 193i lithography, while they may be available with higher resolution processes like EUVL. Since the grouping of the contacts determines the template shape, some contact grouping configurations are not allowed.

In this work, we assume that only collinear contact holes that are aligned on same horizontal or vertical axis can be grouped together, forming a manhattan one-dimensional array. We make this assumption to guarantee that there is a 193nm process available to print the necessary guiding patterns. In addition, there is an upper limit on the number of contacts that can lie within one group (*max_g*).

In this work we study the different flows that can be used in enabling the hybrid DSA-MP process, highlight their pros and cons and conclude whether sequentially combining Multiple Patterning decomposition algorithms and pure DSA grouping algorithms can work well to deliver a hybrid DSA-MP technology.

2.Alternative Flows for solving the DSA-MP problem

As introduced in section 1.3, having a hybrid DSA-MP process requires a solution which performs the DSA grouping as well as the mask assignment. This problem can be handled by multiple flows as shown in Figure 2.

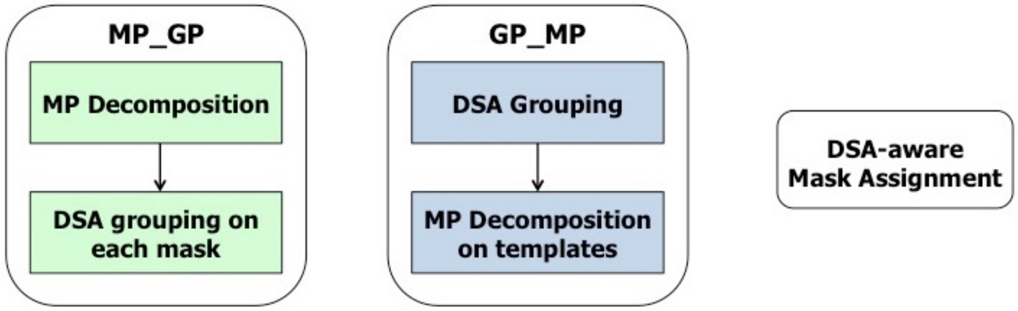


Figure 2. Different flows to do DSA grouping and MP decomposition for hybrid DSA-MP processes.

The first two flows are the decomposition-then-grouping (**MP_GP**) and the sequential grouping-then-decomposition (**GP_MP**) approaches. In **MP_GP**, mask decomposition is performed first, then DSA grouping is performed on each resultant mask separately. Alternatively, in **GP_MP**, DSA grouping is attempted on the complete layer, and then mask assignment is done on the resulting groups. The third alternative is a DSA-aware mask decomposition algorithm. Each of these flows has its pros and cons.

The **MP_GP** approach is friendly to DSA because it inherently favors smaller groups which produce smaller placement errors and a lower defect rates [8], [9], [10], [11]. This is because the mask decomposition essentially scatters the neighboring contacts onto different masks. However it tries to resolve conflicts for a larger number of entities (in comparison to doing the decomposition on the grouped contacts). This can make it harder to get to a conflict-free decomposition result, especially that Triple Patterning and Quadruple Patterning problems are NP-hard problems [12] and thus MP solvers are usually approximate and sub-optimal.

The **GP_MP** approach on the other hand, leads to fewer decomposition conflicts since the decomposition is performed on the DSA groups and not on the individual contacts; however, this flow is not friendly to DSA because it does not give higher priority to the smaller groups which are more reliable from a DSA perspective. In addition, the DSA-incompliance that stems from DSA topology constraints may not be resolved by MP decomposition which is distance-driven.

Finally, a DSA-aware coloring should produce better results, if it considers DSA challenges within the formulation of the problem, but handling the two problems (grouping and decomposition) simultaneously is expected to be a harder problem to solve. In this paper we investigate the results of the first two flows, and we leave the study of the third flow in length to subsequent work.

3.Experiments

In this section we show results of the **MP_GP** and **GP_MP** approaches. Both **MP_GP** and **GP_MP** have been implemented by using existing Multiple Patterning and Directed Self Assembly tools, which are not aware of the process being hybrid DSA-MP.

We ran our experiments on the Via1 layer of AES and MIPS from Open Cores [13], as well as an ARM Cortex M0 processor and a Leon3 Sparc V8 processor. These layouts that have been synthesized, placed and routed using commercial 45nm SOI libraries then sized and scaled.

