Layer Reassignment for Antenna Effect Minimization in 3-Layer Channel Routing *

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Abstract

As semiconductor technology enters the deep submicron era, reliability has become a major challenge in the design and manufacturing of next generation VLSI circuits. In this paper we focus on one reliability issue - the antenna effect in the context of 3-layer channel routing. We first present an antenna effect model in 3-layer channel routing and, based on this, an antenna effect cost function is proposed. A layer reassignment approach is adopted to minimize this cost function and we show that the layer reassignment problem can be formulated as a network bipartitioning problem. Experimental results show that the antenna effect can be reduced considerably by applying the proposed technique. Compared with previous work, one advantage of our approach is that no extra channel area is required for antenna effect minimization. We show that layer reassignment technique can be used in yield-related critical area minimization in 3-layer channel routing as well. The trade-off between these two objectives is also presented.

1: Introduction

Continued advances in IC technology along with the development of packaging technologies with superior thermal characteristics enable an increase in the level of integration of VLSI systems. In this process, the aggressive scaling of device and interconnect dimensions has played, and in the foreseeable future will still play, an important role in achieving significant improvements in VLSI performance and circuit density. However, scaling has a detrimental effect on reliability due to increase in current density, electric field, leakage currents and oxide breakdown [1]. As a result, reliability has become a major issue and challenge in the design and manufacturing of next generation deep-submicron VLSI circuits [2, 3, 4, 5].

In this paper, we focus on the antenna effect [6, 7, 8, 9], one of the important reliability issues in today's VLSI systems, in the routing stage of VLSI design. The antenna problem is a side effect of various plasma-based manufacturing processes such as etching, etc. These plasma-based processes are widely used to get the fine feature size of modern IC. Plasma etchers or ion implanters can induce a voltage into isolated leads, overstressing thin gate oxides. The leads (polysilicon or metal) act like an antenna to collect charges and the accumulated charges may result in oxide breakdown. These charges may also have a negative effect on hot-carrier device aging lifetime [10]. As device scaling goes on, the oxides of new devices are getting thinner and thinner and, as a result, the problem of antenna effect is expected to become worse and worse.

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Though the plasma-induced charging mechanism is not fully understood, it has been found that the charging appears to be a problem when some poly and/or metal wires, which are neither covered by a shielding layer of oxide nor connected to the substrate by previously formed p-n junctions, are exposed to plasma [6, 7, 8, 9]. It has also been found that stressing due to plasma etching can be modeled as a constant current stress with the stressing current being proportional to the peripheral length of the metal or polysilicon patterns [6, 7]. In channel routing, the peripheral length can be simply represented by the length of the metal or poly wire segments and therefore, minimization of the antenna effect in channel routing can be achieved by minimizing the length of potential antennas.

The only published research in the area of routing for antenna effect minimization has been done at the University of California in Santa Barbara by Wang et al [11]. They proposed several techniques to minimize the antenna effect in 3-layer channel routing. One drawback of their approach is the penalty of channel height increase. For example, their router requires two more tracks (14 tracks compared with 12 tracks obtained by their own conventional 3-layer router) in the Deutsch difficult example to minimize the antenna effect. This is a 17% increase in routing area, which is unacceptable in many cases.

We adopt a different approach. Instead of creating a new router to target the antenna effect, we developed a layer reassignment algorithm that can be used as a layout post-processor to modify any already routed layout to minimize the antenna effect with no increase in routing area. Experimental results show that this approach is promising and substantial reductions in antenna length have been achieved.

The paper is organized as follows. First, in Section 2, the antenna effect in 3-layer channel routing is analyzed, and a new objective function for antenna effect is presented. Then, in Section 3, the problem of layer reassignment for minimum antenna effect is formulated as a network bipartitioning problem. The relationship between antenna effect minimization and yield optimization is studied in Section 4. In Section 5, some experimental results are presented and it is shown that the antenna effect as well as the critical area can be reduced substantially by layer reassignment. The conclusions are summarized in the last section.

