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Abstract. In the paper silicon on insulator layout decomposition algorithms for the double patterning lithography on high performance computing platforms are discussed. Our approach is based on the use of a contradiction graph and a modified concurrent breadth-first search algorithm. We evaluate our technique on both real-world and artificial test cases including non-Manhattan geometry. Experimental results show that our soft computing algorithms decompose layout successfully and a minimal distance between polygons in layout is increased.

Keywords: VLSI, Layout, Double Pattering, Parallel Algorithms, High-Performance Computing, Radiation Hardening.

1 Introduction

Collective awareness systems for sustainability and social innovation are information and communications technology (ICT) platforms using electronic components and networks to drive social innovation. Chernobyl (1986) and Fukushima (2011) nuclear incidents demonstrate an increasing role of radiation hardening for emergency systems, especially for very-large-scale integration (VLSI) chips. Design of electronic devices resistant to damage caused by radiation requires new approaches. Reliability is the main silicon on insulator (SOI) technology advantage in a comparison with bulk-silicon technology [1]. However, floating body effect is the major parasitic effect in SOI technology. It results in circuit instabilities. In order to overcome this negative effect multi-gate transistors were proposed [2]. The use of pi-gate, sigma –gate transistors etc. results in non-Manhattan layout topology.

Currently, double and multiple patterning technologies play an important role because the extreme ultraviolet lithography (EUV) has been delayed for the emerging technology nodes. For the multiple patterning technologies layouts are decomposed into two or more masks. Fig. 1 demonstrates a layout decomposition case for double patterning. In [3] the sequential algorithms based on a conflict graph and integer linear programming were discussed. In [4] the sequential algorithms based on a contradiction graph and graph coloring were proposed. The contradiction graph
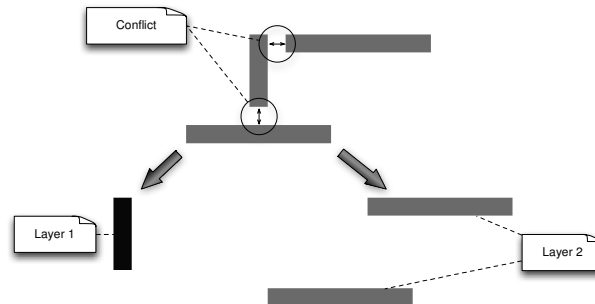
Fig. 1. An example of the layout decomposition for double patterning technology. Layer 1 and Layer 2 are layout layers after decomposition.

accumulates information about contradictions between requirements of minimal distance between polygons and negative diffraction effects for adjacent objects. The approach proposed in [4] was implemented in the TPLConverter program [5]. However, high-performance computing platforms are requires for SOI layout decomposition for double patterning technology because of non-Manhattan layout and huge size of layout data file. However, the application of sequential algorithms for high-performance computing platforms results in the decrease of computing productivity [6]. Parallel algorithms are required for these computing systems.

In [7] concurrent algorithms of the VLSI layout decomposition for double pattering were proposed. However, these algorithms are valid for Manhattan layouts only.

In this article, we propose methods of SOI VLSI layout decomposition for double patterning. In comparison with the algorithms [7] these methods can be applied for both Manhattan and non-Manhattan layouts including H-transistors, O-transistors etc. The proposed algorithms were implemented in ParallelDPLayout Migrator software for high-performance computing systems. Preliminary experimental results for artificial and real-world tests are outlined.

The rest of paper is structured as follows. The next Section reviews collective awareness platforms features. Section 3 presents our methods for layout decomposition for double patterning. We discuss our experimental results in Section 4. Finally, conclusions are derived in Section 5.

2   Relationship to Collective Awareness Systems

The coming revolution in personal and community risk awareness is based on collective awareness platforms. Chernobyl and Fukushima nuclear incidents showed a danger of radiation for a person and a community. In addition, many radioactive isotopes are used in industry and health care. A radiation level can be monitored by individual devices and data about radiation are collected. Neris [8] project has started in 2008. Safecast project [9] has started in 2011. In 2012 more 3 million radiation data points were collected using individual devices.

However, commercial devices can be damaged or malfunctioned because of radiation. Special radiation hardened electronic devices have to be used in emerging collective awareness platforms. SOI [1] including silicon on sapphire (SOS) technologies were developed for radiation-hardened applications. SOI devices are more reliable for the applications in emerging systems. Another way to do radiation hardened circuits is redundancy. But this technique increases area of a chip design. However, some negative effects hinder their wide applications.

In particular, floating body effect results in variation of delay time, circuit parameters etc. In order to overcome these deficiencies multi-gate transistors are used. Many multi-gate transistors have non-Manhattan layouts that realize in a non-Manhattan layout of chips. In addition, layout data file size is increased that result in huge computational efforts to manipulate by the data. Some files to be processed have to be divided and special methods to verify, decompose or to migrate have to be used for these layouts.

High performance computing is one of promising solutions for the mentioned above problem. However, new methods to process layout and then modify them for a target technology are required.

