ARTICLE IN PRESS

INTEGRATION the VLSI journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

INTEGRATION, the VLSI journal

journal homepage: www.elsevier.com/locate/vlsi

Discrete relaxation method for contact layer decomposition of DSA with triple patterning☆

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A R T I C L E I N F O

Keywords:
Mask and template assignment
Directed self-assembly
Triple patterning lithography
Conflict
Template cost
General layout

A B S T R A C T

Block copolymer directed self-assembly (DSA) is a simple and promising candidate next-generation device fabrication technology, which is low-cost as complement with multi-patterning for contact layer patterning. In this paper, we consider the contact layer mask and template assignment problem of DSA with triple patterning lithography of general layout. To address this problem, first we construct a weighted conflict grouping graph, in which edges with negative weights are introduced, then a discrete relaxation based mask assignment problem is proposed. The integer linear program (ILP) formulation of the discrete relaxation problem is solved for obtaining a lower bound on the optimal value of this problem. In order to improve the lower bound, some valid inequalities are introduced to prune some poor relaxation solutions. At last, the obtained discrete relaxation solution is transformed to a legal solution of the original problem by solving a template assignment problem on the layout graph, which provides an upper bound on the optimal value of the original problem. Experimental results and comparisons show the effectiveness and efficiency of our method. In addition, under the discrete relaxation theory, the quality of our experimental results can be evaluated by the obtained upper and lower bounds. Specifically, the gap between the obtained upper and lower bounds is 0 for most of the sparse benchmarks, and the average gap is 0.4% for dense benchmarks.

1. Introductions

As the pitch size between features shrinking and the number of nodes increasing, manufacture of integrated circuit (IC) layout is more and more difficult. This urges on series of manufacture technologies, such as 193 nm ArF immersion optical lithography and the related multiple patterning lithography, electron beam lithography, block copolymer directed self-assembly, and extreme ultra violet lithography [1–3]. IC layouts consist of patterned lines and holes. The lines define the active device regions, gate electrodes, and the wirings between the devices. The holes define the electrical contacts between the wires and the transistors [4,5]. Some of the above manufacture technologies are popularly used to pattern line features in a layout [6], but the DSA technology is fit for patterning the dense hole features [7]. Especially, in 7 nm nodes distribution of the features on contact/via layer is dense and aligned [8], hence the DSA technique is necessary.

To pattern contact holes by DSA, guiding templates are usually used to form contacts [9,10]. For sparse structure, a number of single-hole templates are used to form contacts. For dense structure, too close templates would generate conflicts [11–13]. To reduce the conflicts, some of the contacts within a short distance would be grouped together in a multi-hole template [11–13]. As shown in Fig. 1(a), the left contact is contained in a single-hole template, and the right two close contacts are grouped in a two-hole template.

However, grouping more than one contacts in a multi-hole template may introduce overlays. For different guiding templates with different shapes or sizes, the overlays are different. Specifically, complex (irregular shape) guiding templates may introduce large overlays and the contained contacts may not be patterned correctly [11]. Hence, during template assignment, the cost of a guiding template should be considered.

Furthermore, for a very dense contact layer layout, the contact layer fabricated by single patterning is unqualified due to a number of conflict errors. Hence the DSA with multiple patterning (DSA-MP) technology is a solid choice, and a crucial problem in DSA-MP is the mask and template assignment. An example of mask and template assignment for DSA with triple patterning (DSA-TP) is shown in Figs. 1(b) and (c). Fig. 1(c) is a template assignment of the layout in Fig. 1(b), where the three colors represent three masks, and the right two contacts are contained in a vertical two-hole template, and a

☆ Research supported by the National Natural Science Foundation of China under Grants 61672005 and 11501115.

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https://doi.org/10.1016/j.vlsi.2017.11.004
Received 14 April 2017; Received in revised form 3 September 2017; Accepted 16 November 2017
0167-9260/

Please cite this article as: Li, X., INTEGRATION the VLSI journal (2017), https://doi.org/10.1016/j.vlsi.2017.11.004

Fig. 1. An example of contact layer decomposition for DSA with TPL. (a) A template assignment for the sparse layout. (b) A dense layout. (c) A mask and template assignment for the dense layout.

conflict is generated between the two green one-hole templates due to the small pitch between them.

Recently, some works concerned the mask and template assignment problem of DSA-MP [12,13], including the mask and template assignment problem of DSA with double patterning (MTADD) and with triple patterning (MTADT). For the MTADD problem, Ref. [13] has obtained good enough solutions for the tested benchmarks comparing with the solutions of the exact integer linear program formulation. However, the solutions still have many unresolved conflicts, although under their conflict spacing setting, the distributions of contacts in the tested layouts are sparse. Therefore, it is necessary to use triple masks for the contact layer with 7 nm nodes. In this paper, we consider the mask and template assignment problem of DSA-TP (MTADT).