After modification of the layouts, the via-width is 14nm and the minimum spacing is 21nm. The size of each of the test cases, in number of vias is shown in Table 1.

Test case	Number of vias
AES	48123
CortexM0	35255
LEON3	93474
MIPS	34784

Table 1. Number of vias in test cases.

The assumed parameters of the used DSA process are shown in Table 2. The flows were executed on every test case, for 2 masks [Double Patterning (DP)] and three masks [Triple Patterning (TP)].

min_dsa	20
max_dsa	42
$litho\_dist$	66
max_g	4
$contact\ width$	14
L_0	34
N	2 (DP) and 3(TP)

Table 2. Parameter Values used in experiments [nm].

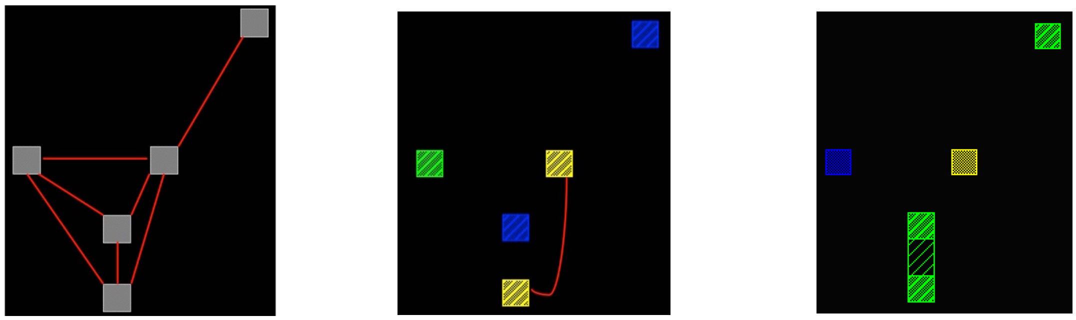
The results of running **MP_GP** and **GP_MP** approaches are shown in Table 3 where the total numbers of spacing violations between the resulting DSA groups on the same mask are shown. It is important to point out that in some cases a DSA group can be composed by a single contact.

On all test cases except one, **MP_GP** outperforms **GP_MP**, from the point of view of producing less number of violations. This is contrary to the expectation discussed in section 2. The reason for that is that the DSA grouping algorithm is rule-based and in many cases when there are several pairs of contacts within the DSA grouping distance, it does not selectively determine groups that would prevent violations and groups them in a sub-optimal fashion. Thus for that type of grouping algorithm, having the contact scattered onto different masks before grouping produces a fewer violations.

Test case	N	MP_GP Violations	GP_MP Violations
AES	2	641	696
CortexM0	2	488	487
LEON3	2	642	680
MIPS	2	315	324
AES	3	6	29
CortexM0	3	7	28
LEON3	3	1	7
MIPS	3	5	13

Table 3. Results of **MP_GP** and **GP_MP** decomposition approaches.

In order to assess the quality of the **MP_GP** and **GP_MP** approaches, we present some layout snippets, along with the results of the two approaches.



(a) Original Snippet. Arrows mark pairs of contacts at distance less than *litho_dist*.

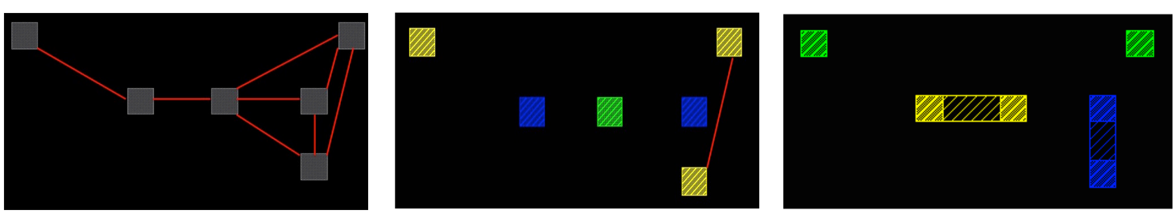
(b) Result of MP_GP and GP_MP. The marker shows a spacing violation between two vias on the same mask.

(c) Conflict-free grouping and decomposition for the same snippet.

Figure 3. Sample of **MP_GP** and **GP_MP** results on snippet #1, with TP. The output shows that the sequential **MP_GP** and **GP_MP** approaches can fail to produce a good solution even for simple configurations.

