COMPUTER-AIDED DESIGN ON THE VLSI 45° -MASK COMPACTION*

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ABSTRACT

In this paper, we combine 1-D compaction with reshaping—a new action, to improve the result of compaction. Our algorithms change layout elements' shapes automatically according to some criteria and make neighboring layout elements' shapes as similar as possible. The more similar they are, the more compactable space we can obtain. The main part of our compaction is reshaping. If elements of certain 45°-layout can be reassigned their geometric shapes, we reshape them in order to gain more compactable space. Some experimental results of this 45°-compactor with and without reshaping of both manhattan and nonmanhattan-45° layouts are shown.

INTRODUCTION

Recently, computer-aided design for VLSI chip implementation has been investigated extensively. Compaction algorithm is of importance in the mask layout of VLSI chip design, but 1-D compaction has no further impressive progress and 2-D compaction is proved as an NP-complete problem [1]–[3]. With separate X- and Y-compactions for 1-D compaction, the designer knows all elements will be moved only along the direction of compaction. With two-dimensional compaction, however, the designer can no longer easily predict the outcome because of the additional degree of freedom. So, it seems to be stuck in predicament for compaction desinger. Reshaping will be the turning point of layout compaction, we try to combine traditional one dimensional compaction with reshaping to reach some amazing goal.

The most essential step for a compactor is to select a fit-for data structure favorable to the data of mask extraction. For the geometrical features of layout masks, spatial data structures will be candidates for our choice. Comparisons between spatial data structures and our considerations will be described. Some spatial relationships between layout tiles will be defined for clarifying our algorithms. Then, we will discuss the one-dimensional moving strategy. After that, we will present the reshaping algorithm. Some experimental results and discussions will be summarized.

TRAPEZOIDAL CORNER STITCHING

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The varieties of the shapes of layout elements are wide and complicated, not like those rectangle layouts traditional compactions deal with. Using symbolic layouts will include a lot of new symbols, the efficiency of the compactor will slow down. Contrastly, mask layouts meet our needs. Mask layouts to be cooperated with a suitable spatial data structure are the best combination for our compaction. So, we use trapezoidal corner stitching as the data structure of our compaction [4]–[6].

1-D MOVING

The reshaping based on modified traditional 1-D compaction will lead to satisfying result. At the same time, it avoids involving the complexity of 2-D approaches. Our compaction contains two individual parts: reshaping and one-dimensional moving. We modify the scan-line algorithm into our 1-D moving algorithm. Unlike original scan-line approach, 1-D moving doesn't need such a sophisticated computation for distance the scan line should move. The chief reason for that is our 1-D moving doesn't construct constraint graphs, and we fully take advantage of our data structure-trapezoidal corner stitching to gain the spatial relations between neighboring tiles instead of time-consuming computing.

The task of 1-D moving is to pick up an proper tile and get the distance it can move, then move it and all tiles associated with it to new locations. The problems for our 1-D moving approach are as following:

- How to decide which tile to be chosen?
- In there an easy way to get the information about neighborhoods around the tile chosen?

We will discuss solutions for these problems below.

1. Tile Sifter

The function of tile sifter is to choose a proper tile for 1-D moving. What is a proper tile?

A proper tile is a tile no un-moved tile blocks its way to move. All tiles left to a proper tile have been handled, hence, a proper tile is free to move left. Obviously, the direction to select a proper tile will be from left to right, just like the direction of a scan line movement. Because 1-D moving doesn't need such sophisticated processes, and it must match our data structure, we design a scan window for the selection task.

2. Scan Window

Expanding the width of a scan line (it is zero) to non-zero gets a scan window. The width is set to the minimum width the technology allows. A movement unit of the scan window is the same as its width, the minimum width. A scan window will be passed through all data planes at the same location. A scan line in constraint-graph approach gets the information of neighboring tiles, a scan window in our tile sifter extracts a proper tile for moving. Fig. 1 illustrates a scan window being passed through different layers.

Fig. 1 Scan window

Area searching will be used to extract a proper tile within the scan window through all layers. On the same layer, area searching extracts tiles from left to right and from top to bottom. Every tile will be checked two qualities: solid tile or space tile; and whether auxiliary bit equals to 1 or not (an auxiliary bit will be set to zero after moving, otherwise, set to 1).