2: Antenna Effect in 3-Layer Channel Routing

The basic channel routing problem can be formulated as follows. Given a rectangle channel, which has horizontal grid tracks and vertical columns, and a netlist, which is usually represented by two lists of net terminals on the top and bottom of the channel, respectively, we are asked to connect all the nets such that the height of the channel is minimized. The constraint that must be observed during the routing procedure is that wires of different nets cannot overlap or intersect in the same layer. Among all the terminals for each net, one terminal is the driver or source of the signal, and the remaining terminals are receivers. We distinguish between driver and receiver because they play an important role in determining the antenna effect as will be elaborated later in this paper.

We study 3-layer channel routing in this paper. The two most common routing styles for 3-layer channel routing are HVH (horizontal-vertical-horizontal) and VHV (vertical-horizontal-vertical). In [11], it was shown that in VHV routing, the length of each antenna can be limited to the height of the routing channel by insisting that for each net its driver is connected to a vertical wire segment in layer one. This is not a very restrictive constraint and there is typically no increase in channel height by doing this. This suggests that the antenna effect can usually be eliminated in VHV routing. We will therefore focus on HVH routing, which is also more important than VHV routing in practice since a HVH router can usually achieve a better result than a VHV router [12].

In HVH routing, two layers can be used to route horizontal wire segments. Without losing generality, we assume that the two horizontal layers in all the examples used in this paper are Metal_1 and Metal_3, respectively, and the vertical layer is Metal_2.

During the manufacturing process, all terminals belonging to the same net will finally be connected. However, before the net becomes fully connected there are situations when some interconnects are fabricated while they are connected to receivers only, and this can cause an antenna effect. More specifically, after the Metal_2 etching and Metal_1/Metal_2 via fabrication in HVH routing, some receiver type terminals may be connected to long incomplete interconnects which comprise Metal_1 and Metal_2 segments, and they are not connected to their drivers due to the lack of the Metal_3 interconnects. Those long incomplete interconnects act like antennas and the charges collected by them during the previous manufacturing processes can have a negative effect on the gate oxide of the receivers. An example of an antenna in 3-layer channel routing is shown in Figure 1, where Figure 1(a) is a given layout and the antenna in this layout is shown in Figure 1(b).

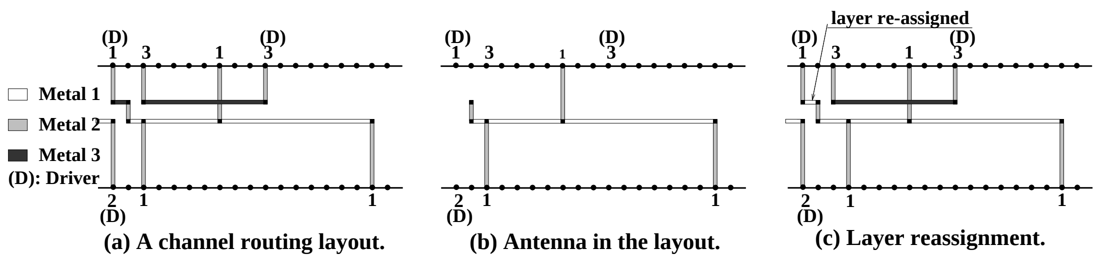


Figure 1: Antenna effect in 3-layer channel routing.

Since the risk of the gate oxide damage is proportional to the charge collected by the antenna, which is in turn proportional to the antenna length, we can reduce the gate oxide unreliability due to the antenna effect by minimizing the antenna length for each net. Based on this argument, we formulate our objective function as minimizing the longest antenna in the channel

$$Minimize\ Max\ \text{(antenna length of net i)} \qquad \text{for every net i} \tag{1}$$

If two or more solutions tie in the cost function defined in (1), we can use the following secondary cost function to break the tie:

$$Minimize \sum_{\text{all nets}} \text{(antenna length of net i)} \tag{2}$$

3: Layer Reassignment to Minimize Antenna Effect

We assume that we are given a layout which may have been generated by any HVH router. Several such routers are available [13, 14, 15]. We keep the vertical wire segments unchanged and for each horizontal wire segment there are two possible choices for layer assignment, one is Metal_1, and the other is Metal_3. To illustrate the basic idea of layer reassignment for antenna effect minimization, we use the example in Figure 1 (a). We can reassign one of the wire segments of net 1 from Metal_3 to Metal_1, as shown in Figure 1 (c), and all the antennas in net 1 can be eliminated by this layer reassignment.