In Figure 3a, we show a simple layout snippet of five vias. The two approaches **MP_GP** and **GP_MP** got to the same solution, which is shown in Figure 3b. For this snippet, **MP_GP** and **GP_DP** failed to use the grouping to resolve conflicts, resulting in all DSA groups with one contact each. A possible conflict-free solution for the same snippet is shown in Figure 3c.

Two other examples are shown in Figure 4 and Figure 5. It is clear that the sequential approaches **MP_GP** and **GP_MP** failed even on these simple snippets. **MP_GP** failed because the MP decomposer gave equal priority to all pairs of polygons having an intra-distance less than *litho_dist*, without considering that the pairs of contacts that are aligned on the same vertical or horizontal axis could have been DSA-grouped and accordingly assigned to the same mask. The **GP_MP** approach failed because a lot of contacts were within *max_dsa* distance, which led to very complex groups that are disallowed by DSA compliance, due to the lithography and self-assembly constraints. Accordingly, many DSA groups were disqualified, leaving the spacing violations to be handled mostly by the MP decomposition step, which in turn led to a large number of violations. Thus, a DSA-aware coloring algorithm is required to handle the hybrid DSA-MP process since the sequential *MP_GP* and *GP_MP* performed poorly.

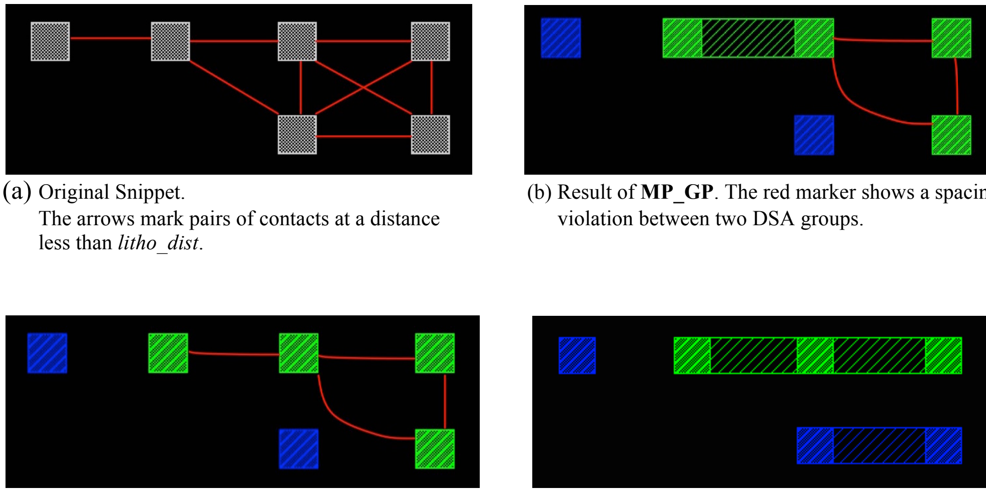


(a) Original Snippet. Arrows mark pairs of contacts at distance less than *litho_dist*.

(b) Result of **MP_GP** and **GP_MP**. The markers show spacing violations between two DSA groups on the same mask.

(c) Conflict-free grouping and and decomposition for the same snippet.

Figure 4. Sample of **MP_GP** and **GP_MP** results on snippet #2 with TP.



(a) Original Snippet.
The arrows mark pairs of contacts at a distance less than *litho_dist*.

(b) Result of **MP_GP**. The red marker shows a spacing violation between two DSA groups.

(c) Result of **GP_MP**. The red marker shows a spacing violation between two DSA groups.

(d) Conflict-free grouping and decomposition for the same snippet.

Figure 5. Sample of **MP_GP** and **GP_MP** results on snippet #3 with DP.

4.Conclusions

In this paper, we have considered the integration of DSA into MP technologies with the objective of saving one mask for a less costly process. We studied two sequential approaches considering MP decomposition and DSA grouping as two independent steps. Results indicate that these two sequential approaches can fail to find a solution to the problem even under very simple layout configurations. Thus, a solution that simultaneously considers the constraints of DSA and those of MP, and can perform DSA-aware mask assignment, is required and will be the focus of our future work.

Acknowledgements

This work was partly supported by IMPACT+ center (http://impact.ee.ucla.edu).

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