3. Non-Horizontal Tile

The traditional method for doing 1-D compaction is to move layout elements and stretch horizontal elements instead of moving them. In 45° mask layouts, tiles cannot be classified simply into two kinds: vertical and horizontal tiles, because shapes of tiles are full of variety. In addition to vertical and horizontal tiles, we define another type - non-horizontal tile:

Definition 4.1: Given tile A, $RUT(A)$ (or $LUT(A)$) is tile B and $RLT(A)$ (or $LLT(A)$) is tile C. Then tile A is a non-horizontal tile, if:

- $(B \neq NULL) \text{ and } (B_20 \leq A_00), (A_10 \leq B_30)$
- $(C \neq NULL) \text{ and } (C_00 \leq A_20), (A_30 \leq C_10)$

4. Design-Rule Window

The second problem we want to solve is moveable distance for the tile chosen by tile sifter described above. In fact, not only a tile will be moved, all tiles connected to that tile chosen by tile sifter will, too. It is unnecessary to use sophisticated computation to get moveable distance, simple one is enough for 1-D moving.

For a tile on some layer (e.g. poly layer), there are several constraints between this tile and other tiles on different layers (e.g. poly-poly, poly-n diffusion and poly-p diffusion). A design-rule window is created for specific design rule constraint, there are different design rule windows for different constraints in different layers.

5. Creation of Design-Rule Window

A design-rule window is not like a scan window, it doesn't move. The right edge of a design-rule window is extended left edge of a tile, the length of extra portion depends on the concerned constraint. The width of a design-rule window also depends on the concerned constraint. As shown in Fig. 2, a poly tile owns two design-rule windows with different sizes on different layers such as poly-n_diffusion.

Fig. 2 Design-rule window

6. Function of Design-Rule Window

Because design-rule windows are created under design rules, there must be no solid tile found within windows. If it does, it violates the design rules in original layout. Our compactor informs users of that fact and stops proceeding. Otherwise, area searching will extract all space tiles in windows of all relative layers, and the minimum value among all minimum widths of space tiles will be the moveable distance for this tile which the design-rule window belongs to. A minimum width of a tile is the smaller length between top edge and bottom edge of it. Fig. 3 shows the moveable distance for a tile on a single layer.

Fig. 3 Moveable distance of A (in a layer) = $\min(\text{width}(B), \text{width}(C), \text{width}(D), \text{width}(E), \text{width}(F))$.

Because the feature of corner stitching - no space tile will be next immediately to a space tile, a space tile must lies between solid tiles. All space tiles found in a design-rule window created by one solid tile, whose left neighbor tiles are other solid tiles, that is why the minimum width of all space tiles lying within design-rule windows is the moveable distance for a concerned tile.

7. Overall Moveable Distance

All tiles connected to the tile chosen by tile sifter must be taken into account for overall moveable distance, because these tiles will be disconnected to it at new location after moving that chosen tile. There are four kinds of such connected tiles:

- connection tiles on the same layer,
- connection through contacts, and
- connection through MOSes.

RESHAPING

Reshaping is one of novel ideas used in our compactor. What is reshaping? In brief, reshaping gives one layout element a new shape and changes its shape into more compactable one. It is shown in Fig. 4. Without doubt, after such rearrangement we can compact entire chip into much denser size than before. Problems face with us are:

- Reshaping will affect tiles' locations, so not all tiles can be reshaped. How to decide whether one tile is reshapeable or not is an essential problem.
- What is the optimal new shape which a tile should be reshaped? What is the criteria applied to reshape?

Fig. 4 Basic idea of reshaping, (a) before reshaping and (b) after reshaping.

As usual, our ideas are presented below.

1. Conditions to Reshape

We conclude the following conditions. If a tile meets these conditions then it is not reshapeable. If we concern tile A, these conditions are:

- The shape of A is not S1, S5 or S9. Because, reshaping does no special good for tiles right to tile A according to the reshaping method we use, it will be described later.
- Connection tiles through contacts or MOSFETs will be not connected to the tile after reshape tile A. This is obvious, disconnection will make circuits malfunctioned.
- Connection tiles on the same layer cannot follow the movement when reshape tile A.

2. New Shape Determining

Determining a new shape is classified into two aspects: local reshaping and bending reshaping. A local reshaping changes a tile's shape slightly and a bending reshaping bends a tile into two tiles.

a. Local Reshaping

Local reshaping is some kind of "divide and conquer" strategy, and it cuts a layout element into several smaller tiles and reshapes them. Local reshaping wants to change least and reaches the expected goal of reshaping. The first step of local reshaping is to cut a tile into some single-neighbor tiles. A single-neighbor tile is a tile which owns one and only one left neighbor tile and right neighbor tile.

b. Single-Neighbor Tile

We take advantage of the feature of corner stitching to cut through a tile into several single-neighbor tiles. Just delete all space tiles extracted from a tile's left neighborhood, it will cut that tile into single-neighbor tiles automatically. Fig. 5 shows a result of deleting space tiles left to one tile.