Basically, a horizontal wire segment will not become part of an antenna iff

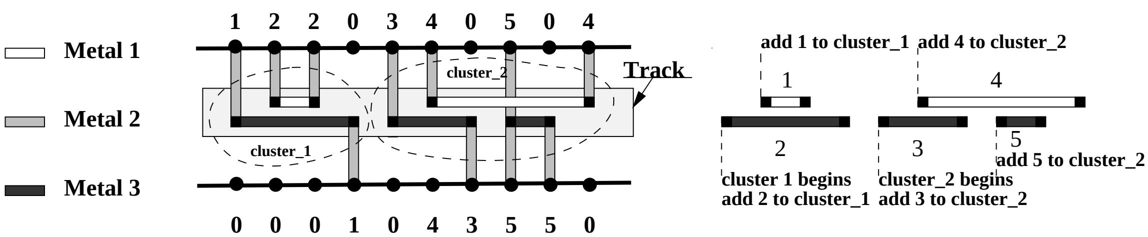
- it is Metal_3, or

- it is Metal_1 but it can be connected to its driver without using any Metal_3 wire segments

We can use these two criteria to determine the contribution of a horizontal wire segment to the antenna effect during layer reassignment.

By representing each horizontal wire segment as a vertex in a graph, we can formulate the layer reassignment problem as a network bipartitioning problem. There are two possible choices for each node, Metal_1 or Metal_3, and our problem is to find an optimal bipartitioning of the nodes such that the objective function defined in (1) and (2) can be minimized. This is similar to the classical network bipartitioning problem; however, in our problem the assignments of vertices, which represent the horizontal wire segments, are not independent, which means that sometimes two wire segments must be placed in the same layer, while sometimes they must be put in different layers. This is illustrated in an example shown in Figure 2 (a). In Figure 2 (a), there is an one-track channel, and there are five wire segments belonging to five different nets in this track. To get a valid channel routing solution, *wire_1* of *net_1* and *wire_2* of *net_2* must be placed in two different layers to prevent *net_1* from connecting with *net_2*.

To solve this inter-dependence problem, we introduce the notion of *cluster*. A *cluster* is a set of wire segments whose layer assignments are dependent on each other. Clusters in a track can be easily found by scanning the track from one end to the other. When the scan line encounters a new wire segment, we check whether this segment overlaps with other wire segments in current cluster. If it is, we add this segment to the current cluster, otherwise, we finish the current cluster and start a new one. An example of building a cluster is shown in Figure 2 (b), where five wire segments form two clusters. We select one wire in each cluster as a reference point to represent the layer the cluster belongs to, and there are only two possible layer assignments for any cluster, one is assigning the reference wire segment to Metal_1 and the other assigning it to Metal_3. The layer assignment of different clusters is independent of each other. By using clusters to represent the horizontal wire segments, we can get a formulation similar to the classical network bipartitioning problem, but they are not identical since we are minimizing here the objective function defined in (1) and (2) instead of the total weighted cuts between the bipartite subgraphs.



(a) A channel routing layout. **(b) Building a cluster.**

Figure 2: A set of wire segments can be grouped into a cluster.

4: Relation with Yield Enhancement

Since layer reassignment can also be used for reducing yield related critical area [16], it is interesting to compare solutions for these two different objectives. If we assume that the probabilities of an open-circuit type fault for the two horizontal layers are the same, layer reassignment of the horizontal wire segments will not change the total length of wires, or the total open-circuit type critical area in the channel. Therefore, we can focus on the critical area for short-circuit faults, which are also much more important than open-circuit faults in practice [17]. Since the vertical wires are kept unchanged during layer reassignment, so does the critical area between vertical wires. As a result, we only need to consider the critical area between horizontal wires. The critical area between two horizontal wires is represented by the length of their overlap if these two wires are in the same layer and they reside in adjacent tracks. We ignore the critical area between two wires which are not in adjacent tracks, and this simplification is based on the observation that the diameter x of a defect has a density function $f(x)$ that decreases as $1/x^3$ [18], and therefore, the error introduced by ignoring the critical area between non-adjacent wire segments is small. Similar to layer reassignment for antenna effect minimization, we use clusters to represent a group of wire segments. Each cluster can be represented as a node in a graph, and there is an edge between two clusters iff there is at least a pair of wires, one from each cluster, which are adjacent and overlap. We further assume that the probabilities of short-circuit faults for Metal_1 and Metal_3 are the same. Under this assumption, the weight of a edge between two clusters can be defined as $Critical\_Area_{diff} - Critical\_Area_{same}$ [16], where $Critical\_Area_{diff}$ and $Critical\_Area_{same}$ are the critical areas between these two clusters when the reference wires of these two clusters are assigned to different layers and the same layer, respectively. The critical area minimization problem can thus be formulated as a network bipartitioning problem where we want to partition the graph to minimize the total weighted cuts.

