MASK AND TEMPLATE ASSIGNMENT ON DSA-MP WITH TRIPLE BCP MATERIALS LITHOGRAPHY

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ABSTRACT

In the sub-7nm technology nodes, as the mask cost for printing the dense via layers increases dramatically with conventional lithography techniques, triple block copolymer (triple-BCP) materials for directed self-assembly (DSA) lithography is considered as a promising technology to reduce the mask cost. In this paper, we consider triple-BCP and template assignment for triple patterning lithography with DSA. Firstly, we formulate the problem as a maximum weighted independent set (MWIS) problem, and then use the integer linear programming (ILP) to obtain its solution. Furthermore, to gain a better trade-off between runtime and solution quality, we proposed a modification of the Fiduccia-Mattheyses heuristic method (MCFM) to efficiently solve the MWIS problem. Experimental results verify the effectiveness of our method, and indicate that adopting three different BCP materials can dramatically reduce conflict numbers compared with existing works using double BCP materials.

INTRODUCTION

With continuous shrinking of the technology node, directed self-assembly (DSA) of block copolymers (BCP) with multiple patterning (MP) has emerged as an attractive alternative on the high density layers, because it can reduce the manufacturing cost for via layers [1]. DSA uses a special material called block copolymers (BCP), after the annealing process, the three monomers are separated, while fewer monomers form cylinders that can be used to create tiny holes and thus vias.

To generate vias at specified positions, the guiding templates surrounding vias would be required. However, most of the previous studies only considered a limited number of alignment and adjacent vias as manufacturable with multi-hole templates. Due to the limited resolution of guiding templates, the multiple patterning lithography (MPL) is adopted to generate the template, resulting in the hybrid lithography DSA-MP [1]. Some research has developed algorithms to solve the problem of template and mask assignment in DSA-MP [2], [3], [4], [5]. For example, Ou et al. proposed an ILP formulation and a bound approximation algorithm to solve the ILP problem more efficiently [3]. These results indicate that using double-BCP remarkably outperforms a single-BCP. However, these works are still subject to low manufacturability due to the limited type of feasible guiding templates. In order to maximize the flexibility of DSA-compatible pattern matching, we proposed a concept of using three different BCP materials in DSA-MP in this paper. As shown in Figure 1, by carefully choosing the second BCP material and the third BCP material, the number of feasible guiding templates could be tripled.

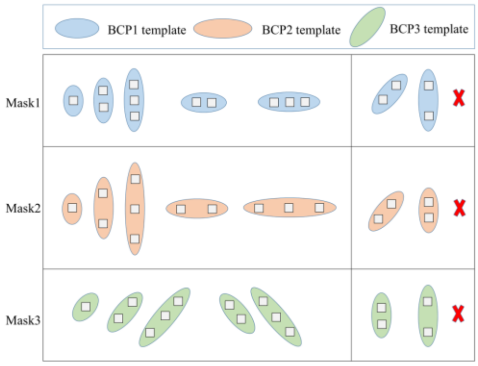

Figure 1. Feasible guiding templates considered in this work. Each BCP material can only be applied to multi-hole template with the same pitch.

In this paper, we propose the first work of guiding template assignment and layout decomposition simultaneously by using three different BCP materials in DSA-MP. The overall flow of our algorithm is illustrated in Figure 2. The major contributions of this work are summarized as follows:

- We present the first work to consider triple-BCP materials in the DSA pattern assignment and triple patterning lithography decomposition process.
- We formulate the triple-BCP decomposition problem as a maximum weighted independent set (MWIS) problem and solve it by using an integer linear programming (ILP).
- To achieve a better trade-off between runtime and solution quality, we propose a modification of the Fiduccia-Mattheyses heuristic method (MCFM) to solve the MWIS problem rapidly.
- Experimental results verify the effectiveness of our method, and indicate that adopting three different BCP

materials can dramatically reduce conflict numbers compared with existing works of using double BCP materials.

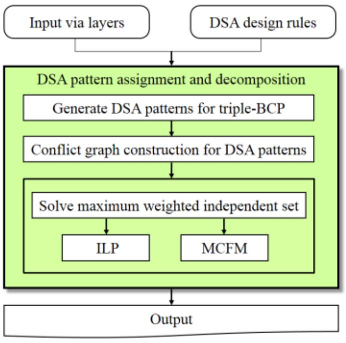

Figure 2. Our algorithm flow.