For the row structure layout, Xiao et al. [11] proposed three methods and compared their effectiveness. These methods are: 1) color first iterative; 2) group first iterative; 3) shortest path based optimal decomposition. By comparisons, the shortest path based method achieved the best decomposition. For the general layout, Badr et al. [12] first considered the MTADM problem and formulated it as an integer linear programming problem, and proposed a maximum cardinality matching (MCM) based method to quickly obtain a result. However, the method in [12] has some issues. In the aspect of problem formulation, the method in [12] does not consider the template cost, which is different for different types of templates. In the aspect of solution method, Ref. [12] proposed two methods for the MTADT problem. However, since many variables and constraints of template grouping are introduced, the ILP formulation is too complex to fast solve. Moreover, the MCM based method is a grouping first method, and the solution quality is unknown.

In order to improve the quality of decomposition results of the MTADT problem, Kuang et al. [13] considered the simultaneous template optimization and mask assignment problem of DSA with triple patterning. They proposed a look-up table (LUT) based assignment method, which finds all the possible 3-colorable sub-graphs by removing some edges. The method is fast and effective for sparse and small graph. However, since the number of 3-colorable sub-graphs of a graph is exponential, the storage size of LUT would not be scalable for very dense or large graph, and it is time consuming to check the LUT. In order to reduce runtime, the method in [13] does not store and check all 3-colorable sub-graphs. This will lose optimality of the results, and the gap between an obtained solution and the optimal solution is still unknown.

In this paper, we propose a discrete relaxation based decomposition method to solve the MTADT problem of general layout. The discrete relaxation method is a general scheme for dealing with hard discrete optimization problems, which relaxes a hard problem to an easier one, and then the relaxation solution is legalized to a solution of the initial problem [14]. An advantage of the method is that the solution quality can be evaluated in the experiment. The evaluation of a solution is significant for an NP-hard problem. If we know the gap between an obtained result and the optimal value of an instance, then we will know whether the solution is good or not. This scheme has been proposed and used to address the triple patterning layout decomposition problem [14]. However, the discrete relaxation method should be designed carefully according to the feature of an addressed problem.

For the MTADT problem of general layout, our main contributions are listed as follows.

- We sum up general rules for the costs of vertical or horizontal templates with different sizes, and construct a weighted conflict grouping graph.
- Basing on the weighted conflict grouping graph, we propose a novel integer linear program for the MTADT problem, which is not equivalent to the MTADT problem but provides a lower bound on the optimal value of the MTADT problem. Moreover, some valid inequalities are introduced for cutting some no good solutions, and obtaining a better lower bound.
- We propose a template assignment approach to transform a relaxation solution to a feasible solution of the MTADT problem, which provides an upper bound on the optimal value of the MTADT problem. According to the obtained lower bound and upper bound, we can evaluate the quality of our experimental results. Specially, if the upper bound is equal to the lower bound, then we obtain an optimal solution of the MTADT problem.
- Comparisons of experimental results show that our decomposition method is effective. More specifically, the gap between the obtained upper and lower bounds is 0.0% for most of the sparse benchmarks, which shows the optimality of the obtained results. And the average gap is 0.4% for the dense benchmarks, which shows the goodness of the obtained results for dense layouts.

The rest of this paper is organized as follows. Section 2 shows the template types and problem formulation. Section 3 introduces the discrete relaxation decomposition method, and the feasible solution generation method is introduced in Section 4. Experimental results are presented in Section 5, and conclusions of our work are made in Section 6.

2. Preliminaries

In this section, first we introduce the types of the DSA guiding templates, and then we describe the mask and template assignment problem of DSA-TP.

2.1. DSA guiding template

To print contact holes by DSA, guiding templates are needed, which are usually fabricated by conventional optical lithography technology [5]. Thus the resolution is limited by the pitch of guiding templates. For sparse structure, the contact pitch is big enough, hence the contacts can be contained in a series of single-hole templates. But for dense structure, the contact pitch is too small to satisfy the resolution for numerous single-hole templates, and multi-hole template would be used to guide a group of contacts for improving the resolution.

Theoretically, the type of multi-hole template could be of any shape [15]. However, complex guiding template may introduce large overlay and the intended contacts may not be patterned correctly [11]. Such as the diagonal templates (Fig. 2(e)), the local diagonal templates (Fig. 2(f)), or the “L” shape templates (Fig. 2(g)), they cannot be printed reliably, hence the results after printed should be verified by