In this paper our focus is on layout decomposition for double patterning technology while the proposed layout processing methods can be applied for VLSI routing, layout migration, verification etc.

3 Concurrent Algorithms for VLSI Layout Decomposition for Double Patterning

3.1 Concurrency during Layout Processing

Special techniques are requiring handling a non-Manhattan SOI layout including multi-gate transistors with circular structure. We propose a special data structure for the concurrent VLSI layout processing. Fig. 2 illustrates our approach for a layer of a circular structure transistor (O-transistor).
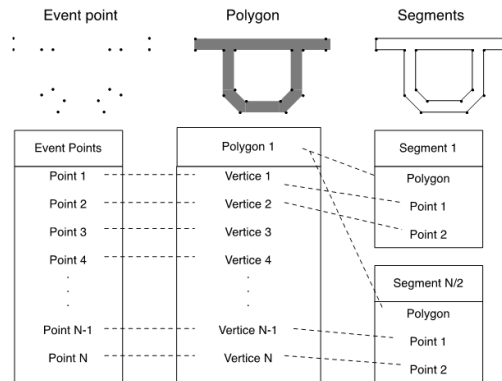
Fig. 2. An example of our data structure for the SOI VLSI layout processing.
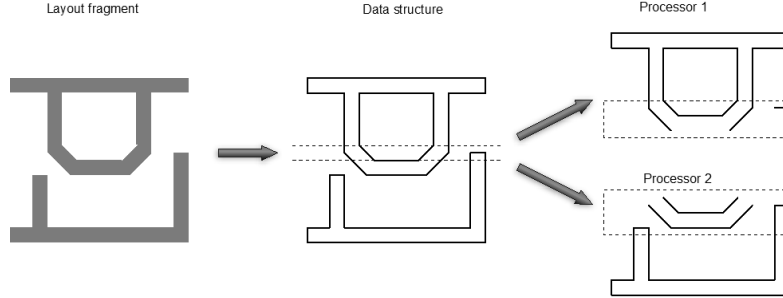
Fig. 3. An example for the two processors case.

The VLSI layout represents a set of polygons. Each polygon consists of a set of segments. Each segment is stored as two references to boundary points. Every point is stored in the "events points" array. This data structure allows us to describe non-Manhattan layout.

Our algorithm assumes the high-performance computer (HPC) platform architecture to be a one-dimensional mesh of processors. Each layer splits to horizontal bars. The number of horizontal bars is equal to the number of processors. To avoid conflicts in adjacent bars they overlay each other. Therefore, one geometric object splits to two features and two overlapping ones are assigned to two different processors to be decomposed. Fig. 3 illustrates our approach for the test layer case including F- and O-transistors for two processors. We apply our approach for layout decomposition for double patterning. However, this approach can be expanded for compaction and verification of SOI VLSI layouts as well.

3.2 Constraint and Contradiction Graphs Construction

We propose a modified sweep line algorithm to construct constraint and contradiction graphs. Each vertex in constraint and contradiction graphs is crisp and corresponds to a polygon in a layout layer. Each edge in a constraint graph is crisp and depends from spacing constraints for objects in layers. A contradiction graph is a fuzzy graph [10]

$$\sim G=(V, \sim E) \tag{1}$$

where V is the node set, ~E is the fuzzy edge set, characterized by the matrix of membership functions depending from the double patterning technology parameter $\mu_E(x)$.

If a distance x between two segments related to different polygons is smaller than the double pattern technology parameter the correspondent edge and its value defined by the membership function $\mu_E(x)$ are added to a contradiction graph.
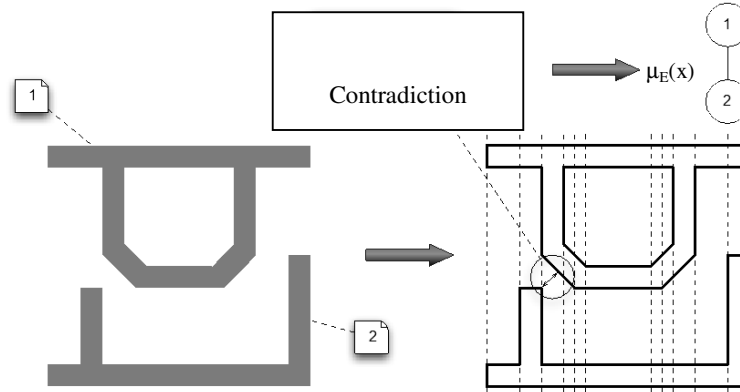
Fig 4. An example of the contradiction graph construction flow.

The contradiction graph accumulates an information about all contradictions in a given layout and a level of the contradiction according to the membership function for double patterning technology. Fig. 4 illustrates our approach for our test layer case including F- and O-transistors.

3.3 Parallel Layout Decomposition Algorithm

The parallel algorithm for the layout layer decomposition is discussed below. This algorithm based on testing bipartiteness for α-cuts family of the contradiction graph

$$\mu_E\,(x) \geq \alpha, \tag{2}$$

where the α-cut of a contradiction graph is the crisp graph.