Fig. 5 Cut into single-neighbor tiles.

c. Best Shape to Reshape

For two neighbor solid tiles (e.g. tile A and tile B in Fig. 6(a)), the best situation for compaction is the right edge of tile A and left of B have the same declination angles, like tile B in Fig. 6(b). Of course, the right edge of tile B must follow declination of the left edge and tiles right to tile B can be moved left further. Processes described above can be implemented easily.

Fig. 6 Best shape to reshape, (a) before reshaping and (b) after reshaping.

If top equals to bottom then it is unnecessary to change the shape, the original shape is good enough for compaction. BL(t_i) is to extract the space tile immediately right to t_i , and to compute the length of top and bottom edge of the space tile, LENGTH(t_i). By top and bottom, we can easily get the same declination angles described above. Because the same declination angles result in that top and bottom of the space tile must be equal.

d. Bending Reshape

In some cases, an unreshapeable tile will waste a remarkable uncompactable space. In Fig. 7, tile C is unreshapeable with tile B, it leaves a large uncompactable space between tile D and C.

Fig. 7 An example for an unreshapeable tile.

Bending reshape is performed on such a situation, it replaces a tile with two tiles - one vertical and one horizontal. In other words, it bends a tile. Fig. 8 shows bending reshape on Fig. 7. The space between tile C and D as shown in Fig. 7 is compactable as given in Fig. 8. That is bending reshape.

Fig. 8 Tile C is compactable after bending reshape.

e. Conditions to Bending Reshape

The conditions which must be checked before bending reshape on a tile are as follows:

- The tile is unreshapeable for local reshaping.
- The shape of the tile is S5 or S9.
- Connection tiles through contacts or MOSFETs are still connected to the tile after reshaping tile A.
- The height of a tile is no less than double minimum width the technology permits.

We only concern two types of shapes that often cause uncompactable space described above, that is S5 and S9. In the same time, we don't need to check those connection tiles on the same layer, because the ends of the tile to be reshaped will not be changed. It is important to assure that the height must be no less than double minimum width, otherwise, it will violate the design rules after replacing it with two tiles.

f. Methods of Bending

Simply, we delete an old tile then insert two tiles, one horizontal and one vertical (as shown in Fig. 8).

EXPERIMENTAL RESULT

We design several simple layouts to test our algorithms. We test in two phases: one does reshaping and one doesn't. Detailed results on this work are described in Table 1.

Reshaping is optional operation, if user needs faster result or 45° masks are few, it can rule out the reshaping part—just do 1-D moving part.

Of course, our compaction is not perfect. Regular layouts limit the function of reshaping, that is because the shapes of masks in regular layout are very similar. Since the critical situation is manhattan layout, all tiles are shape S1 in manhattan layout. So, it is unreshapeable according to our algorithm. By our observations, non-manhattan layouts are likely to be reshaped into manhattan layouts. The chief reason is the contours of all chips are rectangle.

Table 1. 1-D Moving and Reshaping Result

Example	#Tiles	S_b	no reshaping			reshaping		
			N_m	S_a	CPU [secs]	N_m	S_a	CPU [secs]
S0127	32	1538	20	1041	17.33	23	665	32.35
S3061	49	2095	47	917	30.59	23	715	35.44
S3063	40	1651	21	1139	10.81	11	1132	8.81
S3181	50	1826	29	1624	12.88	23	931	17.00
S3182	46	1921	10	1777	6.57	12	1633	11.80
S3103	89	5172	51	2481	25.74	46	2422	37.91
S0602	85	31178	132	19969	220.87	196	10165	361.82

#Tiles : the number of tiles within an example.

S_b : space area before compacting [λ^2].

S_a : space area after compacting [λ^2].

N_m : the number of moved tiles.

CONCLUSIONS

In practical applications, non-manhattan layout is more useful and preferable than manhattan layout. In addition to its flexibility, it produces denser layout area than manhattan layout. In nowadays manufacture technology, 45° masks are available. So, compactors which can deal with 45° layouts are necessary. In this work, we present a new 1-D compactor and it can accept both manhattan and 45° mask layouts. At the same time, 45° masks provide a great chance to involve a new action. That is the most important feature of our compaction-reshaping.

Reshaping really improve the results of compaction in our experiments, but it is limited by some conditions. And our criteria of reshapeability-check are not sophisticated enough to handle all possible cases, there are a lot of cases we can not deal with and that degrade the power of reshaping. Nevertheless, reshaping should be an easier approach to compaction design. It doesn't need involve the complicated situations of 2-D compaction, but obtains more denser area than traditional compaction does.

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