TRIPLE-BCP PATTERN ASSIGNMENT AND DECOMPOSITION ALGORITHM

A. DSA Pattern Assignment and Decomposition

The pitch-range (PR) for the BCP material can be denoted as $PR = [L_{min}, L_{max}]$[1]. Vias can be grouped in the same DSA pattern if their distance is within PR. In DSA pattern assignment and decomposition, we need to design vias to different DSA patterns, and then determine which mask these patterns have been decomposed to. For triple-BCP DSA, the pattern assignment and decomposition problem is fairly different from the conventional approach. The maximum size of vias in a DSA pattern is limited to three in this work in order to improve the yield.

B. Conflict Graph Construction for DSA Patterns

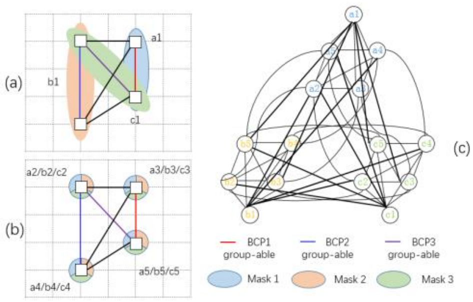

Figure 3. (a) Size 2 DSA patterns for the vias. (b) Size 1 DSA patterns for the vias. (c) Conflict graph for DSA patterns.

At first, we enumerate all the possible DSA patterns for the vias, and then construct a new conflict graph (CG) for the DSA patterns. In a via layout, an edge is added between two vias if their distance is less than the minimum lithography distance (Min-litho). As shown in Figure 3(a) and 3(b), these DSA patterns are denoted as the vertices in Figure 3(c), the weight of each vertex is assigned as the number of vias in the DSA pattern. Because of the maximum number of vias in a DSA pattern is limited to three in this work, so the weight of all vertex at most three. As shown in Figure 3(c), a conflict edge is increased between two vertices when they overlap with each other in Figure 3(a) and 3(b), furthermore, an extra conflict edge will be added between two vertices with the same BCP material if they violate the minimum lithography distance design rules.

C. ILP Formulation

Because the weight of vertices denoted the number of vias in the DSA pattern, we can maximize the total weight of the selected vertices to maximize the number of vias printed by DSA. The ILP formulation is shown in Equation (1), where x_{v_i} is a binary variable. $x_{v_i} = 1$ indicates that vertex v_i is selected, and w_{v_i} indicates the weight of vertex v_i. The constraint (1b) is used to avoid violation of DSA design rules, at most one of the DSA patterns can be selected when they are connected by a conflict edge. In a CG, v_i indicates the vertex in conflict graph, and E indicates the edge set of the conflict graph, N indicates the number of vertices in the conflict graph.

$$\max \quad \sum_{i=1}^{N} w_{v_i} \times x_{v_i} \tag{1a}$$

$$\text{s.t.} \quad x_{v_i} + x_{v_j} \leq 1, \qquad \forall \{v_i, v_j\} \in E, \tag{1b}$$

$$x_{v_i} \in \{0,1\}, \qquad i = 1,2, \dots, N \tag{1c}$$

D. MCFM Algorithm

In MCFM, we first use the greedy algorithm to obtain an initial solution of the MWIS problem. In Algorithm 1, d_{v_i} indicates the degree of the vertex v_i, $N_G(v_i)$ is the set of vertices adjacent to v_i, S is the independent set, and W is the weight set. Algorithm 1 describes the details.

Algorithm 1: Initial Solution Generation

Input: All connected component of $CG(V, E, W)$;

Output: Initial solution x^0 of the MWIS problem;

1: Set $S = \emptyset, T = V$, compute $d_w(v_i, G) = \frac{d_{v_i}}{w_{v_i}}$ for all v_i;

2: **while** T is non-empty **do**

3: Selected a minimum $d_w(v_i, G)$ vertex, v_i;

4: Set $S \coloneqq S \cup \{v_i\}$ and $T \coloneqq T - v_i - N_G(v_i)$;

5: **end while**

6: **return** $x^0 = (x_{v_1}, \dots, x_{v_i}, \dots, x_{v_n})$.

Definitions

(1). Distance measure: For any $x, y \in \varphi$,

$$\varphi = \{x = (x_1, x_2, \dots, x_n) | x_i \in \{0,1\}, ie., x \in \{0,1\}^n\}.$$

let $I = \{i | x_i \neq y_i, i = 1, \dots, n\}$. The distance between x and y is defined as $dist(x, y) = |I|$.