Sometimes we want to minimize both antenna effect and critical area; this can be achieved by minimizing a weighted sum of these two objective functions, which is defined as follows

$$Minimize\ COST = a \cdot COST_{ant} + (1 - a) \cdot COST_{cri} \qquad (3)$$

where a is the weight parameter which has a value between 0 and 1. $COST_{ant}$ and $COST_{cri}$ are the cost functions for antenna effect and critical area, respectively. By adjusting the value of a, we can change the relative importance between antenna effect and critical area in our objective function.

5: Experimental Results

To test the effectiveness of the proposed technique, three-layer layouts have been generated for a set of channel routing examples by using the three-layer channel router described in [15]. The information about each benchmark, such as number of nets, number of tracks and number of columns of the channel is shown in Table 1.

Examples	#nets	#tracks	#columns
ex1[20]	34	6	35
ex3b[20]	46	9	61
ex3c[20]	54	9	79
D1[15]	65	9	155
Diff[21]	72	10	174

Table 1: 3-layer channel routing benchmark examples.

Since no driver/receiver information is provided in these benchmarks, we randomly select one terminal from each net as a driver while assigning all other terminals in the net as receivers. We use the Kernighan-Lin based network bipartitioning algorithm [19] to perform layer reassignment to minimize the antenna effect and the critical area. The cost functions for antenna effect and critical area are the maximum antenna length and the critical area between horizontal wires, respectively, both normalized by their original values. The total cost function is defined as in (3) with a weight parameter a. Various values of a have been tried, and for each value, 50 examples with different randomly assigned drivers and receivers have been run. The results for each example with different values of a are shown in Table 2, and the average percentage gains in antenna effect and critical area are summarized in Table 3.

Examples	a	max antenna (% increase)	critical area (% increase)
ex1[20]	original	4.38	119.00
	0.00	5.62 (18.7)	71.00 (-40.3)
	0.25	4.80 (9.6)	72.50 (-39.1)
	0.50	4.28 (-2.2)	85.22 (-28.4)
	0.75	4.14 (-5.5)	89.52 (-24.8)
	1.00	4.14 (-5.5)	119.40 (0.3)
	1.0+	4.14 (-5.5)	115.26 (-3.1)
ex3b[20]	original	7.90	207.00
	0.00	7.90 (0)	146.00 (-29.5)
	0.25	7.86 (-5.1)	146.00 (-29.5)
	0.50	7.86 (-5.1)	146.00 (-29.5)
	0.75	7.86 (-5.1)	146.00 (-29.5)
	1.00	7.80 (-5.1)	240.84 (16.3)
	1.0+	7.80 (-5.1)	146.00 (-29.5)
ex3c[20]	original	9.86	403.00
	0.00	14.36 (45.6)	280.00 (-30.5)
	0.25	8.06 (-18.2)	292.70 (-27.4)
	0.50	7.84 (-20.5)	296.12 (-26.5)
	0.75	7.84 (-20.5)	296.12 (-26.5)
	1.00	7.84 (-20.5)	344.48 (-14.5)
	1.0+	7.84 (-20.5)	310.98 (-22.8)
D1[15]	original	72.94	620.00
	0.00	55.72 (-23.6)	445.00 (-28.2)
	0.25	9.64 (-86.8)	461.00 (-25.6)
	0.50	9.04 (-87.6)	464.14 (-25.1)
	0.75	9.04 (-87.6)	462.10 (-25.5)
	1.00	9.00 (-87.7)	557.46 (-10.1)
	1.0+	9.00 (-87.7)	485.62 (-21.7)
Diff[21]	original	56.94	865.00
	0.00	58.50 (3.2)	810.00 (-6.3)
	0.25	22.74 (-59.9)	828.48 (-4.2)
	0.50	19.98 (-64.7)	845.44 (-2.3)
	0.75	15.50 (-72.6)	890.60 (3.0)
	1.00	14.02 (-75.2)	1016.14 (17.5)
	1.0+	14.02 (-75.2)	961.14 (11.1)

Table 2: Results of the layer reassignment technique on benchmark examples.