If the corresponding crisp graph is bipartite this layer could be decomposed into two new ones for the current α-cut.

We propose a modified concurrent breadth-first search algorithm to test bipartiteness of the α-cut of a contradiction graph. For the current α we can find either two-coloring for the graph or an odd cycle for non-bipartite graph in linear time. If the algorithm did not find an odd cycle, then the α-cut of the graph is bipartite according to [11].

Our algorithm is given below.

```
Input: A graph ~G, α_min, α_max.
Output: All design alternatives, a coloring of the α-cut of ~G
and α.
```

Begin
```
Step 1. α=α_min.
   Repeat
```

```
   Step 2. The crisp graph G is constructed for the current α.
   The current color is equal to 1. Assign 1 color to the
   source vertex.
   Repeat
   Color all the neighbors with 2 color.
   Color all neighbor's neighbor with 1 color.
   If an edge from i to j exists and destination j is colored
with the same color as i
   Then design alternatives for the current α-cut are collected
and α is increased.
   Else
   Until all vertices are colored. If all vertices are colored
Then Step 3.
   Until α<α_max
Step 3. Our algorithm stops when a design decision for double
patterning technology is found or α=α_max. In the last case,
recommendations  for  multi-patterning  technology  are  given
according the found minimal number of the required colors.
End
```

Fig. 5 illustrates our approach for one design alternative. The metal layer for the 4AND cell layout and the corresponding crisp graph are shown on Fig. 5, a. Fig. 5, b shows the corresponding crisp graph that has been colored using two colors. Fig. 5, c shows the metal layer of the 4AND element layout after decomposition. The first layer polygons are shown as grey objects, while the second layer polygons are shown as black objects.

4   Experimental Results

The proposed approaches were implemented using C++ programming language on Cent OS 5.5 operating system. Additionally, we use Boost libraries and OpenMP framework.

a)   b)   c)
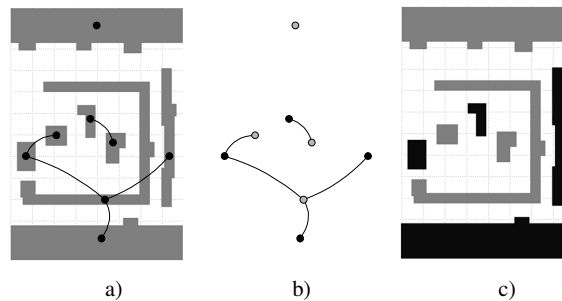
Fig 5. The 4AND element metal layer decomposition for double patterning: a – the layout layer and the α-cut of the contradiction graph; b – the α-cut of the contradiction graph after coloring; c – two new layout layers (the first layer is shown as grey objects, the second layer is given as black objects).

Table 1 summarizes our simulation results for our artificial and real-world tests. We evaluate our solutions with respect with solution quality. We use the relative minimal distance between the polygons after the decomposition that is calculated as the ratio of the minimal distance between the polygons of the layer i ($i = 1, 2$) after the decomposition to the minimal distance in the critical layer before the decomposition [7].

Table 1. Test cases parameters.

Layout	Polygons, total/ Layer 1/Layer 2	Relative minimal distance, Layer 1	Relative minimal distance, Layer 2
Multiplexer	18 / 13 / 5	1,15	3,68
4AND	8 / 4 / 4	1,65	2,18
4NOR	7 / 5 / 2	1,27	6,35
XNOR	9 / 7 / 2	1,15	1,18
Memory Cell	278 / 249 / 29	1,10	1,24
4xAdder	79 / 58 / 21	1,80	2,05
Total	67 / 56 / 11	1,35	2,78

It should be mentioned that one of the simplest DFM rules is an increase of the minimal distance between polygons [12]. In average, the minimal distance between the polygons in the layer for all our tests is increased above 35%. It is obvious that the reproducibility of the critical layout layer will be better in a comparison with the initial design. However, this improvement strongly varies for several test cases, from the minimum of 10% for the memory cell to 80% for the adder. In addition, this parameter varies for layers (Layer 1 and Layer 2) that were created after layout decomposition for double patterning. This deficiency has to be overcome to increase yield.

5   Conclusion

We have proposed a novel layout decomposition algorithm to address design needs for radiation hardened layout design. Our approach practically and effectively improves layout quality. It has been implemented using the contradiction graph and our modified concurrent breadth-first search algorithm. Our soft computing approach to manage contradictions in the layouts is novel and has advantage in terms of adaptability. Another aspect of our research is the use of high performance computing platforms for our design iterations. Our experiments using artificial and real-world test cases indicate that minimal distance is increased for all test cases.

Our ongoing research is in the following directions. The irregularity of layouts after decomposition results in lower yield. In order to overcome this deficiency optimization techniques will be used.

Our results can be used in design flow of radiation hardened electronics for several applications including space industry, collective awareness systems, emerging systems etc.

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