(2). Neighborhood: For any $x = (x_1, x_2, \dots, x_n) \in \varphi$, the neighborhood of x is defined by

$$N(x) = \{y \in \varphi | dist(x, y) \leq 1\}.$$

(3). Neighborhood gain: Define the $gain(i, x)$ of a vertex i as the objective value of the MWIS problem. The value of gain would increase if the vertex i is moved from its current subset to the complement subset, which is defined as follows:

TABLE I EXPERIMENTAL RESULTS

Benchmarks	#V	ILP(double-BCP)		ILP(triple-BCP)		MCFM(double-BCP)		MCFM(triple-BCP)	
		#Cft	CPU(s)	#Cft	CPU(s)	#Cft	CPU(s)	#Cft	CPU(s)
dp1-Via1	307739	24420	150.12	19299	198.92	17967	86.94	16234	118.90
dp1-Via2	256885	6966	762.49	4854	1148.87	9198	80.91	8399	95.09
ed1-Via1	400123	1545	775.67	767	1308.46	5978	263.87	5662	338.51
ed1-Via2	301607	4807	305.60	3443	408.37	7485	132.73	6271	173.72
fft1-Via1	99509	5794	34.29	4327	43.69	5064	11.25	4560	15.51
fft1-Via2	90114	2658	278.73	1887	362.75	3340	12.12	3084	13.56
mm1-Via1	429664	24693	194.25	18861	252.34	21645	180.98	19045	280.35
mm1-Via2	341789	7740	275.38	5160	366.50	11591	149.79	10565	179.99
pb1-Via1	79635	4061	23.47	3109	28.77	3404	7.53	2921	12.11
pb1-Via2	59110	2385	208.47	1863	249.69	2445	7.49	2120	8.38
Total	1194599	85069	3008.47	63570	4368.36	88117	933.61	78861	1227.74
Ratio		1.34	0.69	1.00	1.00	1.12	0.76	1.00	1.00

$$
\begin{aligned}
gain(i,x) &= f(y) - f(x) \\
&= f(x_1,\dots,1-x_i,\dots,x_n) - f(x_1,\dots,x_i,\dots,x_n) \\
&\begin{cases} -w_i, & if\ i \in S. \\ w_i - \sum_{j\in N_G(i)\cap S} w_j\,, & if\ i \in S^*. \end{cases}
\end{aligned} \quad (2)
$$

In Equation (2), S is an independent set, and S^* indicates that complement set of the independent set. MCFM iteratively moves an unlocked vertex with the highest gain from its current subset to the complement subset. Then, we use the solution x^0 as the initial solution of the MCFM algorithm. We using *UL* indicates the unlocked vertices.

Algorithm 2: MCFM

1. Generate initial solution $x^0 = x$ by Algorithm 1.
2. **repeat**
3. Set *UL*={*1,2,…,n*}, $x_{max} \coloneqq x, and\ x_{ini} \coloneqq x.$
   Calculate $gain(i,x)$, for all $i \in UL$.
4. **repeat**
5. Let $gain(j,x) = max\{gain(i,x) : i \in UL\}$.
   Set $x' \coloneqq (x_1,\dots,1-x_j,\dots,x_n)$.
6. if $f(x_{max}) < f(x')$ then
7. Set $x_{max} \coloneqq x'$ and *UL:= UL* \{*j*}.
8. if $f(x_{max}) = f(x')$ then
9. Set *UL:= UL* \{*j*},calculate $gain(i,x')$.
10. else
11. Set $x \coloneqq x'$.
12. **until** $|UL| \leq n - p.$
13. Set $x \coloneqq x_{max}$.
14. **until** $f(x_{max}) = f(x_{ini})$.
15. **return** x_{max} as a maximizer of MWIS problem.

EXPERIMENTAL RESULTS

We implemented our algorithms with C++ programming language and conducted experiments on a Linux system with 3.7 GHz CPU and 4 GB memory. The benchmarks provided by Li et al. [4] are used to verify the performance of our proposed algorithm. We used Cplex as the ILP solver. The via width and minimum via spacing are set as 10nm and 20nm, respectively. The minimum mask spacing is set to 100nm. The maximum grouping size of vias in a DSA pattern is set to 3. We assume the width of BCP pitch-range is fixed 22nm according to [1], and the appropriate pitch-ranges for BCP1, BCP2 and BCP3 are (40nm, 62nm), (60nm, 82nm) and (56nm, 78nm).

The experimental results are shown in TABLE I, where "#V" gives the number of vias of each benchmark, "#Cft" lists the number of conflicts. The conflicts of triple-BCP have been reduce 34% than double-BCP which using ILP to solve MWIS problem. In addition, the conflicts of triple-BCP have been reduce 12% than double-BCP which using MCFM algorithm to solve it. The experimental results also indicate that triple-BCP outperforms double-BCP in reducing the conflicts and mask costs.

CONCLUSIONS

In this paper, we considered triple-BCP materials in the DSA pattern assignment and triple patterning lithography decomposition process. Experimental results indicated that, adopting three different BCP materials can dramatically reduce conflict numbers compared with using double-BCP.

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