In Table 2, the second column is the value of a, where $a = 1.00$ means minimizing antenna effect only, while $a = 0$ means minimizing critical area only. Values between 0 and 1 result in a trade-off between antenna effect and critical area. The meaning of $a = 1.0+$ will be explained later. The third column in Table 2 is the maximum antenna length and its percentage increase, and the last column shows the critical area between horizontal wire segments and its percentage increase in a channel.

The results for different examples in Table 2 are averaged and summarized in Table 3. From Table 3, we can see the impact of our layer assignment technique on antenna effect and critical area minimization. If antenna effect is our only optimization goal, we can get an average of 38.7% decrease in maximum antenna length by setting $a = 1.00$ in our cost function. Or we can get an average of 27.0% decrease in critical area by setting $a = 0$, if we want to optimize critical area only. We can reduce both antenna length and critical area by setting a to a value between 0 and 1. By adjusting the value of a we can make trade-offs between antenna effect minimization and yield optimization. We have also tested the possibility of first performing antenna effect minimization and then yield optimization by using the new maximum antenna length as a constraint. The results are shown in Figure 2 and Figure 3 under the label "$a = 1.0+$". We find that this approach can obtain an average of 13.2% reduction in critical area with no increase in antenna effect.

a	Average	
	max antenna (% increase)	critical area (% increase)
0.00	8.8	-27.0
0.25	-32.6	-25.2
0.50	-36.0	-22.4
0.75	-38.3	-20.6
1.00	-38.7	5.9
1.0+	-38.7	-13.2

Table 3: Results summary.

Considering the average improvement only may be misleading, since the amount of improvement varies significantly from one example to the other. Taking $a = 0.50$ as an example, the decrease of the antenna length can be as high as 87.6% in benchmark D1, or as low as 2.2% in ex1, as shown in Figure 2. The reason behind this is that ex1, as well as exyk3b and exyk3c, has a very short antenna in its original layout due to the lack of doglegs in its original routing solution, and therefore the room for improvement is much smaller compared with D1 and Diff, which have more nets and occupy larger channels, as shown in Table 1. From the yield point of view, our layer reassignment approach has a less satisfactory performance in the Deutsch difficult example compared with the situations in other benchmark examples. As shown in Table 2, the best we can get for critical area reduction in the Deutsch difficult example is 6.3%. In some cases ($a = 0.75$, 1.00 and 1.0+), antenna effect minimization comes at the cost of an increase of the critical area. This is mainly due to the high channel density in the Deutsch difficult example resulting in less room for yield improvement than in other examples.

Since the 3-layer channel router used in [11] is unavailable [22], we cannot use their router to generate antenna effect optimized routing solutions for the benchmark examples and compare them with those obtained by our layer reassignment technique. The only comparison we can do is comparing our result on the Deutsch difficult example with theirs. Since they don't consider the critical area in their approach, we use the result when $a =$ 1.0. Both results for the Deutsch difficult example are shown in Table 4.

	max antenna length	average antenna length	#tracks used
Result in [11]	15	7.22	14
Our Result	14.02	7.54	10

Table 4: Comparison with previous work.

From Table 4, we can see that the two approaches achieve similar quality solutions for the Deutsch difficult example in terms of maximum antenna length and average antenna length. However, in [11] 14 tracks were used, while we use only 10 tracks. This corresponds to a 30% savings in channel area.

6: Conclusion

A layer reassignment technique has been developed to minimize the antenna effect in 3-layer channel routing. Experimental results show that an average of 38.7% reduction in antenna effect can be obtained on a set of benchmarks by applying the proposed layer reassignment technique. Compared with previous work, this improvement in antenna effect reliability comes with no penalty of a channel height increase. We have also shown that layer reassignment can be used to reduce yield related critical area in 3-layer channel routing as well. Trade-offs between these two different optimization goals can be obtained by adjusting the weight parameter in the cost function.

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